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Program
SC-2 | Integrated Circuits for Detector Signal Processing

Coordinator: Paul O’Connor, Brookhaven National Lab, USA

This one-day course is intended to introduce physicists and detector specialists to the fundamentals of integrated circuit front end design. The class begins with a discussion of low-noise signal processing and semiconductor devices and then delves into the details of implementing practical circuits in modern CMOS technology. A basic knowledge of detectors and electronics is assumed.

Outline

1. Pulse Processing Fundamentals
   - Signal formation in detectors
   - Noise and gain mechanisms
   - Pulse processing for amplitude and timing extraction

2. Semiconductor Technology for Integrated Circuit Front Ends
   - Operation and characteristics of MOS and bipolar transistors
   - Sub-micron CMOS and BICMOS technology
   - Feature size scaling
   - Radiation effects and reliability
   - Mixed-signal circuits
3. Brief introduction to design methodology, CAD tools and foundry access for research-scale projects

4. Analog circuit design
   - Elementary amplifier configurations
   - Building blocks for the analog channel: charge-sensitive and pulse-shaping amplifiers, baseline stabilizers, peak detectors, track/hold, multiplexers, output stages
   - Feature extraction: event occurrence, position, time, energy
   - Analog-to-digital and time-to-digital converters (ADC and TDC)

5. Application examples from particle physics, astrophysics, photon science, and medical imaging

Instructors

Paul O'Connor is a group leader in the Instrumentation Division at Brookhaven National Laboratory. After receiving the Ph.D. degree in solid-state physics from Brown University he worked from 1980-1990 at AT&T Bell Laboratories prior to joining BNL. His research interests are in the field of instrumentation systems for radiation detection, particularly those involving low noise front-end electronics. He is author and co-author of about 130 publications and has been an IEEE member since 1980.

Christophe de La Taille is Director of OMEGA microelectronics lab at Ecole Polytechnique and CNRS/IN2P3 (France). After receiving engineering and Ph.D. degree from Ecole Polytechnique, he joined LAL Orsay and worked on the readout of the ATLAS calorimeter at CERN/LHC and other high energy physics experiments. He was subsequently CTO of IN2P3 and recently founded a design lab at Ecole Polytechnique. He is now coordinator of CMS HGCAL electronics. His research interests are in the field of detectors and mixed signal ASIC design. He is author and co-author of about 168 publications and has been an IEEE member since 2003.

Sergio Rescia is a scientist at the Instrumentation Division at Brookhaven National Laboratory. He received an engineering degree from University of Pavia, Italy and a Ph.D. degree from University of Pennsylvania, Philadelphia, USA. After joining Brookhaven National Laboratory he has worked on the readout of liquid argon calorimeters (Helios-NA48, Atlas), silicon detectors, time projection chambers (MicroBoone, SBND, Dune, nEXO) and medical electronics. His research interests center in the field of instrumentation
for particle and radiation detectors, particularly optimizing the detector – low noise front end interface. He is author or co-author of over 130 publications and has been an IEEE member since 2002.
This two-day course provides an overall review of the basic principles that underlie the operation of all major types of instruments used in the detection and spectroscopy of charged particles, gamma rays, and other forms of ionizing radiation. Examples of both established applications and recent developments are drawn from areas including particle physics, nuclear medicine, homeland security, and general radiation spectroscopy. Emphasis is on understanding the fundamental processes that govern the operation of radiation detectors, rather than on operational details that are unique to specific commercial instruments. This course does not cover radiation dosimetry nor health physics instrumentation. The level of presentation is best suited to those with some prior background in ionizing radiation interaction mechanisms. Those with prior experience in radiation measurements would benefit from discovering concepts and applications outside their experience base. A complete set of course notes is provided to registrants, and a recent copy of Radiation Detection and Measurement by G. F. Knoll is highly recommended.

Outline

- Fundamental Concepts in Ionizing Radiation Detection
- Gas-Filled Detectors
- Scintillation Detectors
- Semiconductor Detectors
- Analog and Digital Electronics for Radiation Measurements
- Pulse Shape Discrimination and Multi-modality Sensing
- Recent Detector Developments and Summary
Instructors

Sara Pozzi is a Professor of Nuclear Engineering and Radiological Sciences at University of Michigan. She previously worked at the Oak Ridge National Laboratory, and currently serves as the Director of the Consortium for Verification Technology. She and her group have developed new methods for digital pulse shape discrimination using organic scintillators read out by photomultiplier tubes and silicon photomultipliers for applications in nuclear nonproliferation and homeland security.

Robert Redus is a Member of the IEEE and is the Chief Scientist and Director of Engineering at Amptek, an Ametek company in Bedford, MA. He has spent over thirty years designing instruments for radiation detection and measurement, for many applications and many customers. These include X-ray spectroscopy, gamma-ray spectroscopy using compound semiconductors, scintillators, and HPGe detectors, and space radiation measurements.

Kanai Shah is the President of Radiation Monitoring Devices, Inc. His research areas of interest include novel scintillation materials for high resolution gamma-ray spectroscopy including CeBr3, LuI3:Ce and SrI2:Eu and dual mode scintillators such as Cs2LiYCl6:Ce, Cs2LiLaBr 6:Ce and Cs2LiLa(Br,Cl)6:Ce for combined detection of gamma-rays and neutrons. He has also worked in the areas of ceramic scintillators including garnets and silicates, and organic crystalline and plastic scintillators for neutron detection.

Graham Smith is a Senior Physicist at Brookhaven National Laboratory. He received a Ph.D. in Physics from Durham University, England. He has worked for the last thirty-five years at Brookhaven National Laboratory, USA, on development of advanced radiation instrumentation for experimental studies using neutrons, X-rays and charged particles, specializing in gas-filled detectors. He is an IEEE Fellow.

Lothar Strueder is the scientific director of PNSensor GmbH and professor at the University of Siegen. He earned his Ph.D. in Experimental Physics at the TU Munich in 1988. His interests include position-, energy-, and time-resolving detectors for photons and particles. He is author or co-author of more than 300 technical and scientific publications. He has been issued 13 worldwide patents in scientific instrumentation.

David Wehe is Professor of Nuclear Engineering and Radiological Sciences at University of Michigan. He worked at the Oak Ridge National Laboratory as a Wigner Fellow, and served as Director of the Michigan Phoenix Memorial Project, which included the 2-MW Ford Nuclear Reactor. His teaching and research have focused on applied radiation
measurements, and is an editor for Nuclear Instruments and Methods in Physics Research.
SC-3 | Fast timing detectors for HEP and medical applications

**Coordinators:** Jona Bortfeldt, LMU, Germany; Nicolo Cartiglia, INFN, Italy

This **two-day course** will cover fast timing detectors and their application in high energy and medical physics. The first day focuses on high energy physics instrumentation. Different timing detectors, based on charge detection in silicon and gas, or light detection from scintillators and Cherenkov radiators are described, their working principles and characteristics are discussed. Signal analysis and reconstruction are described and the influence of analog and digital electronics is discussed in detail. The last lesson of the day focuses on the system aspects and the challenges of designing a complex ASIC, using examples from the latest ASIC currently in the R&D phase.

On the second day, the course is instead focused on the application of fast timing detectors in medical physics, namely in TOF-PET or in-beam PET systems, in prompt-gamma imaging or in beam monitoring applications. Signal generation and analysis, analytical and Monte Carlo based modeling are described, together with an in-depth review of currently available and novel commercial PET systems. The development and performance of new scintillator materials are reviewed, and suitable photo-detectors are discussed.

**Outline**

1. Silicon detectors for 4D tracking in High Energy Physics (**Cartiglia**)
   - Basics of signal formation, Ramos’ theorem
   - Signal from thin and thick Silicon detectors
   - Why thin sensors with internal gain are critical to a good time resolution
   - Radiation damage effect on the gain mechanism
2. Gaseous detectors for timing measurements (Bortfeldt)
   - Large area, cost-effective timing, and trigger detector
   - Functional principles, characteristics and performance of different gaseous timing detectors: Resistive Plate Chambers, Thin Gap Chambers, Fast Timing MPGD

3. Readout electronics for fast timing detectors (de La Taille)
   - Electronics speed and noise impact on timing resolution
   - Preamplifier configurations for high-speed response: voltage vs. current or charge sensitive
   - Theoretical expressions for jitter due to electronics noise
   - Examples of simulated and measured responses from different configurations
   - Examples of preamplifier schematics

4. ADC-based waveform samplers for timing detectors (Gui)
   - Overview of waveform samplers for timing detectors
   - ADC-based waveform sampler design: targeting specifications and challenge
   - Circuit architectures and design techniques (Successive Approximation Register (SAR) and Pipelined SAR structures)
   - Time-interleaving approach to achieve a very high sampling rate
   - Calibration methods for intra-channel and inter-channel mismatches
   - Example ADC designs and simulation/measurement results

5. System aspects for fast timing detectors (Liu)
   - Design methodology to optimize front-end design from a system point of view
   - System power and cooling constraint and how it influences ASIC design
   - Precision clock distribution considerations: from system to detector, to chip, to pixel and to each TDC delay unit
   - Design for monitoring and calibration considerations
   - Time-frame of ASIC development: choice of “several miniASICs vs. single full ASIC”
   - Examples of ASICs developed in recent years
6. Introduction to fast timing applications in Medical Physics (Schaart)
   - Time-of-flight positron emission tomography (TOF-PET)
   - Organ-specific and in-beam PET systems
   - Prompt gamma detection in hadron therapy
   - Basic principles of fast timing scintillation detectors in Med Phys
   - Theory of scintillation detector time resolution timing properties of the scintillation signal
   - Monte Carlo modeling of time resolution
   - Analytical models of time resolution
   - Order statistics and Cramer-Rao modeling

7. Photosensors in fast timing scintillation detectors (Schaart)
   - Signal formation in common photosensors
   - Temporal properties of common photosensors
   - Factors affecting time resolution
   - Readout of fast timing photosensors

8. Exploiting timing information in particle therapy (Cerello)
   - Timing in particle therapy: where and how?
   - Beam monitoring applications
   - Range monitoring applications
   - New delivery concept(s)
   - Flash therapy

9. Development on scintillators for fast timing detectors (Auffray)
   - Scintillation mechanisms
   - Key factors and limits of the scintillators properties for fast timing detection
   - The recent development on scintillators fields to push time resolution toward 10ps

10. System review: the latest commercial TOF PET systems (Surti)
    - Detector design of PMT based TOF PET systems and their limitations.
    - Detector design of the latest digital TOF PET systems and other system design improvements.
    - TOF image reconstruction methods and their impact on clinical lesion detection and quantitative measurement performance.
New developments in PET system design with a focus on long axial FOV systems.

Instructors

Etienne Auffray is a Member of the IEEE, and she has been a member of the RISC committee. She is a senior physicist at CERN, Geneva, Switzerland. She has spent over twenty-five years in the field of scintillators and their applications in particular in high energy physics and medical applications. She was actively involved in the construction of the electromagnetic calorimeter of the CMS experiment at CERN made of 75848 crystals of PWO and now in its operation. She is involved in research activities on scintillating materials for the development of PET and TOFPET through the Crystal Clear collaboration of which she is the spokesperson since 2010. In recent years she has coordinated several European projects related to scintillating materials and their applications in particular in recent years for fast timing detectors.

Jonathan Bortfeldt is Staff Scientist at the Department of Medical Physics of the Ludwig-Maximilians-Universität (LMU) Munich, Germany. He received his Ph.D. in High Energy Physics from LMU Munich in 2014, developing novel micro-pattern gaseous detectors. After post-doctoral work at LMU, he became CERN-COFUND fellow, working on the ATLAS New Small Wheel upgrade with Micromegas. In 2018, he took over the instrumentation lab at the Department of Medical Physics of LMU Munich. He is co-convener of the Picosec Micromegas collaboration, and member of the RD51 and the ATLAS collaborations. Dr. Bortfeldt’s main research interest is the development of high (spatial and temporal) resolution instrumentation for pre-clinical research and laser-accelerated beams.

Nicolò Cartiglia is a Senior Scientist at INFN-Torino. After receiving his Ph.D. from UCSC, he moved to Columbia University and then in 1998 joined INFN. His carrier focuses on the development of new instrumentation for high energy particle experiments. He worked on several experiments, specializing on Silicon sensors. Currently, he is working on the development of a Silicon-based tracking system able to measure time and position concurrently. In recent years, he has been awarded a European ERC-advanced grant and a PRIN grant from Italy.

Piergiorgio Cerello is Senior Researcher at INFN, Italy, Torino Unit. He received his Ph.D. in Nuclear Physics in 1995 and is among the founders of the ALICE experiment at the CERN LHC. In the past two decades, he focused mostly on Medical Applications, setting up a Medical Imaging group in Torino, active on both software and hardware.
projects. It applied artificial intelligence techniques to the search for lung nodules in chest CT, by developing an algorithm that was clinically validated. Recently, the group took part, with a major role, in the development of the INSIDE hybrid scanner for online range monitoring in particle therapy.

**Ping Gui** is a Full Professor of Electrical and Computer Engineering at Southern Methodist University, Dallas, TX, USA, and an IEEE senior member. Her research focuses on analog and mixed-signal IC design, including radiation-tolerant and high-speed ADCs, PLLs, and data link design. Her research group has developed 56GSps ADCs for 100/400G optical communications, 4x10Gbps laser driver and E-links for the LpGBT and the Versatile Link Plus projects (VL+), and PLL and Data Links capable of operating under cryogenic environments in the DUNE Project. Ping Gui is currently the principle investigator on a DoE awarded project to develop high-speed high-resolution ADCs and waveform samplers for high-energy physics applications.

**Christophe de La Taille** is director of OMEGA microelectronics lab at École Polytechnique and CNRS/IN2P3 (France). After receiving engineering and Ph.D. degree from École Polytechnique, he joined LAL Orsay and worked on the readout of the ATLAS calorimeter at CERN/LHC and other high energy physics experiments. He was subsequently CTO of IN2P3and recently founded a design lab at École Polytechnique. He is now coordinator of CMS HGCAL electronics. His research interests are in the field of detectors and mixed signal ASIC design. He is author and co-author of about 168 publications and has been an IEEE member since 2003.

**Tiehui Ted Liu** is a senior scientist at Fermilab. After receiving his Ph.D. in physics from Harvard in 1995 (CLEO experiment at Cornell), he worked at Princeton from 1995-1997 (on BELLE at KEK), Berkeley Lab from 1997-2000 (BABAR at SLAC), and then moved to Fermilab since year 2000 (on CDF and then CMS). He has been involved in many aspects of particle physics instrumentation, ranging from (current) CMS Endcap Timing Layer upgrade, to tracking trigger R&D for HL-LHC, various trigger systems at CDF and BABAR, Aerogel-based Cherenkov detector at Belle, and Time-of-Flight system at CLEO.

**Dennis R. Schaart** is head of the section Medical Physics & Technology at the Radiation Science & Technology department of Delft University of Technology (TU Delft). He started his career as an R&D physicist at Nucletron (now Elekta), where he developed new devices for radiotherapy. In his private time he wrote a Ph.D. thesis on the subject of intravascular brachytherapy, for which he obtained his doctoral degree (with highest honors) at TU Delft in 2002. He subsequently joined the university to set up a new research
line on in-vivo molecular imaging technology, with special focus on ultrafast detectors for time-of-flight positron emission tomography (TOF-PET). His main research interests include novel methods and technologies for in vivo molecular imaging and for image guidance in (proton) radiotherapy. Since 2016, he coordinates the research activities of TU Delft within the R&D program of the Holland Proton Therapy Centre (HollandPTC), a joint initiative of Erasmus Medical Centre (Erasmus MC), Leiden University Medical Centre (LUMC), and TU Delft. He furthermore serves as a member of the HollandPTC R&D Program Board. Dr. Schaart is a Senior Member of the IEEE and has served on the IEEE Nuclear and Medical Imaging Sciences Council (NMISC). He has (co-)authored more than 100 peer-reviewed papers and is a frequently invited speaker.

**Suleman Surti** is a Research Associate Professor in the Physics and Instrumentation group in the Department of Radiology at the University of Pennsylvania. He obtained his Ph.D. in Physics at the University of Pennsylvania and continued his post-doctoral work and faculty appointment in PET imaging research at Penn. Dr. Surti has been involved in PET imaging for over twenty years focusing on system development, optimization, and evaluation of several PET scanners developed at the University of Pennsylvania as well as new commercial systems ranging from small-animal PET through application-specific PET (brain, breast, proton) to whole-body PET (Non-TOF, TOF, long axial field-of-view). His work has spanned development of scintillation detectors and electronics, their incorporation in optimized scanner geometries, evaluation of system performance and data/image correction techniques, and optimization of imaging protocols.
WS-QTS | Quantum Technologies and Sensing Workshop

Ian Shipsey
Marcel Demarteau

Quantum technologies and sensors offer unprecedented sensitivity in many areas, exploiting quantum effects in particles, coherence or entanglement. Examples of quantum sensors include atomic vapours and clocks, and SQUIDs. This workshop is for researchers interested in quantum effects including (but not limited to):

- Fundamentals of quantum technologies and detection
- Quantum magnetic sensing of charge flow, cellular and brain activity, surveying, and/or imaging
- Gravity sensing and its applications in mining, engineering and homeland security sectors
- Manipulation of light and its transport
- Quantum clocks and timing applications
WS-QTS-01

WS-QTS-02 8:30 AM

Introduction
Ian Shipsey
Oxford University, UK

WS-QTS-03 8:35 AM

The promise of the 2nd quantum revolution
J.C. Seamus Seamus Davis
Oxford University, Oxford, UK

The promise of the 2nd quantum revolution with reference both to the way it can transform society and enable tests of the fundamental physics through quantum sensing.

WS-QTS-04 9:05 AM

Quantum Sensing for Fundamental Physics- A UK Programme
Ian Shipsey
Oxford University, UK

In the 20th century, our discovery, formulation and understanding of quantum mechanics heralded a new generation of scientific advances that in turn led to technologies from micro-electronics and computers to MRI, which are vital in sustaining and improving the human condition. These technologies underpin significant sections of the economies
of developed nations and have driven the “1st Quantum Revolution”. Future scientific and technological exploration, exemplified by this programme, will have deep and transformational consequences and form part of a “2nd Quantum Revolution”, embedding quantum technologies into the fabric and to the service of our society. In the near-term this will profoundly influence areas including communication, finance, healthcare, aerospace, and defence. A new programme Quantum Technologies for Fundamental Physics (QTFP) has just been announced by UKRI. It focuses on quantum technologies addressing major themes of the international roadmap of fundamental science, including the search for dark matter and probing the fundamental symmetries of the universe. Following investment in foundational technologies (the UKRI National Quantum Technology Programme – NQTP), QTFP is a major step towards harnessing these technologies, providing a positive feedback mechanism and driving practical applications of quantum sensors. Additionally positioning the UK as a first rank nation in the scientific exploitation of quantum technology while changing the way we understand and interact with our world.

WS-QTS-05 9:35 AM

Quantum materials for sensing applications

Yong Chen

Purdue University, USA

Quantum materials can feature intriguing properties and responses to external stimuli that may make them promising for a range of sensing applications. In this talk, I will discuss a few examples along these lines from our recent experimental research. Topics will include: 1) Topological insulators (TI) with spin-helical surface Dirac electrons: observation of a topological “spin battery” effect which may lead to an all-electrical nano-scale NMR-like sensor for nuclear spins [1], and a highly-skewed “ballistic” current-phase-relation (CPR) in Josephson junctions and SQUIDs made out of our TIs [2] that may have implications for magnetometers. In addition, a polarization-sensitive photocurrent is observed, suggesting potential applications in photodetectors with polarimetry. 2) Graphene and 2D materials in conjunction with undoped semiconductor substrates [3] or plasmonic structures [4] can enable novel photo detectors and radiation sensors. Time permitting, I may also discuss our recent work exploring NV centers and other color centers [5] in 2D materials as quantum sensors for magnetic/electric fields and their fluctuations.

WS-QTS-06  
COFFEE

WS-QTS-07  
Atom interferometry for fundamental physics and gravitational wave detection  
Jason Hogan  
Stanford, USA

Atomic sensors can be a powerful tool for discovery in fundamental physics. I will describe a new type of atom interferometry based on narrow-line optical transitions that combines inertial sensitivity with features from the best atomic clocks, allowing for increased immunity to technical noise and systematic errors. This technique is central to the Mid-band Atomic Gravitational wave Interferometric Sensor (MAGIS) proposal, which is targeted to detect gravitational waves in a frequency band complementary to existing detectors (0.03 Hz – 10 Hz), the optimal frequency range to support multi-messenger astronomy. I will also discuss MAGIS-100, a 100-meter tall atomic sensor now being constructed at Fermilab that will serve as a prototype of such a gravitational wave detector, and that will be sensitive to proposed ultra-light dark matter (scalar and vector couplings) at unprecedented levels.

WS-QTS-08  
Atom interferometry for fundamental physics on the ground, in microgravity and in space  
Waldemar Herr  
Hannover University, Germany

Atom interferometry is widely used for measuring rotations and accelerations with applications in navigation, geophysics/geodesy, and fundamental physics. Today’s inertial sensitive atom interferometry devices operate mostly with sources of laser cooled atoms. The finite temperature and size of these sources limit the efficiency of employed beam splitters and the analysis of systematic uncertainties. These limits can be overcome by the use of ultra-cold...

**WS-QTS-09**

**11:30 AM**

**Atom interferometry for fundamental physics and how quantum technology can help**

Kai Bongs

*Birmingham University, UK*

I will provide a brief introduction to atom interferometry and its applications in fundamental physics. I will highlight technical challenges and discuss programmes for atom interferometry in space and within the UK National Quantum Technology Hub in Sensors and Metrology, which provide pathways to more robust systems and economic impact.
Optical atomic clocks: from international timekeeping to fundamental physics

Helen Margolis
NPL, UK

Optical clocks are based on precision spectroscopy of narrow-linewidth atomic transitions. In the best clocks, perturbations to the atomic transition frequency can be controlled and evaluated to within a fractional uncertainty of just 1 part in 1018. This exceptional accuracy has enabled optical clocks to support many different applications, from international timekeeping to fundamental physics. The UK’s National Physical Laboratory is developing a range of optical atomic clocks and frequency combs with fibre links to allow high-accuracy optical frequencies to be compared against each other, both locally and internationally. Such comparisons are essential before incorporating optical clocks into international time scales. However, many aspects of fundamental physics can also be tested with these exceptionally accurate measurements. For example, frequency comparisons between clocks in different locations on the rotating Earth have placed new constraints on violations of Lorentz Invariance and have also been used to search for Dark Matter in the form of topological defects. This talk will present an overview of the state-of-the-art in optical clocks and frequency comparisons and highlight some of their applications.
fundamental limit, the so-called shot-noise-limit. It is known that this limit can be overcome by preparing the probe in a non-classical state. In my presentation, I will give an overview over the different non-classical states that have been implemented in the motion of single trapped ions and discuss their individual advantages and limitations. Possible applications for the presented experiments are the measurement of small oscillating electric fields and trapping frequencies. I will focus on our experimental work on Fock states, where quantum enhanced sensing in both scenarios is possible with the same quantum state.

**WS-QTS-13**

**Atomtronics for Quantum Sensing**

Malcolm Boisher  
*LANL, USA*

Atomtronics is the emerging technology of building circuits where the current is a flow of ultracold atoms propagating as coherent matter waves inside suitable waveguides. In this talk I will describe our atomtronic technology in which the waveguides are created with laser light via the optical dipole potential, and then discuss two quantum sensors based on it. First, we have demonstrated the atomtronic analogue of the dc SQUID and shown that it exhibits the quantum interference that gives the Superconducting Quantum Interference Device its name. In the conventional SQUID this is seen as a periodic variation of critical current with magnetic flux. In the atomtronic SQUID it causes a periodic variation of critical current with rotation, enabling the device to function as a gyro. Second, we have just created an atomtronic version of the Fiber Optic Gyro, in which rotation is measured by the Sagnac effect. In our device a Bose-Einstein condensate is split, reflected, and recombined inside a waveguide that is translated so that the wavepackets travel around a loop and realise a waveguide Sagnac atom interferometer.

**WS-QTS-14**

**COFFEE**
WS-QTS-15
3:30 PM

From dark matter detection to artificial intelligence: applications of superconducting nanowire single photon detectors
Sae Woo Nam
NIST, USA

Single-photon detectors are an essential tool for a wide range of applications in physics, chemistry, biology, communications, computing, imaging, medicine, and remote sensing. Ideally, a single photon detector generates a measurable signal only when a single photon is absorbed. Furthermore, the ideal detector would have 100% detection efficiency, no false positive (dark counts), and transform-limited timing resolution. Since the first reported detection of a single photon using a superconducting nanowire in 2001[1], steady progress has been made in the development and application of superconducting nanowire single photon detectors (SNSPD or SSPD) with ideal properties. I will briefly describe progress in detector developments, use of these detectors in new applications, and opportunities for future work.

WS-QTS-16
4:00 PM

Pushing dark matter axion detectors to higher frequencies with quantum sensors and microwave cavity networks
Christian Boutan
PNNL, USA

The discovery of a hypothetical elementary particle called the axion could simultaneously solve deep mysteries in quantum chromodynamics and cosmology. As direct-detection microwave cavity searches like the Axion Dark Matter eXperiment (ADMX) continue to look for yocto-watt power excess from axion-to-photon conversion at exceedingly higher axion masses, two losses in signal-to-noise need to be combatted: 1) the loss in signal power from decreasing detector volumes and 2) the increase in the quantum noise limit imposed by the uncertainty principal. I will motivate the axion as an excellent dark matter candidate, present an overview of ADMX, outline the challenges ahead and discuss the need for quantum information science solutions.
Quantum sensing technologies for the life sciences

Lykourgos Bougas

University of Mainz, Germany

In this lecture, I'll discuss recent developments in quantum sensing technologies and how these can, and are, transforming the life sciences. I'll present a general overview of different technologies with a primary focus on magnetometric and chiral-sensitive ones, and discuss how these allow for new insights into biological processes that were not possible with traditionally applied techniques. Finally, I'll present exciting results from developments in our laboratory that include the detection of biomagnetic signals from living organisms using quantum sensors, the development of biomedical diagnostics, as well as new approaches in detecting chirality at the nanoscale.
WS-RAP | Robotics and Autonomous Platforms in the Nuclear Industry

Barry Lennox (Manchester)
Malcolm J. Joyce (Lancaster)

For some years robotic systems have been used in the nuclear industry for a variety of requirements due to their ability to survive in environments that are hazardous to humans, perform repetitive tasks and to carry out precision operations. This workshop is for researchers interested in robotics and autonomous platforms in nuclear applications, including (but not limited to):

- Remote-operated and teleoperated machines designed for use in the nuclear sector
- Autonomous systems and the use of artificial intelligence for assisting in nuclear activities
- Walking (hexapod), twin-armed manipulators and wheeled robots, submersibles and remote deployment systems
- The resilience of these systems in harsh environments
- Impact of these systems on task management, remote assessment and reconnaissance activities.
WS-RAP-01

Introduction by workshop chairs

WS-RAP-02

Robotics and AI for Nuclear (RAIN) Research Hub (#2914)


Manchester, Electrical & Electronic Engineering, Manchester, UK

Content

In recognition of the risks associated with performing manual operations in extreme environments, the UK Government recently invested approximately £93m into the development of robotic solutions that would eliminate the need for humans to enter such environments, with a particular focus on nuclear, space and oil & gas. Of this funding, £12m was allocated to establish the RAIN Hub, which has attracted an additional £50m of support from research institutes and industry. The aim of RAIN is to develop robotic technology able to solve complex challenges that exist across the nuclear industry, covering the decommissioning of legacy facilities, monitoring of existing and new build power plants and the operation and maintenance of next generation nuclear fusion reactors. This presentation will begin by describing some of the challenges that the RAIN Hub is trying to address and will continue with an overview of some of the work completed in the first 2-years of RAIN. Robotic systems from the various research institutions involved in RAIN: Manchester, Bristol, Lancaster, Leeds, Liverpool, Newcastle, Nottingham, Oxford, Reading, Sheffield and the UKAEA’s Remote Operations in Challenging Environments (RACE) centre, will be discussed and a number of deployments into active facilities will be described. These include the deployment of submersible robots into legacy storage facilities on the Sellafield site and the research reactor at Ljubljana and the use of ground-based vehicles to detect and locate alpha contamination. In completing its research, RAIN has engaged extensively with industry and regulatory bodies, such as the Office for Nuclear Regulation, to ensure that the robotic solutions that are developed are suitable for deployment. The future work programme for RAIN will be described and opportunities for other researchers to get involved through, for example secondments, will be discussed.
Toward the Design of a Multi-Sensor Radiation Detector in Nuclear Robotics with a Focus on Standardisation (#2857)

PhD/MD student Rosie Newton, PhD/MD student Rosie Newton, Prof. Malcolm Joyce, Prof. Malcolm Joyce, Dr. Tilly Alton, Dr. Tilly Alton, As a part of the RAIN (Robotics and AI in Nuclear research) collaboration.

The University of Lancaster, Engineering, Lancaster, UK

Content
Robots have found applications in nuclear environments for decades, such as decommissioning, accident recovery and routine monitoring. The current and potential use cases for robots includes situations that are hazardous to humans, such as ionising radiation, or because of other constraints like limited space or task repetition. The designs of these robots has varied and includes among them wheeled and submersible. These will also come with a suite of sensors which are used to navigate with, however more can be included to characterise the radiological environment and provide useful data to aid decision making and planning. The provided data is often relayed back to the operator, however the expanding field of robotic autonomy allows for the robot to process and use the data while deployed with many potential uses, one of these being to locate radiation hot-spots.

The Robot Operating System (ROS) is used for programming a robot and has become ubiquitous across academia and industry for many different robot designs. ROS itself allows sensors to be included on the robot and they can publish the data, allowing it to be sent to an operator or analysed further on the robot. When current sensors, such as a camera communicate through ROS they use a standard template to ease the integration of similar hardware.

The drive towards robots in nuclear scenarios means that unfortunately the hardware for radiation detection does not yet have a convenient way to connect to ROS. This workshop will present information on the integration of a number of radiation detectors with ROS focusing on flexibility of robot platform, data produced and the ability to swap to similar hardware. The detectors are two γ-ray detectors capable of spectroscopy and a CCD radiation detector. One of the γ detectors uses the Red Pitaya STEMlab 125-14 as a user programmable MultiChannel Analyser along with a CeBr₃ scintillator and PhotoMultiplier Tube. The onboard FPGA uses pre-existing code to operate the ADC and analyse the data, the custom CPU code reads the FPGA results and publishes them to ROS through ethernet. The other γ detector uses a Brightspec bMCA with NaI:Tl scintillator and a Raspberry Pi 3B (RPi). The RPi connects to the bMCA using USB and publishes to ROS using the same template as the Red Pitaya. The CCD detector is a combination of Starlight Xpress CCD with an RPi which itself operates the CCD and publishes the data in ROS. The advantage of this setup is the possibility of using image processing before the data is published.
TORONE: Total Characterisation by Remote Observation of Nuclear Environments (#2874)

Dr. Andrew West¹, Dr. Ioannis Tsitsimpelis², Dr. Paul Coffey³, Dr. Michael Aspinal², Prof. Nicholas Smith⁴, Prof. Malcolm J. Joyce², Prof. Philip A. Martin³, Prof. Barry Lennox¹

¹ The University of Manchester, Department of Electrical and Electronic Engineering, Manchester, UK; ² Lancaster University, Department of Engineering, Lancaster, UK; ³ The University of Manchester, Department of Chemical Engineering & Analytical Science, Manchester, UK; ⁴ National Nuclear Laboratory, Warrington, UK

Content
The UK’s Nuclear Decommissioning Authority (NDA) deem characterisation as an integral constituent for effective waste management and decommissioning of legacy and future nuclear fission and fusion sites. On a global scale, robotics is expected to have a significant impact on vital work in the nuclear industry, with the development of systems for these tasks being profound in the past decade; stemming in part from the need for fundamental technological advances to deal with the decommissioning challenges of the stricken power plants at Fukushima. Characterisation of nuclear environments involves a range of tasks, from radiological surveying, visual inspection, material identification, and mapping of physical spaces. For instance, assessment of the elemental and chemical composition of materials is important in terms of monitoring asset health, such as checking for signs of corrosion, detection of radiochemical contamination. Furthermore, radiation detection and localisation is important with regard to identifying radioactive isotopes, and contamination. An instrumentation suite able to provide such characterisation measurements can increase the overall safety of radiation workers, and provide stakeholders with a deeper understanding of hazardous environments, which is critical in allocating time and budget for various monitoring, decommissioning and waste management activities. A robotic platform equipped with these features allows for in-situ measurement without the need for manual sample retrieval and laboratory analysis, greatly reducing associated lead-times and cost. Furthermore, by not removing materials from a location, allowing re-examination and monitoring for changes over time.

The TORONE project, funded by the UK EPSRC, comprises of work packages related to the design and development of instrumentation for integration with mobile robotic platforms. The aim is to map radiation and material identification onto reconstructions of physical spaces, and manage the collected data to create a database available to stakeholders. The demonstrator being developed integrates a Clearpath Jackal robotic platform, with LiDAR and RGB-D sensors for Simultaneous Localisation and Mapping (SLAM), as well as RGB cameras and 3D LiDAR to produce physical reconstructions of unknown environments. Laser diagnostics such as Laser Induced Breakdown Spectroscopy (LIBS) and Raman spectroscopy are utilised for material identification, whilst single detector gamma and neutron radiation apparatuses are used for high resolution spectroscopy and imaging. During this workshop, we deliver an overview of the subsystems that are being developed, and the challenges that relate to the compatibility of various off-the-shelf and custom scientific instruments with a mobile robotic platform and the Robot Operating System (ROS). Moreover, we will present example data and lessons learned from deploying our demonstrator to carry out radiation mapping, radioactive source localisation.
An Odometer-Free Approach for Unmanned Ground-Based Vehicle Simultaneous Localization and Mapping (#2880)

Dr. Xiaowei Gu\textsuperscript{1,2}, Prof. Plamen Angelov\textsuperscript{1,2}, Dr. Muhammad Aurangzeb Khan\textsuperscript{1,2}, This work is funded by Innovate UK under the project “Collaborative Technology Hardened for Underwater and Littoral Hazardous Environments” (Ref. 104061).

\textsuperscript{1} Lancaster University, School of Computing and Communications, Lancaster, UK; \textsuperscript{2} Lancaster University, Lancaster Intelligent, Robotic and Autonomous Systems Centre (LIRA), Lancaster, UK

Content

Simultaneous localization and mapping (SLAM) in unknown GPS-denied environments is a very challenging problem due to the complex environment factors and the lack of prior knowledge of such environments. The performance of standard SLAM methods is dependent on odometer measurements, which, however, are unlikely to be reliable in a challenging operating environment. In this paper, a novel odometer-free approach is introduced for unmanned ground-based vehicle (UGV) to perform SLAM using only LIDAR/SONAR scans in the form of discrete point clouds. The proposed odometer-free SLAM (OF-SLAM) approach can precisely align successive sensor scans without involving other auxiliary information, e.g., odometer readings. By converting the accurately aligned point clouds into continuous local grid maps using kernel tricks, OF-SLAM creates a dynamically updating global map of the surrounding environment and further accurately localizes the UGV on the map. Simulation experiments verify the validity and effectiveness of OF-SLAM and demonstrate the proposed approach as an attractive alternative for UGV to perform SLAM and explore complex unknown environments.
A dual-arm, hydraulically-actuated robot for operations in radiologically contaminated environments (#2893)

Olivia Albrecht, Dr. Stephen D. Monk, Dr. Manuel Bandala, Dr. Allahyar Montazeri, Prof. Charles J. Taylor

Lancaster University, Engineering Department, Lancaster, UK

Content

Nuclear decommissioning environments are an ideal example of where robotics can be utilised incredibly constructively. Decommissioning generally can be an unpleasant manual task with traditional civil engineering hazards, such as high temperature or extreme noise, alongside the radiological ones. Thus, the use of robotics in such environments is a popular one – even if there are many difficulties which may not be obvious initially. Electrically actuated robots are the most common and easiest robot type to use, but suffer from low payload limits and are vulnerable to high radiological fluence. Another problem is in teleoperation of the robots – a highly skilled operator is required to work for long hours and human error often increases with fatigue. We present here a hydraulically actuated two arm robot, each possessing seven degrees of freedom and a payload of 75 kg. Each of the joints within the arms feature potentiometer based feedback which can be used to inform any software algorithm of the position and orientation of the arms at any time. Further, the end effectors can be equipped with a variety of tools such as saws, grippers or buckets. The two manipulators can be controlled tele-operationally via twin joysticks, although this is often a highly complex operation requiring significant experience. The alternative is semi-autonomous control which is implemented here via three elements. Firstly, a commercially available vision system, the Microsoft Kinect, which has been widely utilised in numerous fields in research. The information from the Kinect is fed into the MATLAB software environment, with user interaction allowing the location and orientation of cut to be determined. This position and required orientation data is fed into National instruments LabVIEW software, where the inverse kinematic mathematics are performed and the required joint angles of the robotic arm are determined. Finally, a Compact Field Point (CFP) controller is used to physically move the joints of the arms into the required positions, thus desired operations can be undertaken. The example task chosen is the cutting of a single plastic pipe at an unknown orientation and location. The intention is that the right arm grips the pipe at the location chosen by the user in the MATLAB program, while the left arm, equipped with a small circular saw, performs the actual cutting operation. Both tele-operational and semi-autonomous control of the system was employed here in order to compare the two systems, with times taken to cut the pipe compared as well as the quality of cut.
Content

Many nuclear power plants are reaching the end of their economic lifetime and the decommissioning of legacy nuclear facilities is an important challenge in the next few decades. Since the radiation level in these facilities is significant, autonomous robots are likely to be a large part of the solution. For this purpose, the mapping and inspection of nuclear facilities can be performed using autonomous Micro Aerial Vehicles (MAVs). Recently, there are many studies on achieving a stable and reliable MAV flight to perform accurate missions with high performance. Since human access is highly restricted in nuclear environments, conventional navigation systems are not able to complete many of the required tasks. Track follower MAVs have been implemented in many applications, such as water channels and railway inspections. To illustrate some of the issues involved, this research considers a line-following method and compares two attitude controllers. The approach can be divided into three tasks: 1) the image processing algorithm, 2) the path planning strategy and 3) attitude stabilisation. The environment under study contains a ground floor with predetermined red tracks over which the MAV moves. We explain each task briefly in the following.

Image Processing: First, a colour detection algorithm is applied to form a thresholded image. To make the image smoother and to reduce noise effects, Dilation and Erosion algorithms are applied. Then, in each iteration, a vector is created by the boundary layer of the provided image. Morphological operations are performed to remove small discontinuities for each cluster. Here the goal is to find the midpoint of each cluster, known as keypoints. Finally, the obtained vector should be re-mapped to its original image matrix.

Path Planning: The methodology for selecting the appropriate target point is to compare the distance between the keypoints and the target. For the take-off phase, the keypoint with smaller y in the image frame is chosen and, for the remaining iterations, the keypoint with lower distance to the target is selected. Then, the desired velocity in the body frame is calculated.

Attitude Controller Design: Two controllers are considered to stabilise the attitude of the MAV. First, a linear Proportional-Integral-Derivative (PID) controller is selected. A linear PID control for yaw torque is derived. Secondly,
a conventional sliding surface for the yaw channel is defined and, by applying Lyapunov’s direct method, the stability of the system is guaranteed. The yaw control torque is derived as a function of the designed positive sliding gain. Finally, to avoid chattering phenomenon, one can approximate the discontinuous signum function with the hyperbolic one.

**WS-RAP-10**

**Point-cloud mapping of radiation environments: an unmanned ground vehicle with LIDAR, and radiation detectors** (#2912)

**Dr. Chris M. Tighe**, Dr. Tilly Alton, Dr. Luke Pitt, Dr. Yannick Verbelen, PhD/MD student Sam White, Dr. Thomas Wright, Prof. Nick Hawes

1 Lancaster, Engineering, Lancaster, UK; 2 Oxford, Oxford Robotics Institute, Oxford, UK; 3 Bristol, School of Physics, Bristol, UK; 4 Manchester, Department of Electrical & Electronic Engineering, Manchester, UK

**Content**

Remotely-operated vehicles and robotics have long been used in the nuclear industry to protect workers, increase efficiency and carry out precision operations. Robotics research for nuclear applications has had a recent boost with activities such as RAIN (Robotics and AI in Nuclear, https://rainhub.org.uk) to help address vital global challenges that both current and legacy nuclear industries present. RAIN actively encourages the collaboration between multiple institutions throughout each project period to maximise crossovers in specialities, such as radiation detection and measurement; and AI and automation in robotics.

Recently, research has been carried out between Oxford, Bristol, Lancaster and Manchester universities as part of RAIN, in the form of a hackathon, to integrate gamma-ray detectors (cerium bromide and cadmium zinc telluride) onto a robotic platform hosting a LIDAR (Light Detection and Ranging) imaging system. This constitutes a scanning mechanism that when linked with a point-cloud painter application using ROS, can image an area and heat-map the gamma radiation in the area by the intensity of radiation measured in counts per second.

A hackathon is generally reserved for computer programmers and others involved in software development. This event involved grouping programmers, engineers and nuclear engineers and tasking them with developing a desired capability intensively over the course of a few days. Simply, it grouped those with the means and knowledge together to meet a specific target.

The research involved mapping the area with LIDAR, and radiation detection of the area with a gamma-ray detector attached to a pan-tilt unit (PTU) atop the robot. The output of the research comprised of a painted map of radioactivity within the test space at The University of Bristol, created with a combination of a Kromek GR1™ (https://www.kromek.com/product/gr1/), LIDAR, and PTU mounted atop a Clearpath Husky™ unmanned ground vehicle (https://clearpathrobotics.com/husky-unmanned-ground-vehicle-robot/). The group plan to meet again in the near future to continue developing the systems and apply the successes of the first collaboration campaign to a variety of radiation source environments, autonomously.

This research has immediate applications in a variety of environments in the nuclear industry, dependent on the chosen robotic deployment platform. The research is due demonstration in early January in an environment based closely on an intermediate level waste (ILW) storage. It is hoped implementation in industrial environments will follow
this successful demonstration, in areas requiring routine inspection, hazardous environments and regions difficult for humans to navigate.

**WS-RAP-11**

2:20 PM

**Continuum robotics for inspection and repair in industrial applications**

(#2913)

**Dr. Xin Dong**, Prof. Dragos Axinte

*University of Nottingham, Department of Mechanical, Materials and Manufacturing Engineering, Nottingham, UK*

**Content**

Continuum robotics knew as elephant trunk robot, has become an essential and promising branch in the modern robot family over decades of development. Unlike conventional rigid-link robots, composed of revolute and translation joints with high positioning accuracy and good dynamic performance, continuum robots employ compliant materials (soft material, spring , and NiTi alloy, etc.) or compliant mechanism to construct the arm and actuators, which prevent them from rigid collisions with the surrounding environments and provides a universal and efficient solution to access to constrained environments. So far, most of the works focused on healthcare applications, especially minimally invasive surgery. In this talk, some progress of the continuum robots for industrial applications in the last five years will be introduced. In the University of Nottingham, a family of tendon-driven continuum robots with small diameter and long length were developed to help human operators have their ‘eyes and hands’ into challenging and extreme environments for in-situ inspection and repair, e.g., removing and adding materials. These operations can significantly reduce the unscheduled downtime of the high-value facilities (e.g. aero-engine and nuclear power station). Most of these continuum robots reached high Technology Readiness Level, e.g., TRL four and six. Based on these research, ten papers have been published in top academic journals (e.g., IEEE/ASME Transactions on Mechatronics, IEEE Robotics & Automation Magazine, Robotics and Computer-Integrated Manufacturing, Mechanism and Machine Theory) and nine international patents have been filed or granted.

**WS-RAP-12**

3:00 PM

**Closing remarks by workshop chairs and coffee/tea to close**
This two-day course provides an overall review of the basic principles that underlie the operation of all major types of instruments used in the detection and spectroscopy of charged particles, gamma rays, and other forms of ionizing radiation. Examples of both established applications and recent developments are drawn from areas including particle physics, nuclear medicine, homeland security, and general radiation spectroscopy. Emphasis is on understanding the fundamental processes that govern the operation of radiation detectors, rather than on operational details that are unique to specific commercial instruments. This course does not cover radiation dosimetry nor health physics instrumentation. The level of presentation is best suited to those with some prior background in ionizing radiation interaction mechanisms. Those with prior experience in radiation measurements would benefit from discovering concepts and applications outside their experience base. A complete set of course notes is provided to registrants, and a recent copy of Radiation Detection and Measurement by G. F. Knoll is highly recommended.

Outline

- Fundamental Concepts in Ionizing Radiation Detection
- Gas-Filled Detectors
- Scintillation Detectors
- Semiconductor Detectors
- Analog and Digital Electronics for Radiation Measurements
- Pulse Shape Discrimination and Multi-modality Sensing
• Recent Detector Developments and Summary

Instructors

Sara Pozzi is a Professor of Nuclear Engineering and Radiological Sciences at University of Michigan. She previously worked at the Oak Ridge National Laboratory, and currently serves as the Director of the Consortium for Verification Technology. She and her group have developed new methods for digital pulse shape discrimination using organic scintillators read out by photomultiplier tubes and silicon photomultipliers for applications in nuclear nonproliferation and homeland security.

Robert Redus is a Member of the IEEE and is the Chief Scientist and Director of Engineering at Amptek, an Ametek company in Bedford, MA. He has spent over thirty years designing instruments for radiation detection and measurement, for many applications and many customers. These include X-ray spectroscopy, gamma-ray spectroscopy using compound semiconductors, scintillators, and HPGe detectors, and space radiation measurements.

Kanai Shah is the President of Radiation Monitoring Devices, Inc. His research areas of interest include novel scintillation materials for high resolution gamma-ray spectroscopy including CeBr₃, LuI₃:Ce and SrI₂:Eu and dual mode scintillators such as Cs₂LiYCl₆:Ce, Cs₂LiLaBr₆:Ce and Cs₂LiLa(Br,Cl)₆:Ce for combined detection of gamma-rays and neutrons. He has also worked in the areas of ceramic scintillators including garnets and silicates, and organic crystalline and plastic scintillators for neutron detection.

Graham Smith is a Senior Physicist at Brookhaven National Laboratory. He received a Ph.D. in Physics from Durham University, England. He has worked for the last thirty-five years at Brookhaven National Laboratory, USA, on development of advanced radiation instrumentation for experimental studies using neutrons, X-rays and charged particles, specializing in gas-filled detectors. He is an IEEE Fellow.

Lothar Strueder is the scientific director of PNSensor GmbH and professor at the University of Siegen. He earned his Ph.D. in Experimental Physics at the TU Munich in 1988. His interests include position-, energy-, and time-resolving detectors for photons and particles. He is author or co-author of more than 300 technical and scientific publications. He has been issued 13 worldwide patents in scientific instrumentation.
David Wehe is Professor of Nuclear Engineering and Radiological Sciences at University of Michigan. He worked at the Oak Ridge National Laboratory as a Wigner Fellow, and served as Director of the Michigan Phoenix Memorial Project, which included the 2-MW Ford Nuclear Reactor. His teaching and research have focused on applied radiation measurements, and is an editor for Nuclear Instruments and Methods in Physics Research.
WS-INM-I | Instrumentation and Measurement in Nuclear Media Workshop I

Malcolm J. Joyce (Lancaster)
Laurent Ottaviani (Marseille)

Non-Destructive-Assays for material, fuel and radioactive waste characterization and control
Advances and main challenges in Nuclear Non-Destructive Measurements for Nuclear Fuel Cycle characterization, monitoring and control

Prof. Abdallah LYOUSSI

CEA, Cadarache, France

Non-destructive nuclear measurements in support to nuclear industry
(#2853)

Dr. Bertrand Pérot

CEA, DEN, Cadarache, DTN/SMTA/LMN, Saint-Paul-lez-Durance, France

Content
Since the 1980’s, the Nuclear Measurement Laboratory of CEA Cadarache, France, is developing non-destructive nuclear measurement methods and systems (gamma-ray spectroscopy, passive and active neutron measurements, X-ray and neutron imaging, neutron activation analysis, photofission) in support to French nuclear industry. Legacy and main ongoing applications are related to nuclear fuel cycle, from uranium mining to spent fuel reprocessing, including radioactive waste characterization and dismantling of nuclear facilities. Another historic activity is the measurement of contamination transfers in the primary circuit of nuclear power plants. In the past decade, the laboratory has significantly diversified its activity in the field of non-destructive exams for the future experimental JHR reactor, nuclear accident monitoring and corium studies, as well as homeland security. This talk will focus on recent developments of LINAC-based techniques (high-energy X-ray imaging and radioscopy, dual energy imaging, photofission), new gamma-spectroscopy approaches for uranium mining, innovative methods for passive and active neutron coincidence counting with plastic scintillators, neutron activation analysis, JHR non-destructive exams (underwater X-ray imaging and gamma spectroscopy, neutron radiography), combined measurements, and nuclear process monitoring.
Recent Developments in Nuclear Instrumentation, Test Evaluation and Its Qualification for Nuclear Safety, Safeguards and Security

Dr. Massimo MORICHI
CAEN Sys, Viareggio, Italy

Nuclear instrumentation and their relative measurements are subject to international standards that well describe the measurement conditions. However, those standards do not describe and neither imply a selection of use cases or specific scenarios that are often part of the real life for nuclear operators in Nuclear Safety, Safeguards and Security. This work shows how recent developments have been executed not only considering such international standards (ISO, ANSI, IEEE, etc.), but also requirements that are necessary for a good practical operation and for enhancing capabilities and efficiency of procedures to be implemented for specific scenarios. Those "non-standard" but important requirements are taken into account and are leveraging the design and realization of innovative nuclear instruments. Those are based on enabling technologies, which removes existing limitations and complexity in nuclear operator procedures; moreover, their performance and deployment ease exceed the technical capabilities commonly expected from radiation measurement equipment. Results of tests and characterization of those innovative instruments will be reported with real use cases such as the following ones. Safeguards: a fresh fuel non-destructive assay technique, based on gamma and neutron detection, allows inspectors to better verify assembly enrichment in less than one tenth of the current measurement time; Environmental: a platform of spectroscopic autonomous environmental stations can become a network of heterogeneous sensors for data fusion and for different emergency scenarios; Nuclear Security: a novel gamma-neutron detection technology for special nuclear material detection can identify a plutonium sample at a distance twenty times the one reported by the standards for similar instruments.
Reducing the spectrum-shift of a NaI(Tl) detector by optimizing the pulse integration time (#2831)

Prof. Qingyang Wei¹, Prof. Zhaohui Zhang¹, Dr. Tiantian Dai², Dr. Tianpeng Xu³, Nianming Jiang³, Prof. Yaqiang Liu⁴

¹ University of Science and Technology of Beijing (USTB), School of Automation and Electrical Engineering, Beijing, China; ² China-Japan Friendship Hospital, Department of Radiation Oncology, Beijing, China; ³ Beijing Novel Medical Equipment Ltd., Beijing, China; ⁴ Tsinghua University, Department of Engineering Physics, Beijing, China

Content

NaI(Tl) spectrometry is widely used in many areas for gamma-ray detection as its higher cost performances. It can be used for both activity measurement and isotope identification. However, the light generation of NaI(Tl) is sensitive to temperature changes which will lead to spectrum-shift. Several calibration methods have been proposed, while they are complicate. In this paper, we developed a 2L NaI(Tl) spectrometry for indoor monitoring and studied the temperature influences from 5 ºC to 35 ºC. We found that the severity of the temperature-dependent spectrum-shift varied using different integration points (i.e. integration time) for energy calculation. There exists an optimal integration point for achieving the smallest spectrum-shift, which varies as the temperature range changes. The energy resolutions are slightly affected by the temperature and integration point. In conclusion, the spectrum-shift phenomenon can be reduced by using an optimal integration time. Thus, the indoor monitoring NaI(Tl) spectrometry might work properly for isotope identification without the complicate calibration procedure.
WS-OPD I | Data Libraries

David A. Brown (Upton)
Maria Grazia Pia (Genova)

This session encompasses an overview of major physics data libraries used in Monte Carlo particle transport and in scientific and engineering applications.
WS-OPD I-01  
**Introduction to the workshop (#2901)**

**Dr. Maria Grazia Pia¹, Dr. David Brown²**

¹ INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy; ² Brookhaven National Laboratory, Upton, USA

Content

We introduce the scope of the workshop, the topics on the agenda and a few relevant items to discuss.

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WS-OPD I-02  
**Introduction to Physics Data Libraries (#2903)**

**David Brown², Dr. Maria Grazia Pia¹**

¹ INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy; ² BNL, Upton, USA

Content

This session includes an overview of some major physics data libraries and reports of their use.

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WS-OPD I-03  
**Overview of the OECD-NEA Working Party on International Nuclear Data Evaluation Cooperation (WPEC) (#2918)**

**Dr. Michael Fleming**

*OECD, Nuclear Energy Agency, Paris, France*

Content

The OECD Nuclear Energy Agency (NEA) Working Party on International Nuclear Data Evaluation Cooperation (WPEC) was established in 1989 to facilitate collaboration in nuclear data activities. Over its thirty-year history, different Subgroups have been created to address topics in nearly every aspect of nuclear data, including: experimental measurements, evaluation, validation, model development, quality assurance of databases and the development of software tools.

WPEC has recently completed activities on fission yield evaluation, the general nuclear database structure (GNDS) to replace the ENDF-6 format, methods to provide feedback to evaluation, studies of specific capture cross sections,
new methods in thermal scattering kernel evaluation and the Collaborative International Evaluated Library Organisation (CIELO) Pilot Project. Ongoing activities in GNDS application programming interface (API) development, methods for covariance evaluation and quality assurance in nuclear data validation using the International Criticality Safety Benchmark Evaluation Project (ICSBEP) database are complemented by the work of two Expert Groups that oversee the High-Priority Request List (HPRL) for Nuclear Data and the continuous development of the GNDS. New activities on the use of integral experiments for nuclear data validation and adjustment, as well as the use of the Shielding Integral Benchmark Archive and Database (SINBAD) for validation have begun and will be coordinated alongside a follow-up of the work advancing the state-of-the-art in thermal scattering data and a new initiative to design the systems required for a fully reproducible nuclear data evaluation.

**WS-OPD I-04**  
**JENDL project and related activities** (#2878)  
**Dr. Kenichi Tada**, Dr. Osamu Iwamoto  
*Japan Atomic Energy Agency, Nuclear Science and Engineering Center, Tokai-mura, Japan*

**Content**  
The latest version of general-purpose file JENDL-4.0 (Japanese Evaluated Nuclear Data Library) was released in 2010. After the release of JENDL-4.0, efforts to extend energy range up to 200 MeV have been made in order to meet needs from various accelerator applications such as ADS. They were complied with proton induced reaction data into JENDL-4.0/HE (High Energy File) and released in 2015. We also released two special purpose files. One is JENDL/PD-2016 (Photo-nuclear Data File) which contains the photo-nuclear reaction cross sections covering a wide area of the nuclear chart. The other is JENDL/AD-2017 (Activation Cross Section File for Nuclear Decommissioning) which provides production cross sections of radioactive nuclei by neutrons. Regarding the general-purpose file, we are planning to release the next version of JENDL, which would be made available in FY2022 as JENDL-5. To contribute to the important problems concerning the nuclear energy in Japan such as nuclear waste and nuclear safety as well as various application fields of nuclear data, it is intended to raise reliability of simulation calculation of nuclear reactors and neutron transportation in structure materials. Nuclear data processing is an important interface between an evaluated nuclear data and nuclear transport calculation codes. The transport codes require cross section library which is generated by a nuclear data processing code. The nuclear data processing code is not just a converter. It performs many processes, e.g., linearization, reconstruction of the resonance region, Doppler broadening, etc. We developed a new nuclear data processing code FRENDY (FRom Evaluated Nuclear Data library to any application) to process evaluated nuclear data files. FRENDY version 1 was released in March 2019 as an open source software under the 2-clause BSD license. FRENDY can be downloaded from JAEA’s web site. In this presentation, we will explain overview and future plan of the JENDL project and FRENDY.
WS-OPD I-05  
9:55 AM

The ENDF library as an Open Data Library

David N. Brown
USA

Abstract to be included.

WS-OPD I-06  
10:15 AM

Discussion
This session reviews the current status and open problems of data libraries concerning electromagnetic interactions of particles with matter, which are currently facing a critical situation.
WS-OPD II-01

Introduction to Atomic Data (#2904)

David Brown\(^2\), Dr. Maria Grazia Pia\(^1\)

\(\text{INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy; } \text{BNL, Upton, USA}\)

Content
Despite the key role they play in the experimental life-cycle, atomic data face a critical situation. This session is devoted to review the current status and open problems, and to discuss concrete actions to address them.

WS-OPD II-02

Overview of electromagnetic data libraries for particle transport (#2876)

Dr. Maria Grazia Pia

\(\text{INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy}\)

Content
This brief overview of electromagnetic data libraries used introduces a few topics to be discussed in the workshop: a selection of popular cross section tabulations and compilations of atomic parameters, their availability, the status of their validation and related open issues. Despite they play a fundamental role in in Monte Carlo particle transport, electromagnetic data libraries face a critical situation: some lack support, others are not openly available, and validation is generally limited. A collaborative international effort would be desirable to address the current problems.

WS-OPD II-03

Atomic data libraries in ENDF/B

David N. Brown

\(\text{BNL, USA}\)
WS-OPD II-04
11:45 AM

Atomic data in EGSnrc (#2916)
Dr. Reid W. Townson
National Research Council Canada, Metrology, Ottawa, Canada

Content
The EGSnrc Monte Carlo toolkit models photon, electron and positron transport through media. EGSnrc has several options of photon cross-sections, including those calculated by EPDL97, XCOM (Berger & Hubbell), and Storm & Israel. Atomic relaxations are explicitly modelled using transition probabilities from EADL. Binding energies in the simulation are selected depending on the photon cross section library, and then used for photo-electric, Compton, electron impact ionization, and atomic relaxations to ensure consistency. Radionuclide source modelling is performed explicitly using ENSDF.

WS-OPD II-05
12:05 PM

Current Activities in Atomic and Molecular Data at the IAEA (#2884)
Christian Hill, Kalle Heinola
International Atomic Energy Agency, Nuclear Data Section, Vienna, Austria

Content
The Atomic and Molecular Data (AMD) Unit [1], in the Nuclear Data Section of the IAEA, is dedicated to the provision of evaluated data on atomic, molecular and plasma-material interaction, with a particular focus on those data that are of relevance to nuclear fusion research. In addition to hosting Technical Meetings of experts to address specific data needs, the AMD Unit also organises several 3 – 4 year long Coordinated Research Projects (CRPs) to facilitate collaborative research between 10 – 15 research groups with the aim of producing and evaluating data within a focused domain. Ongoing CRPs include:

• Data for Atomic Processes of Neutral Beams in Fusion Plasma (2017 – present) [2]
• Atomic Data for Vapour Shielding in Fusion Devices (2019 – present) [3]

The AMD Unit also hosts several databases, which are currently being upgraded with new relational database schemas and online interfaces. The most important of these are ALADDIN (“A Labelled Atomic Data Interface”) [4] and AMBDAS [5], a bibliographic database.
Since its creation in 1977, the AMD Unit has been responsible for coordinating the activities of the Data Centres Network (DCN) [6] in evaluating and recommending fundamental atomic and molecular data for fusion research, and to set priorities for future data needs in this area. This Network is composed of 12 national data centres and holds a biennial meeting to discuss its members’ research, establish standards, and to plan joint activities.

Online Resources
WS-OPD II-06

Questions
WS-INM-II | Instrumentation and Measurement in Nuclear Media Workshop II

Bertrand Pérot
Massimo MORICHI

Advanced radiation detection and measurement for/in nuclear reactors
WS-INM-II-01  2:00 PM

Calorimeter dedicated to measuring adsorbed dose rate in Material Testing Reactors. State of the art and Challenges. (#2898)

Dr. Christelle Reynard-Carette¹, Prof. Abdallah Lyoussi², Dr. Michel Carette¹, Dr. Julie Brun¹, Adrien Volte¹

¹ Aix-Marseille Université, IM2NP UMR 7334, MARSEILLE, France; ² CEA, DEN/DER/SPESI/LDCI, ST PAUL LEZ DURANCE, France

Content
The rate of energy deposition induced by interactions between nuclear rays and matter (called the nuclear-heating rate or absorbed-dose rate) within the experimental channels of Material Testing Reactors is sufficiently intense to be quantified by means of calorimeters based on temperature measurements. In other reactors such as ZPRs, other sensors and technics are required such as TLDs, OSLDs and dosimeters. More precisely in MTRs, the calorimeters correspond to heat-flow calorimeters (non-adiabatic sensors) due to the great amount of energy-deposition rate (up to 20W/g or 20kGy/s inside the future Jules Horowitz Reactor at a nominal power of 100MWth, MTR under construction in France). Two types of calorimeter exist: single-cell calorimeter and differential calorimeter. They allow continuous online measurements. For instance, they can be used to determine axial profiles of the nuclear-heating rate before integrating an irradiation device inside an experimental channel or to measure the nuclear heating in various material samples or more recently to estimate the residual power after a reactor shutdown. Over the last ten years, research in this field has intensified, particularly in Europe. The purpose of this oral communication will be to realize a state of the art in in-pile calorimetry. Research works are carried out in laboratory conditions without nuclear rays to optimize these sensors, propose new technologies with increased performance and calibrate them, but also during irradiation campaigns to qualify them and compare them using multi-sensor systems (a new trend). These experimental and numerical works will be discussed. The different sensors will be compared by giving their advantages and drawbacks. New challenges will be identified and detailed.

WS-INM-II-02  3:00 PM

4H-SiC Epitaxial Radiation Detectors for Harsh Environment Applications

F. Ruddy

Ruddy Consulting, USA
WS-INM-II-03  
3:40 PM

Neutron detection stability of Silicon-Carbide- and Diamond-based sensors – results and perspective

L. Ottaviani

Aix-Marseille University, IM2NP, France

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WS-INM-II-04  
4:10 PM

Conclusion and end of the workshop
WS-OPD III | Validation and Uncertainty Quantification

David A. Brown (Upton)
Maria Grazia Pia (Genova)

This session is focused on collaborative instruments supporting the validation of physics data libraries and the associated uncertainty quantification. Further presentations concerning validation tests are included in NSS session N-12 (Tuesday 29 October, 1.40 pm).
WS-OPD III-01

Introduction to Validation and Uncertainty Quantification (#2906)

David Brown\textsuperscript{2}, Dr. Maria Grazia Pia\textsuperscript{1}

\textsuperscript{1} INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy; \textsuperscript{2} BNL, Upton, USA

Content

Validation is a critical issue for physics data libraries; uncertainty quantification is a related problem. A session of the workshop is devoted to review and discuss the current status and plans for a cooperative effort in this domain, including open access to experimental data for validation tests.

WS-OPD III-02

The HEPData open database (#2895)

Prof. Michael Spannowsky, On behalf of the HEPData-Collaboration

Durham University, Physics, Durham, UK

Content

HEPData is the open data database for high-level analyzed experimental data in particle physics. In this talk the paradigms underpinning the creation of the HEPData project and it continued development are presented, and how they are implemented. Future directions will be discussed and lessons from more than 3 decades of continued development and operation will be drawn.

WS-OPD III-03

Potential validation possibilities using data archived in the EXFOR library

Boris Pritychenko

USA

Abstract to be included.
WS-OPD III-04

Libraries facilitating access to data libraries (#2902)

Tullio Basaglia

CERN, RCS-SIS, Geneva, Switzerland

Content
Libraries are striving to position themselves as intermediaries between sources of information such as online bibliographic databases and data libraries and the researchers’ community. Based on a concrete experience, I will show you how a library has successfully operated between benchmark data providers and scientists, delivering data needed to validate particle transport codes.

WS-OPD III-05

Monte Carlo simulations and the propagation of experimental errors

Paolo Saracco

Italy

Abstract #2302.

WS-OPD III-06

Questions
WS-OPD IV | Open Data Libraries: Planning the Future

David A. Brown (Upton)
Maria Grazia Pia (Genova)

This session includes reports on ongoing activities concerning. For lasting impact of this workshop, we propose to launch a Manifesto for Open Physics Data Libraries.
WS-OPD IV-01  4:00 PM

Introduction to Planning the Future (#2917)

David Brown\(^2\), Dr. Maria Grazia Pia\(^1\)

\(^1\) INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy; \(^2\) BNL, Upton, USA

Content
This session offers a perspective on initiatives for the future of physics data libraries and promotes discussion on international cooperation in this domain. Contribution to the discussion from the experimental community are welcome.

WS-OPD IV-02  4:05 PM

Implementation of the Generalized Nuclear Data Structure, a new international format for storing nuclear and photo-atomic data (#2885)

Dr. Marie-Anne Descalle, Dr. Bret Beck, Dr. Caleb Mattoon, Dr. Eric Jurgenson, Dr. Scott McKinley, Dr. Teresa Bailey

Lawrence Livermore National Laboratory (LLNL), Livermore, USA

Content
The Generalized Nuclear Data Structure (GNDS) is a new format for storing nuclear and photo-atomic reaction data. GNDS was developed by an international committee under the auspices of the Nuclear Energy Agency Working Party on Evaluation Cooperation. The development of this flexible and modern format was motivated by the desire to address the evolving needs of nuclear data users, and the need to easily share evaluated as well as processed data across institutions within a single modern framework. As such, it is meant to replace ENDF-6, the fifty-year-old format in use in most evaluated data libraries worldwide, while also supporting processed data. In addition to reaction data, the GNDS committee also designed a structure for storing particle data (e.g., mass, spin, halflife) which is called Properties of Particles (PoPs).

Lawrence Livermore National Laboratory (LLNL) has developed a complete suite of open source codes including a processing code (FUDGE) and three C++ APIs (PoPI, GIDI and MCIGIDI) to handle GNDS formatted data and enable particle transport simulations. FUDGE (For Updating Data and Generating Evaluations) can read GNDS evaluated data and process them into forms suitable for use in Monte Carlo and deterministic (e.g., multi-grouping) transport codes. The processed data are also stored in PoPs and GNDS files which can be read by Monte Carlo and deterministic transport codes using the PoPI (Properties of Particle Interface) and GIDI (General Interaction Data Interface) C++ APIs, respectively. GIDI has class functions that allow for easy access of multi-group data as needed by deterministic transport codes. MCGIDI (Monte Carlo GIDI) is a C++ API which facilitates the use of GNDS data for use in Monte Carlo transport codes. MCGIDI uses GIDI to read in a GNDS file and then extract data needed for Monte Carlo transport. MCGIDI has class functions for cross section lookup, and for sampling a reaction and its
outgoing particles. PoPI, GIDI and MCGIDI have been implemented in LLNL’s deterministic (Ardra) and Monte Carlo (Mercury) transport codes. This paper discusses features of the GNDS format, current translation and processing capabilities of the FUDGE code and PoPI/GIDI/MCGIDI APIs, and reports validation results for integral benchmark experiments using Ardra and Mercury.

Prepared by LLNL under Contract DE-AC52-07NA27344.

WS-OPD IV-03

The IDataLib Project (#2907)

Sandra Parlati\textsuperscript{2}, Dr. Maria Grazia Pia\textsuperscript{1}, Elisabetta Ronchieri\textsuperscript{3}, Paolo Saracco\textsuperscript{1}

\textsuperscript{1} INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy; \textsuperscript{2} INFN LNGS, Assergi, Italy; \textsuperscript{3} INFN CNAF, Bologna, Italy

Content

Recent evolutions - both in theoretical calculations and in experimental applications - open up new perspectives for physics data libraries; the concept of Open Science, supported by the European Commission and other national and international entities, provides an ideal framework for future developments. On these grounds, the IDataLib project intends to contribute the experience developed within INFN (the Italian National Institute for Nuclear Physics) experimental and computational research. The project is focused on electromagnetic data libraries and encompasses three synergic areas: the data libraries, their validation and the experimental data for this purpose. An innovative feature of this project is the integration of the validation process within the library management.

WS-OPD IV-04

Conclusion: a Manifesto for Physics Data Libraries (#2905)

David Brown\textsuperscript{2}, Dr. Maria Grazia Pia\textsuperscript{1}

\textsuperscript{1} INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy; \textsuperscript{2} BNL, Upton, USA

Content

This conclusive overview summarizes the outcome of the workshop.
Discussion
NP-1 | NSS Plenary I

Cinzia DaVia (Manchester)
Yoshinobu Unno (Tsukuba)
NP-1-01  8:00 AM
Introduction
Cinzia DaVia
The University of Manchester, Manchester, UK

NP-1-02  8:01 AM
Welcome address from the Conference General Chair Paul Marsden
Paul Marsden
King’s College, London, UK

NP-1-03  8:06 AM
Opening of the 2019 Nuclear Science Symposium
Cinzia DaVia
The University of Manchester, Manchester, UK

NP-1-04  8:21 AM
Presentation of the 2018 IEEE Marie Sklodowska-Curie Award by Jose M.F. Moura, IEEE President
Jose M. Moura
USA
NP-1-05 8:27 AM

2018 IEEE Marie Sklodowska-Curie Award Lecture: Stories from the Margin — Connecting the Dots

David Nygren

University of Texas at Arlington, Arlington, USA

In this talk, I attempt to show how working at the margins, meant here to mean taking some bits of knowledge from some other field, usually related in some way to my own interests but sometimes not, has provided me with unexpected springboards to enable some new directions in experimental particle physics. In some cases, a new idea generated such robust enthusiasm that major obstacles were confronted directly and expeditiously vanquished. This tendency to find a way to connect the dots — however faint the pattern — has surely been enormously helpful to me; perhaps an enduring lesson lurks here.

NP-1-06 9:07 AM

The Square Kilometre Array, a radiation detector of a different nature

Prof. Philip Diamond

SKA Organization, Manchester, UK

The Square Kilometre Array (SKA) will be the next-generation radio telescope. It is being built by a partnership of 12 countries on two sites, one in Australia, the other in South Africa. The headquarters of the project are at Jodrell Bank, 20km south of Manchester in the UK. SKA is a billion-euro scale project, using state-of-the-art detector systems to generate enormous quantities of data. The purpose being to explore and extend our understanding of the Universe and its underlying physics. I will describe the science we hope to do with the SKA; the technology being developed, the systems we are designing to handle the PetaBytes of data and the current status of the project.
SC-3 | Fast timing detectors for HEP and medical applications

Coordinators: Jona Bortfeldt, LMU, Germany; Nicolo Cartiglia, INFN, Italy

This two-day course will cover fast timing detectors and their application in high energy and medical physics. The first day focuses on high energy physics instrumentation. Different timing detectors, based on charge detection in silicon and gas, or light detection from scintillators and Cherenkov radiators are described, their working principles and characteristics are discussed. Signal analysis and reconstruction are described and the influence of analog and digital electronics is discussed in detail. The last lesson of the day focuses on the system aspects and the challenges of designing a complex ASIC, using examples from the latest ASIC currently in the R&D phase.

On the second day, the course is instead focused on the application of fast timing detectors in medical physics, namely in TOF-PET or in-beam PET systems, in prompt-gamma imaging or in beam monitoring applications. Signal generation and analysis, analytical and Monte Carlo based modeling are described, together with an in-depth review of currently available and novel commercial PET systems. The development and performance of new scintillator materials are reviewed, and suitable photo-detectors are discussed.

Outline

1. Silicon detectors for 4D tracking in High Energy Physics (Cartiglia)
   - Basics of signal formation, Ramos’ theorem
   - Signal from thin and thick Silicon detectors
   - Why thin sensors with internal gain are critical to a good time resolution
   - Radiation damage effect on the gain mechanism
   - The interplay of sensor and front-end electronics
2. Gaseous detectors for timing measurements (Bortfeldt)
   - Large area, cost-effective timing, and trigger detector
   - Functional principles, characteristics and performance of different gaseous timing detectors: Resistive Plate Chambers, Thin Gap Chambers, Fast Timing MPGD

3. Readout electronics for fast timing detectors (de La Taille)
   - Electronics speed and noise impact on timing resolution
   - Preamplifier configurations for high-speed response: voltage vs. current or charge sensitive
   - Theoretical expressions for jitter due to electronics noise
   - Examples of simulated and measured responses from different configurations
   - Examples of preamplifier schematics

4. ADC-based waveform samplers for timing detectors (Gui)
   - Overview of waveform samplers for timing detectors
   - ADC-based waveform sampler design: targeting specifications and challenge
   - Circuit architectures and design techniques (Successive Approximation Register (SAR) and Pipelined SAR structures)
   - Time-interleaving approach to achieve a very high sampling rate
   - Calibration methods for intra-channel and inter-channel mismatches
   - Example ADC designs and simulation/measurement results

5. System aspects for fast timing detectors (Liu)
   - Design methodology to optimize front-end design from a system point of view
   - System power and cooling constraint and how it influences ASIC design
   - Precision clock distribution considerations: from system to detector, to chip, to pixel and to each TDC delay unit
   - Design for monitoring and calibration considerations
   - Time-frame of ASIC development: choice of “several miniASICs vs. single full ASIC”
   - Examples of ASICs developed in recent years

6. Introduction to fast timing applications in Medical Physics (Schaart)
Time-of-flight positron emission tomography (TOF-PET)
Organ-specific and in-beam PET systems
Prompt gamma detection in hadron therapy
Basic principles of fast timing scintillation detectors in Med Phys
Theory of scintillation detector time resolution timing properties of the scintillation signal
Monte Carlo modeling of time resolution
Analytical models of time resolution
Order statistics and Cramer-Rao modeling

7. Photosensors in fast timing scintillation detectors (Schaart)
   - Signal formation in common photosensors
   - Temporal properties of common photosensors
   - Factors affecting time resolution
   - Readout of fast timing photosensors

8. Exploiting timing information in particle therapy (Cerello)
   - Timing in particle therapy: where and how?
   - Beam monitoring applications
   - Range monitoring applications
   - New delivery concept(s)
   - Flash therapy

9. Development on scintillators for fast timing detectors (Auffray)
   - Scintillation mechanisms
   - Key factors and limits of the scintillators properties for fast timing detection
   - The recent development on scintillators fields to push time resolution toward 10ps

10. System review: the latest commercial TOF PET systems (Surti)
    - Detector design of PMT based TOF PET systems and their limitations.
    - Detector design of the latest digital TOF PET systems and other system design improvements.
    - TOF image reconstruction methods and their impact on clinical lesion detection and quantitative measurement performance.
    - New developments in PET system design with a focus on long axial FOV systems.
Instructors

Etiennette Auffray is a Member of the IEEE, and she has been a member of the RISC committee. She is a senior physicist at CERN, Geneva, Switzerland. She has spent over twenty-five years in the field of scintillators and their applications in particular in high energy physics and medical applications. She was actively involved in the construction of the electromagnetic calorimeter of the CMS experiment at CERN made of 75848 crystals of PWO and now in its operation. She is involved in research activities on scintillating materials for the development of PET and TOFPET through the Crystal Clear collaboration of which she is the spokesperson since 2010. In recent years she has coordinated several European projects related to scintillating materials and their applications in particular in recent years for fast timing detectors.

Jonathan Bortfeldt is Staff Scientist at the Department of Medical Physics of the Ludwig-Maximilians-Universität (LMU) Munich, Germany. He received his Ph.D. in High Energy Physics from LMU Munich in 2014, developing novel micro-pattern gaseous detectors. After post-doctoral work at LMU, he became CERN-COFUND fellow, working on the ATLAS New Small Wheel upgrade with Micromegas. In 2018, he took over the instrumentation lab at the Department of Medical Physics of LMU Munich. He is co-convenor of the Picosec Micromegas collaboration, and member of the RD51 and the ATLAS collaborations. Dr. Bortfeldt's main research interest is the development of high (spatial and temporal) resolution instrumentation for pre-clinical research and laser-accelerated beams.

Nicolò Cartiglia is a Senior Scientist at INFN-Torino. After receiving his Ph.D. from UCSC, he moved to Columbia University and then in 1998 joined INFN. His carrier focuses on the development of new instrumentation for high energy particle experiments. He worked on several experiments, specializing on Silicon sensors. Currently, he is working on the development of a Silicon-based tracking system able to measure time and position concurrently. In recent years, he has been awarded a European ERC-advanced grant and a PRIN grant from Italy.

Piergiorgio Cerello is Senior Researcher at INFN, Italy, Torino Unit. He received his Ph.D. in Nuclear Physics in 1995 and is among the founders of the ALICE experiment at the CERN LHC. In the past two decades, he focused mostly on Medical Applications, setting up a Medical Imaging group in Torino, active on both software and hardware projects. It applied artificial intelligence techniques to the search for lung nodules in chest CT, by developing an algorithm that was clinically validated. Recently, the group took part,
with a major role, in the development of the INSIDE hybrid scanner for online range monitoring in particle therapy.

Ping G"ui is a Full Professor of Electrical and Computer Engineering at Southern Methodist University, Dallas, TX, USA, and an IEEE senior member. Her research focuses on analog and mixed-signal IC design, including radiation-tolerant and high-speed ADCs, PLLs, and data link design. Her research group has developed 56GSp ADCs for 100/400G optical communications, 4x10Gbps laser driver and E-links for the LpGBT and the Versatile Link Plus projects (VL+), and PLL and Data Links capable of operating under cryogenic environments in the DUNE Project. Ping Gui is currently the principle investigator on a DoE awarded project to develop high-speed high-resolution ADCs and waveform samplers for high-energy physics applications.

Christophe de La Taille is director of OMEGA microelectronics lab at École Polytechnique and CNRS/IN2P3 (France). After receiving engineering and Ph.D. degree from École Polytechnique, he joined LAL Orsay and worked on the readout of the ATLAS calorimeter at CERN/LHC and other high energy physics experiments. He was subsequently CTO of IN2P3 and recently founded a design lab at École Polytechnique. He is now coordinator of CMS HGCAL electronics. His research interests are in the field of detectors and mixed signal ASIC design. He is author and co-author of about 168 publications and has been an IEEE member since 2003.

Tiehui Ted Liu is a senior scientist at Fermilab. After receiving his Ph.D. in physics from Harvard in 1995 (CLEO experiment at Cornell), he worked at Princeton from 1995-1997 (on BELLE at KEK), Berkeley Lab from 1997-2000 (BABAR at SLAC), and then moved to Fermilab since year 2000 (on CDF and then CMS). He has been involved in many aspects of particle physics instrumentation, ranging from (current) CMS Endcap Timing Layer upgrade, to tracking trigger R&D for HL-LHC, various trigger systems at CDF and BABAR, Aerogel-based Cherenkov detector at Belle, and Time-of-Flight system at CLEO.

Dennis R. Schaart is head of the section Medical Physics & Technology at the Radiation Science & Technology department of Delft University of Technology (TU Delft). He started his career as an R&D physicist at Nucletron (now Elekta), where he developed new devices for radiotherapy. In his private time he wrote a Ph.D. thesis on the subject of intravascular brachytherapy, for which he obtained his doctoral degree (with highest honors) at TU Delft in 2002. He subsequently joined the university to set up a new research line on in-vivo molecular imaging technology, with special focus on ultrafast detectors for time-of-flight positron emission tomography (TOF-PET). His main research interests include novel methods and technologies for in vivo molecular imaging and for image
guidance in (proton) radiotherapy. Since 2016, he coordinates the research activities of TU Delft within the R&D program of the Holland Proton Therapy Centre (HollandPTC), a joint initiative of Erasmus Medical Centre (Erasmus MC), Leiden University Medical Centre (LUMC), and TU Delft. He furthermore serves as a member of the HollandPTC R&D Program Board. Dr. Schaart is a Senior Member of the IEEE and has served on the IEEE Nuclear and Medical Imaging Sciences Council (NMISC). He has (co-)authored more than 100 peer-reviewed papers and is a frequently invited speaker.

Suleman Surti is a Research Associate Professor in the Physics and Instrumentation group in the Department of Radiology at the University of Pennsylvania. He obtained his Ph.D. in Physics at the University of Pennsylvania and continued his post-doctoral work and faculty appointment in PET imaging research at Penn. Dr. Surti has been involved in PET imaging for over twenty years focusing on system development, optimization, and evaluation of several PET scanners developed at the University of Pennsylvania as well as new commercial systems ranging from small-animal PET through application-specific PET (brain, breast, proton) to whole-body PET (Non-TOF, TOF, long axial field-of-view). His work has spanned development of scintillation detectors and electronics, their incorporation in optimized scanner geometries, evaluation of system performance and data/image correction techniques, and optimization of imaging protocols.
SC-4 | Medical image reconstruction: from foundations to AI

Coordinator: Andrew Reader, Kings College London, UK

Using the primary example of positron emission tomography (PET), this one-day course covers key foundational principles for fully 3D image reconstruction through to state-of-the-art methods using artificial intelligence (AI). The course will start with analytic 2D and 3D filtered back projection (FBP) methods, and then cover more advanced data modelling with iterative and statistical image reconstruction methods, including compensation for noise through Bayesian regularisation.

After covering these foundations, relatively recent reconstruction advances will be considered, including guided and synergistic PET-MR image reconstruction, fully 4D image reconstruction along with direct estimation of kinetic parametric maps from dynamic emission tomography data.

The last section of the course will provide a comprehensive introduction to the key concepts of artificial intelligence (AI), more specifically machine and deep learning, in the context of emission tomographic image reconstruction, and review some of the latest methods which exploit AI to enhance reconstructed image quality.

Outline

1. Foundations
   - Object representation, emission tomography data, linear shift-invariant (LSI) systems
2. Iterative and statistical image reconstruction
   - Maximum likelihood (ML) reconstruction
   - Poisson log-likelihood, simple gradient method
   - Complete data and expectation maximisation (EM)
   - Factorised system models, PSF modelling
   - Ordered subsets EM (OSEM), ordinary Poisson (OP)-OSEM
   - Properties of ML estimates
   - Maximum a posteriori (MAP) / Bayesian reconstruction
   - Types of prior, simple EM algorithms
   - Optimisation transfer methods
   - Modelling and data corrections
   - Attenuation, scatter, randoms, normalisation, motion correction

3. Recent advances
   - Guided regularised image reconstruction
   - MLEM, MAP and kernel EM (KEM)
   - Synergistic PET-MR image reconstruction
   - Joint estimation, and alternating example methods
   - 4D and direct parametric image reconstruction
   - Linear methods, non-linear models

4. Artificial intelligence (AI) in PET image reconstruction
   - Introductory concepts, direct methods, convolutional neural networks (CNNs), post-reconstruction methods
   - Introduction to unrolled reconstruction methods with deep learning
   - State-of-the-art current examples of deep learning in PET image reconstruction
Instructors

Andrew Reader is a Professor of Imaging Sciences at King's College London, United Kingdom. He is in the School of Biomedical Engineering and Imaging Sciences, and is also an adjunct Professor at McGill University. He received his Ph.D. in medical physics from the University of London in 1999 on the subject of PET image reconstruction. He was a Canada Research Chair based at the Montreal Neurological institute for 6 years, and returned to the UK in 2014 taking up his post at King’s College London. He has co-authored over 200 scientific outputs. His research interests include PET and multi-modal image reconstruction, data modelling and the application of machine learning to PET-MR imaging.

Jinyi Qi is a Professor of Biomedical Engineering at the University of California – Davis (UC Davis), USA. He received his Ph.D. in electrical engineering from the University of Southern California in 1998. He was a research scientist at the Lawrence Berkeley National Laboratory before joining the faculty of UC Davis in 2004. He has been an Associate Editor for IEEE Transactions on Medical Imaging since 2006. He is a Fellow of IEEE and AIMBE. His main research interests concern the development of advanced image formation and processing tools to push the boundary of molecular imaging using positron emission tomography (PET)/computed tomography (CT). His lab combines in silico modelling of tracer kinetics, imaging system response and human observation to create new image reconstruction algorithms and design future imaging systems that provide higher sensitivity and specificity for clinical applications.

Kris Thielemans is a Professor in Medical Imaging Physics at University College London (UCL), United Kingdom. He received his PhD degree in String Theory from KU Leuven in 1994. Prior to UCL, he worked as a Researcher at Hammersmith (London, UK) for the Medical Research Council and General Electric, and at King’s College London (KCL). His research interests encompass all aspects of quantitative PET image reconstruction with emphasis on the development of advanced reconstruction techniques for PET and SPECT including motion correction. He developed along with others an open source software for tomographic image reconstruction (STIR) which has been cited more than 250 times. More recently he leads a project in synergistic image reconstruction (the synergistic image reconstruction framework (SIRF)).
NP-2 | NSS Plenary II

Cinzia DaVia (Manchester)
Yoshinobu Unno (Tsukuba)
NP-2-01  10:20 AM

Introduction

Yoshinobu Unno

KEK, Japan

NP-2-02  10:25 AM

The Human Brain Project and SpiNNaker

Prof. Stephen Furber

The University of Manchester, Manchester, UK

The SpiNNaker (Spiking Neural Network Architecture) platform has been developed to support real-time modelling of large-scale biological neural networks. It currently incorporates a million ARM processor cores with a bespoke interconnect fabric specifically designed to enable the very high connectivity of biological brains to be modelled. As neuron and synapse models are implemented in software, SpiNNaker is very flexible, and it can be used to model novel neuron models and learning rules. The SpiNNaker platform is openly accessible under the auspices of the EU Flagship Human Brain Project, and is currently being used to support a wide range of neuroscientific research. A second generation machine is also under development.

NP-2-03  11:05 AM

The European Spallation Source

Prof. John Womersley

ESS, Lund, Sweden

I will present an update on the European Spallation Source. The ESS is Europe’s next-generation neutron scattering facility, and is under construction in Lund, with the data management and software centre hosted in Copenhagen. It will be the world’s most powerful accelerator driven neutron source offering capabilities an order of magnitude beyond what currently exists. It is being built by a partnership of 13 European nations and has a total cost of roughly 2 billion Euros. Civil construction is nearing completion and operation of the first accelerator components is now starting. The initial suite of user instruments has been defined and we are making significant progress towards bringing the first three online in 2023. I’ll describe progress on the project, outline the technical challenges and some of the science
opportunities that ESS will offer. I’ll also give an update on the work being done to understand and prepare for the start of operation of the facility in the coming decade.

NP-2-04 11:45 AM

**NSS 2019 Awards Introduction**

Paul Le Coq

*CERN, Switzerland*

NP-2-05 11:52 AM

**Radiation Instrumentation Early Career Award Award**

NP-2-06 11:57 AM

**IEEE Emilio Gatti Radiation Instrumentation Technical Achievement Award**
Glen Knoll Radiation Instrumentation Outstanding Achievement Award
N-01 | Scintillators, Photodetectors and Applications I

Marek Moszyński (Świerk (Otwock))
Ren-yuan Zhu (Pasadena)

This session is focused on systems, ranging from single detector instruments to apparatus based on a large number of units.
**SiPMs for direct scintillation light detection in noble liquids** (#2278)

**Dr. Thomas Tsang**

*Brookhaven National Lab., Upton, USA*

**Content**

The extremely low dark count rate of the state-of-the-art vacuum ultraviolet sensitive SiPMs working in cryogenic temperature is about five orders of magnitude lower than at room temperature. However, the dark rate or the corresponding dark current of the same SiPM working in purified noble liquids of Ar, Kr, and Xe are generally higher. We show that the higher dark rate is caused by the nonzero scintillation light events triggered by environmental radioactivity in an ordinary laboratory at sea-level. Although these background scintillation light in noble liquids are in single-photon low light level, in some applications it might be a nonnegligible background.

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**Cryogenic SiPM technology for a direct dark matter detection experiment (DarkSide-20k)** (#1477)

**Alberto Mazzi**, Fabio Acerbi, Marco Marcante, Giovanni Paternoster, Veronica Regazzoni, Nicola Zorzi, Alberto Gola

*Fondazione Bruno Kessler, Center for Materials and Microsystems, Trento, Italy*

**Content**

We describe the development of cryogenic silicon photomultiplier (SiPM) technology that was carried out at Fondazione Bruno Kessler (FBK) to meet the project requirements of DarkSide-20k (DS-20k) experiment. DS-20k is a direct dark matter detection experiment, which will be installed at INFN Gran Sasso National Laboratory, Italy. It is based on a time projection chamber filled with low background liquid argon (LAr). The photodetection modules of DS-20k are based on SiPMs, with a total photosensing area of 14 m². SiPM technology allows flexibility in detector design and assembly, low power consumption, high efficiency and low background thanks to improved radiopurity. The dedicated development of FBK SiPMs, based on NUV-HD technology, led to a specialized version, known as NUV-HD-Cryo. The SiPM production process was deeply redesigned, with a lower peak electric field at the junction, a highly stable quenching resistor with small temperature variations, and a process adjustment to reduce correlated noise at cryogenic temperature. The resulting NUV-HD-Cryo SiPMs show a photon detection efficiency of 50% at 6 V excess bias, at 420 nm with 30 µm cells. The primary dark count rate is of 10 mHz/mm² at 6 V, at LAr temperature, with 22% direct crosstalk probability and ~10% afterpulsing probability. These results are enabling for the use the use of SiPM in the readout of liquid scintillators, allowing large area photodetector readout with low background level. The assembly of test photodetection modules is now in progress and will allow in the next months to evaluate detector performance at cryogenic temperature with integrated electronic readout.
Characterization of CLLBC Coupled to Silicon Photomultipliers (#1524)

Dr. Felix Liang, Dr. Jason Smith

FLIR Systems, Inc., Oak Ridge, USA

Content

Cs$_2$LiLa(Br$_x$Cl$_{6-x}$):Ce (CLLBC) has high energy resolution for gamma detection and high sensitivity for neutron detection. It is one of the neutron-gamma dual-mode scintillators developed in recent years. This work studies the performance of an 18 mm CLLBC cube for gamma and neutron detection for temperatures between –20 and 50 °C. In addition, the scintillator was coupled to the SensL C- and J-series silicon photomultipliers (SiPMs) for comparison. Throughout the temperature range, better energy resolution is observed for the scintillator coupled to the J-series SiPMs which can be attributed to the higher photon detection efficiency. For neutron detection, the output of the detector was recorded by a waveform digitizer and analyzed offline on a computer. To distinguish neutrons from gammas, a pulse shape discrimination technique was utilized. A good separation between neutrons and gammas is observed for all the temperatures. However, separating neutrons from the intrinsic alphas is somewhat difficult at low temperatures. In spite of that, this 18 mm CLLBC is a high-performance scintillator and is suitable for deployment in radiation detectors for safeguard and security applications.

Energy Resolution, Pulse Shape Discrimination, and Coincidence Time Resolution with CLLBC Scintillators Coupled to Silicon Photomultipliers (#2536)

Joshua W. Cates$^1$, Ryan Pavlovsky$^1$, Kai Vetter$^{1,2}$

$^1$ Lawrence Berkeley National Laboratory, Applied Nuclear Physics, Berkeley, USA; $^2$ University of California Berkeley, Nuclear Engineering, Berkeley, USA

Content

Cs$_2$LiLa(Br$_x$Cl$_{6-x}$):Ce (CLLBC) is a recently developed elpasolite scintillator with excellent energy resolution for gamma rays, and it is lithium-loaded for thermal neutron detection. The Cl content of the crystal also facilitates a channel for fast neutron detection, although with lower efficiency than the thermal absorption channel. Achievable energy resolution is typically <4% for 662 keV deposited energy, and differing ionization kinetics for hot recoil electrons from gamma interactions and heavy, charged particles resultant from thermal neutron absorption facilitate pulse shape discrimination between gamma and neutron interactions. In this work, we present achievable energy resolution, pulse shaped discrimination, and coincidence time resolution (CTR) with 1.2x1.2x1.2 cm$^3$ and 2.4x2.4x5.0 cm$^3$ CLLBC crystals from Radiation Monitoring Devices Inc. coupled to arrays of SensL-J SiPM arrays. With an optimized signal...
processing chain, energy resolution of ~3% is achievable at 662 keV energy deposition for 1.2x1.2x1.2 cm³ crystals and ~3.5% is maintained for the 2.4x2.4x5.0 cm³ crystals coupled to larger SiPM arrays at room temperature. A temperature probe inside the hermetically sealed packaging of the crystal and photosensor allows corrections to be applied to spectral data to maintain this energy performance across a large temperature range. Excellent pulse shape discrimination (PSD) between gamma and neutron events is observed for both crystal geometries (FOM>3) using standard tail-to-total methods and also techniques that facilitate PSD using only a single charge integrator and analog-to-digital converter (FOM>2.5). We also report on the CTR between identical pairs of 1.2x1.2x1.2 cm³ and 2.4x2.4x5 cm³ CLLBC crystals using a high frequency electronic readout designed to combat the large device capacitance of the SiPM array.

N-01-05  2:52 PM

High-Speed, Efficient, High-Resolution Gamma Ray Imaging, The ClearMind Project (#1650)

Dr. Dominique Yvon¹, Dr. Viatcheslav Sharyy¹, PhD/MD student Megane Follin¹, Jean-Pierre Bard¹, M.Sc./M.A. Dominique Breton², M.Sc./M.A. Jihane Maalmi², Prof. Christian Morel³

¹ CEA, Paris-Saclay Univ, IRFU, Gif sur Yvette, France; ² CNRS-IN2P3, LAL-Orsay, Orsay, France; ³ Aix-Marseille Univ, CNRS-IN2P3, CPPM, Marseille, France

Content

The ClearMind project develops a monolithic gamma ray detector (0.5 MeV to few MeV) with a large area (≥25 cm²), high efficiency, high spatial accuracy (< 4 mm³ FWHM) and high timing accuracy. We use PbWO4 scintillating crystals on which are directly deposited photoelectric layers of refractive index greater than that of the crystals.

The crystal is encapsulated with a micro-channel plate multiplier tube (MCP-PMT) with a densely pixelated anode plane, in order to optimize photo-electrons timing and positioning measurements. The MCP-PMT is read out using transmission lines and a SAMPIC fast waveform recorder.

Our detector assets consist in:

• Improving the efficiency of light collection in a high-density, and high-effective atomic number crystal. We expect a factor 4 gain on light collection efficiency compared to conventional assemblies.

• Using the Cherenkov light emission for detection. The gain in optical coupling optimizes the detection efficiency of Cherenkov photons, inherently very fast.

• Using the map of photoelectrons produced at the surface of the crystal to reconstruct the properties of the gamma interactions. The scintillation photons provide the necessary statistics for a measurement of the energy deposited in the crystal, modest but compatible with a use on a PET imager, and an accurate positioning of the gamma ray interaction.

• Using the SAMPIC waveform recorder and transmission lines, which allows excellent timing and spatial resolution with a reduced number of readout channel.

We will present the detector concept and simulation results supporting the foreseen performances as well as measured performances of our prototype bialkali photocathode deposited on PbWO4. A companion paper (M. Follin et al.) will be devoted to the ultrafast MCP-PMT readout technologies using the SAMPIC waveform digitizers.

N-01-06  3:10 PM

Development of x-ray talbot-lau imaging system using submicron-diameter phase-separated scintillator fibers (#2597)

Dr. Kei Kamada¹,² Hiroaki Yamaguchi¹, Dr. Kyoung Jin Kim¹, Dr. Akihiro Yamaji¹, Prof. Vladimir Kochurikhin³,², Prof. Shunsuke Kurosawa¹, Prof. Yuui Yokota¹, Yasuhiro Shoji²,¹, Prof. Yuji Ohashi¹, Prof. Akira Yoshikawa¹,²

¹ Tohoku University, Sendai, Japan; ² C&A Corporation, Sendai, Japan; ³ Prokhorov General Physics Institute of RAS, Moscow, Russia

Content
The 25 x 25 mm² wafers of Tb doped GAP/a-Al₂O₃ eutectic were fabricated by μ-PD method using the Ir crucible with a 25 x 25 mm² die. The prototype of X-ray phase imaging detector was developed using the CMOS sensor with the FOP and eutectic wafer. X-ray spots with 8.24mm period was observed using the detector. X-ray phase imaging of the nylon ball was carried out in this study. It could be confirmed that a phase change of about 2 μm as the phase change occurs in the air and the nylon spherical interface. A technique of X-ray phase imaging could be realized in the absence of absorption grating.

In this study, X-ray phase imaging without absorption lattice using eutectic structure have demonstrated for the first time in the world.

It is possible to fundamentally solve the reduction in sensitivity and the accompanying increase in the amount of X-ray irradiation to the subject, which is a problem in conventional X-ray phase imaging using absorption gratings.
N-02 | Radiation Hardness of Detectors and Systems I

Ian Dawson (Sheffield)
Stephen J. Watts (Manchester)
N-02-01  1:40 PM

Radiation Hardness Study on a Fully Depleted Pinned Photodiode CMOS Image Sensor (#1277)

Dr. Xiao Meng, Dr. Konstantin D. Stefanov, Prof. Michael A. Holland, Prof. Andrew D. Holland

The Open University, Centre for Electronic Imaging, Milton Keynes, UK

Content
The radiation hardness of a fully depleted Pinned Photodiode (PPD) CMOS image sensor (CIS) has been evaluated with gamma and proton irradiations. The sensors employ an additional n-type implant in pixel which allows full depleletion to be achieved by reversing biasing the substrate, and have been irradiated alongside reference devices in which the implant has been omitted. Event analysis under X-ray illumination has been used to study the charge collection and charge diffusion in the sensors. The results show no obvious charge collection degradation at 10 MeV equivalent proton fluence of up to $10^{11}$ p/cm$^2$. Moreover, it has been shown that charge diffusion is largely suppressed in the fully depleted sensors. After exposure to a total dose of 100 krad(Si), both the fully depleted and the reference sensors show high sense node leakage current. This is believed to be due to an exposed edge of the shallow trench insulation (STI) oxide near the sense node. Dark signal distribution shows that hot pixels are dominant for both sensors after proton irradiation. An activation energy of $\sim$0.62 eV derived from the temperature-dependent dark current result suggests that irradiation induced bulk defects is the main dark current source.

N-02-02  1:58 PM

Radiation hardness test results on a new anisotropic conductive adhesive to replace bump-bonding in HEP detectors (#2508)

Dr. Julie D. Segal¹, Dr. Christopher J. Kenney¹, Andrew Stemmermann², Dr. Manian Ramkumar³, Madhu Stemmerman², Dr. Jasmin Has³, Martin K. Anselm³

¹ SLAC National Accelerator Laboratory, Menlo Park, USA; ² Sunray Scientific, Long Branch, USA; ³ Rochester Institute of Technology, Rochester, USA

Content
Particle tracking experiments in high energy physics deploy hybrid pixel detectors based on a sensor array connected pixel by pixel to a read-out ASIC. Bump-bonding is used to create the parallel contacts. New flip-chip bonding techniques are needed to accommodate smaller pitch and to avoid damage to thinner components, and for cost reduction. Anisotropic Conductive Adhesives (ACA) have the potential to meet these challenges, if they can be shown to meet the radiation hardness requirements of the HEP environment. SunRay Scientific’s ZTACH®ACA features sub-micron, ferromagnetic particles within a modified epoxy. When placed between the sensor and read-out chip and exposed to a magnetic field, the particles self-assemble into conductive columns that connect the contact points. The adhesive is cured using either minimal heat or UV radiation, without applying pressure to the circuits. We have bonded
test structures with ZTACH®ACA and subjected the samples to gamma rays and neutron radiation. Electrical behavior and material characteristics were unchanged by exposure to gamma ray irradiation of 1 MGray of total ionizing dose, and neutron fluence of $1 \times 10^{15}$ Mev neutrons/cm$^2$.

**N-02-03**

**Performance of High-Voltage Silicon JFETs after Neutron Irradiation** (#1827)

**Gabriele Giacomini**, Wei Chen, David Lynn

*Brookhaven National Lab, UPTON, USA*

**Content**

A High-Voltage vertical JFET was conceived at Brookhaven National Laboratory as a candidate for the High-Voltage Multiplexing switch in the ATLAS upgrade of the silicon microstrip Inner Tracker (ITk). While based on a vertical structure, with the drain being the epitaxial layer, it was fabricated at BNL using only the planar process routinely adopted for the fabrication of silicon sensors. Both $n$-type and $p$-type HV-JFETs have been successfully fabricated. Probe station measurements of un-irradiated devices show low leakage currents and high breakdown voltages (up to 600V) in the OFF state, and high currents in the ON state, which satisfy the requirements for the switch, at least before irradiation. Then, a neutron irradiation has been performed at the TRIGA nuclear reactor at Jozef Stefan Institute (Ljubljana, Slovenia) to assess the suitability of this device at the radiation levels foreseen in the ITk. The irradiated devices have been characterized as well. We will present the concept of the HV-JFETs and their electrical characterization before and after irradiation.

