VIII International Course

Detectors and Electronics for High Energy Physics, Astrophysics, Space Applications and Medical Physics

INFN National Laboratories of Legnaro

1-5 April 2019

Abstracts of the lectures

April 1, Monday (afternoon)

14.00-14.10 **Welcome address**

Diego Bettoni *(Director of the INFN National Laboratories of Legnaro)*

Mauro Mezzetto *(Director of the INFN Section of Padova)*

Francesca Soramel *(Director of the Physics and Astronomy Department, University of Padova)*

Introduction to radiation and semiconductor detectors

14.10-15.50 **Introduction to radiation damage: basic physics and concepts**

Serena Mattiazzo
(DFA, University and INFN Padova)

The interaction mechanisms between particles and matter are both at the basis of the working principles of detectors and microelectronics systems developed for scientific and industrial applications and, in some cases, of their malfunctions. The study of radiation (natural and artificial) effects on semiconductor devices and microelectronic systems is an important and lively field of scientific and technological research. Tolerance to radiation is an important issue for all those applications where electronic devices and sensors have to survive in very harsh environments (space research, telecommunications, avionics, high energy physics, nuclear plants, medical applications, etc. etc.). In this lesson the basic concepts and the definitions of the physical quantities involved (dose, linear energy transfer, non-ionizing energy loss, single event effects, cross-section) will be introduced.

16.20-18.00 **Principles of semiconductor detectors**

Gian-Franco Dalla Betta *(University of Trento and INFN TIFPA)*

The aim of this lecture is to provide the attendees with basic knowledge about semiconductor radiation detectors with emphasis on silicon, that are widely used in many application fields. Starting from a review of semiconductor physics concepts, the talk will cover the operation principle of semiconductor detectors, their main figures of merit, design, simulation and technological issues. Then, an overview of different variants of semiconductor detectors will be given, from simple pad (diode) detectors, to segmented detectors (strips and pixels), to more advanced detector concepts (e.g., drift detectors, CCDs, DEPFET, 3D and active edge detectors), also touching some hot topics like avalanche based detectors (LGAD, SiPM) and CMOS monolithic active pixel sensors (MAPS).

April 2, Tuesday (morning)

Semiconductor detectors: radiation effects and state of the art

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9.00-10.40 **Macroscopic effects of radiation on silicon detectors**

Erik Butz *(Karlsruher Institut für Technologie, Germany)*

Silicon-based detectors are used ubiquitously in HEP experiments today and the effects of radiation on silicon are an active field of study. The lecture will discuss the macroscopic effects of radiation on silicon detectors. Emphasis will be put on showing how the microscopic defects have macroscopic effects which evolve with time, temperature and irradiation. We will discuss how this affects the operation of silicon detectors with some emphasis on the CMS pixel and strip tracker. We will also discuss how the effects can be simulated for both silicon sensors and readout electronics and how predictions can help to shape the operation of the detectors and to ensure their longevity.

11.10-12.50 **Microscopic radiation damage in semiconductor detectors**

Mara Bruzzi *(University and INFN Firenze)*

Semiconductor based devices are widely used in a variety of fields of application characterized by an hostile radiation environment. For this reason, radiation damage research on semiconductor detectors has received extensive attention in past years, in order to assess the radiation induced performance degradation in operational conditions. This lecture presents an overview on microscopic disorder and its influence on the device performance, with special reference to detectors developed for high energy physics experiments.

14.00-15.40 **Silicon Sensors for tracking particles in space and time**

Nicolò Cartiglia *(INFN Torino)*

In these lessons I will review the progresses towards the development of Silicon sensors able to track particles in space and time with a precision of ~10 micron and ~10 picosecond. The lessons will cover the basics of signal formation in Silicon detectors, and then they will explain the sensor characteristics to obtain the above precisions. The effect of radiation damage and the solutions to limit a degradation in performances will also be addressed.

16.10-17.00 **Pixel front-end electronics for high time resolution**

Adriano Lai *(INFN Cagliari)*

Future colliders planned for the next decades require unprecedented performance in terms of space and time resolution. In the last years various ideas have been introduced to develop pixel sensors providing time resolutions in the range of tens of ps. The effective use of such sensors in vertex and tracking detectors requires the design of a new generation of front-end circuits, able to add precise time information at the single pixel level. The very front-end circuit (preamplifier and shaper) will have different requirements with respect to a traditional one. High precision TDC have to be integrated at the pixel level as well. This is a very challenging task considering CMOS technologies presently available. This lesson addresses the issue of high time resolution at the pixel level, starting from first principles concerning time measurements by means of electronic circuits. Some case studies and some recent implementation examples are also illustrated.