**N-02-04**

**A comparison of proton and neutron induced defects within CCDs** (#1786)

**Dr. Nathan Bush**, Dr. Jonathan Keelan, Dr. David J. Hall, Prof. Andrew D. Holland

*The Open University, Physical Sciences, Milton Keynes, UK*

**Content**

Silicon Charge Coupled Devices (CCDs) are selected for high precision astronomy missions due to their high quantum efficiency, low readout noise and rich space heritage. The transfer-reliant architecture of the device means that CCDs are susceptible to the effects of radiation damage, particularly silicon defects that can defer signal charge and increase Charge Transfer Inefficiency (CTI). Flight instruments are typically shielded, and so the particle spectrum is the convolution of the space radiation environment and the shielding surrounding the detector. The use of high-Z shielding, such as Molybdenum and Tantalum, can result in a significant fluence of secondary neutrons that
induce cluster defects, while protons and electrons predominantly produce point defects. Cluster defects are of particular concern for instruments that operate with low signal levels, as they have the potential to render columns of the detector unusable. Here, we present a study whereby devices were irradiated using 74 MeV protons and 5 MeV neutrons and the distribution of silicon defects compared using the “single trap pumping” technique. Specific attention is paid to the double acceptor state of the silicon divacancy (VV\(^-\)), where it is shown that the ratio of point defects to cluster defects is sensitive to particle energy for the case of proton irradiation, while the neutron irradiation almost exclusively produces cluster defects.

N-02-05

Proton-Induced Radiation Damage in Fast Crystals (#2552)

Chen Hu\(^1\), Fan Yang\(^2\), Liyuan Zhang\(^1\), Ren-Yuan Zhu\(^1\), John Kapustinsky\(^3\), Ron Nelson\(^3\), Zhehui Wang\(^3\)

\(^1\) California Institute of Technology, HEP, Pasadena, USA; \(^2\) Nankai University, Tianjin, China; \(^3\) Los Alamos National Laboratory, Physics, Los Alamos, USA

Content

Inorganic scintillators are widely used in high-energy physics (HEP) experiments. With \(5\times10^{34}\) cm\(^{-2}\)s\(^{-1}\) luminosity and 3,000 fb\(^{-1}\) integrated luminosity, the HL-LHC will present a severe radiation environment. Bright and fast cerium doped lutetium yttrium oxyorthosilicate (Lu\(_{2(1-x)}\)Y\(_x\)SiO\(_5\)::Ce or LYSO) crystals are proposed for a CMS precision timing detector at the HL-LHC, where up to 2.5 Mrad ionization dose, \(1.7\times10^{13}\) charged hadrons/cm\(^2\) and \(2\times10^{14}\) neutrons/cm\(^2\) are expected. With an ultrafast scintillation of less than 0.6 ns decay time and a suppressed slow component yttrium doped BaF\(_2\) crystals (BaF\(_2\):Y) promise an ultrafast calorimeter for the Mu2e-II experiment at Fermilab. We report results on proton-induced radiation damage in LYSO, BaF\(_2\) and BaF\(_2\):Y, irradiated by 800 MeV protons up to \(1.7\times10^{15}\) p/cm\(^2\) at the blue room of LANSCE as well as by 24 GeV protons up to \(1.3\times10^{15}\) p/cm\(^2\) at CERN.

N-02-06

Experimental determination of proton hardness factors for radiation hardness studies. (#2683)

Prof. Phil Allport\(^1\), Felix Boegelspacher\(^3\), PhD/MD student Rhiann Canavan\(^1\), Dr. Alexander Dierlamm\(^3\), Dr. Laura Gonella\(^1\), PhD/MD student Patrick Knights\(^1\), PhD/MD Isidre Mateu\(^2\), Dr. Michael Moll\(^2\), Prof. Kostas Nikolopoulos\(^1\), Ben Phoenix\(^1\), Dr. Tony Price\(^1\), M.Sc./M.A. Lydia Ram\(^1\), Dr. Federico Ravotti\(^2\), PhD/MD student Cameron Simpson-Allsop\(^1\)

\(^1\) University of Birmingham, School of Physics and Astronomy, Birmingham, UK; \(^2\) CERN, IRRAD Proton Facility, Geneva, Switzerland; \(^3\) Karlsruhe Institute of Technology, Karlsruhe, Germany

Content
The effects of irradiation with beams of different particle species and energy are compared using their respective hardness factors. The hardness factors for proton beams at three different energies have been measured by analysing the I–V and C–V characteristics of BPW34F photodiodes. This was done by performing irradiations at the University of Birmingham’s MC40 Cyclotron, the cyclotron at the Karlsruhe Institute of Technology, and the IRRAD proton facility; the hardness factors were measured to be $2.21 \pm 0.40$ for 24 MeV protons, $1.97 \pm 0.38$ for 23 MeV protons, and $0.62 \pm 0.04$ for 24 GeV protons. The hardness factors currently used in these three facilities are in agreement with the respective measurements.
N-03 | Computing Perspectives

Maria Grazia Pia (Genova)
Gian-Franco Dalla Betta (Trento)

An open-minded overview of current computing R&D
Belle II distributed computing system: development and operation status (#1530)

Takanori Hara², Kiyoshi Hayasaka⁵, Kunxian Huang⁴, Yuji Kato³, Paul J. Laycock¹, Hideki Miyake², Dmitry Neverov³, Hiroaki Ono⁶, Siarhei Padolski¹, Ikuo Ueda², Michel H. Villanueva⁷, On behalf of Belle II Collaboration

¹ Brookhaven National Laboratory, Physics Department, Upton, USA; ² High Energy Accelerator Research Organization, Institute of Particle and Nuclear Studies, Tsukuba, Japan; ³ Nagoya University, Institute for the Origin of Particles and the Universe, Nagoya, Japan; ⁴ National Taiwan University, Department of Physics, Taipei, Taiwan; ⁵ Niigata University, High Energy Physics Laboratory, Niigata, Japan; ⁶ Nippon Dental University School of Life Dentistry at Niigata, Department of Physics, Niigata, Japan; ⁷ University of Mississippi, Department of Physics and Astronomy, Oxford, USA

Content
The Belle II experiment at the SuperKEKB energy-asymmetric e⁺e⁻ collider is a substantial upgrade of the former Belle experiment at the KEKB accelerator, operated at Tsukuba, Japan. The design luminosity of the SuperKEKB accelerator is 8x10³⁵ cm⁻²s⁻¹, which is about 40 times larger than that of the KEKB accelerator, and the Belle II experiment is aiming to collect 50 ab⁻¹ of data, a factor of 50 more than the Belle experiment. With this rich amount of data, various physics programs are anticipated, including search for new physics particles which are theoretically predicted but not observed yet. The beam data processed by the Belle II data acquisition system will reach several tens of petabyte per year, under an operation of SuperKEKB accelerator with a designed instantaneous luminosity. Since a single computing site is difficult to handle such huge amount of data, the Belle II experiment introduced a distributed computing system to exploit collaborators or commercial computing resources in the world, and connect them with high speed network. The Belle II distributed computing system is based on DIRAC interware, which was initially developed for LHCb experiment but nowadays employed by various field of scientific programs, e.g. ILC, CTA, or GridPP. The key components of the Belle II distributed computing system are production system for job management, distributed data management system for data management, and automatized monitoring system. These sub systems are implemented by python based DIRAC API. Job processing and data transfer statuses are monitored by collaboration-wide data production shifts for 24 hours a day. Once an issue is reported, computing experts begin to resolve the issue. In this presentation, overview of the Belle II distributed computing system, current operation status, and future plan will be shown.
Gaussino - a Gaudi-based core simulation framework (#2217)

Dr. Benedetto G. Siddi\textsuperscript{2}, Dr. Dominik Mueller\textsuperscript{1}, On behalf of the LHCb collaboration

\textsuperscript{1} CERN, Meyrin, Switzerland; \textsuperscript{2} INFN, Sezione di Ferrara, Ferrara, Italy

Content

The increase in luminosity foreseen in the future years of operation of the Large Hadron Collider (LHC) creates new challenges in computing efficiency for all participating experiment. To cope with these challenges and in preparation for the third running period of the LHC, the LHCb collaboration currently overhauls its software framework to better utilise modern computing architectures. This effort includes the LHCb simulation framework (Gauss). In this talk, we present Gaussino, an LHCb-independent simulation framework which forms the basis for LHCb's future simulation framework which incorporates the reimplemented or modernised core features of Gauss. It is built on Gaudi's functional framework making use of multiple threads. Event generation is interfaced to external generators with an example implementation of a multi-threaded Pythia8 interface being included. The detector simulation is handled by the multithreaded version of Geant4 with an interface allowing for the parallel execution of multiple events at the same time as well as for parallelism within a single event. Additionally, we present the integration of DD4hep geometry description into Gaussino to handle the detector geometry and conversion.

The curse of software size (#2665)

Dr. Elisabetta Ronchieri\textsuperscript{1}, Dr. Maria Grazia Pia\textsuperscript{2}

\textsuperscript{1} INFN - Istituto Nazionale di Fisica Nucleare, CNAF, Bologna, Italy; \textsuperscript{2} INFN - Istituto Nazionale di Fisica Nucleare, Genova, Genova, Italy

Content

Correlation between software size (number of lines of source code) and characteristics of the software such as effort of comprehension, reliability and maintainability is a controversial issue in the software engineering literature. Empirical studies report discordant conclusions: either the complexity measures they examined were highly correlated with lines of code or they did not observe a strong correlation between complexity metrics and the size of the code. This issue is especially relevant to the computational environment of particle and nuclear physics, and of related experimental physics fields, which is characterized by large scale software systems, reflecting the great complexity of the problem domain. Nevertheless, the relationship between the size of scientific software systems and other characteristics associated with software engineering quality has not been quantitatively evaluated yet. This presentation illustrates the outcome of the first (to the best of our knowledge) quantitative analysis of correlation between software size and a wide collection of established software quality metrics, performed over a scientific software system. It concerns Geant4 and applies rigorous statistical methods. The findings are discussed in the light...
of Lehman laws of software evolution (continuing change and growth, increasing complexity, declining quality, self-regulation).

Sensor Drift Estimation for Rector Systems by Fusing Multiple Sensor Measurements (#2464)

**Dr. Nageswara S. V. Rao**¹, Dr. Christopher Greulich¹, Dr. Pradeep Ramuhalli¹, Dr. Sacit M. Cetiner¹, Dr. Pravallika Devineni¹

¹ Oak Ridge National Laboratory, Oak Ridge, USA; ² Oak Ridge National Laboratory (ORNL), Computational Science and Engineering Division, Oak Ridge, USA

**Content**

A nuclear power plant is instrumented with a variety of sensors to continually monitor its health state, and if needed, initiate reactive or corrective actions. Drifts in sensor calibrations are an important issue that affects such health state assessments by potentially introducing bias and other measurement errors, which in turn affect critical response decisions. The sensors measure variables that are typically related to each other under the underlying system laws, which are often characterized by smooth or bounded variance regression surfaces. We address the problem of estimating drifts in measurements of a sensor of primary coolant system of a power reactor system by using fusers of measurements collected by multiple sensors. We propose a machine learning approach to train these fusers by utilizing sensor measurements collected under known no-drift conditions. The fusers provide an estimate of the sensor measurement by using measurements from other sensors, and the difference between the actual sensor measurement and this estimate is an estimate of the sensor drift. We present experimental results for estimating the drift of a differential pressure sensor of the heat exchanger of a primary coolant system. We employ the support vector machine and ensemble of trees regression methods to implement and train the fusers, and they provide smooth and non-smooth regression estimates, respectively. We assess their performance under twenty controlled test scenarios implemented over an emulation testbed of the primary loop of a nuclear power plant that uses a heater as a surrogate fuel source. Results indicate that positive and negative drifts are captured by both methods in scenarios ranging from slow and small to rapid and large drifts. The root mean square errors of estimated drifts are within 1.89% and 2.08% percent of the maximum sensor reading for the support vector machine and ensemble of trees methods, respectively, across all twenty scenarios.
N-03-05 2:52 PM

Complex Geant4 Simulation Study for the Optimisation of Multi-Grid Detector (#2678)

Eszter Dian¹,², Dr. Kalliopi Kanaki², Dr. Richard J. Hall-Wilton²,³, Dr. Anton Khaplanov², Dr. Thomas Kittelmann², Dr. Péter Zagyvai¹

¹ Hungarian Academy of Sciences, Centre for Energy Research, Budapest, Hungary; ² European Spallation Source ESS ERIC, Lund, Sweden; ³ Università degli Studi di Milano-Bicocca, Milano, Italy

Content
The unique neutron yield and high performance requirements of the European Spallation Source (ESS) ERIC, and the current ³¹He-shortage opened a new frontier for neutron detector development. A potent new solution for large area detectors is the Multi-Grid thermal neutron detector: an Ar/CO₂ gas filled detector with solid ¹⁰B₄C converter, developed for the chopper spectrometers at the ESS. For these instruments a high Signal-to-Background Ratio (SBR) is a key requirement, so understanding the effect and sources of the scattered neutron background, considering the intrinsic detector background as well is essential for instrument optimisation. Thanks to the recently introduced neutron simulation tools, a detailed Geant4 model of the Multi-Grid detector was developed and validated against measured data for Monte Carlo simulations. These simulations allow a novel, holistic approach to understand the intrinsic detector background and to determine the effect of different detector components as sources of neutron scattering, and their impact on the measured signal. The model became a powerful tool in the development of the detector design and was applied for the optimisation of the SBR via background reduction. The model was used to determine the impacts of different detector components e.g. the background contribution from the neutron scattering on the aluminium vessel and grids, the shielding properties of additional coating layers and their impact on the detection efficiency and the background-reducing potential of a complex, internal detector shielding, etc. All these phenomena were studied in a detailed simulation of detector response. The model was also applied to dissect and understand the composition and sources of the measured signal from recent prototype tests at the SEQUOIA instrument. The obtained results contribute to the optimisation of the shielding, coating and vessel design of the Multi-Grid detector module, leading to instruments with better SBR by design.

N-03-06 3:10 PM

Diversity in open access and conventional publications (#1522)

Dr. Maria Grazia Pia

INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy

Content
Open access publishing – i.e. a publication model by which authors pay fees to publish their research articles, rather than libraries and other institutional organizations pay subscriptions to scholarly journals – is promoted by various
social bodies as a global shift towards making publicly funded research findings available free of charge for readers. This scientometric study analyzes how open access affects diversity in publications and citations; it concerns scientific areas represented at the IEEE Nuclear Science Symposium (nuclear and particle physics, astrophysics, medical physics and related disciplines), with emphasis on technological research. In this context, diversity is defined according to its usage in the domain of ecology and is quantified by statistical methods, which are related to the concept of entropy in information systems. Measures of diversity are complemented by econometric methods, which quantify inequality in the publication sample and identify trends in the evolution of open access publication over the past decade. The results of the analysis show possibly controversial effects that may be counterintuitive and could be helpful in shaping ongoing initiatives aiming to extend open access publication in scientific research.
N-04 | Nuclear Reactor Instrumentation I

Malcolm J. Joyce (Lancaster)
Christelle Reynard-Carette (Marseille)

Instrumentation is essential to the control, operation and safety of nuclear reactors worldwide, whether they are aimed at materials, research, propulsion or for power applications. This session focuses on the cutting-edge research relating to the use of instrumentation for these purposes and, specifically: monitoring for severe accident purposes, prompt gamma-ray diagnostics, in-core calorimetry, muon tomography, reactor pulse tracking and isotopic distribution characterisation.
Examination of Applicability of Nd:YAG with the Photon Emission Wavelength of around 900nm to a Fiber Optic Radiation Monitor for Severe Accident Conditions  (#1154)

Takahiro Tadokoro¹, Shuichi Hatakeyama¹, Katsunori Ueno¹, Uichiro Ueno¹, Keisuke Sasaki², Akira Ozone², Toru Shibutani²

¹ Hitachi, Ltd., Research & Development Group, Hitachi, Japan; ² Hitachi, Ltd., Control System Platform Division, Hitachi, Japan

Content

Fiber optic radiation monitors are promising dosimetry devices for remote and real time radiation monitoring in nuclear power plants. The transmission performance for the optical fiber of light with a wavelength less than 800nm suddenly decreases for the optical fiber irradiated at a high dose (over 1MGy), so conventional light emission elements cannot be used under severe accident conditions. We have been developing a fiber optic radiation monitor using neodymium-doped yttrium aluminum garnet crystal (Nd:YAG) as a light emission element which emits light with the wavelength of 1,064 nm. We confirmed that the monitor had a capability for measuring dose rates from $10^{-2}$ Gy/h to $6.1 \times 10^4$ Gy/h using the single photon counting method. However, the environmental temperature at the monitor installation position is assumed to be over 200°C under severe accident conditions and the monitor cannot measure the dose rate of $10^{-2}$ Gy/h when there is an influence by the heat radiation background. Nd:YAG also emits light with the wavelength around 900nm in addition to 1,064nm light, and heat radiation decreases as wavelength becomes shorter. Thus, the focus of this presentation is on the examination of applicability of Nd:YAG with the photon emission wavelength of around 900nm to a fiber optic radiation monitor for severe accident conditions. The derived counting rate of photons (around 900nm) as heat radiation at 230°C obtained using measured counting rate at the no photon emission wavelength region of Nd:YAG was 116 counts/10min/(10^{-2} Gy/h)). Thus, it was confirmed that the monitor was able to measure the dose rate of $10^{-2}$ Gy/h at 230°C using the measured counting rates of photons both around 900nm and then photon emission wavelength region of Nd:YAG. Counting rate of photons (around 900nm) was proportional to the laser beam (808nm) power. Thus, we also confirmed that checking the actual measurement conditions of the monitor was possible as in the case of the 1,064nm light.
System development and challenges for delayed gamma-ray nondestructive assay in safeguard verification of nuclear material

PhD/MD Fabiana Rossi¹, PhD/MD Douglas C. Rodriguez¹, Michio Seya¹, Ton Takahashi¹, Mitsuo Koizumi¹, Kamel Abbas², Jean M. Crochemore², Bent Pedersen², Tatjana Bogucarska², Giovanni Varasano², Peter Schillebeeckx³, Stefan Kopecky³, Gasper Žerovnik³, Stephan Oberstedt³


Content

New active-interrogation nondestructive assay techniques are needed for safeguard purpose. They can be used for the quantification of the fissile composition in high radioactivity nuclear material samples. One of the techniques under evaluation by the Japan Atomic Energy Agency together with the European Commission Joint Research Centre is delayed gamma-ray spectroscopy. It utilizes a combination of high rate neutron sources and moderation to thermal energy to induce fission in the fissile nuclides. This will allow enhancing the amount of observable coming from the fission of the fissile compared with the fertile nuclides that are usually more abundant in the sample. Analyzing the peaks ratios of gamma-rays with energy above 3 MeV emitted by the short lived fission products produced in the sample, it is possible to verify the initial composition of the fissile nuclides. We are currently designing and testing several different systems with the goal to design a practical and compact system that can be installed in current reprocessing facilities. In particular, this paper describes the different systems currently tested focusing on the different neutron source and moderator material and geometry as well as different gamma-ray detectors. We will also show the new neutron and gamma-ray detector systems we will implement for future test and development.

Review of calorimetry work dedicated to absorbed dose rate measurement in MTR and realized in the framework of the INCORE and MAHRI-BETHY programs. (#1698)

Dr. Christelle Reynard-Carette¹, Dr. Julie Brun¹, Dr. Michel Carette¹, Dr. Adrien Volte¹, Dr. Abdallah Lyoussi²

¹ Aix-Marseille University, IM2NP UMR 7334, Marseille, France; ² CEA, DEN/DER, Saint-Paul-Lez-Durance, France
The CEA and Aix-Marseille University (AMU) are involved in the IN-CORE program “Instrumentation for Nuclear radiations and Calorimetry Online in Reactor”. This program is coupled to a research program MAHRI-BETHY dedicated to improving calorimetric sensor thanks to parametrical studies under non-irradiation conditions. These two programs began at the end of 2009. They are conducted in the framework of the LIMMEX laboratory created in 2010 (laboratory run jointly by AMU, the CEA and the CNRS, dedicated to Instrumentation and Measurement Methods under Extreme conditions). One important scientific aim of these two programs concerns the improvement of the quantification of the nuclear energy deposition rate (called absorbed dose rate or nuclear heating) in Material Testing Reactors (MTRs) by means of calorimeter. The studied calorimeter-type is differential heat flow calorimeter. The paper will focus on the review of the studies realized during the last ten years. The methodology developed to design, characterize, calibrate, qualify/test such a sensor will be detailed. It corresponds to experimental studies carried out under laboratory conditions and during irradiation campaigns (for instance in the OSIRIS and MARIA reactors), coupled to numerical studies (thermal simulations with specific codes (CASTEM, COMSOL Multiphysics), and Monte Carlo simulations of interactions between radiations and matter (MCNP)). Two major challenges were targeted: the miniaturization of differential calorimeters and the design of new sensors which can be used in reactors requiring innovative measurement devices such as the Jules Horowitz MTR (a new European reactor under construction in the south of France which will start in 2023 and will generate a great nuclear heating value (up to 20W/g)). Key experimental, numerical and theoretical results will be discussed for a usual calorimeter patented in 2011 by the CEA and a new compact one suited to JHR and patented in 2015 by AMU and the CEA.

Content
Muon tomography (MT) has been shown to be a viable candidate for the assay of nuclear storage containers. The EU Horizon-2020 funded CHANCE project will focus on the discrimination and identification of heterogeneous mixtures of different materials in waste packages. We are currently in the process of commissioning a mobile muon tomography detector in a non-laboratory environment at the University of Bristol from a combination of drift chambers and resistive plate chambers. Each of these sub-systems are operational and have begun taking test data. The validation of the reconstruction algorithms and merging of the data from each sub-system is now underway, with the first images from imaging cemented waste packages expected this year. After commissioning, the performance of the CHANCE muon tomography system will be benchmarked. Several benchmarking methods, inspired by ISO spatial resolution tests for cameras, have been developed to understand the minimum size of features that may be observable with the system. The benchmarking techniques developed rely on imaging test objects of known size with decreasing spacings until individual objects are indistinguishable. This makes it possible to extract quantifiable figures of merit for drastically different algorithms. These tests are being

N-04-04
Commissioning and Benchmarking the CHANCE Muon Tomography Detector for Nuclear Waste Packages Assay (#2362)

Dr. Patrick Stowell1, Ahmad Alrheli1, Dr. Daniel Kikola3, Mohammed Mhaidra3, Dr. Anna Kopp2, Dr. Elie Valcke5, Dr. Jaap Velthuis2, Dr. Holger Tietze-Jaensch4, Prof. Lee Thompson1, Michael Weekes1

1 University of Sheffield, Sheffield, UK; 2 University of Bristol, Bristol, UK; 3 Warsaw University of Technology, Warsaw, Poland; 4 Forschungszentrum Julich GmbH, Julich, Germany; 5 SCK•CEN, Mol, Belgium

Content
Muon tomography (MT) has been shown to be a viable candidate for the assay of nuclear storage containers. The EU Horizon-2020 funded CHANCE project will focus on the discrimination and identification of heterogeneous mixtures of different materials in waste packages. We are currently in the process of commissioning a mobile muon tomography detector in a non-laboratory environment at the University of Bristol from a combination of drift chambers and resistive plate chambers. Each of these sub-systems are operational and have begun taking test data. The validation of the reconstruction algorithms and merging of the data from each sub-system is now underway, with the first images from imaging cemented waste packages expected this year. After commissioning, the performance of the CHANCE muon tomography system will be benchmarked. Several benchmarking methods, inspired by ISO spatial resolution tests for cameras, have been developed to understand the minimum size of features that may be observable with the system. The benchmarking techniques developed rely on imaging test objects of known size with decreasing spacings until individual objects are indistinguishable. This makes it possible to extract quantifiable figures of merit for drastically different algorithms. These tests are being
used to directly compare the performance of several algorithms with qualitatively different outputs, and understand the effects that shielding and background materials could have on muon tomographic images of cement waste packages.

In this talk we will present the commissioning status of the CHANCE muon tomography detector and the first test data from the system before discussing the benchmarking methods developed for the project and their applications in the field of muon tomography.

**N-04-05**  
2:52 PM

**Reactor Pulse Tracking Response using Micro-Pocket Fission Detectors in Research Reactors (#2459)**

**PhD/MD student Daniel Nichols**¹, M.Sc./M.A. student John Boyington¹, PhD/MD student Ye Cheng¹, PhD/MD Ryan Fronk², PhD/MD Wenkai Fu¹, Joseph Hewitt¹, Caden Hilger¹, Robin M. Hutchins¹, Katharine Kellogg¹, Jared Medina¹, Taylor Ochs¹, PhD/MD Michael Reichenberger³, M.Sc./M.A. student Sarah Stevenson¹, Tanner Swope¹, M.Sc./M.A. Kevin Tsai², M.Sc./M.A. Troy Unruh², Prof. Jeremy Roberts¹, Prof. Douglas McGregor¹

¹ Kansas State University, Mechanical and Nuclear Engineering, Manhattan, USA; ² Idaho National Laboratory, High Temperature Test Laboratory, Idaho Falls, USA; ³ Idaho National Laboratory, Radiation Measurements Laboratory, Idaho Falls, USA

**Content**

A series of experiments are reported which serve as milestones in the development of the MPFD technology. Each test involved reactor pulsing, a controlled power excursion that results from rapid removal of control rods. During a reactor pulse, the power level increases by several orders of magnitude in a fraction of a second resulting from prompt-critical neutron generation in the core. Preliminary reactor pulse testing was conducted at the Kansas State University TRIGA Mk. ll nuclear reactor (KSU). The MPFD was used to track reactor pulses of $2.77$ and $2.50$ worth of reactivity insertion with measured Full Widths at Half Maximum (FWHM) of $13.2$ and $16.1$ ms compared to theoretical FWHM of $12.2$ and $14.4$ ms using the Fuchs-Nordheim Model. At the University of Wisconsin Madison Nuclear Reactor (UWNR), a set of seven detectors, each with four independent chambers was deployed as part of the NEUP–NEAMS collaboration between UWNR and KSU. Nine of the time-synchronized chambers were able to track three reactor pulses to provide a spatial map of neutron flux. Finally, a two-chamber MPFD was deployed inside the Idaho National Laboratory Transient Reactor Test Facility (TREAT) reactor core and successfully monitored the power excursion of a $13$ GWth reactor pulse with an estimated neutron flux of $10^{16}$ n/cm²/s. These preliminary tests highlight the multi-faceted capability of the MPFD as an instrument in different research and power reactors.
Development of a High-Rate, High-Resolution Associated Particle Imaging System for the Determination of 3D Isotopic Distributions
(#2471)

PhD/MD student Mauricio Ayllon Unzueta\textsuperscript{1,2}, John John\textsuperscript{3}, Dr. Bernhard Ludewigt\textsuperscript{2}, Dr. Arun Persaud\textsuperscript{2}

\textsuperscript{1} University of California, Nuclear Engineering, Berkeley, USA; \textsuperscript{2} Lawrence Berkeley National Laboratory, Accelerator Technology & Applied Physics, Berkeley, USA; \textsuperscript{3} Lawrence Berkeley National Laboratory, Engineering Division, Berkeley, USA

Content
Associated Particle Imaging (API) is a nuclear technique that allows for the non-destructive determination of 3D isotopic distributions. The technique involves the detection of the alpha particle associated with the neutron emitted in the deuterium-tritium fusion reaction in order to determine the direction and time of the emitted 14 MeV neutron. Inelastic neutron scattering leads to characteristic gamma-ray emission from certain isotopes such as \textsuperscript{12}C, which can be correlated with the neutron interaction location. An API system consisting of a sealed-type neutron generator, lanthanum bromide and sodium iodide gamma detectors, and a position sensitive alpha detector has been built. First tests demonstrate an x-y resolution of better than 5 cm and a depth resolution of about 5 cm. We will present the instrument design, the experimental characterization of the instrument's capabilities, and report on high-rate and other data acquisition challenges.
R-01 | RTSD Opening

Paul Sellin (Guildford)
Michael Fiederle (Freiburg)

Opening Session
R-01-01

Advancement of 4×4×1.5 cm³ CdZnTe Detectors (#2594)

Prof. Zhong He, Dr. Yuefeng Zhu
University of Michigan, Nuclear Engineering and Radiological Science, Ann Arbor, USA

Content
After more than a decade of developing and commercializing CdZnTe detectors of dimensions of 2×2×1.5 cm³, the world's largest single-crystal CdZnTe detectors with dimensions of 4×4×1.5 cm³ have been the focus of research and advancement at University of Michigan. These 24 cm³ detectors can offer similar or faster time-to-detect sensitivity compared to the popular 2 inch by 2 inch NaI scintillation detectors to detect most gamma-ray isotope sources. Multiple 24 cm³ CdZnTe detectors, manufactured by Redlen Technologies in Canada and eV/Kromek in the United States, have been tested and evaluated in our laboratory. The 3-dimensional position-sensing technology has been applied to study the characteristics of detectors, including their charge transport properties, material uniformities, as well as problems on electrode fabrication and detector attachment process. Our test results have shown energy resolutions in the range of 0.4% – 0.9% FWHM at 662 keV for single-pixel events on most 24 cm³ CdZnTe detectors manufactured by both companies. This study has demonstrated the feasibility of constructing larger single-crystal CdZnTe detectors, that have high detection sensitivity, better than 1.0% FWHM energy resolution for all events at 662 keV, and real-time gamma-ray imaging capability in real-world applications.

R-01-02

Performance of Perovskite CsPbBr₃ Single Crystal Detector for Gamma-rays Detection (#2815)

PhD/MD student Lei Pan¹, PhD/MD student Teddy Feng², Dr. Praneeth Kandlakunta¹, Prof. Jinsong Huang², Prof. Lei R. Cao¹

¹ The Ohio State University, Nuclear Engineering, Department of Mechanical and Aerospace Engineering, Columbus, USA; ² The University of North Carolina at Chapel Hill, Department of Applied Physical Sciences, Chapel Hill, USA

Content
The lead halide perovskites show a great potential in X- and gamma-rays detection with a desirable high attenuation coefficient, a wide band gap energy, and a large mobility-lifetime (mt) product. The all-inorganic CsPbBr₃ perovskite has its own advantages due to the structural stability over the organic-inorganic perovskites. We report a gamma-rays detector made of CsPbBr₃ single crystals that are able to produce energy spectra from Cs-137 and Co-57 source with energy resolution, in full-width-at-half-maximum, of 5.5% at 662 keV and 13.1% at 122 keV, respectively. The 59.5 keV gamma-rays from Np-237 nuclear decay is also clearly distinguishable with resolution of 28.3% when the detector is exposed to an Am-241 source. Electron-hole averaged mobility-lifetime mt product is evaluated to be 7.91×10⁻⁴ cm² V⁻¹ s⁻¹ by Hecht equation fitting. A better hole transport properties compared to that of electron are
demonstrated at spectroscopy level by acquiring gamma-rays' spectra induced mainly by holes or by electrons. A Digital Pulse Processing (DPP) algorithm is also developed to process the preamplifier signal with potentially long rise time (in the order of tens of micro seconds) in perovskite detectors, which ensures the elimination of ballistic deficit in the charge collection as well as in pulse shaping for distortion-free energy histogram reconstruction.

**R-01-03**  
**2:28 PM**  
**Thick Thallium Bromide Arrays for Radio-isotope Identification (#1512)**  
Hadong Kim¹, Paul Bennett¹, Alireza Kargar¹, Kanai Shah¹, Yaroslav Ogorodnik¹, Suyoung Kim¹, Leonard Cirignano¹, Michael Squillante¹, Zhong He², Charles Leak², Matthew Petryk², Erik Swanberg³, Sean O'Neil³, Stephen Payne³

¹ Radiation Monitoring Devices, Inc., Watertown, USA; ² University of Michigan, Department of Nuclear Engineering and Radiological Sciences, Ann Arbor, USA; ³ Lawrence Livermore National Laboratory, Nuclear and Chemical Sciences Division, Livermore, USA

**Content**  
Thallium bromide is a dense, high atomic number, wide band-gap semiconductor with potential to be a lower cost, higher efficiency alternative to CZT, currently the state-of-the-art room temperature semiconductor gamma-ray spectrometer material. In this paper we report on the development of TlBr arrays approximately 10 mm thick and with pixel pitch in the range of 1.7 mm to 2.5 mm. Depth corrections were applied to improve energy resolution, with information obtained from electron drift time measured through cathode signals. Energy resolution (FWHM @ 662 keV) reached 1.7% for single pixels, and 2.1 % collectively for extended groups of pixels, after 3D corrections were applied. All measurements were carried out at room temperature. These detectors show promise for applications in radio-isotope identification devices and for medical imaging. This work has been supported by the US Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded contract 70RDND18C0000019. This support does not constitute an express or implied endorsement on the part of the Government.

**R-01-04**  
**2:46 PM**  
**Charge transport in CdZnTe detectors with Schottky contact (#1326)**  
Dr. Eduard Belas¹, Dr. Roman Grill¹, Dr. Jindřich Pípek¹, Dr. Petr Praus¹, Dr. Marián Betušiak¹, Dr. Georgios Prekas²

¹ Charles University, Institute of Physics, Faculty of Mathematics and Physics, Prague 2, Czech Republic; ² Redlen Technologies, Saanichton, Canada

**Content**
Semiinsulating CdZnTe is one of the most important semiconductors for fabrication of room-temperature radiation detectors due to relatively high average atomic number, moderate energy band-gap and high electron mobility at room temperature. One of the main problems of preparation of high performance detectors is still the formation of long-term stable electrical contacts resulting in high charge collection efficiency with the absence of detector polarization. In this work transport properties of the high quality indium-doped CdZnTe detectors with platinum Schottky contact are evaluated from the shape of current waveforms using either continuous or pulse biased L-TCT. The shape is analyzed depending on the bias, illumination intensity, beam focusing and correlated position of the optical pulse and leading edge of the bias. White continuum pulsed laser completed by band-pass optical filters separating wavelength 670nm is used for the generation of free carriers. Current waveforms created by drifting charge carriers are amplified by current sensitive preamplifier and recorded by digital sampling oscilloscope. Fast high voltage synchronous bias switching electronics is used in order to get precisely correlated laser pulse and bias leading edge time position to eliminate the space charge formation in detectors. All experimental results are subjected to the theoretical analysis based on the Shockley-Read-Hall trap assisted recombination model. It was found that the detector leakage current was significantly eliminated using Schottky contact, however negative space charge is formed rather fast due to the hole depletion, which results in the detector polarization. The dynamics of negative space charge formation for slowly and quickly polarized detector is investigated. Based on I-V characteristics it was deduced that slowly polarized detector is not subjected to complete polarization due to lower Schottky barrier and consequently weaker hole depletion.

Response and spectroscopic performance of a CdTe pixel detector at deep sub-microsecond signal processing time (#2242)

PhD/MD student Martina Sammartini¹,², PhD/MD Massimo Gandola¹,², PhD/MD student Filippo Mele¹,², Dr. Bruno Garavelli³, PhD/MD Daniele Macera¹, Dr. Pietro Pozzi³, Prof. Giuseppe Bertuccio¹,²

¹ Politecnico di Milano, Department of Electronics, Information and Bioengineering, Como, Italy; ² INFN - National Institute of Nuclear Physics, Sezione di Milano, Milan, Italy; ³ XNEXT s.r.l., Milan, Italy

Content

Advanced scientific and industrial applications based on x and γ ray spectroscopic imaging need systems able to handle high incoming radiation flux (>1 Mcount/s). Guaranteeing a fast response, without compromising the spatial and energetic resolution, still presents a complex challenge and it is object of the most recent research worldwide. Room temperature operation and high absorption efficiency (up to 100 keV of photon energy) is required in many applications and CdTe or CdZnTe are the best semiconductor detectors. In this framework we have developed a research grade spectroscopic system based on a pixelated Schottky CdTe detector coupled to SIRIO-6, a CMOS charge preamplifier specifically designed to have ultra-low noise and fast response in order to study the spectroscopic capability of CdTe pixel detectors at very short signal processing times. The fast rise time of the system (10 ns) paired with its low noise allows to accurately acquire current signals from the detector, well-discriminating electron and hole components, thus enabling the extraction of crucial parameters for optimal operation. At the optimum peaking time of 600 ns an unprecedentedly reported linewidth of 510 eV FWHM on the 59.54 keV of ²⁴¹Am source has been measured with an intrinsic energy resolution of 314 eV, additionally allowing to accurately evaluate the Fano factor.
(F=0.12±0.02) even at room temperature. Deep sub-microsecond spectroscopy at 50 ns with trapezoidal pulse shaping (50 ns flat-top) has been successfully accomplished with linewidths of 600 eV and 455 eV FWHM on the 59.54 keV of $^{241}\text{Am}$ and pulser lines.
R-02 | Pixel Detectors I

Elias Hamann
Characterization of high-Z sensors using the low noise, charge-integrating pixel detector JUNGFRAU (#2120)

Dominic Greiffenberg1, Marie Andrae1, Anna Bergamaschi1, Paolo Busca2, Sabina Chiriotti-Alvarez1, Roberto Dinapoli1, Pablo Fajardo2, Erik Fröjd1, Markus Meyer1, Davide Mezza1, Aldo Mozzanica1, Sophie Redford1, Marie Ruat2, Bernd Schmitt1, Xintian Shi1, Gemma Tinti1, Jiaguo Zhang1, On behalf of the Synerjix collaboration between PSI and ESRF

1 Paul Scherrer Institute (PSI), SLS Detector Group, Villigen, Switzerland; 2 ESRF, Grenoble, France

Content

The most common sensor material for detectors at synchrotron sources and free electron lasers is silicon due to its outstanding material quality in terms of uniformity and charge carrier transport properties. However, sensors with high atomic number like CdTe and GaAs, so-called high-Z sensors, provide absorption efficiencies that are significantly higher in the energy range above 20 keV. Compared to silicon, high-Z sensors are (still) lacking in several aspects: homogeneity, charge transport properties, charge trapping (leading to polarization effects), long ranged fluorescence photons, and others.

Several low noise, charge-integrating readout chips with dynamic gain switching logic allowing for a dynamic range of up to $10^4$ 12.4 keV photons per pixel have been developed at PSI. One of them is JUNGFRAU with a pixel pitch of 75 x 75 µm², a noise performance of 79 e- ENC (or 0.34 keV) and a dynamic range of around 120 keV in the high gain (CdTe (e- Schottky) sensor at RT, sensor HV: -500 V, tint: 5 µs). Charge-integrating detectors can offer interesting insights into the sensor properties as each pixel provides a direct measure of the collected charge of a well-defined area as output and is very sensitive to temporal as well as spatial sensor effects, which affect the charge collection (e.g. fluorescence, dislocation lines, detrapping of charge carriers etc.)

Various high-Z sensors (Ohmic type CdTe, Schottky type CdTe and GaAs:Cr) have been investigated. The presentation will show results from different generations of sensors, focusing of the dynamic behavior (like signal stability, polarization, afterglow) of the high-Z sensors when being irradiated with photon fluxes up to $10^{10}$ ph/(mm²·s).

An insight into the implications of the short lifetime of holes in the GaAs:Cr sensors will be given as this severely affects the usability of GaAs:Cr not only with charge-integrating readout chips. First results of CdTe quad sensors with an active area of 4 x 4 cm² will shown.
Evaluation of Timepix3 Si and CdTe hybrid-pixel detectors spectral performances on X and gamma-rays (#1992)

PhD/MD student Guillaume Amoyal¹, PhD/MD Yves Menesguen², PhD/MD Vincent Schoepff¹, PhD/MD Frédéric Carrel¹, PhD/MD Nicolas Blanc Delanaute³, PhD/MD Jean-Claude Angélique⁴

¹ CEA Saclay, LIST/DM2I/LCAE, Saclay, France; ² CEA Saclay, LIST/DM2I/LNHB, Saclay, France; ³ MIRION TECHNOLOGIES, Montigny-le-Bretonneux, France; ⁴ Université de Caen/CNRS, IN2P3, Caen, France

Content
The Timepix3 hybrid-pixel readout chip consists in a matrix composed of 256 × 256 square-shaped pixels with 55 µm pitch, which can be hybridized to several semi-conductors, such as Si or CdTe of thicknesses up to 5 mm. Working as an event based readout chip, it simultaneously records in each pixel the Time-over-Threshold (ToT) that gives access to deposited energy, and the time-of-arrival (ToA) with a time resolution of 1.5 ns.

In this paper, we present the energy calibration of Timepix3 bump bonded with a 300 µm thick silicon sensor, and of Timepix3 bump bonded with a 1 mm thick cadmium telluride sensor. Both detectors are calibrated with a so-called per-pixel calibration using the monochromatic SOurce of Low-Energy X-rays (SOLEX from LNHB at CEA Saclay) and a set of laboratory sealed radioactive sources. Evaluation were carried out over an energy range from 6 keV to 122 keV for Timepix3 Si and from 20 keV to 1.3 MeV for Timepix3 CdTe. Results of this calibration allowed determining an energy resolution of 3.97 keV at 59.5 keV for Timepix3 Si, and 5.6 keV, 27.24 keV, and 47.4 keV at respectively 59.5 keV, 661.7 keV and 1.332 MeV for Timepix3 CdTe. It is the first time that CdTe bump-bonded Timepix3 spectral performances are evaluated for gamma-rays above MeV. The reconstruction of the total absorption peak for such high energies is possible by means of the ToA measurement which allows the identification of each interaction (scattering and absorption) of an incoming gamma-ray in the semiconductor.

SWAD: The Effect of Pixel Geometry on the Temporal Response of Multi-Well Avalanche Amorphous Selenium Detectors (#2624)

PhD/MD student Jann Stavro¹, Prof. Amir H. Goldan², Prof. Wei Zhao³

¹ Stony Brook University, Biomedical Engineering, Stony Brook, USA; ² Stony Brook University, Radiology, Stony Brook, USA; ³ Stony Brook University, Radiology, Stony Brook, USA

Content
Spectral x-ray imaging based on energy dispersive photon counting detectors (PCDs) has the potential to outperform perform conventional energy integrating detectors. Currently, PCDs are based on crystalline sensors which are hindered by performance limitations and high production costs. We are developing a novel direct conversion
amorphous Selenium (a-Se) based field-shaping multi-well avalanche detector (SWAD) for photon counting breast imaging applications. The SWAD design utilizes separate non-avalanche absorption (bulk) and avalanche sensing (well) regions to overcome the limitations of low carrier mobility and low charge conversion gain in a-Se. The sensing region is composed of a high density array of wells with electrodes embedded within each sidewall, which create a localized high field for tunable, depth-independent avalanche gain. The embedded electrodes also function as high granularity Frisch grids, establishing a strong near field effect which achieves unipolar time-differential charge sensing and results in the fast sensor response needed for photon counting applications. We developed a numerical simulation to model the signal formation process of SWAD and compare the temporal response of single- and dual-grid SWAD configurations designs. Our simulation results show that the dual grid SWAD configuration had the best the temporal performance due to a stronger near-field effect and substantially improved electrostatic shielding. In addition, we present x-ray time-of-flight measurements for prototype single- and dual-grid SWAD sensors.

R-02-04 5:00 PM

**Charge loss correction of multiple sharing events in sub-millimetre CZT pixel detectors** (#2137)

**Dr. Leonardo Abbene**¹, PhD/MD Fabio Principato¹, Prof. Gaetano Gerardi¹, PhD/MD student Antonino Buttacavoli¹, PhD/MD Nicola Zambelli¹, PhD/MD Manuele Bettelli², Dr. Paul Seller³, PhD/MD Matthiew Veale³, Dr. Andrea Zappettini²

¹ University of Palermo, Palermo, Italy; ² IMEM/CNR, Parma, Italy; ³ Rutherford Appleton Laboratory, Didcot, UK; ⁴ due2lab s.r.l., Reggio Emilia, Italy

**Content**

Charge losses after charge sharing addition (CSA) are typically observed in cadmium–zinc–telluride (CZT) pixel detectors. The interpretation of these effects is often not well defined: it is related to the energy threshold of read-out electronics, the presence of electric field distortions at the inter-pixel gap and the induced charge components in the shared pulses. In this work, we present some original techniques able to correct charge losses after CSA in CZT pixel detectors for uncollimated and poly-energetic radiation sources. Sub-millimetre CZT pixel detectors with different anode arrays (pixel pitches of 500 and 250 µm) and thicknesses (1-3 mm) were investigated. Adjacent and corner pixels were studied at energies below and above the K-shell absorption energy of the CZT material. Charge loss correction, after the application of charge sharing addition (CSA), was successfully applied at different multiplicities. These activities are in the framework of an international collaboration on the development of energy-resolved photon counting (ERPC) systems for high-flux spectroscopic X-ray imaging (5-150 keV).
Influence of CdTe Sensor Thickness on Subpixel Spatial Resolution
(#2390)

Dr. Szymon Procz¹, Julian Fey¹, Prof. Carlos Avila², Michael Schuetz¹, Gerardo Roque², Carlos Navarrete², Prof. Michael Fiederle¹

¹ University of Freiburg, FMF, Freiburg, Germany; ² Universidad de los Andes, Departamento de Física, Bogotá, Colombia

Content
The high absorption efficiency of photon counting detectors with high-Z semiconductor sensor materials like CdTe or CdZnTe is able to improve the quality of various X-ray examination methods. For highest X-ray attenuation a sensor thickness as large as possible is desirable, but this contrasts with the spatial resolution. Due to charge sharing thicker sensors feature a lower spatial resolution than sensors with lower thickness if X-ray photons are counted without a correction for charge sharing. Yet, if a single event cluster analysis is performed it is not only possible to reduce the spatial resolution loss caused by charge sharing, but also to achieve an even higher subpixel resolution by calculation of center of mass of each event.

While previous pixelated photon counting semiconductor detectors such as the Timepix or Medipix3 allowed single event analysis only for low photon fluxes that are rather unsuitable for imaging purposes, the new Timepix3 detector allows for the analysis of single events even at high X-ray fluxes due to its data driven data output. The Timepix3 features energy and time-of-arrival information for each incident photon, therefore a subsequent correction for charge sharing effects by cluster analysis is possible. The Timepix3 readout chip is under continued development by the “Medipix3 Collaboration” at CERN and offers 256x256 pixels with a native pixel pitch of 55x55 µm² and can be bump bonded to different semiconductor sensor materials.

CdTe sensors in different thicknesses from 450 µm up to 3 mm were used in this work. Object of interest was the influence of charge sharing and X-ray fluorescence on achievable spatial resolution. The analysis of the sensor thickness dependent subpixel spatial resolution will be presented here as well as its use for X-ray imaging using a mammography phantom as example.
N-06 | Neutron Detectors and Gamma Imaging I

Erik Brubaker (Livermore)
Sion Richards (Didcot)

Imaging using encoding, compression or reconstruction techniques
N-06-01 8:00 AM

Various Design for 2-D Time Encoded Aperture Gamma-neutron Imaging System (#1459)

PhD/MD Xiuzuo Liang, Prof. Lei Shuai, Prof. Xianchao Huang, Prof. Yantao Liu, Prof. Zhiming Zhang, Prof. Cunfeng Wei, Prof. Long Wei

Institute of High Energy Physics, Beijing, China

Content
Various design of 2-D time-encoded aperture system was investigated for both gamma and neutron imaging. The advantage of time-encoded imaging system for localization of radiological sources relies on its 360-degree horizontal field of view (FOV). Based on the previous report on the two-dimensional time-encoded imager (2D-TEI) for fast neutron, we have developed more attracting TEI systems also effectual for gamma-ray imaging. In this paper, three TEI systems with different coding methods of detector and rotating mask will be demonstrated via Monte Carlo simulation. Lots of radiation scenes support that these systems all have an imaging capacity of multipoint and extended gamma/neutron sources. It is recommended that these designs will provide an alternative panoramic imaging way of search and localization of radioactive hot spots.

N-06-02 8:18 AM

Simultaneous Reconstruction of Emission and Attenuation in Passive Gamma Emission Tomography of Spent Nuclear Fuel (#2196)

M.Sc./M.A. student Rasmus Backholm, Dr. Tatiana A. Bubba, Dr. Camille Bélanger-Champagne, Prof. Tapio Helin, Prof. Peter Dendooven, Prof. Samuli Siltanen

1 University of Helsinki, Helsinki Institute of Physics, Helsinki, Finland; 2 University of Helsinki, Department of Mathematics and Statistics, Helsinki, Finland; 3 LUT University, School of Engineering Science, Lappeenranta, Finland; 4 TRIUMF, Vancouver, Canada

Content
The International Atomic Energy Agency (IAEA) has recently approved passive gamma emission tomography (PGET) as a method for inspecting spent nuclear fuel assemblies (SFAs), an important aspect of international nuclear safeguards. The PGET instrument is essentially a single photon emission computed tomography (SPECT) system that allows the reconstruction of axial cross-sections of the emission map of the SFA. The fuel material strongly self-attenuates its gamma-ray emissions, so that correctly accounting for the attenuation is a critical factor in producing accurate images. Due to the nature of the inspections, it is desirable to use as little a priori information as possible about the fuel, including the attenuation map, in the reconstruction process. Current reconstruction methods either do not correct for attenuation, assume a uniform attenuation throughout the fuel assembly, or assume an attenuation map based on an initial filtered back projection reconstruction. Here, we propose a method to simultaneously...
reconstruct the emission and attenuation maps by formulating the reconstruction as a constrained minimization problem with a least squares data fidelity term and regularization terms. The performance of the proposed method, with two different regularizers, is evaluated with simulated data that includes missing rods and rods replaced with fresh fuel. The method is shown to produce good results when comparing the reconstructions to the ground truth by various numerical metrics, and when classifying the rods with the method currently employed by the IAEA. Additionally, the proposed method is shown to allow for an enhanced classification method that uses also the reconstructed attenuation map.

N-06-03  8:36 AM

Algorithmic construction of images for a fine-spatial resolution Cerenkov imaging array (#2615)

PhD/MD student Luke J. Maloney, Dr. Anna Erickson, PhD/MD student Arith Rajapakse

Georgia Institute of Technology, Nuclear and Radiological Engineering and Medical Physics, Atlanta, USA

Content

Silicon photomultipliers improve on traditional photomultiplier tubes in radiation detection applications in form factor, cost, and spatial resolution. Fused silica and other Cerenkov detectors are cheaper and easier to process than scintillators with high energy resolution. Previous work has shown that 25 mm diameter quartz crystals may be used as Cerenkov detectors for high-energy gamma radiation, and that resultant spectral features can be employed for crude spectroscopy. In this work, 6 mm square silicon photomultiplier elements optically coupled to fused silica crystals of the same cross-sectional area are used in an imaging array with LYSO interspersed to maintain energy resolution fidelity. Resultant spectral features from high-energy gamma sources including americium-beryllium are integrated to form transmission images - the imaging system is used as a model of a cargo radiography system. An algorithm for reconstruction of images from the array utilizes linear interpolation for a scanning-type translational imaging schema and incorporates the fine energy resolution power of LYSO to enable material discrimination in image space. Spatial resolution analysis of images is underway – simulation work suggests an expected spatial resolution for the system of less than or equal to 5mm.

N-06-04  8:54 AM

Application of a Novel Machine Learning Approach to SiPM-Based Neutron/Gamma Detection and Discrimination (#1529)

PhD/MD student Matthew Durbin, PhD/MD student Marc A. Wonders, Prof. Azaree T. Lintereur, Prof. Marek Flaska

The Pennsylvania State University, Department of Nuclear Engineering, State College, USA
Content

Silicon photomultipliers (SiPMs) are becoming an increasingly common component of radiation detection systems and have shown promise in their ability to distinguish neutrons and gammas when coupled with detectors sensitive to both particle types. This work investigates the use of a novel machine learning (ML) approach to aid in this discrimination. The proposed machine learning algorithm performs a regression on a conventionally calculated pulse shape parameter (PSP), producing a more representative modified PSP while allowing for direct comparison to the traditional pulse shape discrimination (PSD) technique. This work also investigates how the proposed ML based PSD approach can benefit different scintillator and light-sensor combinations with varying levels of traditional PSD performance, especially those based on SiPMs. A preliminary implementation of the regression method with a SensL SiPM and stilbene scintillator combination on a data set of mixed gamma and neutron pulses from $^{252}$Cf resulted in an increase in the figure of merit of approximately 45% compared to the traditional PSD technique. Finally, the PSD technique developed in this work will be further optimized to provide quantifiable improvements in the neutron-gamma discrimination capability for different detector types.

N-06-05  
9:12 AM

Adaptive Imaging using a Cylindrical, Time-Encoded Imaging System
(#2319)

Niral P. Shah¹, Dr. Peter Marleau², Prof. David K. Wehe¹

¹ University of Michigan, Nuclear Engineering and Radiological Sciences, Ann Arbor, USA; ² Sandia National Laboratory, Livermore, USA

Content

We present results from an adaptive, cylindrical, time-encoded imaging (c-TEI) system. Unlike a conventional c-TEI system where the detector is at the center of the mask, here the detector can move to any position inside of the mask during data acquisition. This allows the system to leverage collected data and adapt to the sources within its field of view thereby collecting higher quality data to accomplish a specific task such as generating higher resolution images. We show that adaptively moving the detector improves the system’s angular resolution by resolving multiple point sources that would otherwise appear as an single source to a conventional, c-TEI system. Additionally, we show results from a recent measurement campaign at the Zero Power Physics Reactor at Idaho National Laboratory where we imaged special nuclear material in complex arrangements.
Quantitative 3D Reconstruction of the Activity and Position of Radiological Sources (#2490)

Dr. Tenzing H. Y. Joshi, Dr. Mark S. Bandstra, Dr. Kathryn Meehan, PhD/MD student Daniel Hellfeld, Mustapha Saad, Victor Negut, Dr. Joshua W. Cates, Dr. Ryan T. Pavlovsky, Dr. Donald L. Gunter, Dr. Brian J. Quiter, Dr. Reynold J. Cooper, Prof. Kai Vetter

1 Lawrence Berkeley National Laboratory (LBNL), Applied Nuclear Physics, Berkeley, USA; 2 University of California, Department of Nuclear Engineering, Berkeley, USA; 3 Gunter Physics LLC, Livermore, USA

Content
The ability to quantitatively map the distribution of radiological sources in unknown three dimensional environments has application in contamination mapping, emergency response, nuclear safeguards, and radiological source search. Such a capability, accurately locating sources, estimating their activities, and estimating uncertainty of these parameters, requires well characterized detector response functions, accurate time-dependent detector pose data, an understanding of the 3D environment in question, and appropriate image reconstruction and uncertainty quantification methods. 3D mapping of the relative intensity of gamma-ray emitters with free-moving detectors systems has been previously demonstrated in a framework referred to as nuclear Scene Data Fusion (SDF). In this work we present the first demonstration of quantitative SDF. We describe experimental and simulation-based detector response characterization of multi-element gamma-ray detection systems and the provision of 3D environmental and pose data. Algorithmic developments to generally and accurately perform the 3D image reconstruction, enabling quantitative intensity reconstruction, of point and distributed source distributions are discussed in detail. Finally, we present experimental results from hand-carried and airbourne measurements with point and distributed-sources in known configurations, showing the first demonstration of accurate reconstruction of the location and activity of sources in complex 3D environments.
N-07 | Analog and Digital Electronics I

Shaorui Li (Upton)
Angelo Rivetti (Torino)
MPA-SSA, design and test of a 65 nm ASIC-based system for particle tracking at HL-LHC featuring on-chip particle discrimination. (#1788)

Davide Ceresa¹, Gianmario Bergamin², Alessandro Caratelli², Jan Kaplon¹, Kostas Kloukinas¹, Simone Scarfi², Yusuf Leblebici², on behalf of the CMS Tracker Group.

¹ European Organization for Nuclear Research (CERN), EP-ESE-ME, Geneva, Switzerland; ² École polytechnique fédérale de Lausanne (EPFL), Microelectronic System Laboratory (LSM), Lausanne, Switzerland

Content

Particle tracking detector for High Energy Physics needs a new readout technique to cope with the increase of collision rate foreseen for the High Luminosity LHC upgrade. In particular, the selection of interesting physics events at the first trigger stage becomes extremely challenging at high luminosity, not only because of the rate increase, but also because the selection algorithms become inefficient in high pileup conditions. A substantial increase of latency and trigger rate provides an improvement that is not sufficient to preserve the tracking performance of the current system. A possible solution consists of using tracking information for the event selection. Given a limited bandwidth, the use of tracking information for the event selection implies that the tracker has to send out self-selected information for every event. This is the reason why front-end electronics need to perform a local data reduction. This functionality relies on the capability of continuous particle discrimination on-chip based on transverse momentum.

The high complexity of the digital logic for particle selection and the very low power requirement of < 100 mW/cm² drive the choice of a 65 nm CMOS technology. The harsh environment, characterized by a high ionizing radiation dose of 100 Mrad and low temperature of around -30°C, requires additional studies and technology characterization. Several architectures for particle tracking have been studied and evaluated with physics events from Monte-Carlo simulations. The chosen architecture reaches an efficiency of > 95 % in particle selection and a data reduction from ~30 Gbps/cm² to ~0.7 Gbps/cm². Two full-size and full-functionalities prototype, called MPA and SSA, have been designed, produced and tested. These two readout front-end ASICs perform pixel-strip sensors binary readout, full-event storage with triggered readout and continuous data selection with trigger-less readout.
First experimental results with the TOFHIR1 readout ASIC of the CMS Barrel Timing Layer (#1809)

Edgar Albuquerque², Joao Varela¹, Diogo Bastos¹, Ricardo Bugalho², Viorel Dubceac², Luis Ferramacho², Agostino Di Francesco¹, Michele Gallinaro¹, Tahereh Niknejad¹, Luis Oliveira³, Ksenia Shchelina¹, Jose Carlos Silva¹

¹ Laboratory of Instrumentation and Experimental Particle Physics, Lisboa, Portugal; ² PETsys Electronics, Oeiras, Portugal; ³ DEE, CTS-UNINOVA FCT-UNL, Caparica, Portugal

Content
The CMS Detector will be upgraded for the HL-LHC to include a MIP Timing Detector (MTD). The MTD will consist of barrel and endcap timing layers, BTL and ETL, respectively, providing precision timing of charged particles. The BTL sensors are based on LYSO:Ce scintillation crystals coupled to SiPMs with TOFHIR ASICs for the front-end readout system. A resolution of 30 ps for MIP signals at a rate of 2.5 Mhit/s per channel is expected at the beginning of HL-LHC operation. We present an overview the TOFHIR requirements and design, and the first measurements with silicon samples of the TOFHIR version 1.

Analog front-end design perspective of a 14 nm finFET technology (#2215)

Prof. Lodovico Ratti¹,³, Prof. Massimo Manghisoni²,³, Prof. Valerio Re²,³

¹ Università di Pavia, Dipartimento di Ingegneria dell’Informazione, Pavia, Italy; ² Università di Bergamo, Dipartimento di Ingegneria e Scienze Applicate, Dalmine, Italy; ³ INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, Pavia, Italy

Content
This paper is concerned with the characterization of devices from a finFET technology with a minimum feature size of 14 nm. N- and P-type transistors with different gate size have been tested from the standpoint of static current-voltage characteristics, small signal parameters and noise properties in view of analog front-end applications. Device electrical features are found to be compliant with the scaling trend as carried on with planar CMOS technologies. Comparison with standard, less scaled bulk CMOS processes points out that transition from planar, single-gate to vertical, multiple-gate structures does not affect significantly the transistor analog performance. On the other hand, the increase, as compared to less advanced process nodes, of the threshold voltage over VDD ratio may force the analog designer to favour simpler architectures and/or look for innovative design solutions.
An ultra-low power, fast 10-bit SAR ADC for multi-channel readout ASICs in 65 nm CMOS (#2291)

Dr. Tomasz Fiutowski, Dr. Miroslaw Firlej, Prof. Marek Idzik, Dr. Jakub Moron, Dr. Krzysztof Swientek

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Content
The design and measurement results of two versions of ultra-low power fast 10-bit SAR ADC prototypes, fabricated in CMOS 65 nm technology, are presented. The ADC architecture is fully differential and comprises bootstrapped switches, capacitive DACs, dynamic comparator and dynamic asynchronous logic. Two prototypes use different capacitive DACs, based either on MIM or MOM capacitances. Each of the prototypes consist of eight channels placed in parallel in 60 um pitch in order to verify multi-channel performance. A set of measurements has been done revealing that both prototypes are fully functional and achieve good quantitative performance. Static linearity measurements show that both integral (INL) and differential (DNL) linearity errors are below 1 LSB. For dynamic measurements performed at 0.1 Nyquist input frequency the effective number of bits (ENOB) of about 9.25 was obtained for sample rates up to 60 MSps. The MIM capacitance based ADC works up to 90 MSps with the ENOB decreasing to 8.8 bits at the highest rate while the MOM capacitance based ADC works up to 80 MSps with the ENOB decreasing to 8.5 bits at the highest rate. The power consumption is linear with sampling frequency and at 40 MSps it is around 550 uW for the MIM capacitance based ADC and 600 uW for the MOM capacitance based version. The operation of both ADC prototypes was also verified for all channels working in parallel. The measured performance is similar to single channel performance.

A 128-channel SALT ASIC for the readout of Upstream Tracker in the LHCb Upgrade (#2190)

Dr. Krzysztof Swientek, On behalf of LHCb UT Working Group

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

Content
SALT is a dedicated 128-channel ASIC, designed in CMOS 130 nm process, for readout of silicon strip detectors in the upgraded tracker of Large Hadron Collider beauty (LHCb) experiment. It extracts and digitises analogue signals from the sensor, performs Digital Signal Processing (DSP) and transmits serially the output data. SALT uses the innovative architecture comprising of low power analogue front-end and 40 MSps 6-bit ADC in each channel. The prototypes of SALT have been tested confirming full chip functionality and fulfilling expected specifications. For 10 pF of input sensor capacitance the SNR of about 20 was achieved with activated Mean Common Mode algorithm which is a part of the DSP. The design and results of test measurements are presented.
Recent Advances in Serial Powering of Silicon Pixel Detectors (#1730)

PhD/MD student Florian Hinterkeuser¹, Dr. Matthias Hamer¹, Dr. Fabian Hügging¹, Dr. Hans Krüger¹, Prof. Michael Karagounis², Dominik Koukola³, Dr. Stella Orfanelli³, M.Sc./M.A. Andreas Stiller², Prof. Norbert Wermes¹, Prof. Klaus Desch¹

¹ Universität Bonn, Physikalisches Institut, Bonn, Germany; ² Fachhochschule Dortmund, Fachbereich Elektrotechnik, Dortmund, Germany; ³ CERN, Geneva, Switzerland

Content

The high luminosity upgrade for the Large Hadron Collider at CERN requires a complete overhaul of the current inner detectors of ATLAS and CMS. The inner layers of these new, all silicon, tracking detectors will consist of modules with pixelated sensors and readout chips, which are developed by the RD53 collaboration for both experiments in a 65 nm CMOS technology. A serial powering scheme has been chosen as a baseline for the pixel detectors to cope with the higher number of modules and the higher power consumption of the new front-end chips, spatial constraints and the need to minimize the material budget of the trackers. This powering scheme, which will be applied in a pixel detector for the first time, provides challenges for the electrical and mechanical design of the detectors. Building on the experience from previous test setups based on FE-I4b modules, a new prototype using RD53A chips with representative services and power supplies has been designed with the goal to verify this powering scheme and its implications on the detector design. First results from the evaluation of this prototype, which consists of 8 RD53A quad chip modules, are presented. Emphasis is put on the full electrical characterization of the serial powering chain in general and the modules in the chain in particular. Previous studies have also underlined the necessity to add new features to the voltage regulators on the front-end chip. The upgraded regulator design and a detailed characterization of the new regulators using dedicated test chips are presented.
N-08 | Novel and Emerging Technologies I

Andrei Nomerotski (Brookhaven)
Beatrice Fraboni (Bologna)

Fast timing technologies
N-08-01  8:00 AM

A Time-Resolved Beam Halo Monitor for Accelerator Beam Diagnostics using Diamond Detectors and High Speed Digitizers (#2631)

Dr. Isar Mostafanezhad¹, Dr. Benjamin Rotter¹, Dr. Luca Macchiarulo¹, Dr. Erik Muller²

¹ Nalu Scientific, LLC, Honolulu, USA; ² Brookhaven National Lab, Instrumentation, Upton, USA

Content

In this report we describe the Time-Resolved Beam Halo Monitor (TR-BHM): a proposed detector for the measurement and characterization of the particle halo that accompanies accelerated particle bunches both spatially and temporally by utilizing diamond strip detectors read out by system-on-chip (SoC) high speed waveform digitizers developed by Nalu Scientific LLC (NSL). The theory, detection methodology, and planned instrumentation will be discussed, as well as initial measurements.

N-08-02  8:18 AM

3D Diamond Detectors for Particle Tracking and Dosimetry (#1285)

PhD/MD student Alice L. Porter

University of Manchester, School of Physics and Astronomy, Manchester, UK

Content

Diamond has many desirable properties as a radiation detector material. Paired with a 3D electrode geometry extremely radiation hard devices can be fabricated. The investigation is into optimising their use in radiation therapy and for beam condition monitoring at HEP experiments. Graphitic electrodes can be fabricated with a femtosecond laser focused in the bulk of the diamond material to form a 3D geometry. This allows for a smaller inter-electrode distance, increasing the charge collection efficiency. The detectors are characterised with X-rays, radiative sources (Sr-90, Fe-55, Am-241) and protons. This is done alongside TCAD simulations to qualitatively understand and optimise the electric field distribution inside the detector. Currently in development is the use of a 3D printed plastic mouse phantom containing a 3D diamond dosimeter. The mouse provides a standardized phantom which can be made universal between hospitals and reduce the large deviations in pre-clinical inter-laboratory dosimetry. The impact of this project will aid advances in precision radiotherapy and the frontiers of particle physics.
Fabrication of AC-coupled Low-Gain Avalanche Diodes at BNL (#2398)

Dr. Gabriele Giacomini, Dr. Wei Chen, Dr. Gabriele D’Amen, Dr. Alessandro Tricoli
Brookhaven National Laboratory, Physics, Upton, USA

Content
We present the fabrication and the first functional tests of a new class of silicon devices: the AC-coupled Low-Gain Avalanche Diode (AC-LGAD). Because of its good timing performance, the LGAD was originally developed to support the silicon tracker for the discrimination of signal events in p-p collisions at the LHC from background events originating from additional interactions in the same bunch crossing (pile-up). Pile-up events occur at slightly different times and the additional information in the fourth dimension (time) is crucial to resolve them. However, LGADs developed for the timing detectors at the LHC suffer from poor spatial resolution. AC-LGADs offer a solution to this drawback, while retaining the good timing performance. Test structures have been fabricated at BNL, using the in-house silicon processing facility, and have been tested with fast electronics and radioactive sources. Large gains, and fast signal have been measured, while the noise stays low and comparable to standard LGADs. Batches of AC-LGADs have been fabricated in different structures, and some with a pitch compatible to TimePix3 readout ASIC.

The VSiPMT 2-inches industrial prototype (#1964)

Dr. Felicia Carla Tiziana Barbato1,2, Prof. Giancarlo Barbarino1,2, M.Sc./M.A. Riccardo de Asmundis2, Prof. Gianfranca De Rosa1,2, M.Sc./M.A. student Luigi Lavitola1, M.Sc./M.A. Carlos M. Mollo2, M.Sc./M.A. student Michele Mormile1, Dr. Daniele Vivolo2, Dr. Atsuito Fukasawa3
1 University of Naples Federico II, Physics Department, Napoli, Italy; 2 INFN, Sezione di Napoli, Napoli, Italy; 3 Hamamatsu Photonics KK, Hamamatsu, Japan

Content
Photon detection is a key factor to study many physical processes in several areas of fundamental physics research. Focusing the attention on photodetectors for particle astrophysics, we understand that we are very close to new discoveries and new results. In order to push the progress in the study of very high-energy or extremely rare phenomena (e.g. dark matter, proton decay, neutrinos from astrophysical sources) the current and future experiments require additional improvements in linearity, gain, quantum efficiency and single photon counting capability. To meet the requirements of these classes of experiments, we propose a new design for a modern hybrid photodetector: the VSiPMT (Vacuum Silicon PhotoMultiplier Tube).

The idea is to replace the classical dynode chain of a PMT with a SiPM, which therefore acts as a single stage Geiger electron detector and amplifier, without statistical fluctuations. The aim is to match the large sensitive area of a photocathode with the performances of the SiPM technology. The previous VSiPMT prototypes already showed many attractive features such as low power consumption, very large dynamic range, excellent photon counting capability...
and low voltage driven gain. We now present the results of the full characterization of the latest and largest version achieved up to now, a 2-inches VSiPMT manufactured by Hamamatsu.

N-08-05 9:12 AM

Integrating Fast-Emitting Materials with State-of-the-Art Scintillators as a Pathway to New Timing Performance (#1465)

PhD/MD Rosana Martinez Turtos1,3, PhD/MD Matteo Salomoni1,2, PhD/MD Stefan Gundacker1,2, PhD/MD Etienne Auffray1, PhD/MD Paul Lecoq1

1 CERN, EP-CMX-DA, Meyrin, Switzerland; 2 Università degli Studi di Milano-Bicocca, Physics Dpt, Milano, Italy; 3 Aarhus University, Physics Dpt, Aarhus, Denmark

Content
The possibility of reaching real-time molecular imaging for cancer diagnosis using time-of-flight positron emission tomography scanners (TOF-PET) requires dedicated efforts to improve the time resolution of scintillators materials. Recent advances in high-frequency readout electronics have proven to be able to benefit from prompt-photon emission in the form of Cherenkov photons or sub-1ns radiative decay times exhibited by CdSe/CdS semiconductor nanoplatelets. In this frame, a sampling pixel geometry allowing for 511keV energy sharing between a high-Z material and a fast plastic scintillator has been used as a proof-of-concept readout to demonstrate a time resolution improvement for a fraction of the events. In this contribution we extend the study of a sampling pixel geometry combining state-of-the-art scintillators with fast-emitting materials using longer pixels up to 15mm height, which are representative of a TOF-PET scanner. The study aims to replace the plastic scintillating plates with a denser, faster emitter and to understand the key parameters to improve in the light collection of a larger sampling pixel, where DOI information is crucial to the overall timing performance. For our first readout attempt, we obtain coincidence time resolution results of around 188ps for all 511keV gammas fully deposited in a BGO+BC-422 3.8x3.8x15mm3 pixel. This result contrast to the 210ps value obtained with the same readout for bulk BGO crystal 15mm long. Together with the overall timing performance of scintillating pixels, in this contribution we will cover the latest results on the development of nanocomposites layers able to perform as time taggers in a sampling pixel geometry. These research activities are at the center of our strategy to develop a new generation of ultrafast scintillators.

N-08-06 9:30 AM

Investigation of trench technology on silicon device fabrication (#1849)

Wei Chen1, Gabriele Giacomini1, Thomas Krings2, Abdul K. Rumaiz1, David P. Siddons1

1 Brookhaven National Laboratory, Upton, USA; 2 Forschungszentrum, Julich, Germany

Content
This work was motivated by simplifying the process steps on silicon device fabrication. This simplification could benefit other silicon detector fabrications and have the possibility of terminating the junction edges in other detector designs, ... This is our new attempt of exploring a different trench technique which originated from the high-purified germanium (HPGe) detector fabrication onto silicon device process. The simulation has shown good pixel isolations; it has also shown that it does not require multiple guards to lower the potential from the active area; furthermore, it has shown that this trench isolation scheme leads to a reduced inter-pixel capacitance. Preliminary trench test-runs have been successfully conducted by using reactive ion etcher (RIE). The parameters used in the silicon trench fabrication have already been selected. The mask design for device fabrication has been completed. As soon as the new device fabrication is completed, the bench test will be carried out. The device performances will be compared to simulation results and will be presented in the conference.
N-09 | Astrophysics and Space Instrumentation I

Alexander Moiseev (Greenbelt)
Development and performance verification of a novel Compton camera for imaging MeV gamma rays (#1387)

M.Sc./M.A. student Hiroki Hosokoshi¹, Prof. Jun Kataoka¹, M.Sc./M.A. Saku Mochizuki¹, M.Sc./M.A. Masaki Yoneyama¹, M.Sc./M.A. student Soichiro Ito¹, M.Sc./M.A. student Hiroaki Kiji¹, M.Sc./M.A. student Fumiya Nishi¹, Prof. Shuji Miyamoto²

¹ Waseda University, Graduate School of Advanced Science and Engineering, Tokyo, Japan; ² University of Hyogo, Laboratory of Advanced Science and Technology for Industry, Hyogo, Japan

Content

In gamma-ray astronomy, 1-10 MeV range is one of the most difficult energy bands to observe owing to low photon signals and considerable amount of background contaminations. This energy band, however, comprises a substantial number of nuclear gamma-ray lines that may hold the key to understand the nucleosynthesis at the core of stars, spatial distribution of cosmic rays, and interstellar medium. Although several research works have attempted to realize a better angular resolution and sensitivity in this range, the development of a detector for astronomy has not progressed since NASA launched the Compton Gamma Ray Observatory (CGRO) in 1991. In this work, we conducted a performance verification of the newly developed Compton camera, which is used for imaging the MeV gamma rays. This camera is very compact compared to the Compton Telescope (COMPTEL) aboard CGRO. To mimic the situation of astronomical observation, we used a MeV gamma-ray beam produced by laser inverse Compton scattering at NewSUBARU, Hyogo in Japan. As a result, we obtained sharp peak images of incident gamma rays irradiating from incident angles of 0° and 20°. The angular resolution of the Compton camera was measured by the Angular Resolution Measure. It was estimated to be 3°.4±0°.1 (full width at half maximum (FWHM)) at 1.7 MeV and 4°.0±0°.5 (FWHM) at 3.9 MeV, which are comparable with respective values of COMPTEL. Moreover, we achieved an intrinsic efficiency of 0.5-1.0% below 2 MeV owing to the compact and dense structure of the camera, which is to 1.5-3 times higher than that of COMPTEL in the same energy range.

Development of a Modular CdZnTe Imaging Detector for Gamma-ray Astronomy (#2448)

Carolyn A. Kierans¹,², Aleksey Bolotnikov³, Gabriella Carini³, Elizabeth Hays¹, Alexander Moiseev¹,⁴, Makoto Sasaki¹,⁴, David Thompson¹, on behalf of the AMEGO Team

¹ NASA, Goddard Space Flight Center, Greenbelt, USA; ² Universities Space Research Association, Columbia, USA; ³ Brookhaven National Laboratory, Yaphank, USA; ⁴ University of Maryland, College Park, College Park, USA

Content

We will present our work towards an imaging telescope for gamma-ray astronomy based on a novel approach of 3-dimensional (3D) position-sensitive virtual Frisch-grid cadmium zinc telluride (CdZnTe) detectors. This detector can
operate as a stand-alone Compton telescope, as the backplane of a coded-mask imager, or as a position-sensitive calorimeter such as that proposed for the All-Sky Medium Energy Gamma-ray Observatory (AMEGO). By measuring photons with energies from 100 keV to 20-50 MeV with excellent energy resolution and good position resolution, this technology can be used to probe the astrophysically unexplored MeV Gap. Using a 3D virtual voxel approach taking into account the photon interaction position, one can correct for imperfections in the spectral response associated with material defects in the CdZnTe. With this approach, initial measurements show an excellent energy resolution of 1% FWHM at 662 keV and the position resolution is measured to be < 1 mm in all 3 dimensions. The prototype detector we are building utilizes Frisch-grid CdZnTe bars with a cross-section of 6x6 mm² and length of 2 cm. The crystals are arranged in modules of 4x4 bars, and the modules themselves are assembled into a larger array giving a 10x10 cm² active detector area. We will report on our recent progress integrating this prototype detector with custom-made application specific integrated circuits (ASIC) and will give an overview of initial tests of the system.

Polarimetric performance of a Multilayer CdTe Spectro-imager for High-energy Astrophysics (#2273)

M.Sc./M.A. Miguel Moita¹,², Dr. Rui M. Curado da Silva¹, Prof. Jorge M. Maia³,¹, Dr. Ezio Caroli⁴, Dr. Enrico Virgilli⁵, Dr. Natalia Auricchio⁶, Dr. John B. Stephen⁴, Prof. Filippo Frontera⁵,⁴, Prof. Stefano Del Sordo⁶

¹ LIP - Laboratório de Instrumentação e Física Experimental de Partículas, Coimbra, Portugal; ² University of Coimbra, Department of Physics, Coimbra, Portugal; ³ University of Beira-Interior, Department of Physics, Covilhã, Portugal; ⁴ INAF, - Osservatorio di Astrofisica e Scienza dello spazio, Bologna, Italy; ⁵ University of Ferrara, Department of Physics and Earth Sciences, Ferrara, Italy; ⁶ INAF, Institute Space Astrophysics and Cosmic Physics, Palermo, Italy

Content

In the multi-messenger era, gamma-ray polarimetry may contribute to a wider understanding of gamma-ray transients associated to gravitational waves detection. Furthermore, allows a deep understanding of the physical processes, geometry and magnetic fields of sources such as pulsars, solar flares, active galactic nuclei or galactic black holes. Herein, we analysed the performances of a prototype in a 2 layers Compton configuration based on two CdTe spectro-imagers operated in coincidence. The two CdTe detectors have an anode segmented in 8’8 pixels (2 mm pitch) on 2 mm thick crystals. The detection system configuration will allow assessing the scattering polarimetric performance of a 3D spectro-imager by changing the distance between the two layers over the 100-600 keV energy range. These conclusions will be of fundamental importance for both high efficiency Laue lens telescope focal plane and all sky advanced Compton telescope design for next generation space mission. The polarimetric modulation factor was evaluated at distances between planes ranging from 8mm up to 16mm at different Compton scattering angles. Results will be presented and discussed.
Demonstration of detecting soft X-rays using the CMOS detector toward future astronomical mission (#1948)

Dr. Makoto Arimoto1, Naoki Ogino1, Dr. Tatsuya Sawano1, Prof. Daisuke Yonetoku1, Dr. Junko Hiraga2, Dr. Satoshi Hatori3, Dr. Kyo Kume3, Takashi Hasegawa3

1 Kanazawa University, Institute of Science and Engineering, Ishikawa, Japan; 2 Kwansei Gakuin University, School of Science and Technology, Hyogo, Japan; 3 The Wakasa Wan Energy Research Center, Fukui, Japan

Content
For future space mission of wide-field surveys in the soft X-ray band, we have carried out a detailed study of a back-illuminated CMOS (11 × 11 μm²), fabricated by Gpixel (GSENSE 400BSI/TVISB). It has a good energy resolution of 201 eV (FWHM) at 5.9 keV at a frame rate of 10 frames/s. For this CMOS, X-ray events are briefly categorized into two groups: the single-pixel and multi-pixel events. Considering the two types of events, we found that the lower detectable energy of 0.4 keV can be achieved with a detection efficiency of > 50%. We tested the radiation tolerance against gamma-rays (60Co for 30 krad) and 220-MeV helium (~3×10⁹ He/cm²). After the irradiation, the CMOS functions worked properly without significant degradation in performance and its noise level can be suppressed to below 1 keV at -20 °C. These results suggest that the prototype CMOS can be a promising detector for use in future astronomical missions such as HiZ-GUNDAM.

Latest results for fast low-noise CCD for Lynx (#2286)

Dr. Gregory Prigozhin1, Dr. Marshall Bautz1, Dr. Barry Burke2, Michael Cooper2, David Craig2, Richard Foster1, Dr. Catherine Grant1, Beverly LaMarr1, Dr. Christopher Leitz2, Andrew Malonis1, Dr. Eric Miller1, Dr. Daniel Schuette2, Dr. Vyshi Suntharalingam2, Caroline Thayer1

1 Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, Cambridge, USA; 2 Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, USA

Content
Lynx is a mission concept currently being studied by NASA as a next generation high resolution X-ray telescope in space. Charge Coupled Devices (CCD) are one of the possible technologies that are being considered for use in two of the Lynx focal plane instruments. In this work we report on the latest results achieved while testing an advanced detector designed at MIT Lincoln Laboratory for the Lynx High Definition Imager and X-ray Grating Spectrometer. The device has been tested at serial register pixel rates up to 5.0 Mpix/s with transfer clock swings as low as 1.0 V peak-to-peak. We measure read noise of 4.2 electrons RMS as 2.5 MHz rate and X-ray spectral resolution of 136 eV FWHM at 5.9 keV for single-pixel events. We find that confining charge to narrow trough in buried channel can noticeably improve charge transfer efficiency. Simulations of electron diffusion during drift towards potential wells suggest that charge splitting between adjacent pixels may become nontrivial for detectors as thick as 100 microns
and pixels as small as 8 microns. This has been confirmed by experiment. Analysis of interpixel charge distribution led us to a novel, more accurate technique of measuring detector depletion depth. Measurements at different substrate bias voltages will be presented.

N-09-06 9:30 AM

First Results from Flight-like Sensors for Athena's Wide Field Imager (#2669)

Johannes Müller-Seidlitz¹, Dr. Michael Bonholzer¹, Valentin Emberger¹, Dr. Peter Lechner², Dr. Norbert Meidinger¹, Dr. Wolfgang Treberspurg¹

¹ Max-Planck-Institute for Extraterrestrial Physics, High Energy Group, Garching, Germany; ² Semiconductor Laboratory of the Max-Planck-Society, München, Germany

Content

Athena is Europe's next generation X-ray space telescope designated to investigate the hot and energetic universe. Its primary science objectives are the formation of the large scale structures and how supermassive black holes grow and shape the cosmos. To be able to study large spatial angles with a reasonable effort, one of the two instruments will be a wide field imager. In a field of view of approximately 40' x 40' it features time-resolved photon counting with a Fano-limited spectroscopic capability. The focal plane of the Wide Field Imager is equipped with a large detector array of four 512 x 512 pixel sensors and a fast detector of 64 x 64 pixels that is read out in two halves to increase the frame rate. To achieve the demanding requirements of the instrument, specific active pixel sensors – arrays of depleted p-channel field effect transistors – for X-ray astrophysics were developed further. In the technology development phase, various prototype sensor layouts and fabrication technologies were studied on 64 x 64 pixel devices to define an optimum variant for the mission. The selected sensor option was used for the pre-flight production. This fabrication run includes flight-size sensors for the first time. To ensure a high yield of the large area sensors, the wafer processing was optimized and the layout was slightly adapted to enable a simplified metal layer routing. We present the status of the detector development. This includes the first results of flight-like active pixel sensors for Athena’s Wide Field Imager.
R-03 | Imaging & Applications I

Simon Procz (Freiburg)
GaAs and CdTe sensors with LAMBDA readout for synchrotron experiments (#2272)

Dr. David Pennicard1, Sergej Smoljanin1, Florian Pithan2, Hagen Stawitz2, Dr. Julian Becker1, Dr. Andre Rothkirch3, Dr. Yueling Yu1, Dr. Hanns-Peter Liermann1, Dr. Martin von Zimmerman1, Dr. Alex Fauler3, Prof. Michael Fiederle3, Dr. Oleg P. Tolbanov4, Dr. Andrei Zarubin4, Dr. Anton Tyazhev4, Prof. Georgy Shelkov5, Prof. Heinz Graafsma1,6

1 DESY - Deutsches Elektronen Synchrotron, Hamburg, Germany; 2 X-Spectrum GmbH, Hamburg, Germany; 3 Albert-Ludwigs-University Freiburg, Freiburg, Germany; 4 Tomsk State University, Functional Electronics Laboratory, Tomsk, Russia; 5 JINR - Joint Institute for Nuclear Research, Dubna, Russia; 6 Mid Sweden University, Sundsvall, Sweden

Content
Photon-counting hybrid pixel detectors are widely used in X-ray scattering experiments at synchrotron beamlines, due to their high sensitivity, effectively noise-free operation, and high readout speeds. For hard X-ray scattering experiments, it is necessary to use high-Z sensor materials to achieve high quantum efficiency. Detectors using Gallium Arsenide and Cadmium Telluride sensors have been built using the LAMBDA readout system, based on the Medipix3 chip, which was developed for synchrotrons. Firstly, large-area Chromium-compensated GaAs sensors fabricated on new 4" wafers have been tested. These sensors had ohmic contacts, 55 µm pixel size and 500 µm thickness. These showed similar performance to sensors previously produced from 3" wafers, with high pixel yield and a stable granular structure visible in the flatfield X-ray response. Secondly, ohmic CdTe detectors have been tested, with 55 µm pixel size and 1000 µm thickness. These show a high pixel yield, and lower pixel-to-pixel variation than GaAs. Nonuniformities in this material show a slow change in response over an operating period of 16 hours. Finally, larger multi-module high-Z systems have been constructed. A total of 6 GaAs modules (4 megapixels) have been used in high-pressure experiments at a synchrotron beamline.

Energy sensitive X-ray Phase Contrast Imaging with a CdTe-Timepix3 Detector (#2587)

Carlos Navarrete1, PhD/MD Simon Procz2, M.Sc./M.A. Julian Fey2, M.Sc./M.A. Gerardo Roque1, Prof. Carlos Avila3, M.Sc./M.A. Michael Schuetz2, Prof. Alessandro Olivo3, PhD/MD Michael Fiederle2

1 Universidad de los Andes, Department of Physics/Faculty of Science, Bogota, Colombia; 2 Universität Freiburg, Freiburg Materials Research Center (FMF), Freiburg, Germany; 3 University College London, Department of Medical Physics and Biomedical engineering, London, UK

Content
The Timepix3 is a photon counting semiconductor detector that enables to simultaneously measure the energy and time of arrival of each incident x-ray photon. These properties, along with the high spatial resolution and high efficiency, due to the CdTe sensor material, can be exploited for several imaging applications, such as X-ray phase contrast imaging (XPCI). XPCI relies on the phase shift suffered by x-rays when traversing the sample, which is explained by the real part of the refractive index. By means of different phase-sensitive methods, such principle can be employed to generate contrast up to three orders of magnitude higher than conventional x-ray imaging. We focus our studies on Free-space Propagation and Single Mask Edge Illumination (SM-EI) methods, which are two approaches that are well suited for laboratory implementations. Although, the SM-EI implementation is much more robust with decreasing spatial coherence and non-interferometric. Since both techniques are highly sensitive to charge-sharing, we use the Timepix3 energy and time information for each photon, to minimize this effect by using clustering methods. In addition, we study the performance of both XPCI techniques across the energy range covered by typical polychromatic x-ray sources using the high-resolution energy-resolving capabilities of the detector. In both cases, we assess the phase contrast and signal-to-noise ratio as a function of different energy bins of the spectrum.

R-03-03
8:42 AM

Bragg Magnifier Optics Coupled to High-Z Medipix Detector for High Resolution and Dose Efficient X-Ray Imaging at Synchrotrons (#2762)

Dr. Elias Hamann1, PhD/MD student Rebecca Pretzsch2, PhD/MD student Holger Hessdorfer1, PhD/MD student Mathias Hurst2, Dr. Valerio Bellucci3, Prof. Michael Fiederle1,4, Prof. Tilo Baumbach1,2

1 Karlsruhe Institute of Technology (KIT), IPS, Karlsruhe, Germany; 2 Karlsruhe Institute of Technology (KIT), LAS, Karlsruhe, Germany; 3 Skanray Europe srl, Bologna, Italy; 4 University of Freiburg, FMF, Freiburg, Germany

Content
In this work we present the most recent results obtained at synchrotron beamlines with our novel high-resolution (sub-µm), dose efficient X-ray imaging system based on Bragg Magnifier crystal optics, coupled to a high-Z Medipix detector. The Bragg Magnifier (BM) consists of four independent quasi-channel-cut silicon 220 single crystals with which the X-ray beam can be directly magnified up to 200 times in two dimensions at unprecedented working energies of around 30 keV. By coupling the BM optics to a large area single photon counting Medipix detector with a high-Z sensor, very high dose efficiencies of >90% can be achieved at effective pixel sizes of a few hundred nanometer. The resulting Bragg Magnifier Microscope is particularly suited for phase contrast imaging of biological samples, where both dose efficiency and high resolution are of high importance, e.g. for in vivo imaging of cellular processes in the field of developmental biology. Another benefit of this system is that by placing the sample behind the BM, a very large field of view of up to 55x55 mm² can be achieved for imaging larger, cm-sized samples at medium resolution, which is rarely possible at modern synchrotron sources. We here describe and characterize our setup in detail and present the most recent measurements performed at synchrotron sources, proving the high spatial resolution, dose efficiency and, by making use of the coherent synchrotron beam, its potential for phase contrast X-ray imaging of biological model organisms.
Evaluation of Timepix3 Detector Properties for Energy Dispersive XRD, SAXS and WAXS (#2282)

Dr. Jan Jakubek¹, Daniel Turecek¹, Dr. Jan Kehres²

¹ ADVACAM s.r.o., Prague, Czech Republic; ² Technical University of Denmark, Department of Physics, Kgs. Lyngby, Denmark

Content
The diagnostic methods based on X-ray diffraction (XRD), small and wide angle x-ray scattering (SAXS, WAXS) present valuable source of information on material microstructure of various samples. These methods are used in many application fields such as engineering, metallurgy, composite materials, mining, semiconductors etc. The typical measurement systems implementing these methods work with highly collimated pencil beam of monochromatic X-rays directed to the sample and detector system recording diffracted or scattered radiation over certain solid angle. The detector presents essential component of the measurement system determining its final properties.

In this study the properties of the Timepix3 pixel detector with various sensors are evaluated for application in energy dispersive XRD, WSAXS and WAXS methods. The particle tracking hybrid detectors of the Timepix3 type have unique properties: High granularity (256 x 256 pixels with pitch of 55 µm), spectral and temporal sensitivity. Timepix3 can be coupled with high-Z sensors such as CdTe, CZT or GaAs for imaging applications with hard X-rays where the scintillator based imagers have dominated so far. The spectral sensitivity of Timepix3 detector allows XRD measurements with polychromatic X-ray beam avoiding usage of monochromators which dramatically improves beam intensity and makes measurements significantly faster. The detector’s high spatial resolution allows for XRD measurements in very close geometry maintaining good angular resolution. The XRD setup can be then very compact and portable. The Timepix3 detector with CdTe sensor allows XRD techniques to be used with hard X-rays for highly absorbing samples.

In this work a comparison of the Timepix3 detector performance is shown for several sensor types: Silicon 300 µm, CdTe 1 mm, CZT 2 mm and GaAs 500 µm. Several practical applications are shown as well: annealing near weld, fiber orientation mapping in carbon fiber composites, XRD of ore samples at 120 keV.

Fluorescent X-ray Computed Tomography to Investigate Oriental Potteries and Various Metal Components (#2197)

PhD/MD student Ajin Jo¹, PhD/MD student Ajin Jo¹, Prof. Wonho Lee², Prof. Wonho Lee²

¹ Korea University, Department of Bio-convergence Engineering, Seoul, South Korea; ² Korea University, School of Health and Environmental Science, Seoul, South Korea
Content
Fluorescent X-ray Computed Tomography (FXCT) system is a material analysis system based on the yield and energy information of characteristic X-rays. The system is composed of a transmission X-ray detector array, a fluorescent X-ray detector array and able to reconstruct 2D structure and material distribution images. In this study, a look-up table containing characteristic X-ray energy information obtained by experiment for commercially pure materials was used for the analysis of unknown materials. Oriental potteries, original and imitational gold plates and electronic circuits were analyzed by the FXCT system based on look-up table data. The colors of potteries were changed depending on the combination of elements. The original and imitational gold products were also clearly distinguished. The material components of an Arduino circuit were also successfully analyzed without any preliminary information.
SC-5 | Hybrid nuclear medicine devices: instrumentation and application

**Coordinator:** Georges El Fakhri, PhD, DABR

This **one-day course** covers both physical aspects of SPECT/PET-CT and MR (instrumentation, requirements for integration) as well as clinical applications of hybrid nuclear medicine imaging. Basics of PET, SPECT T and MR physics and instrumentation as they pertain to SPECT/CT, PET/CT, PET/MR are discussed in detail. An overview of wide range of detector technologies from Anger camera to state-of-the-art PET/MR systems will be provided.

Challenges in terms of attenuation correction, geometry integration, etc are discussed and opportunities afforded by detection of PET/SPECT and CT or MR signals (e.g., motion compensation, partial volume correction) are explored.

We will also introduce the state-of-art deep learning method for image reconstruction and quantitation for hybrid imaging system.

These discussions will culminate with detailed assessment of what clinical applications can benefit from SPECT/CT, PET/CT or PET/MR and how to leverage its use both in the animal and human research as well as in the clinical setting.

**Outline**

1. SPECT&PET Basic Instrumentation & Image Formation (**Georges El Fakhri**)
2. PET/MR & SPECT/PET/CT Instrumentation (**Hamid Sabet**)
3. Image Reconstruction & Quantitation (**Quanzheng Li**)

8:30 AM – 5:30 PM

Hilton Hotel - Deansgate 1
4. Clinical Applications (Georges El Fakhri)

Instructors

Georges El Fakhri, PhD, DABR. Dr El Fakhri is the Alpert Professor of Radiology at Harvard Medical School (HMS) and the founding Director of the Endowed Gordon Center for Medical Imaging at Massachusetts General Hospital and HMS with over 140 members. He is also co-Director of the Division of Nuclear Medicine and Molecular Imaging. Dr El Fakhri is an internationally recognized expert in quantitative molecular imaging (SPECT, PET-CT, and PET-MR) especially as it pertains to quantitative imaging, pharmacokinetic modeling and probing pathophysiology in brain, cardiac and oncologic PET/CT/MR. He has authored or co-authored over 200 papers and mentored over 90 students, post-docs and faculty. He has been a chartered member of many NIH study sections pertaining to Medical Imaging and Radiotherapy as well as DOD, DOE and other Foundations. He has received many awards and honors, including the Mark Tetalman Award and the E.J. Hoffman Award from the Society of Nuclear Medicine and Molecular Imaging and the Dana Foundation Brain and Immuno-Imaging Award. He was elected Fellow to the SNMMI, AAPM and IEEE for “contributions to biological imaging”.

Quanzheng Li, PhD. Quanzheng Li is an Associate Professor of Radiology at Massachusetts General Hospital and Harvard Medical School. Dr. Li is also Core faculty in the Gordon Center for Medical Imaging and scientific director of MGH/BWH Center for Clinical Data Science. He received his B.S degree from Zhejiang University in 1997, M.S. degree from Tsinghua University in 2000, and his Ph.D degree in Electrical Engineering from the University of Southern California (USC) in 2005. He did his post-doctoral training at USC from 2006 to 2007, and was a Research Assistant Professor from 2008 to 2010. In 2011, he joined the Radiology Department at Massachusetts General Hospital. Dr. Li is the recipient of 2015 IEEE Nuclear and Plasma Sciences Society (NPSS) early achievement award. He is an associate editor of IEEE Transaction on Image Processing, and members of editorial boards of Theranostics and Physics in Medicine and Biology. His research interests include image reconstruction and analysis in PET, SPECT, CT and MRI, and data science in health and medicine.

Hamid Sabet, PhD. Hamid Sabet is an Assistant Professor of Radiology at Harvard Medical School, and faculty at Gordon Center for Medical Imaging and Nuclear Medicine and Molecular Imaging Division at Massachusetts General Hospital. He earned his PhD in Quantum Science and Energy Engineering from Tohoku University, Japan in 2008. After a postdoctoral training at Rush Medical Center in Chicago (2009-2010), he worked as staff scientist at RMD Inc. from 2011 to 2014. He joined MGH/Harvard as faculty in 2014 and established Radiation Physics and Instrumentation Lab in GCMI, Radiology department.
The research theme of his Lab is development of novel detector technologies for nuclear medicine and x-ray imaging, and image-guided surgical applications.
SC-6 | Artificial intelligence for medical image analysis and processing

Coordinator: Jorge Cardoso, King’s College London, UK

This one-day course will cover important aspects of deep learning with a particular focus on medical imaging applications, and provide hands on experience in using and training deep learning models. The tutorial aims to provide an introduction to the basics and fundamental concepts of deep learning, practical advice for the use of deep learning for medical imaging tasks, and gives an overview of latest developments and opportunities for future research. The tutorial is targeted at all levels and for any researcher interested in deep learning. The first lectures are tailored for people new to the field (e.g., first year PhD students), while later lectures cover more advanced topics and latest developments which should be of interest to anyone already working with deep learning methods.

Outline

- Introduction to deep learning
- Applications of deep learning in Medical Imaging
- Semantic deep learning: segmentation and regression
- Architectures and optimization
- Transfer Learning and Domain adaptation
- Learning useful information from unlabeled data
- Generative adversarial networks
- Practical Hands-on Session
Instructors

Dr Jorge Cardoso is a Senior Lecturer in Artificial Medical Intelligence at King’s College London, where he leads a research portfolio on big data analytics, quantitative radiology and value based healthcare. He is also the CTO of the new InnovateUK-funded “London Medical Imaging and AI Centre for Value Based Healthcare”, where he is developing a software platform and associated computing infrastructure to enable data aggregation, machine learning and actionable analytics at scale across the three King’s Health Partners trusts. Jorge also co-lead the development of NiftyNet, a deep-learning platform for artificial intelligence in medical imaging, and is a founder and CSO of BrainMiner, a medtech startup aiming to bring quantitative biomarkers and predictive models to neurological care.

Dr Ben Glocker is a Senior Lecturer in Machine Learning for Imaging at Imperial College London and one of three academics leading the Biomedical Image Analysis Group. He is also an Adviser – Medical Image Analysis at HeartFlow and leading the London-based HeartFlow-Imperial Research Team. Ben works as scientific adviser for Definiens and Kheiron Medical Technologies. His research is at the intersection of medical image analysis and artificial intelligence aiming to build computational tools for improving image-based detection and diagnosis of disease.

Dr Carole Sudre is an Alzheimer’s Society Research Fellow at the School of Biomedical Engineering & Imaging Sciences at King’s College London. During her PhD at UCL, she developed algorithms to automatically segment brain lesions commonly observed in ageing populations. Her current research focuses on the development of machine learning solutions for quantification and characterisation of magnetic resonance imaging biomarkers associated with cerebrovascular damage.
JS-01 | New detectors and systems

Ralf Engels (Jülich)
Guillaume Montémont (Grenoble)
Characterization of Amorphous Silicon Based Microchannel Plates with High Aspect Ratio (#2140)

PhD/MD student Samira Frey, PhD/MD student Janina Löffler, Prof. Christophe Ballif, Priv.-Doz. Nicolas Wyrsch

Ecole Polytechnique Fédérale de Lausanne, Institute of Microengineering/Photovoltaics and thin film electronics laboratory, Neuchâtel, Switzerland

Content
Amorphous silicon based microchannel plates (AMCPs) are a promising alternative to conventional lead glass microchannel plates (MCPs). With the development of AMCPs with high aspect ratio values of about 20 instead of 10, a significant increase in the multiplication gain is expected, compared to previous generations. For the current work, performance and gain values of AMCPs are determined using a specifically designed photocathode source in quasi steady-state. First multiplication gain values in excess of 100 could be measured for the last development. Additionally, the electrical properties of the devices are analyzed using the electron beam induced current technique. This provided visible proof of the electron multiplication inside the channels and helped identifying effects like the localized charging of the decoupling layer with high beam currents as well as analyzing the possible detrimental effects of fabrication defects.

Development of GGAG radiation imaging system with discrimination capability of the types of radiations and application to alpha particle distribution measurements (#1317)

Prof. Seiichi Yamamoto¹, Shinsuke Terazawa², Dr. Tadashi Watabe³, Dr. Jun Hatazawa³

¹ Nagoya University, Graduate School of Medicine, Nagoya, Japan; ² Hitachi Metal, Co, Ltd, Mishima, Japan; ³ Osaka University, Graduate School of Medicine, Suita, Japan

Content
Gd3(GaAl)5O12:Ce (GGAG) is a ceramic scintillator originally developed for X-ray CT, and it was also an excellent material for the development of an event-by-event-based radiation imaging detector when it was combined with a position sensitive photomultiplier (PSPMT). With the developed GGAG imaging detector, we found that the decay times for alpha particles and gamma photons were different. Also, we found that the decay times for alpha particles and beta particles were different. These characteristics are advantageous for developing an imaging detector for the simultaneous imaging of different types of radiation using pulse shape discrimination. Thus, we tested the separation of the images of the alpha particles and gamma photons using pulse shape discrimination. Also, we evaluated the separation of the alpha and beta particle images. In the pulse shape spectra, we could separate the peaks of Am-
241 alpha particles and Cs-137 gamma photons with a peak-to-valley ratio (P/V) of 3.5. We obtained clearly separated images for Am-241 alpha particles and Cs-137 gamma photons using pulse shape discrimination. We could also separate the peaks of Am-241 alpha particles and Sr-Y-90 beta particles with a P/V of 1.5 in the pulse shape spectrum. We obtained separated images for Am-241 alpha particles and Sr-Y-90 beta particles using pulse shape discrimination. In addition, we could separate electrostatically collected natural alpha particles, Po-218 and Po-214, from the environmental beta particles and gamma photons using pulse shape discrimination. We are now using the imaging system for alpha particle autoradiography administered At-211 to small animals. We conclude that the GGAG imaging detector is promising for simultaneous imaging and separating the images of different types of radiation using pulse shape discrimination.

Development of a Compton gamma camera based on Timepix3 hybrid-pixel detector. (#1994)

PhD/MD student Guillaume Amoyal1, PhD/MD Thomas Dautremer2, PhD/MD Vincent Schoepff1, PhD/MD Frédérick Carrel1, PhD/MD Nicolas Blanc Delanaute4, PhD/MD Jean-Claude Angélique3

1 CEA Saclay, LIST/DM2I/LCAE, Gif-Sur-Yvette, France; 2 CEA Saclay, LIST/DM2I/LM2S, Gif-Sur-Yvette, France; 3 Université de CAEN / CNRS, IN2P3, Caen, France; 4 MIRION TECHNOLOGIES, Montigny-le-Bretonneux, France

Content
Gamma imaging is a technique that allows the spatial localization of radioactive sources. One asset of this technique is the ability to locate radioactive sources associated with a quantitative information on their intensity. One of the gamma imaging techniques is Compton imaging. Compton imaging takes advantage of scattering kinematics. The energy deposited during scattering process will determine the scattering angle, and the positions of interactions will determine the direction of the incoming gamma-rays. The position of the radioactive source may be limited to a cone, which apex corresponds to the scattering position. Using multiple interactions, multiple Compton cones can be determined and will eventually intersect in the source location. Developing a Compton camera requires the use of detectors providing information on energy, positions of interactions, and a sufficient time resolution to identify coincidence events. Compton cameras are usually composed of two detection layers: a scatterer (most often a Si semi-conductor), and an absorber (most often a CdTe or CZT semi-conductor).

In 2013, CERN developed the Timepix3 readout chip. It works as an event based readout chip and simultaneously records in each pixel the deposited energy, and the time-of-arrival (1.5 ns time resolution). The Timepix3 chip has the necessary requirements to perform Compton imaging: energy measurement, fast time sampling, and fine pixelisation pitch. In this paper, we present two configurations of Compton camera based on Timepix3. The first one, based on one Timepix3 chip hybridized to a 1 mm-thick CdTe semi-conductor. The second one is based on two synchronized Timepix3 detectors, one bump bonded to a 300 µm-thick Si sensor, the second one hybridize to a 1 mm-thick CdTe semi-conductor. Each set-up is able to localize radioactive sources. The double-detector configuration offers better performances in term of spatial resolution because of the lower uncertainty on depth of interaction.
First production of 50 µm thick Resistive AC-Coupled Silicon Detectors (RSD) at FBK (#1470)

**Dr. Marco Mandurrino**, Prof. Roberta Arcidiacono, Dr. Giacomo Borghi, Dr. Maurizio Boscardin, Dr. Nicolò Cartiglia, Prof. Gian-Franco Dalla Betta, PhD/MD student Marco Ferrero, Dr. Francesco Ficorella, Prof. Lucio Pancheri, Dr. Giovanni Paternoster

1 INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Torino, Italy; 2 CERN, Meyrin, Switzerland; 3 Università del Piemonte Orientale, Novara, Italy; 4 Fondazione Bruno Kessler, Trento, Italy; 5 TIFPA-INFN, Trento, Italy; 6 Università degli Studi di Trento, Trento, Italy; 7 Università degli Studi di Torino, Torino, Italy

Content

Resistive AC-Coupled Silicon Detectors (RSD) are innovative particle detectors conceived for 4D tracking in future high-energy physics experiments. They essentially are n-in-p sensors based on the LGAD (Low-Gain Avalanche Diode) technology, i.e. providing an internal multiplication thanks to a specific p-type implant called gain layer, which is located just under the n-electrode. Contrarily to many other state-of-the-art trackers, RSD have a continuous gain implant covering all the detector area. For this reason, they get rid of any segmentation structure between active areas, being the track reconstruction realized only through the segmentation of their readout pads, which represent the real pixel. So, the spatial information is obtained thanks to a resistive cathode, freezing the multiplied charges around each corresponding pad by a characteristic time. RSD have been designed to have such time long enough for the signal to be completely induced on pads via capacitive coupling, but short enough to mitigate pile-up effects.

In this work we present several laboratory measurements which characterize the static and dynamic behavior of our first production of RSD at Fondazione Bruno Kessler (FBK), called RSD1. Moreover, also comparison between experimental data and TCAD simulations will be presented.

A Compact Dual-Mode Neutron/Gamma-Ray Phoswich Scintillation Detector (#1818)

**Dr. Mohammad Nakhostin**, Dr. Matthew Taggart, Prof. Paul J. Sellin

*University of Surrey, Physics, Guildford, UK*

Content

In recent years there have been significant advances in the field of scintillation radiation detectors, including commercial production of new bright scintillator materials such as cerium-doped Gd$_3$Al$_2$Ga$_3$O$_{12}$ (GAGG) and europium-doped SrI$_2$, and the establishment of Silicon Photomultipliers (SiPMs) as a new generation of photodetectors. The large gadolinium content of scintillators such as GAGG makes them very attractive for the detection of thermal neutrons. However, the inherent high sensitivity of gadolinium to external gamma-rays limits the
neutron detection performance of the GAGG scintillator. In this contribution we demonstrate that this problem can be significantly alleviated by using a phoswich arrangement of a thin GAGG scintillator with a second inorganic scintillator. The second scintillator shields the GAGG crystal against the external gamma-rays, thereby significantly improving its neutron response. The design was evaluated with a GAGG crystal separately coupled to BGO, LYSO, and CsI(Na) crystals with SiPM light readout. The SiPM output pulses were directly digitized and a pulse-shape discrimination (PSD) algorithm was used to separate the scintillation pulses. The best PSD result was achieved with the GAGG/CsI arrangement, demonstrating a clear identification of neutron absorption gamma-rays (82 and ∼43 keV) without using any lead shielding in the measurements with an Am/Be neutron source. We will also present the gamma spectroscopy performance of the recently developed SrI₂ crystal coupled to a SiPM over a wide energy range as a candidate for improving the gamma-ray response of the detector. The results of our study show that the phoswich arrangement of GAGG/SrI₂ crystals coupled to a single SiPM is a very promising dual-mode neutron/gamma-ray detector for applications such as nuclear safety, environmental monitoring, and homeland security where compact structure, high sensitivity, and low power consumption are prized.

JS-01-06

Development of Large-Area Deformable HEXITEC-CZT Imaging-Spectrometer for Clinical SPECT Imaging Applications (#2361)

Prof. Ling-Jian Meng¹,², Jiajin Zhang¹, Elena Zannoni², Matt Wilson³, Dr. Kris Iniewski⁴

¹ University of Illinois at Urbana-Champaign, Department of Nuclear, Plasma, and Radiological Engineering, Urbana, USA; ² University of Illinois at Urbana-Champaign, Department of Bioengineering, Urbana, USA; ³ The Science and Technology Facility Council, Rutherford Laboratory, Didcot, UK; ⁴ Redlen Technology, Saanicheton, Canada

Content

Cadmium Zinc Telluride (CdZnTe) detector has found a wide range of applications in medical imaging, high-energy physics and astrophysics, nuclear security and environmental monitoring applications. One of the key strengths of CZT is the combination of its relatively high density, effective Z number, a moderate band-gap and a favorable charge mobility-lifetime product. Combined with low-noise pixel readout circuitries, CZT detectors have the potential of offering an ultrahigh spatial and energy resolution for γ-ray imaging applications. In this work, we collaborate with the STFC Rutherford Appleton Laboratory, UK and the Redlen Technology, Canada to develop a large-area deformable CZT imaging spectrometer based on the HEXITEC ASIC. Our design goal is a CZT detector of >10 cm × 10 cm in a compact detector panel that encapsulates the CZT detectors, analog and digital readout electronics and high-speed onboard data processing units, all in a compact detector module with a minimum dead-area around the peripheral. The detector offers an excellent imaging resolution of 250 µm in X-Y directions, a depth-of-interaction (DOI) resolution of 0.5 mm, an excellent energy resolution of <2 keV at 140 keV and a dynamic range of 5-200 keV or50-600 keV. The HEXITEC-CZT detector combines an ultrahigh imaging resolution with an excellent energy resolution, which makes it an ideal building block for future high-performance clinical SPECT imaging applications.
N-10 | Synchrotron, FEL, XFEL I

Nicola Tartoni (Didcot)
Christer Frojdh
Characterization of a Fast-Framing X-Ray Camera With Wide Dynamic Range for High-Energy Imaging (#2395)

Dr. Katherine S. Shanks¹, Dr. Hugh T. Philipp¹, John T. Weizeorick², Michael Hammer², Dr. Mark W. Tate¹, Prafull Purohit¹, Dr. Antonino Miceli², Prof. Sol M. Gruner¹,³

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Content

We present first characterization results, with a focus on high-flux measurements, of a fast-framing, wide-dynamic-range x-ray camera intended for high-energy imaging. The MM-PAD-2.1 uses an integrating pixel front-end with a charge removal architecture and in-pixel counter to extend the pixel well depth while maintaining low read noise across the full dynamic range. The full-scale prototype detector will have 256 x 384 pixels, a pixel well depth of $10^8$ 20-keV ph/pixel, and will frame continuously at $>1$ kHz with a $>90\%$ duty cycle at maximum frame rate. It will have a 750 µm CdTe sensor to support imaging at $>20$ keV. The charge-removal mechanism is dead-time-less (i.e., incoming signal continues to be integrated by the front-end while charge removal is taking place). The purpose of the high-flux characterization was to determine the maximum sustained incident flux that could be measured while still exhibiting linear behavior. To this end, a 16 x 16 pixel prototype with a 500 µm Si sensor was tested at the Advanced Photon Source at Argonne National Laboratory using 10 keV photons generated by an undulator source. The intensity of the incident beam was varied over 3 orders of magnitude using a series of attenuators, and the signal integrated by the MM-PAD-2.1 prototype was compared to that measured by a He-filled ion chamber directly upstream. Initial results indicate linear performance up to ca. $10^{10}$ ph/s in a spot spanning approximately 2 x 1.5 pixels (FWHM). The onset of transient radiation damage was observed during these measurements, characterized primarily by failure of digital readout from the detector ASIC. These effects were observed to reverse after annealing at 30°C for several hours, with full recovery of the detector readout. Strategies for mitigating radiation damage in future revisions of the detector will be discussed.
Gotthard-II: a Microstrip Detector for the European X-ray Free Electron Laser (#1656)

Dr. Davide Mezza¹, Marie Andrae¹, Rebecca Barten¹, Dr. Anna Bergamaschi¹, Martin Brückner¹, Dr. Sabina Chiriotti-Alvarez¹, Dr. Roberto Dinapoli¹, Dr. Erik Fröjdh¹, Dr. Dominic Greiffenberg¹, Dr. Markus Kuster², Carlos Lopez-Cuenca¹, Dr. Markus Meyer¹, Dr. Aldo Mozzanica¹, Dr. Marco Ramilli², Dr. Sophie Redford¹, Christian Ruder¹, Dr. Bernd Schmitt¹, Dr. Xintian Shi¹, Dhanya Thattil¹, Dr. Gemma Tinti¹, Dr. Monica Turcato², Seraphin Vetter¹, Dr. Jiaguo Zhang¹

¹ Paul Scherrer Institute (PSI), SLS Detector Group, Villigen, Switzerland; ² European X-ray Free Electron Laser Facility GmbH, Hamburg, Germany

Content

Gotthard-II (G-II) is a 1-D silicon microstrip detector developed for the European X-ray Free-Electron Laser (EuXFEL). Among its target applications we find: X-ray absorption/emission spectroscopy, hard X-ray high resolution single-shot spectrometry (HiREX), energy dispersive experiments, beam diagnostics, as well as veto signal generation for large area pixel detectors currently being operated at the EuXFEL, such as AGIPD and LPD. The detector will provide single photon resolution at 5 keV (S/N > 5) and will operate with photon energy in the range 5 keV – 20 keV. Concerning the speed, G-II can cope both with the 4.5 MHz burst mode frame rate of the EuXFEL and a frame rate of > 660 kHz in continuous mode making it suitable for usage at synchrotrons and future EuXFEL upgrade to continuous mode. G-II uses a silicon microstrip sensor with a pitch of 50 μm or 25 μm and with 1280 or 2560 channels wire-bonded to readout chips (ROCs). In the ROC, a high DC gain charge sensitive preamplifier, a fully differential Correlated-Double-Sampling stage, a 12-bit Analog-to-Digital Converter with a sampling/conversion rate of 18 MS/s as well as a Static Random-Access Memory capable of storing all the 2700 images of the EuXFEL bunch train have been implemented. The G-II ROC has been designed in 110 nm UMC technology and submitted in early February 2019 after an extensive characterization of several test structures made in the last few years. The final ROC is expected to be available in mid May 2019. In this contribution the performance of the G-II ROC in terms of noise, linearity, dynamic range, coupling between channels and speed will be presented.

Tristan1M detector, characterization and use in microsecond regime time resolved experiments (#1751)

Giulio Crevatin, Graham Dennis, Eva N. Gimenez-Navarro, Alan Greer, Ian C. Horswell, David Omar, Jonathan Spiers, Scott Williams, Nicola Tartoni

Diamond Light Source, Didcot, UK

Content
Tristan1M is a 1 million pixel module prototype of a larger X-ray detector (Tristan, 10 million pixels, currently under development) for time resolved experiments which exploits the data driven mode and time stamp capabilities of the Timepix3 ASIC. Tristan1M is made out of a monolithic silicon sensor bonded to 16 Timepix3 ASICs - arranged in an 8 by 2 matrix - and custom data acquisition electronics, firmware, and software developed for this project. In this contribution, after summarizing the architecture of Tristan1M, the outcome of the characterization and validation of the prototype is reported. Particular emphasis will be given to Tristan1M timing capabilities across the entire matrix of ASICs and its limitations in terms of counting rate and data volume challenges when scaled to a larger number of ASICs.

More importantly the preliminary results of some test experiments with actual user samples are also reported. The test experiments have been carried out to demonstrate the timing capabilities of Tristan1M in real situations and to show how efficiently such a class of experiments can be carried out, as compared to those using more conventional detector technologies. The experiments operate in the microsecond regime. Tristan1M has begun its contribution to the science ongoing at Diamond by producing data which may be incorporated in future scientific papers. This gives clear indication of the potential of detectors of the Tristan class for time resolved experiments.

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**N-10-04**

**11:14 AM**

**Calibration Methods for Adaptive Integrating Pixel Detectors; Application to ePix10k (#1837)**

**Dr. Gabriel Blaj**¹, **Dr. Faisal Abu-Nimeh**¹,², **Dr. Bojan Markovic**¹, **Pietro Caragiulo**¹, **Dr. Maciej Kwiatkowski**¹, **Dr. Dionisio Doering**¹, **Dr. Christopher Kenney**¹, **Dr. Angelo Dragone**¹, **Dr. Gunther Haller**¹

¹ SLAC National Accelerator Laboratory, TID/ AIR, Menlo Park, USA; ² Apple, Cupertino, USA

**Content**

Integrating pixel detectors that automatically switch their gain mode, based on the input charge, have many advantages over fixed-gain integrating pixel detectors. They provide a high-dynamic-range across the entire pixel array, single-photon counting at low beam intensities and noise that is limited by the Poisson statistic for large signals. The calibration methods for these auto-switching detectors depend mainly on the isolated responses for given gain settings. Nonlinearities and discontinues in the transition points between different gain modes make the calibration method more challenging to achieve. Therefore, we compile a comparison between different auto-switching, integrating pixel ASIC families: AGIPD, ePix10k, and Jungfrau and their approaches in calibrating different pedestal and gain responses across the pixel array. Finally, we will present an in-depth analysis of ePix10k calibration methods, results, and implementation for in-situ calibration at the Linac Coherent Light Source (LCLS) at SLAC.
Characterization of PFM3, a 32x32 readout chip for PixFEL X-ray imager (#2085)

Matteo Pezzoli1,3, Luca Lodola5, Massimo Manghisoni2,3, Fabio Morsani4, Lodovico Ratti1,3, Valerio Re2,3, Elisa Riceputi2,3, Gianluca Traversi2,3

1 University of Pavia, Dept. of Electrical, Computer and Biomedical Engineering, Pavia, Italy; 2 University of Bergamo, Dept. of Engineering and Applied Sciences, Dalmine, Italy; 3 INFN, Sezione di Pavia, Pavia, Italy; 4 INFN, Sezione di Pisa, Pisa, Italy; 5 STMicroelectronics, Cornaredo, Italy

Content

In the framework of the PixFEL project, a readout chip for pixel sensors has been designed and fabricated in a 65 nm CMOS technology. The detector in the PixFEL project is intended for application to coherent X-ray diffraction imaging (CXDI) at the next generation free electron lasers (FELs). This paper will present a characterization of PFM3 chip at various stages of the signal chain. Characterization data has been collected from the (CSA) stage, implementing a dynamic compression of the input signal, from the trapezoidal filter and the 9-bit SAR ADC, with a focus on the former. Measurements validating the input-output characteristic of the CSA for various (1 keV, 2 keV and 3 keV) gain settings are shown.

EIGER: a 20-70 kHz frame rate pixel detector for synchrotron applications (#2202)


Paul Scherrer Institute (PSI), Villigen, Switzerland

Content

The hybrid pixel detector EIGER, featuring 75μm x 75 μm pixel size, is a photon counter designed for use at synchrotrons. The chip and the complete readout system were designed at the Paul Scherrer Institut, Switzerland. A single chip consists of 256 x 256 pixels and can acquire data up to 22 kHz frame rate with 4-bit counter depth. In a full module, 4 x 2 chips are bonded to a single Si sensor with dimension approximately 8 cm x 4 cm. The readout electronics of a module has been specifically developed to preserve the high frame rate capability of the chip, with the possibility to transfer data at 2 x 10Gb/s and buffer 8 GB (30000 images in 4-bit mode). Larger modules systems, up to 9 Mpixel detectors, have been built by tiling modules and preserving the high frame rate capabilities. Time resolved and continuous fast experiments at synchrotrons at unprecedented speeds have been possible in the last couple of years.
thanks to EIGER. Scientists' demand of even higher time resolution has lead us to explore the possibility of reading out only a part of the detector at even higher frame rates. Time resolved powder diffraction experiments have been recorded at 42 kHz and 73 kHz frame rate illuminating respectively a detector area of 8 cm x 2 cm and 8 cm x 1 cm. In addition to these new measurements, we will also show the stability of the noise and calibration performance at 20-70 kHz frame rate compared to the one at low frame rates.
N-11 | Gaseous Detectors I

Francesco Renga
N-11-01  10:20 AM

A high pressure time projection chamber with optical readout (#2280)

Dr. Alexander Deisting¹, PhD/MD Abbey Waldron², The development of the high pressure TPC is common effort of working groups at: RWTH Aachen, Université de Genève, Imperial College London, Lancaster University, Royal Holloway University London, University College London, University of Warwick

¹ Royal Holloway, University of London, Egham, UK; ² Imperial College London, London, UK

Content

Gas filled Time Projection Chambers (TPCs) are promising candidates to characterise neutrino interactions at future long baseline neutrino oscillation experiments such as DUNE, because of their low energy threshold for particle detection, the fact that the detection medium serves at the same time as scattering target and because they can detect interactions with high efficiency in 4π. Using a High Pressure (HP) gas improves interaction statistics, allowing an HPTPC to better measure neutrino-nucleus interactions than TPCs at atmospheric pressure.

We have built an HPTPC prototype and operated it in a test beam at CERN. The amplification stage of is composed out of three meshes, where the induced charge on each mesh is read out. Furthermore, four CCD cameras - each of them focused on one quadrant of the amplification stage - read out the 2D projection of a particle's tracks on the readout plane. This optical readout provides an optical plate scale linear dimension of 230 μm and images a total area larger than 1 m². The TPC itself is embedded into one of the world largest HP test stands, which has a volume of 850 l and is rated up to an absolute pressure of 6 bar.

In the fall of 2018 the HPTPC's performance was tested during a beam test at the CERN PS, measuring interactions of low momentum protons (< 0.5 GeV/c) with the counting gas. Several mixtures with Argon predominance have been tested for their light yield and gas gain. We will present results on the HPTPC performance, with the aim of measuring the proton-Ar cross-section at low momentum, as well as preliminary results of the first operation of an ALICE multi-wire proportional Outer ReadOut Chamber (OROC) at HP. The OROC has been mounted in our high pressure test stand, replacing the meshes, in order to assess the potential of similar chambers for the future DUNE near detector's HPTPC.

N-11-02  10:38 AM

Passive Gating Grid for Ion Back Flow Suppression in High Luminosity Collider Experiments (#2345)

Dr. Prakhar Garg, Dr. Klaus Dehmelt, Dr. Thomas Hemmick, PhD/MD student Vladislav Zakharov

Stony Brook University, Department of Physics and Astronomy, Stony Brook, USA

Content
Time Projection Chamber (TPC) is one of the main tracking systems for many of the current and future collider experiments at RHIC and LHC. It has a capability to measure the space points of charged tracks for good momentum resolution as well as the energy loss (dE/dx) for particle identification with good energy resolution. Both the features depend strongly on the amount of space charge in the TPC gas volume, mainly due to the ions from amplification stage. An active gating has been used so far to gate the electrons and ions by switching the polarities of the gating grid. Therefore, active gating does introduce a limitation for the data taking rates in high luminosity collisions. In this presentation we propose several options of a passive gating, where a significant reduction of ion back flow is possible in a high luminosity environment without any dead time due to gating operation. Particularly, the application of a TPC passive gating for sPHENIX experiment at RHIC will be presented, which is currently under development.

N-11-03 10:56 AM

Performance of Small-Pad Resistive Micromegas for operation under high particle flow (#2516)

Maria Grazia Alviggi\textsuperscript{1,2}, Maria Teresa Camerlingo\textsuperscript{5,4}, Vincenzo Canale\textsuperscript{2,1}, Massimo Della Pietra\textsuperscript{2,1}, Camilla Di Donato\textsuperscript{3,1}, Paolo Iengo\textsuperscript{6}, Mauro Iodice\textsuperscript{4}, \textbf{Fabrizio Petrucci}\textsuperscript{5,4}, Givi Sekhniaidze\textsuperscript{1}

\textsuperscript{1} INFN Napoli, Naples, Italy; \textsuperscript{2} Università di Napoli Federico II, Naples, Italy; \textsuperscript{3} Università di Napoli Parthenope, Naples, Italy; \textsuperscript{4} INFN Roma Tre, Rome, Italy; \textsuperscript{5} Università Roma Tre, Rome, Italy; \textsuperscript{6} CERN, Geneva, Switzerland

Content

Motivated mainly by future upgrades at high-luminosity LHC (HL-LHC) and detectors at future accelerators, most of the HEP R&D collaborations are focusing on the design of new particle detectors for operation under very high particle flow. In the field of Micro-Pattern-Gaseous-Detectors, the small-pad resistive Micromegas prototypes were designed to overcome the limitations of current resistive strip Micromegas chambers. In these new prototypes, pads with 1x3 mm\textsuperscript{2} area replace the readout strips to reduce the occupancy, and the spark protection resistive layer has been redesigned and optimized with different techniques to permit a safe behaviour of the detector, without efficiency loss, at rates of the order of tens MHz/cm\textsuperscript{2} over large surfaces. The firstly-developed design exploits a pad-patterned embedded resistor layout made by screen-printing, while the most recent technique involves uniform sputtered DLC (Diamond Like Carbon structure) layers, where the charge evacuates through the several vias connected to the ground. Comparative studies have been conducted on the performance of the detectors with two resistive layouts, and between two DLC prototypes with different pitch of vias and surface resistivity. The results of the tests performed with high intensity X-rays and with high energy charged particle beams will be presented.
Fast Timing Micropattern gaseous detector: working principle and latest progresses in the detector development. (#2232)

Dr. Ilaria Vai\textsuperscript{1,2}, M.Sc./M.A. student Chiara Aimè\textsuperscript{1,4}, Dr. Alessandro Braghieri\textsuperscript{1}, PhD/MD student Simone Calzaferri\textsuperscript{1,4}, PhD/MD Davide Fiorina\textsuperscript{1,4}, Dr. Marcello Maggi\textsuperscript{3}, Dr. Martina Ressegotti\textsuperscript{1,4}, Prof. Cristina Riccardi\textsuperscript{1,4}, PhD/MD student Christos Roskas\textsuperscript{6}, Dr. Paola Salvini\textsuperscript{7}, PhD/MD student Federica Simone\textsuperscript{3,5}, Dr. Michael Tytgat\textsuperscript{6}, Prof. Paolo Vitulo\textsuperscript{1,4}, Dr. Piet Verwilligen\textsuperscript{3}

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Content

Significant progress has been made with Micropattern Gaseous Detectors (MPGD) in recent years, with the introduction of resistive materials to build compact spark-protected devices. Exploiting this technology further, various features such as space and time resolution, sensitive area, operational stability and radiation hardness can be improved. A new type of MPGD, the Fast Timing Micropattern (FTM) detector, based on a fully resistive WELL structure, was firstly introduced in 2015 \cite{1} with the aim of reaching a sub-nanosecond time resolution. The FTM consists of a stack of several coupled fully resistive layers where drift and WELL multiplication stages alternate in the structure, yielding a significant improvement in timing properties due to competing ionization processes in the different drift regions. The very first prototype, including two consecutive drift and amplification layers, was tested at the SPS test beam facility with muon and pion beams and reached a time resolution of the order of 2 ns, with a factor three-four improvement compared to a standard Triple-GEM detector \cite{2}. This contribution will present the new multi-layer prototype, designed to host up to twelve layers. Preliminary results on the detector characterization will be shown as well.

Recent Developments in the Read-Out Electrodes for the Spherical Proportional Counter (#2641)

Patrick Knights¹,², Ioannis Giomataris², Ioannis Katsioulas¹, Konstantinos Nikolopoulos¹, Robert Ward¹

¹ University of Birmingham, School of Physics and Astronomy, Birmingham, UK; ² CEA, Université Paris-Saclay, IRFU, Gif-sur-Yvette, France

Content
The spherical proportional counter is a versatile gaseous detector with a relatively simple design comprising a spherical cathode with a centrally-located, spherical anode. With sub-keV energy thresholds, variable gas targets, and single channel readout in the simplest form the detector offers many advantages and is well suited to several applications from direct dark matter searches to fast neutron spectroscopy. Each of these different applications present new challenges to the detector, whose instrumentation is constantly being developed to achieve them. Among these developments are improvements to the electric field homogeneity and detector stability to sparks through the use of high-resistivity second electrodes. ANSYS finite-element software calculations of the electric field will be presented along with experimental results with the produced sensor. A second challenge is the reduction in electric field as the detector size scales, which reduces electron collection efficiency. To address this, a multi-anode structure, ACHINOS, has been developed. Experimental results collected with this will be presented and compared to finite-element models.

Two-dimensional imaging technique based on LTCC-GEM with cold and thermal neutron beam. (#1088)

Kazuki Komiya¹, Dr. Yoko Takeuchi¹, Prof. Shoji Uno², Prof. Takahisa Koike³

¹ Tokyo Metropolitan Industrial Technology Research Institute, Electronics group, Tokyo, Japan; ² High Energy Accelerator Research Organization, Tsukuba, Japan; ³ Kyorin University, Tokyo, Japan

Content
A gas electron multiplier (GEM) detector is a kind of micro pattern gas detectors, which was developed in CERN in 1997. Since the detector can capture a charged particle, it is well applied to a radiation detector. This is a detector which is a densely pierced foil coated with electrodes on both sides, and able to achieve high amplification gains. The traditional GEM foils installed in a GEM detector have a 0.06 mm diameter of hole with 0.12 mm pitch and thickness of 0.05 mm to 0.2 mm. The traditional GEM foils are based on an organic material of Liquid Crystal Polymer (LCP) or Polyimide (PI). Therefore, the GEM foils are often broken because of abnormal discharges between top and bottom electrode, which is formed by a metal on the both side of the GEM foils during the operation. Thus, we developed the new generation GEM foil based on the Low Temperature Co-fired Ceramics (LTCC). The LTCC is an
inorganic material and there is no short-circuit failure due to electrical discharge. The LTCC-GEM has a 0.1 mm hole with a 0.2 mm pitch, which is simply fabricated by punching out. Furthermore, the performance of the effective gain and the energy resolution are equivalent to the traditional GEM with LCP or PI. We succeeded to acquire two-dimensional imaging of 100mm square size with cold neutrons and thermal neutrons beam using the LTCC-GEM foils in accelerator-driven compact neutron source (RANS) at RIKEN, Japan. The cold and thermal neutron imaging of acrylic 5-mm-thickness plate was obtained and LTCC-GEM foils did not interfere with thermal neutron and cold neutron detection.
JS-02 | New detectors timing / data acquisition

Chiara Guazzoni (Milano)
Dennis R. Schaart (Delft)
Multi-Well Avalanche Selenium Detector for Time-of-Flight PET (#1546)

PhD/MD student Andy LaBella¹, Dr. Wei Zhao², Dr. Paul Vaska², Dr. Amir H. Goldan²

¹ Stony Brook University, Department of Biomedical Engineering, Stony Brook, USA; ² Stony Brook University, Department of Radiology, Stony Brook, USA

Content

Time-of-flight (TOF) PET uses detection timing differences to localize coincident gamma rays to a small line segment along the line-of-response, resulting in improved image quality, decreased scan time, and/or decreased dose to the patient. Performing TOF-PET requires coincidence timing resolution (CTR) on the order of hundreds of picoseconds. This requires ultrafast photodetectors, which come in the form of arrays of silicon-based Geiger-mode single-photon avalanche diodes known as silicon photomultipliers (SiPMs). While SiPMs can achieve single-photon time resolution (SPTR) values less than 100 ps, they have poor production scalability and suffer from poor detection efficiency due to their low fill factors, which results in relatively suboptimal CTR in practice. In this work, we propose the use of our patented multi-well selenium detector, which we’ve recently shown can achieve SPTR ~ 100 ps and linear-mode avalanche gain, as a photodetector for TOF-PET due to its large active area, low production cost, and high quantum efficiency for blue photons. Using Cramér-Rao Lower Bound analysis, we show the potential of our selenium detector and compare it to the optimal performance of SiPMs. The calculated lower bound on CTR for primary triggers was ~150 ps for SiPMs and ~70 ps for our selenium detector. In addition, we show that CTR < 100 ps can be achieved even when triggering on the first couple of hundred scintillation photons, making the selenium detector viable despite being a linear-mode device. Our analysis shows that our multi-well selenium detector is a potential alternative to SiPMs in TOF-PET.
Achieving sub-100 ps Coincidence Time Resolution (CTR) is now possible with 20-mm long crystals. Despite the current pace in timing improvements of scintillators and photodetectors, reaching 10 ps CTR would remain elusive without DOI correction. Nonetheless, this momentum opportunistically brings up the prospect of a fully time-based DOI encoding method since timing signals with reduced statistical variability intrinsically carry DOI information. Indeed, the timing signal in standard single-end readout crystals is essentially made up of two waves of photons, one traveling towards the photodetector and the other one going the opposite way before being reflected back, with a time separation directly linked to the DOI. Consequently, comparing the arrival time of a later trigger (from the second wave) to an early trigger (from the first wave) could uncover the spatial origin of the signal. In this work, we explored the scintillation and photodetection requirements to encode the DOI through the signal arrival time distribution. This pure time-based DOI encoding approach could overcome the DOI barrier to reach 10 ps CTR provided a high photon time density can be achieved, either through reduced scintillator decay time and/or prompt photons population. In these conditions, the timing response of current SiPMs reaching ~30 ps single photon time resolution sigma would be suitable to implement the proposed DOI encoding method and reach the 10 ps CTR target. We undertook an experimental evaluation with 2x2x20 mm³ LSO:Ce:Ca crystals and FBK NUV-HD SiPMs read out by new fast high-frequency electronics at CERN. A DOI-dependent CTR trend was observed with this state-of-the-art detector setup that can not be explained by photon statistics only. Further measurements with a dual-threshold analog triggering approach could enhance DOI-dependent pulse shapes discrimination. These studies will help setting up the detector design criteria to fully exploit the timing signal aiming at 10 ps CTR.

Timing performance of Cherenkov-radiator-integrated MCP-PMT (#1652)

PhD/MD student Ryosuke Ota1,2, Dr. Kyohei Nakajima2, Dr. Izumi Ogawa2, Prof. Yoichi Tamagawa2, M.Sc./M.A. Hideki Shimoi3, Dr. Motohiro Suyama3, Prof. Tomoyuki Hasegawa4

1 Hamamatsu Photonics K.K., Central Research Laboratory, Hamamatsu, Japan; 2 University of Fukui, Faculty of Engineering, Fukui, Japan; 3 Hamamatsu Photonics K.K., Electron Tube Division, Iwata, Japan; 4 Kitasato University, School of Allied Health Science, Sagamihara, Japan

Content

An ultimate goal of detectors for time-of-flight positron emission tomography (PET) is to achieve a coincidence time resolution (CTR) of 10 ps to directly localize the position along the line of response (LOR) for a pair of annihilated 511 keV gamma rays. Although Cherenkov emission plays an important role to improving the CTR, a number of Cherenkov photons emitted is only 30 at most when the 511 keV gamma rays interact with a Cherenkov radiator. Therefore, the Cherenkov photons should be effectively transported to a photocathode. From this point, a Cherenkov-radiator-integrated microchannel plate photomultiplier tube (CRI), in which optical boundaries from the Cherenkov radiator to the photocathode are alleviated, has been previously developed. Thanks to the alleviation of the optical boundaries, the CTR of 41.9 ps full width at half maximum (FWHM) has been obtained without any event selections. In this study, more detailed experiment was performed to enhance reliability of the CRI’s timing capability. In the experiment, a 22Na point source collimated by a Pb collimator of 1.0 mm Ø × 50 mm was scanned along the LOR of a pair of the CRIs with several step sizes while the pair of the CRIs was located at fixed positions during the measurements. The source position was estimated from a histogram of the time difference between the CRIs, and the position estimation accuracy was evaluated by comparing the estimated position to the known position. Several
thousands of coincidence events were recorded for each source position. The experiment provided an average CTR of 41.4 ps FWHM, which is consistent with the former results. Thanks to such a high CTR, two positions 7.5 mm away from each other, which is equivalent to the CTR of 50 ps, could be clearly resolved. The position estimation accuracy better than 0.3 mm was obtained. These results will enhance the reliability of the timing performance of the CRIs.

**JS-02-04**

2:34 PM

**Design and Electro-optical Characterization of a Novel, Fully Digital CMOS SPAD Array for Ultra-fast Neutron Tracking in Particle Therapy**

(#2130)

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**Content**

We present the architecture and electro-optical characterization of a time-resolved single photon detector specifically designed for particle trackers based on plastic scintillating fibers. The sensor has been developed within the MONDO (MOnitor for Neutron Dose in hadrOntherapy) project, which aims at investigating the effects of secondary generated neutrons in particle therapy. The experiment poses significant challenges on the tracker readout chip to reconstruct the energy released by the neutron in the fibers and the absolute time at which the interaction took place. Moreover, the readout chip must be fully autonomous in the acquisition of the events, which are sparse in time and, due to the nature of the fibers, fast and weak. A first prototype of photon detector based on single-photon avalanche diodes has been designed and manufactured in a 150 nm 1P6M CMOS standard technology. The photon detector comprises a 16×8 array of pixels of 125×250 μm² area. Each pixel has photon counting and photon timestamping capabilities, and is fully autonomous in the acquisition process. A novel, integrated triggering mechanism copes with the poor signal-to-noise ratio available at the photon detector by means of a distributed architecture. The chip represents a unique tool for the readout of plastic scintillating fibers and, with respect to similar implementations in the literature, it has the highest level of integration in a relatively small pixel area while maintaining a high sensitivity.
A Distortion-Free Square-Bordered Position Sensitive SiPM for Potential Applications in Ultrahigh Resolving Nuclear Imaging (#1393)

PhD/MD student Yu Peng, PhD/MD student Yu Peng, M.Sc./M.A. student Wenxing Lv, M.Sc./M.A. student Wenxing Lv, M.Sc./M.A. student Lei Dai, M.Sc./M.A. student Lei Dai, Dr. Tianqi Zhao, Dr. Tianqi Zhao, Dr. Kun Liang, Dr. Kun Liang, Dr. Ru Yang, Dr. Ru Yang, Prof. Dejun Han, Prof. Dejun Han

Beijing Normal University, Novel Device Laboratory (NDL), Beijing, China

Content

In the past a few years, NDL (Novel Device Laboratory, Beijing) has been developing a two-dimensional (2D) tetra-lateral position sensitive SiPM, which is benefit to acquire high resolved scintillation imaging with greatly reduced readout channels. However, it suffered small active area (2.77 mm × 2.77 mm), large "dead" space in border area and corner distortion (thus requiring tedious corrections). In order to overcome those drawbacks, a distortion-free 2D square-bordered PS-SiPM with an active area of 6 mm × 6 mm is reported in this conference. Its electrode configuration was innovated to obtain a linear response and eliminating the position distortion caused by the interactions between the electrodes. The device features a geometrical factor of ~91.8%, while the corresponding parameter of the 2D tetra-lateral PS-SiPM was ~89.4 %. The primary results of the device show the position resolutions at (0, 0) is ~81.3 μm and 78.7 μm in X, Y direction separately, when the diameter of light spot is 300 μm and mean photoelectron number (MPEN) is ~1000. Maintaining the merits of the original 2D tetra-lateral PS-SiPM, the new device takes attractive advantages of negligible position distortion, enlarged active area and geometrical factor, which is very appropriate for potential applications in ultrahigh resolving nuclear imaging. Meanwhile, the feasibility study of the square-bordered PS-SiPM applied to an ultrahigh resolving small-animal PET system is also on going.

Feasibility of Quasi-Prompt PET-based Range Verification in Proton Therapy (#2098)

PhD/MD student Ikechi Ozoemelam¹, Dr. Emiel van der Graaf¹, Dr. Marc-Jan Goethem¹, Dr. Maciej Kapusta², Dr. Nan Zhang², Prof. Sytze Kapusta¹, Dr. Peter Dendooven¹

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Content

Compared to photon therapy, proton therapy allows a better conformation of the dose to the tumour volume with minimal exposure of co-irradiated tissues. In vivo verification techniques including Positron Emission Tomography (PET) have been proposed as quality assurance tools for monitoring errors in proton range. Range error detection
on a short timescale provides a fast trigger for corrective strategies in proton therapy. Conventional PET-based verification precludes such immediate feedback. We have recently performed a proof-of-principle demonstration of in-beam PET monitoring using $^{12}\text{N}$ ($T_{1/2} = 11$ ms). We report here on the range measurement accuracy for delivery of single spots by imaging the $^{12}\text{N}$ activity. PMMA and graphite targets were irradiated with a 150 MeV proton pencil beam consisting of a series of pulses of 10 ms beam-on and 90 ms beam-off. Two modules of a modified Siemens Biograph mCT PET scanner ($20 \times 20$ cm$^2$) were used to image the beam-induced PET activity during the beam-off periods. The modifications enable the detector to be switched off during the beam-on periods, thus protecting the detector from damage due to high radiation levels during the beam-on. $^{12}\text{N}$ images were reconstructed using focal plane tomography. Using a 1D projection of the 2D reconstructed $^{12}\text{N}$ image, the activity range was obtained from a fit of the activity profile with a sigmoid function. Relative range shifts for different target configurations were assessed for $10^8$ and $10^9$ protons per pulse. The standard deviation of the beam range, as a measure of the statistical accuracy of range determination, was determined for the first ten pulses of each irradiation. The accuracy averaged over 3 irradiations is 2.7 and 2.2 mm with $10^8$ protons per pulse and 0.8 and 1.1 mm with $10^9$ protons per pulse for PMMA and graphite targets, respectively. Thus, range errors could be determined with millimetre precision within 50 milliseconds into the irradiation.
N-12 | Simulation Methods and Validation

Marie-Anne Descalle (Livermore)
David A. Brown (Upton)

Recent simulation R&D and validation tests
Atomic Data in EXFOR (#1101)

Dr. Boris Pritychenko, Dr. David A. Brown

Brookhaven National Laboratory, National Nuclear Data Center, Upton, USA

Content

The EXchange FORmat (EXFOR) experimental nuclear reaction database provides access to the wealth of low- and intermediate-energy nuclear reaction physics data. This resource is based on numerical data sets and bibliographical information of 22,615 experiments since the beginning of nuclear science. The principles of the computer database organization, its extended contents and recent data developments are described. New plans for the atomic data compilation, storage, and dissemination are presented.

Photoelectric cross sections: validation tests of recent calculation methods (#1783)

Dr. Maria Grazia Pia1, Tullio Basaglia2, Min Cheol Han3, Paolo Saracco1

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Content

Several evolutions have recently occurred, concerning photoionization cross sections, which affect the simulation of the photoelectric effect in Monte Carlo codes: revised atomic binding energies, included in the last version of the Evaluated Atomic Data Library released in ENDF/B, affect the position of absorption edges; a detailed formulation of the theory of the photoeffect has become available in a form that is suitable for precise computations; new parameterizations similar to the empirical Biggs-Lighthill formulation have been released in Geant4. These evolutions motivate additional validation tests, which complement those published in 2016. The new cross section formulations are compared with a large set of experimental data collected from the literature, using rigorous statistical methods. A further stage of categorical data analysis determines the state of the art of photoelectric cross section calculations among the various available options. These results provide guidance to the maintainers and the users of Monte Carlo codes to optimize the accuracy of the simulation of experimental scenarios involving photon interactions.
Ionization Density-Dependent Scintillation Pulse Shape and Proportionality for Single Decay-Component LaBr$_3$:Ce: Modelling with Transport and Rate Equations (#2705)

PhD/MD Jirong Cang, Prof. Ming Zeng, PhD/MD Yanan Li, PhD/MD Xutao Zheng, PhD/MD Yuyue Gan, Prof. Yinong Liu

Tsinghua University, Beijing, China

Content

Pulse shape discrimination (PSD) is usually achieved using the different fast and slow decay components of inorganic scintillators, such as BaF$_2$, CsI:Tl, etc. However, LaBr$_3$:Ce is considered to not possess different components but has been proved to have the capability of discriminating gamma and alpha events using fast digitizers at room temperature. The physical mechanism of such PSD capability of LaBr$_3$:Ce was still unclear. A model of excitation transport and interaction in a particle track is established to explain such small pulse shape differences in LaBr$_3$:Ce result from different excitation densities. This model takes into account processes of hot and thermalized carrier diffusion, electric-field transport, energy transfer, nonlinear quenching, and radiative recombination. In particular, besides the nonlinear quenching of self-trapped excitons (STE), the nonlinear quenching of excited rare earth ions, Ce, is confirmed herein for the first time to contribute observable ionization α/γ pulse shape differences. With one parameter set, the model reproduces multiple observables of LaBr$_3$:Ce scintillation response, including the ionization density-dependent pulse shape differences, the proportionality response of electrons and quenching factor of alpha particles. Moreover, the model also provides insight on the competition processes of excitations in the track, which can also explain the correlation between proportionality (energy resolution) response and Ce concentration and forecast the generality of ionization density-dependent pulse shape differences in other fast inorganic scintillators, such as LYSO and CeBr$_3$. 
molecular beam epitaxy to photocathode deposition allows much improved control over photocathode composition and structure compared to traditional manufacturing methods. We describe the application of density functional theory (DFT) to model photocathode performance and present results from simulations of photocathode materials. DFT modelling was carried out using MEDEA-VASP DFT simulation software, and included preliminary investigations using DFT on different orthorhombic and cubic crystal structure alloys to develop techniques to model changes in stoichiometry and evaluate change to electron affinity; a crucial parameter for high performance photocathodes. VASP simulations are presented and compared to experimental results obtained using specially constructed test cells. The performance of polycrystalline materials with different stoichiometry and layer geometry are evaluated using DFT with experimentally obtained material parameters, and compared with experimental results.

**N-12-05**

**Monte Carlo Modeling of Electron Multiplication in Amorphous Silicon Based Microchannel Plates (#2712)**

Janina Löffler, Jonathan Thomet, Prof. Christophe Ballif, Dr. Nicolas Wyrsch

Ecole Polytechnique Fédérale de Lausanne (EPFL), Photovoltaics and Thin-Film Electronics Laboratory, Institute of Microengineering (IMT), Neuchâtel, Switzerland

**Content**

Amorphous silicon based microchannel plates are being developed to overcome performance limits of conventional microchannel plates. They offer a new flexibility and ease of fabrication. A comprehensive AMCP model is being developed to analyze the behavior of AMCPs. It includes Monte Carlo simulation of secondary electron emission distribution as a function of energy and angles and finite element analysis multiphysics software to compute electron trajectories. The paper presents the results of Monte Carlo simulations of secondary emission functions in silicon and the high secondary emissive material Al₂O₃ and we discuss the gain and potential performance as a function of geometry of such devices. The validity of the Eberhardt’s model for the analysis of AMCPs is also addressed.

**N-12-06**

**GEANT4 simulation of electron energy deposition: recent evolutions in validation tests (#1333)**

Dr. Maria Grazia Pia¹, Tullio Basaglia², Min Cheol Han³, Gabriela Hoff⁴, Elisabetta Ronchieri⁵, Paolo Saracco¹

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**Content**
Accurate simulation of the energy deposited by electrons in matters is an essential requirement of general-purpose Monte Carlo codes, due to its importance in a wide variety of experimental applications in diverse fields, from fundamental physics to instrumentation R&D, dosimetry and other applied physics areas. A set of experimental measurements, specifically performed at the Sandia Laboratory approximately four decades ago as benchmarks for Monte Carlo simulation of electron energy deposition, still represents the most authoritative reference for the validation of the simulation of this observable. Geant4 capability of reproducing the experimental Sandia data was quantitatively documented for previous Geant4 versions: 8.1 and 9.1 to 9.6. Statistical analysis of the simulated and experimental data distributions highlighted differences in compatibility with experiment across the various physics configurations and Geant4 versions used in the simulation, not always fulfilling the expectation of improvement in the evolution of Geant4 version releases. Preliminary investigations concerning Geant4 versions 10.0 to 10.4 hinted to some improvements in the compatibility between simulation and experiment. This presentation will document a thorough validation test of the simulation of electron energy deposition based on Geant4 versions 10.0 to 10.5 by means of rigorous statistical inference methods. The impact of the results on experimental applications will be discussed.
JS-03 | New applications and dosimetry

Roger Lecomte (Sherbrooke)
Emilie Roncali (Davis)
Positron imaging (#1700)

Prof. Pawel Moskal

Jagiellonian University, Institute of Physics, Krakow, Poland

Content
During the positron emission tomography about 40% of positrons annihilations occur through the creation of positronium which may be trapped within and between molecules. Positronium decays in the patient body are sensitive to the nanostructure and metabolism of the tissues. This phenomenon is not used in the present PET diagnostics, yet it is in principle possible to use environment modified properties of positronium as diagnostic biomarkers for cancer therapy. First in-vitro studies show differences of positronium mean lifetime and production probability in the healthy and cancerous tissues, indicating that they may be used as indicators for in-vivo cancer classification. Here we present a method of positronium lifetime imaging in which the lifetime and position of positronium atoms is determined on an event-by-event basis. The method requires application of $\beta^+$ decaying isotope emitting prompt gamma (e.g. $^{44}$Sc). We discuss the possibility of determining the time and position of positronium annihilation from the back-to-back photons originating from the interaction of positronium with the surrounding atoms and bio-active molecules. The prompt gamma is used for the determination of the time of the formation of positronium. We estimate that with the total-body PET scanners the sensitivity of the positronium lifetime imaging, which requires coincident registration of the back-to-back annihilation photons and the prompt gamma is comparable to the presently achievable sensitivities for the metabolic imaging with standard PET scanners. This opens promising perspective for the in-vivo imaging of positronium properties by combining well established positron annihilation lifetime spectroscopy and PET techniques in one tomography system. With this presentation we show first promising results and encourage broader community to the development of in-vivo tumor classification by means of the measurement of annihilation of positronia produced in the body during PET imaging.

γ-Ray hit-location in large monolithic crystals with SiPM readout:
analytical versus neural-network algorithms (#2633)

Ion Ladarescu, PhD/MD student Victor Babiano, Dr. Luis Caballero, M.Sc./M.A. David Calvo, Dr. César Domingo-Pardo, PhD/MD student Pablo Olleros

CSIC-University of Valencia, IFIC, Paterna, Spain

Content
The main objective of this research was to achieve an excellent gamma-ray position reconstruction with very large monolithic scintillation crystals coupled to pixelated silicon photosensors. Analyzing the scintillation-light distribution
measured along the SiPM-pixels one can get a sub-pixel accuracy for the position reconstruction. The quality of the latter depends on both the characteristics of the crystal-photosensor assembly, and the goodness of the algorithm used to reconstruct the gamma-ray hit location. We have carried out a systematic study for 511 keV gamma-rays using three different crystal thicknesses of 10 mm, 20 mm and 30 mm, all of them with planar geometry and a base size of 50x50 mm². To our knowledge, these are the largest monolithic crystals with SiPM readout aimed at gamma-ray imaging reported in the literature thus far. We have optimized state-of-the-art 3D position-reconstruction methods based on the fit of an analytical model for the propagation of the scintillation light distribution, as well as methods based on artificial neural-networks. In all cases the experimental data-set used was a matrix of 35x35 collimated-source positions measured across the transversal xy-plane on a pitch of 1.5 mm. In terms of spatial resolution, a superior performance is obtained with the analytical-fit methods for the 10 mm and 20 mm thick crystals, with results of 1-2 mm FWHM on average across the full field-of-view of nearly 25 cm². On the other hand, NN-algorithms perform better for thick crystals (30mm), with average position resolutions of 3 mm FWHM and significantly better S/N-ratio and FoV than analytical approaches. This research is intended for the development of a total-energy detector with gamma-ray imaging capability, so-called i-TED, which is aimed at the measurement of neutron-capture cross sections using the time-of-flight technique. The results reported here are of interest for medical imaging, homeland security and Compton astronomy.

JS-03-03

Enhanced Fiberoptical Dosimetry through Time-resolved Single Photon Detection in Proton Fields (#1703)

Dr. Thomas Kormoll¹, Dr. Emiel van der Graaf², Dr. Marc-Jan van Goethem², PhD/MD student Maria Gonzalez Torres¹, Dr. Peter Lachmann¹, Prof. Ardzej Majchrowski⁴, PhD/MD student Kristina Makarevich⁵, Dr. David Weinberger³,6, Prof. Kai Zuber¹, Dr. Tobias Teichmann¹

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Content

Fiberoptical dosimetry uses compact solid state radioluminescence probes coupled to long flexible light guides. Such probes are convenient, robust and small. Especially in the presence of magnetic fields, such optical probes can be advantageous over the transmission of a current signal, e.g. from a photodiode directly attached to a scintillator. These characteristics make such probes attractive for emerging medical applications like particle therapy in combination with MRI. Challenging remains the discrimination of so called “stem effect” light which is generated in the fiber from the actual signal light from the probe. In this work, fiber probes attached to a single photon sensor have been exposed to a proton beam from a proton cyclotron in order to study the feasibility of fiber dosimetry in therapeutic proton fields. Probes with different luminophores have been placed in the beam within a PMMA holder of 1 cm in thickness. The light guide was coupled to a Hamamatsu H12386-210 single photon detector. For timing information, the pulse was sampled and analyzed with a Serious Dynamics DAQ125 board. This is a 16 bit sampling ADC board which was running synchronous to the cyclotron. An interpolated time stamp with a resolution of 30 ps was calculated in real time. It could be shown that a time resolved measurement of the single luminescence photons exhibits the
time structure of the luminophore, e.g. the long decay which appears uncorrelated of beryllium oxide or lithium tetraborate or the decay in the ns range of plastic scintillators. Blank fiber measurements exhibit the microbunch width of the accelerator. Thereby, stem identification in therapeutic hadron fields is possible without further reference measurements. Additionally, the issue of quenching of many luminophores in hadron fields can be addressed. A further beamtime at the AGOR cyclotron in Groningen will be conducted in May 2019 and recent results will be presented at the conference.

JS-03-04 4:54 PM

A Novel Image Reconstruction Approach for 3γ Imaging (#2340)

PhD/MD student Debora Giovagnoli¹, PhD/MD Alexandre Bousse¹, PhD/MD Amadeo Iborra Carreres¹, PhD/MD Thibaut Merlin¹, PhD/MD Nicolas Beaupère², PhD/MD Jean-Pierre Cussonneau², PhD/MD student Clotilde Canot², PhD/MD Sara Diglio², PhD/MD Julien Masbou², Eric Morteau², PhD/MD student Yajing Xing², PhD/MD student Yuwei Zhu², PhD/MD Dominique Thers², Dr. Dimitris Visvikis¹

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Content

We propose a novel image reconstruction technique for 3γ imaging systems that aims at reaching similar image quality to conventional PET using 100 times less activity. 3γ imaging involves a (β+, γ) emitter and the proposed reconstruction technique is based on the utilization of the third gamma information to reduce the portion of the coincidence Line Of Response (LOR) during reconstruction. The third emitted gamma is more energetic than the two 511-keV photons and interacts mostly through Compton scattering. From the interactions’ positions and the energy deposited, we define a Compton cone that gives the direction of the third gamma emission. The intersection of the cone and the two coincidence photons’ LOR is the center of the probability distribution used during reconstruction, whose full width at half maximum (FWHM) depends on detector properties and spatial and energy resolution. We show preliminary reconstruction results using highly realistic GATE Monte Carlo of an imaging device currently under commissioning.
First experimental measurement of the effect on dose distribution of cardio-synchronous brain motion during microbeam radiation therapy (#1346)

PhD/MD student Mitchell Duncan\textsuperscript{1}, PhD/MD student Mattia Donzelli\textsuperscript{3,2}, PhD/MD student Paolo Pellicioli\textsuperscript{5,4}, Dr. Elke Brauer-Krisch\textsuperscript{2}, Dr. Jeremy A. Davis\textsuperscript{1}, Prof. Michael L. F. Lerch\textsuperscript{1}, Prof. Marco Petasecca\textsuperscript{1}

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Content

Microbeam radiation therapy (MRT) is an emerging radiotherapy modality ideal for treating inoperable brain tumours. MRT employs quasi-parallel beams of low energy x-rays produced from modern synchrotrons. A tungsten multi-slit collimator spatially fractionates the broad beam into rectangular beams 50μm wide ("peaks") separated by a centre-to-centre distance of 400μm ("valleys"). The peak to valley dose ratio (PVDR) is of critical importance to the efficacy of MRT. The underlying radiobiological advantage of MRT relies on high peak dose for tumour control and low valley dose for healthy tissue sparing. Cardio synchronous brain motion of the order 100-200μm is comparable to microbeam width and spacing. The motion can have a detrimental effect on the PVDR and resulting dose distribution. We present the first experimental measurement of the effect of brain motion on MRT dose distribution. Dosimetry in MRT is difficult due to the high dose rate (15kGy/s) and small field sizes. A real time dosimetry system based on a silicon strip detector (SSD) has been developed with spatial resolution ~10μm. The SSD was placed in a water equivalent phantom and scanned through the microbeam distribution with and without brain motion. Profiles were reconstructed from the SSD and compared with Geant4 simulation and HD-V2 film. SSD and film profiles agreed within 2μm. With brain motion the SSD shows two times increase in profile FWHM profiles and 50% reduction in PVDR, confirmed by Geant4 and film data. Misalignment of microbeams at treatment delivery will result in a reduced PVDR and irradiation of additional healthy tissue within the valley region. This compromises the radiobiological effectiveness of MRT. The SSD was able to reconstruct dose profiles under motion conditions and predict similar effects on FWHM and PVDR as by the simulation. The SSD is a simple to setup, real-time detector which can provide time-resolved high spatial resolution dosimetry of microbeams in MRT.
Fabrication challenges of silicon-based microdosimeter using 3D technology (#1735)

**Dr. Angela Kok**, Dr. Marco Povoli, Dr. Anand Summanwar, Dr. Linh T. Tran, Dr. Marco Petasecca, Prof. Michael L. F. Lerch, Prof. Anatoly B. Rosenfeld

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**Content**

Microdosimetry provides measurements of stochastic lineal energy deposition on a micrometric sensitive volume (SV), comparable to human cell dimensions. Conventional microdosimeter uses a tissue equivalent proportional counter (TEPC) that requires high voltage operation, are bulky and have poor spatial resolution. Silicon-on-insulator (SOI) microdosimeter fabricated using the so-called ‘3D technology’, provides true cell-like SV that is encapsulated by a through substrate electrode. Furthermore, such detectors provide many attractive advantages such as micrometric spatial resolution, compact design, and easy coupling to readout electronics that provide real-time on-line monitoring. SINTEF in collaboration with Centre for Medical Radiation Physics (CMRP), have developed a full 3D SOI microdosimeter, a 5th generation SOI microdosimeter. Characterisation results of the first prototype run at several heavy ion therapy (HIT) centres demonstrated excellent results with derived radiobiological effectiveness (RBE), comparable with TEPC. Foreseen future manufacture of such dosimeters remains a challenge. One of the major difficulties is the integrity of metal connection joining individual sensitive volumes where the metal must trespass the 3D circular electrodes encapsulating the entire SVs. The problem is further exasperated by the additional enhancement in microdosimetry where all bulk silicon surrounding the SVs is removed. This paper presents the first fabrication review of the results and challenges over several prototype runs carried out at SINTEF Minalab. The review and investigation aim to generate a fabrication technology that have a potential to provide a commercially viable manufacture process with a high yield throughput. Challenging processes such as removal of bulk silicon outside of the microscopic SVs and deposition of tissue equivalent material will also be discussed.
N-13 | Readout, Trigger and DAQ I

Alexander Oh (Manchester)
Peter R. Hobson

This session focuses on DAQ and Trigger systems.
The performance of Belle II Data Acquisition System in the First Physics Run  
(#1571)

**Prof. Ryosuke Itoh**¹, Prof. Mikihiko Nakao¹, Dr. Satoru Yamada¹, Prof. Soh Y. Suzuki², Dr. Tomoyuki Konno³, Prof. Zhen‘An Liu⁴, Dr. Jinzhou Zhao⁴, Dr. Nils Braun⁵, Dr. Yinghui Guan⁶, Dr. Oskar Hartbrich⁷, PhD/MD student Klemens Lautenbach⁸, Dr. Chunhua Li⁹, PhD/MD student Seokhee Park¹⁰, PhD/MD student Simon Reiter⁸, Dr. Bjoern Spruck¹¹, Dr. Qidong Zhou¹¹

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Content
The Belle II experiment is a new generation B-factory experiment at KEK in Japan aiming at the search for New Physics in a huge sample of B-meson decays. The commissioning of the SuperKEKB accelerator was started in 2017 (Phase 1), and then a pilot run with outer detectors was performed in 2018 (Phase 2). From March this year, the full operation has been started for the physics data taking (Phase 3). The Belle II data acquisition system(DAQ) is now fully working in the Phase 3 run. The system consists of the unified readout modules (COPPER) with the optical data link to detector front ends, the readout PCs and the network switch complex for the event building, and the modularized high level trigger(HLT) and storage system. The system features the real time feedback of the track information obtained by HLT to the readout system of the pixel detector for the data reduction. The particle tracks reconstructed using the silicon vertex detector (SVD) and the central drift chamber (CDC) signals are extrapolated to the surface of the pixel detector (PXD) by the real time HLT processing, and only the hits in the sensors associated with the tracks are merged with the data from other detectors after the HLT processing (the 2nd level event building). Currently the accelerator study is still on-going to increase the luminosity and the physics data taking is being performed by sharing the time. During the data taking, sometimes the background rate becomes high and the L1 trigger rate reaches 10kHz, which is the 1/3 of the maximum design rate of the DAQ. In this condition, the performance of Belle II DAQ is reported. Also various kinds of troubles being suffered in the run and their fixes are discussed in detail.
A versatile readout and trigger system for the High Energy Particle Detector onboard the satellite CSES-02 (#1906)

Dr. Valentina Scotti\textsuperscript{1,2}, Dr. Giuseppe Osteria\textsuperscript{2}, for the CSES-Limadou Collaboration

\textsuperscript{1} Università degli Studi di Napoli Federico II, Dipartimento di Fisica "E. Pancini", Naples, Italy; \textsuperscript{2} INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy

Content
This paper describes the system performing the readout of the PMT and the trigger for the High Energy Particle Detector (HEPD) onboard the second satellite of the China Seismo Electromagnetic Satellite (CSES) mission. CSES is developed by CNSA (Chinese National Space Administration) and ASI (Italian Space Agency), to study the ionospheric perturbations possibly associated with and explore new approaches for short-term and imminent forecast. It will also help finding a new way for theoretical studies on the mechanism of earthquake preparation processes.

In order to perform a comprehensive study of ionospheric phenomena, the mission has been conceived to take advantage of a multi-instrument payload comprising nine detectors. One of them, the HEPD, has been developed by the Italian “Limadou” Collaboration to detect electrons in the energy range between 3 and 100 MeV, and protons between 30 and 200 MeV, as well as light nuclei in the MeV energy window.

The HEPD is composed by a tracker, a trigger system and a calorimeter surrounded by a veto system. The trigger board, main focus of this paper, performs the readout of all the scintillator detectors (trigger, energy and veto detectors) and issues and manages the trigger signals for the whole apparatus. The trigger system allows switching between several configurations along the orbit to cope with different fluxes encountered. Each trigger configuration corresponds to different field of view of the apparatus. This paper will provide a thorough description of the design criteria and the architecture of the trigger and a summary of the trigger performance studies.
Three different readout chain boards can be distinguished: front-end hybrid hosting the VeloPix and the control and timing interface ASIC (GBTx) located at 5 mm of the beam, the optical conversion and power distribution board placed outside the vacuum tank and the back-end board 300 m away in the surface. The detector readout chain starts with a new radiation hard, high speed ASIC (VeloPix) based on the Timepix family. The highest occupancy ASICs will produce data rates above 900 Mhit/s adding up to 4 tbsps for the whole detector. The VeloPix is placed in a retractable system inside an extremely high radiation and vacuum environment. One of the challenges of the system is the transmission of data at 5.13 gbps out of the detector acceptance with low mass and flexible links. Due to the relevance of these links, a long campaign of simulation and testing has been carried out in the last five years. The main task of the back-end board is to synchronously collect and process data from different front-ends and send them to the high level trigger at 100 Gb/s.

N-13-04

A µTCA back-end firmware for data acquisition and slow control of the CLaRyS Compton camera (#1679)

PhD/MD student Cairo P. C. Caplan¹, Oreste Allegrini², Jean-Pierre Cachemiche¹, Bruno Carlus², PhD/MD student Xiushan Chen², Dr. Denis Dauvergne⁷, Rodolphe Della-Negra², Dr. Mattia Fontana², Dr. Laurent Gallin-Martel⁷, Dr. Joel Hérault⁵, Daniel Lambert⁶, Dr. Guo-Neng Lu³, Dr. Magali Magne⁶, Dr. Hervé Mathez⁵, Dr. Gerard Montarou⁶, Dr. Christian Morel¹, Marta Rodo Bordera¹, Dr. Etienne Testa², Yannick Zoccarato², CLaRyS Collaboration

¹ Aix-Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France; ² Université Claude Bernard Lyon 1, Institut de Physique Nucléaire de Lyon, Villeurbanne, France; ³ École Centrale de Lyon, Institut des Nanotechnologies de Lyon, Écully, France; ⁴ Université Blaise Pascal, Laboratoire de Physique de Clermont-Ferrand, Aubière, France; ⁵ Centre Antoine Lacassagne, Cyclotron biomédical, Nice, France; ⁶ Université Clermont Auvergne, Laboratoire de Physique de Clermont, Aubière, France; ⁷ Université Grenoble Alpes, Laboratoire de Physique Subatomique et de Cosmologie, Grenoble, France

Content

With the aim to build a real-time controlled time-of-flight Compton camera for an improved ion-range dose delivery control on hadrontherapy, as defined by the CLaRyS collaboration project, a programming data acquisition and slow control back-end electronics is necessary. This paper presents the FPGA based firmware architecture, embedded software and associated tools for the back-end electronics of CLaRyS, that is able to provide multiple 3 Gb/s optical links for data acquisition, trigger distribution and slow control over its detectors. Performance of the system based on simulations and analysis of the results acquired during the characterization of a beam hodoscope will be presented. Experiments were performed with the 65 MeV proton beam of the medical cyclotron at the Mediterranean Protontherapy Institute, in Nice.
N-13-05  
5:12 PM

**New Jet Feature Extraction and Topological Processor modules for ATLAS Phase-I trigger upgrade** (#1144)

**Marek Palka**, Masato Aoki, Of behalf of ATLAS Collaboration

Jagiellonian University, Marian Smoluchowski Institute of Physics, Krakow, Poland; KEK, IPNS, Tsukuba, Japan

**Content**

For Run-3 at the Large Hadron Collider (LHC), ATLAS is planning a major detector and trigger upgrade to be installed during the long shutdown 2. As a part of this, the Level-1 trigger, based on calorimeter data, will be upgraded to exploit the fine granularity readout using a new system of Feature EXtractors (FEXs) and a new Topological Processor (L1Topo) that will process the Trigger Objects (TOBs) send by FEXs and L1Muon, selecting interesting physics events by applying topological constraints. To achieve up to ~3 Tb/s input bandwidth and substantial processing power with tight latency budget of < 390 ns, the trigger boards host up to four Ultrascale+ FPGAs. An overview of the architecture, simulation and test results of full-scale prototypes from integrated tests will be presented.

N-13-06  
5:30 PM

**A Time-Of-Flight Gamma Camera Data Acquisition System for Hadrontherapy Monitoring** (#1863)

**PhD/MD student Xiushan Chen**, PhD/MD student Oreste Allegrini, Bruno Carlus, PhD/MD student Cairo Cheble Pimenta Caplan, Dr. Luigi Caponetto, Jean-Pierre Cachemiche, PhD/MD student Sébastien Curtoni, Dr. Denis Dauvergne, Rodolphe Della Negra, Dr. Mattia Fontana, Laurent Gallin-Martel, Dr. Marie-Laure Gallin-Martel, Dr. Joël Herault, Daniel Lambert, Prof. Guo-neng Lu, Magali Magne, Hervé Mathez, Prof. Christian Morel, Dr. Gerard Montarou, Marta Rodo Bordera, Dr. Etienne Testa, Yannick Zoccarato

University of Lyon 1, L’INSTITUT DE PHYSIQUE NUCLÉAIRE DE LYON (IPNL), Villeurbanne cedex, France; Aix-Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France; Grenoble-Alpes University, Laboratory of Subatomic Physics & Cosmology, Grenoble, France; Centre Antoine Lacassagne, Cyclotron Biomédical, Nice, France; Blaise Pascal university, Laboratory of Physics of Clermont, Aubière cedex, France; University of Lyon 1, Institut des Nanotechnologies de Lyon (INL), Villeurbanne cedex, France

**Content**

A collimated gamma camera consisting of a multi-parallel slit collimator and an absorber has been proposed to be coupled with a beam hodoscope for ion-range verification during hadrontherapy by means of Prompt Gamma (PG) detection. The beam hodoscope associated to this gamma camera provides information on the incident ion position and arrival time to improve the PG image reconstruction and time-of-flight measurement. The data acquisition (DAQ) system of this detection system has been designed to meet the specifications: 1 µs trigger delay, timing resolution < 1 ns, 100 kHz trigger rate and a few 10^8 bits/s final data rate. It consists of 8 frond-end (FE) readout boards of two
types: 2 boards for the hodoscope and 6 boards for the absorber. These FE boards have the same basic structure, consisting of a FPGA, an optical transceiver and a multi-channel analog readout module. The main difference between the two types of FE boards is that the former incorporates two 32-channel readout ASICs, and the latter employs 8-channel DRS4 (Domino Ring Sampling) mezzanines (3 for each board). In addition the system also includes a data-communication module, mainly composed of a data transmission control board called AMC40 which has a 1-Gbit/s Ethernet link for PC connection and 36 available 3 Gbit/s optical links to FE readout boards. On the other hand, we have developed the firmware of every FE board FPGA to realize several multi-phase clock time-to-digital (TDC) convertors: one for the system synchronization and the others for particle’s arrival time tagging. For the 2 hodoscope FE boards, FPGA firmware implementation includes an adjustable-depth measured-data buffer, an histogram-based fast time-of-flight estimation, coincidence-event searching and data zero-suppression. Our designed DAQ system has recently been tested successfully with a reduced-size collimated camera configuration coupled with the beam hodoscope in the Mediterranean proton therapy Institute in Nice (France).
N-14 | Physics Data

Elisabetta Ronchieri (Bologna)
Hideki Miyake
N-14-01

ENDF/B-VIII.0 and Beyond (#1124)

David A. Brown, On behalf of the Cross Section Evaluation Working Group (CSEWG)

Brookhaven National Laboratory, National Nuclear Data Center, Upton, USA

Content
On Friday, February 2, 2018, the Cross Section Evaluation Working Group (CSEWG) released its latest version of the ENDF/B library, ENDF/B-VIII.0. ENDF/B is the most widely used library for neutronics and shielding calculations in the United States and ENDF/B-VIII.0 marks roughly 50 years since the first ENDF/B library release. ENDF/B-VIII.0 builds on experimental and theoretical work from across the United States and the international nuclear science community including many new developments since 2011. These improvements include the new Nuclear Data Standards evaluations, and the CIELO project evaluations for neutron reactions on $^{16}$O, $^{56}$Fe, $^{235}$U, $^{238}$U and $^{239}$Pu and a nearly completely new thermal neutron scattering sublibrary. Other notable advances include updated evaluated data for light nuclei, structural materials, actinides, fission energy release, prompt fission neutron and gamma-ray spectra, decay data and charged-particle reaction data. ENDF/B-VIII.0 is the highest quality and best performing ENDF/B library to date as shown by overall performance in simulations of ICSBEP critical assemblies and shielding benchmarks. The library is issued in the traditional ENDF-6 format, as well as in the new Generalized Nuclear Database Structure (GNDS) format. In this contribution, we will review the highlights of ENDF/B-VIII.0 and note many of its remaining shortcomings. We will lay out CSEWG's path forward for the next library release which, among other things, will include new thermal neutron scattering data, Fission Product Yields, decay data, evaluations for Plutonium isotopes and major revisions to structural materials. Much of this work will be coordinated through the INDEN and continuing CIELO collaborative projects.

N-14-02

General overview of ENDF atomic data libraries (#1839)

David A. Brown, On behalf of the Cross Section Evaluation Working Group (CSEWG)

Brookhaven National Laboratory, National Nuclear Data Center, Upton, USA

Content
The ENDF project maintains three atomic data libraries used in numerous applications. These libraries are: two collisional data libraries, for electron and X-ray transport, and a spectroscopic data library for modeling atomic de-excitation following collisions. We will describe these libraries and provide a brief overview of the history of these libraries. This history culminates in ENDF/B-VIII.0, the latest ENDF library release. In ENDF/B-VIII.0, the atomic data libraries received numerous updates. Unfortunately, many of these updates are problematic and the future development of the ENDF atomic libraries is in an uncertain state. We will discuss what is needed to continue the
active development of these libraries from a "holistic perspective": starting from microscopic experiments, then experimental results compilation, evaluation, data validation and finally inclusion in application codes.

N-14-03  4:36 PM

Electromagnetic data libraries: status and perspectives  (#1997)

Dr. Maria Grazia Pia

INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Genova, Genova, Italy

Content
This is a brief review of the current status and open issues of atomic data libraries, and a report on the outcome of the Workshop on Open Physics Data Libraries concerning this area. These compilations of cross sections and atomic parameters are, directly or indirectly (i.e. through parameterizations of their content), the foundation of Monte Carlo particle transport codes and of other software systems concerned with electromagnetic interactions of particles with matter. An overview of existing data compilations will be illustrated and the status of their validation will be recapitulated. Critical issues with potential impact on experimental research are highlighted. A summary of the discussions and perspectives deriving from the workshop will convey relevant information on this theme to the general audience of the conference.

N-14-04  4:54 PM

Monte Carlo radionuclide source modelling from ENSDF data  (#2128)

Dr. Reid W. Townson

National Research Council Canada, Metrology, Ottawa, Canada

Content
A radionuclide source model was recently added to the EGSnrc Monte Carlo toolkit for radiation transport. While Monte Carlo codes have been commonly used throughout the field of medical physics for many years, nuclear medicine and radionuclide metrology are increasingly demanding accurate source models. The EGSnrc radionuclide source depends directly on nuclear data files in the ENSDF format, from any of the open data repositories. On the surface, this is a useful tool for users to quickly insert complex radionuclide source emissions into their simulations. However, processing ENSDF files into a source model consistent on the decay-by-decay level is not trivial, and users should aim to understand the way the data is being used. For example, the sum of the individual decay intensities for a given radionuclide may not add to 100%. In order to achieve consistency, decay intensities are adjusted in the source model based on the associated uncertainties. In general the ENSDF files do not contain the specific sub-shell vacancy for atomic relaxations, nor sufficient information for complete modelling of internal pair production, so the EGSnrc radionuclide source includes some approximations. After processing, the source decay intensities were found to converge with the input ENSDF data.
The Generalized Nuclear Data Structure: a modern format for representing particle reaction data (#2548)

Marie-Anne Descalle, Bret Beck, Caleb Mattoon, Eric Jurgenson, Scott McKinley, Teresa Bailey

Lawrence Livermore National Laboratory, Physical and Life Sciences, Livermore, USA

Content

The Generalized Nuclear Data Structure (GNDS) is a new format for storing nuclear and photo-atomic reaction data. GNDS was developed by an international committee under the auspices of the Nuclear Energy Agency’s WPEC. The motivation for this flexible and modern format was to address the evolving needs of users, and the need to easily share evaluated and processed data across institutions within a single framework. As such, GNDS is meant to replace ENDF-6, the fifty year-old format in use in most evaluated data, while also supporting processed data. Lawrence Livermore National Laboratory (LLNL) has developed a suite of open source codes including a processing code (FUDGE) and two C++ APIs (GIDI and MCIGIDI) to handle GNDS formatted data and enable particle transport simulations. FUDGE (For Updating Data and Generating Evaluations) can read GNDS evaluated data and process them into forms suitable for use in Monte Carlo and deterministic (e.g., multi-grouping) transport codes. The processed data are also stored in a GNDS file which can be read by Monte Carlo and deterministic transport codes using the GIDI (General Interaction Data Interface) C++ API. GIDI has class functions that allow for easy access of multi-group data as needed by deterministic transport codes. MCGIDI (Monte Carlo GIDI) is an API which facilitates the use of GNDS data for use in Monte Carlo transport codes. MCGIDI uses GIDI to read in a GNDS file and then extracts data needed for Monte Carlo transport. MCGIDI has class functions for cross section lookup, and sampling of a reaction and its outgoing particles. GIDI and MCGIDI have been implemented in LLNL’s deterministic (Ardra) and Monte Carlo (Mercury) transport codes. This paper discusses features of the GNDS format, current translation and processing capabilities of the FUDGE code and GIDI/MCIGIDI APIs, and reports validation results for integral benchmark experiments using Ardra and Mercury. Prepared by LLNL under Contract DE-AC52-07NA27344.

Development of a Nuclear Data Processing Code FRENDY Version 1 (#1113)

Dr. Kenichi Tada, Dr. Satoshi Kunieda, Dr. Yasunobu Nagaya

Japan Atomic Energy Agency, Nuclear Science and Engineering Center, Tokai-mura, Japan

Content
Nuclear data processing is an important interface between nuclear data library and neutronics transport codes. Japan Atomic Energy Agency (JAEA) developed a new nuclear data processing code FRENDY (FRom Evaluated Nuclear Data librarY to any application) in order to process the nuclear data library JENDL (Japanese Evaluated Nuclear Data Library). JAEA released FRENDY version 1 in this spring as an open source software under the 2-clause BSD license. The current version of FRENDY can generate ACE (A Compact ENDF) formatted files for continuous energy Monte Carlo calculation codes such as MCNP and PHITS. It uses the same processing method as NJOY because the implementation of the conventional method is an important step to develop the new code. For verification, we compared the processing results of FRENDY with those of NJOY and confirmed FRENDY provided us with almost the same outputs as NJOY.

FRENDY is coded so as to enhance maintainability, modularity, portability and flexibility. FRENDY is written in the object-oriented language C++ to achieve these requirements. The maintainability and modularity are better than conventional codes written in FORTRAN since all classes in FRENDY are encapsulated. Each class is designed to be compact and independent for portability and flexibility. FRENDY is developed not only to process nuclear data libraries but also to implement the FRENDY modules to other calculation codes. Users can easily use many functions e.g., reading, writing, and processing the nuclear data library, in their own codes. FRENDY accepts two types of input formats. One is the NJOY compatible format and the other is the original input format. The original input format requires only a processing mode and the file name of an evaluated nuclear data library at minimum. Therefore, everyone can process the nuclear data library without expert knowledge of the nuclear data processing.

In this presentation, we will explain the overview and a future plan of FRENDY.
8:00 AM – 9:48 AM

Exchange 11

ExPr-01 | Exhibitor Presentation
Imaging and Tracking Detector MiniPIX TPX3 for Spectral imaging, Gamma Camera, Compton camera, Energy Dispersive XRD, Radiation monitoring and many other applications (#2915)

Dr. Jan Jakubek, Daniel Turecek, Dr. Pavel Soukup, Martin Jakubek

ADVACAM s.r.o., Praha, Czech Republic

Content
The MiniPIX\textsubscript{TPX3} is miniaturized and low power radiation camera with particle tracking and imaging detector Timepix3 (256 x 256 square pixels with pitch of 55 \textmu m). The MiniPIX\textsubscript{TPX3} chip is equipped with sensor according to customer preference (standardly 300 \textmu m thick silicon or 1 mm CdTe). The Timepix3 detector is position, energy and time sensitive: For each ionizing particle (e.g. X-ray photon) it digitally registers its position, energy, time of arrival and track shape - basically all information you can want. The other measures can be often calculated from the track shape (particle type, direction of flight, LET, charge ...). The information on each detected particle is either read-out immediately (pixel mode) at maximal rate of 2.3 million hit pixels per second or accumulated in pair of images (frame mode) and read-out later at maximal speed of 16 frames per second.

The typical and intended applications of MiniPIX\textsubscript{TPX3}:

- **Spectral X-ray imaging**: X-ray fluorescence imaging, X-ray radiography (low flux)
• **Energy dispersive XRD, SAXS or WAXS:** Monochromatic X-ray source is NOT needed! Even high energy for thick samples is possible (e.g. 100 keV)!

• **Spectral gamma ray imaging:** scintigraphy or SPECT, radiography with isotopes.

• **Radiation monitor:** particle type sorting, spectroscopy, directional sensitivity …

• **Gamma camera:** special shielded box and collimators available.

• **Compton camera:** special software module available for image reconstruction.

The MiniPIX TPX3 device is controlled via USB2.0 interface with standard µUSB connector. All major operating systems are supported (MS Windows, Mac OS and LINUX). Extra software modules are available for special functions (e.g. coded aperture image reconstruction, Compton camera image and spectrum reconstruction, radiation field decomposition, networking of many devices …).

After the presentation the floor is open for discussion and enquieres.

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**ExPr-01-04**

8:54 AM

3% energy resolution for NaI(Tl) - from dream to reality. (#2865)

**Dr. Alex Gektin**

**Amcrys, Ltd., KHARKIV, Ukraine**

**Content**

Energy resolution value is the critical scintillator parameter for major detector applications. Historically, this was always the reason both for improving conventional scintillators and for the search of new materials. Alkali halide (AH) scintillators (like NaI:Tl, CsI:Tl, CsI:Na) have long been considered as the optimal solution due to cheapest cost of crystals, the ability to grow crystals at large sizes, and a well developed technology. At this point, only the energy resolution value (about 6% resolution for 137Cs source) needs a 3% improvement, which will then correspond to the fundamental limit.

Past studies have shown a non uniformity of NaI:TL scintillator response due to the non uniformity of track. This is an intrinsic (i.e. not depended on crystal performance) problem for each type of crystal. The proper method of the signal processing based on events clusterization is proposed and justified for all types and different quality AH scintillators. It is shown that this approach allows to justify thin structure of the peak, extract the optimal signal and reach value for such detectors as high as 2.6 – 3.4% energy resolution which is approaching the fundamental limit. The method of the data processing is described.

It has to be noted that new approach allows to reach 3% resolution level at any standard quality AH scintillator. At this moment experimental approval has been received for NaI:Ti, CsI:Ti and CsI:Na scintillators.
ExPr-01-05

How physics-infused artificial intelligence drives innovation in modern spectroscopic detection instruments (#2887)

Dr. Marcus J. Neuer, Peter Henke, Christian Henke

InnoRIID, Düsseldorf, Germany

Content

Artificial intelligence is impacting various areas of research. In spectroscopical applications, the results and measurements are heavily influenced by means of algorithms. These help to interpret the results of a measurement by introducing prior knowledge, a different perspective or even fuse information gained from secondary sensors. The talk shows how proven methods of machine learning are deployed for nuclide identification. It also refers to the application of ontologies and formal logic for enhancing results of such algorithms. Examples will include the masking of special nuclear material and the determination of a dose rate value based on an dimensionally reduced autoencoder subset that allows multi-energy dose rate calculation. The talk will introduce latest radiation instrumentation products that include the above algorithmic novelties. It will demonstrate selected test results.

ExPr-01-06

Integrated Circuits and Systems for Radiation Detection and Imaging (#2847)

Dr. Dirk Meier

Integrated Detector Electronics AS (IDEAS), Oslo, Norway

Content

We will present our latest ROIC/ASICs and detector systems: low-noise amplifiers, PMT and SiPM readout for spectroscopy and energy binned counting (SIPHRA and APOCAT ASICs), focal-plane array readout (NIRCA for earth observation and astronomy) and infrared ROICs. We also show latest results from gamma cameras and spectrometers.

IDEAS designs readout integrated circuits (ROIC) and detector systems. We develop new products based on our ROICs and application specific integrated circuits (ASICs). We have designed integrated circuits for scientists and engineers working at ESA, NASA, JAXA, CAS, ISRO, ESS, ESO, CERN, DESY, INFN, GSI, JINR, KEK, etc. We also work on commercial products with partners and companies in radiation detection and imaging technologies, for example, infrared cameras. We are specialized in analog and digital (mixed-signal design) designing in full-custom CMOS with various foundries.
MP-1 | MIC Plenary I

Dimitra G. Darambara (London)
Suleman Surti (Philadelphia)
MP-1-01

Introduction

Dimitra G. Darambara

The Institute of Cancer Research & The Royal Marsden NHS Foundation Trust, London, UK

MP-1-02

Welcome Address from the Conference General Chair

Paul Marsden

King's College London, London, UK

MP-1-03

Welcome and Opening of the 2019 Medical Imaging Conference- a View from the UK

Paul Hardaker

The Institute of Physics, London, UK

Welcome address and Opening of the 2019 Medical Imaging Conference by Prof. Paul Hardaker, the CEO of The Institute of Physics, the professional body and learned society for Physics in the UK and Ireland

MP-1-04

Welcome from the Chair of Medical Imaging Conference

Dimitra G. Darambara

The Institute of Cancer Research & The Royal Marsden NHS Foundation Trust, London, UK
MP-1-05  8:32 AM

Medical Robotics - The Role of Imaging and Intelligent Navigation

Guang-Zhong Yang

Hamlyn Centre for Robotic Surgery, Imperial College London, London, UK

Keynote address by Prof. Guang-Zhong Yang, director and co-founder of the Hamlyn Centre for Robotic Surgery and Deputy Chairman of the Institute of Global Health Innovation, Imperial College London, UK.

MP-1-06  9:32 AM

Bruce H. Hasegawa Young Investigator Medical Imaging Award Ceremony

Paul Marsden

King's College London, London, UK

MP-1-07  9:42 AM

Medical Imaging Technical Achievement Award Ceremony

Paul Marsden

King's College London, London, UK
NPSS Graduate Scholarship Award, Ronald J. Jaszczak Graduate Award and IEEE Glenn F. Knoll Graduate Educational Grant Announcement

John P. Verboncoeur

Michigan State University, USA
N-15 | Neutron Detectors and Gamma Imaging II

Kalliopi Kanaki
Matthew Durbin (State College)

Scintillators and neutron detectors
N-15-01  

A high rate neutron detector based on real time pulse shape discrimination in FPGA (#1304)

Dr. Sion Richards¹, Dr. Garrett J. Sykora², William Helsby³, Matthew D. Wilson¹

¹ STFC-Rutherford Appleton Laboratory, Technology Department, Didcot, UK; ² STFC-Rutherford Appleton Laboratory, ISIS Pulsed Neutron and Muon Source, Didcot, UK; ³ STFC-Daresbury Laboratory, Technology Department, Daresbury, UK

Content

A high rate neutron detector comprising of EJ-270, a ⁶Li loaded pulse shape discriminating plastic scintillator, digitizer and an FPGA with a customized pulse shape discrimination (PSD) algorithm has been demonstrated. The detector has been used to achieve high count rates with PSD performed in real time. The 2-channel system comprises a 14-bit 500 Msps ADC coupled with an FPGA implemented with a specially developed “tail sum” PSD algorithm. The system is able to process the fast pulses from EJ-270 in real time and output neutron, γ-ray and pile-up events to the ISIS pulsed neutron and muon source data acquisition system for time of flight measurements. It is also capable of simultaneously generating discriminated PSD plots and pulse height spectra allowing for γ-ray spectroscopy to be performed without any neutron events being present in the spectrum. The system has been characterized using a ⁶⁰Co source to measure γ-sensitivity, a moderated AmBe source and on the EMMA and PolRef instruments at the ISIS pulsed neutron and muon source. A figure of merit of 1.29 has been achieved and peak count rates in excess of 500 knps have been measured in real time on the EMMA beamline using a single channel detector.

N-15-02  

High-Performance Composite Scintillators for Multi-modal Gamma and Neutron Detection (#2400)

Dr. Stephanie Lam, Dr. John Fiala, Dr. Ivan Khodyuk, Dr. Piotr Becla, Maria Hackett, Frank Ruta, Dr. Shariar Motakef

CapeSym, Inc., Natick, USA

Content

Composite scintillators enable the production of high-performance low-cost gamma and neutron detectors in large sizes that would be otherwise expensive or impossible to produce. For example, CLYC(Ce) is an ideal candidate for dual-mode nuclear radiation detection, but becomes expensive at large diameters (e.g. 3-in. and greater) due to decreased crystal growth yield. However, the cost of embedding small diameter crystals into a large scintillating plastic matrix such as polyvinyltoluene (PVT) is low, and the plastic matrix can even be shaped to improve light collection. This presentation will discuss the design, fabrication, and performance of CLYC(Ce)-PVT composite scintillators. Fabrication of these composites were guided by Geant4 simulations to characterize the generation,
transport, and collection of photons. We have successfully demonstrated several geometries including a puck geometry for handheld detectors, a tall cylinder for backpack detectors, and more recently, a composite tile that can be assembled to form large-area arrays. Our composite units detectors have achieved 4.5% at 662 keV and a PSD FoM of 2.5-3.5.

This work has been supported by the U.S. Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded contract HSHQDN-17-C-00008. This support does not constitute an express or implied endorsement on the part of the Government.

N-15-03 8:36 AM

Neutron detection with fast-timing LGAD (#2412)

Dr. Gabriele D’Amen, Dr. Gabriele Giacomini, Dr. James Kierstead, Dr. Graham Smith, Dr. Alessandro Tricoli

Brookhaven National Laboratory, Physics, Upton, USA

Content

The detection of neutrons with precise timing, in the orders of a few tens of ps, has several scientific applications, for example in the measurement of the fast neutron flux in space. We illustrate the response of two different sensors, based on Low Gain Avalanche Detector (LGAD) technology, to fast neutrons generated by a Deuterium-Tritium source. The sensors were designed and fabricated at the Brookhaven National Laboratory with different geometries, doping profiles and substrate thicknesses. LGAD sensors are expected to provide good timing resolution, thanks to a combination of high signal-to-noise ratio and short rise time. Preliminary results from the two types of LGADs are compared.

N-15-04 8:54 AM

Measurement of the carbon light yield of organic scintillators over a continuous energy range (#2465)

PhD/MD Thibault A. Laplace1, PhD/MD Bethany L. Goldblum1, PhD/MD Juan J. Manfredi1, PhD/MD Joshua A. Brown2, PhD/MD Erik Brubaker2, PhD/MD Joseph S. Carlson2, PhD/MD Patrick L. Feng2, PhD/MD Edith Bourret-Courchesne3, PhD/MD Darren L. Bleuel4, PhD/MD student Christopher Brand1,4, PhD/MD student Adriana Sweet1, On behalf of the Single Volume Scatter Camera Collaboration

1 University of California, Berkeley, Department of Nuclear Engineering, Berkeley, USA; 2 Sandia National Laboratories, Livermore, USA; 3 Lawrence Berkeley National Laboratory, Berkeley, USA; 4 Lawrence Livermore National Laboratory, Livermore, USA

Content
The primary mechanism for light generation by fast neutrons in organic scintillators, n-p elastic scattering, has been extensively studied. Yet measurements of the light yield from neutron interactions with carbon nuclei are scarce. This work uses a model-independent method to measure the carbon light yield of an organic glass scintillator and the EJ-309 organic liquid scintillator over a broad and continuous energy range at the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory. Using neutrons produced by the deuteron breakup reaction and an array of pulse-shape-discriminating scintillators, the carbon light yield was measured using a kinematically over-constrained system. These data provide key input for simulation of the neutron response of detection systems for a wide range of applications.

N-15-05

A New Organic Glass Scintillator: Property Comparisons to Stilbene, EJ276, and BC404 (#2563)

Dr. William K. Warburton¹, Dr. Joseph S. Carlson², Dr. Patrick L. Feng²

¹ XIA, LLC, Fremont, USA; ² Sandia National Laboratories, Livermore, USA

Content

A new fast organic glass scintillator (dubbed SG5), recently developed at Sandia National Laboratories, has been proposed as a lower cost alternative to stilbene for detecting fast neutrons in high gamma-ray fields where excellent pulse-shape analysis is required. In this paper we evaluate this proposition by measuring SG5's scintillation properties and comparing them to three well known materials: stilbene, EJ276, and BC404. The measured properties were single photon light emission curves, coincidence time resolution (CTR), brightness (photons/MeV), and figure of merit (FOM) for neutron/gamma pulse shape analysis (PSA). The light emission curves showed that SG5 has an 0.82 ns 10-90 risetime, close to EJ276's 0.81 ns and 25% faster than BC404 and stilbene at 0.96 and 1.01 ns, respectively. CTR values were found from 75 to 325 keV, with SG5 approaching 200 ps at 325 keV, compared to 250, 325 and 325 ps for BC404, stilbene, and EJ276, respectively. SG5's brightness, at 13,365 ph/MeV was similar to stilbene (13,787), and much better than BC404 (8,215) and EJ276 (4,775). For PSA, we studied neutron and gamma-ray pulse shapes as a function of energy and investigated various PSA algorithms, finding a properly selected tail/peak ratio to be generally best. SG5 PSA FOM values were found to be twice as large as for EJ276 and almost as good as stilbene's – e.g. 3.8, 1.6, and 4.4 at 3 MeVee. Since SG5 can be produced by lower cost casting techniques, this work supports further development efforts.
**Fast neutron spectroscopy with a nitrogen based gaseous detector**

(#2670)

Ioannis Katsioulas1, Ioannis Giomataris2, Patrick Knights1, Konstantinos Nikolopoulos1, Thomas Papaevangelou2, Robert Ward1

1 University of Birmingham, School of Physics and Astronomy, Birmingham, UK; 2 Universite Paris-Saclay, IRFU, CEA, Gif-sur-Yvette, France

**Content**

A simple, efficient, safe to use but also affordable fast neutron spectroscopic system is the Holy Grail in many scientific and industrial communities. 3He based detectors provide a solution that fulfils most of the requirements but its high demand in combination with its scarcity created a worldwide shortage and efforts are focused on finding an alternative solution. A number of detectors are proposed for this task, such as BF3 proportional counters, plastic scintillators, and recoil detectors, all having disadvantages that make their adoption far from ideal. We propose the N2SPHERE system that utilizes a spherical proportional counter filled with nitrogen-based gas mixtures to exploit the $^{14}\text{N}(n,\alpha)^{11}\text{B}$ and $^{14}\text{N}(n,p)^{14}\text{C}$ reactions for the detection of fast neutrons. 3He and N2 have comparable Q-values and absorption cross sections for fast neutron capture, offering similar detection capabilities.
N-16 | Analog and Digital Electronics II

Andrea Castoldi (Milano)
Katherine Shanks (Ithaca)
A Low Power 3D Digital Silicon Photomultiplier Dedicated to Liquid Noble Gas Experiments (#1544)

M.Sc./M.A. student Tommy Rossignol, M.Sc./M.A. Nicolas Roy, M.Sc./M.A. student Gabriel St-Hilaire, M.Sc./M.A. student Keven Deslandes, Clément Soucy, PhD/MD student Samuel Parent, Caroline Paulin, M.Sc./M.A. Nicolas Viscogliosi, Prof. Serge A. Charlebois, Prof. Jean-François Pratte

Université de Sherbrooke, Institut Interdisciplinaire d’Innovation Technologique (3IT), Sherbrooke, Canada

Content

The recent progress in the developments of the silicon photomultipliers (SiPM) gives new opportunities for the liquid noble gas experiments. The next Enriched Xenon Observatory (nEXO) experiment want to use them to observe neutrinoless double beta decay in liquid xenon. Studies on dark matter also use them for pulse shape discrimination in liquid argon. Both cryogenic applications require a low level of radioactivity and low-power devices. Large areas must be covered to collect scintillation light. The power consumption per photodetector and its electronic must then be minimized. Since a single photon avalanche diode (SPAD) is by nature a binary detector, we propose a digital readout ASIC to be 3D assembled with an array of 4096 SPADs. The photosensitive area of the ASIC covers 25 mm². It is designed for particle physics experiments in liquid noble gases as an alternative for analog SiPMs and their readout. Our device has three complementary outputs: an asynchronous flag which indicates a photon detection, a digital sum of the detected photons and an analog current sum proportional to the number of detected photons. This analog current sum is for validation of the digital sum and can be disabled to reduce power consumption. The flag can be time stamped by an external time-to-digital converter (TDC) for pulse shape discrimination with a time resolution better than 500 ps. The digital sum can be readout by an FPGA as a single acquisition on request or using a sampling period down to 10 ns. Preliminary results have shown the correct operation of all functionalities under both room and cryogenic temperature. Power consumption will be measured as a function of the digital input rate. An external TDC will be used to produce the pixel timing distribution within the array and to get the jitter of the flag.
This work presents the characterization results and methods of the first analog silicon photomultiplier (A-SiPM) with integrated time conversion. The system comprises an A-SiPM developed by On-Semiconductor, with excellent photon detection efficiency (PDE) at 420nm (48%) designed for positron-emission tomography (PET), with integrated time-to-digital converter (TDC) and comparator. This work is divided in three different areas: electrical, optical and radiation characterizations. The integrated TDC is electrically characterized in terms of differential nonlinearity (DNL), integral nonlinearity (INL) single-shot accuracy, and power consumption. The system, which is composed of the A-SiPM, TDC and comparator, is optically characterized in terms of single-photon timing resolution (SPTR) and dark count rate (DCR). Coincidence resolving time (CRT) measurements are performed in order to determine the system performance for positron-emission tomography (PET).

A 40mW/channel Image Sensor Line Driver IC with Independently Tunable Gain and Settling Time (#1248)

Aikaterini Papadopoulou, Carl R. Grace, Peter Denes, Armin Karcher

Lawrence Berkeley National Laboratory, Berkeley, USA

Content

A 16-channel analog front-end integrated circuit (IC) for interfacing an image sensor with single-ended analog output to a differential-input digitizer is presented. The IC is designed for image sensors used in single-electron counting direct detection cameras with applications in cryogenic electron microscopy (cryo-EM), but its high flexibility allows usage with a variety of sensors. An operational transconductance amplifier (OTA) and a transimpedance amplifier (TIA) replace the traditional instrumentation amplifier, to allow power reduction and decoupling of the gain and bandwidth stages. This allows for a tunable gain in order to exploit the digitizer full-scale range, and an independent bandwidth tuning capability to accommodate a variety of sensors. Additionally, the front-end supports a very wide input common-mode range, and provides offset correction capability as well as frame marker operation. The chip is fabricated in a commercially available 180nm CMOS technology using dual 3.3V/1.8V supply. It achieves more than ±10% gain tunability at 0-1.2V sensor dark-level range, and up to 140MHz operation. Power consumption is measured at 37mW/channel with 155μV input-referred noise, at nominal conditions. The chip is a low-power, low-noise, highly optimized solution allowing area and power reduction in camera assemblies.
N-16-04  
8:54 AM

**Single-to-Differential Converter in 65 nm CMOS for the analog readout chain in DUNE Liquid Argon TPC.** (#1481)

**PhD/MD student Mieczysław Dabrowski**¹,²,³, PhD/MD Hucheng Chen², Junbin Zhang², Prof. Filip Tavernier³, Prof. Paul Leroux³

¹ Brookhaven National Laboratory, Instrumentation Division, Upton, USA; ² Brookhaven National Laboratory, Physics Department, Upton, USA; ³ KU Leuven, Leuven, Belgium

**Content**

Differential signaling brings substantial benefits to analog front-end (FE) circuits. It increases dynamic range and resolution of a circuit to levels unachievable with a single-ended equivalent. Additionally, it makes FE circuits much less sensitive to noise from the power supply which is especially beneficial given the increased amount of digital circuitry in each new generation of FE ASICs. Moreover, a great majority of high-resolution ADCs are fully differential, therefore, outputs of analog FEAs interfacing such ADCs must be converted to differential in the signal processing chain. Despite these arguments, effective single- to-differential conversion is still in its infancy in the analog front-end community. We present a Single-to-Differential Conversion (SDC) circuit designed to interface an analog front-end ASIC with a high resolution ADC in the analog readout chain of DUNE LAr TPC. The SDC was designed in 65 nm CMOS, a chip comprising 16 SDC channels was fabricated and measurements on it are currently being performed. Preliminary measurements show the circuit operates at both room (300K) and cryogenic (88K) temperatures, demonstrates INL of 0.2%, is capable of driving a switching load of 5 pF ensuring settling to 0.0125% in less than 75 ns and has an input-referred noise of 50 uV rms at 300K, an order of magnitude lower than the analog front-end itself.

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N-16-05  
9:12 AM

**SMX2.1, a 128 Channel, Event-Driven Tracking Chip for Silicon and Gaseous Detectors** (#2161)

**Dr. Krzysztof Kasiński**, Dr. Robert Szczygiel, Dr. Rafal Kleczek, PhD/MD student Weronika Zubrzycka, Dr. Piotr Otfinowski

AGH University of Science and Technology, Dept. Measurement and Electronics, Krakow, Poland

**Content**

This paper presents an SMX2.1, a read-out chip for double-sided, stereo-angle silicon microstrip sensors and gas electron multipliers (GEM). Particles’ momentum and 2D track determination require both charge and time measurements of each incident particle for an experiment with a collision rate of 10 MHz (CBM experiment at FAIR, Darmstadt, Germany). The ASIC was designed to support different sensor/micro-cable geometries and types of sensors (2 – 20 pF capacitance) and provides a wide range of configurability. The 128-channel read-out IC including...
analog front-end with two-path processing chain (charge-sensitive amplifier with pulsed reset, two-path conditioning circuits driving timestamping circuit and continuous-time ADC in each channel) and a digital back-end (novel to High-Energy Experiments triggerless, event-driven, sparsified read-out, timestamp-based sorting, and throttling functionalities) were fabricated in a 180nm CMOS technology in Q4 2018. The power consumption is kept at the level of 10 mW/channel. A separate, ESD-protection ASIC, designed for low-capacitance and low-leakage is used for GEM setup. It includes also set of different diode, MOS and mixed types of ESD protection circuits for experimental purposes. Paper presents design and improvements’ details, and measurement results.

N-16-06 9:30 AM

Cryogenic Readout Electronics Development for HPGe Detectors for Low-background Physics Experiment (#1428)

Dr. Feng Liu¹,², Prof. Zhi Deng¹,², PhD/MD Li He³, Prof. Yinong Liu¹,²

¹ Tsinghua University, Department of Engineering Physics, Beijing, China; ² Key Laboratory of Particle & Radiation Imaging, Ministry of Education, Beijing, China; ³ NUCTECH Company Limited, Beijing, China

Content

The paper presents the development of full-chain cryogenic readout electronics for ton-scale germanium detectors for the next generation dark matter search and neutrino-less double beta decay experiments. Conventionally HPGe detectors are readout by cryogenic preamplifiers and waveform sampling ADCs at room temperature. Full-chain cryogenic readout can save the cables and improve the signal integrity, which turns to be more and more important for background reduction as the detector array scales up. In this paper characteristics and compact modeling of 180 nm bulk CMOS technology at 77 K are developed, and the relative error between the simulation and experiment achieves 5.34 % by adjusting the critical parameters and modeling the carrier freeze-out effect. A prototype of full-chain cryogenic readout electronics is also demonstrated. It consists of an ultra-low noise CMOS charge sensitive preamplifier, shapers with multiple gains, and a 100 MS/s 10 bits SAR ADC. The linearity of the cryogenic readout system was 0.47 %. The energy resolution of 550 eV FWHM have been achieved at 122 keV from ⁵⁷Co radiation source with optimum digital filter. The best resolution for pulser signal was also monitored to be 243 eV FWHM, corresponding to 34 electrons (r.m.s.) ENC noise. Pulse shape techniques were successfully employed to distinguishing the single-site/multi-site events, bulk/surface events. The pedestal noise with CR shaper was measured to be 223 eV (r.m.s.), and the energy threshold for bulk/surface discrimination was estimated to be less than 2 keV.
N-17 | Fast Detectors, Fast Electronics and Applications I

Nicolò Cartiglia (Torino)
Martin van Beuzekom (Amsterdam)
PMT with AlGaN photocathodes and MCP for BaF$_2$ scintillator detectors in particle physics (#1367)

Dr. Nikolay Atanov$^1$, Dr. Yuri Davydov$^1$, Dr. Vladimir Glagolev$^1$, Dr. Sergey Ivanov$^2$, Dr. Valentin Jmerik$^2$, Dr. Dmitry Nechaev$^2$, Dr. Vyacheslav Tereschenko$^1$

$^1$ Joint Institute for Nuclear Research, Dubna, Russia; $^2$ Ioffe Institute, St Petersburg, Russia

Content

BaF$_2$ crystals are considered as a perspective scintillator to create detectors for high-energy physics. An attention of physicist is attracted by its high radiation strength and short decay time (<1ns) of fast emission component in wavelength range 190-250nm. This may allow creating reliable detectors with high time resolution and short dead time. However high level of a slow emission component requires special approaches to decrease. Using solar-blind photodetectors is one of the possible solutions. In this work solar blind photomultipliers with microchannel plates that uses UVC-range AlGaN photocathode is described. The results of comic ray tests that show its efficiency to register fast emission component of BaF$_2$ crystals and suppress slow component are presented.