17.00-17.50 **Two-tier Geiger-mode avalanche pixel sensors for charged particle detection**

Lucio Pancheri *(University of Trento and INFN TIFPA)*

Impact ionization has been exploited for decades to enhance the Signal-to-Noise Ratio in Avalanche Photodiodes and has more recently enabled high-sensitivity single-photon detectors such as analog Silicon Photomultipliers and CMOS-integrated Single-Photon Avalanche Diode arrays. These detectors can provide the unique combination of picosecond timing resolution and photon counting capability in a pixelated solid-state device. A steadily growing number of research institutions and commercial foundries are now developing the technologies needed to obtain efficient single-photon time-resolved imaging instruments, driven by scientific and consumer applications. This lecture will discuss the opportunities to exploit these technologies in charged particle counting and tracking applications. The first prototypes of two-tier Geiger-mode pixelated avalanche sensor realized in the framework of INFN projects APiX2 and ASAP will be presented. The main characteristics of the sensors will be described, and their application opportunities and open issues will be critically addressed.

April 3, Wednesday (morning)
Electronics: radiation effects and state of the art

9.00-10.40 **Front-end electronics for silicon trackers**

Valerio Re *(University of Bergamo and INFN Pavia)*

This lecture will discuss the general concepts and the technologies that are used for the design of front-end electronics for silicon microstrip and pixel detectors in modern High Energy Physics experiments. Finely segmented detectors have to be read out by mixed-signal front-end integrated circuits fabricated in aggressively scaled technologies. These systems have to comply with severe requirements in terms of low noise, high speed, low power and high radiation tolerance. The lecture will present the main problems that have to be tackled in the development of a microelectronic front-end integrated circuit, from the design of analog blocks to the digital architecture for the chip readout. The discussion will then focus on recent developments of pixel readout chips in a 65 nm CMOS process for the upgrade of trackers at the High Luminosity LHC. Future prospects for the design of advanced front-end electronic systems will also be discussed.

11.10-12.50 **Effects of ionizing and non-ionizing radiation on electronic devices and circuits**

Lodovico Ratti *(University and INFN Pavia)*

Electronic circuits and systems are employed in a number of different fields where some degree of radiation tolerance is required: these fields include, to mention but a few, space and avionic applications, high energy physics experiments, nuclear and thermonuclear power plants, medical diagnostic imaging and therapy. When operated in these environments, electronic systems may be directly struck by particles or highly energetic photons, with a subsequent alteration of their electrical properties. The lecture will be concerned with the effects of ionizing and non-ionizing radiation on electronic devices and circuits in CMOS technology, particularly in high energy physics applications. The fundamental mechanisms underlying performance degradation in electronic components will be described and discussed. Examples of radiation effects will be provided through the analysis of experimental tests. Emphasis will be placed on how radiation tolerance is affected by the evolution of microelectronic technologies and by the growing hostility of the radiation environment.

April 3, Wednesday (afternoon)
Electronics: radiation effects and state of the art

14.00-14.50 **If Moore's Law is over, is this the end of microelectronics?**

Alessandro Marchioro *(CERN, Switzerland)*

An amazing prediction of Gordon Moore in 1965 has defined the development of an entire generation of technology for more than half a century, but nature finally abhors exponential growths.

Still, riding this long wave of growth in microelectronics, particle physicists have built detectors and experiments that simply would not have been possible or even conceivable without it. From pixel detectors with spatial resolution better than emulsions or bubble chambers to calorimeters with areas approaching one thousand square meters, microelectronics has changed the way high energy physics experiments are conceived. Post-Moore's generation devices are likely to boost even further the appetite for resolution, feature extraction and high data rates that has defined the LHC era and match the requirements for generations of experiments to come in HEP.

14.50-15.40 **Novel trends in silicon detectors**

Manuel Dionisio Da Rocha Rolo *(University and INFN Torino)*

Frontier radiation detectors in High Energy Physics and Space applications will demand for increased pixel granularity and event rate capability, faster sensors, lower cost and power consumption, and high robustness. Semiconductor silicon detectors will expectedly continue to play a major role, mainly driven by the proven advantages of strip and hybrid pixel detectors. Advanced integration and packaging technologies allow for the development of 3D integrated systems that are used on particle trackers, X-ray imaging, biomedical and material sciences.