A simulation model of front-end electronics for high-precision timing measurements with low-gain avalanche detectors (#2384)

Cristian Pena$^{1,2}$, Grzegorz Deptuch$^1$, Si Xie$^2$, Artur Apresyan$^1$, Lautaro Narváez$^2$, Tiehui Liu$^1$, Nicolo Cartiglia$^3$

$^1$ Fermilab, Batavia, USA; $^2$ Caltech, Pasadena, USA; $^3$ INFN Torino, Torino, Italy

Content

In this paper we report simulation results of a study aiming to optimize relevant parameters of a detector that uses low-gain avalanche detectors (LGAD) for high-precision timing measurements. The detector is assumed to be composed of a 50 μm LGAD sensor connected to a front-end electronics which is used to measure the time of arrival of minimum ionizing particles. The simulation includes modeling of signal fluctuations in LGAD, variations of the analog bandwidth and signal-to-noise ratio (SNR) of the front-end electronics, time quantization (time-to-digital converter resolution), and effects of radiation damage on LGAD signals. Two approaches to measure the timestamp are considered: leading edge and constant fraction. Additionally, the time resolution is studied as function of the level of irradiation of the sensor. Simulated LGAD pulses before irradiation, and after neutron fluences of 5×10$^{14}$ n/cm$^2$ and 1×10$^{15}$ n/cm$^2$, are studied. The time resolution for 50 μm LGADs was found to be ~35 ps for front-end electronics bandwidths larger than 350 MHz and SNR larger than 30. The time resolution at a SNR of 30 for fluences of 5×10$^{14}$ n/cm$^2$ and 1×10$^{15}$ n/cm$^2$ were found to be 31ps and 37 ps, respectively. Our results indicate that front-end electronics
with realistic specification for LGAD-based detectors for the ATLAS and CMS experiment upgrades can achieve a system time resolution of 35 -- 45 ps.

**N-17-03**

**A High Dynamic Range ASIC for Time of Flight PET with pixelated and monolithic crystals.** (#1773)

Dr. David Gascón², Dr. Sergio Gómez¹, PhD/MD student David Sanchez², Dr. Joan Mauricio², Dr. Ricardo Graciani², PhD/MD student Rafel Manera², PhD/MD student Anand Sanmukh², Dr. José Manuel Cela³, PhD/MD student Lluis Freixas³, Dr. Jesus Marin³, Jose Javier Navarrete³, Juan Carlos Oller³, Dr. Jose Manuel Perez³, Dr. Pedro Rato³, Oscar Vela³

¹ Institut d’Estudis Espacials de Catalunya (IEEC), Universitat de Barcelona (UB), Institut de Ciències Del Cosmos (ICCUB), Barcelona, Spain; ² Universitat de Barcelona (IEEC-UB), Dept. Física Quàntica i Astrofísica, Institut de Ciències Del Cosmos (ICCUB), Barcelona, Spain; ³ CIEMAT, Madrid, Spain

**Content**

The HRFlexToT is a 16-channel ASIC for SiPM anode readout with common cathode connection. It is designed for Positron Emission Tomography (PET) applications and it features high dynamic range (>8 bits), low input impedance, high speed and low power (~3.5 mW/ch). The ASIC has been manufactured using XFAB 0.18 µm CMOS technology. The main characteristics of the HRFlexToT are a new energy measurement readout providing a linear Time over Threshold (ToT) with an extended dynamic range, lower power consumption and better timing response. Initial measurements show an energy linearity error below 3%. Single Photon Time Resolution (SPTR) measurements performed using a Hamamatsu MPPC S13360-3050CS (3x3 mm², 50 µm cell) shows 30% improvement with respect to the previous version of the ASIC, setting this specification in the order of 141 ps FWHM and reducing 3 times power consumption. Coincidence Time Resolution (CTR) measurements with small cross-section pixelated crystals (LFS crystal, 3x3x20 mm³) coupled to a single SiPM (S13360-3050CS, 3x3 mm² and 50 µm pixel pitch) provides a CTR of 180 ps FWHM. Monolithic measurements performed with a larger cross-section crystal (LFS crystal of 25x25x20 mm³) and an SiPM array (S13361-6050NE-04, 6x6 mm² and 50 µm pixel pitch) shows a CTR of 280 ps FWHM after time-walk and skew calibration. Monolithic measurements were taken using a 2x2x5 mm³ LSO:Ce Ca 0.2% coupled to a S13360-3050CS as a reference detector (90 ps FWHM jitter).
A low-power mixed-signal ASIC for SiPM readout at low temperature

PhD/MD student Ramshan Kugathasan
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1 INFN, Torino, Torino, Italy; 2 Politecnico di Torino, Department of Electronics and Telecommunications, Torino, Italy

Content
A mixed-signal ASIC developed to readout SiPM at low temperature is presented. The chip is designed in a 110 nm CMOS technology. Both single photon counting and ToT operating modes are supported. The ToT modality is useful when many photons pile-up to yield a continuous signal. In single photon counting mode an event rate of up to 5 MHz per channel can be accommodated. The time resolution is 50 ps and the target power consumption is less than 5 mW per channel. The architecture of a first 32-channel prototype is described. Dedicated test structures to qualify critical building blocks at cryogenic temperature have also been deployed and experimental results will be shown at the conference.

Timepix3 Telescope Temporal Resolution Studies

Dr. Kazu Akiba, Kevin Heijhoff, Martin van Beuzekom

Nikhef, amsterdam, Netherlands

Content
A beam telescope based on the Timepix3 ASIC was built in order to perform detailed studies of VELO Upgrade prototypes using charged particle beams. The telescope consists of 8 planes of hybrid pixel detectors with 300 um p-on-n silicon sensors. Tracks measured with the telescope have excellent spatial resolution, reaching under 2 um due to the small (55x55 um2) pitch, per-pixel measurements of the deposited charge, and the orientation of the detector planes in order to maximally profit from charge sharing. In addition to precise spatial measurements, the Timepix3 ASIC operates with a 640 MHz oscillator that allows hit time-stamping in steps of 1.56 ns, giving a potential time-measurement resolution of 450 ps per plane. It is of great interest for future pixel trackers to investigate how precise time measurements can be combined to give optimal track time precision. Detailed studies have been performed to investigate the temporal resolution of individual telescope planes and the track timestamp obtained through the combination of the 8 planes. In order to control systematic effects and provide an independent time measurement, two scintillators mounted on fast PMTs were placed at opposing ends of the telescope. Their signals are treated by constant fraction discriminators to minimise jitter. The combination of this setup and the track timestamps results in a temporal resolution of approximately 200 ps, which has allowed the assessment of new prototypes with more promising technologies for precise timing. The sub-nanosecond precision of the track time allows the study of timing structures within the pixel.
chip, along with measurements of other potential systematic effects. Complementary studies are being performed in the lab with a laser setup and preliminary results will be presented. In this presentation the most recent results on the temporal resolution of the Timepix3 telescope will be presented, together with the timing performance of new sensor prototypes.

N-17-06 9:30 AM

**Machine Learning at the Edge for Ultra High Rate Detectors** (#1075)  
*Dr. Audrey C. Therrien*, Ryan T. Herbst, Omar E. Quijano, Dr. Averell Gatton, Dr. Ryan Coffee

*SLAC National Accelerator Laboratory, LCLS, Menlo Park, USA*

**Content**  
Several large physics experiments face an increasingly large “data firehose” problem. Raw data generation exceeds TB/s rates for several existing and planned experiments, generating untenable data sets in very little time. The data often contain limited information and extracting this relevant information online would reduce the offline storage requirements by several orders of magnitude. Additionally, ultra low latency data analysis can be used to drive a fast feedback control system to adjust the experiment in real time, including decisions on data acquisition conditions, detector parameter adjustments and source operation modifications. However, most data state-of-the-art algorithms use computationally expensive operations and require uploading the data to a CPU or GPU compute node. With appropriate training, machine learning can categorize data samples and extract relevant information from raw data using simple arithmetic operations. Placing these fast inference models on FPGAs near the detector—at the edge—would reduce the data velocity at the source. We propose an implementation of Edge Machine Learning for LCLS-II targeting the CookieBox, a diagnostic detector. Data is streamed to the FPGA where a parallel and pipelined inference model extracts the relevant information in less than 100 μs at at the LCLS-II running rate of 1 MHz.

N-17-07 9:48 AM

**Recent results on 3D trench-geometry silicon sensors on timing performance.** (#2923)  
*Dr. Adriano Lai*, on behalf of the TIMESPOT team

*INFN, Sezione di Cagliari, Monserrato, Italy*

**Content**  
Since their invention by S. Parker et al. [1], 3D silicon sensors were supposed to provide very high radiation resistance and, for related physical reasons, also very good time resolution. The first property was widely demonstrated and exploited [2]. However, no dedicated studies and specific measurements have been done up to now to fully demonstrate their timing capabilities.
The TIMESPOT project has been conceived to realize a mini-tracker demonstrator having the maximum achievable radiation resistance and high space and time resolutions as well. The required performance is below 50 ps at the single pixel level.

Trusting in the great potentiality of 3D sensors in this respect, dedicated design studies were performed to optimize sensor geometry and layout. These studies indicate the trench geometry as the most promising about timing.

The first batch of 3D silicon sensors, containing several test structures based on different geometries of the electrodes, has been delivered in June 2019 and has been recently tested both in laboratory under TCT measurements, and under beam as well, in order to test their response to MIPs. The measurements solidly confirm the idea of excellent performance of these devices, showing a time resolution in the range of 20 ps under TCT tests and of 30 ps under beam. Moreover, the test performed under beam show limitations due to the particular front-end electronics used and suggest a possible system optimization for improved performance.

We would be pleased to present our work about this important result in detector physics.

1] see e.g. S. Parker et al., *Increased Speed: 3D silicon Sensors; Fast Current Amplifiers*, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 58, NO. 2, APRIL 2011, and references therein.

N-18 | Strip and Pixels I

Massimo Caccia (Como)
Hwanbae Park
N-18-01 8:00 AM

Upgrading the Inner Tracking System of ALICE (#1760)

Dr. Matthew Buckland, On behalf of the ALICE collaboration.

University of Liverpool, Physics, Liverpool, UK

Content
This talk will give a brief overview of the motivations for the ALICE ITS upgrade, give details about the layout and details about the sensors in addition to reporting on both the construction and commissioning status and plans.

N-18-02 8:18 AM

Radiation-Tolerant Silicon Sensors and precision timing sensors for HL-LHC Tracking Detectors and Space Applications (#2269)

Dr. Ulrich Parzefall¹, Prof. Ben Kilminster², On behalf of the RD50 Collaboration

¹ Albert-Ludwigs-University of Freiburg, Institute of Physics, Freiburg, Germany; ² Universität Zürich, Physik-Institut, Zürich, Switzerland

Content
Silicon sensors are at the center of virtually all particle physics collider experiments, such as the Large Hadron Collider (LHC) at CERN. It is foreseen to significantly increase the luminosity of the LHC by upgrading towards the High Luminosity (HL-LHC) in order to harvest the maximum physics potential. Especially the Phase-II-Upgrade foreseen for 2023 will mean unprecedented radiation levels, significantly beyond the limits of the silicon trackers currently employed. All-silicon central trackers are being studied in ATLAS, CMS and LHCb, with extremely radiation hard silicon sensors to be employed on the innermost layers. Within the RD50 Collaboration, a large R&D program has been underway for more than a decade across experimental boundaries to develop silicon sensors with sufficient radiation tolerance for HL-LHC trackers. As a result, silicon sensors are now available to withstand hadron fluencies up to a few times $10^{16}$ neutron-equivalent. Key areas of recent RD50 research include new sensor fabrication technologies such as High-Voltage (HV) CMOS, exploiting the wide availability of the CMOS process in industry. A further focus area is the field of Low Gain Avalanche Detectors (LGADs), where a dedicated multiplication layer to create a high field region is built into the sensor. LGADs are characterized by a high signal also after irradiation and a very fast signal, with signal rise times below 50fs, compared to traditional silicon detectors with make them ideal candidates for ATLAS and CMS timing layers in the HL-LHC. We will present the state of the art in a number of silicon detector technologies and at radiation levels corresponding to HL-LHC fluencies and beyond. These sensors also have a wide range of space applications, where exposure to both ionizing and non-ionizing radiation over long periods of time is an important effect.
Radiation hard pixel '3D' sensors for use in ATLAS-ITk at LHC (#2175)

Ole Dorholt¹, PhD/MD student Andreas Heggelund¹, PhD/MD student Simon Huiberts², Dr. Ozhan Koybasi³, Dr. Angola Kok³, M.Sc./M.A. Magne Lauritzen², Dr. Marco Povoli³, Prof. Alexander Read¹, Dr. Ole Rohne¹, Prof. Heidi Sandaker¹, Prof. Bjarne Stugu², PhD/MD student Are Traeet²

¹ University of Oslo, Department of Physics, Oslo, Norway; ² University of Bergen, Department of Physics and Technology, Bergen, Norway; ³ SINTEF Digital, Microsystems and Nanotechnology (MiNaLab), Oslo, Norway

Content

In preparation for operation at the High Luminosity LHC, the tracking system of the ATLAS experiment is replaced with a new inner tracker, the ITk. The innermost layers of this system must be designed to withstand a fluence of more than $10^{16}$ cm$^{-2}$ 1 MeV neutron equivalents. At SINTEF, Norway, silicon pixel sensors have been produced in ‘3D’ design to tolerate such high fluences. Some of these sensors have been mounted with prototype readout electronics designed for operation at the ITk, the RD53A chip. The assembled modules have been shown to operate according to expectation in proton and electron test beams at CERN and DESY. Assemblies have subsequently been irradiated with protons up to a fluence of $5 \times 10^{15}$ protons cm$^{-2}$ as well as with neutrons at a fluence of $10^{16}$ cm$^{-2}$. Subsequent beam tests show that the sensors can operate after such fluences with good efficiency. Results from these tests are presented.

A reconfigurable depleted MAPS sensor for Digital Electromagnetic Calorimetry (#2236)

Steven Worm¹, Phil Allport¹, Seddik Benhammadi², Robert Bosley¹, Jens Dopke², Sam Flynn¹, Laura Gonella¹, Ioannis Kopsalis¹, Konstantinos Nikolopoulos¹, Peter Phillips², Tony Price¹, Iain Sedgwick², Giulio Villani², Matt Warren³, Nigel Watson¹, Fergus Wilson², Alasdair Winter¹, Zhige Zhang²

¹ University of Birmingham, School of Physics and Astronomy, Birmingham, UK; ² STFC Rutherford Appleton Laboratory, Didcot, UK; ³ University College London, Department of Physics and Astronomy, London, UK; ⁴ Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany

Content

Digital Electromagnetic CALorimetry relies on a highly granular detector where the cell size is sufficiently small so that only a single particle in a shower enters each cell within a single readout cycle. The DECAL sensor, a depleted monolithic active pixel sensor (DMAPS), has been proposed as a possible technology for future digital calorimeters. A DECAL sensor prototype has been designed and fabricated in the TowerJazz 180 nm CMOS imaging process, using a high resistivity 18 um epitaxial Si layer. The prototype has a pixel matrix of 64x64 pixels with a pitch of 55x55 um, and is read out using fast logic at 40 MHz. It can be configured to function as either a strip sensor, for particle tracking, or a pad sensor, counting the number of pixels above threshold for digital calorimetry. Preliminary results of
chip characterisation, including digital summing logic, analogue pixel performance and threshold scans under laser illumination are presented.

**N-18-05**

**9:12 AM**

**Development of 3D Trenched-Electrode Pixel Sensors with Improved Timing performance (#2237)**

*Giulio T. Forcolin*1,2, Maurizio Boscardin1,3, Gian-Franco Dalla Betta1,2, Francesco Ficorella1,3, Adriano Lai4, Angelo Loi5,6, Roberto Mendicino1,2, Sabina Ronchin1,3, Stefania Vecchi6

1 TIFPA-INFN, Trento, Italy; 2 University of Trento, Trento, Italy; 3 Fondazione Bruno Kessler (FBK), Trento, Italy; 4 INFN Sezione di Cagliari, Cagliari, Italy; 5 University of Cagliari, Cagliari, Italy; 6 INFN Sezione di Ferrara, Ferrara, Italy

**Content**

A new generation of pixel tracking detectors needs to be developed to overcome the challenging conditions expected at collider experiments over the coming years. The high luminosities and increased pile up will require improved spatial and timing resolution to distinguish between the different particle tracks as well as requiring the devices to have an increased radiation hardness. 3D sensors are a viable technology to meet the radiation hardness requirement, due to their short inter-electrode spacing, and are able to achieve the desired spatial resolution. However, they have not yet been exploited to achieve good timing resolution, also due to the lack of dedicated read-out circuits.

The TIMESPOT project aims to develop a complete integrated system for tracking with high precision in both space and time. 3D sensors with a trench geometry are being developed as part of this project, providing very uniform electric and weighting field distributions and allowing for good timing resolution, while maintaining the usual advantages of a 3D geometry. TCAD simulations have been used to optimize the design of these sensors and to evaluate their performance, reaching a compromise between the capacitance of the sensors and their intrinsic speed. The first batch of these sensors, containing pixel sensors compatible with TIMEPIX read-out chip, as well as a large number of test devices has been designed, and the production has been carried out at FBK. We will report on the early characterisation measurements carried out on these devices.

**N-18-06**

**9:30 AM**

**ePixM: a CMOS monolithic sensor for LCLS II (#1909)**

*Camillo Tamma*, Lorenzo Rota, Pietro Caragiulo, Julie Segal, Maciej Kwiatkowski, Gabriel Blaj, Christopher Kenney, Angelo Dragone, Gunther Haller

*SLAC National Accelerator Laboratory, Menlo Park, USA*
ePixM is a novel CMOS Image Sensor designed to meet requirements for soft X-ray imaging and spectroscopy for the LCLS II upgrade. ASIC is optimized for low noise applications with a resolution of 15 e- rms and signal range of 1000 photons at 500 eV. ePixM is composed of 192 x 384 global shutter active pixel sensors, grouped in four banks for parallel readout. The pixel size is 50 μm x 50 μm and includes a charge sensitive amplifier, a correlated double sampling stage and auto-ranging capability inside the collecting well. Periphery of the chip contains bias and digital sections. Each bank of pixels contains replica biases and digital buffering. ASIC is part of the ePix family, a common platform to build modular scalable detectors for LCLS. Thus, the sensor can be connected to an external bank of Sigma-Delta ADCs used in the ePix family balcony, resulting in a simpler and more robust integrated system by flip chip approach. ePixM architecture functionalities and performances will be presented at the meeting.
R-05 | CZT Materials I

Alan Janos (Washington)
Implementation of Accelerated Crucible Rotation Technique (ACRT) to achieve improved yield and detector performance of CdZnTe (#2599)

PhD/MD student Saketh Kakkireni, Dr. Santosh K. Swain, Dr. Jedidiah J. McCoy, Prof. Kelvin Lynn

Washington State University., Center for Materials Research (CMR), Pullman, USA

Content

Cadmium Zinc Telluride (CdZnTe) crystals are grown from Te-rich solution via ACRT, at fast growth speeds (2mm/hr) comparable to those employed in typical stoichiometric melt growth. The detector performance of the as-grown material is on-par with state of the art gamma ray detectors obtained from Travelling Heater Method (THM). CdZnTe is often grown from highly excess Te melts to realize high-purity material resulting from lower growth temperatures and solvent impurity gettering. Due to melt off-stoichiometry, excess Te is continuously rejected into the melt as the growth progresses. Formation of Te rich boundary layer adjacent to the solid-liquid interface is responsible for the onset of constitutional undercooling and capturing of Te droplets in the matrix leading to the formation of second phase extended defects. Here we show that implementation of ACRT with optimized combinations of rotation profile and melt composition can induce flow patterns in the melt, necessary to achieve reduced defect density while growing at fast rates of 2mm/hr. Ingots with fairly low second phase particle size ~2µm are reproducibly obtained, with corresponding mobility-lifetime products exceeding 5×10-2cm2V. Ingots with uniform electrical properties and defect profile is demonstrated with resolutions of ~1.6%@662keV achieved in as-grown crystals without any electronic corrections. It has also been shown that high-single crystalline yield can be achieved by optimizing the growth parameters and detectors as long as ~30mm are obtained.

Nonexponential response in contactless resistivity measurement – what do we measure? (#1184)

Prof. Jan Franc1, Dr. Jakub Závyorka1, Prof. Roman Grill1, Dr. Václav Dědič1, Dr. Pavel Moravec1, Dr. Utpal Roy2

1 Charles University, Faculty of Mathematics and Physics, Institute of Physics, Prague, Czech Republic; 2 Brookhaven National laboratory, Nonproliferation and National Security, Upton, USA

Content

A standard model for evaluation of contactless resistivity measurement relies on the assumption that the charge pulse response to the applied voltage step is exponential. Then a simple evaluation of the substitute electrical scheme of the system provides specific resistivity of the sample. However, frequently non-exponential charge pulse profile is observed. The nonexponentiality was so far mostly explained by inhomogeneous resistivity of the bulk. We will show in this work that in fact in many cases it is caused by the sample surface. The purpose of this work is to analyze the
processes leading to non-exponential behaviour and to look for models that would enable to evaluate the bulk specific resistivity in these cases, what is the goal of the measurement. We used CdTe, CdZnTe and CdZnSeTe samples in the study. We applied several approaches to investigate the reasons leading to non-exponentiality. We focused on various surface treatments including etching, surface oxidation and its time evolution and surface metallization. We also applied illumination of the surface with above bandgap red light during the contactless resistivity measurement. The measured charge response time pulses were evaluated by a two-exponential fit. We conclude that one of the main sources of non-exponentiality is depletion or enrichment of the sub-surface layer and subsequent charge transport between the surface layers and the bulk. Charge pulse response can be also influenced by side surfaces of the measured samples, that can affect the measurement by shunt currents.

R-05-03 8:42 AM

Evaluation of carrier lifetime in Te secondary phase defects free CdZnTe (#1335)

Prof. Kihyun Kim¹, M.Sc./M.A. student Yonghun Kim¹, PhD/MD student Bunjun Park¹, PhD/MD student Eunhye Kim¹, Dr. Aleksey Bolotnikov², Ralph B. James³

¹ Korea University, School of Health and Environmental Science, Seoul, South Korea; ² Brookhaven National Laboratory, Nonproliferation and National Security, Upton, USA; ³ Savannah River National Laboratory, Aiken, USA

Content

We reported on the detector performance of Te secondary-phase defects free CdZnTe implemented through two-step annealing (i.e., first in Cd and the second in Te). Te secondary defects are known as major charge trapping center in CZT so two-step annealed CZT will show great improvement in carrier lifetime. We applied the time-of-flight (TOF) technique to measure the carrier(electron/hole) lifetime in as-grown and two-step annealed CZT samples. TOF has several advantages over Hecht equation fitting such as independence of the electric field distribution, direct measure of lifetime, and accurate for high mobility-lifetime CZT samples. Some of two-step annealed CZT samples showed unimproved carrier lifetime despite the absence of large-sized Te secondary phase defects. These samples exhibited inordinate number and size of prismatic punching defects in HF-based chemical etching for etch pit density (EPD). In this work, we evaluated the variation of carrier lifetime depending on the two-step annealing condition and compared with that of as-grown CZT.
Implementation and comparison of CdTe sensor configurations in a Timepix based γ-camera (#1568)

Julian Fey, Dr. Simon Procz, Michael Schuetz, Dr. Alex Fauler, Prof. Michael Fiederle

University of Freiburg, Freiburg Materials Research Center, Freiburg, Germany

Content

Photon counting hybrid semiconductor pixel detectors (HPD) offer high granularity, high readout speed and low noise due to the direct ionization of charge carrier in the sensor material. The collected charge is compared with a preset minimal threshold and counted digitally in the according pixel cell. This leads to a characteristically excellent signal-to-noise ratio (SNR) and good energy discrimination in combination with a high dynamic range. Thereby, the Timepix, a hybrid pixel detector (HPD) developed by the Medipix2 collaboration CERN, is an ideal detector for spectroscopic measurements and manufacturing of devices such as γ-cameras. Cadmium telluride (CdTe) offers excellent absorption efficiency in the energy region above 30 keV and therefore for the detection of high energy levels of radiation originating from common radioactive sources. The absorption efficiency can be further improved by increasing the sensor thickness. However, an expansion of the sensor layer thickness simultaneously increases the effect of charge sharing which results in a spreading of charge information over multiple pixels.

This work presents the implementation and testing of a thick 3mm CdTe sensor in a Timepix based γ-camera, the iPIX. Measurements with radioactive sources 60-Cobalt, 137-Cesium, 152-Europium and 241-Americium will be shown to distinguish the performance of a 1mm CdTe sensor to a 3mm CdTe sensor. Additionally, a 0.8 mm CdTe Timepix with an increased pixel pitch, resulting in only minimal charge sharing, is compared to the 3mm CdTe configuration. An approach will be presented which uses the information gained by the charge sharing effect and combines them with the energy of the hit to identify the isotope. Since the cluster analysis algorithm combines the information regarding an event to a single pixel, the best possible spatial resolution is ensured regardless of the shape and size of the event which benefits devices like γ-cameras greatly.
Testing performance of 8x8x32 and 10x10x32 mm$^3$ CdZnTe position-sensitive virtual Frisch-grid detectors for high-energy gamma ray cameras (#1538)

Dr. Aleksey Bolotnikov$^1$, Dr. Jason Mackenzie$^2$, Dr. Eric Chen$^2$, Dr. Francis Kumar$^2$, Dr. Saeid Taherion$^2$, Dr. Gabriella Carini$^1$, Dr. Gianluigi De Geronimo$^3$, Dr. Jack Fried$^1$, Giuseppe Camarda$^1$, Dr. Kihyun Kim$^4$, Dr. Ge Yang$^5$, Dr. Emerson Vernon$^1$, Dr. Ralph B. James$^6$

$^1$ Brookhaven National Laboratory, Upton, USA; $^2$ Redlen Technologies Inc., Victoria, Canada; $^3$ Stony Brook University, Stony Brook, USA; $^4$ Korea University, Seoul, South Korea; $^5$ North Carolina State University, Raleigh, USA; $^6$ Savannah River National Laboratory, Aiken, USA

Content

We report on the results from testing 8x8x32 and 10x10x32 mm$^3$ CdZnTe (CZT) position-sensitive virtual Frisch-grid (VFG) detectors for future high-energy gamma ray cameras. Such detectors were fabricated from recently available large volume CZT crystals developed by Redlen Technologies, Inc. The cross-section areas and thicknesses are much greater than those previously used in conventional VFG detectors. The devices can be used for integrating into novel large-area high-efficiency imaging and spectroscopic instrumentation for gamma-ray astronomy, nonproliferation, portal screening, and nuclear safeguards applications. Modified growth and annealing conditions were employed by Redlen to minimize the dark current and improve the energy resolution in their THM-grown CZT.

In this work, we evaluated the spectroscopic properties of such long CZT crystals and measured the responses from position-sensitive VFG detectors fabricated from the crystals. Both digitized waveforms and an analog ASIC were used to read and process the signals from the detectors. The VFG detector design was found to provide economical fabrication and the flexibility to extend the dimensions of the crystals for producing more efficient detection, while correcting the detector response non-uniformity, thereby offering an approach to overcome one of the principal technological barriers limiting the application of CZT detectors.
ExPr-02 | Exhibitor Presentation
**ExPr-02-01**

**Silicon Drift Detector for Ultra-Fast Count Rate Processing** (#2852)


*Hitachi High-Technologies Science America, Inc., Chatsworth, USA*

**Content**

Hitachi High-Technologies Science America, Inc. (HHS-US) is a manufacturer of Silicon Drift Detectors (SDDs) for various applications. We are very well known in the synchrotron community as the supplier of single and multi-element SDDs. Multi-element SDD systems with good energy resolution at very high count rates and are capable of collecting quality spectra and x-ray images in a short time are recently at work in several synchrotron facilities. We have developed several multi-element SDDs which, when combined with advanced Digital Pulse Processors (DPPs), produce spectroscopic systems for high-flux chemical analysis and high quality x-ray mapping. Some of the multi-element SDD products in use are: a 3-element focal design ("Vortex ME3"), a 4-element SDD ("Vortex ME4"), and a 7-element SDD ("Vortex ME7"). In 2018 we completed the development of a 7-element SDD (the Vortex ME7). Each element of the 7-element SDD has a 50 mm$^2$ effective area for a total area of 350 mm$^2$. The 7 elements are designed to have the best "packing factor" to minimize dead space and to locate the elements as close as possible to the center. The snout diameter of the Vortex ME7 is only 1.5" (38.1 mm).

The ME7 resolution (FWHM - Full Width Half Maximum) performance of a manganese (Mn) sample (5.9 keV) is 270 eV at 5 Mcps and 450 eV at 7 Mcps per channel. This performance was measured with an advanced digital pulse processor (DPP). Resolution at low count rate (at 100 Kcps) is better than 140 eV for all elements combined. Each element of the 7-element SDD array is a 50 mm$^2$ effective area for a total area of 350 mm$^2$. There is no additional cooling, for the entire spectrometer, beyond the built-in TEC (Thermo-Electric Cooler). Application results of the new multi-element SDD products including the ME7 will be presented at the conference.

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**ExPr-02-02**

**Readout solutions for SiPM based detection systems** (#2834)

**Dr. Andrea Abba**, Dr. Francesco Caponio, Dr. Cusimano Alberto

*Nuclear Instruments, lambrugo, Italy*

**Content**
In last two years SiPM detectors performance in terms of noise and sensibility have been improved and become a valid alternative to PMT. Nuclear Instruments developed an innovative detection system based on SiPM coupled with scintillator that can fully replace a PMT detector: it includes bias, preamplifier, shaper, MCA, wireless LORA, ethernet, USB communication and a TDC for event time stamping; all these features in less than the size of a PMT with a power consumption of two watts. The long range communication and the low power make it suitable for environmental monitoring solutions.

One of the most common issue with SiPMs is that they change their gain with the temperature. We develop a compact HV bias module that uses a lookup table to compensate in realtime the bias voltage in order to keep constant the gain. In large area detection system or in device used in surgery there is no space to collocate a temperature sensor close to SiPM. We are developing a new method that uses the SiPM detector itself as a temperature sensor in order to make the temperature measurement exactly inside the device without the needed of external detector.

In order to readout SiPM matrix for imaging purpose, Nuclear Instruments (in collaboration with CAEN and WeeROC) developed two new programmable platforms. The first solution uses, Petiroc and Citiroc ASIC and it designed for scientific experiments with very high density of channels. The second system directly samples the SiPM signal, channel by channel, dumping waveforms from each channel, calculating the spectrum and the image, event by event, in realtime.

Due to the large number of application where these two systems can be used, it was impossible to develop a single firmware that could be simply configure in order to make it suitable for every solution. Nuclear Instruments developed a new software called SciCompiler that, starting from a graphical block diagram, it automatically generates the firmware for the readout system.

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**ExPr-02-03**  
**10:56 AM**

**NDL SiPMs and Its Potential Applications** (**#2820**)

**Prof. Dejun Han, Prof. Dejun Han**, PhD/MD Yu Peng, PhD/MD Yu Peng, Dr. Kun Liang, Dr. Kun Liang, Dr. Ru Yang, Dr. Ru Yang

*Beijing Normal University, Novel Device Laboratory, Beijing, China*

**Content**

In the past ~10 years, NDL (Novel Device Laboratory, Beijing) has developed a novel SiPM technology, i.e., a SiPM with epitaxial quenching resistors (EQR). It has small micro APD cells, large micro cell density, high fill factor, simple fabrication technology and cost-effective. It is benefit to achieve large dynamic range while retaining high photon detection efficiency (PDE). On the other hand, EQR-SiPM features a cap resistive layer (CRL) to connect all the micro APD cells, thus is easy to implement for charge division mechanism and realize a position sensitive (PS) SiPM. In this talk, the author will present the latest development of NDL EQR-SiPMs as well as their unique potential applications in HEP (high energy physics) calorimeters, ultra-high resolving scintillation imaging and so on.
Recent developments in photomultipliers and associated electronics
(#2838)

Dr. Thushari Gomes

ET Enterprises Ltd, Uxbridge, UK

Content
ET Enterprises Ltd is a leading manufacturer of photomultipliers and associated electronic products with over 60 years of experience in photomultipliers and electronics design. We offer a wide choice of high-quality photomultiplier tubes with detection areas of 13mm to 280mm covering spectral ranges of 110nm to 900nm. Our newest range of photomultipliers include high quantum efficiency (QE) photomultipliers with QEs up to 35%. We also have a new compact range of photomultipliers which are ideal for scintillation applications. ET Enterprises specialises in electronics development for photomultipliers. Our high voltage power supply range consist of active transistor based high voltage power supplies and those embracing the direct CW based power supplies that have ultra-low power consumption. Our signal conditioning electronics for fast transient signals, photon counting and analogue applications include amplifiers, amplifier discriminators and counter timers. These devices come in a fully integrated detector module form. This year we are releasing a new MCA (Multi-Channel Analyser) Base and a MCA module, especially designed for spectroscopy applications. The MCA base is specifically designed for gamma ray spectroscopy applications with NaI(Tl) scintillation detectors. It consists of a high voltage power supply and a preamplifier and uses powerful digital signal processing to provide a multichannel analyser with a USB connection. Our MCA module is a portable spectrum analyser which comes with three input channels for studying single photo-electron response of photomultipliers, gamma ray spectroscopy applications with NaI(Tl) scintillation detectors and plastic scintillation detectors. Both analysers come with open source windows application software which allows rapid integration into user’s radiation detection systems.

Readout solutions for SiPM arrays. (#2854)

Ricardo Bugalho¹, Dr. Luis Ferramacho¹, Dr. Carlos Leong¹, Dr. Tahereh Niknejad², José Carlos Da Silva¹, Rui Silva¹, Miguel Silveira¹, Prof. Stefaan Tavernier³,¹, João Varela²,¹

¹ Petsys Electronics S>A, Oeiras, Portugal; ² LIP, Lisbon, Portugal; ³ VUB, Physics, Brussel, Belgium

Content
PETsys electronics S.A. is a spin-off company from CERN concentrating on providing readout solutions for applications reading of a large number of SiPM photo-sensor pixels and where a high data rate and excellent time resolution is required. The readout is based on the TOFPET2 ASIC. This is a low power ASIC with 64 channels optimized for reading SiPMs for Time Of Flight PET applications. Typical application are in medical imaging and in
The performance characteristics of the ASIC will be presented, and overview of the readout solution will be given, together with a brief discussion of the possible applications. Further developments of the ASIC will also be discussed.
MP-2 | MIC Plenary II

Dimitra G. Darambara (London)
Suleman Surti (Philadelphia)
**Introduction**

Dimitra G. Darambara  

The Institute of Cancer Research & The Royal Marsden NHS Foundation Trust, London, UK

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**Bringing Photon-counting-detector CT from the Research Lab into Clinical Practice - Current Experience and Future Directions**

Prof. Cynthia H. McCollough  

Mayo Clinic College of Medicine and Science, Rochester, USA

Keynote address by Prof. Cynthia H. McCollough, founder and director of Mayo Clinic’s CT Clinical Innovation Center and the President of the American Association of Physicists in Medicine (AAPM)

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**Edward J. Hoffman Medical Imaging Scientist Award Ceremony**

Paul Marsden  

King’s College London, London, UK

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**Edward J. Hoffman Medical Imaging Scientist Award Address**
R-06 | Perovskite Detectors

Paul Sellin (Guildford)
Growth of Metal halide perovskite bulk crystals for room temperature nuclear radiation detection

Xin Liu, Fangbao Wang, Qihao Sun, Binbin Zhang, Wanqi Jie, Yadong Xu

Rapid development on X-ray and γ-ray spectrometers and imaging arrays result in tremendous opportunities in the field of nuclear medicine, astronomy, high energy physics, non-destructive inspection, and national security. To achieve a higher spatial and energy resolution, semiconductor detectors have exhibited significant advantages, due to the direct photoelectric conversion. Recently, there are considerable interests in identifying new low-cost, heavy element, chemically robust compound materials for room-temperature radiation detection. Among the various semiconductors, the metal halide perovskites are receiving attention as potential radiation detection materials. Here, we report the progress of detector-grade metal halide perovskite bulk crystals and device fabrication for room temperature nuclear radiation detection. The as-grown CsPbBr3 crystals, obtained from either solution or melt method, exhibit resistivity of 109 Ω·cm and carrier mobility-lifetime product of 2×10−3 cm²V−1. The resulting CsPbBr3 detectors achieved an energy resolution of ~10% for the 241Am @ 5.49 MeV α particles. Simultaneously, the full energy peak of 241Am @ 59.5 keV γ-ray was resolved with good peak discrimination. In terms of the organic-inorganic hybrid perovskites, the resistivity is still on the order of 108 Ω·cm. Therefore, the aluminum zinc oxide (AZO) as the anode was proposed to construct a p-n junction structure AZO/MAPbBr3/Au detector, which realized a high X-ray sensitivity of ~529 μC·Gy/air·cm−2 under 80 kVp X-ray at an electric field of 50 V·cm−1. To further improve the stability, the perovskitoid (0-D) Cs3Bi2I9 bulk crystals (Φ15×60 mm³) with high resistivity over 1010 Ω·cm were obtained by a modified vertical Bridgman method. Although the carrier mobility-lifetime products are limited due to its low dimension structure, detectors of 2 mm thickness show the capability to detect 241Am @ 5.49 MeV α particles, with an energy resolution of ~30% under a bias of 500 V. This work was supported by the National Natural Science Foundations of China (Nos. 51872228 and U1631116). Project was also supported by the National Key Research and Development Program of China (2016YFE0115200) and the Natural Science Basic Research Plan in Shaanxi Province of China (2019ZDLGY04-07).
Time Variant Carrier Properties in CsPbBr₃ Perovskite Radiation Detectors (#1763)

PhD/MD student Matthew Petryk¹, Dr. Yihui He², Dr. Mercouri G. Kanatzidis², Dr. Zhong He¹

¹ University of Michigan, Department of Nuclear Engineering and Radiological Sciences, Ann Arbor, USA; ² Northwestern University, Department of Chemistry, Evanston, USA

Content

New classes of room temperature semiconductor radiation detectors, such as perovskites, exhibit significant mobility-lifetime products of both electron and hole signal carriers. These dual-carrier materials offer the possibility of algorithms leveraging the information from both carriers, but first the temporal stability of the carrier properties must be understood. This work studies the relative mobilities and lifetimes of the electrons and holes in perovskite gamma ray detectors. Digital analyses of the waveforms are carried out, and waveform features are correlated with relative carrier properties. Comparisons with expected results from simulations are made. A shift is observed from a significantly dual-carrier nature in which both electrons and holes contribute to the induced charge, towards a single-carrier nature in which only holes contribute to the signal.

Doping of bismuth ions into lead bromide perovskites for decreasing dark current of X-ray detectors (#1506)

PhD/MD student Haodi Wu¹,², PhD/MD student Weicheng Pan¹,², PhD/MD student Nian Liu¹,², PhD/MD student Xinyuan Du¹,², Prof. Guangda Niu¹,², Prof. Jiang Tang¹,²

¹ Huazhong University of Science and Technology, Wuhan National Laboratory for Optoelectronics, Wuhan, China; ² Huazhong University of Science and Technology, School of Optical and Electronic Information, Wuhan, China

Content

Metal halide perovskite-based X-ray detectors have achieved great performance. However, the large dark current severely restricts the dynamic range of the detector and may also cause overflow error for collector capacitance. Here we employed the trace doping of bismuth ions (Bi³⁺) as n-type dopants into MAPbBr₃ perovskites to reduce the dark current for X-ray detectors. The as-prepared MAPbBr₃ thin film with a doping ratio of Pb²⁺ to Bi³⁺ as 10⁷ exhibits a low dark current density of 3.1×10⁻⁵ mA cm⁻², and the volume sensitivity of the fabricated X-ray detector reached 1.3×10⁶ μC Gy⁻¹ cm⁻³ under an electric field of 0.5 V mm⁻¹.
Improved Radiation Sensing with Methylammonium Lead Bromide Perovskite Semiconductors (#1833)

PhD/MD student Ryan Tan¹², PhD/MD student Bogdan Dryzhakov²³, Andrew Shayotovich¹², Andrew Naylor¹², PhD/MD student Kate Higgins²³, Jessica Charest¹², Dr. Bin Hu²³, Dr. Mahshid Ahmadi²³, Dr. Eric Lukosi¹³

¹ University of Tennessee, Department of Nuclear Engineering, Knoxville, USA; ² University of Tennessee, Joint Institute for Advanced Materials, Knoxville, USA; ³ University of Tennessee, Department of Materials Science Engineering, Knoxville, USA

Content

Methylammonium lead bromide (CH₃NH₃PbBr₃ or MAPB) perovskite semiconductors are a potential low-cost option for moderate energy resolution semiconductor detectors for gamma and neutron sensing. MAPB has recently been demonstrated for its ability to sense alpha particles and neutrons, and pertinent electronic properties have previously been reported. In this presentation, we will report on several techniques of improving detector performance to achieve better spectroscopic performance for gamma sensing. These methods include anion and partial cation substitutions of MAPB to improve carrier transport and limit ionic conductivity. We will also describe several surface treatment and metallization techniques for improved carrier extraction and minimization of device polarization. Further, we will present the application of coplanar readouts for single carrier charge sensing.

Direct X-ray detection by stable and radiation hard mixed lead-halide perovskite films (#2435)

Dr. Andrea Ciavatti¹, Dr. Satyaprasad P. Senanayak², Dr. Laura Basiricò¹, Prof. Henning Sirringhaus², Prof. Beatrice Fraboni¹

¹ University of Bologna, DIFA, Bologna, Italy; ² University of Cambridge, Department of Physics, Cambridge, UK

Content

The demand for large area high-energy radiation detection systems combining high sensitivity and low-cost fabrication, has pushed the research in the last ten years to develop and design both novel materials and device geometries. Despite organic semiconductors have attracted a great attention, their low atomic number strongly limits the high-energy radiation absorption and, blending the organic solution with high Z nanoparticles is necessary to maximize their radiation absorption. Hybrid organic-inorganic perovskites have been recently proposed as alternative materials for X- and γ-photon direct detection, thanks to their high Z atoms, combined with high charge mobility. In this work we report on thin film X-ray detectors made of solution processed Cesium-containing triple cation perovskite, namely Cs0.05(MA0.17FA0.78)Pb(I0.8Br0.2)3 (CsFAMA), where cesium (Cs) has added to mixed organic cations (methylammonium (MA) and formamidinium CH3(NH2)2 (FA)) and mixed halides (I and Br). We demonstrate how
X-ray detectors based on solution processed CsFAMA film possess a high sensitivity, with values up to 80 µC mGy⁻¹ cm⁻³ in short-circuit conditions, and up to 380 µC Gy⁻¹ cm⁻² when operated under small (i.e. 4V) bias conditions: two orders of magnitude higher than previous reported perovskite thin films and comparable to some perovskite single-crystal at 50V operating bias. Moreover, high radiation tolerance and improved stability in air have been obtained.
TTS | From publicly funded research to society through industry: dream or reality?

Aurélie Pezous (Geneva)

The Technology Transfer Workshop aims at discussing with experts from industry, academia and research laboratories how Tech Transfer between research organizations and industry works and at sharing best practices and new ideas on how to improve it. It will consist of a short introduction of each speaker and a panel discussion. In order to better understand the best practices in the process of Technology Transfer, panelists will answer a series of questions on the major challenges faced by industrial players when interacting with academia and vice versa.

Target audience

Scientists, people from industry attending the conference, and people from TT offices

Format

Each participant to the panel will give a short presentation (of 7min maximum) introducing the organization they work for and highlighting their experience with tech transfer. Following this round of introductions, Aurelie will animate the debate.
TTS-01 12:00 PM
TBA
Anthony Butler
Mars BioImaging, Christchurch, New Zealand

TTS-02 12:15 PM
Introduction

TTS-03 12:15 PM
TBA
Jacopo Givoletti
CAEN, Germany

TTS-04 12:15 PM
TBA
Steve Mettler
Mirion Technologies, Inc., USA
TTS-05  12:15 PM

TBA

Prof. Simon R. Cherry

*University of California, Department of Biomedical Engineering and Department of Radiology, Davis, USA*

TTS-06  12:15 PM

TBA

Michael Rissi

*DECTRIS, Baden, Switzerland*

TTS-07  12:18 PM

TBA

Gabriella Carini

*Brookhaven National Laboratory, New York, USA*
This session is focused on advanced scintillating materials.
Exploiting cross-luminescence of BaF$_2$ for fast timing detectors (#1230)

PhD/MD student Rosalinde H. Pots$^{1,2}$, Dr. Stefan Gundacker$^{1,3}$, Dr. Rosana Martinez Turtos$^{1}$, Dr. Paul Lecoq$^{1}$, Dr. Etienne Auffray$^{1}$

$^1$ CERN, Meyrin, Switzerland; $^2$ RWTH Aachen, Fakultät 1, Aachen, Germany; $^3$ University Milano Bicocca, Milano, Italy

Content

Recently the interest for fast timing detectors has increased for applications in high energy physics experiments, time-of-flight positron emission tomography and time tagging of soft and hard X-ray photons. This has pushed investigations of scintillators towards fast scintillation mechanisms that are intrinsically faster than for instance the emission from activators in a scintillator. Cross-luminescence is an example of such an intrinsically fast scintillation mechanism and BaF$_2$ is an interesting candidate.

The challenge of scintillation from cross-luminescence is that the produced light is usually in the deep UV, in the case of BaF$_2$, the fast emission bands are at 195nm and 220nm, making the detection not straightforward.

We have measured the emission characteristics of the scintillation light of BaF$_2$ samples from Proteus and EPIC-crystals, excited by a 40keV pulsed X-ray source and measured with a hybrid PMT (HPM-100-07 Becker&Hickl). We have distinguished a fast component with a decay time of 777ps consisting of 5.4% of the scintillation light, a slow component with a decay time of 552ns consisting of 93.4% of the scintillation light and furthermore we found a very fast mode with a decay time of 200ps and an abundance of about 1.2%.

To measure CTR with deep-UV emission, we used state-of-the-art SiPMs from FBK and HPK, that have been previously developed for dark matter experiments. Coupling 2x2x3mm BaF$_2$ crystals to these devices and exciting them with a Na-22 source, gave CTR values of 115+/−10ps FWHM of the HPK and 68+/−5ps FWHM for the FBK SiPM.

To try to improve this performance, we have selected a number of optical couplings that are transparent for deep-UV light to try to improve the light extraction from the crystal. We will present the results and based on these results we will discuss the limitations of using BaF$_2$ for fast timing detectors.

Advanced High-Performance Large Diameter Cs$_2$HfCl$_6$ (CHC) Scintillator (#1348)

Dr. Rastgo Hawrami$^1$, Dr. Elsa Ariesanti$^1$, Vladimir Buliga$^1$, Dr. Arnold Burger$^1$, Dr. Shariar Motakef$^2$

$^1$ Fisk University, Life and Physical Sciences/Physics, Nashville, USA; $^2$ CapeSym, Inc., Natick, USA

Content
Interest in Cs$_2$HfCl$_6$ (CHC) and its family, belonging to the K$_2$PtCl$_6$ cubic crystal structure, as a new high light yield, non-hygroscopic, intrinsic scintillation material has lately increased. CHC has no self-radioactivity, a moderate density of 3.9 g/cm$^3$, and an effective atomic number of 58. This paper focuses on a recent improved growth of a large diameter single phase Cs$_2$HfCl$_6$ (CHC) as well as improvement to its radiometric and scintillation performance. A transparent crack-free single crystal CHC boule of one inch in diameter is grown using the vertical Bridgman method. Sample retrieved from the boule, sized $\Phi 23\text{mm} \times 30\text{mm}$ after lapping and polishing, is characterized for its optical and scintillation properties. Energy resolution of 3.5% (FWHM) at 662 keV, which is comparable to previously reported results for smaller crystals, has been obtained. Studies on light yield, decay time, non-propotionality, as well as detector characterization will be reported.

**N-20-03 2:16 PM**

**Nonequilibrium carrier dynamics spectroscopy as a powerful tool to optimize timing properties of scintillation materials** (#1699)

**Prof. Gintautas Tamulaitis$^1$, Dr. Saulius Nargelas$^1$, Dr. Mikhail Korzhik$^2$**

$^1$Vilnius University, Institute of Photonics and Nanotechnology, Vilnius, Lithuania; $^2$Research Institute for Nuclear Problems, Minsk, Belarus

**Content**

Future experiments at high-luminosity colliders, (e.g., HL-LHC, FCC) and high-spatial-resolution medical imaging require substantial improvement in the response time of the scintillators used in the radiation detectors for these applications. The desirable time resolution shift towards the ambitious target of 10 ps has to be supported by novel characterization techniques in picosecond domain. Mature photonic techniques are available to be transferred to the study of scintillators. We review our current results obtained by the exploitation of nonlinear optical absorption in pump and probe configuration in subpicosecond domain and the capabilities of this approach for further studies of fast scintillators. In the simplest experimental scheme, the sample studied is excited by a short laser pulse and the pump-induced optical absorption is monitored spectrally and in time by a variably delayed probe laser beam. The technique has advantages of i) a high time resolution in subpicosecond domain, ii) the capability to selectively excite specific optical transitions by varying the pump photon energy, and iii) the simultaneous monitoring of spectrum and decay kinetics, which enables the attribution of the features of the differential optical response to certain processes in the crystal. Modification of the characterization technique to a multiprobe mode enables the determination of specific time characteristics of the processes in scintillators like intracenter recombination time in activator ions. The research using these techniques was exercised on many self-activated and Ce-activated scintillators and is currently focused on two scintillators with fast luminescence response and prospective combination of their other scintillation properties: Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce (GAGG:Ce) and (Lu$_x$-Y$_{1-x}$)$_2$SiO$_5$:Ce (LYSO:Ce). The carrier trapping as an important process for the fast luminescence response and the influence of aliovalent doping on the timing properties are especially addressed.
Band Gap Engineering in Transparent Garnet Scintillator Ceramics

(#1236)

Dr. Herfried Wieczorek¹, Dr. Vasiliy Khanin¹,², Prof. Cees Ronda¹, Jack Boerekamp¹, Sandra Spoor¹,³, Roger Steadman¹, Ivan Venevtsev⁴, Dr. Kirill Chernenko⁴,⁵, Prof. Andries Meijerink², Prof. Piotr Rodnyi⁴

¹ Philips Research, Eindhoven, Netherlands; ² Utrecht University, Utrecht, Netherlands; ³ CoorsTek Netherlands B.V., Uden, Netherlands; ⁴ Peter The Great St. Petersburg Polytechnic University, St. Petersburg, Russia; ⁵ MAX IV Laboratory, Lund, Sweden

Content
This paper reviews the properties of multicomponent garnet ceramics (Y,Gd,Lu)₃(Ga,Al)₅O₁₂:Ce for medical imaging. We show that appropriate compositions allow obtaining fully transparent scintillators both for application in computed tomography and positron emission tomography. All samples were prepared at Philips Research Eindhoven by sintering of high purity base oxides at around 1700°C, subsequent annealing in oxygen atmosphere, grinding and polishing. Samples were characterized under UV, gamma and x-ray irradiation at different temperatures. We measured light output, energy resolution, decay times, afterglow, thermal quenching, and thermally stimulated luminescence (TSL) in the 80–550K temperature range. Specific TSL peaks in different compositions are attributed to Cr, Yb, Ti, Eu, and other impurities proven by intentional co-doping of samples. A lately developed method allows extraction of carrier lifetimes, thermal trap depth and frequency factors from TSL and afterglow curves. Detailed analysis reveals the presence of a distribution of trap depths instead of discrete traps, allowing a more accurate modeling of afterglow. Activation energies of thermal ionization determined from photoluminescence lifetime measurements and trap depths obtained from TSL curves show the influence of Lu/Gd and Ga/Al substitution on thermal quenching and on trap position. Results confirm a theoretically predicted non-monotonous dependence of the conduction band edge with Ga content in (Lu,Gd) garnets. Shallow traps are not related to impurities but considered intrinsic. They determine both short term afterglow and secondary decay times. Band gap engineering allows optimizing garnets for use in CT and in time-of-flight PET. The impact of signal height, rise and decay times, and shallow trapping on coincidence resolving times and further on PET image quality is described by analytical models.
One of the major requirements for a scintillator is high detection efficiency, which depends on density of the material and atomic numbers (Z) of its constituents. Therefore the use of high density materials with high Z elements is preferred when possible. In particular photo-fraction benefits from high Z. In the last few years, significant effort has been placed on development of TI-based compounds. The atomic number of TI is 81, which is at the top of the scale amongst the stable isotopes (typically, unstable isotopes are not welcome due to creation of intrinsic background). TI ions are isovalent with alkali ions, very common in scintillators. Therefore a number of compounds have been evaluated where Cs ions were replaced with TI to create a new, more efficient scintillator.

In this presentation, we will summarize current research on the TI-based scintillators, with the focus on work performed at RMD. In the course of our recent research, we have grown and evaluated compositions of multiple crystal families that include TI-elpasolites (e.g. Tl₂LiYCl₆), binary systems such TlSr₂X₅ or Tl₂LaX₅, where X=Cl, Br, or I. For all these materials there are corresponding Cs-based compositions that can be used as a reference. Comparison of these systems leads us to believe that TI substitution not only improves the stopping power of a scintillator but also its light yield and ultimately energy resolution. This work has been supported in part by the US Department of Energy, under a competitively awarded contract DE-SC0015793. This support does not constitute an express or implied endorsement on the part of the Government.

**N-20-06**

3:10 PM

**Boron/CsI:TI Scintillator for High Resolution Neutron Imaging** (#2434)

Stuart R. Miller, Matthew Marshall, Megan Wart, Vivek Nagarkar

*Radiation Monitoring Devices, Inc, Watertown, USA*

**Content**

CsI:TI is a well-known scintillator that is known for its excellent properties in imaging applications due to its relatively high light yield of 54,000 photons/MeV, and highly columnar form that provides enhanced spatial resolution by collimating the scintillation light to the detector. Here we have developed a high-resolution scintillator for neutron imaging by combining enriched $^{10}$B with the well-known CsI:TI scintillator films. To make the scintillator sensitive to neutrons, $^{10}$B (96% enriched) was deposited by e-beam deposition directly to the CsI:TI film. The $^{10}$B thickness was approximately 3 microns deposited on a 15 micron CsI:TI film. Further studies to optimize performance are underway varying the thickness of both layers. The films were tested by integration into the high-resolution “neutron microscope” imaging system at the POLDI beamline at the Paul Scherer Institute (PSI). With our $^{10}$B/CsI:TI scintillator we were able to observe a spatial resolution down to 9 microns. Here we present results with thermal neutron imaging as well as high-resolution neutron computed tomography.
N-21 | Radiation Hardness of Detectors and Systems II

Gian-Franco Dalla Betta (Trento)
Cinzia DaVia (Manchester)
Beam Test Measurements on Planar Pixel Sensors for the CMS Phase 2 Upgrade (#2275)

M.Sc./M.A. Finn Feindt, On behalf of the CMS Tracker Group

University of Hamburg, Institute of Experimental Physics, Hamburg, Germany

Content
The requirements for the CMS pixel detector for the high luminosity upgrade off the LHC experiment are driven by the high expected instantaneous luminosity of up to $7.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. The detectors will have to withstand 1 MeV neutron equivalent fluence of up to $\varphi_{eq} = 2 \times 10^{16}$ cm$^{-2}$ at 2.8 cm distance from the beam axis. To limit pixel occupancies in this environment the current pixel size of 100×150 μm$^2$ will be reduced by a factor of 6. Planar pixel sensors are the baseline technology for the pixel layers 2 to 4, where the irradiation level will reach a 1 MeV neutron equivalent fluence of $\varphi_{eq} = 5 \times 10^{15}$ cm$^{-2}$, as the limit of their radiation hardness is still under investigation. Several variants of new n+p, planar pixel sensors with pixel sizes of 50×50 μm$^2$ and 100×25 μm$^2$ and an active thickness of 150 μm have been designed and bump bonded to ROC4SENS readout chips. Apart from the pixel size, the design variants differ with respect to the implantation and metalization geometry as well as the pixel isolation and biasing scheme. To select the most promising design for the future CMS pixel detector, more than 20 weeks of beam test with a campaign of measurements on more than 50 sensors, non-irradiated and proton or neutron irradiated up to 1 MeV neutron equivalent fluences of $\varphi_{eq} = 1.6 \times 10^{16}$ cm$^{-2}$, have been completed at the DESY II test beam facility. Key observables of the presented study are hit efficiency, signal to noise ratio and spatial resolution. In the beam test measurements tracking is performed with the DATURA beam telescope. The key observables are reconstructed and compared for scans of the bias voltage, different neutron equivalent fluences, proton and neutron irradiation and for different design variants.

Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector (#1500)

Dr. Alex Z. Wang, On behalf of the ATLAS Collaboration

University of Wisconsin Madison, Wisconsin, USA

Content
Silicon pixel detectors are at the core of the current and planned upgrade of the ATLAS detector at the Large Hadron Collider (LHC). As the closest detector component to the interaction point, these detectors will be subjected to a significant amount of radiation over their lifetime: prior to the High-Luminosity LHC (HL-LHC), the innermost layers will receive a fluence of $1.5 \times 10^{15}$ 1 MeV neq=cm$^2$ and the HL-LHC detector upgrades must cope with an order of magnitude higher fluence integrated over their lifetimes. Simulating radiation damage is critical in order to make
accurate predictions for current future detector performance that will enable searches for new particles and forces as well as precision measurements of Standard Model particles such as the recently discovered Higgs boson. A model of pixel digitization is presented that includes radiation damage effects to the ATLAS pixel sensors for the first time. In addition to a thorough description of the setup, predictions are presented for basic pixel cluster properties alongside early studies with LHC Run 2 proton-proton collision data.

N-21-03

Comparison of TCAD simulations of irradiated pixel sensors with beam-test measurements (#2404)

Prof. Erika Garutti\textsuperscript{1}, Dr. Joern Schwandt\textsuperscript{1}, Georg Steinbrueck\textsuperscript{1}, Aliakbar Ebrahimi\textsuperscript{1}, Finn Feindt\textsuperscript{1}, Robert Klanner\textsuperscript{1}, Caroline Niemeyer\textsuperscript{1}, Daniel Pitzl\textsuperscript{2}

\textsuperscript{1} University of Hamburg, Hamburg, Germany; \textsuperscript{2} DESY, Hamburg, Germany

Content

A TCAD model that can reliably predict the effects of radiation damage by hadrons in segmented silicon sensors up to $eq = 2:3 \times 10^{16} \text{cm}^{-2}$, which is expected at the High-Luminosity LHC for an integrated luminosity of 3000 fb\textsuperscript{-1}, is a long-standing problem. Recently, the Hamburg Penta-Trap Model (HPTM) with five effective traps has been introduced, providing a good and consistent description of I-V, C-V and CCEIR (Charge-Collection-Efficiency with infrared light) of pad diodes irradiated with 24 GeV/c protons in the fluence range of $3 \times 10^{14}$ to $1:3 \times 10^{16} \text{neq/cm}^2$. However, I-V, C-V and CCEIR data have only limited sensitivity to the depth dependence of charge trapping, which is essential to predict the response of radiation-damaged segmented sensors, because of highly nonuniform weighting fields. Therefore edge-on beam data have been taken for n+-p sensors with 100 m 25 m pixels and 150 m thickness, irradiated to 2 and 41015 neq/cm\textsuperscript{2} and read out by the ROC4SENS chip. For edge-on, the 5.6 GeV DESY electron test beam traversed the sensor parallel to the sensor surfaces along the 100 m pixels and the charge collected from three pixels closest to the beam track as a function of depth in the sensor has been derived. To compare these data to TCAD simulations and to use them effectively in 2 fits as additional constrains the calculation of the collected charge from the simulations have been treated as a purely geometrical problem. The results of the fits and the effective trap parameters determined will be presented. Finally, the trap parameters are used to predict the dependence of the performance of the pixel sensor on fluence for track angles to the normal of the sensor plane between 0 and 30 and the predictions compared to the test beam results.

N-21-04

The weighting field of irradiated Si-sensors (#2112)

Robert Klanner\textsuperscript{1}, Joern Schwandt\textsuperscript{2}

\textsuperscript{1} Hamburg University, Physics, Hamburg, Germany; \textsuperscript{2} Hamburg University, Physics, Hamburg, Germany
Content

1-D TCAD simulations and analytical calculations of the weighting field, $E_w$, of n$^+$p pad sensors irradiated by neutron equivalent fluences $\Phi_{eq}$ = 0 to $10^{15}$ cm$^{-2}$ are performed. It is found that the time dependence of $E_w$ is related to the resistivity, $\rho$, of silicon in the low-field regions of the sensor. With irradiation $\rho$ at -20°C, the temperature of the study, increases from a few $10^3$ to $2\times10^7$ $\Omega \cdot$ cm. As a result, the time constant of $E_w$ changes from several nsec to tens of $\mu$sec. Above $\Phi_{eq}$$\sim$$7.5\times10^{12}$ cm$^{-2}$ $E_w$ is constant, and it is concluded that for highly irradiated sensors the time-independent $E_w$ of fully depleted, non-irradiated sensors can be used to calculate the signal in irradiated sensors. To the authors’ knowledge, this is the first study of weighting fields in irradiated silicon sensors using a realistic radiation damage model.

N-21-05 2:52 PM

In-situ Annealing and Temperature Monitoring for the Recovery of Silicon Photomultiplier after Radiation Damage (#1226)

PhD/MD student Yu Peng¹, PhD/MD student Yu Peng¹, M.Sc./M.A. student Hongmin Liu¹, M.Sc./M.A. student Hongmin Liu¹, Dr. Thomas Tsang², Dr. Thomas Tsang², M.Sc./M.A. student Jinyan Long¹, M.Sc./M.A. student Jinyan Long¹, M.Sc./M.A. student Wenxing Lv¹, M.Sc./M.A. student Wenxing Lv¹, Dr. Kun Liang¹, Dr. Kun Liang¹, Dr. Ru Yang¹, Dr. Ru Yang¹, Prof. Dejun Han¹, Prof. Dejun Han¹

¹ Beijing Normal University, Novel Device Laboratory (NDL), Beijing, China; ² Brookhaven National Laboratory, Instrumentation Division, New York, USA

Content

Radiation hardness of SiPM is a major concern of some specific experiments in high energy physics and space science. One solution to the recovery of radiated damage of SiPM is annealing. However, it is practically hard for current anneal technique to dismantle the well-installed detectors from a large experiment facility and implement the annealing process with a hot plate or an oven. In this conference, we present an in-situ annealing and temperature monitoring method for the recovery of SiPM after radiation damage. By applying a reverse current, the SiPM can be heated and annealed by a Joule effect; while the annealing temperature can be monitored by employing the PN junction of the same SiPM as a temperature sensor. According to our experiments, after annealing with a constant reverse current of 100 mA applied for 25 seconds, reaching the monitored peak temperature at ~187 °C and 205 °C separately, the dark current of $10^{10}$ neq/cm$^2$ and $10^{11}$ neq/cm$^2$ radiated SiPMs dropped by ~1.5 orders. The photon-number resolving capabilities were also recovered. This method may be extended to other semiconductor detectors based on PN junction, and prolong the lifetime of the detectors in a large experiment.
Neutron-Induced Radiation Damage in Fast Crystals (#2513)

Dr. Chen Hu¹, Prof. Fan Yang², Dr. Liyuan Zhang¹, Dr. Ren-Yuan Zhu¹, Dr. John Kapustinsky³, Dr. Michael Mocko³, Dr. Ron Nelson³, Dr. Zhehui Wang³

¹ California Institute of Technology, 256-48, HEP, Pasadena, USA; ² Nankai University, Physics, Tianjin, China; ³ Los Alamos National Lab, Physics, Los Alamos, USA

Content
Inorganic scintillators are widely used in high-energy physics (HEP) experiments. With $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity and 3,000 fb$^{-1}$ integrated luminosity, the HL-LHC will present a severe radiation environment. Bright and fast cerium doped lutetium yttrium oxyorthosilicate ($\text{Lu}_{2(1-x)}\text{Y}_{2x}\text{SiO}_{5}:\text{Ce}$ or LYSO) crystals are proposed for a CMS precision timing detector at the HL-LHC, where up to 2.5 Mrad ionization dose, $1.7 \times 10^{13}$ charged hadrons/cm$^2$ and $2 \times 10^{14}$ neutrons/cm$^2$ are expected. With an ultrafast scintillation of less than 0.6 ns decay time and a suppressed slow component yttrium doped BaF$_2$ crystals (BaF$_2$:Y) promise an ultrafast calorimeter for the Mu2e-II experiment at Fermilab. We report results on neutron-induced radiation damage in LYSO, BaF$_2$ and BaF$_2$:Y, irradiated at the East Port of LANSCE by fast neutrons up to $3.6 \times 10^{15}$ n/cm$^2$. 
N-22 | Astrophysics and Space Instrumentation II

Francesco S. Cafagna (Bari)
Georgia A. de Nolfo (Greenbelt)
Mini-EUSO: a high resolution detector for the study of terrestrial and cosmic UV emission from the International Space Station (#1912)

Dr. Valentina Scotti\textsuperscript{2,1}, for the JEM-EUSO Collaboration

\textsuperscript{1} Università degli Studi di Napoli Federico II, Dipartimento di Fisica "E. Pancini", Naples, Italy; \textsuperscript{2} INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy

Content

This paper describes the MINI-EUSO experiment, a space mission approved and selected by the Italian (ASI) and Russian (Roscosmos) space agencies and is included in the long-term program of space experiments on the Russian segment of the ISS under the name "UV-Atmosphere". The detector is designed to perform observations of nighttime Earth in the UV spectrum. MINI-EUSO will study different scientific phenomena ranging from strange quark matter and Ultra High Energy Cosmic Rays (UHECRs) to bioluminescence and atmospheric physics. It will also create the first night-time map of the Earth in UV range (300-400 nm) with a spatial resolution of 6.11 km and a temporal resolution of 2.5 μs. The mission will contribute to raise the technology readiness level (TRL) of the future JEM-EUSO (Joint Experiment Mission – Extreme Universe Space Observatory) collaboration missions to observe UHECRs from space. The main telescope has a large field of view (44°), with two 25cm diameter Fresnel lenses (focal length 30 cm) for increased light collection. The measurements will be performed from the ISS through the UV transparent window in the Russian Zvezda Service Module. Launch is foreseen in the second half of 2019 in the framework of the next manned ASI flight with observations planned to continue with Russian cosmonauts for several years.

A compact muon detector for asteroid muography (#2147)

Dr. Alessandra Menicucci, Dr. Daphne Stam, Robert D. Drapeau Hodge

Delft University of technology, Space Engineering Department/Aerospace Engineering Faculty, Delft, Netherlands

Content

In this paper we present the design of a hodoscopic muon detector which can be flown on-board of a small satellite mission to a Near Earth Object in order to characterize its interior. Muography (or muon radiography) is an established technique which is based on the measurement of the absorption of muons, elementary particles of the lepton family, which are produced by the interaction of cosmic rays with any planetary body. The interest for asteroids, or more formally, Small Solar System Bodies, has increased significantly in the last years. Not only the study of near Earth asteroids is key for understanding the origin of our solar system and the origin of life, but also a new economical opportunity is emerging which plans to exploit these objects in the future for mining. Due to their small size and the
large distances from Earth, ground based observations yield limited data, mostly confined to surface characteristics. Also the currently planned space missions targetting asteroids or other SSSBs, are mainly focused upon collecting data from the surface. Information about the interior can be obtained with penetrative techniques like seismology and core drilling which however would require specific equipment and direct landing on the asteroid. Muography can provide an alternative method to investigate deeper structures. We present the design of the Mu-ASTIR (Muon Asteroid Interior) instrument, a muon detector based on 3 sensitive planes, consisting of two semi-conductor based PSD arrays per sensitive plane sandwiching a dual-layer "grid" of borosilicate glass paddles designed to take advantage of the Cherenkov effect caused by transiting, high energy, charged particles. The instrument has been fully simulated with Geant4 and different design options compared. After the application of a preliminary anticoincidence algorithm, the muon identification efficiency for particles passing through the entire detector, is estimated to be at least 72%.

N-22-03 2:16 PM

Optimum configuration of particle detectors for the future LISA and LISA-like space interferometers (#2493)

Dr. Valerio Ferroni

University of Trento, Trento, Italy

Content

In this paper we discuss the optimum characteristics of two-units particle detectors (PD) to be placed aboard LISA and LISA-like interferometers for gravitational wave detection in space. These PDs are aimed to carry out multi-point measurements of the incident flux of nucleons of cosmic and solar origin above 70 MeV n\(^{-1}\) and of solar electrons in the MeV range for test-mass charging monitoring on the ecliptic at million kilometers from Earth. The solar electron detection capability will allow for SEP event forecasting at least 20 minutes before protons will reach the spacecraft constellations of the space interferometers due to particle velocity dispersion. The proposed multipoint SEP event monitoring will provide precious clues on particle flux energy and spatial evolutions and space weather science and investigations.

In the case the LISA mission duration will overlap the ESA LAGRANGE space weather mission, LISA may also contribute to generate alerts for geomagnetic activity. A comparison of the space interferometer PD performance with the ESA New Generation Radiation Monitors (NGRM) will be presented.
First in-flight performances of the High Energy Particle Detector on board CSES (#2014)

Dr. Cinzia De Donato, Dr. Matteo Martucci, Dr. Alessandro Sotgiu, On behalf of CSES-Limadou Collaboration

INFN, sezione Roma Tor Vergata, ROMA, Italy

Content

The China Seismo-Electromagnetic Satellite (CSES) is a scientific mission devoted to the study of electromagnetic, plasma and particle perturbations of atmosphere, ionosphere, magnetosphere and Van Allen belts, with special focus on potential correlation between transient phenomena and high magnitude earthquakes. To this aim CSES comprises nine payloads, including the High-Energy Particle Detector (HEPD), developed by the Italian CSES-Limadou collaboration. HEPD is devoted to the observations of high energy Cosmic Rays in the range 3-200 MeV, measuring both the incident direction and the energy of the incoming particle, discriminating its nature (electrons, protons). The satellite, launched on February 2, 2018 from the Jiuquan Satellite Launch Center (Inner Mongolia, China), underwent the commissioning phase (February-July 2018) during which several configurations were set in order to define the optimal operational conditions throughout the foreseen 5-year mission duration. This paper describes the HEPD instrument, its energy calibration and first in-flight performances, with special emphasis on the calorimeter and trigger subsystems, demonstrating its sensitivity to different particle populations.

Strontium Iodide Radiation Instrument (SIRI) – Early On-Orbit Results (#2768)

Dr. Lee Mitchell\textsuperscript{1}, Dr. Bernard Phlips\textsuperscript{1}, Theodore Finne\textsuperscript{1}, Neil Johnson\textsuperscript{2}

\textsuperscript{1} Naval Research Laboratory, Space Science Division, Washington, USA; \textsuperscript{2} Praxis Inc., Arlington, USA

Content

The Strontium Iodide Radiation Instrument (SIRI) is a single detector, gamma-ray spectrometer designed to space-qualify the new scintillation detector material europium-doped strontium iodide (SrI\textsubscript{2}:Eu) and new silicon photomultiplier (SiPM) technology. SIRI covers the energy range from 0.04 to 8 MeV and was launched into sun-synchronous orbit on Dec 3, 2018 onboard STPSat-5 with a oneyear mission to investigate the detector's on-orbit response to background radiation. The detector has an active volume of 11.6 cm\textsuperscript{3} and an efficiency of 50% at 662 keV along its long axis. Its spectroscopic resolution of 4\% was measured by the full-width-half-max of the characteristic Cs-137 gamma-ray line at 662 keV. Measured background rates external to the trapped particle regions were around 40-50 counts per second for energies greater than 40 keV and is largely the result of short- and long-term activation products generated by transits of the South Atlantic Anomaly (SAA) and the continual cosmic-ray
bombardment. Rate maps determined from energy cuts of the collected spectral data show the expected contributions from the various trapped particle regions and are in agreement with AE9 and AP9 predictions. Early spectra acquired by the instrument show the presence of at least 10 characteristic gamma-ray lines and a beta continuum generated by activation products within the detector and surrounding materials. As of April 2019, the instrument has acquired over 1000 hours of data and is expected to continue operations until the space vehicle is decommissioned in Dec 2019. Results indicate SrI₂:Eu presents a feasible alternative to traditional sodium and cesium iodide based scintillators, especially for missions where only a factor of two in energy resolution will allow the instrument to meet the science objectives. To our best knowledge, SIRI is the first in-orbit gamma-ray spectrometer actively using SiPM readout technology as well as the scintillator material SrI₂:Eu.

The Hyper-Kamiokande Detector (#1798)

Dr. Yousuke Kataoka, this contribution is submitted on behalf of the Hyper-Kamiokande Collaboration

Tokyo University, physics, Tokyo, Japan

Content

Hyper-Kamiokande (Hyper-K) is a proposed next generation underground large water Cherenkov detector with 260 kton of water and 40% photo coverage. With about 10 times larger fiducial volume than Super-Kamiokande, HK will offer a broad science program such as neutrino oscillation studies, proton decay searches, and neutrino astrophysics with unprecedented sensitivities. This presentation describes the detector performance and give an overview and physics potential of HK.
R-07 | Pixel Detectors II

Dominic Greiffenberg (Villigen)
The Challenge of Counting X-rays and Electrons (#2809)

Dr. Michael Rissi, Dr. Christian Disch, Dr. Sonia Fernandez-Perez, Dr. Valeria Radicci, Dr. Peter Trueb, Dr. Pietro Zambon, Dr. Clemens Schulze-Briese, Dr. Christian Broennimann

DECTRIS Ltd, Taefernweg 1, Baden, Switzerland

Content

In the last 15 years, Hybrid Pixel Counting (HPC) detectors have disrupted the field of X-ray diffraction at synchrotron beamlines. The advantages of HPD detectors are obvious: an excellent point spread function, a large dynamic range, high frame rates, a high signal to noise ratio, or a high X-ray flux capability. The development of next generation synchrotron beamlines with higher intensities and higher X-ray energies have led to the need to develop detectors with high detection efficiencies above energies of 25 keV. Luckily, the hybridization process of HPC detectors allows using sensor materials with higher stopping power than Si, namely GaAs, CdTe or CZT. Due to their higher atomic number, High Z materials have K-shell electrons with binding energies in the X-ray energy range between 10 keV (GaAs) and 32 keV (CdTe). Emission of characteristic fluorescence X-rays lead to complex energy spectra. The standard calibration algorithm we used to calibrate our Silicon detectors had to be adapted and improved. Using this calibration, we characterized the spectral response for different pixel sizes.

A further effect differing High-Z material from Silicon is the so-called polarization, where trapping mechanisms inside the bulk or at the contacts of the sensor lead to a reduced collection of charges at high X-ray fluxes. The polarization effect is observed as a reduction of the average signal, leading to a reduction of the count rate. We evaluated the effect of polarization with High-Z material sensors attached to PILATUS and IBEX ASICs. The use of High-Z sensors opens the HPC technology to X-ray energies up to 60 keV or 160 keV by using GaAs or CdTe/CZT sensors, respectively. Furthermore, the use of multiple thresholds allows to distinguish spectral features of the X-ray field at the detector, and thus to distinguish between different material screened by the X-rays, rendering the technology very useful for medical applications.
Development and Characterization of the First High Energetic X-Ray Imaging Telescope (HREXI) CdZnTe (CZT) Detector Modules

Dr. Branden Allen\(^1\), Daniel Violette\(^1\), Jaesub Hong\(^1\), Jonathan Grindlay\(^1\), Scott Barthelmy\(^2\), Phillip Goodwin\(^2\), Marco Rivero\(^1\), Fiona Harrison\(^3\)

\(^1\) Harvard College Observatory, Cambridge, USA; \(^2\) Goddard Space Flight Center, Greenbelt, USA; \(^3\) California Institute of Technology, Pasadena, USA

Content

A new pixelated CdZnTe (CZT) detector system utilizing the NuSTAR ASIC and 3 mm thick Redlen CZT crystals has been developed for use in wide-field coded aperture telescopes for application in high-energy astrophysics with imaging capability over the 3 -- 200 keV energy band. The new readout system includes a detector crystal array (DCA) composed of a front end board capable of supporting a 2 x 2 array of 20 mm x 20 mm detectors with a 32 x 32 pixel pattern on a 604.8 um pitch with a guard ring on the perimeter of the detector. The detector crystal array outer dimensions closely match the form-factor of the detectors in order to enable close tiling for efficient integration of large area (1024 cm\(^2\) or greater) detector planes and maximization of sensitive area. The individual DCAs mount to an optical bench to enable precise alignment and thermal control while under vacuum and interface electrically with a FPGA mezzanine board (FMB) mounted on the opposite surface of the optical bench. The FMB contains a single FPGA which controls and reads out the individual DCA detectors individually. The detector system architecture and the evolution from previously developed tiled CZT array architectures (ProtoEXIST1 and ProtoEXIST2) as well as potential future applications are described in detail. Additionally spatial and spectral characterization and performance of the new detector system is discussed in detail and compared to earlier generations of tiled CZT detector arrays (ProtoEXIST1 and ProtoEXIST2) which utilized 5 mm thick, 20 cm x 20 cm CZT Redlen detectors produced at various points over the past decade. Spatial scanning has been carried out using a custom built X-ray scanning facility at energies up to 70 keV enabling the mapping of spatial and spectral response of CZT detectors at sub-pixel spatial resolutions of 100 um.
We introduced in 2017 NuVISION, a multi-mode coded-aperture/Compton portable gamma-ray imager based on CZT detectors using sub-pixel resolved 3D positioning. Sub-pixel positioning enables precise event localization and helps to improve imaging by restricting backprojection. Each of 256 physical pixels segmented at 2.5-mm pitch is subdivided into 64 subpixels or hundreds of subvoxels. However, this technique relies on detailed signal analysis and can be challenging in practice: signals induced on non-collecting electrodes are weak and keeping low readout noise is essential to locate events with enough precision. We first present this system and describe its architecture. Then, we compare simulations to response obtained with a highly collimated 60-keV synchrotron beam scanning the detector in 2D at 125-micrometer step. Results concretely illustrate detector non-uniformity but also show that experiment and theory are consistent. We also present transient signals generated by gamma-rays for a better insight of what happens in the detector and evaluating physical limits of positioning. Spectrometric and imaging results obtained in laboratory with gamma-ray irradiation are shown to demonstrate in practice 3D positioning. As charge induction is not uniform, spectrometric correction is helpful to cope with depth and charge shared issues but also with spatial non-uniformity. Finally, we show NuVISION imager in application on some concrete examples. Advanced capabilities like scanning and dynamic imaging are presented.

R-07-04

Study of a Medipix3RX CdTe Detector Performance for Low Dose Mammography Imaging (#2380)

Prof. Carlos Ávila¹, M.Sc./M.A. Gerardo Roque¹, Maria Pérez¹, PhD/MD Simon Procz², Prof. Michael Fiederle², Prof. Luis Mendoza³,¹

¹ Universidad de los Andes, Department of Physics / Faculty of Sciences, Bogotá D.C., Colombia; ² Universität Freiburg, Freiburg Materials Research Center (FMF), Freiburg, Germany; ³ Universidad Militar Nueva Granada, Department of Physics, Bogotá D.C., Colombia

Content

As a precursor for development of breast cancer, early detection of microcalcifications in breast tissue is of high importance for the medical diagnosis. Any improvement in image quality or radiation dose reduction could have a significant impact in the field of mammography imaging. The present study focuses on comparing the imaging performance between a standard commercial X-ray mammography setup with a Selenium (Se) sensor, and a Medipix3RX (MPX3RX) electronics readout ASIC, bump-bonded to a 1mm thick Cadmium Telluride (CdTe) crystal as sensible material. The CdTe MPX3RX detector has the potential to improve X-ray imaging, due to a combination of two characteristics. The first one is the novel scheme of the readout electronics for X-ray detection, which allows thermal noise rejection during imaging and individual counting of events. The second is the increased X-ray photon detection efficiency of CdTe, as compared to other semiconductor materials, such as Silicon (Si) or Selenium (Se), mainly due to the different atomic numbers of the materials. We assess the detector performance by measuring Contrast-to-Noise Ratio (CNR) in images of a commercial X-ray accreditation phantom, taken by both, a commercial mammography setup based on a Se sensor, and a custom-made X-ray CdTe MPX3RX system, built to replicate the commercial setup for a direct comparison. We have found that the CdTe MPX3RX setup has a better performance (higher CNR values) than the commercial mammographic system, for detection of microcalcification structures with...
sizes ranging between 240 μm and 540 μm, which means the CdTe MPX3RX system achieves the same CNR of the Se setup at lower radiation doses.

**R-07-05**

**Photon counting X-ray imager by direct charge conversion with TlBr, CdTe semiconductors** (#1862)

*Prof. Toru Aoki*¹², PhD/MD Katsuyuki Takagi²¹, PhD/MD Akifumi Koike²¹, PhD/MD student Toshiyuki Takagi¹, PhD/MD Keitaro Hitomi³

¹ Shizuoka University, Research Institute of Electronics, Hamamatsu, Japan; ² ANSeeN Inc., 303 iPerc, Hamamatsu, Japan; ³ Tohoku University, Graduate School of Engineering, Sendai, Japan

**Content**

A direct charge conversion LSI(ROIC) for photon counting X-ray imager has been fabricated by TSMC 0.18um CMOS process. This LSI is designed to prove a behavior of the direct charge conversion architecture based on charge injection [1] for photon counting with energy information. The LSI has charge-to-digital convertors (QDC) used to read out a charge generated by an X-ray detector such as CdTe and digitize energy information of the source X-ray photon. The QDC realizes 15 energy windows within 200 keV and the LSI provides two 12-bit memories to output two images with differential energy information simultaneously. The LSI has 1600 QDCs and its pixel pitch is 80um. Analogue behaviors of the QDC, characteristics of energy discrimination and a capability to take X-ray/gamma-ray images have been tested. TlBr of 0.8mm-thick or CdTe of 0.75mm wafer was used for hybrid (TlBr or CdTe / SiROIC)-detector, and it was pixelized as 80um pitch pixel. In the case of TlBr, Tl based electrode was deposited on TlBr surface as common electrode and Ag electrodes were used as pixelized electrode. Schottky contact device was used in CdTe case. The ASIC has 32 x 32 pixels with 80um pitch, 16 thresholds, upto 250kcps of count rate by fully digital processing. This ASIC treat generated charge by detector directly, it can be applied both case of TlBr and CdTe semiconductor detector. We detected X-ray / gamma-ray signals as small images. We demonstrate X-ray / gamma-ray images taken by this device and discuss with energy discrimination property and so on.
ExPr-03 | Exhibitor Presentation
Recent Developments of MPPC at Hamamatsu (Part 1) (#2845)

Koei Yamamoto

Hamamatsu Photonics K.K., Solid State Division, Hamamatsu City, Japan

Content
More than 10 years have passed since Hamamatsu started developing the MPPC, which is a part of the SiPM family. The most important feature is its photon counting capability due to its high gain and low noise, but the MPPC has many additional features such as compact size, low operation voltage, robustness, high detection efficiency, and immunity to magnetic fields. Over the years, various types of MPPC technology and devices have been developed for specific applications such as academic research, medical, precise measurement, and industrial. Our most successful developments include the MPPC coupled with a scintillator for HEP and for TOF-PET for cancer detection. Recent developments resulted in covering different wavelength regions such as VUV, VIS, and NIR, to make the MPPC suitable for a wider field of applications. Recently, the demand for NIR-enhanced MPPCs has become very popular in distance measurement applications in the automotive industry. In addition to developing the detectors, Hamamatsu has also developed ASIC, power supplies, and modules using these components to make it easy for customers to design their systems. In this presentation, we will discuss new devices that we call “Hybrid MPPC SPAD.” In these new devices, the 1D or 2D MPPCs are connected, to especially design photon-counting ASICs through wire bonding or bump bonding. We also recently developed the 2D InGaAs MPPC with ASIC, which is an infrared-sensitive SPAD. Some of our modules will be introduced in this presentation.

Recent Developments of MPPC at Hamamatsu (Part 2) (#2846)

Koei Yamamoto

Hamamatsu Photonics K.K, Solid State Division, Hamamatsu City, Japan

Content
More than 10 years have passed since Hamamatsu started developing the MPPC, which is a part of the SiPM family. The most important feature is its photon counting capability due to its high gain and low noise, but the MPPC has many additional features such as compact size, low operation voltage, robustness, high detection efficiency, and immunity to magnetic fields. Over the years, various types of MPPC technology and devices have been developed for specific applications such as academic research, medical, precise measurement, and industrial. Our most successful developments include the MPPC coupled with a scintillator for HEP and for TOF-PET for cancer detection. Recent developments resulted in covering different wavelength regions such as VUV, VIS, and NIR, to make the MPPC suitable for a wider field of applications. Recently, the demand for NIR-enhanced MPPCs has become very popular in distance measurement applications in the automotive industry. In addition to developing the detectors,
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ExPr-03-03

Recent Developments of MPPC at Hamamatsu (Part 3) (#2921)

Koei Yamamoto

Hamamatsu Photonics K.K., Solid State Division, Hamamatsu City, Japan

Content

More than 10 years have passed since Hamamatsu started developing the MPPC, which is a part of the SiPM family. The most important feature is its photon counting capability due to its high gain and low noise, but the MPPC has many additional features such as compact size, low operation voltage, robustness, high detection efficiency, and immunity to magnetic fields. Over the years, various types of MPPC technology and devices have been developed for specific applications such as academic research, medical, precise measurement, and industrial. Our most successful developments include the MPPC coupled with a scintillator for HEP and for TOF-PET for cancer detection. Recent developments resulted in covering different wavelength regions such as VUV, VIS, and NIR, to make the MPPC suitable for a wider field of applications. Recently, the demand for NIR-enhanced MPPCs has become very popular in distance measurement applications in the automotive industry. In addition to developing the detectors, Hamamatsu has also developed ASIC, power supplies, and modules using these components to make it easy for customers to design their systems. In this presentation, we will discuss new devices that we call “Hybrid MPPC SPAD.” In these new devices, the 1D or 2D MPPCs are connected, to especially design photon-counting ASICs through wire bonding or bump bonding. We also recently developed the 2D InGaAs MPPC with ASIC, which is an infrared-sensitive SPAD. Some of our modules will be introduced in this presentation.

ExPr-03-04

SciCompiler: Open-FPGA Configurable DAQ systems (#2863)

Dr. Andrea Abba, Dr. Francesco Caponio, Dr. Alberto Cusimano

Nuclear Instruments, Lambrugo, Italy

Content

The increasing use of programmable logic devices in trigger and data acquisition systems shows the need to have general purpose platforms and technicians dedicated to the firmware development. The advantage of employing programmable logic devices with respect to standard logic modules (like NIM logic modules) is remarkable: a single
programmable logic device includes the potentiality of hundreds of thousands of standard logic modules. For the technicians, who usually work with standard logic modules, the use of specific languages like VHDL or Verilog for the firmware development could represent a limitation in the spread of these powerful devices. In this presentation, we show an innovative method to simplify the firmware development. The method is based on a graphical programming interface consisting of ip-cores developed ad-hoc for nuclear physics applications. As an example, any trigger logic could be implemented by connecting specific blocks in the graphical interface, as easily as physically connecting NIM modules in a rack. The SCI-COMPILER (Scientific Compiler) software allows to develop both purely digital applications, exploiting blocks like scaler, counter, pattern matching, logic analyzer and state machine, and analog processing applications, such as custom multichannel analyzer using charge integration, trapezoidal filter, spectrum and oscilloscope blocks. In addition, the SCI-COMPILER software provides the functionality to read and test the ASICs, enabling the user to develop a sequencer for the ASIC control, to acquire data using digital or analog signals and the I2C or SPI programming. The SCI-COMPILER software focuses the attention only on the functional blocks of the application to be implemented and does not require a deep knowledge of the device in use, enabling the employment of programmable logic devices also to users who are not experts in firmware development.

ExPr-03-05

Developments in Dual Gamma and Neutron Radiation Detection Solutions (#2883)

Diane Fruehaut¹, Guillaume Gautier²

¹ Saint-Gobain Crystals, Applications & Technology, Hiram, USA; ² Saint-Gobain Cristaux, Applications & Technology, Nemours, France

Content

Saint-Gobain Crystals is a leader in radiation detection solutions with superior resolution, gamma-neutron detection, and advanced photo-sensor integration. New scintillators have been developed that can detect both gamma-rays and neutrons. These crystals can replace Sodium Iodide and high pressured Helium 3 tubes that have been industry reference for the past several years. Dual-detecting crystals such as NAI-L and CLLB will enable lighter, efficient, cost-effective and when needed, more powerful detectors – significant attributes for critical applications such as homeland security. The performance of these next-generation scintillation materials will be presented together with a brief discussion of the possible applications.
ExPr-04 | Exhibitor Presentation
ExPr-04-01 4:00 PM

SiPM and SPADs: An update from the SensL Division at ON Semiconductor (#2922)

Dr. Carl Jackson

ON Semiconductor Limited, Sensl Division, Cork, Ireland

Content
SensL Technologies was acquired by ON Semiconductor in May of 2018. The SensL division of ON Semiconductor continues to be focused on creating SiPM and SPAD sensors with market-leading performance and quality for medical and radiation detection applications. With the resources of ON Semiconductor, the SensL team now has access to new capabilities and a world-class sales and distribution system. In this talk, we’ll give an overview of the company, our product portfolio and target applications, as well as taking a look at what is coming next from the SensL Division including large format SPAD arrays.

ExPr-04-02 4:18 PM

3D-IC Technology for Pixel Detectors & Sensor Devices (#2821)

Dr. Makoto Motoyoshi, Dr. Makoto Motoyoshi

Tohoku-MicroTec Co., Ltd (T-Micro), HQ, Sendai, Germany

Content
Large-scale integration (LSI) technology has been widely applied in two dimensions over the past four decades and now moves into the era of sub-10-nm node. To maintain the scaling trend, new transistors with three-dimensional (3D) structures, new materials, and new processes have been introduced. From the economic viewpoint, the development and manufacturing cost of systems on chip has skyrocketed. A 3D-IC is an effective solution for reducing the manufacturing costs of advanced 2D LSI while ensuring equivalent device performance and functionalities. This technology allows for a new device architecture of stacked detectors/sensor devices with a small dead sensor area and facilitates hyper-parallel data processing. Currently, many methods to realize 3D-LSI devices have been developed by focusing on the unit processes of 3D-IC technology: (1) through-silicon via (TSV) formation, (2) bump formation, (3) wafer thinning, (4) chip/wafer alignment, and (5) chip/wafer bonding. However, these unit processes are incompatible in terms of various device and process requirements such as process temperature, device structure, TSV and bump dimensions, yield, reliability, and supply chain. We focus on applying this technology to real circuit test devices, namely, pixel detectors or stacked sensor devices with a compound semiconductor sensor device and silicon readout (RO) integrated circuit. The simplest structure of 3D-pixel detectors and stacked sensors is the two-tile face-to-face stacked device with a fine-pitch μ-bump bonding. This requires bump formation, wafer thinning, chip/wafer alignment with small alignment error, and chip/wafer bonding techniques with the adequate...
temperature and pressure. In my presentation, recent 3D-IC technology and market trend are introduced. And also the two types of Au micro-bump technologies apply to pixel detector/sensor are presented.

ExPr-04-03  
4:36 PM

Photon counting, spectral X-ray imaging at high count rates: Direct Conversion detectors are suited for many applications in medical, dental, NDT and process control imaging (#2891)

Dr. York Haemisch¹, Dr. Jonathan Schock¹, Spencer Gunn³, Christer Ullberg², Dr. Mattias Urech²

¹ Direct Conversion GmbH, Graefelfing, Germany; ² Direct Conversion AB, Danderyd, Sweden; ³ Direct Conversion Ltd., London, UK

Content
Direct Conversion has been pioneering the application of CdTe hybrid detectors in dental imaging through its Ajat brand and currently plays the leading role in the proliferation of photon counting detectors based on CdTe/ASIC hybrids through its XCounter brand of detectors. Several thousands of them are in use all around the globe in industries such as oil & gas (pipe inspection), food inspection, non-destructive testing and quality and process control e.g. in electronics industry. While dental imaging pioneered the medical use of CdTe integrating detectors, a migration to photon counting technology has begun in dental and other medical applications such as breast CT. The benefits achievable with photon counting detectors include but are not limited to lower dose and/or higher speed acquisitions (up to 2000 fps), lower noise/higher contrast images and the capability of separating tissue/materials based on energy thresholding. The current technology, as represented in Direct Conversion’s 3 product lines of Hydra, Thor and Actaeon detectors utilizes two energy bins (thresholds), whereas the next generation technology called “XC-Pyxis” will contain up to 6 energy bins per pixel and add the ability of on-chip binning, thus reducing the data transfer rate requirements. Most importantly, the new XC-Pyxis detector hybrids utilize the so called Through Silicon Via (TSV) technology to readout the hybrids through the back of the stack of chips, thus removing geometrical limitations and enable the design of detectors in various sizes and shapes adapting to all potential applications. Charge sharing correction (CSC) as well as trapped charge release (TCR) algorithms complete the design of Direct Conversion detectors, maintaining consistency in imaging over a wide range of count rates and applications.

ExPr-04-04  
4:54 PM

Drones G – highly capable emergency monitoring system (#2899)

Lucie Fiserova, Tomas Grisa, Lada Kouklkova, Hana Buresova

NUVIA a.s., Trebic, Czech Republic
Drones G stands for gamma detection and spectroscopy UAV system which was designed for surveying of medium size areas to search for potential contamination, orphan radioactive sources or for operations in areas with hazardous dose rate levels as well as surveying areas that aren’t easily accessible by foot or other means of transportation. The system offers an excellent performance and flexibility using 6 different detection modules. Measured data is transmitted in real time to the ground station equipped with DRONIC software providing an immediate overview of the radiation situation in the territory the UAV is operating in. Main technical parameters and measurement examples will be presented in detail.

**ExPr-04-05**  
5:12 PM

**SiPM-based ScintiClear radiation detectors from 0.5 to 50 cm³** (#2900)

*Dr. Ivan Khodyuk*

*CapeSym, Inc., Natick, USA*

**Content**

CapeSym’s **ScintiClear™** is a new high-performance SrI₂(Eu)-based scintillator made in the USA. Our proprietary crystal growth process improves its inherently excellent properties and limits the negative effects of Eu self-absorption. Typical energy resolution of ScintiClear SiPM detectors is 2.2% at 1332 keV, 3.0% at 662 keV and 8% at 60 keV. With 4.6 g/cc density, $Z_{eff} = 49$, and the absence of internal activity, ScintiClear SiPM detectors are an excellent choice for all kinds of applications.

**ExPr-04-06**  
5:30 PM

**FERS-5200: a distributed front-end readout system for multidetector arrays** (#2911)

*Carlo Tintori¹, Dr. Andrea Abba², Nicola Paoli¹, Yuri Venturini¹, Giovanni Burgada¹*

¹ CAEN SpA, Viareggio (LU), Italy; ² Nuclear Instrument SrL, Lambrugo (CO), Italy

**Content**

The FERS-5200 is the new CAEN Front-End Readout System, which is a cost effective, scalable and distributed front-end & data acquisition system for large detector arrays. It consists in a compact and easy-deployable solution integrating front-ends based on ASICs, A/D conversion, data processing, synchronization and readout. Using the appropriate ASIC the solution perfectly fits a wide range of detectors such as SiPMs, multianode PMTs, Silicon Strip detectors, Wire Chambers, Gas Tubes, etc. The first member of the FERS family is the unit A5202, a 64 channel readout card for SiPMs, based on the Citiroc (Weeroc) ASIC chips. Each concentrator board DT5215 manages up to 128 A5202 cards, that is 8192 readout channels.
M-02 | New Radiation Detector Technologies for Medical Imaging I

Antonio J. Gonzalez Martinez (Valencia)
Joshua W. Cates (Stanford)
Timing Properties of Bismuth Germanate Measured Using Simultaneous Microchannel Plate PMT and NUV-HD SiPM Readout (#1548)

Dr. Sun Il Kwon¹, Dr. Alberto Gola², Prof. Simon R. Cherry¹

¹ University of California, Davis, Biomedical Engineering, Davis, USA; ² Fondazione Bruno Kessler, Trento, Italy

Content

Bismuth germanate (BGO) has attractive properties for use in positron emission tomography (PET) scanners. However, BGO has not been considered as a scintillator for time-of-flight PET scanners when scintillation photons are used for timing. While scintillation photons produced in BGO still provide essential energy information, recently, it has been reported that the coincidence timing resolution (CTR) of BGO can be much improved by detecting faint Cerenkov photons using latest generation silicon photomultipliers (SiPMs), which have better photon detection efficiency (PDE) and single photon time resolution (SPTR). In terms of SPTR, microchannel-plate PMTs (MCP-PMTs) are one of the best photosensors, with extremely fast SPTR compared to SiPMs. However, BGO coupled to MCP-PMTs showed very poor CTR due to the low quantum efficiency of MCP-PMTs for the scintillation and Cerenkov photons produced in BGO. Using a dual-ended readout of BGO with a MCP-PMT and a SiPM, we hypothesized that the high PDE of the SiPM might help to effectively discriminate coincidence events triggered by Cerenkov photons at the MCP-PMT, while the high SPTR of the MCP-PMT would improve the CTR. Coincidence events were acquired using two BGO detectors. Each detector consisted of a polished BGO crystal wrapped with polytetrafluoroethylene tape. The BGO crystal was read out from opposite ends by an MCP-PMT (R3809U-58, Hamamatsu) and NUV-HD SiPM (FBK, Italy) coupled to the crystal with optical grease. Using timing information from the MCP-PMTs and SiPMs, we achieved an excellent CTR of 85 ps FWHM between two 3 × 3 × 5 mm³ BGO crystals and 193 ps FWHM between two 3 × 3 × 20 mm³ BGO crystals. Using the same setup, we also captured the entire BGO waveform including Cerenkov emission and two scintillation decay components. The 10%-90% rise time and decay times were derived from the measured waveforms. These experiments show the potential to achieve sub-100 ps coincidence timing resolution with BGO.

On experimental and theoretical timing limits of BGO and its Cerenkov emission in TOF-PET (#2073)

Stefan Gundacker¹,², Nicolaus Kratochwil¹, Rosana M. Turtos¹, Marco Paganoni¹,², Etienne Auffray¹, Paul Lecoq¹

¹ CERN, Geneva, Switzerland; ² UniMiB, Milano, Italy

Content
Bismuth germanate (BGO) used to be the work-horse in the early days of PET due to its high density, high photoelectric absorption and its relatively cost effective production. With the emerging technology of time of flight (TOF) faster crystals like L(Y)SO:Ce became the number one choice. Nowadays, the development of SiPMs has shown impressive advancements in the single photon time resolution (SPTR) and photon detection efficiency (PDE) in the near ultraviolet. With the further use of high-frequency readout we already have shown that intrinsic SPTR values of 70ps FWHM are possible measured with FBK NUV-HD SiPMs, 40μm SPAD size, illuminating the whole 4x4mm² active area. Besides the relatively slow scintillation emission with 300ns decay time BGO as well emits a fair amount of prompt Cherenkov photons. With a time correlated single photon counting setup we measured this value to be on average 15±5 Cherenkov photons emitted in 300-850nm upon each gamma interaction. In this wavelength range the NUV-HD shows a weighted PDE of 40% for the Cherenkov emission. This excellent SPTR, PDE and high-frequency readout makes it possible to achieve a coincidence time resolution (CTR) of 158±3ps FWHM when coupling a 2x2x3mm³ sample and 277±3ps FWHM for 2x2x20mm³ BGO. We tested as well BGO crystals of different cross-section and found a CTR of 167±5ps FWHM for 3x3x3mm³ and 210±5ps FWHM for 3x3x15mm³ size. In particular the low noise high-frequency readout allows to trigger on the very first photons detected, which drastically reduces long tails in the delay-time histogram. This effectively increases the number of fast events. CTR measurements with BGO investigating the performance of other SiPM producers and crystal dimensions will as well be presented. We will further show a complete assesment of the scintillation kinetics of BGO and use it as input for comprehensive Monte-Carlo simulations in order to give an answer on where the real timing limits of BGO in TOF-PET are.