On the other hand, the availability of quadruple wells on deep-submicron technologies allows to integrate readout electronics and sensor into a monolithic CMOS device, while the possibility to perform backside processing on high resistivity wafers offer the perspective of using such devices in an increasing number of applications.

This lecture will discuss relevant trends in silicon sensors and associated electronics, focusing on novel developments for science, industrial and medical applications.

16.00-18.00 **Poster session**

Abstracts are available on line:

http://sirad.pd.infn.it/scuola_legnaro/Documents/Poster-Session-Abstracts.pdf

April 4, Thursday (morning)

Radiation effects on components for space and other applications

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9.00-9.50 **Radiation effects and hardness assurance for space electronics**

Christian Poivey *(ESA ESTEC, The Netherlands)*

Survival and successful operations of space systems in the space radiation environment cannot be ensured without careful consideration of the effects of radiation. Radiation Hardness Assurance (RHA) consists of all those activities undertaken to ensure that the electronics of a space system perform to their specification after exposure to the space radiation environment. A key element of RHA is the selection of components having a sufficient tolerance to radiation effects for their application. However, RHA is not confined to the electronic part level. It has implications with system requirements and operations, system and subsystems circuit design, and spacecraft layout.

The lecture will start with a presentation of the space environment and the methods to quantify radiation levels within a spacecraft. Then, after a short introduction of radiation effects in electronic parts, test methods will be presented. Finally, the RHA process will be described in detail.

9.50-10.40 **Effects of space radiation on COTS memories: the MTCUBE project**

Luigi Dilillo *(LIRMM - University of Montpellier/CNRS, France)*

Space radiation is a harsh environment affecting all electronic devices used on spacecraft, despite the presence of Earth's protective magnetic field in Low Earth Orbit (LEO). Although particles inducing total ionizing dose (TID) can be effectively shielded in LEO, particles responsible for Single Event Effects (SEEs) remain an issue for the reliability of electronics. MTCUBE (Memory Test CUBEsat) project has the objective of comparing accelerated SEE radiation testing and error rate estimation (through simulation) with actual in-orbit data. The aim of the project is to fly in LEO a 1-Unit CubeSat developed at the University of Montpellier, which will fly the RES (Radiation Effects Study) experiment consisting in several types of memories, volatile and non-volatile, with different technologies and architectures. Such type of mission is also useful for testing COTS (Commercial-Off-The-Shelf) components produced with new/emerging technologies and that have little or no flight experience.

11.10-12.00 **Single Event Neutron Effects in electronics and designing appropriate tests for future fusion research reactors**

Jean-Luc Leray *(ANAXAJL Electronics & Radiation Effects Consultancy, France)*

The possibility that a single high energy neutron in atmosphere, of cosmic origin, can trigger transient as do charged particle in Space have been envisaged evidenced in the 80's-90's. First observed in High Voltage-High Power components onboard train engines it was also considered as a major treat in avionics because of the growing of computers such as in aircraft autopilots and engine control. Due to shrinking of digital devices and to the decrease of stored charge per bit, the effect pervaded all kind of electronics in the 2000's including High-Reliability Hi-End data servers used in the Internet backbone as well.

The lecture will address the indirect ionising effects of a single neutron according to the different bins in the neutron energy spectrums typical in Reactors vs in Atmosphere at jet or at ground altitudes. Large Single Event Rate imposed device and architecture design remedies. Symmetrically the JEDEC manufacturer consortium issued a new test standard (JESD89A) to ascertain and assure the products. Future large-scale research neutronic machines as ITER (the Thermonuclear High-Power Reactor), and the High Luminosity Hadron Colliders, will inherently produce a residual number of neutrons of significance even behind a heavy shielding. To obtain high confidence in the qualification test of electronics, test methods appropriate for man-made very diverse neutron spectrums, other than atmospheric, must be issued, and practical considering the diversity of test neutron beam lines.

12.00-12.50 **FPGA in HEP experiments: challenges and radiation effects**

Tullio Grassi *(University of Maryland, USA)*

Field Programmable Gate Arrays (FPGAs) have been increasingly used in HEP experiments and accelerator facilities. The FPGAs that initially appeared on the market consisted of a simple array of programmable logic gates (AND, OR, etc). Modern FPGAs have evolved to include programmable Input/Output buffers, high-speed transceivers, processors, PLLs, etc.

This lecture will introduce existing FPGA technologies, and their use in HEP experiments.

It will start with a tutorial on FPGA architecture, fabrication, and utilization and an overview of major applications of FPGAs outside HEP. A description of the radiation effects on FPGAs will follow. Then it will present design techniques for the mitigation the radiation effects previously described. Testing of the radiation tolerance of FPGAs will be described.