M-02-03  
Depth of Interaction information encoding in a sampling scintillator detector geometry (#2156)

Dr. Marco Pizzichemi¹, Dr. Rosana Martinez Turtos¹, Dr. Stefan Gundacker², Prof. Marco Paganoni², Prof. Paul Lecoq¹, Dr. Etienne Auffray¹

¹ CERN, Meyrin, Switzerland; ² University of Milano-Bicocca, Milano, Italy

Content
The measurement of Time Of Flight (TOF) is a fundamental parameter in modern PET scanners. Nowadays research is more and more pointing towards a new frontier of TOF, with the ultimate goal set to 10ps FWHM coincidence time resolution (CTR). Since the light emission rate of the conventional scintillation mechanism would not allow to reach such a high level of CTR, novel and fast light production mechanisms need to be explored. At the same time long scintillators (around 15-20mm) are mandatory in PET to reach acceptable levels of scanner sensitivity, and it can be shown that for such crystals a timing resolution of 10ps FWHM cannot be reached without knowledge of the depth of interaction (DOI) of the incoming gamma ray along the main axis of the scintillator. We developed a method to obtain DOI information with high resolution in an array of standard 15mm long inorganic scintillators (LYSO:Ce) coupled to a matrix of photo-detectors, and we demonstrated that with this method it is possible to correct for the DOI-induced bias on CTR, and achieve timing resolutions in the order of 150ps FWHM with standard LYSO:Ce scintillators. At the same time, we demonstrated that the use of sampling pixel detectors, composed of several alternating layers of thin (around 100-200um) fast emitting materials, such as BC-422, and conventional scintillators,
like LYSO:Ce and BGO, can represent a valid solution for fast light production. The CTR reached with 3 mm long meta-pixel is in the range of 95ps FWHM for a fraction of 511 keV events deposited in BGO+BC-422 meta-pixels, and 55ps FWHM for LYSO+BC-422 meta-pixels. In this work we combine these two approaches, investigating the possibility to extract DOI from a meta-pixel structure, and evaluating the timing performance and the efficiency of applying DOI correction to improve the CTR.

M-02-04  
4:54 PM

Initial Results for a Small Animal DOI PET Detector with Sub-Surface Laser Engraving Based Trapezoid Geometry (1390)

Dr. Han Gyoo Kang1, Dr. Fumihiko Nishikido1, Dr. Hideaki Tashima1, M.Sc./M.A. Toshiaki Sakai2, Dr. Taiga Yamaya1

1 National Institute of Radiological Sciences (NIRS) in National Institutes for Quantum and Radiological Science and Technology (QST), Department of Nuclear Medicine Science, Chiba, Japan; 2 Hamamatsu Photonics K.K, Hamamatsu, Japan

Content

A small animal depth-of-interaction (DOI) positron emission tomography (PET) detector based on a trapezoid shaped crystal was originally proposed by Simon Cherry’s group at UC Davis as a way to minimize the gaps between detector blocks. However, manufacturing the trapezoid shaped crystal is costly due to the complex geometry. As a more practical idea, here we developed a small animal DOI PET detector using a sub-surface laser engraving (SSLE) based trapezoid geometry. The imaging performance of the proposed PET scanner was presented in the most recent GATE User’s workshop. In the developed detector, we pixelized a 20 mm long monolithic trapezoid LYSO plate (top = 15.3 mm, bottom = 25.6 mm, thickness = 0.9 mm) into a 15 × 1 array by using SSLE to yield a top crystal pitch of 1.02 mm and a bottom crystal pitch of 1.71 mm. The 11 SSLE processed LYSO crystal plates were assembled together to make a 15 × 11 array. The LYSO plates were optically isolated by using as enhanced specular reflector (ESR). A 7×6 array SiPM (S13360-2050VE, Hamamatsu Photonics, Japan) with a pixel pitch of 2.4 mm and an 8×4 array SiPM (S13361-3050NE-04 Hamamatsu Photonics) with a pixel pitch of 3.2 mm were coupled to the top and bottom surfaces of the trapezoid LYSO array, respectively. For an optical coupling, room temperature Vulcanized (RTV) light guides with a thickness of 1 mm were inserted between the LYSO and SiPM array. The SiPM output signals were multiplexed by using a resistive network, and then digitized by CAMAC DAQ. We could identify all the crystals in the 2D flood map. The measured DOI resolution and energy resolution were 2.3±0.6 mm and 11.6±0.7%, respectively. In the future, we want to develop a prototype trapezoid geometry small animal DOI PET scanner for high-resolution and high-sensitivity mouse brain imaging.
Performance evaluation of a large-area Compton PET module

Dr. Peng Peng, Prof. Simon R. Cherry

University of California, Davis, Department of Biomedical Engineering, Davis, USA

Content
In our previous studies, we showed that the Compton PET module, a layered structure PET detector with side readout, could provide high performance in terms of spatial/energy/timing resolution, as well as high gamma ray detection efficiency. However, the previous studies were based on a small-scale detector (four layers of LYSO crystals, each with dimensions of 13.34 x 13.34 x 2.76 mm³). In this study, we evaluate a larger sized module with one LYSO crystal layer with dimensions of 33 x 33 x 3 mm³. All six surfaces of the crystal were polished, the top and bottom surfaces were covered with enhanced specular reflector (ESR), and the other four sides are coupled with four arrays of 9x1 ON Semiconductor's MicroFJ-30035- TSV SiPMs. The 36 analog signals of the SiPMs from detecting the scintillation light are digitized individually in the TOFPET-2 ASIC from PETsys. A convolutional neural network (CNN) is trained to encode the one-to-one relationship between the gamma ray interaction position and the scintillation light distribution pattern on the 36 SiPMs. We compared the results of using two methods to collect the training data: one used a collimated spot beam, the other used a collimated line beam. The first method needed N² irradiation positions, which becomes impractical for large sized detectors. The second method needed only 2N irradiation positions, which dramatically reduced the calibration time, while having the potential to maintain the spatial resolution. The spatial resolution of the module ranged from ~1.25 mm near the edge to ~2.2 mm at the center using collimated spot beam training data. We also investigated the energy resolution for the detector, which was measured to be 8.4% using events across the entire detector.

A novel $k$-Nearest Neighbors ($k$NN) Position Estimation Approach for Monolithic Scintillators to Enable the Application in Large-Scale PET Systems

PhD/MD student Florian Mueller¹, M.Sc./M.A. student Edith F. Baader¹, M.Sc./M.A. Giacomo Borghi²,³, Dr. David Schug¹, PhD/MD Dennis R. Schaart², Prof. Volkmar Schulz¹

¹ RWTH Aachen University, Department of Physics of Molecular Imaging Systems, Institute for Experimental Molecular Imaging, Aachen, Germany; ² Delft University of Technology, Medical Physics & Technology (MST), Delft, Netherlands; ³ Fondazione Bruno Kessler, Integrated Radiation and Imaging Sensors (IRIS), Trento, Italy

Content
Monolithic scintillators are widely considered an alternative for segmented arrays. One of the main challenges to put monoliths into wide application is the position estimation of gamma events in the detector. The $k$-nearest neighbors
\( k\text{NN} \) algorithm is broadly used as it provides good positioning performance and allows a fast calibration process. \( k\text{NN} \) compares the light distribution for every unknown event with a set of light distributions of known interaction position (training data). The positions of the most similar events (nearest neighbors) are filled into a histogram to classify the interaction position. The main challenges of \( k\text{NN} \) are a high computational load and large memory requirement which are determined by the size of the training data; these aspects are of particular importance for clinical PET scanners with a large number of detectors. Recently, we proposed an acceleration of \( k\text{NN} \) by analytically pre-positioning the event. The training data could be shrunk to a region of interest for the individual event. Thus, the computational load was reduced by a factor of about 200. However, the memory requirement remained which is estimated to 852 MB per detector. Here, we present a combination of \( k\text{NN} \) with the machine learning method gradient tree boosting (GTB) to a GTB-enhanced \( k\text{NN} \) (GTB-\( k\text{NN} \)); GTB instead of an analytical approach evaluates the \( k\text{NN} \) histogram. We found GTB-\( k\text{NN} \) to be more stable than \( k\text{NN} \) and providing regression capabilities. This was used to systematically reduce the training data set addressing both memory requirement and computational load. We shrunk the number of training events, the number of calibration positions and applied multiplexing techniques. Using this novel approach, we were able to a) improve the performance with the full training data, and b) to reduce the training data by a factor of 100 to 8 MB maintaining better performance than \( k\text{NN} \) with full training data. This brings GTB-\( k\text{NN} \) in reach of application for large future PET systems.
M-03 | Tomographic Image Reconstruction Techniques I

Andrew J. Reader (London)
Evren Asma (Vernon Hills)
Model-Based Deep Learning PET Image Reconstruction Using Forward-Backward Splitting Expectation Maximisation (#1691)

Dr. Abolfazl Mehranian, Prof. Andrew J. Reader

King’s College London, School of Biomedical Engineering & Imaging Sciences, London, UK

Content

We propose a forward-backward splitting algorithm for maximum-a-posteriori (MAP) PET image reconstruction, which provides an elegant framework for integration of deep learning (DL) into model-based iterative reconstruction. The MAP reconstruction is split into three steps: regularisation, expectation maximisation (EM) and a weighted fusion. For regularisation, use of either a weighted Tikhonov prior (a hypothesis-driven prior based on Markov random fields) or a residual learning unit (a data-driven prior based on convolutional neural networks) were considered. For the latter, our proposed forward-backward splitting expectation maximisation (FBSEM), accelerated with ordered subsets (OS), was unrolled into a recurrent neural network in which the network parameters (including regularisation strength) are shared across all states and learned while PET images are reconstructed from emission data. FBSEM net was trained on simulated brain phantoms using PET-MRI (FBSEM-PM net) and PET-only (FBSEM-P net) data and was compared to OSEM, MR-guided MAPEM and a post-reconstruction U-Net denoiser, trained on the same PET dataset, for different count-levels. Our results showed that FBSEM-PM net accurately reconstructs test data without suppressing PET unique lesions or introducing MR unique lesions. It was also found that FBSEM-P net and U-Net both outperform MAPEM and OSEM reconstructions, and achieve similar performance for moderate-to-high count levels. However, as the count level is reduced, the FBSEM-P net results in notably lower noise-induced hot and cold spots. These results therefore highlight the superiority of model-based DL reconstruction over conventional MAPEM and post-reconstruction DL-based denoising methods. Future work will include realistic 3D simulations and transfer learning for reconstruction of in-vivo PET and PET-MR data.

This work is supported by the EPSRC (EP/M020142/1); the Wellcome EPSRC CME at King’s College London (WT203148/Z/16/Z)

Image Reconstruction Using TOF Back Projection and a Deblurring Neural Network (#2322)

William J. Whiteley¹,², Dr. Vladimir Panin¹, Dr. Deepak Bharkhada¹

¹ Siemens Medical Solutions USA, Inc, Research and Development, Knoxville, USA; ² The University of Tennessee, Department of Electrical Engineering and Computer Science, Knoxville, USA

Content
The increasing timing resolution of PET/CT scanners has facilitated more precise localization of annihilation events, but has yet to achieve enough certainty to produce a crisp image in one step directly from raw data. Hence simple backprojection of time-of-flight (TOF) data, while very fast, produces a blurry output called a histo-image. This article proposes a novel reconstruction pipeline consisting of a back-projection of TOF sinograms to create an intermediate histo-image and a neural network to deblur the histo-image producing a crisp high quality reconstructed image. The proposed pipeline is tested on a simulated data set of 1,083 PET images and obtains a worst case normalized mean squared error of less than 0.1% and a SSIM measure of 0.9998. These results show the promise of combining TOF back-projection and a neural network to rapidly produce high quality images.

M-03-03 4:36 PM

Efficient Neural Network Image Reconstruction from Raw Data Using a Radon Inversion Layer (#2329)

William J. Whiteley\textsuperscript{1,2}, Dr. Jens Gregor\textsuperscript{2}

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Content

Direct neural network image reconstructions methods from raw data are notoriously memory inefficient in the transformation from the measurement space domain to image space by use of one or more fully connected layers. This inefficiency has thus far limited the size of the final image and posed a significant obstacle to studying direct neural network reconstruction methods. However, this memory space challenge can be corrected by observing the measurement data that contributes to the formation of a given image patch and designing a network layer to exploit those observations. This article takes this approach and proposes a novel Radon inversion neural network layer that enables full size direct image reconstruction from Radon encoded raw measurement data with a 99.84% decrease in memory requirements compared to the recently published AUTOMAP direct reconstruction network. We demonstrate high quality full size image reconstruction from a neural network using the Radon inversion layer and compare the results to the SART reconstruction method utilizing a structural similarity measure for comparison.
Iterative PET Image Reconstruction using Adaptive Adjustment of Subset Size and Random Subset Sampling (#1041)

PhD/MD student Robert W. R. Twyman¹, Prof. Simon Arridge², Prof. Brian F. Hutton¹, PhD/MD student Elise C. Emond¹, PhD/MD student Ludovica Brusaferri³, Dr. Sangtae Ahn³, Prof. Kris Thielemans¹

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Content
Statistical PET image reconstruction methods are often accelerated with the use of a subset of projections at each iteration. It is known that many subset algorithms, such as OSEM, will not converge to a single solution but to a limit cycle. Reconstruction methods exist to relax the update step sizes of subset algorithms to obtain convergence. However, this introduces extra parameters that may result in extended reconstruction times. Another approach is to gradually decrease the number of subsets to reduce the effect of the limit cycle at later iterations, but, the optimal iteration for these reductions is data dependent. We propose an automatic method to increase subset size so the reconstruction can take advantage of the acceleration provided by small subset sizes during early iterations, while at later iterations, the estimate converges to a MAP solution. At each iteration two image updates are computed from a common estimate using two randomly sampled, disjoint subsets. The divergence of the two update vectors is measured and, if too great, subset size is increased in future iterations. We show results for both projection binned data and list mode data that use different subset random selection mechanisms.

Bootstrap-Optimised Regularised Image Reconstruction (#1231)

Prof. Andrew J. Reader, Dr. Sam Ellis

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Content
Image reconstruction is often compromised by noise in the measured data, and regularisation is usually employed to avoid noisy images. However, practical and precise specification of the level of regularisation for image reconstruction from a given measured dataset remains a largely unresolved problem. Existing approaches are either empirical (based on test cases or visual impression) or else are computationally intensive cross-validation methods, requiring full reconstructions for a limited set of preselected regularisation hyperparameter values. In contrast, this work proposes a novel methodology embedded within iterative image reconstruction, using a bootstrapped replicate of the measured data for precise optimisation of the regularisation. The approach uses a conventional unregularised iterative update of a current image estimate from the noisy measured data, and then also uses the bootstrap replicate to obtain a bootstrap update of the current image estimate. The method then seeks the regularisation...
hyperparameters which, when applied to the bootstrap update of the image, lead to a best fit of the regularised bootstrap update to the conventional measured data update. This corresponds to determining the most appropriate regularised objective function according to the noise level of the data. For a given regularised objective function (e.g. penalised likelihood), no hyperparameter selection or tuning is required. The method is demonstrated for positron emission tomography (PET) data at different noise levels, and delivers near-optimal reconstructions (in terms of reconstruction error) without any knowledge of the ground truth. Importantly the method delivers automatic and precise optimisation of the level of regularisation appropriate to any measured dataset.

M-03-06 5:30 PM

A novel automatic hyper-parameter estimation for penalized PET reconstruction (#2478)

Dr. Kyungsang Kim, Prof. Quanzheng Li

Massachusetts General Hospital & Harvard Medical School, Radiology Department, Boston, USA

Content

Automatic hyper-parameter selection in the penalized iterative PET reconstruction has remained as an unsolved problem. Although thousands of penalized reconstruction algorithms have been successfully developed in several decades, a hyper-parameter, known as a constant to control between the data fidelity and penalty, still has been selected manually or with simple rules. The major problem is that the optimal hyper-parameter should be decided by the noise distribution in raw data, however, it is still challenging to prefix the noise level in PET reconstruction. Even with a fixed tracer injection dose, the uptake and bio-distribution can greatly vary across individuals. The tracer distribution also depends on tracer type and scan duration, resulting in a high degree of variation in the noise level. To estimate the noise property and preserve the image resolution, the local impulse response (LIR) using Fisher information was used in reconstruction, however, the hyper-parameter selection is still required. To address the hyper-parameter selection, we propose a novel back-projected relative variance (BRV) method to automatically calculate the hyper-parameter which has two steps: 1) a relative (percentage) variance is estimated in sinogram domain by assuming the re-projected sinogram is the mean of the measurement, and then 2) a voxel-wise mean noise variation is calculated by back-projecting relative variance. In the optimization, we use a forward-backward proximal splitting method, which iterates two steps: 1) data fidelity update and 2) denoising process. By using a quadratic penalty having no inner parameter, the penalized PET reconstruction becomes fully automatic. We compare reconstructed images using the conventional OSEM with PSF and the proposed method both quantitatively and qualitatively. We demonstrate that the proposed method is very robust against noise and provides better detectability.
4:00 PM – 5:48 PM

Charter 1

N-23 | High Energy and Nuclear Physics I

Laura Gonella (Birmingham)
Ingrid-Maria Gregor (Hamburg)
The ATLAS Strip Detector System for the High-Luminosity LHC

Dr. Ulrich Parzefall¹, Jan-Hendrik Arling²

¹ Albert-Ludwigs-University Freiburg, Institute of Physics, Freiburg, Germany; ² DESY, Hamburg, Hamburg, Germany

Content
The ATLAS experiment at the Large Hadron Collider (LHC) is currently preparing for a major upgrade of the Inner Tracking for the Phase-II LHC operation (known as HL-LHC), scheduled to start in 2026. In order to achieve the integrated luminosity of 4000 fb⁻¹, the instantaneous luminosity is expected to reach unprecedented values, resulting in about 200 proton-proton interactions in a typical bunch crossing. The particle densities and radiation levels will exceed current levels by a factor of ten. The radiation damage at the full integrated luminosity implies integrated hadron fluencies of more than 2x10¹⁶ nₑq/cm², requiring a complete replacement of the existing Inner Detector. An all-silicon Inner Tracker (ITk) is under development with a pixel detector surrounded by a strip detector, aiming to provide increased tracking coverage up to eta=4. In this contribution, we will give an overview of the strip detector system for this ATLAS upgrade. With the R&D phase and the system design completed, and prototyping in its final stages, we are now for the first time able to present the entire system as it will be built, with results available for the vast majority of system components. This will include detector modules which integrate 6” strip sensors, dedicated radiation hard ASICs and front-end read-out electronics mounted directly on the active side of the silicon strip sensors. We will also present the read-out, powering and control system that services and controls the modules and allows to transport the data collected from the modules to the central read-out and trigger electronics. For this submission, we will focus on the strip detector system as a whole, and highlight the results obtained with the production generation of ASICs and silicon strip sensors. In addition, we will show the expected performance of the strip system, based on recent test-beam results of un-irradiated and irradiated modules.

Results from the first IpGBT-based prototype of the End-of-Substructure card for the ATLAS Strip Tracker Upgrade

Harald Ceslik¹, Helmut Colbow¹, Dr. Mogens Dam², Dr. Sergio Diez-Cornell¹, Dr. Peter Goettlicher¹, Dr. James M. Keaveney³, Jan Oechlse², Dr. Marcel Stanitzki¹, Dr. Chaowaroj Wanotayaroj¹, Jonas Wolff¹

¹ DESY - Deutsches Elektronen Synchrotron, DESY/ATLAS, Hamburg, Germany; ² Niels Bohr Institute, Copenhagen, Denmark; ³ University of Capetown, Department of Physics, Capetown, South Africa

Content
For the ATLAS experiment an upgraded Silicon Tracker is required for the High-Luminosity Upgrade of the LHC. The main building block for the strip tracker is the module which consists of a silicon sensor and a hybrid PCB hosting the read-out ASICs. The modules are placed on so-called staves or petals which provide common services to all the
modules. At the end of a stave or petal, there is the End-of-Substructure (EoS) card, which connects the data, command and the power to the off-detector systems. For all that data transfers the front-end ASICs send their data on 640 Mbit/s differential pairs to the End-of-Substructure (EoS) card. It will collect up to 28 data lines with one or two IpGBT chips and transmit them using the versatile optical link (VL+) with a speed of 10 GBit/s off-detector. From the downlink the LHC-clock is recovered by the IpGBT and the clocks and control data streams for all the modules are generated. A particular challenge is the need of several variants of the EoS board to meet the tight integration requirements of the detector. We have produced first prototypes using the first available versions of the IpGBT and VL+ ASICS’s. Presented will be the design of the electronics, the performance, the thermal behavior and the initial lessons learned. The EoS is powered by a two-Stage DC-DC converter, generating both 2.5 V and 1.2 V out of the incoming 11 V. This DC-DC converter is mounted on a custom-designed daughter board, which will be connected to the EoS during assembly. Prototype boards using a custom-coil design have been produced and the performance of this daughter board and the experience with the two-stage DC-DC converter will be reported. Since each EoS sits at a single-point-of-failure for an entire stave or petal side, a dedicated quality control and assurance procedure for the planned 2000 EoS and DC-DC PCBs has been developed and will be presented.

N-23-03  4:36 PM

Low Gain Avalanche Detectors for Precision Timing in the CMS Endcap (#2146)

Prof. Toyoko J. Orimoto¹, Prof. Roberta Arcidiacono²³, On behalf of the CMS Collaboration

¹ Northeastern University, Physics Department, Boston, USA; ² Universita’ del Piemonte Orientale, Vercelli, Italy; ³ INFN Torino, Torino, Italy

Content

The MIP Timing Detector (MTD) of the Compact Muon Solenoid (CMS) is designed to provide precision timing information (with resolution of ~40 ps per layer) for charged particles, with hermetic coverage up to a pseudo-rapidity of |η|=3. This upgrade will reduce the effects of pile-up expected under the High Luminosity LHC running conditions and brings new and unique capabilities to the CMS detector. The time information assigned to each track will enable the use of 4D reconstruction algorithms and will further discriminate in the time domain interaction vertices within the same bunch crossing to recover the track purity of vertices in current LHC conditions. The endcap region of the MTD, called the Endcap Timing Layer (ETL) will be instrumented with silicon-based low gain avalanche detectors (LGADs), covering the high radiation pseudo-rapidity region between |η|=1.6 and 3.0. Each endcap will be instrumented with a two-disk system of LGADs, read out by Endcap Timing Readout Chips (ETROCs), being designed for precision timing measurements. We present the status of the R&D for the MTD ETL and report on recent test beam results.
Precision Timing with LYSO:Ce Crystals & SiPM Sensors for the CMS MTD Barrel Timing Layer (#2138)

Prof. Toyoko J. Orimoto¹, Dr. Patrizia Barria², On behalf of the CMS Collaboration

¹ Northeastern University, Physics Department, Boston, USA; ² University of Virginia, Physics, Charlottesville, USA

Content
The Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) is undergoing an extensive Phase II upgrade program to prepare for the challenging conditions of the High-Luminosity LHC (HL-LHC). In particular, a new timing detector will measure minimum ionizing particles (MIPs) with a time resolution of ~30-40 ps and hermetic coverage up to a pseudo-rapidity of |η|=3. The precision time information from this MIP Timing Detector (MTD) will reduce the effects of the high levels of pile-up expected at the HL-LHC and will bring new and unique capabilities to the CMS detector. The central Barrel Timing Layer (BTL) will be based on LYSO:Ce crystals read out with silicon photomultipliers (SiPMs). The BTL will use elongated crystal bars, with double-sided read out, with a SiPM on each end of the crystal, in order to maximize detector performance within the constraints of space, cost, and channel count. This unusual geometry enables the instrumentation of large surfaces while minimizing the active area of the photodetectors, and thus noise and power consumption. We will present an overview of the MTD BTL design and will detail the extensive R&D studies carried out to optimize the MTD BTL crystal-based technology and test beam results in which the goal of 30 ps timing resolution has been achieved. We will also present progress in the development of the dedicated readout electronics for the BTL.

Status of the CMS ECAL phase 2 upgrade for high precision timing and energy measurements (#2145)

Paolo Meridiani, On behalf of the CMS Collaboration

L’Università degli Studi di Roma, Roma, Italy

Content
The upgrade of the barrel portion of the electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid Experiment (CMS) for the High-Luminosity phase of the LHC (HL-LHC) will extend the capabilities of the detector in multiple ways to cope with the unprecedented number of pile-up events (up to 200 simultaneous proton-proton collisions) and a challenging increase in data rates. The lead tungstate crystals and avalanche photodiode detectors of the current ECAL barrel detector will remain, while the entire readout electronics will be replaced. The upgraded detector will have a 25 fold improved readout granularity and the sampling rate will increase 4 fold. We will report on recent progress on the front-end electronics, which includes a dual gain trans-impedance amplifier in a 130nm CMOS and an ASIC providing two 160 MHz ADC channels, gain selection, and data compression, in 65nm CMOS.
technology. To support the roughly 100 fold increase in data rates, the back-end electronics are being upgraded to support the Level-1 trigger latency increase from about 4 $\mu$s to a maximum of 12.5 $\mu$s and the trigger rate increase to an average of 750 kHz. We will report on a demonstrator platform, the Barrel Calorimeter Processor demonstrator (BCPd), implemented in an AdvancedTCA (ATCA) blade capable of supporting 56 input and output fibers, 16 Gbps each, serving as the nexus between the detector front-end electronics, the trigger sub-system and the DAQ sub-system. In addition, the upgraded detector will have the capability to provide precision timing measurements, of the order of 30 ps for photons and electrons above 10 GeV which will significantly improve the CMS physics performance under the expected pile-up conditions. The status of the ongoing R&I&D activities for the ECAL barrel upgrade will be presented, together with the latest performance tests with prototypes, and the project status, including the challenging technical and logistical tasks of the ECAL Phase-II upgrade.

N-23-06 5:30 PM

Design of a Highly Selective Muon Trigger System for Future Hadron Collider Experiments (#2410)

Sergey Abovyan, Davide Cieri, Varuzhan Danielyan, Markus Fras, Oliver Kortner, Sandra Kortner, Hubert Kroha, Sebastian Nowak, Robert Richter

Max-Planck-Institut für Physik, München, Germany

Content

Experiments at future hadron colliders like the High-Luminosity LHC or the proposed 100 TeV circular collider FCC-hh will provide a unique opportunity to explore the limits of the Standard Model of the strong and electroweak interactions and to search for physics beyond the Standard Model. Excellent muon identification and trigger capabilities will be crucial to exploit the experiments’ physics potential. To achieve this goal the muon systems of these experiments will use both fast trigger chambers with nanosecond temporal, but poor spatial resolution and slower precision muon chambers with submicrometer spatial resolution for stand-alone momentum measurements. In this contribution a trigger system for the FCC-hh detector is introduced which uses thin-gap resistive plate chambers for bunch crossing identification and small diameter cylindrical drift tube chambers for an accurate momentum measurement both at trigger level and offline. Trigger algorithms and their VHDL implementation will be presented as well as the design of a hardware demonstrator employing modern high-performance FPGAs with more than 100 high-speed transceivers.
N-24 | Synchrotron, FEL, XFEL II

Christer Frojdh
Nicola Tartoni (Didcot)
N-24-01  4:00 PM

P2M: First Optical Characterisation Results of a 2MPixel CMOS Image Sensor for Soft X-Ray Detection (#1660)

Iain Sedgwick¹, Dr. Alessandro Marras²,³, Dr. Cornelia Wunderer²,³, Sabine Lange²,³, Dr. Benjamin Boitrelle²,⁴, Manuela Kuhn², Frantisek Krivan², Igor Shevyakov², Manfred Zimmer², Nicola Guerrini¹, Benjamin Marsh¹, Giuseppe Cautero⁵, Dario Giuessi⁵, Dr. Ralf Menk⁶, Dr. Giovanni Pinarolli⁵, Dr. Jonathan Correa²,³, Luigi Stebel⁵, Alan Greer⁶, Dr. Tim Nicholls⁶, Dr. Seungyu Rah⁷, HyoJung Hyun⁷, KyungSook Kim⁷, Heinz Graafsmá²,³

¹ UKRI STFC, Rutherford Appleton Laboratory, Didcot, UK; ² DESY, Hamburg, Germany; ³ CFEL, Hamburg, Germany; ⁴ SOLEIL, Saint-Aubin, France; ⁵ Elettra, Trieste, Italy; ⁶ Diamond Light Source, Didcot, UK; ⁷ Pohang Accelerator Light Source, Pohang, South Korea

Content

High brilliance synchrotrons and FELs require high performing detector systems to realise their full potential. High dynamic range, low noise and high frame rate are all of great importance. In this paper we present first optical characterization results of the P2M CMOS sensor, designed for soft X-ray detection at such facilities. Previous work is summarised and an overview of the sensor is presented. Test results for the sensor’s column-parallel ADC and readout chain are presented, and first test results for the pixel acquired using the Photon Transfer Curve (PTC) method are shown. Finally, an outline of future work is provided.

N-24-02  4:18 PM

A Coded-aperture Instrument for X-ray Fluorescence Full-field Imaging (#1864)

Dr. D Peter Siddons¹, Dr. Abdul Rumaiz¹, Anthony Kuczewski¹, Dr. Kashmira Nakhoda¹, Dr. Mourad Idir¹, Dr. Ryan Tappero¹, Prof. Varshni Sing²

¹ Brookhaven National Laboratory, NSLS-II, Upton, USA; ² Louisiana State University, Baton ROuge, USA

Content

Abstract— We present the design and construction of an instrument for full-field imaging of the x-ray fluorescence emitted by an irradiated sample. The aim is to produce an x-ray microscope with a few micrometers spatial resolution, which does not need to scan the sample. Since the fluorescence from a spatially inhomogeneous sample may contain many fluorescence lines, the optic which will provide the magnification of the emissions must be achromatic, i.e. its optical properties must be energy-independent. The only optics which fulfill that requirement in the x-ray regime are mirrors and pinholes. The throughput of a simple pinhole is very low, so the concept of coded apertures is an attractive extension which improves the throughput by having many pinholes, and retains the achromatic property. We have fabricated Modified Uniformly Redundant Arrays (MURAs) with 10 micrometer openings and 50% open area using gold in a lithographic technique, fabricated on a 1 micron thick silicon nitride membrane. The gold is 35 microns thick,
offering good contrast up to 20keV. The silicon nitride is transparent down into the soft x-ray region. We have made them with various orders, from 19 up to 73, and in normal and negative contrast. Having both signs of mask will make it possible to correct for any lack of contrast. We will present results of experiments using these optics, imaging both point and extended objects.

**N-24-03**

**Investigation of a robust n+ contact in high purity germanium** (#1867)

**Dr. Abdul K. Rumaiz**, Dr. Gabriele Giacomini, Wei Chen, Dr. Shaorui Li, Thomas Krings, Anthony Kuczewski, Dr. Peter Siddons

1 Brookhaven National Laboratory, NSLS II, Upton, USA; 2 Brookhaven National Laboratory, Instrumentation Division, Upton, USA; 3 Forschungszentrum, Julich, Germany

**Content**

Germanium (Ge) detectors with trenches for pixel isolation have been developed at Brookhaven National Laboratory. Monolithic Ge-detectors were fabricated using the trenching process. This technique typically employs a thick lithium (Li) diffused n+/hole-barrier contact and a B implanted p+ contact. The lithium diffused layer tends to be extremely reliable and its activation only requires a low temperature anneal (less than 400C). However, the thickness of the contact makes it a challenge for low energy applications. The thickness and the process of the Li diffusion makes additional lithography extremely challenging. Additional processing on the n+ side is required for more complicated geometries such as the drift detector. We have explored some alternate n+ contacts such as sputtered Yttrium metal contact and laser annealed P doped contact. Preliminary measurements show good leakage current in the devices. We are currently fabricating diode arrays on these wafers and bench test will be performed when fabrication is complete.

**N-24-04**

**The DSSC 1-Megapixel Camera for the European XFEL** (#2025)

**Dr. Matteo Porro**, on behalf of the DSSC Collaboration

European X-Ray Free-Electron Laser Facility GmbH, Schenefeld, Germany

**Content**

The first complete DSSC 1-Megapixel camera became available at the European XFEL in the Hamburg area in February 2019. It was successfully tested and installed at the Spectroscopy and Coherent Scattering Instrument. DSSC is a high-speed, large-area, 2-D imaging detector system for photon science applications in the energy range between 0.25 keV and 6 keV. The camera is based on direct detecting Si-sensors and is composed of 1024×1024 pixels. 256 ASICs provide full parallel readout, comprising analog filtering, 8-bit digitization and data storage. In order to cope with the demanding X-ray pulse time structure of the European XFEL, the DSSC provides a peak frame rate
The first available megapixel camera is equipped with linear MiniSDD pixel arrays. This limits the dynamic range but allows one to achieve noise values of about 70 electrons rms at the highest frame rate. The challenge of providing high-dynamic range (~10^4 photons/pixel/pulse) and single photon detection simultaneously requires a non-linear system front-end, which will be obtained with the DEPFET active pixel technology foreseen for the advanced version of the camera. This technology will provide lower noise and a non-linear response at the sensor level. Experimental results on the first MiniSDD-based megapixel camera are available for the first time and they will be reported during the presentation. All the measured performance figures are in excellent agreement with the expectations.

In addition, we will briefly discuss the implementation of the second DSSC camera, which will use DEPFET devices fabricated for the first time in a CMOS foundry.

**N-24-05  5:12 PM**

**Synchrotron Caractarization of New Generation Multichannel Germanium X-ray Detectors** (#2193)

**Dr. Vlad Marian**, Pascal Quirin, Dr. Benoit Pirard

*Mirion Technologies (Canberra) SAS, Lingolsheim, France*

**Content**

This paper presents the performance of a new generation HPGe x-ray detector array, exhibiting greatly improved energy resolution and throughput characteristics. The detector consists of a multichannel HPGe sensor (monolithic up to 25 pixels or up to 18 individual elements) cooled using a state-of-the-art electrical cryocooler with active vibration cancellation. The system is capable of resolving several million counts per second and per channel, with energy resolution similar or better that state of the art Silicon Drift Detectors (SDD), while covering a much wider energy range. Compared to previous generation germanium x-ray detectors, beamline tests in various synchrotrons show an increase by a factor of 10 in throughput and an energy resolution divided by a factor of 2 at 6keV and short Shaping time.

**N-24-06  5:30 PM**

**Monte Carlo simulation of dead time in Fluorescence detectors and its dependence on beam structure** (#2314)

**Dr. Sudeep Chatterji**¹, Graham Dennis¹, William Helsby², Dr. Nicola Tartoni¹

¹ *Diamond Light Source Limited, Detector Group, Didcot, UK*; ² *Science & Technology Facilities Council, Daresbury Laboratory, Detector Group, Warrington, Cheshire, UK*
Monte Carlo (MC) simulation study of the dependence of dead time value on the bunch filling pattern of the beam at Diamond Light Source (DLS) synchrotron and its validation using experimental data is reported. There are three bunch patterns in DLS: Standard, Hybrid and 156 bunch modes. A difference has been found between experimental values of dead time for 64-pixel germanium detector for standard mode and hybrid mode. The revolution period of the beam in DLS synchrotron is 1.872 ms. Standard mode consists of 900 bunches of 2ns each followed by a gap of 72 ns while Hybrid mode consists of 686 bunches of 2ns each, then a single bunch in the middle of gap. 10k pulse trains binned into 9360k bins of 2 ns each has been used in our simulation totalling 18.72 ms. A sinusoidal wave function has been used to generate continuous input pulses of duration 2ns each. The probability of having photons within each bunch is given by the Poisson distribution. The mean of this distribution is given by product of Input Count Rate (ICR) and time step of 2 ns. For each ICR, the simulation outputs the corresponding Output Count Rate (OCR) and time stamp of the output photon. Pile-up correction has been implemented in the code to reject the pile-up photons. Time difference ($\delta t_i$) between every consecutive output photons has been extracted which should follow an exponential decay. This technique has been used to extract the ICR back from OCR and hence, to estimate the percentage error in the simulation. MC simulations are within 1.5% error from the experimental data. The simulation has been validated with 36-pixel germanium detector data collected with the beam and X-ray set as also with 64-pixel germanium detector data collected with beam. Validation of this simulation with multi-element Vortex detector is underway. This MC simulation can be used to estimate the impact of bunch structure on dead time of a detector system provided the processing time of detector system is known.
N-25 | Novel and Emerging Technologies II

Beatrice Fraboni (Bologna)
Andrei Nomerotski (Brookhaven)

New technologies based on novel materials
Characterisation of Quantum Dots within Liquid Dispersions and Loaded Plastic Scintillators (#1739)

PhD/MD student Callum L. Grove, PhD/MD student Isabel H. B. Braddock, Dr. Matthew P. Taggart, Prof. Paul J. Sellin, Dr. Caroline Shenton-Taylor

University of Surrey, Department of Physics, Guildford, UK

Content
This project seeks to utilise the tunable emission wavelength of quantum dots to improve detector efficiency of plastic scintillator radiation detectors, producing emission that corresponds more closely to the maximum sensitivity of a photodetector. This paper reports optical characterisation measurements of quantum dots in a liquid dispersion of toluene, optical and X-ray studies of quantum dots within a solid scintillator, and associated Geant4 modelling. The benefit of first studying quantum dots in a liquid dispersion allows assessment of low dot concentrations prior to selection for loading within a scintillator. Cadmium-based CdSe/ZnS and cadmium-free ZnCuInS/ZnS quantum dot materials with varying wavelengths were selected for study, suspended in toluene dispersions of 5 mg/5 ml. By comparison of emission and absorption spectra, Stokes shifts were determined as 15.2±2.1 nm and 127.6±2.1 nm for CdSe/ZnS and ZnCuInS/ZnS respectively. This indicates self-absorption will be more prevalent in a CdSe/ZnS loaded plastic scintillator. The photoluminescence maximum intensity of CdSe/ZnS was approximately 7 times larger although due to the broader peak of ZnCuInS/ZnS, the brightness between materials was comparable. CuInS/ZnS quantum dots were loaded into an EJ290 scintillator at various concentrations. The measured emission spectra was significantly altered from photo and X-ray luminescence measurements. Unloaded EJ290 has peaks at approximately 425 nm and 450 nm, whereas a 2% CuInS/ZnS loaded EJ290 has a primary emission maxima at 550 nm. The EJ290 peak intensities are reduced in the loaded sample which indicates Förster resonance energy transfer between EJ290 emission and CuInS/ZnS absorption. Geant4 modelling of CuInS loaded into polyvinyl toluene (PVT), the base polymer of EJ290, showed that increased percentage of quantum dots yielded a larger gamma detection efficiency. Measurements within this study are discussed in light of future nuclear security applications.
N-25-02  4:18 PM

Rare Gas solids detectors (#1817)

PhD/MD student Marco Guarise1,2, Dr. Caterina Braggio3,4, Prof. Roberto Calabrese1,5, Prof. Giovanni Carugno3,4, Dr. Antonio Dainelli2, Dr. Alen Khanbekyan1,5, Prof. Eleonora Luppi1,5, Prof. Emilio Mariotti6, Dr. Marco Poggi2, Prof. Luca Tomassetti1,5

1 University of Ferrara, Physics and Earth Science, Ferrara, Italy; 2 INFN, National Laboratory of Legnaro, Legnaro, Italy; 3 University of Padova, Physics and Astronomy, Padova, Italy; 4 INFN, Padova, Padova, Italy; 5 INFN, Ferrara, Ferrara, Italy; 6 University of Siena, Physics, Siena, Italy

Content
Low energy threshold detectors are necessary in many frontier fields of the experimental physics. In particular these are extremely important for probing Dark Matter possible candidates and studying physics beyond the Standard Model.

We present a novel scheme for the detection of low energy releases in solid crystals made of inert gases solidified at cryogenic temperature both pure and doped. The devised scheme is based on electrons ionization and in--vacuum emission through the surface of these matrices that are characterized by a band-gap energy of ~tens of eV. In un--doped crystals, a few hundreds of electrons that carry an information of few eV per each, can be detected reaching a low energy threshold scheme of ~tens of eV. Furthermore alkali doping of the crystals, combined with laser--assisted spectroscopy and single electrons detection, should lead in a lower energy threshold in the sub--eV range.

High purity solid crystals with a cm³--volume of Neon, Argon and Xenon were used in our preliminary tests that are aimed to verify electrons drift and electrons emission through the solid--vacuum interface.

N-25-03  4:36 PM

Study on combined operation of superconducting transition edge sensors (#2776)

Prof. Hiroyuki Takahashi

The University of Tokyo, Institute of Engineering Innovation, Tokyo, Japan

Content
Superconducting detectors are usually operated at very low temperature, where the normal amplifiers do not work properly. We are now developing dedicated circuits and the devices based on a new concept of frontend circuits. Combined operation of two transition edge sensors is studied and new strategy of using two TES devices and the new combined device are proposed.
Development of a booster and its components for the dielectric axion haloscope MADMAX (#2164)

Dr. Christoph Krieger, On behalf of the MADMAX collaboration

University of Hamburg, Institute of Experimental Physics, Hamburg, Germany

Content

The axion is the hypothetical low-mass boson predicted by the Peccei-Quinn mechanism solving the strong CP problem. It is naturally also a cold dark matter candidate, thus it could simultaneously solve two major problems of nature. Up to recently, there was no existing experimental effort aiming to detect QCD axions in the mass range around 100 µeV, preferred by models in which the Peccei-Quinn symmetry is broken after inflation. The MAgnitized Disc And Mirror Axion eXperiment is designed to reach sensitivity in the axion mass range of 40 µeV to 400 µeV. This is reached by applying the dielectric haloscope approach, exploiting the axion to photon conversion at dielectric surfaces within a strong magnetic field. For MADMAX a system of 80 movable dielectric discs of about 1 m² area, the so-called booster, inside an approximately 9 T magnetic field is foreseen. The experiment will be located at DESY Hamburg in Germany and is currently entering its prototyping phase for which a booster with twenty discs of 300 mm diameter is foreseen. Many technical tasks are being addressed currently to realize the prototype and its booster, one subset of these are the determination of permittivity and loss tangent for dielectric materials in the microwave regime and at cryogenic temperatures, realization of 1 m² dielectric discs with 1 mm thickness and flatness better than 10 µm, and precise disc positioning with accuracy better than 10 µm using motors at cryogenic temperatures and inside a 9 T magnetic field. In the paper, we present the technical solutions followed and the first results on these three critical aspects of the MADMAX prototype realisation.

Black silicon photodiodes for VUV detection (#2208)

Dr. Thomas Tsang¹, Dr. Aleksey Bolotnikov¹, Antti Haarahiltunen², Juha Heinonen²

¹ Brookhaven Lab, Upton, USA; ² ElFys Oy, FI-02150, Finland

Content

Black silicon (b-Si) is an emerging material made by modifying silicon with nanostructures for photon detection. Photodetectors with b-Si has significantly increased the sensitivity from NIR to the visible wavelengths. Here, we measured the spectral responsivity of b-Si light-trapping photodiodes under Vacuum Ultraviolet (VUV) radiation at normal-incidence. The device exhibits an external quantum efficiency >100% below 200 nm with a responsivity of 0.2 A/W at 175 nm at room temperature in vacuum. These results demonstrate new opportunities of this technology when applied to devices used for VUV photon detection in various scientific applications, including noble gas and...
liquid detectors, and could lead to the development of b-SiPM. We will present other parameters of the black silicon photodiode operated in the cryogenic temperatures.

**N-25-06 5:30 PM**

**Application of Associated Particle Imaging for Carbon-In-Soil Analysis (#2476)**

PhD/MD student Mauricio Ayllon Unzueta¹,², PhD/MD Eoin Brodie³, PhD/MD Craig Brown⁴, PhD/MD Cristina Castanha³, PhD/MD Charles Gary⁴, Prof. Caitlin Hicks Pries⁵, William Larsen², Dr. Bernhard Ludewigt², **Dr. Arun Persaud²**

¹ University of California, Nuclear Engineering, Berkeley, USA; ² Lawrence Berkeley National Laboratory, Accelerator Technology & Applied Physics, Berkeley, USA; ³ Lawrence Berkeley National Laboratory, Earth and Environmental Sciences, Berkeley, USA; ⁴ Adelphi Technology Inc., Redwood City, USA; ⁵ Dartmouth College, Department of Biological Sciences, Hanover, USA

**Content**

Carbon sequestration in soil has large potential to mitigate fossil fuel emissions (a 0.4% increase of carbon in soil would offset 20-35% of global emission). However, currently no adequate measurement method exists to non-destructively measure the carbon distribution in soil. We introduce a new neutron-scattering-based instrument that allows the measurement of a 50 cm × 50 cm × 30 cm (depth) volume with a 5 cm voxel resolution. To achieve this, we apply Associated Particle Imaging, a nuclear technique to measure the locations of different isotopes in a target material. In particular, the 4.4 MeV gamma-ray line of $^{12}$C together with gamma rays from silicon and oxygen are being investigated. The instrument will allow non-destructive and therefore repeatable measurements of the carbon concentration in soil. This instrument also has applications in land-use management and earth sciences. We will show experimental and simulated results from soil samples, discuss the impact of measurement time on resolution, and discuss estimators for the volumetric water content and bulk density. The focus of this paper is on the 3D-reconstruction algorithm used to calculate the carbon density.
N-26 | Artificial Intelligence Applications

Lina Quintieri (Didcot)
Klaus - Peter Ziock (Oak Ridge)

Experimental applications of artificial intelligence methods and tools
N-26-01 4:00 PM

Deep Learning for Elemental Mass Quantification using X-Ray Spectral Radiography (#2792)

PhD/MD student Wesley Gillis¹, Dr. Karl Pazdernik², Dr. Andrew Gilbert², Prof. Anna Erickson¹

¹ Georgia Institute of Technology, Nuclear Engineering, Atlanta, USA; ² Pacific Northwest National Laboratory, Richland, USA

Content
This work presents an alternative, deep learning approach to using spectral radiography to quantify elemental mass of a sample. By creating a training set via Monte Carlo simulation, we train a 3D convolutional neural network to regress the total mass of Bi and O in Bi₂O₃ powder samples. The simulated data is constructed to cover potential experimental uncertainties and transformed using empirical detector characterization. The deep learning model is capable of determining both masses with 1% relative error in samples not used for training.

N-26-02 4:18 PM

Simultaneous reconstruction and segmentation of MRI image by manifold learning (#1447)

Pengcheng Xu, Prof. Huafeng Liu

Zhejiang University, Optical science and Engineering, Hangzhou, China

Content
This paper proposes a method implementing manifold learning techniques to accomplish simultaneous reconstruction and segmentation of brain MRI. Simultaneous reconstruction and segmentation by manifold learning can not only overcome the conflict of the efficiency and precision, but also concentrate on the region of interest. In our study, we present a unified framework for image reconstruction and segmentation based on data-driven supervised learning task that allows a mapping between sensor and image domain. The module was consisted of reconstructing phase and segmenting phase which pre-trained by imageNet, MGH-USC HCP and Neonatal Brain Segmentation public database, respectively. The reconstruction block is developed basing on the cascading of neural networks. And the output including feature map transported to the segmentation block. The segmentation block employs the dilated dense net and spatial pyramid pooling to improve the performance. For evaluation, we have tested our framework on 30 subjects with k space date and manual tagging. Our experiments show the remarkable performances of the proposed method with the reconstruction mean square error of 0.036 and segmentation dice of 0.96. In addition to accomplishing the reconstruction and segmentation performance of existing acquisition methodologies, we anticipate that unified framework will accelerate the development of brain disease diagnosis, progression assessment and monitoring of neurologic conditions.
TrackML: the tracking Machine Learning challenge (#2424)

PhD/MD student Sabrina Amrouche², Dr. Laurent Basara³, Dr. Paolo Calafiura⁵, PhD/MD student Victor Estrade³, Dr. Steven Farrell⁹, Prof. Cécile Germain³, Dr. Vladimir V. Gligorov⁹, Dr. Tobias Golling², Dr. Heather Gray⁵, Prof. Isabelle Guyon⁸, PhD/MD student Mikhail Hushchyn⁷, Dr. Vincenzo Innocente⁶, Dr. Moritz Kiehn², Dr. Edward Moyze⁴, Dr. David Rousseau¹, Dr. Andreas Salzburger⁶, Dr. Andrey Ustyuzhanin⁷, Dr. Jean-Roch Vlimant¹⁰, Dr. Yetkin Yilmaz¹

¹ Laboratoire Accélérateur Linéaire, Orsay, France; ² Université de Genève, Genève, Switzerland; ³ Laboratoire de Recherche en Informatique, Gif-Sur-Yvette, France; ⁴ University of Massachusetts, Amherst, USA; ⁵ Lawrence Berkeley National Laboratory, Berkeley, USA; ⁶ CERN, Geneva, Switzerland; ⁷ Higher School of Economics and Yandex School of Data Analysis, Moscow, Russia; ⁸ Université Paris Saclay, Orsay, France; ⁹ Laboratoire de Physique Nucléaire et des hautes Energies, Paris, France; ¹⁰ California Institute of Technology, Pasadena, USA

Content

The HL-LHC will see ATLAS and CMS see proton bunch collisions reaching track multiplicity up to 10.000 charged tracks per event. Algorithms need to be developed to harness the increased combinatorial complexity. To engage the Computer Science community to contribute new ideas, we have organized a Tracking Machine Learning challenge (TrackML). Participants are provided events with 100k 3D points, and are asked to group the points into tracks; they are also given a 100GB training dataset including the ground truth. The challenge is run in two phases. The first "Accuracy" phase has run on Kaggle platform from May to August 2018; algorithms were judged only on a score related to the fraction of correctly assigned hits. The second "Throughput" phase ran Sep 2018 to March 2019 on Codalab, required code submission; algorithms were then ranked by combining accuracy and speed. The first phase has seen 653 participants, with top performers with innovative approaches (see arXiv:1904.06778). The second phase has recently finished and featured some astonishingly fast solutions. The talk will report on the lessons from the TrackML challenge and perspectives.

Sentiment Analysis for Software Code Assessment (#2725)

Dr. Elisabetta Ronchieri¹, Dr. Marco Canaparo¹, Prof. Radmila Juric²

¹ INFN - Istituto Nazionale di Fisica Nucleare, CNAF, Bologna, Italy; ² University of Southeast Norway, Dep. of Science and Industry systems, Kongsberg, Norway

Content

In this study, we explore the power of machine learning for assessing software code available within open source repositories such as GitHub and GitLub. We focus on the git commit messages of software developers, recorded in these repositories over the last year, upon which we could perform sentiment analysis through machine learning classifiers. The purpose of the sentiment analysis would be to classify commits into positive, negative and neutral, and consequently assess the quality of the software code. We are able to build an appropriate word dictionary that
highlights issues and problems recorded in GitHub logs and commit messages. They in turn serve as a pool for identifying software developers’ opinions expressed during the software development process. These commit messages can be used for creating a training data set and its features for a machine learning classifier. The motivation for this research is to introduce machine learning classifiers in the field of assessing software quality though messages created by software developers. However, the same principles could be used in assessing the quality of machine learning code and consequently can contribute towards the explainability of machine learning algorithms.

N-26-05

5:12 PM

Low-Noise Reconstruction Method for Coded-Aperture Gamma-Ray Imaging Based on Artificial Neural Networks (#1494)

M.Sc./M.A. student Rui Zhang¹, Dr. Pin Gong¹, Prof. Xiaobin Tang¹, Dr. Peng Wang², M.Sc./M.A. student Zeyu Wang¹, M.Sc./M.A. student Dajian Liang¹

¹ Nanjing University of Aeronautics and Astronautics, Department of Nuclear Science and Technology, Nanjing, China; ² Nanjing University of Science and Technology, School of Environmental and Biological Engineering, Nanjing, China

Content

Coded-aperture gamma camera is a technique of great interest in the localization of radioactive hot spots. However, the traditional correlation analysis (CA) method cannot handle signal-independent noise, and the iterative reconstruction method has a low calculation speed which hinders real-time imaging. A novel reconstruction method based on artificial neural networks (ANNs) was proposed to obtain low-noise reconstructed images. Firstly, a reconstruction method based on a convolutional neural network (CNN) was studied. Monte Carlo program was used to simulate the imaging process of radioactive sources. The CNN was trained using the simulation data, and the performance of the trained CNN and CA method was compared. The average contrast-to-noise ratio (CNR) of the reconstructed images obtained by CNN when the Cs-137 source was at 289 different positions is 177.2, and the value obtained by the CA method is 10.6. However, in low-flux situations, the CNN method may indicate a completely wrong source location. To solve this problem, another decoding method based on the back propagation neural network (BPNN) was studied. The BPNN was trained by numerical calculation data. Monte Carlo simulation data were used to compare the performance of trained BPNN and CA method. The average CNR of the reconstructed images obtained by the BPNN model when the Co-57 source was at 289 different positions is 48.75, and the value obtained by the CA method is 13.51. In addition, the reconstructed image obtained using BPNN has lower background noise, especially in low count conditions.
Preliminary results in using Deep Learning to emulate BLOB, a nuclear interaction model (#2726)

PhD/MD student Andrea Ciardiello¹,², Dr. Makoto Asai³, Dr. Barbara Caccia⁴, Dr. G. A. Pablo Cirrone⁵, Dr. Maria Colonna⁵, Dr. Andrea Dotti³, Prof. Riccardo Faccini¹,², Prof. Stefano Giagu¹,², Dr. Andrea Messina¹,², Dr. Paolo Napolitani⁶, Dr. Luciano Pandola⁵, Dr. Elena Solfaroli Cammillocci¹,², Dr. Dennis H. Wright³, Dr. Carlo Mancini Terracciano¹,²

¹ INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Rome, Italy; ² Sapienza Univ. di Roma, Dip. di Fisica, Rome, Italy; ³ SLAC National Accelerator Laboratory, Menlo Park, USA; ⁴ Istituto Superiore di Sanità, National Center for Radiation Protection and Computational Physics, Rome, Italy; ⁵ INFN - Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania, Italy; ⁶ CNRS/IN2P3, IPN, Orsay Cedex, France

Content
Monte Carlo (MC) simulations are of utmost importance in Ion-therapy and for such applications the nuclear interaction models are crucial. Geant4 is one of the most widely used MC toolkit, also for Ion-therapy simulations. However, recent literature has highlighted the limitations of its models in reproducing the secondaries yields measure in ions interaction below 100 MeV/n. To mitigate such a shortcoming, we interfaced a model dedicated to these reactions with Geant4, BLOB (“Boltzmann-Langevin One Body”), obtaining promising results. The BLOB drawback is its computation time, indeed it takes several minutes to simulate one interaction. Even if from the BLOB final state it is possible to sample many physical states, such a running time is too large for any practical application. Therefore, we trained a Deep Learning algorithm, i.e. a Variational Auto-Encoder (VAE) to emulate the BLOB final states.
R-08 | Organic and Neutron Detectors

Arnold Burger (FISK)
R-08-01  4:00 PM

**Radiation Damage Characterisation of Organic Semiconductors**  (#1609)

**PhD/MD student Jessie A. Posar**¹, Prof. Marco Petasecca¹, Dr. Jeremy A. Davis¹, Prof. Paul Sellin², Dr. Matthew Griffith³, Prof. Michael Lerch¹, Prof. Anatoly Rosenfeld¹, Dr. Olivier Dhez⁴

¹ University of Wollongong, School of Physics, Wollongong, Australia; ² University of Surrey, Department of Physics, Guildford, UK; ³ University of Newcastle, Department of Physics, Callaghan, Australia; ⁴ ISORG, Grenoble, France

**Content**
The radiation damage of a fullerene-composite bulk heterojunction organic photodetector was characterised using the time-of-flight method for samples that have been exposed to ionising radiation up to a total accumulated irradiation dose of 40kGy. A picosecond pulsed laser incident upon the sample was used to inject photo-generated charge carriers within the bulk. The measurement of the carrier transient was used obtain the carrier drift time of the organic photodetector. The drift time at 20V bias was determined to be (2.727 ± 0.002)μs and (1.525 ± 0.002)μs for the photodetectors exposed to 0 and 40kGy, respectively. The decrease in drift time due to the accumulated radiation damage is associated with a lower charge collection efficiency. Calculation of the drift mobility shows an increase in carrier mobility as a function of radiation damage. This result combined with the drift time measurements suggests that the effective thickness of the device varies as a function of total ionising dose. A shorter lifetime of the charge carriers in the highly irradiated device is suggested to explain the faster rise and fall time of the transient time. The time-of-flight method has provided valuable insight into the effects of radiation damage upon the charge transport characteristics of organic compounds.

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R-08-02  4:18 PM

**Boosting Direct X-ray Detection in Organic Thin Films by Small Molecules Tailoring**  (#2321)

**Prof. Beatrice Fraboni**¹, Dr. Andrea Ciavatti¹, Dr. Laura Basiricò¹, PhD/MD student Ilaria Fratelli¹, Dr. Stefano Lai², Prof. Piero Cosseddu², Prof. Annalisa Bonfiglio², Prof. John E. Anthony³

¹ Bologna, Physics and Astronomy, Bologna, Italy; ² Cagliari, Electronic Engineering, Cagliari, Italy; ³ Kentucky, Center for for Applied Energy Research, Lexington, USA

**Content**
The attention towards organic electronics for the detection of ionizing radiation is rapidly growing among the international scientific community, due to the great potential of the organic technology to enable large-area conformable sensor panels. However, high-energy photon absorption is challenging as organic materials are constituted of atoms with low atomic numbers. Here it is reported how, by synthesizing new solution-processable organic molecules derived from 6,13-bis(trisopropylsilylethynyl)pentacene (TIPS-pentacene) and 2,8-Difluoro-5,11-bis(triethylsilylethynyl)anthradithiophene (diF-TES-ADT), with Ge-substitution in place of the Si atoms to increase the
material atomic number, it is possible to boost the X-ray detection performance of organic thin films on flexible plastic substrates. TIPGe-pentacene based flexible thin film transistors show an improved performance with higher mobility (0.4 cm² V⁻¹ s⁻¹) and enhanced X-ray sensitivity, up to 9.0 x 10⁵ µC Gy⁻¹ cm⁻³, with respect to TIPS-pentacene based detectors. Further enhancement in X-ray detection has been achieved by tuning the organic polycrystalline film grain size and surface coverage and packing, i.e., controlling the role and activity of electrically active defects. These results can be generalized to organic thin film detectors and clearly show how the versatile tailoring of organic molecules allows to improve X-ray sensitivity combining higher X-ray absorption, mechanical flexibility and large area processing.

R-08-03  4:36 PM

Developing organic semiconducting sensors for thermal neutrons
(#1689)

PhD/MD Prodromos Chatzispyroglou¹, Dr. Sion Richards², Dr. Mark Baker¹, Dr. Paul Seller², Prof. Joseph L. Keddie¹, Prof. Paul J. Sellin¹

¹ University of Surrey, Faculty of Engineering and Physical Sciences, Guildford, UK; ² Science and Technology Facilities Council, Rutherford Appleton Laboratory, Didcot, UK

Content

Recent developments in organic semiconductor technology has resulted in the ability to fabricate large area organic semiconductors using simple deposition techniques. Here we propose the development of a novel organic-inorganic composite material for thermal neutron detection as a potential alternative to current ³He-based detectors that can be prohibitively expensive. A semiconducting polymer, poly(triarylamine), is used as the active electrical component of the sensor and boron nanoparticles embedded in the polymer matrix provide neutron sensitivity. The large thermal neutron capture cross-section of ¹⁰B allows for the efficient capture of thermal neutrons and the subsequent reaction products deposit energy in the polymer for detection. The quantum efficiency of the sensor is a function of the film thickness and the homogeneity of the boron dispersion. Films as thick as 90 μm have been achieved by using a high molecular weight of the polymer with high cohesion resulting from molecular entanglements. Surfactants are used to stabilise the boron dispersion in solvent and to suppress the formation of agglomerated boron nanoparticles, allowing for tighter packing during film formation. Our method fabricates novel materials having an equivalent atom density of up to 8 % of natural amorphous boron. The high boron loading coupled with the large film thickness yields a quantum efficiency estimate of 3 – 4 %.
Investigation of JTE-Mesa Terminated Epilayer PiN SiC Detector for fast Neutron Diagnostics (#1624)

Dr. Shuqing Jiang\textsuperscript{1}, Dr. Cao Han\textsuperscript{2}, PhD/MD student Haili Huang\textsuperscript{2}, Dr. Faqiang Zhang\textsuperscript{1}, Dr. Hui Guo\textsuperscript{2}

\textsuperscript{1} China Academy of Engineering Physics, Institute of Nuclear Physics and Chemistry, Mianyang, China; \textsuperscript{2} Xidian University, Key Laboratory of Wide Band-Gap Semiconductor Materials and Devices, x'ian, China

Content
The JTE-mesa based optimized design was used to fabricate the fast neutron detector using 100μm n-type 4H-SiC epitaxial layer with a doping concentration of $3 \times 10^{14}$ cm$^{-3}$. Curved mesa structure, double zone JTE and NO annealing was introduced to reduce the leakage current. The leakage current of 6.5mm×6.5mm detector at 1500V was confined less than 100 nA to create depletion depth up to 70μm. Characteristics of the detector was evaluated on D-T neutron source driven by accelerator, the observed FWHM of $^{12}$C (n , α)$^{9}$Be reaction as energy resolution is 2.4% produced by 14.1 MeV D-T neutrons.

Simulation of signal formation and imaging in a dual-sided micro-structured semiconductor neutron detector (#1143)

PhD/MD student Sanchit Sharma\textsuperscript{1}, PhD/MD student Diego Laramore\textsuperscript{1}, Dr. Steven L. Bellinger\textsuperscript{2}, Dr. Walter McNeil\textsuperscript{1}, Dr. Amir A. Bahadori\textsuperscript{1}

\textsuperscript{1} Kansas State University, Manhattan, USA; \textsuperscript{2} Radiation Detection Technologies, Inc, Manhattan, USA

Content
Dual-sided micro-structured neutron detectors have the benefit of doubling neutron detection efficiency by staggering $^{6}$LiF-filled trenches between the top and bottom surface of a silicon diode. This produces a more complex electric field distribution and depletion characteristics in the diode and creates a non-direct path for signal carrier transport between device electrodes. Signal formation in this system is simulated with the use of COMSOL Multiphysics for semiconductor physics, Geant4 for radiation transport and interaction modeling, and AllPix\textsuperscript{2} for mobile charge carrier transport and total charge collection determination. The results of this simulation work provide estimates of charge cluster event shape and intensity for a pixel array configuration that matches the TimePix3 read-out system. In addition, the imaging performance for transmission radiography is demonstrated with simple two-dimensional shape in a gaussian beam of thermal neutrons. Simulated neutron detection efficiency was 56.11%.
8:00 AM – 10:00 AM

Exchange Auditorium

MP-3 | MIC Featured Speakers

Dimitra G. Darambara (London)
Suleman Surti (Philadelphia)
MP-3-01  8:00 AM

EXPLORER Total Body PET: Progress, Challenges and Opportunities

Prof. Ramsey D. Badawi

UC Davis, Davis, USA

"Set-the-Scene" presentation by Prof. Ramsey D. Badawi, Professor of Radiology and Biomedical Engineering, Vice-Chair for Research, Department of Radiology and Chief of the Division of Nuclear Medicine, UC Davis, USA

MP-3-02  8:30 AM

MOLECUBES - a sinusoidal journey from academic lab to startup company

Roel Van Holen

MOLECUBES, Ghent, Belgium

"Set-the-Scene" presentation by Dr. Roel Van Holen, CEO of MOLECUBES- High-end bench-top preclinical imaging, Ghent, Belgium

MP-3-03  9:00 AM

MARS: From the Higgs Boson to Molecular Radiology

Prof. Anthony Butler

Department of Radiology, University of Otago, Christchurch, New Zealand

"Set-the-Scene" presentation by Prof. Anthony Butler, Professor and Head of Department, Department of Radiology, University of Otago; Research Professor, Department of Chemical and Physical Sciences, University of Canterbury; Consultant Radiologist, Canterbury District Health Board; Chief Medical Officer, MARS Bioimaging Ltd; and Engineer, CMS, Medipix3, and Medipix4 collaborations, CERN
MP-3-04  
9:30 AM

Precision Imaging for Image-Guided Radiotherapy

Prof. Uwe Oelfke

The Institute of Cancer Research & The Royal Marsden NHS Foundation Trust, London, UK

"Set-the-Scene" presentation by Prof. Uwe Oelfke, Deputy Head of Radiotherapy and Imaging, Head of Joint Department of Physics, Head of Center for Cancer Imaging and Team Leader, Radiotherapy Physics Modelling at the Institute of Cancer Research and the Royal Marsden NHS Foundation Trust
N-27 | Neutron Detectors and Gamma Imaging III

Georgia A. de Nolfo (Greenbelt)
Daniel Shy (Ann Arbor)

Imaging systems
Advancements in the Mira Time Encoded Gamma-Ray Imaging System Using Subpixel Position Sensing of 3D Pixelated CdZnTe Detectors (#1409)

Daniel Shy1, Dr. Yuefeng Zhu1, Dr. Scott Thompson2, Dr. Zhong He1

1 University of Michigan, Nuclear Engineering and Radiological Sciences, Ann Arbor, USA; 2 Idaho National Laboratory, Nuclear Nonproliferation Group, Idaho Falls, USA

Content
Time encoded imaging is a technique to image gamma rays by using a coded aperture to modulate the gamma-ray signal spatially and temporally. The Mira system constructed by Dr. Steven Brown utilizes an analog 3D CdZnTe detector system. In this study, we upgraded to a more advanced digital-ASIC readout detector system that can provide the subpixel position of each gamma interaction. This has shown an improvement in spatial resolution and signal-to-noise ratio in MLEM images. Additional algorithms have been implemented to account for sources that are distributed in depth away from the detector.

Demonstration of 3D-imaging of 137Cs using Compton camera aboard drone in Fukushima (#1701)

M.Sc./M.A. student Takuya Kurihara, Prof. Jun Kataoka, M.Sc./M.A. student Saku Mochizuki, M.Sc./M.A. student Leo Tagawa, M.Sc./M.A. student Kazuhisa Tanada, M.Sc./M.A. student Takuya Maruhashi

Waseda University, Department of Pure and Applied Physics, Graduate School of Advanced Science and Engineering, Shinjuku, Japan

Content
After the nuclear disaster at the Fukushima Daiichi nuclear power plant in 2011, many decontamination operations were carried out. However, many contaminated areas still remain, especially in the forests and woodlands near Fukushima. In this study, we built a compact measurement system for local decontamination purposes by combining a drone and a Compton camera, and established a method for the detailed mapping of the results. Because the Compton camera provides only the direction of incident gamma rays, we first developed a simple method for converting images onto a plane, such as the ground surface. Then, we measured the distribution of the gamma rays at the ground and 10m above the ground. The comparison of these measurements confirmed that the result of the ground-based and aerial measurements are consistent with each other. Finally, we took measurements of bushes and trees from two points for the purpose of 3D-imaging, i.e., “stereo measurement” and succeeded in acquiring the detailed 3D image.
Overview of current results for the single-volume neutron scatter camera (#1894)

Dr. Josh Brown¹, Dr. Erik Brubaker¹, Dr. Belkis Cabrera-Palmer¹, Dr. Joseph S. Carlson¹, Ryan Dorrill², Andrew Druetzler², Dr. Jeffrey W. Elam³, Dr. Michael Febbraro⁴, Dr. Patrick Feng¹, Micah Folsom⁴, Dr. Aline Galindo-Tellez⁵, Dr. Bethany L. Goldblum⁵, Dr. Paul Hausladen⁴, Nathaniel Kaneshige², Kevin Keefe², Dr. Thibault Laplace⁵, Dr. John Learned², Dr. Anil Mane⁵, Dr. Juan Manfredi⁵, Dr. Peter Marleau¹, Dr. John Mattingly⁶, Mudit Mishra⁶, Ahmed Moustafa⁶, Dr. Jason Nattress⁴, Dr. Kurtis Nishimura², John Steele¹, Dr. Melinda Sweany¹, Kyle Weinfurther⁶, Dr. Klaus Ziock⁴

¹ Sandia National Laboratories, Livermore, USA; ² University of Hawaii at Manoa, Honolulu, USA; ³ Argonne National Laboratory, Lemont, USA; ⁴ Oak Ridge National Laboratory, Oak Ridge, USA; ⁵ University of California at Berkeley, Berkeley, USA; ⁶ North Carolina State University, Raleigh, USA

Content

We present the current status of work toward a single-volume neutron scatter camera (SVSC), as well as lessons learned and planned directions for ongoing efforts. Emission imaging of fission-energy neutrons can be used to characterize the spatial distribution of special nuclear material (SNM), or to improve SNM detection in some scenarios. Neutron scatter cameras, analogous to Compton imagers for gamma rays, have a wide field of view, good event-by-event angular resolution, and spectral sensitivity; but to date they have suffered from large size and/or poor efficiency. We are developing smaller and higher-efficiency scatter cameras by eliminating air gaps and detecting both neutron scatters in a compact active volume. This effort relies on recent technological advances that enable excellent time resolution, such as fast photodetectors and fast readout electronics. The SVSC collaboration is pursuing two concepts for a compact, high-efficiency system, namely the monolithic scintillator design and the optically segmented scintillator design; these differ fundamentally in how they collect the emitted scintillation light. For each of these approaches, we will describe results from, and evaluations of, recently constructed prototype systems. We will also present highlights from related work to develop and/or characterize key components of the imagers: fast organic scintillators, photodetectors, electronics, and reconstruction algorithms. We will conclude by summarizing what has been learned through this development effort to date, comparing and contrasting the two approaches, and outlining plans for the next iteration of prototype design and construction.
Design and Characterization of a Platform for Simultaneous Gamma Ray and Neutron Source Mapping with Scene Data Fusion (#2524)

Joshua W. Cates¹, Ryan Pavlovsky¹, Brian Quiter¹, Victor Negut¹, Alex Moran¹, Kai Vetter¹,²

¹ Lawrence Berkeley National Laboratory, Applied Nuclear Physics, Berkeley, USA; ² University of California Berkeley, Nuclear Engineering, Berkeley, USA

Content
Scene Data Fusion (SDF), developed at Lawrence Berkeley National Laboratory (LBNL), enables the rapid localization and identification of distributed and point radioactive sources in 3D and in real-time. High resolution, centimeter-accurate 3D maps are generated from contextual sensor data (e.g. from LiDAR, visual sensors, etc.), fused with radiation data, and streamed to the user in real-time. SDF has been developed and successfully demonstrated in our compact, lightweight contextual sensor and software suite, the Localization and Mapping Platform (LAMP). Recently, we have extended the SDF capabilities from the detection and mapping of gamma-rays to neutrons, utilizing the availability of the new generation of so-called elpasolite scintillators such as CLLBC, which allow simultaneous gamma-ray and neutron detection. In this work, we present the design and characterization of this platform, Neutron-Gamma LAMP (NG-LAMP), comprising a 2x2 array of 2.4x2.4x5.0 cm³ CLLBC crystals and associated electronic readout, coupled to a LAMP platform. We report on key system metrics: Global energy resolution ~3.5% at 662 keV and its temperature stability, gamma and neutron detection sensitivity, optimization of a polyethylene detector housing to maximize thermal neutron detection, and system performance at high count rates. We also present imaging and mapping capabilities of the system, including the simultaneous detection, localization, and visualization of gamma ray and neutron sources in real-time.

Feasibility study of a Compton Camera for nuclear contamination scenarios with varying thicknesses of concrete material (#2071)

PhD/MD student Jaimie M. Platt¹, Dr. Andrew Boston¹, Dr. Laura Harkness-Brennan¹, Dr. Helen Boston¹, Prof. Paul Nolan¹, Dr. Daniel Judson¹, PhD/MD student Ellis Rintoul¹, PhD/MD student Adam Caffrey¹, PhD/MD student Thomas Woodroof¹, Dr. John Simpson², Ian Lazarus², PhD/MD student Sarah Kalantan¹, PhD/MD student Craig Reid¹, PhD/MD student Alice Newport¹, PhD/MD student Hamed A. Alshammari¹

¹ University of Liverpool, Department of Physics, Liverpool, UK; ² STFC, Daresbury Laboratory, Warrington, UK

Content
The University of Liverpool has developed a mobile Compton Camera Gamma-Ray Imaging (GRI+) system for nuclear-decommissioning applications. The sensitivity of the system to a radioactive source through varying

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thicknesses of concrete material was investigated to provide a basis for depth-profiling and quantification. Images can be produced from analysing Compton scattering between a front layer Lithium-drifted Silicon (Si(Li)) detector and a second layer High-Purity Germanium (HPGe) detector, which are both position-sensitive due to electrical segmentation. The data which can create the Compton Image also produces an energy spectrum. This energy spectrum sums the energy deposited from single pixel events from interactions in both the Si(Li) and HPGe detectors. Varying thicknesses of concrete up to 21cm were placed in front of a 15.6MBq caesium-137 point source at a standoff distance of 65cm from the face of the Si(Li), replicating a wall in an in-situ measurement. The peak-to-total ratio, a value comparing the net counts in a photopeak area against the gross total number of events in the spectrum, was determined for the 662keV photopeak in each spectrum produced for the differing thicknesses of concrete. A linear relationship is observed between the natural log of the peak-to-total ratio and the thickness of concrete. The sensitivity of the peak-to-total ratio could be improved by applying a positional gate on the Compton image and recreating the energy spectrum. An essential condition in nuclear decommissioning is the ability to reject the presence of any high-activity off-angle sources that may be present during the measurement. This positional gating would focus entirely on the source being measured and reject any background sources that may be in the vicinity. As well as assessing the image of a characterised area, these results could provide a basis for in-situ measurements to quantify the amount of concrete material in front of a radioactive source.

N-27-06 9:30 AM

A monolithic single-volume scatter camera (#1502)

Jason Nattress1, Micah Folsom2,1, Joshua A. Brown3, Lorenzo Fabris1, Klaus-Peter Ziock1, Belkis Cabrera-Palmer3, Jason Hayward2,1, Erik Brubaker3, Paul Hausladen1

1 Oak Ridge National Laboratory, Oak Ridge, USA; 2 University of Tennessee, Knoxville, USA; 3 Sandia National Laboratories, Livermore, USA

Content

The present work shows the first results using a neutron scatter camera that consists of a single volume of organic scintillator. Traditional neutron scatter cameras rely on observation of neutrons that interact in two distinct detectors. The deposited energies, time difference, and distance between the detectors are then used to calculate the cone of directions from which the neutron was incident on the detector. Although these systems possess good signal-to-background and spectral capability, they are typically large and suffer from poor neutron detection efficiency due to their inherent geometrical constraints. To increase the neutron detection efficiency while reducing the overall geometric footprint, Oak Ridge National Laboratory (ORNL) and Sandia National Laboratories (SNL) constructed a prototype single-volume monolithic-neutron-scatter camera. The compact prototype consists of a single contiguous (5 cm)3 cube of Eljen-204 plastic scintillator optically coupled to two Hamamatsu H12700 multi-anode photomultiplier tubes (MaPMTs). The output of each anode of the MaPMTs is separately digitized in order to infer the times and locations of detected scintillation photons. Using these data, the positions, energies, and times of multiple neutron interactions in the scintillator are directly reconstructed. In the current work, we present validating single and multisite localization with scintillating spheres suspended in non-scintillating liquid at known locations as well as our preliminary experimental event reconstruction results from the prototype imager. The performance of neutron-scatter event reconstruction is quantified for three individual cases-- counting statistics alone, counting statistics combined
with measured cross-talk, and measured experimental data. Limitations of the method due to effects such as electronic cross-talk between the individual anodes will be highlighted.
8:00 AM – 9:48 AM

Charter 2

N-28 | Analog and Digital Electronics III

Gabriella Carini (Upton)
Davide Mezza (Villigen)
N-28-01 8:00 AM

Low-Noise and Low-Power RIGEL ASIC for Pixelated Silicon Drift Detector for Space Applications (#2251)

PhD/MD Massimo Gandola\textsuperscript{1,2}, PhD/MD Marco Grassi\textsuperscript{3}, PhD/MD student Martina Sammartini\textsuperscript{1,2}, PhD/MD student Filippo Mele\textsuperscript{1,2}, Prof. Piero Malcovati\textsuperscript{3}, Prof. Giuseppe Bertuccio\textsuperscript{1,2}

\textsuperscript{1} Politecnico di Milano, Department of Electronics, Information and Bioengineering, Como, Italy; \textsuperscript{2} INFN - National Institute of Nuclear Physic, Sezione di Milano, Milano, Italy; \textsuperscript{3} Università di Pavia, Department of Electrical, Computer, and Biomedical Engineering, Pavia, Italy

Content

An Application Specific Integrated Circuit (ASIC), called RIGEL, designed for a Silicon Pixelated Drift Detector (PixDD) devoted to space applications is presented. The low leakage current (less than 1 pA at +20 °C) and anode capacitance (less than 50 fF) of the pixelated detector, combined with a low-noise electronics readout, permit to reach a high spectroscopic resolution performance even at room temperature. The RIGEL ASIC has been manufactured in 0.35-μm CMOS technology and it is composed of 128 readout channels called Readout Pixel Cells (RPCs), 16 integrated 10–bits Wilkinson ADCs, a configuration register and a trigger management circuit. The characterization of a single RPC has been carried out and the main features are: eight selectable peaking times from 0.5 μs to 5 μs, an equivalent input energy range up to 30 keV, and a power consumption less than 550 μW for channel. The RPC has been tested also with a 4x4 prototype PixDD and a resolution of 167 eV Full Width at Half Maximum (FWHM) at 5.9 keV line of $^{55}$Fe at 0°C and 1.5 μs of peaking time has been measured.

N-28-02 8:18 AM

HEXID3: A Low-Power, Low-Noise Pixel Readout ASIC for High-Energy and Spatial Resolution X-ray Detectors (#1815)

Dr. Shaorui Li\textsuperscript{1}, Yuan Mei\textsuperscript{1}, Qianteng Wu\textsuperscript{4}, Wenbin Hou\textsuperscript{2}, Dr. Gianluigi De Geronimo\textsuperscript{2}, Donald Pinelli\textsuperscript{1}, Abdul Rumaiz\textsuperscript{1}, Wei Chen\textsuperscript{1}, David P. Siddons\textsuperscript{1}, Ryan Tappero\textsuperscript{1}, Jason Tang\textsuperscript{3}, Fabian Kislat\textsuperscript{5}, Richard Bose\textsuperscript{3}, Henric Krawczynski\textsuperscript{3}

\textsuperscript{1} Brookhaven National Laboratory, Upton, USA; \textsuperscript{2} Stony Brook University, Stony Brook, USA; \textsuperscript{3} Washington University in St. Louis, St. Louis, USA; \textsuperscript{4} University of California, Los Angeles, USA; \textsuperscript{5} University of New Hampshire, Durham, USA

Content

We present a new generation of the low-power, low-noise prototype pixel readout application specific integrated circuit (ASIC) for Hyperspectral Energy-resolving X-ray Imaging Detectors (HEXID) with expanded functionalities and higher spatial resolution. The ASICs provide 32-by-32 channels to read out positive or negative charges from 32-by-32 hexagonal detector arrays, at a pitch size ranging from 100 μm to 150 μm, to achieve very high spatial and energy simultaneously, in three spectroscopic imaging detectors for space missions, basic energy science, biological and
environmental research. The target energy resolution is less than 200 eV FWHM at 5.9 keV, at a power consumption of lower than 1 mW per channel.

N-28-03 8:36 AM

**Spectroscopic Performance of TERA: Fast Multichannel Analog Pulse Processor ASIC for X-ray Detection Applications** (#2076)

**Idham Hafizh**²,¹, Marco Carminati²,¹, Carlo E. Fiorini²,¹

¹ INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy; ² Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Italy

**Content**

This work reports the spectroscopic performance of the second release of TERA (Throughput Enhanced Readout ASIC), a multichannel analog pulse processor (APP) ASIC suitable for detectors in ultra-high rate X-ray detection applications (>1Mcps/channel). The chip has been developed to process signals coming from Silicon Drift Detectors (SDDs) coupled to reset-type Charge Sensitive Amplifiers (CSA). The demonstrator chip is composed of 4 parallel readout channels, each channel is composed by 7th-order semi-Gaussian shaping amplifier with controllable shaping times and dynamic range, followed by a peak stretcher and an analog memory. Each pair of channels can be optionally digitized by 12-bit on-chip ADC, providing the maximum sampling rate up to 5MHz. Compared to the first release of TERA that has been presented last year, improved design has been implemented on the second release, enabling to achieve simultaneously high throughput and satisfactory energy resolution. In 55-Fe spectroscopy measurements, using the shortest pulse width of 200ns, FWHM Mn-Kα line of 162.9eV and 206eV were obtained at input rate 6kcps and 1.9Mcps, respectively. At 1.9Mcps input rate, 1.1Mcps throughput was achieved. High-rate performances are, to our knowledge, the best ones for a Spectroscopy analog ASIC and are close to the ones achievable from standard DPPs. Therefore, TERA can represent an attractive detector pulse processing solution for low-power high-density multichannel detection systems.

N-28-04 8:54 AM

**The Integrated Analog Signal Processor for the Readout of the GAPS Si(Li) Tracker** (#1222)

**Massimo Manghisoni**¹,², Valerio Re²,¹, Elisa Riceputi¹,², Mauro Sonzogni¹,², Lodovico Ratti³,², Lorenzo Fabris⁴, Mirko Boezio⁵, Gianluigi Zampa⁵

¹ University of Bergamo, Bergamo, Italy; ² INFN, Pavia, Pavia, Italy; ³ University of Pavia, Pavia, Italy; ⁴ Oak Ridge National Laboratory, Oak Ridge, USA; ⁵ INFN, Trieste, Trieste, Italy

**Content**
This work is about the design and the experimental characterization of the first prototypes of a chip developed for the read out of lithium-drifted silicon, Si(Li), detectors of the General Antiparticle Spectrometer experiment to search for dark matter. The instrument is designed for the identification of antideuteron particles from cosmic rays during an Antarctic balloon mission scheduled for late 2021. A low-noise analog front-end, featuring a dynamic signal compression to comply with the wide input range, has been designed in a commercial 180 nm CMOS technology. The channel has been integrated in two ASICs fabricated in 2018. The paper will provide a thorough description of the design criteria and the architecture of the two prototypes and a summary of the results from their characterization.

**N-28-05**

**9:12 AM**

Advanced System in FPGA for 3D (X, Y, t) Imaging with Cross Delay-Lines (#1998)

Dr. Nicola Lusardi¹, PhD/MD student Fabio Garzetti¹, PhD/MD student Nicola Corna¹, M.Sc./M.A. student Antonio Reale¹, Prof. Angelo Geracci¹, M.Sc./M.A. student Edvard Dobovicnik², Prof. Giuseppe Cautero³, Dr. Carlo Dri³, Dr. Rudi Sergo³, **Dr. Luigi Stebel³**

¹ Politecnico di Milano, Department of Electronics, Information and Bioengineering, Milano, Italy; ² University of Trieste, DEEI, Trieste, Italy; ³ Elettra Sincrotrone Trieste S.C.p.A., Detectors & Instrumentation Laboratory, Basovizza, Trieste, Italy

**Content**

Time-resolved experiments often need detection devices able to provide information about position and arrival time of each detected event. Time resolution is a fundamental requirement for these devices, along with the high versatility and fast real-time computing of the acquisition system. Therefore, it is often fundamental to have detectors able to provide all at once the XY position and the arrival time of each detected event. In this scenario, Cross Delay-Lines detectors (CDL), which use arrival time information also for position detection, are the most suited instruments for this task. Typical architectures, based on Time-to-Digital Converters (TDC) followed by a Field Programmable Gate Array (FPGA), combine very fast parallel computing with a time precision better than hundreds of picoseconds, allowing to perform state-of-the-art time-resolved experiments. Nevertheless, time resolution is still a limiting factor, in particular for imaging applications.

In 2017 at Nuclear Science Symposium, inside “Development of fully FPGA-based 3D (X, Y, t) detection systems using multi-channel Tapped Delay-Line Time-to-Digital Converter with Cross Delay-Line detectors” we presented a new approach, combining FPGA-based multi-channel TDC and an efficient multipurpose readout logic to greatly improve the overall performance and versatility of CDL detector systems. Starting from that, we have completely redesigned the hardware and, thanks to the reconfigurability offered by the FPGA, we have improved the firmware of the TDC reducing the Integral Non-Linearity error (INL) from 80 ps over 50 ns of full scale-range to 16 ps over 2.6 μs, maintaining resolution up to 1 ps and single-shot channel precision lower then 12 ps r.m.s.

This has greatly improved the overall performance of the detected image of CDL detector systems allowing a spatial precision up to 30 μm with local aberrations due to the INL lower than 40 μm. The increasing in accuracy makes negligible these artefacts.
A Multi-channel Picosecond-Precision CMOS Time-to-Digital Converter for Medical Imaging Systems (#1721)

Dr. Xiaochao Fang\textsuperscript{1,2}, Rachid Sefri\textsuperscript{1,2}, Dr. Frederic Boisson\textsuperscript{1,2}, Dr. David Brasse\textsuperscript{1,2}

\textsuperscript{1} Université de Strasbourg, Institut Pluridisciplinaire Hubert Curien (IPHC), Strasbourg, France; \textsuperscript{2} IPHC - CNRS/IN2P3, Strasbourg, France

Content

A Multi-channel Picosecond-Resolution CMOS time-to-digital converter integrated circuit has been designed. Time interval measurement is based on a counter and two-level interpolation realized with stabilized delay lines. Three-level conversion structure enables first the use of a low frequency reference clock (125 MHz) and a large dynamic measurement range with a high resolution. The counter and the DLLs (delay locked loop) in the two-level interpolation are common for all channels in order to well adapt to multi-channel applications. A Digitally-Controlled Oscillator (DCO) used in the DLL avoids using a long delay chain and thus minimizes the mismatch. The third-level interpolation is based on a Vernier method to bypass the technology limitation. A single-stage delay loop used in the Vernier method minimizes the length of the delay line and thus improves the linearity. The key benefits of the proposed TDC are a reduction of the conversion jitter and a better design flexibility to enhance matching performances of delay cells. This approach reaches high conversion linearity regardless of the process technology. A prototype of 16 channels has been implemented in 130 nm CMOS technology. Simulation results show that the TDC achieves a bin size of 3.9 ps rms in a long 800 ns timing window. The differential and integral nonlinearities (DNL and INL) are 0.023 LSB and 0.049 LSB with a standard deviation of 0.022 LSB and 0.021 LSB respectively. Such a TDC will find useful applications in tomographic imaging systems, where several time-correlated single photon counting channels need to be used in a massively parallel configuration.
N-29 | Instrumentation and Concepts for Nuclear Security I

Ikuo Kanno (Kyoto)
David Petersen
Laboratory tests of the C-BORD Rapidly Relocatable Tagged Neutron Inspection System for the detection of explosives and illicit drugs in cargo containers (#1008)

Dr. Alix Sardet¹, Dr. Alix Sardet¹, Dr. Bertrand Pérot¹, Dr. Bertrand Pérot¹, Dr. Cédric Carasco¹, Dr. Cédric Carasco¹, Guillaume Sannié², Guillaume Sannié², Dr. Sandra Moretto³, Dr. Sandra Moretto³, Prof. Giancarlo Nebbia³, Prof. Giancarlo Nebbia³, Dr. Cristiano Fontana³, Dr. Cristiano Fontana³, Dr. Félix Pino³, Dr. Félix Pino³

¹ CEA, DEN, Cadarache, DTN, SMTA, Nuclear Measurement Laboratory, Saint-Paul-lez-Durance, France; ² CEA, LIST, Saclay, DRT, LIST, DM2I, SCI, LCAE, Gif-Sur-Yvette, France; ³ INFN di Padova, Dipartimento di Fisica e Astronomia, Padova, Italy

Content
In the frame of C-BORD project (H2020 program of the EU), a Rapidly Relocatable Tagged Neutron Inspection System (RRTNIS) has been developed for nonintrusive inspection in cargo containers aimed at explosives and other illicit goods detection. Twenty large volume NaI detectors are used to determine the elements composing inspected materials from their specific gamma spectra signatures induced by fast neutrons. The RRTNIS inspection is focused on a specific suspect area selected by X-ray radiography. An unfolding algorithm decomposes the energy spectrum of this suspect area on a database of pure element gamma signatures. A first classification is performed between inorganic materials like metals, ceramics or chemicals, and organic materials like wood, fabrics or plastic goods. Concerning organic materials, the obtained elemental proportions of carbon, nitrogen, and oxygen allow discriminating explosives from illicit drugs and benign substances. This paper reports on the final laboratory tests performed at CEA Saclay, France, to assess the RRTNIS detection performances before further demonstration tests in a real seaport environment. Simulants of explosives and illicit drugs have been hidden at different depths inside iron or wood cargo materials, which are representatives of the different neutron and gamma attenuation properties encountered in real cargo containers. Hundreds of experiments have been performed, showing that a few kg of explosives or narcotics can be detected by the RRTNIS in 10 min inspections.

Enhanced Material Discrimination by Multiple-Monoenergetic, Spectroscopic, Gamma-Neutron Transmission Radiography (#1807)

Jason Nattress¹, Sean McGuinness², Graham Peaslee², Igor Jovanovic¹

¹ University of Michigan, Department of Nuclear Engineering and Radiological Sciences, Ann Arbor, USA; ² University of Notre Dame, Department of Physics, Notre Dame, USA
Content

The challenge of uranium and plutonium detection and differentiation in radiography of optically thick and/or heavily shielded objects is central to some of the most important nuclear security-relevant scenarios such as cargo scanning. More broadly, the ability to detect substances over a broad spectrum of atomic numbers in highly opaque configurations could benefit a wider range of security, safety, and industrial applications. It has been recently experimentally demonstrated that the multi-particle, multiple-monoenergetic spectroscopic transmission radiography has a significant potential to enhance material discrimination, for example among high-Z elements, where gamma/X-ray radiography faces significant limitations. Ion-driven nuclear reactions represent a versatile source of highly penetrating, multiple-monoenergetic gamma rays and neutrons to enable such measurements. Gamma-ray and neutron transmission measurements can be combined into multiple two-dimensional discriminants that can be directly related to corresponding photon and neutron cross sections. Here, we present a significant extension of this methodology by combining up to five spectroscopic signatures (corresponding to two gamma-ray and three fast neutron characteristic energies from a deuteron-driven boron nitride target) and using them in conjunction with principal component analysis to further enhance the material contrast. We present two- and three-dimensional geometrical representations of the results of such transmission radiographic measurements that can visually aid material discrimination, determination of opacity, detection of layered multi-element structures, and non-natural isotopic mixes.

N-29-03 8:36 AM

Compact Superconducting Cyclotron-based Monoenergetic Gamma Radiography System for Special Nuclear Material Detection (#1892)

PhD/MD student Hin Y. Lee, PhD/MD student Steven Jepeal, Dr. Brian Henderson, Dr. Richard Lanza, Dr. Areg Danagoulian

Massachusetts Institute of Technology, Nuclear Science and Engineering, Cambridge, USA

Content

The smuggling of special nuclear materials (SNM) presents a significant threat to national security due to their potential for nuclear terrorism. The detection of such materials by passive detection is challenging due to the weak signatures of intrinsic radiations that can be easily shielded. Hence, active interrogation techniques and gamma radiography are more effective and preferable for screening cargoes potentially containing shielded SNM. However, most of these systems, such as ones that utilize dual-energy bremsstrahlung beams, could induce high radiation doses to potential stowaways. Furthermore, some of those systems are large and impractical as a mobile system. Here, I present a new radiographic system and technique to simultaneously quantify the effective atomic number (Z-eff) and the areal density of mock cargoes. In this new system, a 12 MeV compact superconducting cyclotron is used to simultaneously produce 4.44, 6.13, 6.92, and 7.12 MeV photons through (p,p gamma) reactions on graphite and water. The gammas are then used to perform Multiple Monoenergetic Gamma Radiography (MMGR). By exploiting the Z dependence of photon interactions at different energies, the Z-eff and the areal density of interrogated materials can be reconstructed. Unlike prior RFQ-based systems which used (d,n gamma) reactions, this methodology produces almost no neutrons, thus lowering material activation and radiation doses. The use of superconducting technology in this new cyclotron has also lead to a compact, low power consumption system. More importantly, the
proton-based nuclear reactions on C-12 and O-16 targets can result in gamma emission intensities on the order comparable to that of bremsstrahlung systems. In this presentation, experimental prediction results involving homogeneous and heterogeneous cargoes ranging from $Z \approx 13$-$92$ and areal density $\approx 38$-$120$ will demonstrate accurate reconstruction of $Z$-effective and areal density to within 6.2 and 3.9 respectively.

**N-29-04** 8:54 AM

**Neutron Imaging and Spectroscopy of Plutonium Using a Handheld Dual Particle Imager (#1259)**

**William M. Steinberger**, Nathan Giha, Michael Bondin, Dr. Shaun D. Clarke, Prof. Sara Pozzi

*University of Michigan, Ann Arbor, USA*

**Content**

A prototype handheld dual particle imager composed of stilbene bars coupled to silicon photomultipliers was used to measure a 4.5 kg sphere of alpha-phase weapons-grade plutonium and a canister containing 3.4 kg of plutonium oxide (7% $^{240}$Pu and 93% $^{239}$Pu). Each object was measured independently and both objects were measured in the same field of view separated by 50 cm. Experimental results of the measurements conducted are presented. These results demonstrate the ability of the handheld dual particle imager to image and obtain neutron spectroscopic information for sources that would be of great interest for nuclear safeguards and emergency response applications.

**N-29-05** 9:12 AM

**CLLBC Neutron-Gamma Vest-wearable Isotope Identifier (#1341)**

**Andrey Gueorgueiv**, Dr. Jaroslaw Glodo, Dr. Kanai Shah, Won Kim, Andrey Gueorgueiv

$^1$ Radiation Monitoring Devices Inc, Watertown, USA; $^2$ Draper Laboratory, Cambridge, USA

**Content**

$\text{Cs}_2\text{LiLa(Br,Cl)}_6$ (CLLBC) crystals from the elpasolite family are dual-mode detectors with excellent gamma-ray resolution and efficient neutron detection with pulse shape discrimination (PSD) capability for simultaneous gamma-neutron detection. These properties enabled the development of a compact, lightweight (<700g), low power (>32 days battery operation), high energy resolution (<4% at 662keV), vest-wearable radioisotope identification system for use in detection, localization and identification of nuclear materials. The Elpasolite Dual Mode Vest Kit (E2MV-K) system was designed with the primary goal to be easily worn and used by nuclear search teams. The system consists of 4 detection elements, each one incorporating CLLBC crystal assembled with an array of silicon photomultipliers (SiPM); and with associated processing, data acquisition, MCA and wireless (BLE) electronics. The system design separates the detection elements and its electronics from the analysis engine and graphical user interface (GUI), producing a multi component system interconnected via a wireless link. An Android COTS smartphone is used as an
analysis component by integrating Sandia National Lab’s GADRAS isotope identification algorithm. An Android App is interfacing with the Android Tactical Assault Kit (ATAK) and provides wireless real-time connectivity to CBRNE situational awareness architectures, such as Tactical Assault Kit (TAK) and Mobile Field Kit (MFK). This work has been supported by the US Defense Threat Reduction Agency, under competitively awarded contract HDTRA1-19-C-0024. This support does not constitute an express or implied endorsement on the part of the Government. DISTRIBUTION A: Approved for public release.

N-29-06

9:30 AM

A Compact Epithermal Neutron Resonance Transmission Apparatus for Nuclear Security Applications (#2525)

PhD/MD student Ethan A. Klein, M.Sc./M.A. Ezra M. Engel, Prof. Areg Danagoulian

Massachusetts Institute of Technology, Department of Nuclear Science and Engineering, Cambridge, USA

Content

Neutron resonance transmission analysis uses resonant absorption of epithermal neutrons in a beam to infer the absolute isotopic concentrations in a target object. In the past, this technique involved large user facilities and complex detector systems. However recent advances in compact neutron source intensity have made portable neutron imaging designs increasingly feasible. This work describes the Monte Carlo based design of a compact epithermal neutron resonance transmission radiographic instrument which uses a moderated, compact deuterium-tritium neutron source and an epithermal neutron detector. Such an instrument would have a wide range of imaging applications and would be especially impactful for such scenarios as nuclear inspection and arms control verification exercises, where system complexity and mobility may be of critical importance. The Monte Carlo simulations presented in this work demonstrate highly accurate time-of-flight reconstructions for transmitted energy spectra, capable of differentiating isotopic compositions of nuclear material with high levels of accuracy. A new generation of miniaturized and increasingly more intense neutron sources will allow this technique to achieve faster and more rapid measurements with greater precision.
N-30 | Strip and Pixel II

Konstantin D. Stefanov (Milton Keynes)
Andre Sopczak (Prague)
Yield improvement of the Adaptive Gain Integrating Pixel Detector front-end modules for new experiments at the European XFEL (#1754)

Julian Becker\textsuperscript{1,2}, Annette Delfs\textsuperscript{1,2}, Roberto Dinapoli\textsuperscript{3}, Sergei Fridman\textsuperscript{1,2}, Peter Goettlicher\textsuperscript{1}, Heinz Graafsma\textsuperscript{1,4}, Dominic Greiffenberg\textsuperscript{3}, Helmut Hirsemann\textsuperscript{1,2}, Stefanie Jack\textsuperscript{1,2}, PhD/MD Alexander Klyuev\textsuperscript{1,2}, Hans Krueger\textsuperscript{6}, Michela Kuhn\textsuperscript{1}, Sabine Lange\textsuperscript{1,2}, Torsten Laurus\textsuperscript{1,2}, Alessandro Marras\textsuperscript{1,2}, Davide Mezza\textsuperscript{3}, Aldo Mozzanice\textsuperscript{3}, Jennifer Poehlsen\textsuperscript{1,2}, Bernd Schmitt\textsuperscript{3}, Joern Schwandt\textsuperscript{5}, Ofir Shefer Shalev\textsuperscript{1}, Igor Sheviakov\textsuperscript{1}, Xintian Shi\textsuperscript{3}, Sergej Smoljanin\textsuperscript{1,2}, Stephan Stern\textsuperscript{1,2}, Ulrich Trunk\textsuperscript{1,2}, Jiaguo Zhang\textsuperscript{3}, Manfred Zimmer\textsuperscript{1}

\textsuperscript{1} Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany; \textsuperscript{2} Center for Free-Electron Laser Science (CFEL), Hamburg, Germany; \textsuperscript{3} Paul-Scherrer-Institut (PSI), Villigen, Switzerland; \textsuperscript{4} Mid Sweden University, Sundsvall, Sweden; \textsuperscript{5} University of Hamburg, Hamburg, Germany; \textsuperscript{6} University of Bonn, Bonn, Germany

Content

The Adaptive Gain Integrating Pixel Detector is a fast X-ray detector designed for the experimental stations of the European XFEL, and has to fulfill the requirements of the facility, which delivers high brilliance coherent X-ray pulses in a specific timing structure. The detector has to operate in a burst mode with a frequency of 4.5 MHz, providing a high dynamic range of photon sensitivity, from single up to $10^4$ 12.5 keV photons. The detector is based on a hybrid pixel technology, where an assembly consisting of a semiconductor sensor and application specific integrated circuit chips is glued to a special board and interposer form a front-end module. The sensors are 500 μm thick Silicon custom designs, incorporating 128x512 pixels of 200 μm pitch. The read-out chips serve 64x64 pixels, containing all front-end electronics, as well as output multiplexer and a digital logic for operating the chip. It implements advanced techniques like dynamic gain switching, correlated double sampling and double column read-out and also uses radiation-tolerant solutions. The sensor is connected to the chips with a bump-bonding process. Taking into account complexity of the components and of the assembly production, the front-end module becomes a crucial part of the detector and its quality essential for recording good scientific data. In this paper, we report for the first time about the defect sources analysis and present strategies for yield improvement of the front-end modules. It was found that there are 4 types of defects coming from the different sources and their occurrence could be minimized by adjusting the assemblage techniques and parameters. The production of a front-end module is an irreversible process and it's necessary to test the assemblies of chips and sensor prior to gluing in order to facilitate a rework. For this a special probe station was developed. Design details and test methodology will be presented.
Feasibility Study of Charge Multiplication by Design in Thin Silicon 3D Sensors (#1779)

Dr. Marco Povoli¹, Dr. Maurizio Boscardin²,³, Prof. Cinzia Da Vià⁴,⁵, Dr. Martin Hoeferkamp⁶, Dr. Roberto Mendicino³,⁷, Dr. Lucio Pancheri⁷,³, Dr. Sabina Ronchin²,³, Prof. Sally Seidel⁶, Dr. Dms Sultan⁸, Prof. Gian-Franco Dalla Betta⁷,³

¹ SINTEF Minalab, Oslo, Norway; ² Fondazione Bruno Kessler, CMM, Trento, Italy; ³ INFN, TIFPA, Trento, Italy; ⁴ University of Manchester, School of Physics and Astronomy, Manchester, UK; ⁵ Stony Brook University, Department of Physics and Astronomy, Stony Brook, USA; ⁶ University of New Mexico, Department of Physics and Astronomy, Albuquerque, USA; ⁷ University of Trento, Department of Industrial Engineering, Trento, Italy; ⁸ University of Geneva, Geneva, Switzerland

Content

We report on a novel 3D sensor design, featuring very small inter-electrode distance, aimed at controlled charge multiplication at reasonably low voltages, of the order of 100 V, both before and after irradiation. Moderate gain values of a few units are achieved, which are however sufficient to compensate the loss of charge signal due to the use of thin substrates and to counteract charge trapping effects even after very large radiation fluences. The devices have been studied with the aid of TCAD simulations, allowing the main technological and design issues to be effectively addressed and the performance to be predicted. The first 3D diode prototypes were fabricated at FBK and initial results from the experimental characterization demonstrate the feasibility of the proposed concept.

Design and characterization of new high fill-factor segmented LGADs with trench isolation (#2379)

Giacomo Borghi¹, Giovanni Paternoster¹, Pierluigi Bellutti¹, Nicolò Cartiglia², Marco Ferrero², Francesco Ficorella¹, Alberto Gola¹, Marco Mandurrino², Valentina Sola²,³, Maurizio Boscardin¹

¹ Fondazione Bruno Kessler - FBK, CMM, Trento, Italy; ² Istituto Nazionale di Fisica Nucleare - INFN, Section of Torino, Torino, Italy; ³ University of Torino, Physics, Torino, Italy

Content

Low gain avalanche detectors (LGADs) are currently the state-of-the-art silicon detectors for timing application in HEP experiments. They also have the potentiality to replace standard silicon sensors in almost every application and to open up new detector developments, e.g. low-energy x-ray segmented detectors (< 1 keV) for synchrotron applications. However, many applications are still hampered by the relatively wide dead region present between pixels (40-60 µm) that determines a low effective fill factor for finely segmented sensors. In this work, we will present the new trench-isolated LGAD sensors developed by FBK, in which the standard JTE and isolation structures are replaced by narrow trenches. This new technology has first been investigated by means of TCAD simulations, which
enabled us to identify some promising solutions for the pixel border structures and showed that trench isolation could potentially reduce the width of the inter-pixel dead area to less than 10 µm. An R&D batch has then been produced, in which a wide variety of structures and process splits were implemented. During the conference, the parametric and functional characterization of the produced structures will also be shown. In particular, the characterization will focus on testing the correct isolation between pixels, the correct operation of the sensors, the breakdown voltage of the different guard ring structures and the width of the dead border for the different pixel implementations.

A 48x48 pixel two-tier avalanche sensor for charged particle detection

(Lucio Pancheri) 1,2

Isacco Benedetti 1, Gabriele Bigongiari 3,4, Paolo Brogi 3,4, Gianmaria Collazuol 5,6, Gian-Franco Dalla Betta 1,2, Pier Simone Marrocchesi 3,4, Fabio Morsani 4, Marco Musacci 7,8, Lodovico Ratti 7,8, Arta Sulaj 3,4, Gianmarco Torilla 7, Carla Vacchi 7,8

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Content

This work presents a two-tier pixel sensor based on avalanche detectors for charged particle tracking and counting. The sensor, produced in a 150nm CMOS process, features an array of 48x48 pixels with 75µm x 75µm pixel size and 65.4% geometric Fill Factor. A fully-digital electronic readout channel with in-pixel coincidence and 1-bit memory is included in the pixels. Characterization results of detector dark count rate, uniformity and cross-talk obtained on single tiers are presented.
Large-area Si(Li) detectors for X-ray spectrometry and particle tracking for the GAPS experiment (#1874)

PhD/MD student Field Rogers¹, Dr. Mengjiao Xiao¹, Prof. Kerstin Perez¹, Prof. Steven Boggs², PhD/MD student Tyler Erjavec¹, Dr. Lorenzo Fabris³, Prof. Hideyuki Fuke⁴, Prof. Chuck Hailey⁵, Dr. Masayoshi Kozai⁶, Dr. Alex Lowell², Dr. Norman Madden⁵, Prof. Massimo Manghisoni⁶,⁷, Dr. Steve McBride⁸, Prof. Valerio Re⁶,⁷, PhD/MD student Elisa Riceputi⁶,⁷, PhD/MD student Nathan Saffold⁵, Prof. Yuki Shimizu⁹, Dr. Gianluigi Zampa¹⁰

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Content

Large-area lithium-drifted silicon (Si(Li)) detectors, operable 150ºC above liquid nitrogen temperature, have been developed for the General Antiparticle Spectrometer (GAPS) Antarctic balloon mission. We demonstrate here that these 10 cm-diameter, 2.5 mm-thick, 8-strip detectors can provide the <4keV (FWHM) energy resolution for X-rays and <10% energy resolution for heavy particle tracks necessary for GAPS to identify cosmic antinuclei, while operating in conditions (~40ºC and ~1Pa) achievable on a long-duration balloon carrying a large-acceptance detector payload. This will be the first large-area, high-temperature Si(Li) detector system suitable for X-ray spectrometry operated in an ambient high-altitude mission. Mass production and calibration of ~1000 detectors has begun for the first GAPS flight, scheduled for late 2021. The detectors, while developed specifically for GAPS, may have other applications, e.g., in heavy nuclei identification at rare isotope facilities.

Characterization of Hybrid Pixel Detectors with 100 - 300 keV Electrons (#1508)

Dr. Michael Rissi, Dr. Vittorio Boccone, Dr. Sacha De Carlo, Dr. Christian Disch, Dr. Sonia Fernandez-Perez, Dr. Luca Piazza, Dr. Valeria Radicci, Dr. Peter Trueb, Dr. Pietro Zambon, Dr. Clemens Schulze-Briese, Dr. Christian Broennimann

DECTRIS Ltd., Baden-Daettwil, Switzerland

Content

Hybrid photon counting (HPC) detectors have been successfully developed and deployed for multiple applications in the last 10 years. They revolutionized the field of macromolecular crystallography at synchrotrons and at x-ray diffraction laboratories, thanks to their main properties being high signal to noise ratio, small point spread function...
and high detective quantum efficiency (DQE), high dynamic range, high x-ray flux capability and high frame rates in the range of up to multiple frames/second. Hybridization allows to use different detector materials like Silicon (Si), Cadmium Telluride (CdTe) or Gallium Arsenide (GaAs), suitable for different energy ranges and applications. In order to evaluate the HPC technology for the measurement of electrons in the range from 100 keV to 300 keV, we used a Si DECTRIS EIGER2 500K and 1M detector mounted to the bottom of a FEI Tecnai F20 transmission electron microscope (TEM) delivering electrons with energies up to 200 keV, as well as to a FEI TITAN Themis TEM / scanning TEM (STEM) delivering electrons with energies up to 300 keV. We evaluated the performance of the Si EIGER2 detector in terms of energy resolution and spectrum, rate behaviour and imaging properties like modular transfer function (MTF) and detective quantum efficiency (DQE). Furthermore, we performed simulations of the detector response within the FLUKA framework. Using custom analysis code, we implemented the HPC detector response, and compared the measurements with the simulations.
R-09 | TIBr Detectors

Andrea Zappettini (Parma)
Characterization of 1-cm thick Thallium Bromide Gamma-Ray Detectors (#1427)

Prof. Keitaro Hitomi\(^1\), M.Sc./M.A. Mitsuhiro Nogami\(^1\), Prof. Toshiyuki Onodera\(^2\), Prof. Kenichi Watanabe\(^3\), Kio Matsumoto\(^3\), Dr. Jiyon Lee\(^4\), Prof. Keizo Ishii\(^1\)

\(^1\) Tohoku University, Department of Quantum Science and Energy Engineering, Graduate School of Engineering, Sendai, Japan; \(^2\) Tohoku Institute of Technology, Department of Electrical and Electronic Engineering, Sendai, Japan; \(^3\) Nagoya University, Department of Applied Energy Engineering, Graduate School of Engineering, Nagoya, Japan; \(^4\) Korea Institute of Nuclear Safety, Department of Radiation Safety Research, Deajeon, South Korea

Content

1-cm thick TlBr detectors were characterized in this study. TlBr crystals were grown by the traveling molten zone method from the zone-purified materials. The starting material was commercially available TlBr beads with purity of 99.999%. In order to obtain a large cylindrical crystal ingot, the zone furnace was tilted so that the volume of the pure end of the crystal increased. A cylindrical TlBr crystal 18-mm in diameter and 30-mm in length was obtained from the crystal growth process. Pixelated TlBr detectors 11-mm in thick were fabricated from the grown crystal by constructing electrodes on the polished surfaces by vacuum evaporation of metal containing thallium. The detector had a planar cathode on one surface, and pixelated anodes with the area of 1.5 mm x 1.5 mm and surrounding electrodes on the other surface. Thin gold wires were attached to each electrode with carbon past. The charge transport properties and the spectroscopic performance of the detectors were characterized at room temperature. The detector was irradiated with \(^{241}\)Am and \(^{137}\)Cs gamma ray sources. The 59.5-keV full-energy peak was successfully obtained from the detector. Because 59.5-keV gamma rays creates electron-hole pairs only near the cathode, the created electrons traversed all through the TlBr crystal 11-mm in thick. Using the peak-position shift with the bias voltage, the mobility-lifetime product for electrons in the crystal was estimated to be $5.8 \times 10^{-3} \text{cm}^2/\text{V}$. Clear full-energy peak for 662-keV gamma ray was obtained from the detector with the energy resolution of 3.2% FWHM. The energy resolution of the detector was improved to be 2.5% FWHM by the depth correction.

Crystalline evaluation of TlBr semiconductor detectors using energy-resolved neutron imaging (#1258)

Dr. Kenichi Watanabe\(^1\), M.Sc./M.A. student Kio Matsumoto\(^1\), Prof. Akira Uritani\(^1\), Prof. Yoshiaki Kiyanagi\(^1\), Dr. Keitaro Hitomi\(^2\), Mitsuhiro Nogami\(^3\), Dr. Hirotaka Sato\(^3\), Dr. Winfried Kockelmann\(^4\)

\(^1\) Nagoya University, Dep. Applied Energy Engineering, Nagoya, Japan; \(^2\) Tohoku University, Sendai, Japan; \(^3\) Hokkaido University, Sapporo, Japan; \(^4\) STFC, ISIS, Didcot, UK

Content
Thallium bromide (TlBr) is a semiconductor attractive for fabrication of gamma-ray detectors. TlBr detectors have been shown to demonstrate excellent energy resolution, however, these results were obtained from small crystal detectors. The next step of TlBr development is to increase the detector size and improve the yield rate of detector production. Therefore, we would like to establish a crystal quality evaluation procedure to improve the yield rate of detector production. As one of the crystal quality evaluation methods, we demonstrated the potential of Bragg-dip imaging for the TlBr semiconductor detector. The prepared TlBr crystal showed position-dependent Bragg-dip patterns from which crystal lattice orientations can be determined by using a non-linear least-square fitting method. The observed sample showed that the crystal orientation gradually changes, considered to be induced by crystal defects. Consequently, we concluded that the pulse neutron imaging technique is suitable for crystal quality evaluation of the TlBr samples.

R-09-03

Extremely Stable Unidirectionally Biased Spectroscopic Thallium Bromide Detectors (##2230)

PhD/MD Amlan Datta, PhD/MD Piotr Becla, PhD/MD Shariar Motakef

Capesym, Inc., Research and Development, Natick, USA

Content

Thallium bromide (TlBr) is a wide bandgap, compound semiconductor with high gamma-ray stopping power and promising physical properties. However, performance degradation, spontaneous instability and the eventual irreversible failure of TlBr devices can occur rapidly at room temperature, caused by the electro-migration of Tl+ and Br- ions to the electrical contacts across the device. In previous studies at CapeSym, the defect nucleation and migration phenomena in TlBr devices were extensively explored and reported. It was concluded that without the use of bias switching, a technique where bias polarities are periodically reversed, it is impossible to maintain TlBr device performance for long periods. Also, it was found that both surface conditions and crystal quality (including residual stress) play important roles in the long-term lifetime of TlBr devices. The application of bias switching can be technologically complicated for single charge collection devices. In another complementary approach we used Tl contacts which after reacting with Br- ions form TlBr, and thus do not introduce a foreign component at the metal-semiconductor junction. However, our latest results show that with time the TlBr detectors with Tl contacts becomes noisy and loses stability for radiation detection. Recently, we have invented a novel solution to these problems that results in stable low-noise long-term TlBr detection performance under unidirectional biasing (i.e. without the use of bias-switching). In this presentation, we will report on the results of these experiments and provide comparison with other solutions reported till date.

This work was supported by the U.S. Department of Homeland Security, Domestic Nuclear Detection office contract HSHQDN-16-C-00022. This support does not constitute an express or implied endorsement on the part of the Government.
The Cerenkov Charge Induction (CCI) Detector Approach with TlBr for Time-of-Flight PET and Prompt Gamma Imaging

Dr. Gerard Ariño-Estrada¹, Dr. Gregory Mitchell¹, Dr. Hadong Kim², Leonard Cirignano², Dr. Junwei Du¹, Dr. Sun Il Kwon¹, Dr. Kanai Shah², Dr. Simon R. Cherry¹

¹ University of California, Davis, Department of Biomedical Engineering, Davis, USA; ² Radiation Monitoring Devices, Inc., Watertown, USA

Content
This work reports on the development of a Cerenkov-charge induction (CCI) thallium bromide (TlBr) detector for time-of-flight positron emission tomography (ToF-PET) and prompt gamma imaging (PGI) for proton range verification in hadron therapy. The CCI TlBr detector combines the detection features of semiconductor detectors, fine 3-D segmentation and excellent energy resolution, with the prompt emission of Cerenkov light after the interaction of a gamma ray with the TlBr bulk. A coincidence time resolution (CTR) of 430 ps full width at half maximum (FWHM) between a TlBr crystal, reading out the Cerenkov light, and a reference detector was presented in a previous work. Preliminary data acquired with a CCI TlBr detector with thin strips operated at room temperature and at a field strength of 2 kV/cm showed a CTR <360 ps FWHM and an energy resolution of ~8.5% at 511 keV for the same dataset. Next steps include the improvement of energy resolution at 511 keV and at room temperature. This will be achieved using digital signal processing of the charge sensitive preamplifier signal, and by fabricating CCI TlBr detectors with small pixel elements. After that, the energy and timing resolution at higher energies will be studied to validate the feasibility of this approach for PGI. The much higher Cerenkov generation yield for gammas >1 MeV might allow for pile-up event correction, identification of time sequence of Compton interactions, or measurement of the Cerenkov light cone to reconstruct the momentum of the recoil electron and determine the incident angle of the gamma with maximum accuracy. The development of CCI TlBr detectors is an innovative approach with the potential of leading to a new generation of detectors that combine excellent energy, timing, and spatial resolution with very high detection efficiency.

Performance and Stability of Pixelated Thallium-Bromide Detectors

Dr. Sean P. O'Neal, Dr. Erik Swanberg, Tim Graff, Paul Fontejon, Dr. Steve Payne

LLNL, Livermore, USA

Content
Thallium-bromide (TlBr) is a promising room-temperature semiconductor material due to its wide band gap and high stopping power. Performance of better than 1% FWHM at 662 keV has been achieved in small detectors. The use
of surface treatments has dramatically increased detector longevity, which had been limited by the onset of polarization caused by ionic conduction. In this work, the performance of new 10-mm thick pixelated detectors is presented and the stability of these detectors over long operation time is studied. These large detectors achieve good energy resolution (<2 % FWHM at 662 keV) even at low electric fields (1000 V/cm). The raw energy spectrum is corrected using either the cathode-to-anode ratio (CAR) method or a drift time method, and a comparison between these alternative methods is performed in the case of non-uniform electric fields.
M-04 | New Radiation Detector Technologies for Medical Imaging II

Seiichi Yamamoto (Nagoya)
Srilalan Krishnamoorthy (Philadelphia)
M-04-01 10:20 AM

Study of the Coincidence Time Resolution of New Perovskite Bulk Crystals (#2324)

Li Tao¹, Dr. Yihui He², Dr. Mercouri G. Kanatzidis², Dr. Craig S. Levin¹

¹ Stanford University, Radiology, Stanford, USA; ² Northwestern University, Chemistry, Evanston, USA

Content

Compared to scintillator based PET detectors, semiconductor detectors tend to provide excellent energy and spatial resolution. However, due to the relatively slow charge carrier collection time limited by the carrier drift velocity, semiconductor based detectors have poor time resolution in the range of several nanoseconds or greater. Possibilities exist to collect prompt photons emitted from certain semiconductor materials in order to greatly improve the timing capability. In this work, we studied the prompt photon emission property and fast timing capability of two new perovskite semiconductor materials, CsPbCl₃ and CsPbBr₃, and compared them with TlBr, which has been previously studied for its Cerenkov emission property. The coincidence time resolution (CTR) acquired between a 3×3×3 mm³ semiconductor sample crystal and a 3×3×3 mm³ reference LYSO crystal are 238±16 ps, 468±55 ps and 384±31 ps for CsPbCl₃, CsPbBr₃, and TlBr respectively, when the LYSO crystal was only triggered on photoelectric events. When we lowered the trigger level and allowed the LYSO crystal to be triggered on all events including Compton scattering, we acquired CTR of 281±17 ps, 499±77 ps and 422±46 ps for CsPbCl₃, CsPbBr₃, and TlBr respectively. Combined with the easily scalable crystal growth process, relatively low cost, low toxicity, and high energy resolution (around 3.8% at 662 keV), we conclude that CsPbCl₃ and CsPbBr₃ could be exceptional next generation candidates as semiconductor PET detector materials.

M-04-02 10:38 AM

Investigation of optical property modulation based ionizing radiation detection method for PET: two-crossed-polarizers based method (#2115)

M.Sc./M.A. student Yuli Wang¹, PhD/MD student Li Tao³, Prof. Craig Levin³,⁴, Prof. Jianfeng Xu²

¹ Huazhong University of Science and Technology, China-EU Institute for Clean And Renewable Energy, Wuhan, China; ² Huazhong University of Science and Technology, State Key Laboratory of Digital Manufacturing Equipment and Technology, Wuhan, China; ³ Stanford University, Department of Electrical Engineering, Palo Alto, USA; ⁴ Stanford University, Department of Radiology, Palo Alto, USA

Content

Recent work shows that optical property modulation could be utilized as a novel method for 511 keV ionizing radiation photon detection for positron emission tomography (PET) which could potentially overcome the inherent physical limitation on coincidence time resolution of around 100 ps using scintillation-based detection. In this paper, we embrace this observation and introduce a novel two-crossed-polarizers based setup to achieve similar detection
concept, which is a simpler and more compact setup with comparable ionizing radiation detection capability. We evaluated the performance of our proposed setup with Lithium Niobate (LiNbO$_3$) and Cadmium Telluride (CdTe) detector crystals, and the desired properties of an ideal detector crystal were also discussed. The modulation signal induced by 511 keV photons in both LiNbO$_3$ and CdTe can be detected with repeatable signal amplitude using two-crossed-polarizer based method, while CdTe could provide 8 times higher detection sensitivity for 511 keV photons than LiNbO$_3$, suggesting high effective Z number and high density properties of CdTe, as well as a shorter carrier lifetime and lower carrier mobility of LiNbO$_3$. In addition, the strength of modulation signal increased linearly with bias voltage before saturation. The modulation signal strength in LiNbO$_3$ continued to increase after 2000V due to its high resistivity which could reduce the dark current in the detector, while the modulation signal of CdTe with low resistivity tended to be saturated at a bias voltage higher than 1200V. Therefore, further increasing the bias voltage for detector crystals (especially for LiNbO$_3$) may enhance the modulation strength and improve the detection sensitivity for annihilation photons.

M-04-03 10:56 AM

Evaluation of RF shielding materials for highly-integrated PET/MRI systems (#1646)

PhD/MD student Laiyin Yin, PhD/MD student Laiyin Yin, Franziska Schrank, Franziska Schrank, Dr. David Schug, Dr. David Schug, Prof. Volkmar Schulz, Prof. Volkmar Schulz

RWTH Aachen University, Department of Physics of Molecular Imaging Systems, Institute for Experimental Molecular Imaging, Aachen, Germany

Content

The preclinical integration of PET and MRI precedes several challenges. Conventionally, PET inserts are placed between the MRI’s RF screen and the gradient coil. This limits the RF screen’s diameter, leading to a substantially decreased RF coil sensitivity, especially for small-bore systems. Our target setup is a shared-volume PET/MRI insert in which the PET’s scintillators are passed through the screen into the RF volume. Hence, the screen diameter and coil sensitivity can be increased while additionally moving the PET modules closer to the subject. To enable such an integration, we assess the optical performance and shielding effectiveness (SE) of several shielding materials (coated glasses, foils and meshes). We use an Agilent E5071C Network Analyzer and a set of coils (Langer EMV RF2) for the evaluation of SE. Then, each material is assembled into the PET detector stack between a one-to-one coupled LYSO scintillator and a dSiPM array (PDPC DPC-3200). A dedicated alignment tool with customized scintillator and sensor frames is used for this purpose. The first optical evaluation is based on single gamma interactions with a focus on the energy resolution (dE/E$_\text{Single}$) and photon attenuation (PA). Materials inducing a PA of less than 30 % are selected for a coincidence measurement evaluation of the detector stacks to determine the timing performance with dE/E$_\text{Coinc}$ and the coincidence resolving time (CRT). We observe a high PA for all meshes and exclude them from the second evaluation. The remaining glasses and foils showed minor changes in dE/E at around 11.5 % and a CRT of 207 to 227 ps. One foil degraded to approx. 255 ps. Thus, we did not see a significant decrease in optical performance. Considering the SE of each material, we conclude that one glass and both foils can be used as a transparent RF shielding material. However, if the application requires an SE greater than 10 dB, we recommend the implementation of the HS 9400 coated foil with an SE of around 25 dB.
M-04-04  11:14 AM

Wafer-scale Monolithic CMOS Integrated Pixel Detectors for X-ray Photon Counting (#1759)

Jorge Neves¹, Riccardo Quaglia², Pierre-François Rüedi², Manolis Choumas¹, Franco Bressan¹, Nasser Rasek¹, Marco Hagting³, Philippe Le Corre¹, Hans Von Känel¹

¹ G-ray Medical, Hauterive, Switzerland; ² CSEM - Swiss Center for Electronics and Microtechnology, Neuchâtel, Switzerland; ³ Bruco Integrated Circuits, Borne, Netherlands

Content
A new semiconductor process is being developed for manufacturing monolithic CMOS integrated pixel detectors. The technology is based on direct bonding of 200 mm CMOS wafers to an absorber in a low-temperature, oxide-free, covalent wafer bonding process, and it is applicable to any material such as Si, GaAs or any other high-Z semiconductor compounds available in the form of 200 mm wafers. To demonstrate the concept, a prototype chip was designed in 150 nm CMOS process featuring 240 x 300 pixels of 100 µm pitch. Each pixel has its own single photon counting circuit, with an analog charge sensitive amplifier, leakage current compensation and a shaper, followed by two threshold-programmable discriminators feeding two 12-bit asynchronous counters. The counters can work in parallel, or in cascade-mode by using the second counter as register for simultaneous acquisition/reading. A data acquisition system was developed to readout the front-end board hosting the CMOS chip. The board integrates an FPGA for hardware control and software processing, it handles the image acquisition protocols and assembles data frames to a computer. Preliminary results with a commissioned detector based on a Si absorber demonstrates an effective charge transport across the bonding interface, and promising X-ray imaging performance (both detection efficiency and spatial resolution). In this conference, we shall discuss the first experimental tests and X-ray characterization measurements obtained on the novel kind of detector.

M-04-05  11:32 AM

Radiotherapy MLC Upstream Leaf Edge Detection Using Lassena Large Area MAPS (#2494)

PhD/MD student Jordan Pritchard¹, Dr. Jaap Velthuis¹,³, Dr. Lana Beck¹, Dr. Richard P. Hugtenburg²,¹, Dr. Chiara De Sio¹

¹ University of Bristol, School of Physics, Bristol, UK; ² Swansea University, Swansea University Medical School, Swansea, UK; ³ University of South China, School of Nuclear Science and Technology, Hengyang, China

Content
Multileaf collimators (MLC) are an integral component in modern radiotherapy as they shape the MV photon treatment field and therefore need to be closely controlled. Currently, MLC leaves are calibrated to ±1 mm every 3 months, however leaves can drift beyond this during calibration dates and treatment verification only occurs post-treatment. Furthermore, cases of stuck leaves have been reported. MAPS are radiation hard in photon and electron irradiation, have high readout speeds and low attenuation which makes them an ideal upstream radiation sensor. Here, we report results using the Lassena MAPS, which has a low attenuation of < 1%, is 12 x 14 cm$^2$ in size and is three side buttable. A 2 x 2 matrix of the Lassena sensors covers a large enough area to be clinically deployed. We have previously shown that the Achilles MAPS can reconstruct 1 cm leaf edge positions with a 52 ± 4 μm precision in 0.1 sec of treatment beam. The Achilles however, is 6 x 6 cm$^2$ in size, is not buttable and hence, cannot be used for real time clinical monitoring. Additionally, Achilles has a pixel pitch of 14.5 μm whilst the Lassena has a 50 μm pixel pitch. Experiments were conducted in which the Lassena sensor was placed in the treatment field of an Elekta Synergy LINAC and an MLC leaf of width 0.5 cm, positioned stepwise. Sobel-based methods were used to calculate leaf edge positions, resolutions and plot as a function of set leaf position. Correspondence between reconstructed and set leaf position was excellent and resolutions ranged between 52.9 ± 8.5 μm and 142 ± 31.6 μm at the isocentre for 0.3 sec of treatment beam, which is significantly lower than the ± 0.5 mm uncertainty in LINAC set position.

**M-04-06**

**A diamond beam-tagging hodoscope for online range monitoring in hadrontherapy (#1705)**

PhD/MD student Sébastien Curtoni$^1$, M.Sc./M.A. Germain Bosson$^1$, Prof. Johann Collot$^1$, Dr. Denis Dauvergne$^1$, M.Sc./M.A. Laurent Gallin-Martel$^1$, Dr. Marie-Laure Gallin-Martel$^1$, PhD/MD student Abderrahmane Ghimouz$^1$, Prof. Ferid Haddad$^3$, Dr. Jean-Yves Hostachy$^1$, Dr. Charbel Koumeir$^3$, Dr. Jean-Michel Létang$^4$, Dr. Jayde Livingstone$^1$, Dr. Sara Marcatili$^1$, Prof. Vincent Métivier$^2$, M.Sc./M.A. Jean-François Muraz$^1$, Dr. Fatah E. Rabri$^1$, Prof. Olivier Rossetto$^1$, Dr. Noël Servagent$^2$, Dr. Etienne Testa$^5$, M.Sc./M.A. Mahfoud Yamouni$^1$

$^1$ Université Grenoble-Alpes, Laboratoire de Physique Subatomique et de Cosmologie, CNRS-IN2P3, Grenoble, France; $^2$ Université de Nantes, Subatech, CNRS-IN2P3, Nantes, France; $^3$ GIP ARRONAX, Saint-Herblain, France; $^4$ INSA Lyon, CREATIS, INSERM, CNRS, Villeurbanne, France; $^5$ Université de Lyon, Institut de Physique Nucléaire de Lyon, CNRS-IN2P3, Villeurbanne, France

Content

The efficiency of hadrontherapy could benefit from an online ion range monitoring. This work focuses on a CLaRyS collaboration development: a diamond-based hodoscope in the context of Prompt-Gamma range verification. It aims to provide temporal and spatial tagging of incoming ions. To perform bunch-by-bunch tagging with the best time resolution achievable, the hodoscope has to be very fast and radiation hard. Chemical Vapor Deposition (CVD) diamond detectors exhibit intrinsic properties that would satisfy these requirements. Single channel detectors made of single-crystal and polycrystalline diamonds together with Diamonds grown On Iridium (DOI) have been built. For the two last ones, 2 x 8 channels single diamond double-side stripped prototypes have also been tested. Diamond detectors were characterized with 68 MeV protons at ARRONAX-Nantes and with 8.5 keV X-rays micro-beam at the ESRF-Grenoble. In ARRONAX, a 59 ps RMS Time-of-Flight resolution was measured between a single-crystal diamond and a DOI sample. Using X-rays, a 103 ps RMS intrinsic timing resolution was achieved on a polycrystalline
CVD stripped prototype. In addition to time measurements, the 68 MeV proton beam was used to evaluate the single proton detection efficiency on the polycrystalline CVD and DOI samples. Results were found to be 92\% for the polycrystalline against 50 \% for the DOI. The detection efficiency of the polycrystalline stripped sample was measured at ESRF. A 100\% bunch detection efficiency was easily achieved at strip crossings but severe drops were observed in the inter-strip gaps highlighting a too wide (100 µm) gap (present prototype design). These results encourage the prototyping of a new demonstrator equipped with four stripped diamond sensors (single or polycrystalline) read by a dedicated fast readout integrated electronics developed at LPSC.
This session presents simulation studies of new systems for nuclear imaging and radiation therapy.
**M-05-01  10:20 AM**

**Design of a High Sensitivity Total-Body Small Animal BGO PET Scanner for Low Activity Imaging: A Simulation Study** (#2518)

Dr. Qian Wang, Prof. Simon R. Cherry, Dr. Junwei Du

*University of California, Davis, Biomedical Engineering, DAVIS, USA*

**Content**

Emerging total-body PET scanners with close to the highest possible geometric coverage and high sensitivity can significantly reduce the image acquisition time or the injected radiotracer dose. A major limitation of scanners using lutetium-based scintillators is the intrinsic background radiation, hampering the use of preclinical PET for a range of very low activity applications. To address this challenge, a new total-body PET scanner for visualizing low-signal biological processes in small animals was designed, simulated and characterized. The proposed scanner has 12 detector modules arranged in one ring, an axial FOV of 240 mm and a detector ring diameter of 160 mm to achieve high sensitivity and total-body rat coverage. Each detector module consists of two 12 × 72 arrays of SiPMs coupled to both ends of a 26 × 160 array of 1.44 × 1.44 × 20 (30) mm³ BGO scintillators with a pitch size of 1.5 mm. Using Monte-Carlo and stochastic simulations, PET imaging studies were emulated, and the spatial resolution and sensitivity were estimated. Using a single source tracking algorithm, the trajectories of moving low-activity sources, with different speeds, were reconstructed to mimic individual cell tracking studies. Compared to a PET scanner with 30 mm thick BGO detectors, the design with 20 mm thick BGO better balances the requirements for spatial resolution, sensitivity, point source trajectory reconstruction accuracy and cost, and will be selected for further evaluation. This simulation study characterizes the performance of the proposed PET system and sets a foundation for our future work to develop a system that can be used for monitoring low-signal biological processes.

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**M-05-02  10:38 AM**

**Total-Body Animal PET with a 4-Layer DOI Detector - GATE Simulation Study** (#1397)

Dr. Han Gyoo Kang, Dr. Hideaki Tashima, Dr. Fumihiko Nishikido, Dr. Eiji Yoshida, Dr. Taiga Yamaya

*National Institute of Radiological Sciences (NIRS) in National Institutes for Quantum and Radiological Science and Technology (QST), Department of Nuclear Medicine Science, Chiba, Japan*

**Content**

Recently, the first total-body positron emission tomography (PET) scanner for high sensitivity clinical imaging was developed by a group led by Simon Cherry in UC Davis. However, the long axial FOV causes a parallax error not only in the radial direction but also in the axial direction, and these parallax errors must be mitigated. This can be done by using a depth-of-interaction (DOI) detector. The aim of this study is to investigate appropriate use of DOI detectors to mitigate the parallax errors in a long axial field-of-view PET scanner. The four-layer DOI detector
originally developed for OpenPET and the helmet-type PET are reutilized to build an animal PET prototype as the first demonstration. The proposed total-body animal DOI PET scanner has an inner diameter of 120 mm and an axial length of 316 mm. The DOI PET detector consists of a 4-layer Zr-doped gadolinium oxyorthosilicate (GSOZ) crystal array and an 8×8 array multi-anode PMT. Each crystal layer has a 16×16 array of GSOZ crystals (2.8×2.8×7.5 mm³) which yield a total crystal thickness of 30 mm. The effect of DOI information on the PET image quality is investigated with grid patterned point sources by using GATE Monte Carlo simulation. The parallax error along the radial and axial directions can be reduced by using the 4-layer DOI detector. The total-body animal PET scanner based on the 4-layer DOI detector can provide a uniform spatial resolution of around 1.7 mm across the entire FOV. The peak sensitivity of 25% is obtained at the center of the FOV. In the future, we will develop a prototype total-body animal DOI PET scanner with our other existing 4-layer DOI detectors to demonstrate the usefulness of the DOI information for a long axial FOV PET scanner.

**M-05-03**

**Limited-angle TOF-PET for intraoperative surgical application** (#2580)

Dr. Salar Sajedi, Dr. Lisa Bläckberg, Dr. Georges El Fakhri, Dr. HakSoo Choi, **Dr. Hamid Sabet**

*Massachusetts General Hospital & Harvard Medical School, Boston, USA*

**Content**

Accurate identification of sentinel lymph node (SNL) and complete tumor removal in cancer patients is of critical importance and leads to improved patient recovery and survival. Gamma probes along with near infrared (NIR) probes are the gold standard in SNL identification but have failed to reduce false negative rates (FNR) to the desirable 5% value. By developing a high-resolution Standalone Detector (SD) with time-of-flight (TOF) information, in coincidence with a partially populated half-ring detector system (HDS) in which the SD is placed in various locations while HDS is fixed underneath the patient bed, we are aiming to reduce FNR. In this regard, we modeled variations of the intraoperative system as well as a reference whole-body PET using Monte-Carlo code GATE. Detector blocks in HDS and SD are 13x13 arrays of 3.6x3.6x20 mm³ LYSO:Ce pixels with 3.8 mm pitch. Models varied by the number of detector blocks in the half-ring HDS and location of both SD and HDS with respect to the patient body. Unlike conventional PET with slices along the body axis, here the slices are defined horizontally and parallel with body axis. A torso phantom with background activity of 1/10th of that of hot spheres with 2,4,6,8, and 10 mm diameter and 10 mm spacing was used. Reconstructed images show that 6,8, and 10 mm lesions can be identified with 75 sec image acquisition in that the probe was placed in three locations each with 25 sec time slice. As expected, lesion detectability is reduced when coincidence time resolution (CTR) was changed from 150 ps to 250 ps. One can increase the acquisition time to partially compensate for image degradation.
Simulated and Measured Detector Timing Effects at Clinical Dose Rates in a Compton-camera Based Prompt-gamma Imaging for Proton Radiotherapy. (#1861)

Dr. Paul Maggi1, Dr. Rajesh Panthi2, Dr. Steve Peterson3, Dr. Dennis Mackin2, Dr. Sam Beddar2, Dr. Hao Yang4, Dr. Zhong He5,4, Dr. Jerimy Polf1

1 University of Maryland School of Medicine, Department of Radiation Oncology, Baltimore, USA; 2 University of Texas M D Anderson Cancer Center, Department of Radiation Physics, Houston, USA; 3 University of Cape Town, Department of Physics, Rondebosch, South Africa; 4 H3D Inc, Ann Arbor, USA; 5 University of Michigan, Nuclear Engineering and Radiological Sciences, Ann Arbor, USA

Content

This paper describes a realistic simulation of a Compton-camera (CC) based prompt-gamma (PG) imaging system for proton range verification at a range of clinical dose rates, and its comparison to measured data with our pre-clinical CC system. Our model included the CC housing and detectors and recorded interactions from all gammas in the CC detectors. We used Monte Carlo to model gamma production and energy deposition. We added realistic detector timing effects (e.g. delayed triggering time, event-coincidence, dead time) in post-processing to allow for flexible timing simulations without rerunning the Monte Carlo simulation. We simulated four irradiation setups to provide a range of interaction rates ($5 \times 10^4$ interactions/s, $1 \times 10^6$ int/s, $5 \times 10^6$ int/s, and $1 \times 10^7$ int/s), and acquired measurements at equivalent interaction rates. Both simulations and measurements had three primary effects as the interaction rate increased: 1) reduction in the total number of measured events due to increased dead-time; 2) increase in false-coincidence events (i.e. separate photons, rather than a single, scatter photon interacting in a read-out cycle); 3) loss of distinct PG emission peaks in the energy spectrum. We then used the model to estimate the usability of our measured date, primarily with regards to multi-pixel false coincidence. The simulation results showed we have 5%, 50%, 82% and 90% false two-pixel coincidence at the above interaction rates respectively, and 0.2%, 15%, 54% and 68% false coincidence for three-pixel events. These results imply improvements to detector timing capabilities and/or event selection are needed to achieve high quality data.

Proton scatter radiography with integration-mode detectors by exploiting the West-Sherwood effect (#2105)

Dr. Ahmad Addoum1, Dr. Nils Krah1,2, Dr. Jean-Michel Létang2, Dr. Simon Rit2

1 University Lyon, Institute of Nuclear Physics Lyon (IPNL), Lyon, France; 2 University Lyon, Medical Imaging Research Center (CREATIS)/ Centre Léon Bérard, Lyon, France

Content
We present a model to analytically predict the transmitted protons fluence field on a rear integration-mode detector. Multiple Coulomb scattering (MCS) is taken into account in the fluence signal and the West-Sherwood effect due to transverse heterogeneities is highlighted. We then develop a gradient-based optimization method to retrieve the spatial variance of the Gaussian distribution in each pixel of the detector from the measured fluence. The initial estimation is obtained by correlating the measured attenuation to the variance when assuming a homogeneous water phantom. The proposed method was assessed on Monte Carlo simulation of a homogeneous water phantom containing or not a bone insert. The estimation results show that the algorithm can, under realistic experimental scenarios, retrieve the MCS spatial dispersion with reasonable accuracy for both phantoms. Furthermore, the West-Sherwood effect observed on fluence map is advantageously exploited to improve the quality estimation on tissue boundaries. These preliminary results indicate potential improvement of the spatial resolution of proton imaging using integration-mode detectors.

M-05-06  
11:50 AM

Effects of PET System Performance Characteristics on Image Quality for Neuro-PET (#1794)

Dr. Sangtae Ahn¹, Robert L. Harrison², William C. J. Hunter², Paul Kinahan², Sergei Dolinsky¹, Robert Miyaoka²

¹ GE Global Research, Niskayuna, USA; ² University of Washington, Department of Radiology, Seattle, USA

Content

It is important to predict how scanner design characteristics affect image quality relevant to clinical tasks when developing a new system. It is a complex task to understand the interplay among multiple system parameters such as time-of-flight (TOF) resolution, sensitivity, intrinsic spatial resolution, and depth-of-interaction (DOI) resolution. In this study, we investigate the effects of the performance characteristics on reconstructed images in a context of developing a brain-dedicated positron emission tomography (PET) scanner. For the analysis, we performed Monte Carlo (MC) simulation using SimSET. The results show that DOI information greatly improves image resolution particularly in the peripheral regions, smaller detector elements improve image resolution, and TOF information lowers image noise. The MC simulation analysis provides useful results for optimizing detector geometry and hardware for high resolution neuro-PET scanner design.
10:20 AM – 12:08 PM

Charter 1

N-31 | High Energy and Nuclear Physics II

Daniela Bortoletto
Susanne Kuehn (Geneva)
Final design and current status of the Mu2e crystal calorimeter

Prof. Matteo Martini¹, Dr. Stefano Miscetti¹, Dr. Luca Morescalchi²

¹ INFN, Frascati, Frascati, Italy; ² INFN, Pisa, éisa, Italy

Content

The Mu2e experiment at Fermi National Accelerator Laboratory (Batavia, Illinois, USA) searches for the charged-lepton flavor violating neutrino-less conversion of a negative muon into an electron in the field of an aluminum nucleus. The dynamics of such a process is well modeled by a two-body decay, resulting in a monoenergetic electron with energy slightly below the muon rest mass (104.967 MeV). Mu2e will reach a single event sensitivity of about $2.5 \times 10^{-17}$ that corresponds to four orders of magnitude improvements with respect to the current best limit. The calorimeter of this experiment plays an important role to provide excellent particle identification capabilities and an online trigger filter while aiding the track reconstruction capabilities. The baseline calorimeter configuration consists of two disks each made with about 700 undoped CsI crystals read out by two large area UV-extended silicon photomultipliers. These crystals match the requirements for stability of response, high resolution and radiation hardness since this detector was designed to be operable in a harsh environment where about 10 krad/year will be delivered in the hottest region and work in presence of 1 T magnetic field.

In this paper we present the final calorimeter design based on undoped CsI crystals read out using large area UV-extended custom SiPMs. This final design is the result of a long R&D performed with different crystals and photosensors from different vendors. In this paper we will show the most important results also from irradiation and neutron test. Moreover, we will present the construction and the tests performed using a 51 full size crystals prototype used with electron beam between 60 and 120 MeV and in vacuum to test cooling and thermal exchanges.
achieved by Cosmic Ray Veto (CRV) system enclosing the Mu2e detectors in order to suppress background caused by the cosmic rays. This paper describes the way we achieve such high efficiency alongside CRV modules mass production and quality tests on each steps of production. Over 80 of such modules of different length (from 0.9 to 7.0 meters) and 1-meter width made as a 4-layer sandwich of scintillation counters and aluminum sheets with 64 SiPM on each layer should be produced by summer of 2021. Five of 6-m-long CRV modules were already produced and passed required quality tests. We discuss a way of improving the CRV performance for the 7-meter modules which will suffer from a high neutron fluence (up to $10^{11}$ neutrons per cm$^2$).

**SuperK-Gd benefits and outline (#2135)**

**Lluis Marti Magro**

*University of Tokyo, Institute for Cosmic Ray Research, Tokyo, Japan*

**Content**

Super-Kamiokande (SK), a 50 kton water Cherenkov detector in Japan has been improved ever since its construction finished in 1996. Good examples of these are the constant improvements in the water purification system or the electronics upgrade from SK-IV in 2008. In June 2015 the SuperK-Gd project was approved and the necessary refurbishment of the detector was done between June 2018 and and early 2019. Gadolinium (Gd) has the largest thermal neutron capture cross section and emits a gamma cascade of about 8 MeV and thus, adding about 0.1% in mass, will allow us to detect neutrons with high efficiency. In this talk, I will review the project and have a look ahead at its next steps.

**Development and Performances of the multi-PMT photodetector for the Hyper-Kamiokande experiment (#2301)**

**Prof. Vincenzo Berardi**$^{1,2}$, On behalf of the Hyper-Kamiokande proto-collaboration

$^1$ INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Bari, Italy; $^2$ Politecnico di Bari, Dipartimento di Fisica, Bari, Italy

**Content**

Hyper-Kamiokande (HK) is a 260 kton water Cherenkov detector to be built in Japan. HK is the next generation of the Super-Kamiokande experiment. Its broad physics program includes nucleon decay, neutrinos from astronomical and human-made beam, with the main focus to determine the leptonic CP violation. The primary photo-detector candidate for HK are 20-inch PMTs specifically developed by Hamamatsu Photonics. However, in order to enhance the Hyper-Kamiokande physics sensitivity, the use of multi-PMT modules is considered as a complement of the
primary candidates. A multi-PMT Optical Module is constituted by a pressure vessel instrumented with multiple small diameter photosensors (typically 3-inch PMT), readout electronics and power, offers several advantages as increased granularity, reduced dark rate, weaker sensitivity to Earth’s magnetic field, improved timing resolution and directional information with an almost isotropic field of view. In this talk, we will present the development of the multi-PMT module from the mechanical design to the design of the electronics, which is a crucial point for the correct performance of the system in order to both maximize the physics sensitivity of Hyper-Kamiokande and comply with the detector requirements. We will then show the exhaustive tests of the individual 3-inch PMTs that constitute these modules before to present the incoming perspectives of testing the assembled modules in a test beam. Last but not least, we will briefly discuss the role of mPMT modules as primary photodetector for the Intermediate Water Cherenkov Detector (IWCD) which is the newly proposed near detector for the HK project.

Thinned Commercial Foundry-built High Energy Physics Sensors using Microwave Anneal (#2526)

**Dr. Julie D. Segal**, Dr. Christopher J. Kenney, Dr. Jasmin Hasi, Nicolas Ljetaer, Marco Povoli, Dr. Richard Bates, Craig Buttar, Mark Bullough, Susanne Walsh, Jeffrey M. Kowalski, Jeffrey E. Kowalski

1 SLAC National Accelerator Laboratory, Menlo Park, USA; 2 SINTEF, Trondheim, Norway; 3 University of Glasgow, Glasgow, UK; 4 Micron Semiconductor, West Sussex, UK; 5 DSG Technologies, San Jose, USA

Content

In order to support the high luminosity upgrades at ATLAS and CMS, thinned silicon sensors for hybrid pixel detectors are critical to improve radiation hardness, reduce detector mass, and address high occupancy rates. Because silicon wafer processing tools are not equipped to handle thin wafers, the thinning step cannot be performed until after the majority of the processing steps are complete, requiring post-processing to create the doped region that constitutes the diode contact at the backside of the wafer. However, the high temperature anneal required to activate the dopant would be damaging to the existing front side structures. A new microwave annealing technology can activate the backside implant at low temperature, without damaging the frontside structures. We employed this technique to post-process 6-inch wafers from two different high energy physics (HEP) sensor foundries. Results are promising, indicating that the microwave anneal backside has potential to become a cost-effective solution for manufacturing thin sensors for large area HEP detectors.
Recent results from the PANDA DIRC detectors (N-31-06)

**Dr. Jochen Schwiening**, for the PANDA Cherenkov Group

_GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany_

**Content**

The PANDA experiment at the international accelerator Facility for Antiproton and Ion Research in Europe (FAIR), Darmstadt, Germany, will address fundamental questions of hadron physics using $\bar{p}p$ annihilations. Excellent Particle Identification (PID) over a large range of solid angles and particle momenta will be essential to meet the objectives of the rich physics program. Charged PID in the target region will be provided by a combination of two DIRC (Detection of Internally Reflected Cherenkov light) counters.

The Barrel DIRC, covering the polar angle range of 22-140 degrees, will provide $\pi/K$ separation power of at least 3 standard deviations (s.d.) for charge particle momenta up to 3.5 GeV/c. The design of the Barrel DIRC features narrow radiator bars made from synthetic fused silica, an innovative multi-layer spherical lens focusing system, a prism-shaped synthetic fused silica expansion volume, and an array of lifetime-enhanced Microchannel Plate PMTs (MCP-PMTs) to detect the location and arrival time of the Cherenkov photons.

The novel Endcap Disc DIRC will be placed in forward region, covering polar angles from 5 to 22 degree, and is designed to provide 3 s.d. $\pi/K$ separation up to 4 GeV/c. It is constructed out of four optically isolated quadrants, each comprising a synthetic fused silica radiator plate, focusing optics, and a compact readout region with finely-segmented MCP-PMTs.

Detailed Monte-Carlo simulations were performed and reconstruction methods were developed to study the performance of both DIRCs. We will discuss the status of the technical design and present recent results of the design validation using prototypes in mixed hadron beams at CERN and DESY.
Software developments for experimental applications
N-32-01 10:20 AM

TCoDe: A new multithread simulator for silicon sensors in HEP applications (#2664)

Angelo Loi1,2, Dr. Andrea Contu2, Dr. Adriano Lai2, Dr. Rolf Oldeman1,2, Dr. Stefania Vecchi3, Dr. Concezio Bozzi3, Dr. Benedetto G. Siddi3, Dr. Giulio T. Forcolin4,5

1 Università degli Studi di Cagliari, Dipartimento di Fisica, Monserrato, Italy; 2 Istituto Nazionale di Fisica Nucleare, Sezione Cagliari, Monserrato, Italy; 3 Istituto Nazionale di Fisica Nucleare, Sezione Ferrara, Ferrara, Italy; 4 University of Trento, Povo, Italy; 5 Trento Institute for Fundamentals Physics Applications (TIFPA), Povo, Italy

Content

The TIMESPOT Code for DEtector simulation is a new fast solid-state sensor simulator developed to speed up simulation time for transient simulations and achieving large statistics of data for accurate estimation of sensor performances. A fast computation is obtained running the simulation code on a multithread architecture which can use CPU- and GPU-based platforms depending on the available hardware. The code itself simulates sensor operation by importing the main physical features of the sensor, like electric field and mobility maps, and the interaction with ionizing particles from other software like TCAD, Monte Carlo or GEANT4 and simulates the signal output by applying the Ramo theorem. Signal output and simulation performances of TCoDe were compared with other similar programs like Synopsys TCAD, using a 3D model of the TIMESPOT 3D-silicon sensor prototype, showing a good agreement between the simulated curves.

N-32-02 10:38 AM

Development of a Simulation Framework for Spherical Proportional Counters (#2699)

PhD/MD student Robert Ward, Prof. Konstantinos Nikolopoulos, Dr. Ioannis Katsioulas, PhD/MD student Patrick Knights

University of Birmingham, School of Physics and Astronomy, Birmingham, UK

Content

Spherical proportional counters are a novel type of detector that offer numerous advantages for the detection of low-energy nuclear recoils: a good energy resolution, low capacitance, maximum volume-to-surface ratio, and a flexible choice of target gas which allows for sub-keV energy detection thresholds. The detector response is influenced by the species of interacting particle and the position of interaction, providing background discrimination. This gives the possibility of fiducialisation of the detector. In this study we combined the simulation software packages Geant4 and Garfield++ to create a full simulation of interactions inside the detector, including ANSYS finite-element electric-field maps, the gas simulation program Magboltz, and Heed, which simulates ionisation patterns from relativistic particles. Geant4 models the interactions of initial particles inside the detector; Garfield++ models the avalanche of the resulting
electrons and the induced electric current. The two packages communicate with each other using the Geant4 fast simulation and sensitive detector functionality. The simulated signal properties for initial particles such as muons, electrons and alphas will be presented, as well as the effect of different target gases. The simulation results will be compared with measurements from the 30 cm diameter spherical proportional counter at the University of Birmingham.

**N-32-03**

GEANT4 Simulations for Coated Micro-Particle Detectors with Improved Neutron Detection Efficiency and Light Collection (#2503)

Prof. Marek Flaska, M.Sc./M.A. Faruk Logoglu

*Pennsylvania State University, Nuclear Engineering, State College, USA*

Content

$^6$LiF:ZnS(Ag) micro-particle neutron detectors are a promising technology to further improve neutron detection capabilities for a variety of applications. Specifically, we have been investigating $^6$LiF micro-particles coated with ZnS(Ag) to increase the neutron detection efficiency, light production and light collection efficiency when compared to the existing powder-based technology (EJ-426). Extensive simulations with single micro-particles have been performed to find the optimal $^6$LiF diameter and ZnS(Ag) coating thickness. Full-scale detector simulations also have been performed to determine the optimal pitch (particle-to-particle distance) and detector thickness. Randomization of $^6$LiF radius, ZnS(Ag) coating thickness, position of particles as well as shape of particles and partial coating have been varied to account for possible manufacturing imperfections. EJ-426 detectors have been modeled for reference purposes by defining spherical grains of $^6$LiF and ZnS(Ag) and compared against experiments. The simulation results show that the coated micro-particles should dramatically increase the neutron detection efficiency, light production and light collection efficiency when compared to EJ-426.

**N-32-04**

Modeling Shielded Gamma-ray Sources using Non-negative Matrix Factorization (#2426)

PhD/MD student Kyle J. Bilton$^1$, Dr. Tenzing H. Y. Joshi$^2$, Dr. Mark S. Bandstra$^2$, M.Sc./M.A. Joseph C. Curtis$^2$, Dr. Reynold J. Cooper$^2$, Prof. Kai Vetter$^{1,2}$

$^1$University of California, Berkeley, Department of Nuclear Engineering, Berkeley, USA; $^2$Lawrence Berkeley National Laboratory, Applied Nuclear Physics Program, Berkeley, USA

Content
Accurately accounting for shielded gamma-ray sources and gamma rays that have undergone significant scattering remains a challenge to gamma-ray source identification algorithms. In this work, we introduce a data-driven approach for modeling spectral contributions from shielded sources in gamma-ray identification algorithms. In particular, we build on recent work using Non-negative Matrix Factorization (NMF) for modeling background gamma-ray spectra to introduce multi-parameter source models. The approach introduced here for generating spectral source representations using NMF allows for improved source contribution estimates in the presence of shielding or environmental scattering, ultimately resulting in enhanced identification capabilities. Performance of the method is characterized using NaI(Tl) gamma-ray spectra from a mobile detection system. Furthermore, the method introduced here is general enough to be broadly applicable to gamma-ray spectroscopic analysis, and can be used in applications relying on template matching.

**N-32-05  11:32 AM**

**Can coded apertures be used to replace x-ray screens?** (#1336)

Dr. Klaus - Peter Ziock¹, Dr. Matthew Blackston¹, Dr. Irakli Garishvili¹

¹ Oak Ridge National Laboratory (ORNL), NSITD, Oak Ridge, USA; ² University of Tennessee, Knoxville, Department of Physics and Astronomy, Knoxville, USA

**Content**

The use of coded apertures as a possible replacement for the x-ray screens that control scattered radiation in x-ray radiography systems is explored using both simulations and experiments. Scattered radiation carries information on the electron density in radiographed objects that could be used to enhance the information available from a radiograph. Coded apertures provide a mechanism for imaging such radiation, so instead of blocking it with an x-ray screen, a coded aperture could be used to make an image. Two geometries were explored: In the first, the coded aperture was placed between the object and the detector as a direct replacement for the x-ray screen. In the second, the coded aperture was placed in front of an additional detector not in the direct beam. Results obtained from both simulations and experimental measurements indicate that the first geometry is not viable because the direct beam overwhelsms the scattered signal and because the relationship between the scatter angle and the incident beam of singly scattered x-rays is incommensurate with the requirements of coded-aperture imaging. The results for the second geometry are more favorable, indicating that the approach is viable and could even be used to obtain tomographic images of the object. However, due to the low intensity of the scattered signal, the value of the technique must be evaluated for specific applications.
Range Verification using Prompt Gamma-rays with Energy Spectral Analysis in Geant4 Based Proton Therapy Simulation (#1351)

Prof. Tsukasa Aso¹, Hiroki Oke², Prof. Teiji Nishio³

¹ National Institute of Technology, Toyama College, Electronics and Computer Engineering, Toyama, Japan; ² National Institute of Technology, Toyama College, Advanced Course, Toyama, Japan; ³ Tokyo Women’s Medical University, Department of Medical Physics, Graduate School of Medicine, Tokyo, Japan

Content

Range verification of therapeutic proton beam is crucial in proton therapy to confirm the irradiation field for ensuring effects and safety of the treatment. An irradiation field reconstruction using prompt gamma-rays generated from excited nuclides by proton beam has being studied for the purpose of precision medicine. A simulation tool based on fundamental physics processes employs an important role to understand intermediate relationship between physics interactions and detected observables, and to optimize a detector system with its analysis method. Previously, we reported on the simulation study about an irradiation field reconstruction by using prompt gamma-rays of whole energy range. In this study, we analyzed the energy spectrum and then reconstructed the image of irradiation field by using prompt gamma-rays associating to a particular energy peak. The simulation was performed for proton beam with a target placed at the isocenter by using Geant4 based particle therapy system simulation framework. A simple tubular detector was placed around the target, in which the kinetic energy and the detected position of each gamma-ray were recorded. The irradiation field was reconstructed in the ordered subset expectation maximization method. The reconstructed irradiation fields were compared with the absorbed energy distribution in the target. The peak positions of these depth distributions were compared each other and discussed about the range verification of therapeutic proton beam.
N-33 | NSS Dosimeters and Applications

Anatoly Rozenfeld (Wollongong)
Angela Kok
A new high performance dosimeter based on radiochromic films and opto-electronic instrumentation (#2360)

Dr. Pierluigi Casolaro¹, Dr. Luigi Campajola²,¹, Prof. Giovanni Breglio³,¹, Dr. Salvatore Buontempo¹, Dr. Marco Consales⁴, Prof. Andrea Cusano⁴, Prof. Antonello Cuto³, Dr. Francesco Di Capua²,¹, Dr. Francesco Fienga²,¹, Dr. Patrizio Vaiano⁴

¹ Istituto Nazionale di Fisica Nucleare (INFN), Section of Napoli, Napoli, Italy; ² University of Napoli Federico II, Department of Physics, Napoli, Italy; ³ University of Napoli Federico II, Department of Electronical Engineering, Napoli, Italy; ⁴ University of Sannio, Optoelectronics Group - Department of Engineering, Benevento, Italy

Content

This work describes a new dosimeter that provides real-time spectral response of radiochromic films. Radiochromic films are dosimeters widely used in many applications of radiation physics and mainly in medical physics. The radiation-induced darkening is related to the dose by means of a calibration. Currently the darkening is evaluated with flat-bed scanners and densitometers providing dose values only after the exposure to radiation. The new dosimeter, recently patented by the authors of this work, overcomes this limitation providing real-time dosimetry. The setup consists of a radiochromic film, fiber optic probe, spectrometer, light source and reflector. In addition of exploiting all the potential of radiochromic films and optical fibers, the new dosimeter allows excellent performances as high accuracy, precision and dynamic range. These features are analyzed by discussing recent results carried out with a 20MeV proton beam and with EBT3 Gafchromic films, radiochromic films intensively used in medical physics in the range 1cGy-40Gy. The real-time spectral response of the films is analyzed in the visible and near-infrared ranges by pointing out more than one approach for the calibration. In particular, the calibration at wavelength of 633nm allows extension of films dynamics up to mGy doses with 2% uncertainty. The calibration with the area of the optical density in the range 500-700nm reproduce the performances of commercial flat-bed scanners. Finally the analysis of the spectral response in the range 750-850nm allows extension of dynamics up to kGy doses with 5% uncertainty. Same procedures have been carried out for other radiochromic films as the HD-V2 Gafchromic films with enhanced sensitivity up to hundreds of kGy. Current dosimeter characteristics are suitable for real-time dosimetry in radiation hardness assurance tests. Further insights, aiming at reducing the dimension and cost can pave the way to interesting applications such as in-vivo dosimetry.
Simultaneous Neutron-Photon Dosimetry with a Compact Organic Scintillator Detector (#2517)

Cameron A. Miller¹, Prof. Angela Di Fulvio², William M. Steinberger¹, Dr. Shaun D. Clarke¹, Prof. Sara A. Pozzi¹

¹ University of Michigan, Department of Nuclear Engineering and Radiological Sciences, Ann Arbor, USA; ² University of Illinois, Department of Nuclear, Plasma, and Radiological Engineering, Urbana, USA

Content
In many applications involving radiation fields it is important to determine dose rates imbued by radiation workers and the public. In many scenarios, neutrons and photons can both be significant contributors to the dose rate. Traditionally, separate instruments have been used for each particle's contribution to the dose rate, but it has been shown experimentally that organic scintillator detector can be used to accurately measure both contributions simultaneously. The scalability of an organic scintillator also allows for use in both high- and low-flux environments.

In previous work, we demonstrated the influence of detector size on dose rate measurements. It was shown that a 5.08 cm depth detector EJ-309 liquid organic scintillator with minimal diameter requires the least corrections to accurately measure dose rate. This work builds on the previous study by demonstrating neutron and photon dose rate measurements with a 50 mm depth × 6mm × 6mm stilbene bar, which is similar in composition to EJ-309, coupled to a silicon photomultiplier readout. The experimentally measured dose rates are compared to simulation and traditional dosimeters to verify accuracy. This small detector will allow for highly mobile, accurate dosimetry in the field.

Timepix3 as a Very Fast Real Time Spectrometer in Pulsed X-ray Fields for Dosimetric Applications (#1653)

Jürgen Roth², M.Sc./M.A. Benedikt Bergmann¹, Dr. Oliver Hupe², Christian Fuhg²

¹ Institute of Experimental and Applied Physics at CTU in Prague, Praha, Czech Republic; ² Physikalisch-Technische Bundesanstalt, Abt. 6 Ionisierende Strahlung, Braunschweig, Germany

Content
Timepix3 is chosen as a very promising candidate for development of a pulsed radiation dosemeter. Ionizing particle energy deposition is measured with a time resolution of nominal 1.5625 ns in 256 × 256 pixel of 55 µm pixel pitch. These parameters and the almost dead time free readout mode gives best preconditions for characterizing measurements in pulsed radiation fields. The performance of a Timepix3 detector with a 300 µm thick silicon sensor was studied in referenced pulsed x-ray fields at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig. Temporal pulse shapes were resolved so that characteristic parameters, defined in the ISO standard for pulsed
Radiation, could reliably be extracted from measured data up to a maximal dose rate of 719 mSv/h (tested with the narrow X-ray quality N-60). Ongoing investigation focus on dose assessment, x-ray spectrum reconstruction using deconvolution methods and device performance testing in other tube spectra.

A Sensitive Cube for Measuring Dose from Charged Particles and Neutrons in Space (#1416)

Prof. Charalambos P. Lambropoulos¹,², Dr. Constantinos Potiriadis³, Dr. Gerasimos Theodoratos², M.Sc./M.A. Ioannis Kazas⁴, M.Sc./M.A. Ioannis Glikiotis², Dr. Christos Papadimitropoulos¹,³, Dr. Pavlos Paschalis⁵, Markos Kokavesis², Dr. Evangelia Dimovasili², Dr. Dimitrios Loukas⁴, M.Sc./M.A. George Dimitropoulos²

¹ National and Kapodistrian University of Athens, Athens, Greece; ² ADVEOS microelectronics P.C., Chalandri, Greece; ³ Greek Atomic Energy Commission, Agia Paraskevi, Greece; ⁴ National Center for Scientific Research Demokritos, Institute of Nuclear and Particle Physics, Agia Paraskevi, Greece; ⁵ University of Cyprus, Department of Physics, Nicosia, Cyprus

Content

Radiation doses received by astronauts outside the geomagnetic field are a main risk factor for human space exploration. Determination of LET spectra is necessary in the standard paradigm of risk assessment for mixed radiation fields, because it allows calculation of dose equivalent, while identification of ions by species (or at least by group) is required, if the risk assessment tools developed by NASA are used. The MIDAS device is developed with purpose to achieve mass <50 g, volume < 5 x 5 x 1 cm³ and power consumption <10 mW for an instrument capable to determine the fluence spectrum as a function of charge and energy of the impinging particles, at least for those species with the most significant contribution to dose in space. In addition it is capable to measure fast neutron spectra. The enabling technologies of this device are: (a) Depleted Monolithic Active Pixel Sensors and (b) gamma – neutron plastic scintillator coupled to a Silicon Photomultiplier.
Feasibility of SOI Microdosimeter for DaRT Quality Assurance and Radon Dosimetry in Mines (#1943)

Dr. Linh T. Tran¹, Benjamin James¹, Dr. Dale A. Prokopovich², Dr. Marco Petasecca¹, Prof. Michael Lerch³, Sylvester Werczynski², Dr. Scott Chambers², Dr. Alastair Williams², Dr. Marco Povoli³, Dr. Angela Kok³, Prof. Michael Jackson³, Dr. Joseph Bucci³, Prof. Anatoly B. Rosenfeld¹

¹ University of Wollongong, Centre for Medical Radiation Physics, Wollongong, Australia; ² Australian Nuclear Science and Technology Organization, Australia, Sydney, Australia; ³ SINTEF, Oslo, Norway; ⁴ University of New South Wales, Sydney, Australia; ⁵ St George Hospital, Cancer Care Centre, Sydney, Australia

Content
Diffusing alpha-emitters radiation therapy (DaRT) is a new brachytherapy method utilizing alpha particles to treat solid tumors with interstitial implantable radioactive sources of $^{224}$Ra which continually release $^{220}$Rn, $^{218}$Po and $^{212}$Pb atoms from their surface. In DaRT, it is important to measure not only in vivo absorbed dose measurements, but also to understand Radiobiological Efficiency (RBE) of mixed alpha, beta radiation field. No real time in-vivo quality assurance (QA) for RBE and dose monitoring is available currently for DaRT. Development of such system will accelerate clinical implementation of DaRT technology.

This research proposes to use silicon on insulator (SOI) microdosimeter developed at the Centre for Medical Radiation Physics, University of Wollongong, Australia to monitor dose and derive RBE, to provide an in vivo real time QA for DaRT. Development of such system will accelerate clinical implementation of DaRT technology. It was demonstrated that the microdosimeter was able to measure the microdosimetric energy deposition due to decay of $^{222}$Rn gas in air and diffused isotopically through 1 cm of meat. Obtained results demonstrated the first principle possibility of development microdosimetry based portable wearable radon dose equivalent meter and in vivo real time QA device for DaRT.

NDX: Neutron Dose Rate Meters with Extended Capabilities (#1240)

Dr. Pavel V. Degtiarenko

Jefferson Lab (TJNAF), Radiation Control Department, Newport News, USA

Content
Particle accelerators, irradiation facilities, and nuclear power plants would benefit from using neutron dose rate meters featuring improved energy response covering full range of expected neutron energies, improved dynamic range of measured dose rates while providing the real-time data, and improved ability to operate in harsh radiation environments including heavy photon backgrounds and pulsed beams. The novel design of the neutron moderator for the NDX dose rate meter implements a layer of a Beryllium-loaded medium Z material which, similar to the earlier known WENDI detectors, allows the device to detect higher energy neutron flux and convert it to dose. Using
Beryllium helps to fill the known dip in the response functions around 5-50 MeV. Optimized design parameter set, obtained using FLUKA Monte Carlo simulations, features the NDX moderator made of polyethylene embedding a layer of Be–Cu alloy inside, with the dose rate response constant within ±10% in the neutron energy range from about 100 keV to 500 MeV, and ±25% essentially in the full energy range above thermal. A new sensor technique implemented in the NDX is based on using the Ionization Chamber (IC) filled with $^3$He gas to capture the moderated neutron fluence, and includes a symmetric IC filled with regular $^4$He to evaluate the contributions due to the non-neutron ionizing radiation. Advantages of the method include large accessible dynamic range, relative insensitivity of the IC probes to photon radiation fields, and the ability to subtract their contribution. Two prototype NDX detectors were built, calibrated, and operated in various conditions at the CEBAF 12 GeV electron accelerator at JLab. The first results showed reliable neutron dose rate measurements in the presence of overwhelming photon radiation fields, and at practical high dose rate levels of up to approximately 10 Sv/h. Detector design, operation, first results, and further development plans are presented.
R-10 | CZT Detectors II

Beatrice Fraboni (Bologna)
Characterization of radiation detectors by transient currents and photoconductivity  (#1214)

Prof. Roman Grill, PhD/MD student Jindrich Pipek, PhD/MD student Katarina Ridzonova, Prof. Eduard Belas, Prof. Petr Praus, PhD/MD Artem Musiienko, PhD/MD student Igor Vasylichenko, PhD/MD Jan Kunc

Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic

Content
Credible characterization of radiation detector materials constitutes an indispensable step at the effort to prepare high-quality radiation detectors. Convenient deep defect structure represents one of the most important characteristics for the utilization of detectors affecting both the charge collection efficiency due to carrier's trapping and the electric field homogeneity related with the level's charging. Recently, it has become favored to determine the mobility-lifetime product from the bias dependence of the above-band-gap-excited photoconductivity (PhC). The reason for this treatment is the simplicity of the experiment, which may be easily prepared in laboratory. The method, however, often suffers from a violation of basic prerequisites routinely omitted by researchers, which are put by the theory on the experimental setup as well as on the defect structure. These are especially the homogeneous electric field and a stable fixed lifetime of photocarriers independent of the bias, which should be preserved cautiously. In this contribution, we discuss in detail the possibility to determine basic detector's characteristics, namely the mobility-lifetime product, by PhC. The analysis is based on numerical simulations of transient currents in CdZnTe optically excited both in the laser-induced transient current and PhC regimes. The coupled drift-diffusion and Poisson's equations are solved. The carrier (de)trapping is described with the Shockley-Read-Hall model. It is shown that the conditions put to the PhC setup significantly limit its applicability in common radiation detectors. Special attention is devoted to the chopped PhC, which could surmount some obstacles apparent in the steady state PhC. It is argued that principal problems exist in this case as well. It is concluded that using PhC for the determination of the mobility-lifetime product may often result in significant error both underestimating and overestimating the right value.
We present a novel method of direct electric field vector measurements based on cross-polarizers method exploiting the Pockels electro-optic effect of CdZnTeSe. This new method suitable also for the detectors with non-planar contact configurations is based on the simultaneous rotating of two orthogonal polarizers. If the electric field vector is constant along the optical path in the Pockels setup, with the knowledge of the crystallographic orientation, it is possible to obtain full information about the distribution of magnitudes and directions of the electric field through the whole studied detectors. In the oral presentation the method will be demonstrated on biased quasi-hemispheric and quasi-virtual frisch grid detectors equipped with electrodes with geometry that keeps electric field constant along the optical path. The measured electric fields will be compared with ideal electric field distributions calculated from geometry of the electrodes using the Poisson’s equation.

**R-10-03 10:56 AM**

**Novel electroless deposition technique for platinum contacts on CdZnTe radiation detectors (#2134)**

Dr. Manuele Bettelli¹, Dr. Nicola Sarzi Amadè¹, Dr. Silvia Zanettini¹,², Dr. Lucia Nasi¹, Dr. Francesca Casoli¹, Dr. Leonardo Abbene³, Dr. Andrea Zappettini¹

¹ CNR, IMEM, Parma, Italy; ² Due2lab s.r.l., Reggio E., Italy; ³ Università degli Studi di Palermo, DIFC, Palermo, Italy; ⁴ Università degli Studi di Parma, SCVSA, Parma, Italy

**Content**

One of the major issues for the preparation of CdZnTe-based radiation detectors is contact deposition. Platinum is a good candidate for the realization of blocking contacts on CdZnTe, because its work function of about 5.6 eV (higher than gold) leads to the formation of a high Schottky barrier, that translates into lower leakage current. Blocking contacts are usually adopted to realize high-resolution spectrometers, where minimization of dark current is fundamental. In particular, it recently became clear that platinum is more suitable than gold as contact metal on CdZnTe for specific high-flux applications. Even though several groups have already realized platinum contacts on CdZnTe, they often show poor mechanical adhesion and stability. In particular, CdZnTe thermal instability above 400 - 450 K prohibits performing thermal annealing of the contacts to enhance their robustness.

In this work, we describe a novel procedure to obtain robust platinum contacts by electroless deposition. The electroless solution for platinum deposition is composed by platinum chloride (PtCl₄) dissolved in a mixture of specific solvents. With this method, mechanically stable platinum contacts have been deposited. We have studied how to vary deposition conditions in order to obtain different thickness of Pt contacts. Morphological and electrical characteristics of the platinum contacts are investigated with different techniques such as adhesion tape test, morphological imaging by cross-section transmission electron microscopy, thin film conductivity and current-voltage characteristics measurements. Also the spectroscopic behavior of Pt/CdZnTe/Pt samples characterized with nuclear sources will be presented.
Impeccable regulated doping of p-n junction CdTe diode by backside laser doping (#2606)

PhD/MD student Junichi Nishizawa1, Dr. Hisaya Nakagawa2, Dr. Volodymyr Gnatyuk3, Dr. Akifumi Kolke4, Prof. Toru Aoki2,4

1 Shizuoka Univ, Graduate School of Science and Technology, Hamamatsu, Japan; 2 Shizuoka Univ, Research Institute of Electronics, Hamamatsu, Japan; 3 National Academy of Sciences of Ukraine, Institute of Semiconductor Physics, Prospekt Nauky, Ukraine; 4 ANSeeN, iPERC, Hamamatsu, Japan

Content
We are working on development of p-n junction CdTe diode using laser doping technology for more advanced X-ray detectors. Conventional laser doping techniques utilizes single pulse laser of 100 mJ of irradiation energy to create p-n junction CdTe, which results in evaporation of dopant material. In order to solve this issue, a new method of thermal diffusion doping (we call it backside irradiation) is adopted in which laser is transmitted through CdTe and only contact surface of the dopant material is irradiated with the laser. In backside irradiation, since the dopant material does not evaporate from the surface by the heat of laser irradiation, a p-n junction can be formed even if the conditions of laser irradiation energy is inconsistent. Thereby, it is expected that the intensity of the laser and the number of iterations of irradiation can be easily regulated to control the doping layer and the concentration. We have used Nd: YAG laser (1064 nm) which has a good transmittance in CdTe, to produce CdTe samples by regulating the number of iterations with fixed irradiation intensity. I-V curve characterization of the produced p-n junction CdTe has confirmed expected diode characteristics for X-ray detector, and was also confirmed with the observed gamma ray spectrum.

Fabrication and Characterization of CdZnTeSe Nuclear Detectors (#2540)

Prof. Stephen U. Egarievwe1,2, Dr. Utpal N. Roy2, Dr. Ralph B. James3

1 Alabama A&M University, Electrical Engineering and Computer Science, Huntsville, USA; 2 Brookhaven National Laboratory, Noneploilation and National Security, Upton, USA; 3 Savannah River National Laboratory, Science and Technology, Aiken, USA

Content
Cadmium zinc telluride selenide (CdZnTeSe) is emerging as a promising semiconductor material for low-cost production of nuclear and radiological detection systems capable of operating at room temperature without cryogenic cooling. The introduction of Se into the cadmium zinc telluride (CdZnTe) matrix in the growth process could result in large high-quality crystal yields with less defects. This presentation covers the fabrication of gamma-ray detectors from high-quality CdZnTeSe crystals grown by the traveler heater method (THM). The resistivity of the CdZnTeSe is in the order of 10^{10} Ω-cm. The electron mobility-lifetime (μτ) product characterizing the charge transport properties is
in the order of $10^{-3} \text{ cm}^2/\text{V}$. Energy resolutions as good as 6.5% FWHM for the 59.5-keV gamma-peak of Am-241 were recorded for planner detectors with gold contacts. We will also present the effects of chemical passivation on the detection and electrical properties of the CdZnTeSe detectors.
N-34 | Scintillators and Photodetectors III

Peter R. Hobson
Catherine M. Pepin (Sherbrooke)
3D printing for scintillator detectors (#1446)

Dr. Petr S. Sokolov\textsuperscript{1,2}, Dr. Dmitry A. Komissarenko\textsuperscript{2}, Dr. Georgy A. Dosovitskiy\textsuperscript{1,2}, Dmitry Y. Kozlov\textsuperscript{3}, Alexey E. Dosovitskiy\textsuperscript{4}, Dr. Mikhail V. Korzhik\textsuperscript{1,3}

\textsuperscript{1} NRC «Kurchatov Institute», Moscow, Russia; \textsuperscript{2} NRC «Kurchatov Institute» - IREA, Moscow, Russia; \textsuperscript{3} Institute for Nuclear Problems of Belarus State University, Minsk, Belarus; \textsuperscript{4} NeoChem JSC, Moscow, Russia

Content
The present study demonstrates capability of 3D printing to fabricate different elements of scintillation detectors, particularly reflectors for pixel scintillator detectors with complex shapes. The reflecting surfaces for pixels of different sizes (from 0.8 to 3.2 mm) have been obtained by a low-cost digital light processing stereolithography and subsequently tested. The material for the reflectors is a composite of transparent ultraviolet light-cured resin and light-scattering filler, which is TiO\textsubscript{2} – the most widely used white inorganic pigment. The printing rate of about 1 cm per hour was achieved with the possibility to produce several parts simultaneously. The reflective properties of such surfaces were comparable to conventional Teflon tape wrapping, but allowing much simpler and faster pixel array assembling.

Improvements in light extraction and energy resolution from CsI and GAGG using GRIN photonic crystal imprinting (#2574)

Dr. Bipin Singh\textsuperscript{1}, Dr. Charles S. Sosa\textsuperscript{1}, Dr. Keiko Munechika\textsuperscript{2}, Dr. Carlos Pina-Hernandez\textsuperscript{2}, Dr. Vivek V. Nagarkar\textsuperscript{1}

\textsuperscript{1} Radiation Monitoring Devices, Inc, Watertown, USA; \textsuperscript{2} aBeam Technologies, Inc., Hayward, USA

Content
The objective of this work is to quantify the gain in light extraction (LE) and energy resolution (ER) for GAGG and CsI crystals, all of the same geometry (cube) and dimensions (1×1×1 cm\textsuperscript{3}), after a gradient index (GRIN) photonic-crystal (PhC) structure is imprinted onto the surface of the scintillator used for coupling to a photo-multiplier tube (PMT). A PhC is a repeating material structure that is on the order of the wavelength of light and can be used to manipulate transmission properties at a material interface, for example the light-extraction surface of a scintillator. Each scintillator was characterized with and without a PhC using the same measurement equipment and settings. A Cs-137 gamma-ray source was used to assess improvements in LE and ER at 662 keV. Results demonstrate that LE improved by over 28\% and 50\% for CsI and GAGG, respectively. In addition, ER improved by over 20\% and 14\% for CsI and GAGG, respectively. Details will be presented at the conference.
Processing signals from a Silicon Photomultiplier: a comparative analysis of results based on peak detection and signal integration (#1640)

Prof. Massimo L. Caccia\textsuperscript{1}, Prof. Romualdo Santoro\textsuperscript{1}, PhD/MD student Samuela Lomazzi\textsuperscript{1}, PhD/MD student Luca Malinverno\textsuperscript{1}, Dr. Alexander Martemiyanov\textsuperscript{1,4}, Dr. Edward Marsden\textsuperscript{2}, Dr. Ian Radley\textsuperscript{2}, Dr. Chris Allwork\textsuperscript{3}, Dr. Mark Ellis\textsuperscript{3}

\textsuperscript{1} Università dell’Insubria, Dept. Science and High Technology, Como, Italy; \textsuperscript{2} KROMEK ltd., Sedgefield, UK; \textsuperscript{3} AWE plc, Reading, UK; \textsuperscript{4} ITEP, Moscow, Russia

Content
This paper reports an investigation of the procedure for extracting the information on the number of fired cells by processing the analog signal by a Silicon Photomultiplier (SiPM), either detecting directly the light from a pulsed source or sensing the visible light burst emitted by a scintillating material in response to an incoming sub-atomic particle. The comparison was based on two complementary approaches, retaining as a key figure either the peak value or the integral of the signal.

The analysis of the single photo-electron response yields similar results for the two figures in terms of fluctuations normalized to the average value, where the dominant effect is possibly the residual cell-to- cell gain variation. However, multi-photon spectra based on the use of the peak value clearly shows a better quality since the random occurrence of after-pulses or delayed cross-talk events in the integration window affects in a significant way the natural classification of the sensor response into a discrete number of fired cells.

As far as detection of light by a scintillator, the results strongly depend on the light emission time of the material in use. For slow scintillators, it may be expected that the fraction of photons contributing to the build-up of the signal peak value is limited, affecting the resolution. The opposite may be expected for fast scintillators. Tests were performed using CsI(Tl), with scintillating decay time constants of 600 and 3500 ns, and LYSO, characterized by a 40 ns decay time. The figure of merit was the energy resolution on the 662 keV photopeak by a 137Cs source. For CsI(Tl), the use of the integral lead to 5.7 % resolution, to be compared to 11.3% when the peak value of the signal was used. On the other hand, for LYSO both figures lead to 12.1%, confirming the expectations.

High-energy and high-rate X-ray counting with HfO\textsubscript{2} nanoparticle-doped plastic scintillator (#1603)

Prof. Shunji Kishimoto\textsuperscript{1}, Akehiro Toda\textsuperscript{2}

\textsuperscript{1} High Energy Accelerator Research Organization, Photon Factory, Institute of Materials Structure Science, Tsukuba-shi, Japan; \textsuperscript{2} Tokyo Printing Ink Mfg. Co., Ltd, Saitama, Japan
Content
We fabricated fast scintillators by using HfO$_2$ nanoparticles doped into a plastic scintillator (PLS). Such a heavy metal doped PLS will be useful for measurements of high-energy X-rays up to a high count-rate > 10$^7$ s$^{-1}$. A 40 wt% HfO$_2$ nanoparticle-doped plastic scintillator (Hf-PLS) was successfully polymerized by mixing with polystyrene and (2-(4-tert-butylphenyl)-5-(4-biphenyl))-1,3,4-oxadiazole (b-PBD) as fluorophore. We tested the 40 wt% Hf-PLS (8 mm in diameter, 3 mm thick) mounted on a photomultiplier tube (PMT) using synchrotron X-ray beam at beamline BL-14A of the Photon Factory (PF). The detection efficiency at 50.0 keV reached 44.3 ± 0.2%. Counting rates up to over 10$^7$ s$^{-1}$ were recorded even in the hybrid mode including a high current single electron bunch of the PF ring. The pulse height spectra and time spectra were observed with another PMT detector mounting the 40 wt% Hf-PLS at 67.41 keV for application to synchrotron radiation nuclear resonant scattering. A good time resolution (full width of half maximum) of 0.29 ± 0.06 ns was obtained while we had a time resolution of 0.50 ns at best with a commercially available 5 wt% lead doped PLS. We will also present the test results using a 60 wt% Hf-PLS at the conference.

N-34-05  2:52 PM

A new spectroscopic imager for X-rays from 0.5 keV to 150 keV combining a fully depleted pnCCD coupled to a columnar CsI(Tl) scintillator with Fano limited energy resolution and deep subpixel spatial resolution (#2206)

Dr. Dieter M. Schlosser$^1$, Robert Hartmann$^1$, Alois Bechteler$^2$, Dr. Ali Abboud$^3$, Mohammad Shokr$^3$, Prof. Ullrich Pietsch$^3$, Prof. Lothar Strueder$^{1,3}$

$^1$ PNSensor GmbH, Soft and Hard X-ray spectroscopic Imager, Munich, Germany; $^2$ PNDetector GmbH, Soft and Hard X-ray spectroscopic Imager, Munich, Germany; $^3$ Universität Siegen, Department of Physics, Siegen, Germany

Content
Highly energy and position resolving detectors over a wide energy range are required for space telescopes in high energy astrophysics missions. By combining a low noise fully depleted pnCCD detector with a columnar CsI(Tl) scintillator an energy dispersive spatially resolving detector can be realized with high quantum efficiency in the range from below 0.5 keV to above 150 keV. The detector is exposed to the photon source such that the X-rays first traverse the 450 µm sensitive pnCCD. If they are stopped through the photoelectric effect in the Silicon detector, Fano limited energy resolution is achieved. This is true for all X-rays from a few hundred eV up to approximately 15 keV. Above this energy the conversion probability in the CsI(Tl) is becoming higher. Due to the high atomic number Z of Cs and I (55 and 53) hard X-rays are stopped efficiently for photon energies up to 150 keV for a 0.7 mm thick CsI scintillator. The light from the scintillator is recorded with the same back-illuminated pnCCD. For X-rays from a $^{57}$Co source at energies of 122 keV we achieve an energy resolution of 0.7% (FWHM=850 eV) for the conversion in the Silicon directly while the energy resolution for the conversion in the CsI(Tl) is 10% (12 keV). We have performed “knife edge” measurements at 122 KeV and achieved a position resolution at that energy of 27 µm. Monte-Carlo simulations were showing similar, fully compatible results. In case the X-rays are converted directly in the Silicon the position precision is better than 10 µm. This is close to the physical limits of spatial resolution in such a system which is given by the
length of the tracks of the secondaries in the ionizing process in Silicon and CsI. Spectra, images and the results of the GEANT4 simulations will be shown.

N-34-06 3:10 PM

Predictions of hadron-specific damage from fast hadrons in crystals for calorimetry using FLUKA (#1166)

Francesca Nessi-Tedaldi, Günther Dissertori, Cristina Martin Perez

ETH Zurich, c/o CERN - PH Department, Geneva 23, Switzerland

Content
Inorganic crystals used for calorimetry, like lead tungstate and LYSO, have been observed to suffer from a specific damage due to fast hadrons. The damage mechanism has been recognised in fission tracks, which scatter the scintillation light and reduce its collection efficiency. Where scintillators are planned to be used when fast hadron fluences are anticipated, predictions are important for making an informed choice of technology. In the study presented here, simulations using the FLUKA package have been performed on lead tungstate, LYSO and cerium fluoride, and their results have been compared with measurements. An agreement is found between simulation results and several experimentally accessible observables, which allows to conclude that the damage amplitude in a given material can be predicted in its order of magnitude.
1:40 PM – 3:28 PM

Charter 2

N-35 | Readout, Trigger and DAQ II

Alexander Oh (Manchester)
Masaharu Nomachi (Toyonaka)

This session focuses on front-end systems.
The Phase-I Trigger Readout Electronics Upgrade of the ATLAS Liquid Argon Calorimeters (#2811)

Nikiforos Nikiforou, on behalf of ATLAS LAr collaboration

Slovak Academy of Sciences, Institute of Experimental Physics, Kosice, Slovakia; University of Texas at Austin, Austin, USA

Content

Electronics developments are pursued for the trigger readout of the ATLAS Liquid-Argon Calorimeter towards the Phase-I upgrade scheduled in the LHC shut-down period of 2019-2020. Trigger signals with higher spatial granularity and higher precision are needed in order to improve the identification efficiencies of electrons, photons, tau, jets and missing energy, at high background rejection rates, already at the Level-1 trigger. The LAr Trigger Digitizer system will digitize the 34,000 channels (SuperCells) at a 40 MHz sampling frequency with 12 bit precision after the bipolar shaping of the front-end system. The data will be transmitted to the LAr Digital Processing system in the back-end to extract the transverse energies and perform the bunch-crossing identification. A demonstrator has been installed during Run-2, and the results of the data-taking have helped to validate the chosen technology. Results of ASIC developments including QA/QC and radiation hardness evaluations, performances of the pre-production boards and results of the system integration tests, progress of QA/QC of final production boards will be presented along with the overall system design.

Tile TDAQ interface module for the Phase-II Upgrade of the ATLAS Tile Calorimeter (#1242)

Dr. Xiaoguang Yue, Dr. Pavel Starovoitov, On behalf of the ATLAS TileCal Collaboration

Heidelberg University, Kirchhoff-Institute for Physics, Heidelberg, Germany

Content

In order to meet the requirements for the High-Luminosity Large Hadron Collider (HL-LHC), a completely new architecture will be used to redesign the readout electronics of the ATLAS Tile Calorimeter (TileCal) system for the ATLAS Phase-II Upgrade. In the new Trigger and Data AcQuisition (TDAQ) architecture, the output signals of the Tile detector cells will be digitized in the front-end electronics and transferred for every bunch crossing to the off-detector Tile PreProcessor (TilePPr) modules through high-speed optical links. The TilePPr will then reconstruct energy deposited in each cell from the digitized samples and transfer the pre-processed cell energy data further to the Tile TDAQ interface (TDAQi) modules. The TDAQi will then group the cell energy data to generate trigger primitives with different granularity and implementing interfaces based on different requirements from the Feature Extractor (FEX) and other trigger processor modules. At the same time, the TilePPr will also store the energy
information in pipeline memories and send selected data out to the ATLAS data acquisition system through the TDAQi. The TDAQi module will be implemented on an Advanced Telecommunications Computing Architecture (ATCA) Rear Transition Module (RTM) format and will operate under the ATCA framework. In order to verify the basic functionality and interfaces of the TDAQi, a lightweight prototype, called the TDAQi demo, has been designed and is now under test. This contribution will provide an overview of the new TileCal back-end electronics architecture and present the design and implementation of the TDAQi demo module together with preliminary test results.

**N-35-03**

**FELIX: commissioning the new detector interface for the ATLAS trigger and readout system** (#1324)

Mark Stockton¹, Marco Trovato², I am submitting this on behalf of ATLAS Trigger-DAQ Speakers Committee. If accepted for oral or poster presentation we will assign a final presenter.

¹ CERN, Geneve, Switzerland; ² Argonne National Laboratory, Lemont, USA

**Content**

After the current LHC shutdown (2019-2021), the ATLAS experiment at the LHC at CERN will be required to operate in an increasingly harsh collision environment. The LHC will deliver luminosities up to three times the original design value, with a commensurate increase in the number of interactions per bunch crossing. To maintain physics performance in this new regime, the ATLAS experiment will undergo a series of upgrades during the shutdown. A key goal of this upgrade is to improve the capacity and flexibility of the detector readout system. To this end, the Front-End Link eXchange (FELIX) system has been developed. FELIX acts as the interface between the data acquisition; detector control and TTC (Timing, Trigger and Control) systems; and new or updated trigger and detector front-end electronics. FELIX functions as a router between custom serial links from front end ASICs and FPGAs to data collection and processing components via a commodity switched network. Links may aggregate many slower links or be a single high bandwidth link. FELIX also forwards the LHC bunch-crossing clock, fixed latency trigger accepts and resets received from the TTC system to front-end electronics. FELIX uses commodity server technology in combination with FPGA-based PCIe I/O cards. FELIX servers run a software routing platform serving data to network clients. Commodity servers connected to FELIX systems via the same network run the new multi-threaded Software Readout Driver (SW ROD) infrastructure for event fragment building and buffering. In addition the SW ROD supports detector specific data processing, and serves the data, upon request, to the ATLAS High Level Trigger for Event Building and Selection. This presentation will cover the design of FELIX, the SW ROD, and the results of the installation and commissioning activities for the full system in summer 2019.
Redundant Timing Crosschecking for Frontend Digitization Systems: Principal and Validation Tests (#1611)

Dr. Jinyuan Wu¹, Daren Chen²

¹ Fermi National Accelerator Laboratory, Batavia, USA; ² Hinsdale Central High School, Hinsdale, USA

Content

In contemporary high energy physics experiments, in addition to the regular three dimensional coordinates, the fourth dimension, or the timing information of the charged particle hits becomes necessary. It would be very useful for the frontend digitization system to include a feature of redundant timing crosschecking. The inspiration for the timing crosschecking scheme came from the long-abandoned analog mean-timer schemes. In this mean time based scheme, a cable set with taps connected to the digitization modules is utilized as a pulse path and pulses are driven from both ends alternately without overlapping. The mean times of arrival times of the pulses in different modules represent a common time standard and their variations is recorded and monitored. The time delay drifts of the cable segments are self-cancelled in this scheme and this feature enables easy achievement of good timing precision without need for complex hardware.

A 2D FPGA-based clustering algorithm for the LHCb silicon pixel detector running at 30 MHz (#1856)

PhD/MD student Giovanni Bassi¹,², Dr. Riccardo Cenci¹,², PhD/MD student Federico Lazzari¹,³, Prof. Michael J. Morello¹,², Prof. Giovanni Punzi¹,⁴

¹ INFN, Sezione di Pisa, Pisa, Italy; ² Scuola Normale Superiore, Pisa, Italy; ³ Università degli Studi di Siena, Siena, Italy; ⁴ Università di Pisa, Pisa, Italy

Content

Starting from 2021, the upgraded LHCb readout system will process events at the full LHC collision rate (30 MHz). A common effort in addressing low-level time-consuming tasks at early DAQ stages is being tackled, allowing a significant reduction of computing resources that can be devoted to more specialized tasks. FPGA accelerators are well suited to address, in a high parallel way, logically simple and repetitive processes, that are particularly time demanding on CPUs. A FPGA-based 2D cluster-finding algorithm has been therefore developed in dedicated FPGA cards, for the LHCb silicon pixel VELO detector. Results and performances achieved with this system are presented here, in the context of the LHCb Upgrade I, in view of potential future applications.
Reduction of Dead Time Losses in Neutron Multiplicity Counting Systems

Kiril D. Ianakiev, Metodi L. Iliev, Dr. Andrea Favalli, Dr. Martyn T. Swinhoe

Los Alamos National Laboratory (LANL), Los Alamos, USA

Content

Dead time counting losses in neutron proportional counters can lead to inaccurate quantitative measurements especially when relying on multiplicity analysis. Empirical dead time correction algorithms have been developed for applications such as multiplicity counters, but the theory may not be applicable for some applications. We present a simple hardware-based technology for dramatically reducing the dead time losses in neutron counting systems. We have developed a method (called Zero Dead Time or ZDT) that can recognize pileups in detector pulses based on their pulse height, and can return the otherwise lost pulses to the data stream. The hardware utilizing this technology comprises of charge sensitive preamplifier, Gated Integrator (GI), shaper and a multi-channel analyzer (MCA) with pulse counting outputs to LIST mode or sift register DAQ system. Laboratory prototype measurements demonstrated dead time (DT) reduction of factor of 8 and possibility to work without pre-delay at neutron coincidence measurements.
N-36 | Instrumentation and Concepts for Nuclear Security II

David Petersen
Keitaro Hitomi
N-36-01 1:40 PM

Reconstruction Algorithms for Muon Computed Tomography (#1526)

Dr. Kathryn Hartling, PhD/MD student Kendall Boniface, PhD/MD student Andrew Erlandson, Dr. Evan Rand

Canadian Nuclear Laboratories, Chalk River, Canada

Content

Cosmic-ray muons are a highly-penetrative form of natural radiation which scatters preferentially from materials of high atomic number (Z), such as uranium and plutonium. Muon tomography imaging techniques can therefore be leveraged to address concerns of nuclear safety and non-proliferation. Muon computed tomography generalizes traditional computed tomography algorithms for use with measurements of cosmic-ray muons, and has applications in imaging large nuclear infrastructure such as spent fuel repositories. The muon computed tomography algorithm currently under development at Canadian Nuclear Laboratories was originally based upon the Algebraic Reconstruction Technique (ART). However, results using ART were found to suffer substantially from statistical and ray effects. In the current work, we assess the effect of the choice of reconstruction algorithm upon images reconstructed using muon computed tomography. Measurements of cosmic-ray muons traveling through both a simple cylindrical geometry and CNL's Zero Energy Deuterium (ZED2) reactor have been modeled in a Monte Carlo simulation using the Geant4 software libraries for particle transport. Images have been reconstructed using six different computed tomography algorithms: ART, Adaptive ART, Multiplicative ART, Simultaneous Iterative Reconstruction Technique, L1-NORM, and the Least-Squares Conjugate-Gradient method. The LS CG, L1-NORM, and SIRT algorithms were all found to provide advantages over the standard ART algorithm.

N-36-02 1:58 PM

Correlations between Panoramic Imagery and Gamma-Ray Background in an Urban Area (#2505)

Dr. Mark S. Bandstra¹, Dr. Brian J. Quiter¹, Kyle J. Bilton², Joseph C. Curtis¹, Steven Goldenberg⁵, Dr. Tenzing H. Y. Joshi¹, Dr. Marco Salathe¹

¹ Lawrence Berkeley National Laboratory, Applied Nuclear Physics Program, Berkeley, USA; ² University of California Berkeley, Department of Nuclear Engineering, Berkeley, USA; ³ The College of William and Mary, Computer Science Department, Williamsburg, USA

Content

When searching for radiological sources in an urban area, a vehicle-borne detector system will often measure complex varying backgrounds from natural gamma-ray sources. Much work has been focused on developing spectral algorithms that suppress these backgrounds in order to minimize false positive rates without sacrificing the sensitivity. However, information about the environment surrounding the detector system might also provide useful clues about the expected background, thus improving sensitivity. Recent work has focused on extensive measuring
and modeling of urban areas with the goal of understanding how these complex backgrounds arise. This work presents an analysis of panoramic video images and gamma-ray background data collected in Oakland, California by the Radiological Multi-sensor Analysis Platform (RadMAP) vehicle. Features were extracted from the panoramic images by semantically labeling the images and then convolving the labeled regions with the detector response. A linear model was used to relate the image-derived responses to gamma-ray spectral features derived using Non-negative Matrix Factorization (NMF). We show that some gamma-ray background features highly correlate with image-derived features such as sky or buildings in the panoramic images.

N-36-03  2:16 PM

Development of a HPGe Detector for Ultra High Rate Spectroscopy and Imaging (#1965)

Joanna M. Szornel1, Paul J. Barton2, Reynold J. Cooper2, Heather L. Crawford2, Alexey Drobizhev2, Marco Salathe2, Kai Vetter1,2

1 Department of Nuclear Engineering, University of California Berkeley, Berkeley, USA; 2 Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, USA

Content
A prototype HPGe detector has been designed to maintain energy resolution and throughput performance at count rates in excess of 2 Mcps and offer 3D position sensitivity. Conventional HPGe detectors show significant degradation at such count rates. Applications for the new device include imaging for nuclear medicine, nuclear decommissioning and remediation, the assay of spent nuclear fuel, as well as prompt spectroscopy of super-heavy elements and isotope harvesting. The detector design, a double-sided strip detector with a fine strip pitch of 0.5 mm, was selected by performing analytical and numerical calculations of the expected efficiency, throughput, timing, energy and position resolution for various geometries and electrode configurations. Details of the design and predicted performance will be shown. Results from the fabrication and characterization of the prototype will be presented.

N-36-04  2:34 PM

Using 3D-Scene Data from a Mobile Detector System to Model Gamma-Ray Backgrounds (#2246)

Dr. Marco Salathe, Dr. Mark S. Bandstra, Dr. Brian J. Quiter, Joseph C. Curtis

Lawrence Berkeley National Laboratory, Applied Nuclear Physics Program, Berkeley, USA

Content
Integration of contextual sensors into vehicle-borne mobile radiation detector systems delivers a rich description of the environment that could be used to estimate the complex and variable environmental gamma-ray backgrounds in
urban areas. The predictions could potentially increase the sensitivity for illicit radiological and nuclear materials and could provide realistic inputs to urban radiological search models. Recent work in this field has focused mainly on the predictive power of segmenting and classifying imagery from cameras and elected in its approach to aggregate the fielded detector array to a single point. This work builds upon the previous effort by leveraging LiDARs to create a 3D representation of the detector system and the surrounding scenery and demonstrates further improvement in the capability of attributing observed gamma-ray backgrounds to classes of surrounding materials.

Object Detection, Tracking, and Attribution for Radiological Search

PhD/MD student Matthew R. Marshall¹, PhD/MD Marco Salathe², Dr. Tenzing H. Y. Joshi², PhD/MD student Kyle J. Bilton¹, PhD/MD Nicolas Abgrall², Chun Ho Chow², Jackson Michalski¹, Alex Moran², Victor Negut², PhD/MD Reynold J. Cooper², Prof. Kai Vetter¹,²

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Content

Static gamma-ray detectors have been deployed in complex urban environments to aid in the detection and localization of radiological and/or nuclear material. However, with only spectroscopic data, effectively responding to a radiological alarm is difficult due to the lack of situational awareness. This study investigates the use of contextual information to enable real-time object detection and tracking to augment radiological data to improve situational awareness. Data was collected using a 1.5” CLYC detector that was co-located with a contextual sensor that was left unattended in a facility. We developed a novel detection, tracking, and attribution analysis to perform alarm attribution with video data. We utilized Convolutional Neural Networks to identify objects with bounding boxes, Kalman filtering to track objects between video frames, and Poisson statistics and maximum likelihood estimation to identify the trajectories that are most (and least) likely to have been associated with a radiological alarm. Results show the tracking algorithm tracks multiple objects in real-time with high fidelity and handles temporary occlusions. Also, the attribution algorithm is robust at identifying trajectories that are (in)consistent with the count-rate data. In this work, we demonstrate the ability to improve situational awareness by using a multi-hypothesis approach to integrate contextual sensors with radiological data streams.
First precision spectroscopy of cesium-137 from the ground to 150 m above in Fukushima (#1935)


Waseda University, Department of Pure and Applied Physics, Graduate School of Advanced Science and Engineering, Shinjuku, Japan

Content

After the Fukushima nuclear disaster in 2011, large amounts of radioisotopes (mainly 137Cs and 134Cs) were released into the environment. Various monitoring activities have revealed radiation on the ground both in local and wide areas; however, aerial dose variation in the vertical direction is poorly known. This paper presents the first results of airborne gammaray spectroscopy of a contamination field in Namie, Fukushima, as measured from 0 m to 150 m above the ground by drone. We found that the gamma-ray dose rate measured at 100 m height is about seven times higher than that expected based on ground measuring, which is caused by two factors: (1) the integrated dose includes contamination of upward scattered 662-keV gamma rays and (2) radiation from 137Cs is vertically collimated because 137Cs is buried in the soil. We also argue novel method to obtain the distribution of radioactive substances in the soil only through aerial mapping.
N-37 | NSS Gaseous Detectors and Applications II

Ilaria Vai (Pavia)
Atsuhiro Ochi (Kobe)
Results from the Compact Muon Solenoid GE1/1 Slice Test and Status of the Installation and Commissioning of the GE1/1 Detectors (#1752)

PhD/MD student Elizabeth R. Starling

Université libre de Bruxelles, iihe, Bruxelles, Belgium

Content
The GE1/1 system is the newest subdetector to be added to the CMS (Compact Muon Solenoid) endcap muon system. It consists of a series of 144 triple-GEM (gas electron multiplier) detectors, installed as 36 two-detector “superchambers” in each endcap. Due to the existing mechanical restrictions of CMS, these are further broken down into 18 short (1.61 < |η| < 2.18) and 18 long (1.55 < |η| < 2.18) superchambers in each endcap. These detectors are placed in front of the already-existing CSCs (cathode strip chambers) and will interface with them, allowing for added redundancy in a difficult η region, better tracking in a high rate environment, and measurement of the bending angle at the trigger level to decrease the number of mismeasured muons. During the 2017-2018 run, ten “slice test” detectors were installed in order to serve as a proof of concept and to act as a trial run for the full system. Data was recorded during these runs using both cosmic ray muons and LHC collisions. During this time, a loss of VFAT2 channels was observed, with two detectors exhibiting rapidly-increasing channel loss beginning mid-2018. Investigations as to the cause of this loss were launched, and the lessons learned from these investigations allowed for the improvement of the design of the VFAT3 readout chip in time for the production and installation of the final GE1/1 detectors. In this contribution, we will present the status of the production, installation, and commissioning of the GE1/1 detectors and on the lessons learned throughout the process.