A few case studies will be presented.

April 4, Thursday (afternoon)

Radiation effects on components for space and other applications

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14.00-14.50 **Radiation effects in non-volatile memories: from planar to 3D**

Marta Bagatin *(DEI, University and INFN Padova)*

The effects of ionizing radiation effects in the most popular non-volatile memories will be summarized, with the main focus on Flash memories. Total ionizing dose and single event effects will be illustrated in NAND and NOR Flash memory technologies. The most relevant issues in both the cell array and the control circuitry will be presented. The impact of scaling on the radiation sensitivity of Flash arrays, from floating gate planar cells to recent 3D architecture, will be analysed. The synergies between SEE and TID, as well as the impact of radiation on long-term performances, such as retention and endurance, will also be covered. Finally, a brief overview of the state of other emerging technologies, such as Phase Change Memories (PCM), Resistive memories (ReRAM), and Spin Transfer Torque memories (ST-MRAM), will be provided.

14.50-15.40 **Radiation Effects in CMOS Image Sensors**

Vincent Goiffon *(ISAE-SUPAERO, France)*

Nowadays, CMOS Image Sensors (CIS), also called Active Pixel Sensors (APS), represent the most popular solid state imager technology as illustrated by its ubiquity in mass consumer smartphones and cameras. In particular, CISs are used in various imaging applications in harsh radiation environments (e.g. space remote sensing and, medical imaging). During this lecture, the particularities of the CIS technology (compared to solid state particle detectors) will be briefly presented. In a second part, an overview of the most important total ionizing dose (TID) effects on these imagers will be discussed. Displacement damage effects in CISs will also be developed by focusing on dark current non-uniformities and random telegraph signals (RTS). Finally, single event effects (SEE) specific to these devices will also be addressed.

The lecture will be concluded by an overview of the typical radiation environments in which the use of this technology is envisaged, emphasizing emerging applications such as ITER, inertial confinement fusion and nuclear power plant monitoring.

16.10-17.00 **Single Event Effects in wide band-gap semiconductor power devices**

Francesco Velardi *(DIEI, University of Cassino and Southern Lazio)*

In recent years the role of silicon carbide and gallium nitride, as the candidate to replace or integrate silicon, is grown with broad dissemination in significant markets of the power electronics. Aerospace, avionics, high energy physics, biomedical sectors are just some of the areas requiring reliable power devices to operate in a radiation environment safely. Like their silicon counterparts, SiC power devices (Schottky diodes, MOSFETs, IGBTs) and GaN HEMTs suffer from Single Event Effects. So, the increasing interest in wide band-gap semiconductor power devices addresses the radiation reliability study toward understanding the failure mechanisms that can be triggered in these components by ionizing particles.

The lecture will introduce, with the support of experimental results and simulations, the main physical phenomena that occur in these devices during a heavy ion impact. The discussion will be elementary and wide-ranging and will aim to provide students with a comparison between the performances, regarding tolerance to SEEs, of the various commercial silicon carbide and gallium nitride power devices available today.

17.00-17.50 **Accredited radiation hardness assurance testing**

Christoph.Tscherne *(Seibersdorf Labor GmbH, Austria)*

Seibersdorf Laboratories is responsible for operating standard calibration laboratories for ionizing radiation in Austria for more than 50 years. In the 1990s Seibersdorf Laboratories extended their radiation expertise on space radiation environment for aerospace applications.

Expertise in modelling of space radiation effects to humans have been established and measurement techniques for aviation and space have been developed. Together with an Austrian component manufacturer Seibersdorf Laboratories investigated total dose and single event effects on device level using TCAD modelling tools and Monte Carlo methods.

Experimental comparisons with microdosimetric measurements are a substantial part of all investigations. Seibersdorf Laboratories carried out an extensive campaign of comparing standard and accelerated ELDRS (Enhanced Low Dose Rate Radiation Sensitivity). This finally led to the extension of the existing radiation laboratory capabilities with a new Cobalt-60 facility for 24/7 testing of electronic components and devices regarding ionising radiation hardness assurance, called TEC-Laboratory.

9.00-9.50 **The ChipIR beamline, an atmospheric-like neutron facility for the irradiation of microelectronics.**

Carlo Cazzaniga *(STFC, Rutherford Appleton Laboratory, UK)*

The construction of ChipIr, a new beamline at the ISIS neutron and muon source in the UK, has been motivated by the very limited availability of fast neutron facilities, particularly in Europe, for testing of microelectronics for industry.