Performance of the ATLAS RPC detector and L1 Muon Barrel trigger at sqrt(s) = 13 TeV (#1850)

Dr. Rustem Ospanov, Dr. Rustem Ospanov, on behalf of the ATLAS Muon Coll.

European Organization, CERN, Geneva, Switzerland

Content
The ATLAS experiment at the Large Hadron Collider utilizes a trigger system consisting of a first level hardware trigger and a higher level software trigger. The Level-1 muon trigger system selects muon candidates with six transverse momentum thresholds and associate them with a correct LHC bunch crossing. The Level-1 Muon Barrel Trigger uses Resistive Plate Chambers (RPC) detectors to generate trigger signals for selecting muon candidates within the pseudorapidity range of up to 1.05. The RPC detectors are arranged in three concentric double layers and consist of about 3600 gas volumes, with a total surface of more than 4000 square meters, that operate in a toroidal magnetic field. This contribution will discuss the performance of the RPC detector system and of the Level-1 Muon
Barrel trigger during the 2018 data taking period. Measurements of RPC detector response obtained using muon candidates produced in LHC collisions will be presented. Trigger performance and efficiency measurements that are obtained using Z boson decays to a muon pair will be also discussed. Finally, studies of the RPC detector response at different high voltage and threshold settings will be discussed, in the context of expected detector response after the High Luminosity LHC upgrades.

N-37-03 2:16 PM

Design, Construction and Test of Small-Diameter Drift Tube Chambers for the Phase-1 Upgrade of the ATLAS Muon Spectrometer (#2068)

Dr. Patrick Rieck, Prof. Hubert Kroha, Dr. Oliver Kortner, PhD/MD student Marian Rendel

Max-Planck-Institut for Physics (Werner-Heisenberg-Institut), Munich, Germany

Content
The ATLAS muon spectrometer consists of an efficient muon trigger system and high muon momentum resolution up to the TeV scale. Yet, in the regions at both ends of the inner barrel layer of the muon spectrometer the trigger selectivity is limited. Furthermore, at the future High-Luminosity LHC the efficiency of the resistive plate trigger chambers (RPCs) will decrease due to ageing effects. Therefore, additional RPCs will be installed at the ends of the inner barrel layer of the muon spectrometer in the current long shutdown for the Phase-1 upgrade of the LHC in 2019 and 2020. In order to free space for them, the present muon drift tube (MDT) chambers will be replaced by an integrated system of thin-gap RPCs and small-diameter muon drift tube (sMDT) chambers. Due to their higher background rate capabilities, the new sMDT chambers are also suitable precision muon tracking detectors at future hadron colliders. A comprehensive overview of the production of the sMDT chambers will be given, covering the construction of the drift tubes, the evaluation of the wire positioning accuracy required to be better than 20 microns, deformation measurements using optical alignment systems and the installation and test of the gas distribution system and electronics. The evaluation of the sMDT chamber geometry with a coordinate measuring machine yields a wire positioning accuracy of better than 10 microns m for the 1.5 times 1.5 square metres chambers with up to 744 drift tubes. The sMDT chambers are currently sent to CERN where their installation is planned for September 2019. This upgrade is a pilot project in view of the replacement of half of the MDT chambers of the inner barrel layer scheduled for the Phase-2 upgrade of the ATLAS detector.
MPGD-based photon detectors for the upgrade of COMPASS RICH-1 and beyond. (#1220)
PhD/MD student Chandradoy Chatterjee, COMPASS-RICH Collaboration
INFN Trieste and University of Trieste, Physics, Trieste, Italy

Content
After pioneering gaseous detectors of single photon for RICH applications using solid-state PhotoCathodes (PC) within the RD26 collaboration and by the realization of the MWPCs with CsI PC for the RICH detector of the COMPASS experiment at CERN SPS, in 2016 we have upgraded COMPASS RICH by novel gaseous photon detectors based on MPGD technology. Four new photon detectors, covering a total active area of 1.5 square meters, have been installed in order to cope with the challenging efficiency and stability requirements of the COMPASS physics program. The new detector architecture consists in a hybrid MPGD combination: two layers of THGEMs, the first of which also acts as a reflective PC thanks to CsI coating, are coupled to a bulk Micromegas on a pad-segmented anode; the signals are read-out by analog F-E based on the APV-25 chip. These MPGD-based single photon detectors are the first application in a running experiment. Highlights of the COMPASS RICH-1 Photon Detectors upgrade are presented, including R&D, engineering, mass production, quality assessment. The performance of the MPGD-based photon detectors will be discussed in details. Perspectives for further developments in the field of gaseous single photon detectors will be also mentioned.

The RICH detector of the NA62 experiment at CERN (#1312)
Dr. Mauro Piccini1, Francesco Brizioli2, Prof. Giuseppina Anzivino2, Dr. Patrizia Cenci1, Dr. Monica Pepe1, Dr. Roberto Piandani2, Riccardo Lollini2, Dr. Viacheslav Duk1, Prof. Andrea Bizzeti6, Dr. Bucci Francesca3, Dr. Cassese Antonio3, Ciaranfi Roberto3, Prof. Enrico Iacopini4, Prof. Latino Giuseppe4, Prof. Lenti Massimo4, Dr. Volpe Roberta5, Andrea Parenti4, On behalf of the RICH working group of the NA62 experiment

1 INFN, Sezione di Perugia, Perugia, Italy; 2 University of Perugia, Dipartimento di Fisica e Geologia, Perugia, Italy; 3 INFN, Sezione di Firenze, Sesto Fiorentino, Italy; 4 University of Firenze, Dipartimento di Fisica e Astronomia, Sesto Fiorentino, Italy; 5 Universite Catholique de Louvain (UCL), Centre for Cosmology, Particle Physics and Phenomenology, Louvain-La-Neuve, Belgium; 6 Università degli studi di Modena e Reggio Emilia, Dipartimento di Scienze Fisiche, Informatiche e Matematiche, Modena, Italy

Content
NA62 is the last generation kaon experiment at the CERN SPS aiming to study the ultra-rare $K^+ \rightarrow \pi^+\nu\nu$ decay. The main goal of the NA62 experiment is the measurement of this BR with 10% accuracy. This is achieved by collecting about 100 $K^+ \rightarrow \pi^+\nu\nu$ events.
The challenging aspect of NA62 is the suppression of background decay channels with BR up to 10 orders of magnitude higher than the signal and with similar experimental signature, such as $K^+ \rightarrow \mu^+\nu_\mu$. To this purpose, the NA62 experimental strategy requires, among other conditions, good particle identification (PID) capability and rejection power of the kinematic selection. A key element of PID in NA62 is the Ring-Imaging Cherenkov (RICH) detector, exploiting neon gas at atmospheric pressure as radiator medium. According to the NA62 requirements, the RICH identifies $\mu^+$ and $\pi^+$ in the momentum range between 15 and 35 GeV/c with a muon rejection factor of $10^{-2}$. It also measures the arrival time of charged particles with a precision better than 100 ps and is one of the main components of the NA62 trigger system. The RICH detector has been successfully operated during the 2016, 2017 and 2018 data taking periods of NA62. The main design aspects and operational characteristics of the detector will be described in detail and a detailed report of its performance, directly measured with the data collected, will be presented.

**N-37-06**

**A 1 m$^3$ gas TPC with optical readout for directional dark matter searches: the CYGNO experiment** (#1805)

**Dr. Francesco Renga**, On behalf of CYGNO-Collaboration

*Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Roma, Italy*

**Content**

The aim of the CYGNO project is the construction and operation of a 1 m$^3$ gas TPC for directional dark matter searches and coherent neutrino scattering measurements, as a prototype toward the 100-1000-m$^3$ (0.15-1.5 tons) CYGNUS network of underground experiments. In such a TPC, electrons produced by dark-matter- or neutrino-induced nuclear recoils will drift toward and will be multiplied by a three-layer GEM structure, and the light produced in the avalanche processes will be readout by a sCMOS camera, providing a 2D image of the event with a resolution of a few hundred micrometers. Photomultipliers will also provide a simultaneous fast readout of the time profile of the light production, giving information about the third coordinate and hence allowing a 3D reconstruction of the event, from which the direction of the nuclear recoil and hence the direction of the incoming particle can be inferred. Such a detailed reconstruction of the event topology will also allow a pure and efficient signal to background discrimination. These two features are the key to reach and overcome the solar neutrino background that will ultimately limit non-directional dark matter searches.
R-11 | Imaging and Applications II

Zhong He (Ann Arbor)
MiniPRISM: 3D Realtime Gamma-ray Mapping from Small Unmanned Aerial Systems and Handheld Scenarios (#2607)

Dr. Ryan T. Pavlovsky¹, Dr. Joshua W. Cates¹, Dr. Marcos Turqueti¹, PhD/MD student Daniel Helffeld², Victor Negut³, Alex Moran¹, Dr. Paul J. Barton¹, Dr. Kai Vetter², Dr. Brian Quiter¹

¹ Lawrence Berkeley National Lab, Applied Nuclear Physics, Berkeley, USA; ² University California Berkeley, Lawrence Berkeley National Lab, Berkeley, USA

Content

Lawrence Berkeley National Lab (LBNL) has previously demonstrated gamma-ray mapping of point and distributed sources using small unmanned aerial systems (sUAS) with monolithic CsI(Tl) detectors, as well as Compton imaging from RMAX UAS utilizing gamma-ray imagers [Vetter, Kai, et al. (2018) NIM-A 159-168]. These systems enable gamma-ray mapping through 3D Scene Data Fusion (SDF), where 3D contextual sensor data such as LiDAR is fused with radiation data. sUAS borne radiation detectors systems are desirable as sUAS are highly mobile and flexible platforms for source search, decontamination verification and distribution mapping and can be extended to autonomous operation. Due to computational and payload limits available on sUAS, significant offline processing was previously required to create 3D Compton gamma-ray maps. We now report on the development, first results and performance of a real-time, compact, coplanar grid (CPG) CdZnTe (CZT) gamma-ray imaging and mapping system, dubbed MiniPRISM, for deployment on sUAS or other autonomous platforms. MiniPRISM comprises 64 detector modules each with cubic centimeter volume, enabling $4\pi$ coded mask and Compton imaging. This modular CPG CZT array provides the ability to arrange detector modules in optimized configurations for Compton and coded mask imaging. MiniPRISM implements SDF and utilizes developments of LBNL's contextual sensor, compute and software suite called the Localization and Mapping Platform, LAMP. MiniPRISM generates 3D gamma-ray maps in real-time through fusion of Compton and coded mask gamma-ray imaging modalities with 3D LiDAR data in this new, compact and highly mobile implementation. We demonstrate results of brief ~5min sUAS flights and handheld scenarios to localize low- and high-energy sources in 3D and in real-time as well as system characteristics.

Analysis of metal ornaments produced during Moche period in ancient Peru (#1125)

Dr. Jan S. Iwanczyk¹, Prof. Angel Bustamante², Prof. Roberto Cesareo³, Prof. Soraia Azeredo⁴, Shaul Barkan⁵

¹ Consultant to Hitachi High Technologies Science America, Inc., Chatsworth, USA; ² Universita di Sassari, Sassari, Italy; ³ Universidad Nacional Mayor de san Marcos, Lima, Peru; ⁴ Federal University of Rio de Janeiro, Rio de Janeiro, Brazil; ⁵ Hitachi High Technologies Science America, Inc., Chatsworth, USA

Content

Analysis of metal ornaments produced during Moche period in ancient Peru
There are number of pre-Columbian cultures flourished on the north coast of present-day Peru. Among them the Moche Culture (100-600 AD) was particularly interesting from their very advanced metallurgical technology abilities. Spectacular gold and silver funerary ornaments have recently been excavated and now these items are displayed in the Museum Lord of Sipan and the Museum of Cao. From the initial measurements it is evident that the Moche metallurgy is very complex due to variety of alloys and manufacturing techniques employed. In order to have a better understanding of the composition and production technologies of the investigated objects we have used both an energy dispersive x-ray fluorescence analysis (EDXRF) and a gamma-ray transmission technique. For the EDXRF measurements we used a miniature x-ray generator and a silicon drift detector (SDD). For transmission measurements a gamma source of Am-241 and a novel 1mm thick SDD from Hitachi High Technologies Science America, Inc. have been utilized. EDXRF provides an excellent information about elemental composition only at or near the surface of the objects due to a strong self-absorption of characteristic x-rays within the investigated metals. There are possibilities to get certain information about thickness of the layers by accounting for altered internal ratio of characteristic x-rays Kα/Kβ or/and Lα/Lβ. However, the measurement of “tumbaga” objects is complicated, because the “tumbaga” is composed of Au, Cu and Ag, with the prevailing presence of gold just at the surface, and copper with less than 3% of silver in the rest of the volume. EDXRF very often cannot give a clear answer to the cited problem. An alternative method was, therefore, applied based on the transmission of 60 keV and 26 keV γ-rays.

**XSpectra®: an Advanced Real-Time Food Contaminants Detector**

Dr. Bruno Garavelli¹, Dr. Pietro Pozzi¹, PhD/MD Daniele Macera¹, Dr. Luca Zanotti¹, Dr. Alessandra Mencarelli¹, Dr. Giacomo Bubba¹, Dr. Patrizio Bertoni¹, PhD/MD student Martina Sammartini², PhD/MD Manuele Bettelli³, Prof. Giuseppe Bertuccio², Prof. Giacomo Ghiringhelli⁴, Prof. Andrea Zappettini³

¹ Xnext s.r.l., Milan, Italy; ² Politecnico di Milano, Department of Electronics, Information and Bioengineering, Milan, Italy; ³ Consiglio Nazionale delle Ricerche, Istituto Materiali per l’Elettronica ed il Magnetismo, Parma, Italy; ⁴ Politecnico di Milano, Department of Physics, Milan, Italy

Content

An innovative X-ray inspection technology, named XSpectra®, has been developed with the aim to improve the current state of art in the field of real-time detection of contaminants in food products on production lines. The technology architecture is based on modules equipped with a 128 pixels CdTe array detector each read-out by full-custom Front-End ASICs. A full-custom Multi-Channel-Analyzer reconstructs the radiation spectrum, which is then processed by advanced Neural Network algorithms performing both image reconstruction and foreign bodies detection. The experimental characterization of XSpectra® has demonstrated the sensitivity of the fully operating system to photon energies down to about 10 keV at events rates up to several millions of photons per second. A line-width of 8.5 keV FWHM has been measured, at room temperature, on the 60 keV photo-peak of a synchrotron radiation in low-rate conditions. A spectral non-linearity error within ±0.5% has been obtained within the energy range 25 keV — 100 keV. The effective capability of XSpectra® to detect currently undetectable low-density contaminants inside real food products has also been proved.
**R-11-04** 2:40 PM

**Photon-Counting X-ray Detectors in Medical Imaging: Achievements & Future Directions** (#2794)

*Dr. Martin Petersilka, Dr. Steffen Kappler*

*Siemens Healthcare GmbH, Forchheim, Germany*

**Content**

Registration of all available post-patient X-ray quanta with high spatial, temporal, and spectral resolution can be considered the ultimate goal of X-ray detection in medical imaging. Photon-counting X-ray detectors (PCXDs) based on semiconductor conversion materials represent a major step into this direction. PCXDs are capable of energy-resolved intensity measurements of the post-patient X-ray beam and exhibit no intrinsic energy-weighting. In addition, small pixels can be realized with a high fill-factor, and classical electronics readout noise is not present. These properties make PCDs very attractive to further improve the diagnostic value of medical X-ray imaging modalities, such as Computed Tomography (CT) for instance. In the last decade, PCXDs have taken their way from benchtop experiments into clinical evaluation. In this contribution, we briefly summarize major technological achievements of this arising detector technology, provide a short overview of existing research CT prototype systems, review results from early clinical studies, and give an outlook to potential applications of PCXDs in further X-ray imaging modalities.

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**R-11-05** 3:04 PM

**Forward Modeling Using Experimental Response Functions for High-Resolution CZT Imaging Spectrometers** (#1288)

*Dr. Christopher G. Wahl, Dr. Brian Kitchen, Alec Goldberg, Alan Balkany, Dr. Steven Brown, Dr. Willy Kaye*

*H3D, Inc., Ann Arbor, USA*

**Content**

Large-volume 3D-position-sensitive CdZnTe is used in many applications. In many of these applications, it is useful to quickly predict what the spectral and image response will be to a particular source and environment. For instance, in scenario simulation or measurement planning, one would like to know what output can be expected. Some analysis methods may also benefit from having estimates of the spectrum and simple-back-projection image for many scenarios. Such a forward model is developed here. Instead of traditional method using Monte-Carlo or deterministic transport, or analytic functions, this forward model is accomplished using interpolations between over 2400 hours of characterization measurements. Details of the interpolation methods will be presented along with representative results comparing the forward model with measurements of new scenarios.
M-07 | Medical Imaging Systems I

Robert S. Miyaoka (Seatle)
Volkmar Schulz (Aachen)
A dual-sided sparse-readout quantitative PET scanner for breast-cancer-therapy optimization (#2655)

Dr. William C. J. Hunter¹ ², Dr. Donald DeWitt¹ ², Dr. Larry Pierce¹, Dr. Lawrence MacDonald¹, Dr. Chengeng Zeng¹, Dr. Paul Kinahan¹, Dr. Robert Miyaoka¹

¹ University of Washington, Department of Radiology, Seattle, USA; ² PET/X LLC, Seattle, USA

Content

We are developing a breast PET/X scanner that integrates PET with mammography-tomosynthesis systems to produce high-resolution and quantitatively accurate images of radiotracer uptake in breast cancer. Specifically, we have investigated use of sparse-sensor silicon photomultiplier arrays for reducing the number of photo sensors and digital acquisition channels needed for this quantitative task. Lowering system cost is considered to be a critical requirement for adoption of this system. As proof of concept, we have assembled a smaller 1-layer version of the proposed rectangular scanner with fewer detector blocks (16 versus 120) and a reduced field of view (9x13x3 cm³ versus 10x24x15 cm³). We constructed and tested 16 detector units using scintillation crystal arrays from three different manufacturers. Although all arrays were produced to specifications, one set achieved adequate depth decoding.

To assess image resolution, we imaged a micro-Derenzo hot-rod phantom using a clinically relevant activity level (123 kBq/cc of FDG) and ten million energy-windowed coincidence counts were acquired in 15 minutes with effectively no deadtime. Images were reconstructed using a fully-3D penalized weighted least squares objective function, which was minimized with a preconditioned conjugate gradient algorithm using a statistical weighting matrix. The penalty term was a 3D Huber prior. Coincidence data between 4 detector panels were binned into planograms and reconstructed into 0.5 mm cubic voxels using a 180x260x60 grid. We were able to marginally resolve the 1.6 mm rods and the 2.4 mm rods are readily discernable. We have subsequently performed Monte-Carlo simulation studies based on the above measurements (data not shown) that predicts image resolution will be improved if all detectors achieve adequate depth decoding, as described above.
Hyperion III – A flexible PET detector platform for simultaneous PET/MRI (#2163)

Dr. Bjoern Weissler¹, Dr. David Schug¹, Dr. Thomas Dey¹, Dr. Pierre Gebhardt¹, PhD/MD student Karl Krueger¹, PhD/MD student Nicolas Gross-Weege¹, PhD/MD student Florian Mueller¹, PhD/MD student Harald Radermacher¹, PhD/MD student Laiyin Yin¹, PhD/MD student Vanessa Nadig¹, Rene Bakker², Dimitri Kuznetsov², Dr. Jeremy Brown², Dr. Dennis Schaart², Prof. Volkmar Schulz¹

¹ RWTH Aachen, Department of Physics of Molecular Imaging Systems / Institute for Experimental Molecular Imaging, Aachen, Germany; ² Delft University, Department of Radiation Sciences and Technology, Delft, Netherlands

Content
Commercially available PET/MRI scanner have been designed as whole-body systems. In these, PET spatial resolution and sensitivity are limited. Dedicated PET inserts can potentially overcome these limitations, but every application, e.g., neuro, breast, or preclinical, has different requirements. A new PET detector platform for simultaneous PET/MRI was thus designed, providing the needed flexibility to construct different systems. Scintillation light from the PET detector crystals is detected by sensor tiles. The first implementation contains a 6×6 array of DPC-3200 sensors from PDPC, which offer 144 channels in a sensitive area of approx. 48×48 mm². The sensor tiles are connected with flexible cables to the singles processing units (SPUs). Cable lengths of up to 2 m were tested successfully. Data rates of more than a Gbit/s should be transferable by the current hardware design – 500 Mbit/s are currently implemented in the firmware. Each SPU currently supplies up to 15 sensor tiles with programmable voltages and transmits their data via 10-Gigabit Ethernet to a data acquisition system. Multiple SPUs can be synchronized optically, enabling galvanically separated detector modules as being advantageous for MRI compatibility.

Initial measurements were performed with two PET detector modules using the platform. Placed close to the gradients coils of a 1.5T-MRI scanner during gradient switching (in X-, Y-, and Z-direction, slew rate of 200 mT/(m·ms), switching duty cycle of 5%), neither count rate changes nor variations in coincidence resolving time (259 ps FWHM, DPCs in trigger scheme 2) or energy resolution (10.9% FWHM) were observed. The measurements indicate that the Hyperion III platform can leverage full performance of the used sensors – even during MRI operation. The platform is currently already used to construct a dedicated breast PET insert, a neuro insert for ultra-high-field MRI, and a planning scanner for radiation therapy.
M-07-03

Performance evaluation of the EXPLORER total-body PET/CT scanner based on NEMA NU-2 2018 standard with additional tests for extended geometry (#2596)

Dr. Benjamin A. Spencer¹, Dr. Jeffrey P. Schmall³, Dr. Eric Berg², Zilin Deng³, Songsong Tang³, Dr. Yun Dong³, Edwin K. Leung², Yang Lv³, Weiping Liu³, Jun Bao³, Hongdi Li³, Prof. Terry Jones¹, Prof. Ramsey D. Badawi¹,², Prof. Simon R. Cherry²,¹

¹ UC Davis Medical Center, Radiology, Sacramento, USA; ² UC Davis, Biomedical Engineering, Davis, USA; ³ United Imaging Healthcare, Shanghai, China

Content

UC Davis and United Imaging have collaborated to develop the world’s first total-body PET/CT scanner. The uEXPLORER PET/CT scanner is US FDA approved and the first production scanner will be installed at the UC Davis EXPLORER Imaging Center in early May 2019, with first clinical and research human imaging studies scheduled for June 2019. In this abstract we present a complete, detailed characterization of the uEXPLORER system based on NEMA NU-2 2018 along with additional measurements designed to fully characterize the system’s 194 cm axial FOV. The spatial resolution at three radial positions and eight axial positions, from the center to the edge of the axial FOV, was assessed using F-18 point source measurements following the NU-2 guidelines. The sensitivity was measured using the 5-sleeve line source method using the 70 cm line source specified by NU-2 as well as with an extended NU-2-like 210 cm line source to measure the total-sensitivity of the system. Calculations of the scatter fraction, NECR peak value, peak true count rate, and relative count rate error were obtained using the standard 70 cm long scatter phantom, along with several extended scatter phantom lengths (using additional phantom segments). Lastly, the quantitative image quality was measured using the NEMA IQ phantom, and images were acquired for a range of scan durations, activity concentrations, and axial positioning of the phantom. Overall, the uEXPLORER demonstrates exceptional image quality and consistent quantitative performance along the entire axial FOV.

M-07-04

Monte Carlo sensitivity study of a long axial FOV PET scanner with patient adaptive rings (#2061)

PhD/MD student Maya Abi Akl¹,², Dr. Stefaan Vandenbergh³, Dr. Othmane Bouhali², Dr. Yassine Toufique², Dr. Joel S. Karp³

¹ Universiteit Gent, Ghent, Belgium; ² Texas A&M University at Qatar, Doha, Qatar; ³ University of Pennsylvania, Philadelphia, USA

Content
In this work, we present the simulation results of a compact whole body PET design and an optimized longer axial FOV PET using monolithic detectors. The compact design is a simulation of the proposed European PET system (PET2020) of 70cm bore and axial FOV of 70cm optimized for cost and single organ imaging. The total number of detectors and readout is ‘only’ 2-3 x higher than the current PET-CT systems. The extended FOV system without any additional detectors represents a research upgrade for the compact system to enhance FOV, sensitivity and spatial resolution at no extra cost of detectors for smaller objects than the available bore diameter. The compact system design consists of 14 rings of 70cm bore and an axial FOV of 70cm. Each ring is composed of 40 blocks of 50x50x16mm monolithic LYSO. The upgraded design consists of 28 rings of 20 blocks each over a length of 140cm; rings are then half-populated but the FOV is doubled without any additional detectors. Another advantage of this design is the presence of 50 % gaps between the detectors block which enables the reduction of the diameter to a value of 35cm per ring. This allows the use of the scanner in adaptive mode where selected or all rings can be adjusted to have the smallest diameter possible while enclosing the patient partially of fully (in paediatric mode). Results show that the compact design (70 cm axial long, 70 transverse diameter) is 7 times more sensitive than its equivalent of 20cm axial FOV (standard FOV for most of the clinical PET scanners) for body scans. For the upgraded design, further increase in sensitivity is observed with extended axial length and decreasing bore diameter. In the limit of a completely closed 35cm diameter system with 140cm axial length, the solid angle is even 11 % higher than that of the recently launched 2m long Total body PET system (while only requiring one third of the detector material). This will mostly be relevant for paediatric patients.

Dynamic imaging on the long axial field of view PennPET Explorer

PhD/MD student Varsha Viswanath¹, Dr. Austin R. Pantel², Dr. Margaret E. Daube-Witherspoon², Mark Muzi³, Dr. David A. Mankoff², Prof. Joel S. Karp²

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Content

Long axial field of view (AFOV) PET scanners open the door to whole-body dynamic PET imaging and the study of novel oncoligic tracers and brain-body relationships. Expanding PET’s toolbox of radiopharmaceuticals is a key component of precision medicine, tailoring treatment to specific cancer phenotypes. The increased axial coverage and improved sensitivity of long AFOV PET overcome the limited axial coverage and temporal sampling used with clinical systems. For this study we used data from a normal volunteer injected with FDG and imaged on the 64-cm AFOV PennPET Explorer for 60 min. We created a dynamic dataset that emulated a patient with active disease by using the subject’s left ventricular (LV) blood curve and embedded 10-mm lesions with a range of flux and a time-activity distribution based on published data. Data were reconstructed frame-by-frame using list-mode time-of-flight OSEM. The time-activity curves (TACs) were measured, and kinetic parameters were estimated using a two-compartment model with trapping in PMOD with the LV blood curve as the image derived input function (IDIF). Additionally, high flux curves were fit using various measured IDIFs from other vessels, such as the pulmonary and carotid arteries to study the effect of time dispersion and partial volume effects on kinetic parameter estimation.
Preliminary results show that estimated flux values have a bias of less than 10% for all lesions except those with low flux. This research will characterize and quantify the advantages of long AFOV scanners with high sensitivity for dynamic applications.

Fast Dynamic Total-Body PET Imaging on EXPLORER (#1834)

Dr. Xuezhu Zhang¹, Dr. Zhaoheng Xie¹, Dr. Jun Bao³, Dr. Hongdi Li³, Dr. Simon R. Cherry¹,², Dr. Ramsey D. Badawi¹,², Dr. Jinyi Qi¹

¹ University of California, Davis, Department of Biomedical Engineering, Davis, USA; ² UC Davis Medical Center, Department of Radiology, Sacramento, USA; ³ United Imaging Healthcare, Shanghai, China; ⁴ Zhongshan Hospital, Shanghai, China

Content
The world's first 194-cm long total-body PET/CT scanner (uEXPLORER) was constructed to offer a transformative platform for human molecular imaging in clinical research and healthcare. Its total-body coverage and ultra-high sensitivity provide opportunities for more accurate analysis in studies of physiology, biochemistry and pharmacology. The objective of this study is to develop a method to perform ultra-high-temporal-resolution dynamic PET imaging by applying the kernel-regularized reconstruction paradigm to uEXPLORER data. We aim to capture the dynamics of initial tracer distribution and cardiac motion. To demonstrate the effectiveness of the method, a one-hour total-body dynamic scan was acquired during and following an intravenous injection of 6.9 mCi of 18F-FDG. We divided the dataset into 0.1-second temporal frames and analyzed the data in the first and last minute of the scan. Dynamic data were reconstructed using the kernel-based algorithm with quantitative corrections. The reconstructed images show good quality. Cardiac motion is clearly visible in the 0.1-second temporal frames. The extracted time activity curves show the dynamic change of tracer distribution in the left ventricle and major arteries during cardiac contraction and expansion. Furthermore, cardiac motion signal was extracted directly from the reconstructed images and used to perform cardiac gating. Reconstructed gated images using the kernel method show better contrast versus background noise tradeoff than the standard ordered subset EM reconstruction. Conclusion: This study demonstrated the capability of total-body high temporal resolution dynamic PET. The results showed that the kernel-regularized reconstruction can achieve superior image quality for motion frozen quantitative studies for total-body PET.
M-08 | Parametric Imaging and Kinetic Modelling

Vesna Sossi (Vancouver)
Guobao Wang (Sacramento)
Noninvasive Estimation of Macro-parameters for Dynamic PET Images Using Deep Learning (#1376)

Bo Wang, Dongsheng Ruan, Prof. Huafeng Liu

Zhejiang University, the State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Hangzhou, China

Content
Macro-parameters in dynamic Positron Emission Tomography (PET) can quantitatively characterize the physiologic state of the tracer in vivo. Traditional methods for estimating the macro-parameters require accurate input functions which are difficult to obtain under noninvasive conditions. We developed a noninvasive method to estimate the macro-parameters without input function. The macro-parameters were considered as a nonlinear function of the activity concentration of the tracer. Deep learning was used to determine this nonlinear function to obtain the macro-parameters from dynamic PET data. Our approach was divided into two phases: training and estimation. In the training phase, a deep neural network (DNN) learned the potential relationships between the dynamic PET data and the macro-parameters. In the estimation phase, the macro-parameters could be directly obtained when the dynamic PET data were inputted to the DNN. The experiment based on simulation dataset of 18F-labeled fluorodeoxyglucose were conducted as validation. Our experimental results were compared with those obtained by Patlak plot, which demonstrated our approach outperformed Patlak plot in terms of accuracy and robustness. In addition, our method did not suffer from the problem of negative bias which occurs in graphical methods when there are statistical noises in the data.

The Effects of Delay on the Input Function for Early Dynamics in Total Body Parametric Imaging (#2590)

Dr. Tao Feng1, Yizhang Zhao2, Dr. Hongcheng Shi3, Dr. Hongdi Li1, Dr. Xuezhu Zhang4, Dr. Guobao Wang5, Dr. Ramsey D. Badawi3,4, Dr. Patricia Price6, Dr. Terry Jones5, Dr. Simon R. Cherry5,4

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Content
The recently developed total-body PET scanner enables high temporal resolution in dynamic imaging. Due to the much improved temporal resolution and large field of view, delay and the dispersion effects in the input function, which vary for different tissues and organs, may affect the accuracy in parametric imaging. In this paper, the delay effect was studied using the early dynamics of an FDG scan. In the early dynamic process, the 1-tissue compartment model can be used to approximate the dynamics of FDG.
Dynamic reconstructed frames were acquired using the total-body PET scanner with 1-second frames for the first 30 seconds and 2 seconds for the subsequent 60 seconds. The image-derived input function was acquired from the reconstructed dynamic sequence in the descending aorta. Voxel-specific delay times for the plasma input function were also modeled within the 1-tissue compartment model. A total of 4 parametric images were generated. Image-based parametric image generation was achieved with a maximum likelihood estimation method. Parametric images with and without the modeling of delay time in the input function were compared. Quantitative evaluation was achieved by calculation of the coefficient of determination ($R^2$). The voxel-specific parameters of the 1-tissue compartment together with the delay time were successfully reconstructed using the proposed method. The estimated delay time showed variations as large as 40 seconds. With the modeling of delay, an increase of 100%, 11%, and 25% for the value of $K_1$ in the myocardium, brain, and the thighs was observed. The calculated $R^2$ was much higher with delay modeling, indicating inaccurate model fitting when the effects of delay on the input function were ignored.

We have shown that with the use of total-body PET and the increased sensitivity, it is possible to estimate parametric images using the very early stages of the FDG injection. The combined effects of delay and dispersion will be studied in the future.

**Evaluation of EM and Nested-EM algorithms for direct reconstruction of parametric images with the simplified reference tissue model**

**M-08-03**

Dr. Jean-Dominique Gallezot, Kathryn Fontaine, Tim Mulnix, Dr. Yihuan Lu, Prof. Chi Liu, Prof. Richard E. Carson

Yale University, Department of Radiology and Biomedical Imaging / Yale PET Center, New Haven, USA

**Content**

**Objective:** Direct reconstruction of parametric images from raw PET data is a promising approach to reduce noise in parametric images by taking advantage of the known Poisson statistics of raw PET data. However, with direct reconstruction, the properties of the PET tracer and its kinetic model now influence the performance of the reconstruction algorithm. In this study we evaluated the performance of two reconstruction algorithms, previously tested with the one-tissue compartment model (1TBV) for cardiac blood flow imaging with $^{15}$O-water, and the generalized Patlak (GP) model for tumor imaging with $^{18}$F-FDG, respectively, when applied to the simplified reference tissue model (SRTM) and the D2/D3 dopamine receptor radiotracer $^{11}$C-PHNO. The first algorithm is based on the Expectation Maximization (EM) method. The second algorithm is based on the Optimization Transfer framework and uses EM-like equations in a nested loop (Nested-EM, or N-EM algorithm). The two algorithms showed somewhat slow convergence when tested initially. The goal of the study was to investigate convergence speed in the new application to SRTM and $^{11}$C-PHNO.

**Methods:** After a change of variables, the operational equations of the three kinetic models are identical, and thus the two reconstruction algorithms can be readily employed for SRTM. They were tested on simulated brain data.

**Results:** Both algorithms showed rapid convergence when applied to SRTM and $^{11}$C-PHNO data, and produced images with lower noise than the conventional indirect approach. Comparing the two algorithms, the N-EM algorithm had faster convergence, and could achieve a better noise-bias trade off, but excess iterations induced higher noise.
Conclusion: The EM and N-EM algorithms are both promising approaches to produce low noise images for $^{11}$C-PHNO studies with the SRTM model, and convergence speed does not appear to be an issue in this application.

M-08-04 4:54 PM

**Generation of Synthetic Static and Parametric PET Images of Synaptic Density from FDG Images Using Deep Learning Methods**

**PhD/MD student Rui Wang**$^{1,2}$, Dr. Hui Liu$^1$, Dr. Takuya Toyonaga$^1$, PhD/MD student Luyao Shi$^1$, Dr. Jing Wu$^1$, Prof. John A. Onofrey$^1$, Dr. Yu-Jung Tsai$^1$, Dr. Yihuan Lu$^1$, Prof. Tianyu Ma$^{2,3}$, Prof. Yaqiang Liu$^{2,3}$, Prof. Richard E. Carson$^1$, Prof. Chi Liu$^1$

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Content

Positron Emission Tomography (PET) imaging with various tracers is increasingly used in Alzheimer’s disease studies. However, in clinical practice, the access to PET scans using new or less-available tracers with sophisticated synthesis and short half-life isotopes may be very limited. Therefore, it is of great clinical significance and interest to generate synthetic PET image of less-available tracers from the PET image of another common tracer, in particular FDG.

We implemented advanced deep learning methods using U-net model to predict the SV2A PET image of synaptic density from FDG PET data. 20 subject data were used for training and testing. 4 network models including FDG SUV images to SV2A SUV images, FDG $K_i$ images to SV2A SUV images, FDG SUV images to SV2A $BP_{nd}$ images, FDG $K_i$ images to SV2A $BP_{nd}$ images were set up. The normalized mean square error and bias of various ROIs in the brain were calculated for prediction accuracy evaluation. Our results showed that all the four network models obtained reasonable SV2A static and parametric images. The ROI quantification bias were below 10% for most ROIs for all four networks. For SV2A SUV images prediction, using FDG $K_i$ images as input provided similar bias but slightly lower variance than using FDG SUV images as input. For SV2A $BP_{nd}$ images prediction, using FDG SUV images provided slightly lower bias and variance than using FDG $K_i$ images as input.

In conclusion, our optimized 3D U-Net based methods have been shown to be robust to generate synthetic SV2A PET images by using FDG images as input.
Identification of Transient Neurotransmitter Response Using Anomaly Detection Framework (#2446)

Dr. Ivan S. Klyuzhin1, M.Sc./M.A. student Connor W. J. Bevington2, Dr. Ju-Chieh (Kevin) Cheng2,3, Dr. Vesna Sossi2

1 University of British Columbia, Department of Medicine, Division of Neurology, Vancouver, Canada; 2 University of British Columbia, Department of Physics and Astronomy, Vancouver, Canada; 3 University of British Columbia, Pacific Parkinson’s Research Centre, Vancouver, Canada

Content
Measurement of transient neurotransmitter response (TNR), such as dopamine release, on a voxel level typically suffers from high false positive rates. In this work, the problem of identifying true TNR is treated as the task of anomaly detection in 4D PET data using artificial neural networks (ANN). Based on our previous determination that ANNs often outperform conventional methods of dynamic PET denoising, we hypothesized that ANNs should be more effective at classifying voxels with TNR than standard statistical tests. We use simulated [11C]raclopride data to train and test ANNs with different architectures for the task of voxel-level dopamine release detection. The networks were trained to output the probability of TNR presence in a given voxel's time-activity curve. The F-test of the linear parametric neurotransmitter PET (lp-ntPET) model fit residuals was used as the baseline method. The areas under the receiver operating characteristic curves were 0.84–0.88 for the ANNs and 0.65 for the F-test. At a fixed false positive rate of 0.2, the true positive rates were 0.7–0.8 for the ANNs and 0.4 for the F-test. These results demonstrate that using the ANN-based anomaly detection framework is an effective approach to identify voxels with transient dopamine release and other types of TNR. Future work will focus on testing more advanced methods, such as deep convolutional spatio-temporal ANNs and conventional methods that incorporate cluster analysis.

Respiratory Motion Correction in Dynamic PET with a Single Attenuation Map (#2218)

Elise C. Emond1, Dr. Alexandre Bousse2, Maria Machado1, Dr. Joanna Porter3,4, Dr. Kjell Erlandsson1, Ashley M. Groves1, Prof. Brian F. Hutton1, Prof. Kris Thielemans1

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Content
In addition to static tracer uptake values used routinely in clinical facilities, PET imaging can provide useful information on tracer kinetics via the use of dynamic acquisitions where a set of time frames are acquired starting from the injection/inhalation of the radiotracer. In lung studies, kinetic parameters, estimated from compartmental modelling,
are however affected by respiratory motion. When only one attenuation image is available, most existing motion compensation strategies are not appropriate for the initial short time frames, especially as the activity distribution changes rapidly over the early part of the dynamic acquisition. This work presents a preliminary study to handle respiratory motion using a two-step process that uses gated dynamic data as input. We first use joint reconstruction of activity and motion on the entire gated PET data to estimate deformation fields. This allows the subsequent reconstruction of each time frame separately with motion compensation. We present results comparing on one hand the compartment model fit residuals with and without respiratory motion compensation and on the other hand the diaphragm position in non-attenuation corrected images and from this method.
N-38 | Neutron Detectors and Gamma Imaging IV

Laurent Ottaviani (Marseille)
Niral P. Shah (Ann Arbor)

Neutron beamlines, fast and solar neutrons
N-38-01  4:00 PM

The Solar Neutron TRACking (SONTRAC) Instrument for the Detection of Fast Neutrons (#1845)

Dr. Georgia A. de Nolfo1, Dr. George Suarez2, Dr. John G. Mitchell3, Dr. Jason S. Legere4, Richard Messner5, James M. Ryan4, Jeff DuMonthier2, Iker Liceaga-Indart6, Alessandro Bruno1, Teresa Tatoli6

1 NASA/GSFC, Heliophysics Division, Greenbelt, USA; 2 NASA/GSFC, Instrument Electronics Development Branch, Greenbelt, USA; 3 George Washington University/ NASA-GSFC, Heliophysics Division, Greenbelt, USA; 4 University of New Hampshire, Space Science Center, Durham, USA; 5 University of New Hampshire, Electrical and Computer Engineering, Durham, USA; 6 University of Maryland, Baltimore County / NASA-GSFC, Heliophysics Division, Greenbelt, USA

Content
The detection of fast neutrons has important applications in several fields including solar, geospace and planetary physics. Neutrons are challenging to detect and measurements of them typically suffer from high background rates. High-energy neutrons (>50 MeV) pose even more challenges, because the traditional double-scatter technique based on a time-of-flight (ToF) measurement is limited by short flight paths and small detector sizes characteristic of small satellite platforms. It is now possible to perform high-energy neutron measurements inside a large monolithic detector by imaging the recoil proton tracks, thus eliminating the need for a measure of the time-of-flight. The concept is based on a spectrometer assembled from numerous thin hydrogenous scintillating fibers that allow ionization track imaging. Fine grained readout is now possible with arrays of 1-mm pitch silicon photomultipliers (SiPMs). The Solar Neutron TRACking (SONTRAC) instrument, equipped with scintillating fibers readout with SiPMs sensors, provides high-resolution, fine grained, imaging of fast (between 20-200 MeV) neutron scatters in a compact, low-power design ideal for small satellite (and aircraft) platforms. We discuss below applications of this technology and performance characteristics of the prototype SONTRAC instrument.

N-38-02  4:18 PM

The NitroGEM, a fast beam monitor for high intensity neutron beamlines (#2201)

Dr. Davide Raspino, Jacob Young, Dr. Erik Schooneveld, Dr. Nigel Rhodes

UKRI- STFC, ISIS, Chilton Didcot, UK

Content
The NitroGEM is a neutron beam monitor under development at the ISIS Neutron and Muon source for the high intensity beamlines that ISIS is building for the ESS. It combines low efficiency achieved by using nitrogen as neutron absorber, with high rate capability provided by the GEM. One of the main requirements of a neutron beam monitor is to minimize the amount of material in the beam to reduce neutron scattering and absorption. In the NitroGEM only the thin aluminium entrance and exit windows a single GEM and the counting gas are located in the neutron beam.
In this configuration, a transmission above 96% was measured for neutrons up to 10 Å. The NitroGEM uses the vessel entrance window as a cathode while the signal is picked up from the bottom electrode of the GEM. The GEM electrodes are fed with positive high tension facilitating transport of the primary electrodes towards the GEM and electron multiplication in its holes. We tested the NitroGEM on ISIS against a standard ISIS scintillator monitor. We will report the measured neutron detection efficiency. We will show how the accurate control of the amount of nitrogen in the monitor allows precise tuning of the monitor efficiency in the range between $10^{-4}$ and $10^{-7}$. The NitroGEM preserves the excellent gamma/neutron discrimination even at the lowest neutron efficiency. The NitroGEM is able to operate at peak rates above 1 MHz and can thus be used in a neutron flux above $10^{12}$-$10^{13}$ n/s. We will present further results at the conference including the time resolution and the stability of the NitroGEM as a function of time and temperature. The combination of all these properties makes the NitroGEM an ideal beam monitor for the high intensity beamlines at ESS and other high intensity neutron beamlines.

**Beam Monitors for the Instruments of the European Spallation Source ERIC** (#2292)

**Dr. Kalliopi Kanaki**¹, Vendula Maulerová¹, Steven Alcock¹, Ioannis Apostolidis¹, Dr. Richard J. Hall-Wilton¹²

¹ European Spallation Source ERIC, Detector Group, Lund, Sweden; ² Università degli Studi di Milano-Bicocca, Milan, Italy

**Content**

The design and deployment of 15 neutron instruments in three halls, equipped with more than 150 choppers and numerous optical components is the challenge the European Spallation Source ERIC is confronted with in the immediate future. In order to diagnose the correct transport of the neutron beam, approximately 50 beam monitors are required to be installed at various locations along the neutron instruments, e.g. in the bunker to offer information on the target moderator flux, behind choppers to ensure the correct energy selection and resolution, as well as before and after the sample for data normalisation. This abstract presents the effort to qualify, optimise and standardise existing detectors (multiwire proportional counters, ionisation chambers, fission chambers, GEM detectors, Vanadium monitors, scintillators) to this purpose by means of experimental campaigns and Monte Carlo simulations, as well as to optimise more novel designs of parasitic or less invasive beam monitoring approaches. The results of the experimental characterisation and optimisation are presented in terms of beam monitor efficiency, attenuation, scattering, time (time-of-flight) resolution and flux capability. Instrument requirements for beam monitors are discussed and the roadmap to the installation and the cold commissioning is presented.
Experimental quantification of internally generated thermal neutron fluence in heavy ion therapy (#2578)

PhD/MD student Andrew Chacon1,2, Dr. Akram Mohammad3, M.Sc./M.A. Nicholas Howell2, Dr. Ryan Middleton2, Dr. Benjamin Fraser2, M.Sc./M.A. Naomi Wyatt3, PhD/MD student Harley Rutherford1,2, Dr. Daniel R. Franklin4, Dr. Sodai Takyu3, Dr. Fumihiko Nishikido3, Dr. Ryoichi Hirayama3, Prof. Taiga Yamaya3, Prof. Naruhiro Matsufuji3, Prof. Anatoly Rosenfeld1, Dr. Susanna Guatelli1, Dr. Mitra Safavi-Naeini2,1

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Content

During heavy ion therapy, some particles in the beam undergo atomic nuclear inelastic collisions with other nuclei in the target, resulting in the production of a range of nuclear fragments, including neutrons. The neutron component is moderated by matter in the target, causing them to lose energy and thermalise. These neutrons are of particular interest as they offer the potential for therapeutic applications via neutron capture. Accurate and reliable quantification of the thermal neutron fluence produced during particle therapy will provide valuable information regarding the feasibility of therapeutic exploitation of this thermal neutron field. However, measurement of thermal neutron fluence is extremely challenging due to the intense and diverse mixed radiation field in the target volume. In this work, we present the results of experimental quantification of thermal neutron fluence, performed using the gold activation method, during carbon and helium beam therapy. Geant4 Monte Carlo simulations were used to validate the approach, establishing that the activation of gold is almost exclusively due to neutron capture, and that nearly all gamma photons detected in the vicinity of 411 keV result from the decay of the activated gold. The method was then applied to experimentally measure the fluence of thermal neutrons per Gy(RBE) of delivered dose during carbon and helium beam therapy, both inside and outside of the beam in a poly(methyl methacrylate) (PMMA) phantom. Thermal neutron fluence was measured at four different depths: at the entrance, distal edge, middle of the SOBP and in the tail region of the spread-out Bragg peak (SOBP). To our knowledge, this is the first time that this method has been used in particle therapy.
Development of Real-Time Detector for Direct Neutron Measurements at Accelerator Based Boron Neutron Capture Therapy in Hospitals (#1353)

Prof. Masashi Takada¹, Dr. Tetsuro Matsumoto², Dr. Akihiko Masuda³, Dr. Tomoya Nunomiya³, Prof. Satoru Endo⁴, Dr. Hiroki Tanaka⁵, Dr. Satoshi Nakamura⁶, Kei Aoyama³, Masataka Narita³, Osamu Ueda³, Prof. Takashi Nakamura⁷,³

¹ National Defense Academy of Japan, Applied Physics, Yokosuka, Japan; ² National Institute of Advanced Industrial Science and Technology, National Metrology Institute of Japan, Tukuba, Japan; ³ Fuji Electric Co. Ltd, Hino, Japan; ⁴ Hiroshima University, Quantum Energy Applications, Graduate School of Engineering, Higashi-Hiroshima, Japan; ⁵ Kyoto University, Institute for Integrated Radiation and Nuclear Science, Kumatorì, Japan; ⁶ National Cancer Center Hospital, Department of Medical Physics, Tokyo, Japan; ⁷ Tohoku University, Cyclotron and Radioisotope Center, Sendai, Japan

Content

Neutron beam fluxes used for Boron Neutron Capture Therapy, or BNCT, have been measured using a neutron activation technique of gold foils, while, at the accelerate-based BNCT facilities their staff have requested to continuously monitor the change of BNCT neutron beam. For their request, the real-time neutron detector is necessary to measure intense neutron beam with $10^9$ (n/cm²/s), separately from high dose-rate gamma rays, around 500 mGy/h, and minimizing neutron damage. In this study, we have developed an active neutron detector for BNCT, which is called DAD-BNCT, to be able to measure direct neutron beam at the BNCT facilities. The DAD-BNCT consists of a thin silicon detector with 40 μm in thickness and ultra thin coated LiF neutron converter. The detection efficiency for thermal neutrons was experimentally obtained at the research reactor in Institute for Integrated Radiation and Nuclear Science of Kyoto University, and its result is $2.9 \times 10^{-6}$ (# cm²). The detection efficiency is simply changeable, adjusting the thickness of LiF radiator. To confirm the specification of DAD-BNCT, we measured depth distribution of BNCT neutron beam in acrylic phantom at the National Cancer Center Hospital. The depth distribution of neutron flux was obtained from the measured pulse heights and the neutron detection efficiency. The experimental results are compared to the neutron activation method. Our results are in good agreement with the activation method. Neutron damage of DAD-BNCT has never been observed through several neutron experiments. The DAD-BNCT is useful detector to be able to measure the BNCT neutron beam in real time and directly, and it can measure neutrons well separately from gamma rays. It will be used for neutron beam monitor at the accelerator-based BNCT facilities.
Multi-channel Readout of the SONTRAC Instrument for the Detection of Fast Neutrons (#1859)

Dr. George Suarez², Georgia A. de Nolfo¹, John G. Mitchell³, Jason Legere⁴, Richard Messner⁵, James M. Ryan⁴, Jeff DuMonthier², Iker Liceaga-Indart⁷, Alessandro Bruno¹, Teresa Tatoli⁶

¹ NASA/GSFC, Heliophysics Division, Greenbelt, USA; ² NASA/GSFC, Instrument Electronics Development Branch, Greenbelt, USA; ³ George Washington University/ NASA-GSFC, Greenbelt, USA; ⁴ University of New Hampshire, Space Science Center, Durham, USA; ⁵ University of New Hampshire, Electrical and Computing Engineering, Durham, USA; ⁶ University of Maryland, Baltimore County/ NASA-GSFC, Greenbelt, USA; ⁷ Catholic University / NASA-GSFC, Greenbelt, USA

Content

Solar neutrons are the tell-tale of highly energetic processes (e.g. solar flares) at the Sun in which particle acceleration is taking place over a broad range in energy. Unlike charged radiation, neutrons escape unscathed from the ambient magnetic fields, providing a view of particle acceleration unhindered by the effects of transport. High-energy neutrons are challenging to measure with the traditional double scatter technique based on time-of-flight (ToF). This technique is limited by the finite flight path and active scintillator sizes required by small satellite platforms. The new SOlar Neutron TRACking (SONTRAC) concept, based on scintillating-fiber bundles, will provide high-resolution imaging of fast neutrons at energies where the bulk of solar and magnetospheric neutrons resides. Recent development of the new SONTRAC instrument concept’s advanced electronics and processing algorithms are presented.
N-39 | High Energy and Nuclear Physics
Instrumentation III

Richard J. Hall-Wilton (Lund)
Eric J. Mannel (Upton)
The Alignment of the LHCb Vertex Detector: Performance in Run 2 and studies for the Upgrade (#2178)

Dr. Kazu Akiba¹, Dr. Lucia Grillo², PhD/MD student Biljana Mitreska²

¹ Nikhef, amsterdam, Netherlands; ² University of Manchester (GB), physics department, Manchester, UK

Content

The LHCb detector at the LHC is a general purpose detector in the forward region designed to reconstruct decays of b and c hadrons. The Vertex Locator (VELO), consisting of a series of silicon strip sensors placed along the beam direction, allows the reconstruction of primary and secondary vertices and precise lifetime measurements. In Run 2 (2015-2018), a real-time alignment and calibration procedure was developed. Data collected at the start of each LHC fill are processed to evaluate the alignment using a Kalman filter method. An overview of the alignment algorithm and the real-time procedure is presented emphasizing the performance and its stability during the Run 2 data taking period.

The VELO operates in a secondary vacuum with a bi-phase CO₂ running through cooling blocks attached to the module base, with heat conducted through a TPG core. The cooling temperature is -30 degrees and the sensors operate at -8 degrees. Tests involving a change of the operational temperature to higher values up to -20 degrees were made to take dedicated samples at each temperature. These samples were analysed to evaluate the dependency of the module position as a function of the VELO temperature and were compared with measurement on a single module.

For Run 3 (2021-2023), a new tracking system is being developed, including a VELO based on silicon pixel sensors and an improved alignment procedure is under development, building upon the success of the Run 2 strategy. From recent tests, misalignments can arise from potential distortions of the VELO upgrade modules when cooled to their operating temperature. A study on simulated data has been performed to evaluate the effect of the distortions on the physics performance. A broad variety of detector movements are simulated and the residual distortions are determined by the alignment procedure. Results of these studies and the on-going optimisation of the upgrade VELO alignment procedure are presented.
Improvement of the Detection Efficiency of a Time-of-Flight Detector for Superheavy Element Search (#1936)

**PhD/MD student Satoshi Ishizawa**1,3, Dr. Kouji Morimoto1, Dr. Daiya Kaji1, Prof. Fuyuki Tokanai2, Dr. Taiki Tanaka1,4

1 RIKEN, Nishina Center for Accelerator-Based Science, Wako, Japan; 2 Yamagata University, Research Institute, Yamagata, Japan; 3 Yamagata University, Graduate School of Science and Engineering, Yamagata, Japan; 4 Kyusyu University, Department of Physics, Fukuoka, Japan

**Content**

At RIKEN, we have been studying superheavy element. Our present project is to synthesize of the new element Z=119. A superheavy element can be identified by the information from the detection system, which consists of a time-of-flight detector and Si-detector box. The superheavy element passes through the time-of-flight detector, and is implanted in the Si-detector box. If the superheavy element passes through the mylar foil of the time-of-flight detector, the secondary electrons are emitted and guided toward the microchannel plate of the time-of-flight detector. The time-of-flight detector serves two purposes. One purpose is to measure the time-of-flight of incoming superheavy elements to estimate their mass. The other purpose is to distinguish between the decay and implantation of superheavy element. To identify the decay events of superheavy element with high accuracy, the time-of-flight detector must have high detection efficiency. For the center region of the mylar foil, we can obtain a detection efficiency of more than 95.5±1.4% for the alpha particles from $^{241}$Am. However, the detection efficiency decreases to 23.1±2.3% for the particles passing through the edge of the mylar foil. Therefore, we simulated the time-of-flight detector to understand the reason for the decrease. From the simulation, we found that the secondary electrons emitted from the edge of the mylar foil cannot be fully collected by the microchannel plate. Thus, we modified the internal electric field of the time-of-flight detector such that all secondary electrons can be guided toward the microchannel plate. The effect on the detection efficiency was examined by impinging alpha particles from $^{241}$Am and reaction products and their background particles from $^{50}$Ti($^{159}$Tb, xn)$^{209}$Fr (beam experiment). Consequently, we achieved a detection efficiency of more than 99.8±1.4% for alpha particles, and more than 97.8±1.0% for the beam experiment at the edge of the mylar foil.
Development of high resolution and radiation hard electromagnetic calorimeter for the DVCS experiment (#2364)

PhD/MD student Ho San Ko¹,², PhD/MD Julien Bettane¹, PhD/MD Giulia Hull¹, PhD/MD Carlos Munoz Camacho¹, PhD/MD Thi Nguyen Trung¹, PhD/MD Emmanuel Rindel¹, On behalf of NPS-Collaboration

¹ Institut de Physique Nucléaire Orsay, Orsay, France; ² Seoul National University, Department of Physics and Astronomy, Seoul, South Korea

Content

The electromagnetic calorimeter for the Deeply virtual Compton Scattering (DVCS) experiment requires high energy resolution and radiation hardness. The calorimeter for the experiment will be assembled using 1080 PbWO₄ crystals supported by a carbon fiber structure. In order to achieve an energy resolution of ~ 1.3 % for 7 GeV gamma-rays, the thickness of the carbon structure was decided to be 0.5 mm based on Geant4 Monte-Carlo simulation. The detector will be operated in a harsh radiation environment (~ 5 Gy/hr), which will induce a severe decrease of the PbWO₄ light transmission over exposure time. For this reason, an optical bleaching method, based on the use of blue LEDs and quartz optical fibers will be used to regularly recover the crystals. For the radiation hard crystals, we found that the damage from 30 Gy of ionizing irradiation can be recovered by 2 hours of optical bleaching with 1 mm and 800 μm diameter fibers. In this communication, we will present the current status of the detector R&D and construction, as well as simulation results of its performance.

First Compton imaging tests with i-TED (#2644)

PhD/MD student Victor Babiano, Dr. Luis Caballero, M.Sc./M.A. David Calvo, Dr. César Domingo-Pardo, Ion Ladarescu

CSIC-University of Valencia, IFIC, Paterna, Spain

Content

The objective of this work is to demonstrate the Compton imaging capabilities of a novel gamma-ray Total-Energy Detector called i-TED. The latter is intended for neutron-capture cross-sections measurements of astrophysical interest, thereby enhancing detection sensitivity by means of the simultaneous combination of neutron Time-of-Flight with gamma-ray Compton-imaging techniques. The developed Compton demonstrator comprises five position-sensitive radiation detection modules of high energy resolution, which feature an overall position-sensitive field-of-view of 125 cm². Each detector module is based on 50x50mm² large LaCl₃(Ce) monolithic crystals optically coupled to 8x8 pixels silicon photomultipliers. In previous works we have determined the energy resolution (3.92(3)% at 662 keV) and spatial resolution (1-3 mm FWHM) for the detectors used in i-TED. In this work we investigate the impact of different experimental effects in the reconstructed Compton image by means of distant point-like gamma-ray source measurements. Apart from the Compton image algorithm itself, we investigate experimentally the impact of
the scatter-absorber distance in the efficiency and resolution of the reconstructed Compton image. Other experimental effects play an important role, in particular the intrinsic position-reconstruction algorithm chosen for both the transversal xy-coordinates and the depth-of-interaction. These results will be presented together with a discussion focused on the technique and scope of the project. This work is of interest for other applications requiring high gamma-ray imaging efficiency, such as nuclear medicine and homeland security.

N-39-05

First performance evaluation of the ΔE-TOF detector of the FOOT experiment (#2033)

Dr. Matteo Morrocchi¹², Prof. Nicola Belcarì¹², Dr. Sandro Bianucci², Dr. Niccolò Camarlinghi¹², Dr. Pietro Carra¹², Dr. Esther Ciarrocchi¹², Dr. Micol De Simoni⁶,⁵, Prof. Alberto Del Guerra¹², Dr. Marta Fischetti⁷,⁵, Dr. Luca Galli², Eliana Gioscio⁶, Dr. Aafke C. Kraan², Dr. Marco Francesconi¹², Dr. Michela Marafini⁸,⁵, Dr. Riccardo Mirabelli⁸,⁵, Dr. Andrea Moggi², Dr. Silvia Muraro⁴, Prof. Vincenzo Patera⁷,⁵, Alessandro Profeti², Dr. Marco Pullia³, Prof. Valeria Rosso¹², Prof. Alessio Sarti⁷,⁵, Prof. Adalberto Sciubba⁷,⁵, Dr. Giancarlo Sportelli¹², Dr. Giacomo Traini⁵,⁶, Prof. Maria G. Bisogni¹²

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Content

In this contribution we describe the assembly of the whole ΔE-TOF detector of the FOOT experiment and the results of the first test-beam measurements with carbon ions, which took place at the CNAO hadrontherapy center (Pavia, Italy) in March 2019. The FOOT experiment has the goal of improving the quality of treatment planning in particle therapy by measuring the fragmentation cross section of the nuclei within the human body (mainly C and O) during the irradiation. The ΔE-TOF detector is composed of two subsequent layers of plastic scintillator bars with transverse orthogonal arrangement, with each bar being readout at both ends by silicon photomultipliers. In the FOOT experiment, fragments resulting from nuclear interactions between carbon and oxygen projectiles with carbon and hydrogen-enriched targets will be studied at various energies in the therapeutic range. The ΔE-TOF detector will measure the energy deposited in the plastic scintillator bars and the time-of-flight with respect to a start counter, thus providing the fragment atomic number. The pair of triggered bars in the two layers will provide also the interaction position. In this study, the detector was irradiated directly with 115-400 MeV/u carbon ions, and it was moved vertically and horizontally to irradiate the center of each bar in both layers, thus also scanning the central vertical and horizontal bars. The light attenuation with beam position along the central scintillator bars was studied, the coincidence time resolution between the two layers was determined, and the detector response to the deposited energy was calibrated. So far, we have obtained coincidence time resolutions $\sigma = 41 \pm 3$ ps between the central bars of the two layers, suggesting a time performance in compliance with the FOOT experiment requirements.
N-39-06 5:30 PM

The Large Area Picosecond Photodetector (LAPPD) 8” MCP-PMT: Recent Results (#1126)

Mark A. Popecki¹, Michael J. Minot¹, Cole J. Hamel¹, William Worstell¹, Bernhard W. Adams¹, Alexey Lyashenko¹, Camden D. Ertley¹, Till Cremer¹, Michael R. Foley¹, Jeffrey W. Elam², Anil Mane²

¹ Incom, Inc., Charlton, USA; ² Argonne National Laboratory, Lemont, USA

Content
The LAPPD is a 400 cm² microchannel plate photomultiplier (MCP-PMT) with a timing resolution better than 60 pS. The large area and high speed makes the LAPPD suitable for viewing large area scintillators or large experimental volumes, and for applications such as neutron detectors or Čerenkov light detectors. It has sensitivity to single photoelectrons with a gain of ~7E6 or higher. It incorporates a bi-alkali Na₂KSb photocathode, with a peak sensitivity below 365 nm. Photocathodes with quantum efficiencies as high as 30% have been fabricated. The 20 cm square microchannel plates are fabricated using a glass substrate and thin films for resistance and gain, using the Atomic Layer Deposition technique. The timing resolution of the LAPPD has been measured as low as 59 pS, limited by electronics methods presently in use. This work presents new results for time resolution, and for gain response as a function of excitation rate. Time resolution is a function of both MCP and photocathode voltage. A rapid timing improvement was observed as the photocathode voltage was raised to 50 volts. At higher voltages, the time resolution continued to improve, but at a diminishing rate. A similar improvement occurred with an increase in MCP voltage, up to a point beyond which there was no further benefit. Gain has been measured as a function of light pulse repetition rate. As the laser trigger rate increased, the LAPPD gain fell to approximately half of the initial value at repetition rates of 12 to 38 kHz/mm². Gain recovery time has also been measured. The LAPPD was triggered with a laser repeatedly at a high rate, then allowed to recover before the next laser pulse. The gain recovered to its initial value with a 15 mS recovery time, and half the initial value with a 5 mS recovery time. These measurements of gain, timing, gain recovery at high rates, and additional measurements of position resolution and quantum efficiency will be shown, and applications will be discussed.
N-40 | Novel and Emerging Technologies III

Andrei Nomerotski (Brookhaven)
Beatrice Fraboni (Bologna)

New detection systems based on novel technologies
FoCal: A highly granular digital calorimeter (#1991)

Dr. Naomi van der Kolk\textsuperscript{1,2}, On behalf of the ALICE-FoCal Collaboration

\textsuperscript{1} Utrecht University, Utrecht, Netherlands; \textsuperscript{2} Nikhef, Amsterdam, Netherlands

Content

In light of the upgrade program of the ALICE detector a calorimeter at forward rapidities (FoCal) is being considered. This detector would measure photons, electrons, positrons and jets for rapidities eta > 3, offering a wealth of physics possibilities. Its main focus is on measurements related to the structure of nucleons and nuclei at very low Bjorken-x and possible effects of gluon saturation. The FoCal electromagnetic calorimeter must be able to discriminate decay photons from direct photons at very high energy, which requires extremely high granularity. A dedicated R&D program is ongoing to develop the technology needed for such a high-granularity device. Within this program we have constructed a unique prototype of a digital electromagnetic calorimeter based on CMOS monolithic active pixel sensors (MAPS). This prototype has demonstrated the unique capabilities of such highly granular digital calorimeter, providing unique shower profile measurements and good linearity and energy resolution. The prototype calorimeter was based on the MIMOSA chip, which is however not fast enough for application in a full detector at LHC. As a next step, the ALPIDE chip, developed for the ALICE Inner Tracker Upgrade, is being investigated for performance with high occupancy. A new prototype based on this chip is currently being constructed and tested. This contribution presents results from the first prototype, and the performance of the ALPIDE in a calorimeter from the first measurements with the new prototype.

SEM Characterization of a Silicon Drift Detector for Electron Spectroscopy (#2023)

PhD/MD student Matteo Gugiatti\textsuperscript{1,2}, PhD/MD Matteo Biassoni\textsuperscript{3}, PhD/MD Stefano Pozzi\textsuperscript{4,3}, Prof. Marco Carminati\textsuperscript{1,2}, PhD/MD student Pietro King\textsuperscript{1,2}, Prof. Carlo E. Fiorini\textsuperscript{1,2}, Prof. Maura Pavan\textsuperscript{4,3}, PhD/MD Oliviero Cremonesi\textsuperscript{3}, Dr. Peter Lechner\textsuperscript{5}, Prof. Susanne Mertens\textsuperscript{6,7}

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Content

Silicon Drift Detectors, widely employed in X-ray spectroscopy for high resolution and high count-rate applications, could find their application also in β-decay spectroscopy. The detection of electrons, instead of photons, yields a different response of the detector, since electrons are absorbed in the very superficial layer of the SDD where the quantum efficiency is not unitary. A novel SDD-based detector system is being developed in the context of the
TRISTAN (Tritium Investigation on STerile to Active Neutrino mixing) project that searches for the presence of a keV-scale *Sterile neutrino* by means of the investigation of the tritium $\beta$-decay spectrum. A detailed model of the SDD response is required for this specific application. This work presents the experimental characterization of a single SDD pixel in a Scanning Electron Microscope used as a monoenergetic electron source. The experimental data is then compared to *Monte Carlo* simulations of the interactions between the electrons and the SDD. The free parameters, defining the quantum efficiency profile of the entrance window model of the detector, are then optimized to the values minimizing the differences between real and simulated spectra.

N-40-03  4:36 PM

**VHDL Based Artificial Intelligence Framework For Deploying Streaming Inference Engines On FPGAs** (#2277)

*Ryan T. Herbst*, Benjamin Reese, Larry Ruckman

*SLAC National Accelerator Laboratory, Menlo Park, USA*

**Content**

There is growing interest in deploying Artificial Intelligence networks close to the detector. Applications include image correction and feature extraction for photon sensitive cameras at modern FELs, trigger primitive generation for front end electronics experiments and global trigger logic engines for larger HEP experiments. The processing latency and processing bandwidth requirements require a hardware based solution deployed fully in FPGAs or ASICs. SLAC’s Advanced Instrumentation For Research Division (TID-AIR) team has developed a VHDL framework for deploying low latency, high bandwidth inference engines in FPGAs and ASICs.

N-40-04  4:54 PM

**3D Real-time Simultaneous Mapping of Gamma-ray and Neutron Sources with the Neutron-Gamma Localization and Mapping Platform (NG-LAMP)** (#2504)

*Dr. Ryan T. Pavlovsky*¹, Dr. Joshua W. Cates², M.Sc./M.A. Joe Vanderlip², Dr. Andrew Haefner¹, Dr. Tenzing H. Y. Joshi¹, Erika Suzuki¹, Dr. Ross Barnowski¹, Victor Negut¹, Alex Moran¹, Dr. Brian Quieter¹, Dr. Kai Vetter²

¹ Lawrence Berkeley National Lab, Applied Nuclear Physics, Berkeley, USA; ² University of California Berkeley, Nuclear Engineering, Berkeley, USA

**Content**

We have previously reported on the utility and potential of real-time gamma-ray mapping for point source and dispersed radiological materials using the Scene Data Fusion (SDF) architecture with our Localization and Mapping
Platform (LAMP). SDF with LAMP fuses 3D, real-time volumetric reconstructions of radiation sources with contextual information (e.g. LIDAR, camera, etc.) from the environment around the detector system. This information, particularly when obtained in real time, can be indispensable for directed search for lost or stolen sources, consequence management after the release of radioactive materials, or contamination avoidance in security-related or emergency response scenarios. Our 3D maps localize contamination or hotspots to specific areas or objects, providing higher speed, specificity, and resolution than conventional 2D approaches, enabling more efficient planning and response. In this work, we present the expansion of these generic gamma-ray mapping concepts to neutrons. This is achieved with LAMP, integrated with a custom CLLBC detectors as payload, which we refer to as Neutron-Gamma LAMP (NG-LAMP). Crystals for this payload are provided by Radiation Monitoring Devices, Inc. coupled to SensL J-series SiPM arrays. NG-LAMP’s payload enables simultaneous gamma-ray mapping at ~3.5% energy resolution and fast/thermal neutron mapping. With NG-LAMP and the SDF architecture we demonstrate the ability to detect and localize surrogate Special Nuclear Materials (SNM) in real-time and in 3D based on thermal and/or fast neutron signatures alone, which is critical for the detection of heavily shielded SNM when no gamma signatures are detectable. We present this capability in the detection and localization of heavily shielded Pu-surrogate sources (with about 1 significant quantity Pu equivalent embedded in 5.5” of lead and tungsten) as well as demonstrate handheld and aerial gamma-ray and neutron mapping.

N-40-05 5:12 PM

High-Flux CZT for New Frontiers in Computed Tomography (CT), Non-Destructive Testing (NDT) and High-Energy Physics (#1054)

Dr. Kris Iniewski¹, Dr. Matthew Veale², Prof. Magdalena Bazalova-Carter³

¹ Redlen Technologies, Inc., Saanichton, Canada; ² STFC, Oxfordshire, UK; ³ UVic, Victoria, Canada

Content

Advances in THM growth and contact engineering of high-flux CZT sensors have enabled dramatically improved hole mobility-lifetime product completely resolving historical problems with detector polarization. In addition, CZT semiconductor production has moved away from custom tile manufacturing to silicon wafer processing improving yields and lowering manufacturing costs. As a result, new opportunities spanning various engineering fields in commercial and scientific words have emerged. In this talk we will illustrate recent advances in CZT based spectral Computed Tomography (CT) that enable K-edge imaging, Non-Destructive Testing (NDT) that enable material discrimination in routine food inspection and High-Intensity X-Ray Imaging at Free Electron Lasers.
Direct Ionized Charge Measurement in Single-phase Liquid Xenon Compton Telescope for 3γ Medical Imaging (#1753)

PhD/MD student Yajing Xing¹, PhD/MD student Yajing Xing¹, Stéphane Acounis¹, Stéphane Acounis¹, Nicolas Beaupère¹, Nicolas Beaupère¹, Jean L. Beney¹, Jean L. Beney¹, Julien Bert², Julien Bert², Stéphane Bouvier¹, Stéphane Bouvier¹, Clotilde Canot¹, Clotilde Canot¹, Thomas Carlier³, Thomas Carlier³, Michel Cherel⁴, Michel Cherel⁴, Jean P. Cussonneau¹, Jean P. Cussonneau¹, Sara Diglio¹, Sara Diglio¹, Debora Giovagnoli², Debora Giovagnoli², Jérome Idier⁵, Jérome Idier⁵, François Kraeber Bodéré³, François Kraeber Bodéré³, Patrick Le Ray¹, Patrick Le Ray¹, Frédéric Lefèvre¹, Frédéric Lefèvre¹, Julien Masbou¹, Julien Masbou¹, Eric Morteau¹, Eric Morteau¹, Jean S. Stutzmann¹, Jean S. Stutzmann¹, Dominique Thers¹, Dominique Thers¹, Dimitris Visvikis², Dimitris Visvikis², PhD/MD student Yuwei Zhu¹, PhD/MD student Yuwei Zhu¹

¹ SUBATECH, IMT Atlantique, CNRS/IN2P3, Université de Nantes, Nantes, France; ² INSERM, UMR1101, LaTIM, CHRU Morvan, Brest, France; ³ Centre Hospitalier Universitaire de Nantes, Nantes, France; ⁴ INSERM U892 équipe 13, Nantes, France; ⁵ LS2N, Ecole Centrale de Nantes, CNRS/Inp, Université de Nantes, Nantes, France

Content

The accurate ionized charges sequential measurement in Liquid Xenon Time Projection Chamber (LXeTPC) without electroluminescence amplification is a key point of the success of 3γ imaging. It provides the possibility of Compton interactions measurement and discrimination for Compton cone reconstruction in XEMIS2. For the sake of continuous read-out with ultra-low noise and negligible dead-time, a new developed self-trigger ionization measurement chain dedicated for XEMIS2 has been accomplished. The first version was newly implemented and qualified in the prototype XEMIS1, whose experimental results showed a good performance. Meanwhile, we present the computing process for the new DAQ, where a specific detector response Monte Carlo simulation has been done to optimize the Clusterization method for charge measurement and sequential Compton interactions distinction. A new approach to Compton scattering angular calibration is underway for further study.
R-12 | RTSD Award Presentation and SiC Detectors

Michael Fiederle (Freiburg)
RTSD Award 2019: High Performance Semiconductor Radiation Detectors and Front-End Electronics at Room Temperature and Beyond (#2799)

Prof. Giuseppe Bertuccio

Politecnico di Milano, Milano, Italy

Content
Radiation detectors based on semiconductors are widely used in a large number of scientific, medical and industrial applications since decades but an intense worldwide R&D is constantly running in order to continuously improve the performances or to realize detection systems with increasing complexity or able to operate under particular stringent conditions such as room temperature, high radiation levels, high speed or low electric power consumption. Material science, detector and front-end electronics design, manufacturing and interconnection technologies are all linked together and real progress is the result of joined efforts in all these fields. In this presentation, some of the high performance detection systems operated at room temperature will be discussed together with some challenging applications. The crucial role of the front-end electronics design will be focused and examples of systems successfully operated beyond room temperature will be presented.

Fabrication and Characterization of High Resolution 250 µm Thick n-type 4H-SiC Epitaxial Schottky Barrier Radiation Detectors: Electron Beam Induced Current, Deep Level Transient Spectroscopy, and Pulse Height Measurements (#2567)

Prof. Krishna C. Mandal, PhD/MD student Joshua W. Kleppinger, PhD/MD student Mohsin Sajjad

Department of Electrical Engineering, University of South Carolina, Columbia, USA

Content
High resolution n-type 4H-SiC epitaxial layer of ~250 µm thick Schottky barrier radiation detectors have been fabricated by depositing nickel (Ni) contacts for both front- and backside. Current-voltage (I-V) measurements at room temperature (300 K) showed high barrier height and nearly ideal diode ideality factor of ~1.75 eV and 1.02 respectively. The leakage current at -350 V reverse bias was ≤ 10^-9 A. Capacitance-Voltage (C-V) measurements revealed a doping concentration of 2 x 10^14 cm^-3. Electron-beam-induced current (EBIC) measurements have shown device performance limiting defects in 4H-SiC Schottky barrier devices (SBDs) with reference to dislocations, stacking faults, open core dislocations, threading closed & open core screw dislocations. Planar line scan and energy dependent mapping method is used for extraction of carrier diffusion lengths at particular defects and defect free
regions. Deep level transient spectroscopy (DLTS) was performed to investigate defect levels and capture cross sections. Various defects levels at Ec – 0.14 eV, Ec – 0.18 eV, Ec – 0.62 eV, Ec – 1.42 eV, and Ec – 1.52 eV have been observed. Theoretical defect calculations were performed using VASP and implemented within density functional theory (DFT) with the Perdew–Burke–Ernzerhof (PBE) exchange-correlation function. The unit cell of 4H-SiC was procured from the materials project database and used to build a 3×3×1 supercell of 72 atoms. In-detailed silicon and carbon vacancies as well as substitutional defects were investigated, and the results will be presented. A 0.9 µCi $^{241}$Am radiation source was used to assess detectors’ performance by pulse height spectroscopy (PHS) and the detector showed energy resolution of 0.22% full-width half maxima (FWHM) for alpha particles at 5.486 MeV. A noise analysis in terms of equivalent noise charge revealed that the white series noise due to the detector capacitance has substantial effect on their spectroscopic performance.

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R-12-03

4:48 PM

**Material discrimination and identification with Medipix3RX and Timepix3 detectors with CdTe sensors** (#2097)

Michael K. Schütz$^1$, Simon Procz$^1$, Julian Fey$^1$, Gerardo A. Roque$^2$, Carlos F. Navarrete$^2$, Carlos A. Ávila$^3$, Michael Fiederle$^1$

$^1$ Albert-Ludwigs-University Freiburg, Freiburg Materials Research Centre (FMF), Freiburg im Breisgau, Germany; $^2$ Universidad de Los Andes, Departamento de Física, Bogotá, Colombia; $^3$ Karlsruhe Institute of Technology (KIT), IPS, Eggenstein-Leopoldshafen, Germany

**Content**

The ability to non-destructively differentiate materials using X-ray imaging techniques is of great interest for medicine, materials research, industry and homeland security. Traditional X-ray imaging techniques only allow a distinction between different absorption rates of investigated materials without taking photon energies into account. Therefore, a differentiation between multiple materials is not possible. In contrast to traditional X-ray detectors, the newest photon counting semiconductor detectors like Medipix3RX and Timepix3 provide information about X-ray photon energies. With this information conclusions can be drawn about the underlying material by using increased absorption probability of photons with energies above the respective K-edge energy. If high-Z sensor materials like CdTe are used, the discrimination over a wide range of energy is possible due to their high absorption efficiency. The Medipix3RX readout chip offers up to eight adjustable energy thresholds in each pixel with individual counters. The Timepix3 readout chip records for every incident photon the position and energy of every event. These spectroscopic working principles give information about the change of the X-ray spectrum caused by the underlying material. Therefore, a material separation by use of the K-edge method is possible. An absorption phantom with eight materials in different thickness was developed and acquired with Medipix3RX and Timepix3 detectors with 1mm CdTe sensors in a wide energy range. The measurements with the Medipix3RX were performed in single-pixel spectral mode, the measurements with the Timepix3 were performed in ToA+ToT mode. The results of the measurements and the possibility of differentiation of the investigated materials will be presented and compared.
CdZnTe-based X-ray Spectrometer for Absolute Density Determination and Compositional Analysis (#1787)

Dr. Silvia Zanettini¹,², Dr. Nicola Zambelli², Dr. Giacomo Benassi², Andrea Bettati², Andrea Zappettini¹

¹ CNR, IMEM, Parma, Italy; ² due2lab, Scandiano, Italy

Content
Due2lab s.r.l. developed a CdZnTe-based X-ray spectrometer system capable of determining the absolute density value of a sample material and additionally extracting information on its elemental composition point-by-point. This technology has been developed specifically for non-destructive in-line inspection of industrial production. In particular, the system is an extremely powerful tool for tracing density spatial variations in wood panels and ceramic tiles, but it could be of interest also for other applications such as petrology and archeology, plastic recognition and medical transmission radiography.

The X-ray spectrometer works in transmission configuration, similarly to X-ray multichannel transmission radiography. According to X-ray photon attenuation physics, the transmitted spectrum (collected after the X-ray beam travels through the absorber material for a distance t) contains all the necessary information to extract the absolute density value and the chemical composition of the investigated sample. The inspected spot size can vary depending on the aperture of the brass collimator between X-ray tube and sample. Several samples of different materials have been measured such as graphite, wood, plastics (polyethylene and polystyrene) and ceramic tiles; samples thickness is between 1 mm and 20 mm. Their absolute density value has been extracted after the application of a best-fit procedure minimization of the photon attenuation curve. Depending on the material, typical density values ranged from 0.4 g/cm³ up to 3 g/cm³. The accuracy on the density value determination obviously depends on the spectrum acquisition time: the trade-off relation between these two parameters will be discussed in more detail.
STIR | STIR Users’ & Developers’ Meeting

Charalampos Tsoumpas (Leeds)
Nikos Efthimiou (Hull)

STIR is Open Source software for use in tomographic imaging. Its aim is to provide a Multi-Platform Object-Oriented framework for all data manipulations in tomographic imaging. Currently, the emphasis is on image reconstruction in emission tomography (PET and SPECT) but other imaging modalities can be added in the future. During this annual meeting experienced users and developers will present their recent work with STIR with technical emphasis on software and algorithmic development. More information can be found in STIR website: http://stir.sf.net
Welcome & Introduction
Dr. Charalampos Tsoumpas
University of Leeds, Leeds, UK

Deep-Learning based PET reconstruction with STIR forward operator
(#2896)
Dr. Massimiliano Colarieti-Tosti, M.Sc./M.A. student Alessandro Guazzo, Dr. Camille Pouchol, Dr. Olivier Verdier
KTH, Royal Institute of Technology, School of Technology and Health, Stockholm, Sweden

Content
We have used STIR forward operator as the basis for different reconstruction strategies that make use of Deep Learning (DL) for improving on standard reconstruction methods. A first application that will be presented is a simple Convolutional Neural Networks (CNN) denoising of one-iteration MLEM reconstructions of data from a small animal PET. As a second example, we would like to present our results obtained using the learned primal-dual reconstruction approach presented in [1], where STIR:s forward operator has been incrementally improved using CNN:s. Finally, results on the simultaneous DL-based reconstruction of image and deformation in presence of movement during data acquisition will be presented.


Updates to STIR projectors (#2860)
Richard Brown1, Pawel Markiewicz2,3, Casper da Costa Luis3, Prof. Kris Thielemans1

1 University College London, Institute of Nuclear Medicine, London, UK; 2 University College London, Dept. Medical Physics & Biomedical Engineering, London, UK; 3 King's College London, School of Biomedical Engineering & Imaging Sciences, London, UK
Various changes have been made to STIR’s forward and back projectors. It is important to be aware of these changes, as some of them break backwards compatibility. Others should enhance functionality, including the wrapping of NiftyPET’s GPU projectors. Other enhancements include the improvement of data processors (e.g., image smoothing or motion) before and after the forward and back projections, respectively.

STIR-04

Implementation of SPECT functionalities in the STIR library (#2848)

Dr. Daniel Deidda¹², Dr. Benjamin Thomas², Prof. Kris Thielemans²

¹ National Physical Laboratory, Nuclear Medicine, Medical Radiation Physics, London, UK; ² University College of London (UCL), Institute of Nuclear Medicine (INM), London, UK

The software for tomographic image reconstruction (STIR) package is widely used by researchers in the field of emission tomography reconstruction. Intensive work has been carried out for positron emission tomography (PET), whereas single photon emission tomography (SPECT) still needs extensive effort to be able to support all the steps involved in the reconstruction process. We have developed the ability to process the raw data, list mode (LM) and sinogram, to estimate scattered events and attenuation values, perform decay, uniformity and center of rotation (COR) corrections, and other processing functionalities for SPECT. This extension was designed in a way that a more generalised set of classes were introduced to include both PET and SPECT LM functionalities as derived classes. For each scanner, we derive from the PET or SPECT class to read and process the data accordingly. The Mediso AnyScan Trio SPECT scanner has been implemented using this new class hierarchy, however the information for the cannot be made available to the public. For the estimation of scatter and attenuation specific utilities were created, and a bin normalisation SPECT class was also added. The availability of this extension in an open source library enables SPECT image reconstruction with all the required corrections, and can make the reconstruction process a more traceable and reproducible task.
STIR-05 6:59 PM

Synergistic reconstruction for the Albira Si preclinical PET system with STIR. (#2864)

PhD/MD student Harry Tunnicliffe1,2, Dr. Charalampos Tsoumpas2, Prof. Jurgen Schneider2, Prof. Daniel Lesnic1

1 University of Leeds, School of Mathematics, Department of Applied Mathematics, Leeds, UK; 2 University of Leeds, School of Medicine, Leeds Institute of Cardiovascular and Metabolic Medicine, Leeds, UK

Content
The Albira Si is a multi-modal preclinical imaging system comprised of PET, SPECT, and CT. The PET subsystem consists of 24 detector blocks, 8 per ring, arranged octagonally. Each block consists of a continuous scintillation crystal interfaced with a 12x12 array of silicon photomultipliers that allow for 3D localization of the detection event within the crystal. The Software for Tomographic Image Reconstruction (STIR) is an open-source library for the reconstruction of PET and SPECT images. STIR also includes reconstruction algorithms for synergistic reconstruction with spacially registered images from other modalities such as the Kernalised Expectation Method (KEM). STIR has recently been extended to include the ability to model block detector geometry, as opposed to a simple cylindrical approximation. This is important for preclinical PET systems with smaller bore diameters and fewer modules per ring as they are not well modelled by the cylindrical approximation. This work demonstrates the implementation of the Albira Si scanner within STIR and synergistic reconstruction.

STIR-06 7:17 PM

Image reconstruction challenges of Total Body PET scanners using STIR (#2886)

Dr. Nikos Efthimiou1, Prof. Stephen Archibald1

1 University of Hull, PET research centre, Faculty of Health Sciences, Hull, UK; 2 University of Ghent, Department of Electronics and information systems, Ghent, Belgium

Content
Long axial PET scanners, usually referred to as Total Body (TB) gradually are gaining momentum. Two of the most popular implementations originate from the EXPLORER project, but only recently the first commercially available, were presented. Their main area of focus will be kinetic and low dose imaging. Due to their large intrinsic sensitivity new applications in pediatrics have been proposed. In order to investigate the performance of such scanner geometry we used GATE Monte Carlo toolkit (v.8.1) to simulate geometries inspired from the PENN PET scanner. The axial FOV ranged from 23 cm to approx 2m. Reconstructions were performed using the STIR image reconstruction library (unstable branch). Various modification had to be done in the source code in order to handle the available memory in more efficient ways.
Initial results showed that STIR with slight modifications is able to reconstruct data from very long PET scanners. Further improvements need to be made in TOF and correction algorithms.

**STIR-07**  
**Future outlook on STIR and SIRF** (#2877)  
**Prof. Kris Thielemans**, Dr. Nikos Efthymiou, Dr. Charalampos Tsoumpas  

1 University College London, Institute for Nuclear Medicine, London, UK; 2 University of Hull, Hull, UK; 3 University of Leeds, Leeds, UK

**Content**  
In this talk, we will give an overview of upcoming features in STIR and plans for future releases. In addition, we will give an update on SIRF, the open source platform for dual-modality reconstruction from the UK Collaborative Computational Project for Synergistic PET/MR Reconstruction (CCP PET-MR), which uses STIR for PET reconstruction.

**STIR-08**  
**Closing**
M-09 | High-Resolution Application-Specific Imaging Systems I

Andrew L. Goertzen (Winnipeg)
Jae Sung Lee (Seoul)
Synchrotron High Resolution X-Ray Imaging of Micro-Vasculature in A Rat Model of Osteoarthritis (#2582)

Dr. Arash Panahifar1,2, Prof. Dean Chapman3, Dr. Sheldon Wiebe2, Dr. David M. L. Cooper3

1 Canadian Light Source, Biomedical and Therapy Beamline, Saskatoon, Canada; 2 University of Saskatchewan, Medical Imaging / College of Medicine, Saskatoon, Canada; 3 University of Saskatchewan, Anatomy Physiology and Pharmacology / College of Medicine, Saskatoon, Canada

Content
Synchrotrons provide X-ray beams with the unique properties of high flux, narrow and tunable energy bandwidth, and very high resolution. The aim of this study was to use intense parallel X-ray beam from a 4.3T wiggler to detect the micro-vasculature in the bone of a rat model of osteoarthritis to test the hypothesis that vascular invasion to subchondral bone plate witnessed in early stages is the initiating cause of the disease. Microvasculature in bone was imaged in-vivo and ex-vivo bymicro-CT at the BioMedical Imaging and Therapy (BMIT) beamline at the Canadian Light Source synchrotron after injection of various contrast agents including several formulations of iodine, barium, gold nanoparticles, and lead compounds. Imaging was performed either at 6.5μm or 13μm voxel size using monochromatic X-ray beam above the K-edge of the elements. For in-vivo experiment a programmable injection pump was used to minimize the time between completion of injection and beginning of imaging, as iodine is rapidly removed from the blood circulation. Ioversol (Optiray 240) contrast agent provided sufficient vascular circulation time for acquiring CT images immediately after injection (30s scan) and provided required contrast for segmentation of vascular system from soft tissues, however, contrast between micro-vessels and bone was not sufficient. Ex-vivo imaging allowed for infusion of higher concentration of the contrast agent (mixture of barium sulfate and gelatine), as well as possibility of dual energy K-edge subtraction imaging, which together significantly increased the ability to detect micro-vessels (up to 20-30μm in diameters) within bone. In conclusion, in-vivo micro-angiography for visualization of 5-10μm micro-vessels within bone is not feasible due to the limitation in the volume of the contrast agent that can be injected, which subsequently limits the contrast. The ex-vivo imaging using barium/gelatine is a promising alternative.

NEMA NU-4 Performance Evaluation of HiPET, a High Sensitivity and High Spatial Resolution DOI PET Tomograph (#1816)

Dr. Zheng Gu1, Dr. Richard Taschereau1, Dr. David Prout1, Dr. Nam Vu2, Prof. Arion Chatziioannou1

1 University of California, Los Angeles, Crump Institute for Molecular Imaging, Los Angeles, USA; 2 Sofie Biosciences, Culver City, USA

Content
HiPET is a recently developed prototype preclinical PET scanner dedicated to high sensitivity and high resolution molecular imaging. The HiPET system employs a phoswich depth of interaction (DOI) detector design, which also allows identification of the large majority of the cross layer crystal scatter (CLCS) events. This work evaluates its performance characteristics following the National Electrical Manufacturers Association (NEMA) NU4-2008 protocol. HiPET consists of twenty flat panel type detectors arranged in two rings. The diameter is 160 mm and the axial FOV is 104 mm. Each detector is comprised of two layers of phoswich scintillator crystal arrays, a tapered, pixelated glass lightguide and a multichannel photomultiplier tube (MAPMT). The front (gamma ray entrance) layer is a $48 \times 48$ pixelated cerium doped lutetium yttrium orthosilicate (LYSO) scintillator array with individual crystals measuring $1.01 \times 1.01 \times 6.1$ mm. The back (towards the PMT) layer is a $32 \times 32$ pixelated bismuth germanate (BGO) scintillator array with individual crystals measuring $1.55 \times 1.55 \times 8.9$ mm. With an energy window of 350–650 keV, the peak absolute sensitivity was 10.3% including CLCS events and 8.8% excluding CLCS events at the center of the FOV. The average detector energy resolution derived by averaging the individual crystal spectra was 11.7±1.4 % for LYSO and 17.0±1.4 % for BGO. The maximum likelihood expectation maximization (ML-EM) reconstructed image of a point source in air, ranges from 0.73 mm to 1.19 mm, with an average value of 0.93±0.09 mm. The peak noise equivalent count rate (NECR) and scatter fraction were 179 kcps at 12.4 MBq and 6.9% for the mouse-sized phantom, and 63 kcps at 11.3 MBq and 18.3% for the rat-sized phantom. For the NEMA image quality phantom, the uniformity was 5.8%, and the spillover ratios measured in the water- and air-filled cold region chambers were 0.047 and 0.044, respectively. The recovery coefficients (RC) ranged from 0.31 to 0.93.

M-09-03  8:36 AM

Characterization of a Large Volume Cadmium Zinc Telluride Preclinical PET System (#2371)

Andrew Groll, Craig S. Levin

Stanford University, Radiology, Stanford, USA

Content

This work focuses on the performance characterization of a large volume CZT preclinical PET system. Two full heads of the final four-headed box-shaped system have been constructed with each head composed of 24 CZT crystals; each crystal is of size $40 \times 40 \times 5$ mm$^3$. Crystals are paired to form modules with an anode-cathode-cathode-anode configuration. Each CZT crystal has 39 anode strips, and 38 electrodes. Anode strips are 100 μm wide with a 1 mm pitch and steering electrodes are 400 μm wide. The cathode side of the detector module is composed of 8 strips which are 4.9 mm wide with a pitch of 5 mm. Photons enter the crystal in an "edge-on" orientation and pass through the $5 \times 40$ mm$^2$ edge, which results in a detection efficiency equivalent to that of 2 cm of LSO scintillator. The readout of the cathode and anode strips are supported by custom front end electronics designed around a readout ASIC. The configuration has 3456 readout channels available with only an effective 1872 anode channels and 384 cathode channels. We have begun characterizing the energy, coincidence timing, and spatial performance of the system. Results indicate that 70% of the anode channels in the system are producing energy resolvable photopeaks with an average percent energy resolution after charge trapping correction at $11.79 \% \pm 3.19 \%$. 
Pilot Results of an Edgeless Small Animal PET Insert (#2399)

PhD/MD Andrea Gonzalez-Montoro¹, PhD/MD Andrea Gonzalez-Montoro¹, PhD/MD student Gabriel Cañizares¹, PhD/MD student Gabriel Cañizares¹, PhD/MD student Marta Freire¹, PhD/MD student Marta Freire¹, PhD/MD Ahmadreza Rezaei², PhD/MD Ahmadreza Rezaei², PhD/MD student Efthymios Lamprou¹, PhD/MD student Efthymios Lamprou¹, PhD/MD Stuart S. Berr³, PhD/MD Stuart S. Berr³, PhD/MD Stan Majewski⁵, PhD/MD Stan Majewski⁵, PhD/MD Johan Nuyts², PhD/MD Johan Nuyts², Carlos Correcher⁴, Carlos Correcher⁴, PhD/MD Abel Orero⁴, PhD/MD Abel Orero⁴, PhD/MD Filomeno Sanchez¹, PhD/MD Filomeno Sanchez¹, PhD/MD Jose María Benlloch¹, PhD/MD Jose María Benlloch¹, PhD/MD Antonio J. Gonzalez¹, PhD/MD Antonio J. Gonzalez¹

¹ Institute for Instrumentation in Molecular Imaging (i3M), Valencia, Spain; ² KU Leuven, Leuven, Belgium; ³ University of Virginia, Charlottesville, USA; ⁴ Bruker NMI, Valencia, Spain; ⁵ University California Davis, Davis, USA

Content

PET detector technology is based either on pixelated or monolithic scintillators modules. Both configurations present gaps in between detectors decreasing system sensitivity and exhibiting certain detector deterioration towards their edges in terms of spatial and energy resolution. We have demonstrated in a prior study the system enhancement if an edgeless detector would be enabled. Therefore, we proposed and now built a PET system based on a single edgeless LYSO scintillation crystal. Overall dimensions are 52 mm axial and, 62 and 80 mm, inner and outer diameters, respectively. These dimensions are currently suitable for mice, but it could also be extended to larger FOVs by gluing scintillator segments together. In the current work we show the design details of this system which readout electronics are based on high-density SiPMs. We have shown the capability to return light distribution profiles with the two coincidence impacts, extracting accurate 3D impact coordinates. Light distributions agree well with nuclear and optical Monte Carlo simulations. DOI resolution is about 3 mm FWHM combined with energy FWHM of 16-18%. Pilot reconstructions based on FBP and MLEM are already available, exhibiting about 1.25 mm FWHM with 1 mm in diameter Na-22 sources.
Initial performance of a high resolution MRI compatible small animal PET scanner with SiPM based dual-ended readout detectors (#1420)

M.Sc./M.A. Zhonghua Kuang¹, Dr. Xiaohui Wang¹, Ning Ren¹, San Wu¹, Dr. Mengxi Zhang², Juan Gao¹, Dr. Chunhui Zhang¹, Qian Yang¹, Dr. Ziru Sang¹, Dr. Zhanli Hu¹, Dr. Junwei Du¹, Prof. Yongfeng Yang¹

¹ Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Paul C. Lauterbur Research Center for Biomedical Imaging, Shenzhen, China; ² University of California-Davis, Department of Biomedical Engineering, Davis, USA

Content
A MRI compatible small animal PET scanner with high spatial resolution, high sensitivity and long axial field of view was developed with depth encoding detectors by using dual-ended readout of LYSO arrays with SiPM arrays. The scanner consists of 4 detector rings and with 12 detector modules per ring. The ring diameter of the scanner is 111 mm and the axial field of view (AFOV) is 106 mm. Each of the LYSO arrays have 23×23 elements and with a crystal size of 1.0 mm×1.0 mm×20 mm. The LYSO arrays are read out by two 8×8 Hamamatsu SiPM arrays placed at opposite ends. The size of each SiPM pixel is 3 mm×3 mm. The 64 pixels of a SiPM array are read out with a resistor network circuit to reduce the number of signals from 64 to 4. The system electronics inside MRI consists of readout boards of 48 detectors, 48 preamplifier boards and 4 SiPM bias supply boards. The signal processing electronics outside MRI consists of 12 singles processing units (SPU), a coincidence processing unit (CPU) and a system clock and synchronizing board. The initial performance of the scanner was measured by using a Na₂₂ point source placed at the center AFOV with different radial offsets. The images are reconstructed by using the maximum likelihood expectation maximization (MLEM) algorithm without warm background. The MRI compatibility of one PET detector module was also measured. All crystals can be clearly resolved from the flood histogram measured by our system electronics. The detector achieved a DOI resolution of 1.96 mm and an energy resolution of 19.1%. A uniform spatial resolution of ~0.8 mm was obtained for the center 50 mm of the field of view. A sensitivity of 15.1% was achieved at center of the scanner for an energy window of 250-750 keV. The MRI has negligible effect on the performance of PET detector and PET detector has small effect on the SNR of MRI image. In the next step, the NEMA performance of the scanner will be measured and phantom and animal studies will be performed.
Performance evaluation of SimPET-X: simultaneous PET/MRI for mouse total-body imaging (#1975)

PhD/MD Guen Bae Ko1,2, PhD/MD student Kyeong Yun Kim1, PhD/MD Jeong-Whan Son1, Yina Chung1, Kyuwan Kim1, PhD/MD student Ji-Yong Park2,3, Prof. Yun Sang Lee2,3, Prof. Jae Sung Lee1,3

1 Brightonix Imaging Inc., R&D Center, Seoul, South Korea; 2 Seoul National University, Medical Research Center, Seoul, South Korea; 3 Seoul National University, Department of Nuclear Medicine, Seoul, South Korea

Content
Total-body imaging is preferred in preclinical positron emission tomography (PET) scans because it allows single-bed scans without moving animal bed and assessment of the whole-body biodistribution of the radiopharmaceutical. In addition, total-body imaging greatly increases system sensitivity, thus improving image quality more than short axial field-of-view (FOV) systems and reducing radiation dose and/or scan time. However, increasing the axial FOV in preclinical PET inserts for simultaneous PET/MR imaging is challenging because PET detectors are located very close to the scanning object due to the limited space within the magnet bore. Also, the number of signal lines should be minimized. Therefore, we need sophisticated analog and digital electronics that can operate without performance degradation at high count rates. SimPET-X, newly developed simultaneous PET/MR scanner of Brightonix Imaging Inc, covers 110 mm long axial FOV and enables total-body imaging for mice. To process the large amounts of data from this highly sensitive scanner without data loss, analog signal shape was optimized and real-time coincidence detection techniques have been applied. The performance of this new PET insert was investigated according to the standards set out by the National Electrical Manufacturers Association (NEMA) NU4-2008 protocol and various imaging studies.
M-10 | Tomographic Image Reconstruction Techniques II

Frederic Noo (Salt Lake City)
Samuel Matej (Philadelphia)
M-10-01 8:00 AM

Low-dose dual energy CT image reconstruction using non-local deep image prior (#2351)

Dr. Kuang Gong¹, Dr. Kyungsang Kim¹, Dr. Dufan Wu¹, Prof. Mannudeep K. Kalra², Prof. Quanzheng Li²

¹ Massachusetts General Hospital and Harvard Medical School, Gordon Center for Medical Imaging, Boston, USA; ² Massachusetts General Hospital and Harvard Medical School, Radiology, Boston, USA

Content
For low-dose dual energy CT (DECT) scans, the difference image between the low and high energy images are noisy and always post-smoothed to achieve diagnosis value. Recently the deep image prior framework shows that convolutional neural networks (CNNs) can learn intrinsic structural information from the corrupted images, without pre-training or high-quality training labels. Inspired by this concept, we represented the low-energy and the difference images as the two-channel output of a CNN and embedded this representation into the DECT system model. Summation of low and high energy CT images reconstructed using FBP was treated as the prior image and supplied as the network input. A non-local layer calculated based on the prior image was integrated into the network structure as additional constraints. Through this CNN representation, the low and high energy images are reconstructed jointly and benefit from the features extracted from the prior image. We formulated the proposed DECT joint reconstruction framework as a constrained optimization problem and solved it using the alternating direction method of multipliers (ADMM) algorithm. Experimental evaluation based on a low-dose DECT dataset shows that the proposed method can outperform the reference denoising methods.

M-10-02 8:18 AM

Geometric tomography for measuring rectangular radiotherapy fields from six projections (#1560)

Laurent Desbat¹, Simon Rit², Rolf Clackdoyle¹, Patrice Jalade⁴, Julien Ribouton⁴, Patrick Pittet³

¹ Univ. Grenoble Alpes, CNRS, Grenoble INP, TIMC-IMAG, Grenoble, France; ² Université de Lyon, INSA-Lyon, Université Claude Bernard Lyon 1, UJM-Saint Etienne, CNRS, Inserm, CREATIS UMR 5220, Lyon, France; ³ CNRS UMR5270, Université Lyon 1, Institut des Nanotechnologies de Lyon INL, Villeurbanne, France; ⁴ Centre Hospitalier Lyon Sud, Service de Physique Médicale et de Radioprotection, Pierre-Bénite, France

Content
Quality assurance (QA) of x-ray radiotherapy is crucial but the dosimetry of small fields is still a challenge. We are investigating the use of scintillating parallel fibers which measure the integral dose along a line, thus providing a one-dimensional (1D) parallel projection of the dose of the x-ray field in a plane of a tissue equivalent medium. By stacking a few layers of scintillating fibers, each with a different orientation, one obtains a sinogram of the dose of the x-ray field sampled with a few angles and sub-millimetric resolution of each projection. We propose a geometric approach
based on projection moments to identify the few parameters defining the irradiation field (e.g., center, orientation, width, length and intensity for a rectangle). The order-0 moment of at least one projection provides an estimate of the integral dose. The order-1 moments of at least two projections gives the center of mass, i.e., order-1 moments of the dose map. The order-2 moments of at least three projections identify order-2 moments of the dose map. In the specific case of a uniform rectangular field, we show that the length, the width, and the orientation of the rectangle can be derived from the order-2 moments of the dose map. The formulas are extended to the case of a non-uniform field due to a lateral Gaussian penumbra. Our approach was validated on simulated data of rectangular fields with increasing levels of noise and demonstrates an accurate, robust and rapid estimation of the rectangle parameters from six projections only. A proof of concept experiment with scintillating fibers imaged with a sCMOS camera irradiated under a 30x30 mm$^2$ square field of a 6 MV linear accelerator gave 31.7x31.4 mm$^2$ without accounting for the penumbra and 28.6x28.3 mm$^2$ with an estimated $\sigma = 4$ mm penumbra.

M-10-03 8:36 AM

Calibration and data consistency in parallel and fan-beam linogram geometries (#2359)

Laurent Desbat, Rolf Clackdoyle, Jérome Lesaint

Univ. Grenoble Alpes, CNRS, Grenoble INP, TIMC-IMAG, Grenoble, France

Content
Self-calibration of tomographic imaging systems refers to the use of redundant data in the measurements to tease out geometric misalignments of the physical system which can then be corrected for improved imaging. The redundant data is expressed as data consistency conditions (DCC). An understanding of these conditions is vital to proposing such self-calibration methods. For conventional circular scanning, there are several known properties of the parallel projections. We consider five of these properties and examine how they apply in linogram geometries where DCC are less familiar: (i) the mass of the scanned object is the sum of the line-integrals making up each projection; (ii) the projection of the center of mass in the phi direction equals the center of mass of the phi projection; (iii) reversing the direction of scan results in a mirror-flipped image; (iv) offsetting the direction of the projections by a fixed angle rotates the reconstructed image by that angle; and (v) offsetting the ray index of each projection results in inconsistent data. We established the following new results. For linograms in parallel format, the corresponding results are true for (i), (ii), (iii) but not (iv) and (v). Offsetting the projection index of parallel linograms, (iv), results in a shear transformation of the object, rather than a rotation. And offsetting the ray index, (v), does provide consistent data, corresponding to a translated version of the object. For linograms in fan-beam format, (i) and (ii) remain true but only for specially weighted versions of the object. Offsetting the projection index, (iv), or offsetting the the ray index, (v), will result in shear transformations of the object. We do not yet have a description for the effect of reversing the sign of the fan-beam projection index. Understanding linogram DCCs is vital to constructing self-calibration systems in linogram format, such as an x-ray source travelling linearly, parallel to a fixed detector.
On the Value of the Non-Negativity Constraint in CT

Viktor Haase\textsuperscript{1,2}, Viktor Haase\textsuperscript{1,2}, Katharina Hahn\textsuperscript{1}, Katharina Hahn\textsuperscript{1}, Dr. Harald Schöndube\textsuperscript{1}, Dr. Harald Schöndube\textsuperscript{1}, Dr. Karl Stierstorfer\textsuperscript{1}, Dr. Karl Stierstorfer\textsuperscript{1}, Prof. Andreas Maier\textsuperscript{2}, Prof. Andreas Maier\textsuperscript{2}, Prof. Frédéric Noo\textsuperscript{3}, Prof. Frédéric Noo\textsuperscript{3}

\textsuperscript{1}Siemens Healthcare GmbH, Forchheim, Germany; \textsuperscript{2}Friedrich-Alexander-Universität Erlangen-Nürnberg, Pattern Recognition Lab, Erlangen, Germany; \textsuperscript{3}University of Utah, Department of Radiology and Imaging Sciences, Salt Lake City, USA

Content

Model based iterative reconstruction (MBIR) has attracted a lot of attention in X-ray computed tomography (CT). A strength of MBIR over classical filtered backprojection is its ability to apply constraints over the voxel values, which can be critical to improve image quality. Given that the linear attenuation coefficient of X-rays is non-negative, applying a non-negativity constraint appears very natural. Indeed, most MBIR-related publications in CT invoke it. However, there is little to no information in the literature on the intrinsic value of the non-negativity constraint. In this work, we shed light on this question in the context of two challenging imaging scenarios: (i) heavy truncation, (ii) photon starvation due to a metal implant. Real CT data sets are used, and the effect of the constraint is examined in terms of image similarity and closeness to a preferred ground truth. Additionally, convergence properties are examined. The reconstruction is performed using a provably converging algorithm applied with a large number of iterations to nearly reach convergence, and is also performed using ordered subsets to obtain a result in a manner that is more practical for clinical routine applications. Our results show that the non-negativity constraint can be both beneficial and detrimental depending on the imaging scenario. However, the observed differences tend to be much smaller than the overall level of inaccuracy in the image. We also find that the non-negativity constraint can prevent divergence when using ordered subsets, but this gain does not translate into a satisfactory reconstruction. Altogether, we conclude that strong value for the non-negativity constraint is difficult to demonstrate. This constraint could thus be discarded in favor of other constraints or utilization of algorithms that cannot handle it.

Simultaneous Dual Isotope ToF-PET Imaging

Dr. Zhengzhi Liu, Dr. Min Sun Lee, Dr. Garry Chinn, Prof. Craig Levin

Stanford University, Departments of Radiology/Molecular Imaging Program at Stanford (MIPS), Stanford, USA

Content

Positron emission tomography (PET) is a powerful molecular imaging technique. PET using multiple tracers can improve the specificity of PET and broaden its uses. For instance, there are demonstrated benefits to sequential imaging using two different tracers staggered in time. Unfortunately, this staggered imaging approach is logistically challenging but also may lead to errors due to changes in physiology and molecular behavior that occurs between
Simultaneous dual isotope PET imaging has previously been investigated using a pure emitter and a "dirty" emitter (produces a third photon in cascade with the two annihilation photons). The main challenges of simultaneous dual isotope imaging are low detection efficiency of triple coincidences and low separability of pure and dirty positron emitters. In this work, we used a novel method to separate dirty emitters from pure emitters in PET images. A simulation of a complex mixed source phantom in a dedicated brain PET system with an end-cap detector to increase detection efficiency for the third photon of a dirty emitter was carried out in GATE to demonstrate this proof of concept of simultaneous dual isotope PET imaging using time of flight (ToF) information. For pure and dirty sources, a relative distinguishability error between pure and dirty emitters of about 3% was achieved in the region of interest.

**M-10-06  9:30 AM**

**Effects of TOF Resolution Models on Edge Artifacts in PET Reconstruction from Limited Angle Data** (#2418)

**Dr. Paul Gravel, Dr. Samuel Matej**

*University of Pennsylvania, Philadelphia, USA*

**Content**

Limited angle data, such as data obtained from a dual panel Breast-PET system, result in substantial image blur in the directions coinciding with the missing cone of the image spectrum. On systems with time-of-flight (TOF) capabilities, this blur is reduced in length as given by the TOF uncertainty, with the image spectral data correspondingly being expanded into the missing spectral cone. Modeling of the TOF uncertainty in the reconstruction is expected in turn to deconvolve the TOF blurring, at least for ideal noiseless data. We have however observed that, as a tradeoff, the TOF de-blurring process, when reconstructing limited angle data, also introduces ringing artifacts at the de-blurred objects edges, analogous to the edge effects observed with resolution modeling of the point-spread function (PSF) within image reconstruction which attempts to deconvolve the blur due to spatial resolution degradation effects. However, in the former case, the ringing artifacts are much wider due to the size of the TOF uncertainty kernel as compared to the size of typical LOR resolution kernels. In this contribution, we illustrate and investigate the effects of using matched as well as under- and over-modeled TOF resolution kernels on edge artifacts in PET reconstruction from limited angle data, and compare those with the effects of TOF reconstruction of complete data from a conventional full-ring scanner.
NSS-41 | NSS Closing Session

Cinzia DaVia (Manchester)
Yoshinobu Unno (Tsukuba)

What is the future of radiation instrumentation holding? Pioneers in all relevant fields of radiation instrumentation accepted to present their view on emerging technologies, their evolution and how such technologies will impact the field in few years from now. The session is organised as a plenary event with presentations followed by a brief discussion session where the audience will have the opportunity to ask questions and present comments. After the coffee break the second group of awards will be delivered starting with the prestigious NPSS Society Merit Award that this year will honour the work of our esteemed colleague Paul LeCoq. At the end of the session awards will be delivered to the best students posters and oral presentations.
NSS-41-01  

**Introduction**  

Cinzia Da Via  

*The University of Manchester, UK*

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NSS-41-02  

**What Junior Scientists Should Know**  

Robert Klanner  

*DESY, Germany*

In this talk I will concentrate on issues related to future detectors and radiation damage with a short overview over historical development, the ethics of publications and the relevance of high-quality publications for the career of junior scientists.

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NSS-41-03  

**Future: Imaging of Quanta with Attopixels**  

Erik Heijne  

*IEAP-CTU Prague and CERN Geneva, Czech Republic*

The incredible progress of nanoelectronics technology is continuing into the 3rd dimension with stacking of extremely thin silicon layers, resulting in powerful processing devices, including smart imagers for professional use and entertainment. Pixel detectors for particle physics experiments using the hybrid bump-bonding technique were a forerunner, and improved, cheaper approaches are now in sight. The current, much smaller dimensions enable signal processing with few electrons noise, thanks to pixel capacitance in the attofarad range. Fairly complex circuitry would be implemented in additional, stacked layers, which also would accommodate cooling and routing for the terabytes of data.
Novel trends in development and utilization of semiconductor position-sensitive neutron detectors

Stanislav Pospisil

IEAP CTU, Prague, Czech Republic

Efficient position and energy sensitive detection of neutrons is fundamental for advance in neutron imaging, neutron dosimetry and within subfields of nuclear and high-energy physics, nuclear energy, nondestructive structural analysis in biology and inanimate materials as well as in space applications. The general principles of neutron detection based on a brief overview of specific interactions of neutrons of different energies will be reminded in the presentation with the aim to summarize advantages and disadvantages of individual types of active neutron detectors commonly used compared to semiconductor detectors adapted for neutron detection. This will focus on the concept of semiconductor pixel detectors with converters of neutrons to strongly ionizing charged particles designed for detection of neutrons in radiation hard environment. The detection devices will be described in terms of the converter-sensor geometry, sensor materials and associated mechanisms for neutron conversion to well recognizable electronic signal according the needs of individual applications. Particular attention will be given to challenges associated with growing interests in neutron imaging with submicron resolution and in noiseless detection of single neutrons in mixed n-gamma radiation fields. Perspectives of the proposed concept will be backed up by the latest experimental results obtained with Timepix pixel detectors using the methodology of "particle track pattern recognition".

The future of tracking in Particle Physics

Daniela Bortoletto

Oxford University, UK

New particle accelerators are being planned for the future of particle physics. The new facilities, which are currently under discussion, include electron-positron colliders for precision studies of the Higgs boson and ultra-high energy and high luminosity proton-proton colliders. Experiments at these facilities will require improved tracking detector concepts that will depend on the different environments. The latest trends emerging from technological advancements will be discussed. These include improvements in timing capabilities, detector radiation hardness, scattering material, and cooling approaches.
NSS-41-06

Future Photodetectors for Fundamental Science

Olivier Limusin

CEA, France

NSS-41-07

COFFEE
M-11 | X-Ray Imaging Systems

Xiaochuan Pan (Chicago)
Katsuyuki Taguchi (Baltimore)
M-11-01  10:20 AM

CZT Detector Pixel to Pixel Interference and Its Impact over Material Decomposition in Photon Counting CT (#1878)

Dr. Xiaochun Lai, PhD/MD student Kevin Zimmerman, Dr. Liang Cai, Dr. Madhuri Kaul, Dr. Xiaohui Zhan, Dr. Yi Qiang, Dr. Richard Thompson

Canon Medical Research USA, CT, Vernon Hills, USA

Content
As an emerging spectral CT technique, photon-counting CT has great potential of changing clinical CT applications and has been of great research and development interest both within academia and industry. A photon-counting CT employs a photon-counting detector (PCD) based on cadmium zinc telluride (CZT) or cadmium telluride (CdTe). To handle high x-ray flux in the clinical CT applications, a small pixel design, typically sub-500 μm, is used. With a such small pixel size, charge sharing and characteristic x-ray escape & absorption can distribute an x-ray photon’s energy to multiple pixels. The detector pixel response is not only affected by x-rays that the pixel directly interacts with but also the ones hitting surrounding pixels. Such pixel to pixel detector interference should be taken into account when performing domain material decomposition, i.e., the estimation of material path lengths along each measured ray. We not only need to consider the x-ray’s energy and flux directly hitting each pixel, but also need to include the impact of x-rays from its surrounding. However such interference has not been well accounted with conventional method, in which the material composition of each pixel is estimated independently using the overall pixel response. Such method could introduce strong bias when the flux and spectrum in the surrounding pixels are significantly different. In this presentation, we will investigate the impact of such pixel interference to material decomposition with different conditions, e.g, flux levels, spectra and phantoms, through simulation studies.

M-11-02  10:38 AM

Application of the X-ray Transmittance Modeling-Based Three-Step Algorithm to a Prototype Photon Counting Computed Tomography (#2534)

Dr. Okkyun Lee1,2, Dr. Christoph Polster3, Dr. Karl Stierstorfer3, Dr. Steffen Kappler3, Dr. Kishore Rajendran4, Dr. Shuai Leng4, Dr. Cynthia H. McCollough4, Dr. Katsuyuki Taguchi1

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Content
Background. Recently, we have developed an x-ray transmittance modeling-based 3-step algorithm for spectral photon counting detector-based computed tomography (PCD-CT) in order to compensate for the effect of spectral
distortion due to charge sharing and K-escape x-rays. Computer simulation studies showed that the 3-step algorithm produced very little biases and noise, which was either comparable or lower than the Cramer Rao lower bounds. The purpose of this study was to assess if the 3-step algorithm is effective with a prototype PCD-CT system using phantom and animal data.

Methods. The forward imaging chain links x-ray spectra exiting from a bowtie filter to attenuation within the object to the spectral distortion modeled by photon counting toolkit (PcTK) to the output of PCDs. Measured projections of cylindrical water-equivalent phantoms with different sizes placed at different off-centered locations were used to relate the output of a prototype PCD-CT system (SOMATOM CounT; Siemens Healthineers) to the output of PcTK. A water-equivalent cylinder with iodine inserts and a contrast-enhanced chest and abdomen of a pig was scanned.

Results. Results were compared with those obtained by a single energy threshold (≥20 keV, “PolyCT”) and image-based material decompositions (IMD). The 3-step algorithm had the least bias between iodine inserts (i.e., the least beam hardening effect) (+3 HU vs –20 HU for PolyCT and –15 HU for IMD) and much weaker ring artifacts than either PolyCT or IMD as the calibration absorbed the PCD pixel-to-pixel variations effectively. Comparing with IMD, the 3-step algorithm had a comparable noise level over 40–120 keV with the test phantom and 80–120 keV with animal images.

Conclusion. The 3-step algorithm was effective with the prototype PCD-CT system, suppressing the beam hardening effect and making voxel values consistent.

Image quality metrics for selecting gradient sparsity regularization strength: RMSE exposed (#2546)

Dr. Emil Y. Sidky¹, Dr. Ingrid Reiser¹, Dr. Gregory Ongie², Dr. Xiaochuan Pan¹

¹ University of Chicago, Department of Radiology, Chicago, USA; ² University of Chicago, Department of Statistics, Chicago, USA

Content

Determination of gradient sparsity regularization strength is investigated for a breast computed tomography (CT) simulation. An image quality metric is sought that can be evaluated objectively and that is a potential candidate for agreement with subjective visual assessment. As the work is based on simulation, a number of metrics are available that exploit knowledge of the truth. Root-mean-square-error (RMSE) is one such metric, and in the study it is seen that RMSE does not correlate well with subjective visual assessment; low RMSE is observed to correspond to over-smoothed images that lead to patchy image distortions. As an alternative, image quality assessment based on a signal-known-exactly/background-known-exactly detection task of a small point-like signal is seen to have the potential to agree well with subjective visualization.
Comparative Study of Image Quality in Time-of-Flight Computed Tomography (#2527)

M.Sc./M.A. student David Gaudreault\(^1,2\), PhD/MD student Julien Rossinol\(^1,2\), Prof. Yves Bérubé-Lauzière\(^1\), Prof. Réjean Fontaine\(^1,2\)

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Content
Computed Tomography (CT) is an anatomical imaging modality largely used to measure the material density. High spatial resolution can be obtained with this technique at the cost of radiation exposure. Cone-beam CT (CBCT) scanners are used to produce 3D images in a single rotation, reducing the exposition of the subject to radiation. These systems are subject to heavy scattering noise that prevent their use for imaging large volumes. This noise, measured as the ratio of scattered to primary radiation (SPR), is highly dependent on the volume exposed to the source emission and can reach values higher than 100% for body imaging. Anti-scatter grids (ASG) are frequently used to reduce the effect of the scatter noise at the cost of sensibility. Recently, time-of-flight computed tomography (TOF-CT) has been proven to be an interesting new method to remove scattered photons especially in CBCT. This study aims at comparing the image quality and SPR obtained in TOF-CBCT, in fan-beam CT, in collimated CBCT and in a reference CBCT. The four systems have been simulated in the Monte Carlo Simulator GATE. A 1 x 256 array of 2 x 2 x 1 mm\(^3\) pixel detector was positioned 620 mm behind the phantom. The phantom is a 288 mm wide water cylinder with two bone inserts. The source is positioned 1033 mm in front of the phantom. As expected, the TOF-CBCT produced the highest contrast-to-noise ratio (CNR) and SPR ratio amongst the CBCT systems. TOF-CBCT was close to achieve the same image quality as the fan-beam CT, known to be less affected by scatter noise.

Development of an x-ray photon counting multispectral imaging detector for predicting dose enhancing effects produced by in vivo gold nanoparticles. (#2224)

Oliver L. P. Pickford Scientist\(^1,2\), Prof. Jeff Bamber\(^1,2\), Dr. Dimitra Darambara\(^1,2\)

\(^1\) Institute of Cancer Research, Radiotherapy and Imaging, London, UK; \(^2\) Royal Marsden NHS Trust, Multi-modality Molecular Imaging team, London, UK

Content
Researchers are investigating gold nanoparticles (AuNPs) as adjuvants for radiotherapy, due to their dose enhancing effects (DEE). AuNPs may be molecularly targeted to cancer cells and have been shown to increase cell
radiosensitivity by a combination of physical, chemical and biological mechanisms. Maximising AuNP usefulness in this context requires: a method for quantitatively imaging their distributions \textit{in vivo} and a relation between AuNP concentration and DDE. The first of these requirements is addressed by optimising an x-ray photon counting multispectral imaging (x-CSI) detector for detecting AuNP distributions. x-CSI optimisation was performed \textit{in silico} using an in house, experimentally validated simulation framework: CoGI. The latest incarnation of CoGI utilises a novel reshaping approach to determine the optimal detector response without having to first optimise shaping time. Additionally, a range of charge sharing correction (CSC) algorithms can be selected during signal generation. In total, 72 different x-CSI detectors were simulated this way, utilising CdTe pixels of varying thickness, pitch and CSC algorithm used. The detectors were calibrated over a range of medically relevant x-ray energies (20 – 140 keV). Assuming $k$-edge imaging will be relevant to AuNP quantification, these detectors were compared for energy resolution, spectral efficiency and absolute detection efficiency at the $k$-edge for gold (~80 keV). The second requirement is then addressed by cell work to determine the relation between AuNP concentration and DEE. Several AuNP types and several cancer cell lines were studied, with the aim of finding a common relation. Detailed analysis of cell results will be presented.

**M-11-06  11:50 AM**

**Label-Free Molecular Imaging using a Polarized X-ray Fluorescence Computed Tomography System with Multi-Leaf Compton Mirror** (#2570)

**PhD/MD student Xingchen Nie**, **PhD/MD Yunlai Chen**, **Prof. Lingjian Meng**

1 University of Illinois at Urban Campaign, Nuclear, Plasma and Radiological Engineering, Urbana, USA; 2 University of Illinois at Urban Campaign, Beckman Institute for Advance Science and Technology, Urbana, USA

**Content**

The concept of Polarized Energy-Dispersive X-ray Fluorescence (PEDXRF) has been widely used by X-ray fluorescence spectroscopy community. This technique is demonstrated to offer a greatly improved ratio between fluorescence signal a Compton scattering noise. Whereas, the current implementation of the PEDXRF technique has two major limitations. First, the increased peak to background ratio has always been associated with a greatly reduced count-rate. Second, the current PEDXRF techniques are primarily limited to point-to-point raster scan of 2D samples, which require excessive sample preparation and long measurement time. In this presentation, we discuss a novel polarized X-ray fluorescence emission tomography (PXFET) technique that incorporates several design aspects to alleviate the limitations of the conventional XFET techniques. First, high intensity X-ray source (MicroMax™-007 HF) will be used to produce a high flux of polarized X-rays to excite the target metals in the object. Second, the X-rays are collimated to a fan beam striking a multi-layer Compton mirror (MLCM). The MLCM is designed to ensure that each X-ray photon from the source will intersect with at least 4 or more layers of the mirror material and maximize the efficiency for scattering the X-ray. Third, two direct-conversion CCD cameras are placed above and below the sheet-beam. With these three design attributes discussed above, the PXFET system could provide a greatly improved signal-to-noise ratio over regular XFET system. This development could provide a critically needed imaging capability for 3-D mapping of trace metals. Since the system is based on laboratory X-ray sources, we could envision the PXFET technique to be disseminated to a wide range of biology labs for studying the role of trace metals.
M-12 | Image Quality Assessment and Standardization

Matthew A. Kupinski (Tucson)
Dimitris Visvikis (Brest)
Qualification of the Seven Dementias Platform UK PET-MR scanners for multicentre trials (#2348)

Dr. Georgios Krokos¹, Dr. Jane MacKewn¹, M.Sc./M.A. Lucy Pike¹, Dr. William Hallett², Dr. Pawel Markiewicz³, Dr. Anna Barnes⁴, Dr. Marilena Rega⁴, Dr. Tim D. Fryer⁵, Dr. Roido Manavaki⁵, Dr. Jose M. Anton-Rodriguez⁶, Dr. Elizabeth Howell⁸, Dr. Catriona Wimberley⁹, Tim Clark⁹, Dr. Gillian Macnaught⁹, Prof. Paul Marsden¹, Dr. Julian Matthews⁷

¹ King’s College London, School of Biomedical Engineering and Imaging Sciences, London, UK; ² Invicro, Hammersmith Hospital, London, UK; ³ University College London, Centre for Medical Image Computing, London, UK; ⁴ UCL Hospitals NHS Foundation Trust, The Institute of Nuclear Medicine, London, UK; ⁵ University of Cambridge, Departments of Clinical Neurosciences and Radiology, Cambridge, UK; ⁶ University of Manchester, Division of Informatics, Imaging and Data Sciences, Manchester, UK; ⁷ University of Manchester, Division of Neuroscience and Experimental Psychology, Manchester, UK; ⁸ Newcastle University, PET Centre, Newcastle, UK; ⁹ University of Edinburgh, Centre for Clinical Brain Sciences, Edinburgh, UK

Content
Standardisation of PET scanners participating in multicentre trials is important in achieving reliable results and in maximizing the power of the study. The first multicentre clinical trial studies involving seven PET-MR scanners in the UK (four GE SIGNA and three Siemens mMR) are underway, led by Dementias Platform UK. In this study, the qualification of the seven scanners was tested using the NEMA image quality phantom. Consistent scanning methodology was followed across all sites with a 5:1 sphere-to-background contrast ratio and a CT-based μ-map used for attenuation correction. The reconstruction parameters were consistent between scanners of the same manufacturer. The SUV\text{mean} and SUV\text{max} for all spheres were comparable between all scanners and within EARL performance specifications. Moreover, the averaged SUV values from all scanners were similar with the averaged corresponding values from 25 PET-CT scanners across the UK currently eligible to participate in multicentre trials. In conclusion, these preliminary results support the reliable comparison of PET performance across the PET-MR scanners.

Novel volume based approach to estimate contrast recovery for NEMA image quality phantom (#1238)

Dr. Ahmadreza Ghahremani, Dr. Deepak Bharkhada, Dr. Maurizio Conti

Siemens Medical Solutions USA, Inc., KNOXVILLE, USA

Content
In medical imaging the quality and performance of scanners always need to be checked. This standard is also necessary to make image quality comparisons between scanners. In case of positron emission tomography (PET),
the National Electrical Manufacturers Association (NEMA) has established a standard procedure to help evaluate and compare instrumentation performance. In the method described by the NEMA document to measure contrast recovery, strong emphasis is placed on placement of the phantom so sphere locations are in expected positions. Only one plane is used for analysis and it is necessary to locate centers of hot spheres in the same plane. Observing unrealistic measured data based on this 2D method (higher value of contrast recovery reported for small sphere compare to larger spheres) was the main motivation to improve measurement of contrast recovery. In this study, a new approach for image processing of measuring contrast recovery of NEMA IQ phantom is proposed. Several algorithms (like implementing a hot sphere activity-digitally, using correlation coefficient theory to check similarity between two images, and considering parabolic curve fitting technique in numerical computation) were applied to find centroid of the activity inside 3D image. By dividing each image voxel to smaller cubic unit (sub-voxel), an accurate way for volume integration was determined. The major error caused by volume integration (partial volume effect) has been reduced by shrinking the size of sub-voxels. We compared our proposed method (3D) to current NEMA NU2 2018 standard (2D) used to estimate contrast recovery. The proposed novel 3D method presents good stability, high accuracy, and more reliability for measuring contrast recovery NEMA IQ test.

**Content**

The trade-off between sensitivity and spatial resolution is a well understood principle in single-pinhole SPECT imaging. To increase sensitivity while maintaining high spatial resolution, some systems have adopted multi-pinhole apertures. However, this introduces multiplexing, i.e., the undesired overlap of images, which results in photon origin ambiguity and consequently artifacts in the reconstruction. It has been shown that the deleterious effects of multiplexing may be mitigated by using tandem cameras to collect data at different magnifications. However, such systems are complicated to optimize and are often fixed in their geometry. By capitalizing on the design of the AdaptiSPECT system, a real-time adaptable imager, we replicate the data collected by a tandem detector system by sequentially acquiring both high-resolution single-pinhole images and high-sensitivity multi-pinhole images, and concatenating the two data sets to form the final image data. Before acquiring this data, a scout scan is taken to generate an object reconstruction (scout object) that is used to determine the system parameters of the final diagnostic scan. The times spent in the single- and multi-pinhole configurations of the diagnostic scan are determined from the sparsity of the scout object and the detector distances of each pinhole configuration are determined from the object's support. For single-pinhole images, the detector distance is chosen such that the image maximizes the active detector regions. Conversely, the optimal detector distance of the multi-pinhole configuration occurs when the rate of change of image multiplexing as a function of detector distance is at a maximum. This function is calculated by projecting the support of the scout object through simulated system geometries via a GPU based Monte Carlo simulator. The combination of both data sets results in improved object reconstructions that carry greater information for both detection and estimation tasks.
Estimation of full-dose 4D CT perfusion images from low-dose images using conditional generative adversarial networks (#2200)

PhD/MD student Mahdieh Dashtbani Moghari\textsuperscript{1}, Dr. Luping Zhou\textsuperscript{2}, PhD/MD student Biting Yu\textsuperscript{3}, Krystal Moore\textsuperscript{4}, Prof. Noel Young\textsuperscript{4}, Prof. Roger Fulton\textsuperscript{5,4}, Dr. Andre Kyme\textsuperscript{1,5}

\textsuperscript{1} University of Sydney, Biomedical Engineering, Sydney, Australia; \textsuperscript{2} University of Sydney, Electrical and Information Engineering, Sydney, Australia; \textsuperscript{3} University of Wollongong, Computing and Information Technology, Wollongong, Australia; \textsuperscript{4} Westmead hospital, Sydney, Australia; \textsuperscript{5} University of Sydney, Health Sciences, Sydney, Australia

Content

CT Perfusion (CTP) imaging is one of the most common tools for diagnosing acute stroke and assessing patient treatment options. The CTP imaging protocol typically involves the rapid acquisition of about 33 frames of the brain volume over ~1 minute, following contrast administration. It therefore carries a relatively high radiation dose. The ability to reduce this dose, especially in younger patients, without compromising the accuracy of image-based stroke analysis is highly desirable. However, a reduction in dose is accompanied by an increase in noise, which can compromise computation of important haemodynamic parameters during stroke analysis. Our aim in this work was to investigate the feasibility of using 3D conditional generative adversarial networks (3D c-GANs) to achieve CTP dose reduction while preserving image quality. We simulated low-dose CTP images corresponding to tube currents of 100 mAs and 45 mAs for 18 positive acute stroke subjects and applied a 3D c-GANs model to estimate the standard dose CTP images from the simulated low-dose images. We also compared two different strategies for handling the 4D nature of the CTP data in the 3D c-GANs model. Qualitatively, the results showed excellent agreement between the estimated low-noise images and the true images. Quantitative assessment also showed good performance of the model associated with high peak signal-to-noise ratio (PNSR) around 40 dB, normalized mean squared error (NMSE) close to zero, and structural similarity index (SSIM) close to 1. By stacking the original data rather than concatenating all volumes, the results were improved by 1.05 dB PNSR, 0.005 NMSE, and 0.01 SSIM at the simulated exposure of 100 mAs, and by 0.93 dB PNSR, 0.019 NMSE at the simulated tube current of 45 mAs. The results show good promise for dose reduction in CTP, however we are currently performing full stroke modelling analysis on the synthetic images to validate the method.
**Standardization of Multicentric Image Datasets with Generative Adversarial Networks (2443)**

PhD/MD student Clément Hognon\(^1,2\), PhD/MD student Clément Hognon\(^1,2\), Dr. Florent Tixier\(^3\), Dr. Florent Tixier\(^3\), Dr. Olivier Gallinato\(^1\), Dr. Olivier Gallinato\(^1\), Dr. Thierry Colin\(^2\), Dr. Thierry Colin\(^2\), Dr. Dimitris Visvikis\(^2\), Dr. Dimitris Visvikis\(^2\), Vincent Jaouen\(^1\), Vincent Jaouen\(^1\)

\(^1\) LATIM, Université de Bretagne Occidentale, UMR1101 Inserm, Brest, France; \(^2\) Sophia Genetics, Bordeaux, France; \(^3\) Department of Medical Physics, Memorial Sloan Kettering Cancer Center, New York, USA

**Content**

Due to the sensitivity of medical images to acquisition parameters, multicentric image studies often suffer from a lack of homogeneity in terms of statistical characteristics, also known as the *center effect*. There is therefore a clear need for image-based standardization techniques that reduce center-induced variability while preserving the properties (e.g. diagnostic power) of individual images. In this paper, we propose a machine learning-based framework in which multicentric, heterogeneous images are translated to match the statistical properties of a standard domain, such as a template reference image. The proposed approach is a two-step process based on paired and unpaired image-to-image translation generative adversarial networks. The source dataset is first translated to an intermediate domain through unpaired learning, which helps better preserving structures of interest in the final translation step. We apply our standardization model to a publicly available magnetic resonance multicentric dataset, where we show that we reduce cross-domain while preserving within-domain variability. Future works will focus on further validating the approach in the context of multimodal image segmentation and radiomics using modalities such as PET and computed tomography.

**The image quality evaluation with different number of units based on the first total-body uEXPLORER scanner (1627)**

PhD/MD Zilin Deng, PhD/MD Yu Ding, PhD/MD Yun Dong

Shanghai United Imaging, Shanghai, China

**Content**

The world first total-body uEXPLORER scanner, which can be able to provide the clinical imaging in a single breath hold, at high spatial resolution and high sensitivity, mainly consists 8 units in axial direction with an total axial field of view of 194 cm. In conventional PET whole body imaging, the scanning range is usually from head to upper thigh that is less than 120 cm, about the length of 5 units in the uEXPLORER. In this study, the image quality was investigated with different number of units based on the uEXPLORER scanner.
NSS-42 | NSS Closing Session

Cinzia DaVia (Manchester)
Yoshinobu Unno (Tsukuba)
Presentation of the Merit Award by the NPSS President Ronald Schrimpf

NPSS Merit Award Lecture: Future Trends in Scintillator Research
Paul Le Coq
CERN, Geneva, Switzerland

For a long time, the discovery of new scintillators has been more serendipitous than driven by a deep understanding of the mechanisms at the origin of the scintillation process. This situation has dramatically changed now with an increased demand for scintillators of better performance for large particle physics experiments as well as for medical imaging. It is now possible to design a scintillator for a specific purpose. The bandgap can be adjusted, the traps energy levels and their concentration can be finely tuned and their influence can be damped or on the contrary enhanced by specific doping for an optimization of the performance of the scintillator. The progress in nanotechnologies open also new perspectives for the development of meta-scintillators, a new class of multifunctional multi-intelligent scintillators combining the high stopping power and photo-fraction of well known scintillators, such as BGO, LSO, and the ultrafast scintillation of quantum confined excitons in nanocrystals.

Trends in Computing
Maria Grazia Pia
INFN Genova, Italy

NSS 2003 closing session in Portland ended with a talk on "Trends in Computing"; sixteen years later, the subject is revisited in a changed world. The limited time allocation at NSS 2019 permits only a cursory glance at a complex and rapidly evolving domain, whose impact extends far beyond the scope of scientific research: a few successes, new challenges and persisting lacunae in nuclear science computing are briefly reviewed, along with a glimpse at developments in other areas.
NSS-42-04  11:01 AM
Questions and Round Table Discussion

NSS-42-05  11:31 AM
Remission of the Best Student Presentation and Poster Awards

NSS-42-06  11:41 AM
Presentation by the 2020 NSS Chair

NSS-42-07  11:56 AM
Closure of the NSS 2019

Cinzia Da Via
The University of Manchester, UK
M-14 | Medical Imaging Systems II

Lefteris (Eleftherios) Livieratos
Roger R. Fulton (Sydney)
Lightweight PET calibration source (#1013)

James J. Hamill, Stefan Siegel

Siemens Medical Solutions USA, Inc., Molecular Imaging, Knoxville, USA

Content

Introduction. PET scanners are commonly calibrated with cylindrical sources, about 20 cm in diameter, in which positron-emitting radioactivity is mixed. The sources are heavy and may require massive shielding for storage. In this work we ask if scanner setup can instead be based on hollow, lightweight sources based on small beta sources and positron flight across the air, reducing the shielding requirements, and providing a nearly scatter-free source with negligible photon attenuation.

Methods. Two positron-emitting (beta) sources were created by depositing a 0.7-mm layer of polyurethane resin, containing a total of 42.6 MBq Ge-68 on two copper plates. These were positioned inside a hollow polyethylene cylinder with 21.3 cm outer diameter, 33 cm length and 7 mm wall thickness. The sources were at the cylinder’s two flat ends. Depending on the positrons' direction after beta decay, the positrons either stopped in the beta source or flew across the air until they encountered the cylinder’s walls, causing the emission of annihilation radiation. The cylinder was positioned in an SiPM-based PET/CT scanner. A scan of the cylinder and a time of flight (TOF) calibration were performed.

Results. Fused PET/CT images showed that positrons stopped both in the cylinder's inner wall (33% of all positrons emitted by the source) and in the air inside the cylinder (5%), not including positrons outside the scanner's field of view. Standard software was used to measure 211 ps TOF resolution, comparable to the value derived from traditional extended sources. TOF resolution measurements might be further improved with calibration software designed for this source. A lightweight, hollow, scatter and attenuation-free source is a practical alternative to the current state of the art.

Processing of Compton events in PETALO readout system (#2172)

Dr. Joshua E. Renner¹, Dr. Vicente Herrero-Bosch², Dr. Raul Esteve², Dr. Rafael Gadea², Dr. Ramón J. Aliaga², Dr. Javier Rodríguez², Dr. José F. Toledo², Dr. Francisco Ballester², PhD/MD student Rubén Torres-Curado², Dr. Juan J. Gómez-Cadenas³,⁴, Dr. Paola Ferrario³,⁴

¹ CSIC-UV, Instituto Física Corpuscular (IFIC), Paterna, Spain; ² Universidad Politecnica de Valencia, Instituto de Instrumentación para Imagen Molecular (I3M), Valencia, Spain; ³ DIPC, Donostia, Spain; ⁴ Basque Foundation for Science, IKERBASQUE, Bilbao, Spain

Content
PETALO (Positron Emission TOF Apparatus based on Liquid xenOn) exploits the unique characteristics of liquid Xenon as a scintillator. Its fast time response and high scintillation yield allow for the construction of large area detectors with customizable shape which are required for full body PET scanners. The PETALO continuous detector concept is based on a cylindrical structure with its outer wall covered by a densely packed array of VUV sensitive SiPMs and a layer of liquid xenon acting as scintillator medium. In order to benefit fully from PETALO’s capabilities a readout architecture was designed to handle the large amount of data generated by the detector without degrading timing characteristics. Image compression techniques have been applied to relieve data link speed requirements making readout more affordable in terms of cost and complexity. However the true potential of the continuous detector has not yet not been fully exploited. A deeper processing of the light distribution acquired by the detector could enhance its performance. Monte Carlo analysis of the gamma ray detection process shows a remarkable amount of events that although affected by Compton scattering, introduce a neglectable deviation in final position estimation. In this paper a novel processing technique based on a hardware-implemented neural network inside the readout is presented. This new element provides a quality tagging mechanism which measures the potential position reconstruction error due to Compton scattering during event detection. This information is available in the first stage of the data acquisition system which allows for early rejection of the worst events thus further reducing data traffic. Also reconstructed image quality can be improved by adding a confidence level parameter to the accepted events which can be used during the image reconstruction process.

Simultaneous multi-nuclide in vivo imaging using GAGG-SiPM Compton-PET hybrid camera (#2114)

Mizuki Uenomachi¹, M.Sc./M.A. student Wei Seng Foong¹, Dr. Kenji Shimazoe¹, Prof. Hiroyuki Takahashi¹, Dr. Miwako Takahashi², Dr. Kei Kamada³, Dr. Tadashi Orita⁴

¹ The University of Tokyo, Department of Nuclear engineering and management, Tokyo, Japan; ² National Institute for Quantum and Radiological Science and Technology, Chiba, Japan; ³ Tohoku University, Miyagi, Japan; ⁴ Kavli-IPMU, Chiba, Japan

Content
Positron emission tomography (PET) and single photon emission computed tomography (SPECT) have been widely used for clinical diagnosis. PET can observe metabolic processes and is mainly used to detect cancers by imaging the glucose accumulation. PET detects coincidence of annihilation gamma-rays with an energy of 511-keV, which determines the line of response (LOR) and the location of the tracer. On the other hands, SPECT is used for molecular biological diagnosis. SPECT tracers are single photon emitters. Conventional SPECT imaging restrict gamma-ray incident directions with a collimator and determines the location of tracers in a line. PET and SPECT imaging methods are different in principle. Therefore, PET and SPECT examinations are performed separately. By contrast, simultaneous imaging of PET and SPECT tracers can provide a more accurate diagnosis and also reduce the burden of patients. However, it is difficult to integrate PET and SPECT systems because conventional SPECT imaging requires Pb-based collimation. Another promising method to visualize SPECT tracers is Compton imaging, which is based on Compton scattering kinetics. To realize simultaneous PET and SPECT imaging, we have developed GAGG-SiPM Compton-PET hybrid camera. A detector consists of two layers of a scatter and an absorber to detect events for Compton imaging and PET imaging. In this method, coincidence events of Compton scattering
and photoelectric effect for visualizing SPECT tracers are detected in a scatter and an absorber of each detectors, respectively. On the other hand, coincidence events with an energy of 511-keV for visualizing PET tracers are detected in opposite absorbers. In this research, we demonstrated simultaneous imaging of $^{111}$In (SPECT tracer) and $^{18}$F-FDG (PET tracer) using GAGG-SiPM Compton-PET hybrid camera.

**M-14-04**

## The MRC-SPECT-II System: Preliminary performance evaluation of the second-generation MR-compatible SPECT system (#1749)

**PhD/MD student Elena Maria Zannoni**¹, M.Sc./M.A. student Jiajin Zhang², Prof. Ling-Jian Meng²,¹

¹ University of Illinois Urbana Champaign, Bioengineering, Urbana, USA; ² University of Illinois at Urbana Champaign, Nuclear, Plasma and Radiological Engineering, Urbana, USA

**Content**

Recent years have seen a rapid growth of in vivo multi-modality imaging, including simultaneous nuclear (SPECT and PET) and MR imaging. Hybrid MRI and nuclear imaging modalities (PET/MRI and SPECT/MRI) combine highly sensitive functional imaging capability with an excellent soft-tissue contrast without inducing extra dose like CT, which has great potential for brain studies and oncological applications. While combined PET/MRI has enjoyed rapid progress in the last years, combining SPECT and MRI lags behind, partial because of the technical challenges to integrate SPECT hardware with MR. We are currently developing the second generation of the MR-compatible SPECT (MRC-SPECT-II) system to further advance the capability of this unique imaging platform.

The MRC-SPECT-II system design is based on a compound-eye gamma camera inspired by the natural compound eyes and on high-performance solid-state gamma-ray detectors. The Monte Carlo simulations show that the proposed design can achieve peak geometrical sensitivity of $\sim$0.2% and consistently greater than 0.12% across the central FOV of 4 cm D x 3cm, providing an imaging resolution of 750 μm within the central focal region. The MR-compatible gamma-ray detector used is a 2 cm × 2 cm solid-state detector, divided into 80 × 80 square pixels of 250 μm ×250 μm. Each pixel provides a full energy spectrum in two optional energy ranges, 5-200 keV or 40-600 keV, with an unprecedented energy resolution of 0.76% at 140 keV (Tc-99m) and 1.13% at 364 keV (I-131).

In this presentation we will (a) discuss the research efforts for the development of MR-compatible electronics based on high-resolution solid-state detectors; (b) present in detail the system prototype, including a MR-compatible tungsten collimator based on the Synthetic Inverted Compound geometry produced using rapid additive manufacturing with selective laser melting of MR-compatible tungsten powder and (c) show a preliminary experimental evaluation of the system performance.
A SiPM-Based Clinical MRI-Compatible SPECT Insert (#2259)

Prof. Marco Carminati1,2, M.Sc./M.A. student Ilenia D’Adda2, PhD/MD student Ashley J. Morahan3, PhD/MD Kjell Erlandsson3, PhD/MD Kalman Nagy4, Zoltan Nyitrai4, Miklos Czeller4, Prof. Rosa M. Moresco5, PhD/MD Annarita Savi5, Pieter Van Mullekom6, Prof. Brian F. Hutton3, Prof. Carlo E. Fiorini1,2

1 INFN - Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milano, Italy; 2 Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Italy; 3 University College London, Institute of Nuclear Medicine, London, UK; 4 Mediso Ltd., Budapest, Hungary; 5 San Raffaele Scientific Institute, Milano, Italy; 6 Nuclear Fields, Vortum-Mulleom, Netherlands

Content
The first SiPM-based clinical SPECT ring for brain simultaneous imaging in standard MR scanners has been put into operation after 6 years of development. The static gantry is composed of 20 MRI-compatible γ-detection modules mounting 5 cm × 10 cm CsI(Tl) scintillators for a total of 1440 pixels (targeting a trans-axial FoV of 20 cm). Here we present ultimate hardware solutions, such as enhanced dual cooling, and the results of a preliminary characterization showing 220 kcps max. count rate, 365 cps/MBq sensitivity with the multi-slit-slat collimator, ~17% energy resolution and an extrinsic spatial resolution of ~10 mm in the trans-axial plane.

Acquisition Correction and Reconstruction for a Clinical SPECT/MRI Insert (#2300)

PhD/MD student Ashley J. Morahan1, PhD/MD Kjell Erlandsson1, M.Sc./M.A. student Ilenia D’Adda2, PhD/MD Marco Carminati2, Annarita Savi5, Rosa-Maria Moresco3, PhD/MD Debora Salvado1, PhD/MD Carlo E. Fiorini2, Prop. Brian F. Hutton1

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Content
The INSERT project has overseen the development of the first clinical simultaneous Single Photon Emission Computed Tomography (SPECT) and Magnetic Resonance Imaging (MRI) system. In this work, we have implemented a novel calibration procedure and acquired tomographic images on the complete clinical system. The calibration and image reconstruction procedures are used here to evaluate the system performance capabilities and correct for image inhomogeneity. An analytical function was derived for fitting the sensitivity profiles corresponding to the novel multi-mini-slit-slat collimator. This study solved issues involving incomplete data sets and pixel failure in detectors, by implementing corrections a measure of trans-axial image resolution determined average values of 9.14 mm and 6.75 mm in the radial and tangential directions respectively. The work carried out on the complete system
allowed us to evaluate the feasibility of clinical use of this system and establish improvements in data acquisition and image processing.
M-15 | Data Corrections and Quantitative Imaging Techniques

Elise C. Emond (London)
Adam M. Alessio (East Lansing)
Time-of-flight double scatter simulation for PET (#2501)

Charles C. Watson, Chuanyu Zhou, Jicun Hu

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Content
To further the goal of more accurate multiple scatter correction in PET, we have added time-of-flight (TOF) discrimination capability to our double scatter simulation (DSS) algorithm, using the same approach employed for TOF single scatter simulation (SSS). We present a detailed comparison between the TOF SSS/DSS results and a TOF Monte Carlo (MC) simulation of an asymmetrical phantom. The two calculations are independently normalized by simulated unscattered trues efficiency functions, to make the sinograms consistent with attenuated Radon transforms of the phantom. No cross-scaling between the simulations is used. The SSS/DSS absolutely scaled sinograms agree well with their corresponding MC sinograms in their radial, angular and TOF structure and amplitude. Further, we find that the sum of the SSS and DSS sinograms only slightly underestimates the MC total scatter sinogram, suggesting that single plus double scatter simulation may be an adequate approximation to the total scatter for modern scanners with good energy resolution and a narrow photopeak energy window, reducing the need for scaling the simulated scatter sinogram to measured data. We are currently integrating the TOF DSS algorithm into a clinical reconstruction workflow, and expect to present results for measured phantom and human data in the final paper.

SPECT/CT scatter correction using deep learning: implementation in Y-90 imaging (#1292)

PhD/MD student Haowei Xiang¹, PhD/MD student Hongki Lim¹, Dr. Jeffrey A. Fessler¹, Dr. Yuni K. Dewaraja²

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Content
Since Monte Carlo (MC) scatter estimation is computationally expensive, simpler but less accurate energy window-based estimates are commonly used in clinics. Furthermore, window-based methods are generally valid only for gamma-rays with associated photopeak(s) and not for bremsstrahlung photons where the spectrum is continuous. MC based scatter modeling in Y-90 bremsstrahlung SPECT has demonstrated improved quantitative accuracy, but at the expense of computational complexity. This paper presents a novel deep learning approach for SPECT/CT scatter correction (SC) leveraging MC simulation data of realistic digital phantoms for training. Our deep Convolutional Neural Network (CNN) takes the projections from the SPECT camera and CT-based attenuation map
as input and outputs the scatter estimate for each projection. MC simulation data is needed only during the training process since the network is trained to match the MC scatter estimation. We trained the CNN using mean squared error training loss with 512 projection views from four phantoms and (virtual) patients. Compared with a previous MC based method the new method shortens the scatter estimation time from several hours to about a minute. In testing with a phantom simulation, a clinically relevant liver phantom measurement, and a patient study the OS-EM reconstruction with CNN and MC based scatter estimation showed similar results. The Contrast Recovery in hot spheres with CNN ranged from 0.46 - 0.73 compared with 0.15 - 0.34 without SC for spheres of diameter 8 - 29mm. The coefficient of variation in the uniform region of the liver phantom background, was 0.23, 0.35, 0.36 for no SC, MC SC, and CNN SC respectively. Furthermore, for the digital phantom there was good agreement between reconstruction using CNN and 'true' scatter estimate. To our knowledge, this is the first implementation of deep Neural Network for SPECT SC and is clinically significant because of the short processing time while maintaining accuracy.

M-15-03 4:36 PM

Comparison of Maximum Likelihood and Conventional PET Scatter Scaling Methods On $^{18}$F-FDG, $^{68}$Ga-DOTATATE, and $^{18}$F-Fluciclovine Quantification During Human Imaging (#2181)

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Content

Background: A possible source of error in the most common PET scatter correction algorithms is attributed to scaling the initial scatter distribution to match acquired scattered events. Recently, a maximum likelihood (ML) background scaling (MLBS) method was developed that iteratively estimates scaling factors jointly with activity values.

Objective: To quantify differences between MLBS and two conventional scatter scaling algorithms during human imaging.

Methods: A secondary analysis was performed on subjects injected with $^{18}$F-FDG (N=71), $^{68}$Ga-DOTATATE (N=11), or $^{18}$F-Fluciclovine (N=8) and imaged with time-of-flight (ToF) PET-CT. The scatter distribution was estimated with the single scatter simulation approach. Conventional scaling algorithms included: 1) tail fitted background scaling (TFBS), which scales the scatter to “tails” outside the emission image support, and 2) absolute scatter correction (ABS), which utilizes the initial scatter distribution directly. MLBS consisted of an alternating iterative reconstruction with a ToF Neg-ML activity image update and ML scaling estimation. Scatter corrections were compared using reconstructed images as follows: 1) Normalized relative difference images were generated and maximum values and locations recorded and 2) liver ROIs were drawn to compute mean SUVs.

Results: Bland-Altman plots demonstrated that although the mean is ~0, when comparing MLBS with TFBS, relatively large absolute differences exceeding 20% were noted in 28% of $^{18}$F-FDG subjects. For all tracers, images reconstructed with ABS scatter scaling had higher activity values than those corrected with MLBS. For $^{68}$Ga-DOTATATE, MLBS images showed a median maximum difference of -42% compared to ABS. Mean liver SUVs showed relatively low variability between the scatter corrections.
Conclusions: Reconstructed image quantification with MLBS is similar to TFBS, and differs greatly from ABS, in most exams, but, may be improved in cases where TFBS performance suffers.

M-15-04

A data-driven quality control method for head motion tracking in PET
(#1412)

Chen Sun, M.Sc./M.A. Enette Mae Revilla, M.Sc./M.A. Kathryn Fontaine, PhD/MD Takuya Toyonaga, Dr. Jean-Dominique Gallezot, Dr. Tim Mulnix, Dr. Richard E. Carson, Dr. Yihuan Lu

Yale University, Department of Radiology and Biomedical Imaging, New Haven, USA

Content

Background: In brain PET imaging, head motion reduces image resolution, lowers apparent concentration in high-uptake regions and causes inaccurate parameter estimates in tracer kinetic models. Among all the motion correction methods, real-time hardware-based motion tracking, e.g., Polaris Vicra optical motion tracking system (referred as Vicra), in principle, would yield the highest accuracy in motion correction. However, due to light-reflecting marker fixation issues, i.e., marker permanent displacement or large head motion induced marker wobbling, Vicra may yield suboptimal motion tracking (Vicra failure). Identification of the Vicra failure is challenging, and no existing method can precisely tell when the Vicra failure happens. Without such information, it will be challenging to correct the inaccurate motion tracking information due to Vicra failure.

Methods: In this study, we proposed a data-driven quality control (QC) method for Vicra motion tracking, i.e., to detect Vicra failure using PET raw data itself. The QC method was based on a motion corrected center of tracer distribution (MCCOD), which is a 1D trace which is generated based on the motion corrected PET raw data. We hypothesized that the MCCOD trace would be smooth, i.e., without abrupt displacements, if the information used for motion correction is accurate. We also demonstrated how to use the QC information to improve the motion correction in the final reconstructions. The new QC method was validated using simulation studies and was tested on the real human datasets for multiple tracers on a HRRT PET scanner.

Results and conclusions: The proposed data-driven QC method can effectively detect motion tracking failure. The methods proposed for correcting the tracking failure were shown to be effective. Although the proposed QC method was validated and used for detecting Vicra failure in this study, this method can also be applied to any other rigid motion tracking/estimation methods.
Data-driven respiratory phase-matched attenuation correction without CT (#1567)

PhD/MD student Donghwi Hwang1, PhD/MD student Seung Kwan Kang1, PhD/MD student Kyeong Yun Kim1, Prof. Seongho Seo3, Prof. Hongyoon Choi2, Prof. Jae Sung Lee1,2

1 Seoul National University, Department of Biomedical Sciences, Seoul, South Korea; 2 Seoul National University Hospital, Department of Nuclear Medicine, Seoul, South Korea; 3 Gachon University, Department of Neuroscience, Incheon, South Korea

Content
Respiratory motion is one of the patient factors that degrade image quality and quantitative accuracy of PET. The anatomical mismatch between PET and CT due to different breathing patterns during CT and PET scans also cause artifacts in attenuation correction in PET/CT. Although various approaches have been proposed to mitigate the motion blur and artifacts, they either required external devices or gated-CT. In this study, we propose a deep learning based data-driven respiratory phase-matched gated-PET attenuation correction method without acquiring gated-CT. The proposed method starts from the multi-step processes including data-driven respiratory gating, gated attenuation map estimation using MLAA, and enhancement of the gated attenuation maps using CNN. Using the gated MLAA attenuation maps enhanced by CNN, we could reconstruct phased-matched attenuation corrected gated PET images. Robust estimation of motion vector field required for generating motion-free static PET images was also possible using the high-quality MLAA attenuation maps enhanced by CNN.

The attenuation corrected gated and motion-free static PET images generated using the proposed method showed sharper organ boundaries and better noise characteristics than conventional gated and static PET images. In conclusion, we have developed a deep learning based data-driven respiratory phase-matched attenuation correction method which results in improved PET image quality and reduced motion artifacts.

PCA regression for continuous estimation of head pose in PET/MR (#2677)

Ashley G. Gillman1,2, PhD/MD Alaleh Rashidnasab3, PhD/MD Richard Brown3, PhD/MD Nicholas Dowson4, PhD/MD Benjamin Thomas3, Francesco Fraioli2, Prof. Stephen Rose1,2, Prof. Kris Thielemans3

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With the availability of improved hardware and local point-spread function modelling, the presence of patient motion has become a major barrier to further improvements in the quality of PET images and their clinical efficacy. Although numerous approaches to compensate for patient motion have been proposed and are even commercially available, the additional hardware and extended setup time can preclude their routine clinical use. The magnetic resonance (MR) modality on combined PET and MR scanners can be used to correct motion with almost no additional setup time but currently must replace other MR acquisitions that may be required for clinic use. To overcome these problems, principal component analysis (PCA) and other data-driven techniques have been demonstrated to be able to reliably provide a signal related to patient motion based on raw PET data. Typically, these signals are used to split the PET acquisition into a discrete set of approximately motion-free time segments. This work introduces an approach where the PCA-signals are used as direct surrogates for the motion and regressed against rigid head motion parameters, enabling continuous pose estimation. A proof-of-concept is presented in which the approach is applied to upsample a low temporal resolution MR motion estimate. This proof-of-concept uses rapid echo planar imaging (EPI) data together with PET-derived motion signals. In a comparison of four techniques, nearest neighbour (NN) and linear temporal interpolation and linear and radial basis function (RBF) regression of pose against the PCA surrogate, we demonstrate that the model can be used to accurately interpolate pose continuously throughout the scan.
MIC-16 | High-Resolution Application-Specific Imaging Systems II

Sun Il Kwon (Davis)
Scott D. Metzler (Philadelphia)
High-Resolution SPECT with a Flat Panel Detector and Detailed Collimator Modeling (#1511)

M.Sc./M.A. Martijn M. A. Dietze, Dr. Wilco J. C. Koppert, Prof. Hugo W. A. M. de Jong

University Medical Center Utrecht (UMCU), Radiology and Nuclear Medicine, Utrecht, Netherlands

Content

**Purpose:** Detectors with high intrinsic spatial resolution (e.g. CZT modules) have had few implementations in SPECT because the required collimator normally limits the reconstruction resolution. We propose to use a flat panel detector (308 µm pixel size) for SPECT imaging and incorporate the detailed collimator response in the reconstruction algorithm to overcome this limitation. The purpose of this study is to illustrate the feasibility of nuclear imaging with a flat panel detector and to evaluate the expected SPECT reconstruction quality.

**Methods:** A parallel-hole collimator (29.1 mm hole length, 2.49 mm inner diameter, and 0.50 mm septal thickness) was positioned directly in front of a commercially available flat panel detector. This experiment set-up was also modeled in GATE and the profiles of the experiment and the simulation were compared. A simulation study compared SPECT reconstructions from the flat panel detector with those obtained from a conventional gamma camera. Spatial resolution was assessed by identification of the spheres in the Jaszczak phantom. Reconstructions were performed with and without detailed collimator model to study its impact.

**Results:** The collimator structure could be distinguished in the profile obtained with the experiment. The profile obtained from the simulation accurately compared to the profile from the experiment. The simulation study showed that the incorporation of the detailed collimator response was required to retrieve high resolution SPECT reconstructions from the flat panel detector. The spheres of 4.8 mm in diameter of the Jaszczak phantom could be distinguished with the flat panel detector, whereas this was not possible with the conventional gamma camera.

**Conclusion:** Nuclear imaging with a flat panel detector is feasible. High resolution reconstructions are obtained from a flat panel detector, provided that the detailed collimator response is incorporated in the reconstruction algorithm.
Self-collimating emission tomography with multi-layer interspaced mosaic detectors (#1979)

Dr. Tianyu Ma\textsuperscript{1}, Dr. Qingyang Wei\textsuperscript{3}, PhD/MD student Debin Zhang\textsuperscript{1}, Dr. Zhenlei Lyu\textsuperscript{1}, Dr. Tianpeng Xu\textsuperscript{1}, PhD/MD student Hongyang Zhang\textsuperscript{1}, PhD/MD student Rui Wang\textsuperscript{3}, Dr. Rutaoy Yao\textsuperscript{4}, Dr. Jiahong Dong\textsuperscript{2}, Dr. Yaqiang Liu\textsuperscript{1}, Dr. Zuo-Xiang He\textsuperscript{2}

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Content

Emission tomography, including single photon emission computed tomography (SPECT) and positron emission tomography (PET), is a powerful technology that can quantitatively image molecular level biological processes deep within a living body with sub-nanomolar sensitivity. However, a key element of the existing emission tomography systems, photon collimation, suffers fundamental limitations that handicap the performance of emission tomography: the mechanical collimation in SPECT forces a compromise between spatial resolution and detection efficiency, and the electronic collimation in PET is subject to the uncertainties of positron physics. Here we propose a novel collimation strategy termed self-collimation and implement it with a new multi-layer interspaced mosaic detectors (MATRICES) architecture. With MATRICES, the detectors on an outer layer, farther from the imaging object, collect gamma photons collimated by the inner layer detectors instead of physical collimators. Only the innermost layer detectors use a metal layer with apertures for collimation. Theoretical analysis, Monte Carlo simulations and proof-of-concept experiments have confirmed the advantages of this strategy. With a 3-detector-layer MATRICES, a simulated human brain SPECT achieves 0.5 mm resolution at 3.88% efficiency, and the system’s resolution is verified experimentally; A simulated mouse SPECT achieves 50 μm resolution at 1.25% efficiency. These performance levels are at least 5 times higher than their best counterparts reported in the literature. The self-collimating approach is generally applicable to gamma photons over a broad energy range, giving it the ability to image both SPECT and PET tracers. This work paves the way to the development of a new generation of emission tomography technology that will further advance molecular imaging applications.
Development and Initial Characterization of 7T MR-compatible Human Brain PET Insert (#1444)

Haewook Park¹,², Jun Yeon Won¹,², Seungeun Lee¹,², PhD/MD student Jeong-Whan Son³, PhD/MD student Guen Bae Ko³, Kyeong Yun Kim³, Yina Chung³, PhD/MD Seongho Seo⁴, Prof. Jae Sung Lee³,²

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Content

Previously, we developed an initial prototype brain PET scanner and obtained a good image quality of 2D Hoffman brain phantom. However, the initial prototype was not MR-compatible and had limited axial coverage of 2.6 cm. Therefore, we have newly developed the second prototype brain PET insert that has a long axial FOV of 16.7 cm and is compatible with a 7T whole-body MRI scanner. Our second prototype brain PET insert is assembled with 18 sectors, featuring a maximum axial coverage of 22.4 cm and a bore size of 33.0 cm. The block detector consists of a dual-layer staggered LSO crystal block coupled with a 2×2 array of 16-channel SiPMs (S13361-3050NE-04, HPK). The upper crystal-layer was an 11×11 array of 2.09×2.09×8 mm³ crystals, and the lower crystal-layer was a 12×12 array of 2.09×2.09×12 mm³ crystals. In analog front-end boards, the anodes of 8×8 SiPMs were multiplexed into four position signals based on a resistive charge division circuit and the common-cathode was fed into a high-speed amplifier and an LVCMOS comparator to generate a timing signal. The FPGA DAQs that include 64 energy and 16 timing channels subsequently digitized all the output signals from the 16 block detectors. For RF screening, each sector was individually shielded using a trapezoidal copper box fabricated using a 2-layer PCB that has a copper-thickness of 18 μm with staggered-slits on both sides. Within the RF shield box, the major heat sources were directly coupled with copper heat pipes via thermal pads; and subsequently, the copper heat pipes were connected to an ethyl-alcohol-based air-cooled chiller via aluminum heat sinks to perform liquid cooling of the PET system. During the conference, we will introduce our new brain PET insert and present the detector performances, MR-compatibility, cooling efficiency, phantom images, and so on.
Performance Evaluation of a Digital Brain PET Based on the Plug&Imaging Technology (#1960)

PhD/M.D student Emanuele Antonecchia\textsuperscript{1,2}, Prof. Nicola D'Ascenzo\textsuperscript{1,2}, PhD/MD student Min Gao\textsuperscript{1}, M.Sc./M.A. student Marvin Kuhn\textsuperscript{3,2}, Weidong Wang\textsuperscript{4}, Chien-Min Kao\textsuperscript{5}, Xiangsong Zhang\textsuperscript{6}, Shihao Liu\textsuperscript{7}, Bo Zhang\textsuperscript{7}, Lingli Yang\textsuperscript{7}, Prof. Qingguo Xie\textsuperscript{1,2}

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Content
This paper describes the Plug&Imaging (P&I) sensor technology used to assemble a novel digital brain PET scanner, then the evaluation methods and the results of its performances. The peculiar advantage of P&I is the fast electronics readout, which enables a signal digitisation free of significant fractional dead time, favoring the acquisition of huge datastreams even from low radioactivity inlets. As opposed to conventional PET systems, the P&I allows to record all prompts widening the margins of image optimization. One P&I unit consists in 72 LYSO/SiPM channels (pitch 4.2 mm, coupling 1:1) served by a printed circuit board that provides the voltage for the signal sampling. The sampling electronics is based on the Multi Voltage Threshold (MVT) logic: the signal is digitised by individuating 8 reference points (time vs. voltage) to record. The signal is offline reconstructed fitting the 8 points and treated as conventional.

On the basis of the P&I technology, we built a brain PET prototype consisting of a cylindrical scanner with a 375 mm diameter and a 201.6 mm axial length, assembled using 176 P&I units. The performance evaluation has been done according to the standard protocols described by NEMA NU 2. The count rate test evidences a maximal noise equivalent count rate (NECR) of 73 kcps for a 6.57 kBq/ml activity. The sensitivity test indicates 52.94 cps/kBq (5.84% absolute sensitivity) as the peak value in a 20 mm interval around the Field Of View (FOV) centre. The spatial resolution test shows a constant axial value of 1.8 mm, while radial and tangential resolution from 1.8 mm at FOV centre degrade towards the scanner edges. Such performances define a highly competitive scanner with the state-of-the-art brain PET machines. In particular we appreciate an increased sensitivity and NECR for low radioactivity, mainly due to the MVT logic that offers a prompts readout electronics 2-3 times averagely higher.
**MIC-16-05**

**Preliminary Evaluation of the BiPlanar Breast PET** (#2445)

**Dr. Laura Moliner**¹, M.Sc./M.A. Jorge Alamo², M.Sc./M.A. Constantino Morera², M.Sc./M.A. Santiago Jiménez-Serrano², M.Sc./M.A. Vicente Cutanda², M.Sc./M.A. Javier Cuallado², PhD/MD Michel Herranz³, Dr. Maria Jose Rodríguez-Álvarez¹, Dr. Victor Ilisie¹, Dr. Jose Maria Benlloch¹

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*Content*

In this work we present the BiPlanar Breast PET (BBPET) system. It is composed of two movable pallets than can be placed in several configurations in order to allow the imaging of the breast and the pectoral wall. Each pallet is formed by several continuous crystals detectors coupled to SiPM arrays. The system has been evaluated measuring the spatial resolution, NECR, uniformity and contrast coefficients. The results show a transaxial resolution of 1.5mm, a NECR peak of 319kcps at 12.6MBq, a uniformity of 10% and recovery coefficients >0.7 for the 3, 4 and 5mm rods. The system has good imaging capabilities for imaging patients in the clinical routine.

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**MIC-16-06**

**Test Results for a Dual-detector Gamma Camera with a Variable Angle Slant-hole Collimator** (#1299)

**Dr. Seungjoon Lee**¹, Dr. Andrew Weisenberger¹, Dr. Benjamin Welch²

¹ Thomas Jefferson National Accelerator Facility, Nuclear Physics, Newport News, USA; ² Dilon Technologies, Newport News, USA

*Content*

We have developed a computer controlled motorized variable angle slant-hole (VASH) collimator for a molecular breast imaging detector. The VASH collimator enables the acquisition of multiple projections without detector movement and provides limited 3D image reconstruction. The range of collimation angle of the current VASH collimator is 28 degrees for each direction which is 15 % of 360 degree full scan. Due to this limited angular sampling range, vertical image resolution is poor compare to horizontal image resolution. To reduce this drawback, we are developing dual-detector using two VASH collimators. The dual-detector camera system is expected to have more sensitivity and better resolution. Initial tests were performed with a gamma camera and an additional virtual camera to simulate a dual-detector system. Test results show significant improvement in terms of image resolution and quality.
MIC-17 | Imaging in Radiotherapy, Proton and Hadron Therapy

Chiara Gianoli (Garching)
Akram Mohammadi (Chiba)
Three-dimensional (3D) dose distribution measurements of proton beam using a glass plate (#1319)

Ryo Horita, Prof. Seiichi Yamamoto, Dr. Katsunori Yogo, Dr. Masataka Komori, Dr. Toshiyuki Toshito

Nagoya University, Graduate School of Medicine, Nagoya, Japan

Content

The measurements of the three-dimensional (3D) dose distribution of proton beams in water are critical for proton therapy for quality assessment (QA). Although ionization chambers are commonly used for this purpose, such measurements take a long time to calculate precise 3D dose distribution. To solve this problem, we measured 3D dose distributions using a glass plate. We placed a 1-mm thick float glass plate on the upper inside of a black box with a water tank set above the float glass plate outside the black box and irradiated the proton beam to the water tank from the upper side. The attenuated proton beam by water in the tank was detected by the float glass plate and a scintillation image was formed in the plate. The image was reflected by a first-surface mirror set below the float glass plate and detected by a cooled charge-coupled device (CCD) camera from the side. We changed the water depths in the tank and measured the scintillation images at each depth. Then we calculated the 3D scintillation images from the measured images by stacking them in the depth direction. Measurements were made for 71.2- and 100-MeV proton pencil beams and a spread-out Bragg peak (SOBP) using the imaging system. From the images, we successfully formed 3D scintillation images without quenching. The depth profiles measured from the scintillation images showed almost identical distribution with those measured by the ionization chamber within a maximum difference less than 5%. The lateral profiles were also almost identical within width differences less than 2 mm. We conclude that our proposed method is promising for the 3D dose distribution measurements of proton beams.

A 100 ps TOF detection system for on-line range-monitoring in hadrontherapy (#1556)

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Content
Online Range monitoring is crucial to increase the precision of treatment delivery in hadrontherapy. This work describes the development of a TOF-resolved (time-of-flight) Prompt Gamma (PG) imaging system with 100 ps time resolution. The system consists of a diamond-based beam hodoscope for single proton tagging, operated in time coincidence with one or more gamma detectors placed downstream of the patient. The TOF between the proton trigger in the hodoscope and the PG trigger provides an indirect measurement of the proton range in the patient with a precision strictly related to the system time resolution. We already developed a single channel version of this detector based either on BaF$_2$ or LaBr$_3$ scintillators of large volume (~38 cm$^3$). The detector was tested using 68 MeV protons impinging on a heterogeneous PMMA target with an air insert of variable size. From the PG TOF spectra we were able to detect the position and width of the air insert: with this approach a 3 mm shift can be detected at 2s within a single irradiation spot (~10$^8$ protons). For the BaF$_2$ we obtained a coincidence time resolution of 102 ps σ. We are conceiving a multi-channel version of our system consisting of ~30 pixel detectors of reduced size surrounding the target region. Knowing the PG hit position and time of arrival it is possible to reconstruct analytically the longitudinal PG vertex on an event-by-event basis. The center of gravity of the hit detectors provides the vertex coordinates in the transverse plane. We are currently studying the expected performances of this detector through Monte Carlo simulation. At the same time, we are testing different technologies for the pixel detector (standard scintillators or Cherenkov radiators coupled to Silicon PM). We will present the experimental performances in terms of range shift sensitivity of our single channel detector, as well as the expected performances of the 3D system as obtained from Monte Carlo simulations.

**Uncertainty Limits of Range Verification in Proton Therapy by Means of Prompt Gamma-Ray Timing (PGT) (#1737)**

Theresa Werner$^{1,3}$, Dr. Toni Koegler$^{1,3}$, Felicia F. Permatasari$^3$, Dr. Johannes Petzoldt$^4$, Katja E. Roemer$^2$, Dr. Andreas Wagner$^2$, Prof. Wolfgang Enghardt$^{1,6}$, Dr. Guntram Pausch$^{1,3}$

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**Content**

Range verification in clinical treatments could improve the precision and safety of proton therapy. In spite of a breakthrough in prompt gamma-ray imaging achieved with IBA’s knife-edge slit camera there are ongoing activities to develop alternative systems distinguished by lower expense, lower weight, easier integration in the therapy facility, and potentially higher precision. In this context OncoRay’s Prompt Gamma-Ray Timing (PGT) method has been further explored with the focus on quantifying uncertainty contributions in potential clinical applications. Besides the limited number of events, the instable phase relation between proton-beam bunches and accelerating RF turned out to be the weakest point, at least in the given facility. This phase relation must be monitored at a time scale of split seconds. If corresponding means are available, PGT could provide range verification with 2-3 mm accuracy at PBS.
spot level, supposed that eight PGT detection units are deployed. Technically even a larger number of detectors could be arranged around the nozzle, which would further reduce the uncertainty.

**Experimental quantification of the relative biological effectiveness of radioactive heavy ion beams** (#1424)

**PhD/MD student Andrew Chacon**1,3, Dr. Akram Mohammadi2, Dr. Abdella M. Ahmed3, Dr. Go Akamatsu2, Dr. Yuma Iwao2, Dr. Soudai Takyu2, Dr. Fumihiko Nishikido2, Dr. Lachlan Chartier3, Dr. Thuy L. Tran1,3, PhD/MD student Benjamin James1, Dr. Dale Prokopovich3, Dr. Daniel R. Franklin4, Dr. Hideaki Tashima2, Dr. Susanna Guatelli1, Prof. Taiga Yamaya2, Prof. Anatoly Rosenfeld1, Dr. Mitra Safavi-Naeini3,1

1 University of Wollongong, Centre for Medical Radiation Physics, Wollongong, Australia; 2 National Institutes for Quantum and Radiological Science and Technology, National Institute of Radiological Sciences (NIRS), Inage-ku, Japan; 3 The Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia; 4 University of Technology Sydney, School of Electrical and Data Engineering, Sydney, Australia

Content

The use of positron-emitting radioactive isotopes for heavy ion therapy has been proposed as a means to increase the number of annihilation photons available for Positron Emission Tomography (PET)-based quality assurance (QA) imaging. The particle stopping point itself, which highly correlates to point of maximum dose, can be directly obtained from PET images with the use of these isotopes. An important step for clinical realisation of this idea is to evaluate the relative biological effectiveness (RBE) of the positron-emitting radioactive heavy ions and compare them to those of the corresponding stable nuclides. In this study, the RBE at 10% survival of two positron-emitting radioactive beams, $^{11}$C and $^{15}$O, and their corresponding non-radioactive isotopes $^{12}$C and $^{16}$O, were experimentally evaluated by measuring microdosimetric lineal energy deposition using a silicon-on-insulator mushroom microdosimeter. It was found that the RBE$_{10}$ of the radioactive beams were statistically indistinguishable from their respective stable counterparts in each of the entrance, Bragg peak and tail regions. The microdosimetric dose-mean lineal energy, $y_D$ was also evaluated for each ion species, with multiple measurements made along the path of the beam, and post-irradiation PET images were acquired and compared between the radioactive and stable beams, demonstrating the greatly improved signal to noise ratio (SNR) which can be achieved with positron-emitting radioactive ion beams.
Radiation Therapy Induced Changes to Biological Washout of Proton-Produced PET Isotopes (#1871)

PhD/MD Kira Grogg1, PhD/MD Xuping Zhu1, PhD/MD Helen Shih2, PhD/MD Nathaniel Alpert1, PhD/MD Georges El Fakhri1

1 Massachusetts General Hospital, Gordon Center for Medical Imaging, Boston, USA; 2 Massachusetts General Hospital, Radiation Oncology, Boston, USA

Content
Proton therapy naturally generates positron emitting isotopes from nuclear interactions of protons with tissue. These positron emitting isotopes can be imaged using positron emission tomography (PET) and is being investigated to assess the accuracy of radiation dose placement. Efforts have been made to correct for biological washout of the isotopes before and during imaging to adjust simulations of the images or recover the original distribution. As a secondary consequence of this method, we also obtain measures of the biological washout rate. We hypothesize that the washout rate of isotope from tissue changes over the course of treatment in response to the radiation therapy effect on tissues, mostly as a result of changes in vascularization. Dynamic PET images were acquired shortly after treatment of 2 Gy in 10 brain and head & neck patients. The imaging was repeated during a second fraction at least 3 weeks later. Eight patients received the same set of treatment fields. A kinetic model was applied to the dynamic PET images to obtain biological washout factors. Washout from early-in-treatment images was compared to that from late-in-treatment images for a select set of tissue types. We found statistically significant changes in some patients and tissue types, but no consistent trends were found in the preliminary dataset. Additional patients and analysis will help illustrate any consistent trends in washout changes in the cranium, which can also be potentially be correlated outcome and side effects.

Using a TRAPS Upstream Transmission Detector to Verify Multileaf Collimator Positions during Dynamic Radiotherapy Delivery (#2417)

Dr. Lana Beck1, Dr. Jaap J. Velthuis1,4, Jackie Haynes2, Sally Fletcher2, Dr. Richard P. Hugtenburg3, On behalf of the TRAPS collaboration

1 University of Bristol, Physics, Bristol, UK; 2 University Hospitals Bristol NHS Foundation Trust, Bristol Haematology and Oncology Centre, Medical Physics & Bioengineering, Bristol, UK; 3 University of Swansea, Medicine, Swansea, UK; 4 University of South China, School of Nuclear Science and Engineering, Hengyang, China

Content
The advancement of radiotherapy treatments towards higher precision, higher dose rates and higher energies necessitates new means of monitoring treatments to detect errors. Here we propose using Monolithic Active Pixel
Sensors (MAPS) to monitor dynamic treatments in which the linear accelerator’s multileaf collimators are continuously moving. We use the TRAPS system consisting of the Achilles sensor, DAQ and custom firmware. The Achilles has been shown to have an attenuation of $1.04 \pm 0.03\%$, where a 1% attenuation is the benchmark for clinical use. As a significant proportion of the silicon in the sensor is there for support, it can be thinned significantly, reducing the attenuation. Hence it is possible to have the TRAPS system present for all treatment fractions. Comparison of the measurements from the TRAPS to the treatment planning system could result in automatic halting of the treatment if a deviation from the plan were to occur. We show that it is possible to track leaves with speeds up to 3.5 cm/s and that leaf position errors as small as 0.5 mm can be detected.
MIC-18 | Deep Learning and Computational Intelligence Techniques for Image Analysis

Joyita Dutta (Lowell)
Kyungsang Kim (Boston)
3D convolutional adversarial micro-networks for low count PET-MR post-processing (#1148)

Casper O. da Costa-Luis, Prof. Andrew J. Reader

King’s College London, School of Biomedical Engineering and Imaging Sciences, London, UK

Content
In positron emission tomography (PET), decreasing patient radiation exposure or scan time leads to a reduction in acquisition counts and noisy reconstructed images. Common approaches such as post-smoothing (PS) and total variation (TV) de-noising can help reduce noise at the cost of resolution or bias, respectively. However, recent advances in convolutional neural networks (CNNs) have led to promising results in low count PET. Some of these can take advantage of jointly acquired data from other modalities such as magnetic resonance (MR). However, there are many considerations when designing an architecture depending on the specific task and data available. This work compares some of the current state-of-the-art approaches. Results demonstrate that more powerful, complex networks do not necessarily yield better performance. Normalised root means squared error (NRMSE) is decreased by 85.5% compared to standard maximum likelihood expectation maximisation (MLEM) PET reconstruction by using a 3-layer linear micro-network on very low (3.01M) count simulation data. This compares to reductions of 80.2% and 85.3% when total variation (TV) and adversarial discriminator losses are incorporated, respectively. Using both TV and a discriminator produces a slightly better whole-brain NRMSE reduction of 86.0%, though with a risk of false positive lesions. This indicates that more investigation is required to determine general rules for choosing architectures and hyperparameters for low count PET.

Self-Supervised Super-Resolution PET Using Generative Adversarial Networks (#1924)

PhD/MD student Tzu-An Song¹, Dr. Samadrita R. Chowdhury¹, PhD/MD student Fan Yang¹, Prof. Joyita Dutta¹,²

¹ UMass Lowell, Electrical and Computer Engineering, Lowell, USA; ² Harvard Medical School and Massachusetts General Hospital, Gordon Center for Medical Imaging, Boston, USA

Content
Resolution limitations pose a continuing challenge for PET quantitation. While deep learning architectures based on convolutional neural networks (CNNs) have produced unprecedented accuracy at generating super-resolution (SR) PET images, most existing approaches are based on supervised learning. The latter requires training datasets with paired (low- and high-resolution) images, which are often unavailable for clinical applications. In this paper, we present a self-supervised SR (SSSR) technique for PET based on dual generative adversarial networks (GANs),
which obviate the need for paired training data, ensuring wider applicability and adoptability. Our network receives as inputs a low-resolution PET image, a high-resolution anatomical MR image, and spatial information. An imperfect SR image generated by a separately-trained auxiliary CNN serves as an additional input to the network. This CNN is trained in a supervised manner using paired simulation datasets. The loss function for training the dual GANs consists of two adversarial loss terms, a cycle consistency term, and a total variation penalty on the SR image. The method was validated on clinical data by comparing the SSSR results with those generated from a supervised approach and from deconvolution stabilized by a total variation penalty. Our results show that SSSR, while weaker than its supervised counterpart, noticeably outperforms deconvolution as indicated by the peak signal-to-noise-ratio and structural similarity index measures.

**MIC-18-03  10:56 AM**

**Low-Dose CT Image Denoising Using Cycle-Consistent Adversarial Networks** (#1937)

Zeheng Li¹, Dr. Junzhou Huang¹, Dr. Lifeng Yu², Dr. Mingwu Jin³

¹ University of Texas, Arlington, Computer Science, Arlington, USA; ² Mayo Clinic, Radiology, Rochester, USA; ³ University of Texas, Arlington, Physics, Arlington, USA

**Content**

Computed tomography (CT) has been widely used in modern medical diagnosis and treatment. However, ionizing radiation of CT for a large population of patients becomes a concern. Low-dose CT is actively pursued to reduce harmful radiation, but faces challenges of elevated noise in images. To address this problem and improve low-dose CT image quality, we develop an image-domain denoising method based on cycle-consistent adversarial networks (CycleGAN). Different from previous deep learning based denoising methods, CycleGAN can learn data distribution of organ structures from unpaired full-dose and low-dose images, i.e. there is no one-to-one correspondence between full-dose and low-dose images. This is an important development of learning-based methods for low-dose CT since it enables the model growth using previously acquired full-dose images and later acquired low-dose images from different patients. As a proof-of-concept study, we used the NIH-AAPM-Mayo Clinic Low Dose CT Grand Challenge data to test our CycleGAN denoising method. The results show that the proposed method not only achieves better peak signal-to-noise ratio (PSNR) for quarter-dose images than non-local mean and dictionary learning denoising methods, but also preserves more details reflected by images and structural similarity index (SSIM). Future work will focus on optimizing the network structures of CycleGAN with more image samples and comparing it with other deep-learning based denoising methods.
PET Image Noise Reduction Learning from Noisy Labels (#1942)

**Dr. Chih-Chieh Liu**, Prof. Jinyi Qi

*University of California, Davis, Department of Biomedical Engineering, Davis, USA*

**Content**

Deep neural network (DNN) has been proposed to enhance PET signal-to-noise ratio (SNR). While the standard way to train a DNN requires noise-free images as the label, it has been shown that a DNN can be trained using noisy labels. The objective of this work is to evaluate the performance of a DNN trained using noisy labels for PET image denoising compared with the same network trained with noise-free labels. Twenty normal brain phantoms were used to generate noisy PET data with Poisson noise at various count levels ranging from 5 to 200 million. Two independent identically distributed realizations of the noisy PET data were generated for preparing training inputs and labels. The PET images were reconstructed using the maximum likelihood expectation maximization (MLEM) with 50, 100, 150 and 200 iterations. The noisy images were used to train an U-net DNN. The U-net was also trained with the noise-free images as labels for comparison. The mean squared error (MSE) between the network predictions and noise-free PET images was calculated for performance evaluation. The results show that the U-net trained with noisy data achieved comparable performance to the U-net trained with noise-free labels with a less than 0.15 increase in MSE. The higher the count level of the training data is, the less the MSE reduction would be in the predictions. For example, the MSE was reduced by 90.4% and 92.3% from the noisy inputs for 50th and 200th iteration counts at 5 million count level, respectively, while the reductions were 55.6% and 70.9% at 200 million count level. By converting the MSE results to equivalent count levels, we found that in many cases, it is beneficial to divide existing data into two independent lower count realizations and perform N2N training to improve the image quality over the original scan.

Use of Ensembles in Deep Learning Based PET Image De-noising (#1832)

**Dr. Scott D. Wollenweber**, Dr. Tyler J. Bradshaw

1 GE Healthcare, MICT Engineering, Waukesha, USA; 2 University of Wisconsin Madison, Radiology, Madison, USA

**Content**

Image quality in radionuclide imaging is limited by system sensitivity, administered dose, and imaging time - all of which contribute to the noise properties of resulting images. This work investigates the use of deep learning (DL) based de-noising for PET images in the case of 4x shorter scan duration. A typical approach is to train a DL model with random initialization of weights, then apply the trained model to similar data for inference. In this work, ensembles of 10 models were trained for PET image de-noising where the models differed only in the randomization of the input data and initial weights. A set of 38 PET/CT studies were used – 30 for training and validation and 8 for independent
testing. Each study consisted of 3 bed positions and 6 min/bed acquisition. Scans were split into 1.5 min/bed acquisitions as input to training. In the 8 independent datasets, 29 tracer-avid features were defined for comparison. Mean of the ensemble results and standard deviation across the ensemble outputs were generated and compared to the input (short-duration) and target (long-duration) images for feature SUV, liver bias and liver noise. Further, the ensemble standard deviation image was compared to the standard deviation image computed from the four 1.5 min/bed images.

**Results:** On average, the quantitative results using the ensemble approach show a ~55% reduction in noise compared to the ¼-duration images accompanied by a 15-20% lower feature SUV\(_{\text{max}}\). The percent standard deviation of feature SUV\(_{\text{max}}\) across the ensemble was on average ~5% for both DL models. An advantage of the ensemble approach included understanding what if any additional variation resulted from model fit initialization, providing a sense of where in the de-noised images the results are most robust.

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**MIC-18-06**

**Identification of pathological mediastinal lymph nodes in lung cancer patients: a PET/CT radiomic analysis involving handcrafted and deep features** (#2086)

**PhD/MD student David Wallis**, Dr. Irene Buvat, Dr. Michael Soussan, PhD/MD student Maxime Lacroix

*CEA, Inserm, Univ Paris Sud, CNRS, Université Paris Saclay, Imagerie Moléculaire In Vivo, Orsay, France*

**Content**

The detection of pathological mediastinal nodes in lung cancer patients is of importance for both staging and deciding whether to perform surgery. We investigated radiomic models to replace the visual and time consuming detection as currently performed by radiologists/nuclear medicine physicians using PET/CT scans. Both handcrafted radiomic features and features from a convolutional neural network (CNN) were studied. These feature sets were tested individually and in combination. Features were calculated in 3D-PET/CT cubes at 3 different scales (20mm, 30mm, 50mm cube side length). Our results show a significant difference between the handcrafted and CNN features only at the 50mm scale (AUC 0.77 v 0.82, PPV 0.25 v 0.31, Sensitivity 0.60 v 0.64). The combined feature sets perform better than using the handcrafted or CNN features individually (at 50mm AUC 0.86, PPV 0.44, Sensitivity 0.76). A multi-scale model including features from the 3 cube sizes performed better than the features at individual scales (PPV 0.64, Sensitivity 0.82). These results are a promising first investigation into automated detection of mediastinal nodes. They show the value that can be gained from using both handcrafted and CNN based features at different scales.
MIC-19 | Emerging Applications of PET, SPECT and X-ray Techniques

Ling-Jian Meng (Urbana)
Marco Carminati (Milano)
A PET/EPR simultaneous imaging system for assessing tumor hypoxia: development and initial imaging results (#1265)

Dr. Heejong Kim1, Dr. Boris Epel2, Subramanian Sundramoorthy2, Dr. Hsiu-Ming Tsai1, Eugene Barth2, Dr. Howard Halpern2, M.Sc./M.A. Yuexuan Hua4, Dr. Qingguo Xie3, Dr. Chin-Tu Chen1, Dr. Chien-Min Kao1

1 University of Chicago, Department of Radiology, Chicago, USA; 2 University of Chicago, Department of Radiation and Cellular Oncology, Chicago, USA; 3 Huazhong University of Science and Technology, Biomedical Engineering Department, Wuhan, China; 4 Raycan Technology Co., Ltd, Suzhou, China

Content

We present a combined imaging system of positron emission tomography (PET) and electron paramagnetic resonance imaging (EPR) developed for assessing tumor hypoxia. Tumor hypoxia has been known to be resistant for cancer treatment such as radiation therapy. Therefore, precise quantitative measurement of tumor hypoxia is important for effective cancer treatment planning in radiation therapy. In clinic, PET imaging by using 18F-fluoromisonidazole (F-MISO) have been performed to delineate tumor hypoxia. However, the effectiveness of PET imaging based hypoxia targeting in radiation therapy was not yet firmly established. EPR is a non-invasive imaging method capable of measuring the partial pressure of oxygen (pO2) in tissue precisely. However, EPR is not available for clinical use currently. The combined imaging system is to use EPR as a gold standard to measure the pO2 in hypoxic tumor in animal, and aims to evaluate the validity of PET imaging in tumor hypoxia by simultaneously acquired EPR. The PET component of the combined system, which was originally developed as an insert for MRI, consists of total 14 detector modules. Each PET detector module uses of 8x4 LYSO arrays (3x3x10 mm3) coupled to Hamamatsu S13361 MPPC arrays (3.2 mm pitch). The detector modules are encased in a cylindrical plastic holder with 60 mm inner diameter and 115 mm outer diameter in a ring configuration. The axial field of view of the PET is 25.6 mm. The EPR component of the system is built with two permanent magnets (25 mT), three gradient field coils for spatial encoding (the maximum 15mT/m) and a RF resonator. The PET is installed to fit into the two EPR magnets (12 cm distance apart) so that the PET detector center is aligned to the magnet center. The compatibility of two imaging modalities were tested by using a 22Na point source and imaging phantoms. Animal imaging with F-MISO and FDG were also performed by running the PET/EPR simultaneously. Initial imaging results are reported.
MIC-19-02

Whole gamma imaging of $^{89}$Zr-injected mouse: comparison of PET and Compton imaging (#2248)

Dr. Hideaki Tashima¹, Dr. Eiji Yoshida¹, Hidekatsu Wakizaka¹, Dr. Miwako Takahashi¹, Dr. Kotaro Nagatsu¹, Dr. Atsushi Tsuji¹, Dr. Kei Kamada², Prof. Katia Parodi³, Dr. Taiga Yamaya¹

¹ National Institutes for Quantum and Radiological Science and Technology (QST), National Institute of Radiological Sciences, Chiba, Japan; ² C&A Corporation, Sendai, Japan; ³ Ludwig-Maximilians-Universität München, Garching, Germany

Content

Whole gamma imaging (WGI) is our original idea to combine PET imaging and Compton imaging by inserting a scatterer ring into a PET ring. Not only PET nuclides but also various types of single gamma emitters can be imaged. In this work, for a proof-of-concept of WGI, we developed a scatterer ring (GAGG+MPPC, diameter of 94 mm), which was inserted into a PET ring (GSO+PMT, diameter of 660 mm). We demonstrated animal imaging to clarify one of the current technological limitations of Compton imaging in the WGI. We performed a 1-hour long acquisition for a mouse, 22 hours after injection of 9.8 MBq $^{89}$Zr oxalate. The $^{89}$Zr emits 909 keV gamma rays as well as positrons. Therefore, we can directly compare Compton imaging performance with PET imaging performance. As a result, we acquired both PET and single gamma images of the mouse, in which $^{89}$Zr assimilated in the bone. Although these images were well correlated, the spatial resolution of the single gamma image was inferior to the PET image and distorted. The distortion of the reconstructed image occurs due to mismatch between actual and modeled systems. The proof-of-concept showed the spatial resolution limitation of the current prototype for Compton imaging and the necessity for improving the system modeling to mitigate the distortion.

MIC-19-03

Hyperspectral single photon imaging of targeted alpha therapy: development of the alpha-SPECT system based on advanced CZT imaging spectrometers (#2396)

PhD/MD student Jiajin Zhang¹, PhD/MD student Elena M. Zannoni², Dr. Eric Frey³, Dr. Yong Du³, Dr. Ling-jian Meng¹,²

¹ University of Illinois, Nuclear, Plasma and Radiological Engineering, URBANA, USA; ² University of Illinois, Bioengineering, URBANA, USA; ³ Johns Hopkins University, Radiology, Baltimore, USA

Content

Targeted alpha therapies (TAT) have been proven highly effective against disseminated cancer [1]. Because α-particles can cause highly disruptive and largely irreparable DNA double strand breaks. Radiation damage caused by α-particles is considered impervious to conventional cellular resistance mechanisms such as effusion pumps,
signaling pathway redundancy, and cell cycle modulation. Since α-particles travel a short distance (50-100 mm), the damage is usually confined to the vicinity of targeted cells or cell clusters. In human studies which have been progressed beyond phase I, α-emitters have yielded significant survival results in adult leukemia, glioblastoma multiforme and hormone-refractory metastatic prostate cancer, all cancers for which there are few or no treatment options.

Currently we are developing the Alpha-SPECT system for in vivo study of the distribution of therapeutic alpha-emitters and their daughters in patients and large-animals. In this work, we collaborate with Redlen Technology and the Science and Technology Facility Council (STFC) to develop a large-area, deformable CZT imaging-spectrometer. This detector platform offers an excellent spatial resolution of 250 μm and an unprecedented energy resolution of 1.5 keV at 140 keV (and 2.5 keV at 250 keV) and a broad dynamic range of 30-500 keV, which is ideally suited for detecting the gamma rays emitted by therapeutic alpha emitters, such as Ac-225, Pb-212 and Th-227, and their daughters, such as Fr-221, Ac-217, Bi-213, Ti-209 and Pb-209. In this presentation, we will discuss the design of the Alpha-SPECT system, the large-area deformable CZT imaging-spectrometers, and preliminary imaging results of TAT using CZT detector panels.

Neutron Capture Enhanced Particle Therapy (NCEPT): In vitro proof of concept (#2428)

Dr. Mitra Safavi-Naeini1,2, M.Sc./M.A. Nicholas Howell1, Dr. Ryan Middleton1, PhD/MD student Andrew Chacon2, Dr. Benjamin Fraser1, M.Sc./M.A. Naomi Wyatt1, Dr. Keith Bambery1, Dr. Joseph Bevitt1, Dr. Ulf Garbe1, Dr. Justin Davies1, M.Sc./M.A. Attila Stopic1, PhD/MD student Harley Rutherford2,1, Dr. Daniel R. Franklin3, Dr. Anthony Dosseto4, Dr. Akram Mohammadi5, Dr. Ryoichi Hirayama6, Dr. Susanna Guatelli2, Prof. Louis Rendina6, Prof. Naruhiro Matsufuji5, Prof. Anatoly Rosenfeld2

1 Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia; 2 University of Wollongong, Centre for Medical Radiation Physics, Wollongong, Australia; 3 University of Technology Sydney, School of Electrical and Data Engineering, Sydney, Australia; 4 University of Wollongong, Wollongong Isotope Geochronology Laboratory (WIGL), Wollongong, Australia; 5 National Institutes for Quantum and Radiological Science and Technology, National Institute of Radiological Sciences (NIRS), Inage-ku, Japan; 6 The University of Sydney, School of Chemistry, Sydney, Australia

Content

Neutron Capture Enhanced Particle Therapy (NCEPT) is a novel adjunct to proton and heavy ion therapy, which enhances the radiation dose delivered to a tumour relative to surrounding healthy tissue by capturing thermal neutrons produced during proton or heavy ion therapy. NCEPT utilises 10B and 157Gd-enriched tumour-specific neutron capture agents presently approved or in development for neutron capture therapy. NCEPT improves tumour control probability by increasing the dose at the target volume, while reducing the normal tissue complication probability by reducing the primary radiation dose, hence reducing the radiation dose to normal tissue. Additionally, NCEPT can deliver a significant dose to nearby satellite lesions outside of the primary treatment volumes. In this work, we report the outcome of two successful rounds of in vitro experiments, conducted at the National Institutes for Quantum and Radiological Science and Technology (NIRS, QST) Heavy Ion Beam research facility, which have provided the first experimental proof of concept for NCEPT.
Preliminary Trials of *In Vitro* Circulating Tumor Cell Cluster Tracking with the MiniEXPLORER II Total-Body PET/CT Scanner (#2487)

Dr. Qian Wang, Dr. Xuezhu Zhang, Prof. Simon R. Cherry

*University of California, Davis, Biomedical Engineering, DAVIS, USA*

**Content**

An in-depth understanding of the mechanisms of cancer metastasis is critical for improving cancer diagnosis, prognoses and developing more effective therapies. The goal of this study is to develop a more effective strategy for *in vitro* cell tracking using the total-body PET/CT miniEXPLORER II scanner in order to help understand both static and dynamic characteristics of metastatic cells. Instead of using a single or a large number of cells, as is commonly done in cell tracking studies, we used radiolabeled tumor circulating cell (CTC) clusters to track cells. Aggregated CTCs, which are reported to avoid an immune response, have controllable sizes and provide an increased signal during imaging as compared to single cells, making them more stable and easier to be visualized. Prior to *in vitro* studies, the ability of miniEXPLORER II in capturing a dynamic low-activity cell-like source was assessed by imaging point sources with different activities (11-290 Bq) driven by a robot arm traveling in the PET field of view (FOV) at different speeds (0.4-4.8 cm/s). The results demonstrate that the miniEXPLORER II can track a point source of just ~10 Bq at low speeds (<1 cm/s), and 50 Bq at higher speeds. We then conducted trials on tracking single MDA-MB-231 cell clusters that were directly radiolabeled with $[^{18}F]FDG$ and flowed through a helical tube of the phantom positioned at the center of the PET scanner. Two digital microscopes were installed at the inlet and outlet of the phantom to simultaneously monitor cell cluster flow and morphology. This preliminary data suggests that single cell clusters can be tracked *in vitro* with miniEXPLORER II. Based on the experience gained from this study, *in vivo* cell tracking of CTC clusters will be performed to further our understanding of cancer metastasis.
is essential for optimizing this therapy. The goal of the project is to strengthen the control of the doses delivered to thyroid during benign and malign diseases treatment, providing a novel mobile gamma imaging device specifically dedicated to measurements of the bio-distribution and kinetics of the radio-tracer at the patients's bedside. The first prototype of the camera has 5×5 cm² FoV and consists of a parallel-hole high-energy tungsten collimator, coupled to a 6 mm thick continuous CeBr₃ scintillator, readout by an array of Silicon Photomultiplier detectors. The overall detector response was calibrated, in terms of spatial resolution and sensitivity as a function of the source-to-collimator distance, by using various sources filled with 131I and placed in air and in tissue-equivalent medium. The camera shows a system SR of (3.14±0.02) mm and a sensitivity ranging from 1.64 cps/MBq to 1.38 cps/MBq for a 0.5 cm and 4 cm source diameter placed at 5 cm. Preclinical imaging with 3D-printed thyroid phantoms shows the high image quality compared to a standard high-energy gamma-camera and high capability of quantification, both with single and conjugate view methods (recovery coefficient of 97%).
MC-CL | MIC Closing Plenary Session - Roadmap for the Future of Medical Imaging

Dimitra G. Darambara (London)
Suleman Surti (Philadelphia)
MC-CL-01 1:20 PM

Student Paper Award Ceremony

Dimitra G. Darambara, Suleman Surti

The Institute of Cancer Research & The Royal Marsden NHS Foundation Trust, London, UK; University of Pennsylvania, Philadelphia, USA

MC-CL-02 1:25 PM

Grand Challenges in Medical Imaging

Simon R. Cherry

UC Davis, Davis, USA

Keynote address by Prof. Simon R. Cherry, Distinguished Professor of Biomedical Imaging, UC Davis, USA and Editor-in-Chief of Physics in Medicine and Biology

MC-CL-03 1:55 PM

Panel Discussion


MC-CL-04 2:30 PM

Invitation to 2020 MIC, Boston, USA

Georges El Fakhri

Massachusetts General Hospital, Harvard Medical School, Boston, USA
MC-CL-05

Closing of 2019 MIC

Dimitra G. Darambara

The Instituite of Cancer Research & The Royal Marsden NHS Foundation Trust, London, UK
WS-AI | Emergence and perspectives of artificial intelligence (AI) methods in radiation-based imaging sciences

This session aims to provide both a general introduction as well as in-depth elucidation of AI methods state-of-the-art and future perspectives for radiation-based medical imaging. We aim to provide an overview of how these methods are increasingly applied in imaging including radiology and nuclear medicine/molecular imaging. We will review state-of-the-art applications in several areas (e.g., image reconstruction, radiomics and predictive modelling, etc.). We will also discuss current challenges, limitations, and ways forward. The course is intended to provide the attendees with deeper understanding of emerging AI techniques and applications, and tools needed for translation of these methods to routine clinical imaging, with the potential to significantly improve diagnosis, prognosis and treatment response assessment, and to take a significant step towards realization of precision (personalized) medicine. We also aim to provide a venue for significant Q&A as well as panel discussions in this categorical.

Provisional program

- **15:00** - Introduction and program

- **15:05** - State of the art of A.I. for medical image reconstruction and corrections
  
  *G. Schramm*

- **15:30** - A history of Radio(geno)mics
  
  *M. Hatt*
• **15:55** - Limitations and challenges of A.I. in medical imaging: standardization - imaging  
  _R. Boellaard_

• **16:05** - Limitations and challenges of A.I. in medical imaging: standardization – analysis  
  _A. Zwanenburg_

• **16:30** - FDG PET radiomics to predict disease free survival in cervical cancer  
  _M. da Silva Ferreira_

• **16:45** - Statistical exploration of relationships between routine and agnostic features towards interpretable risk characterization  
  _E. Wolsztynski_

• **17:00** - Panel discussion about future perspectives and opportunities

• **17:15** - End