The fast neutron spectrum is generated by the spallation interaction of the ISIS accelerator 800 MeV proton beam on a tungsten target. The design of the beamline has been optimized for Single Event Effect testing at the device-level, board-level and system-level, which require a beam of high and uniform intensity over a selectable area from a few to hundreds of cm2.

Characterization measurements of the beam flux, spectrum and uniformity are presented. The methods that have been used are neutron activation foils analysis, solid state detectors (silicon and diamond detectors), and single event upset monitors with reference electronics. These methods provide complementary information and pro and cons will be discussed.

9.50-10.40 **The LNL fast neutron irradiation facility NEPIR**

Luca Silvestrin *(DFA, University of Padova)*

NEPIR (Neutron and Proton Irradiation facility) is a project devoted to develop and build a new, fast neutron irradiation facility at INFN Legnaro National Laboratories (LNL). The project is in an advanced design phase and partially founded.

The facility will exploit the LNL 30-70 MeV, high current proton cyclotron of the SPES laboratory to feed different compact neutron sources to generate high flux neutron beams with different energy spectra:

- a thick beryllium target to produce white spectrum neutrons with a variable cut-off value, as a function of the energy of the impinging proton beam in the 20-70 MeV rage;
- QMN will produce a Quasi Mono-energetic Neutron beam, with controllable energy peak in the same energy range;
- ANEM will produce fast (E > 1 MeV) neutrons, with an energy distribution similar to that of neutrons naturally present at sea-level (atmospheric neutrons), generated by the interaction of energetic cosmic rays with the Earth atmosphere. This will be used to study atmospheric neutron-induced single event effects in electronics. Using additional moderator panels, the same source can be used to further shape the white spectrum to resemble that of other environments (eg. surface of Mars or Moon).

11.10-12.00 **Research and development for Hadrontherapy in Italy**

Emanuele Scifoni *(INFN TIFPA, Trento)*

Hadrontherapy is a major example of successful translational research in particle physics. Italy was from the very beginning a leading force for research in this field, and INFN was at the forefront with many challenging projects and breakthroughs, e.g., on dosimetry, imaging, biophysical modelling, and treatment planning. One of the outcomes of this, is the presence in Italy of 3 of the first clinical centres in Europe (CNAO, CATANA and Trento PTC). After a couple of decades of development, now hadrontherapy with protons and heavier ions is becoming an established option, with several fully active clinical centres and protocols in play and many more in course of opening or in construction. Still, the need to improve the cost/benefit ratio and to increase the applicability of this therapeutic option, calls for further research and development on several fronts, from dose delivery to in beam imaging, from radiobiology to multiscale interaction modelling and to dose computation engines, including exploration of different beams or exploitation of new processes for specific radiosensitizing combinations. After a short introduction on fundamental physics and radiobiology concepts, an overview of the present state of the art and challenges in physics related research in hadrontherapy is reviewed together with some notes on the running dedicated INFN projects, such as MoVe IT, FOOT and NEPTune.

12.00-12.50 **The LARAMED project at LNL: a new radionuclides production facility**

Micol Pasquali *(INFN Legnaro National Laboratories)*

The continuous progress in Nuclear Medicine (NM) in the last decades has always been related to the development and use of new, more effective, radiopharmaceuticals products. Such a goal has been achieved by combining the biological behaviour of new molecules coupled with the main nuclear properties of novel radioisotopes. Radionuclides are therefore fundamental tools for NM technology, which in turn constitutes one of the most important imaging modality and therapeutic approach for the treatment of many critical diseases. Current functioning of NM is crucially dependent on the availability of essential radionuclides in sufficient amount to ensure widespread distribution to hospital. Similarly, progress in NM is always tightly linked to the continuous development of effective production processes of novel radionuclides having peculiar nuclear properties that might help finding unprecedent solutions to unsolved clinical issues.

The goal of the INFN-promoted, government-funded LARAMED (LAboratory of RAdionuclides for MEDicine) project, under construction stage at LNL, is to get advantage of the new, BEST 70p high performance cyclotron (35-70 MeV, up to 750 μA) installed in 2015. In particular, the project is aimed at the R&D aspects related to the study of yet unexplored nuclear reaction routes for alternative/new radionuclides having potential interest in NM, along with the related radiochemistry and technological issues to improve both production and recovery.

An overview of the main research projects underway carried out by the LARAMED research group at LNL, aimed at investigating the production of both conventional and emerging radionuclides will be discussed.

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