17th (Virtual) ”Trento” Workshop on Advanced Silicon Radiation Detectors

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Book of Abstracts

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MALTA monolithic active pixel sensor Test Beam results

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The MALTA monolithic active pixel sensor is a full-scale particle detector in the Tower Semiconductor 180 nm architecture, with a small collection electrode design. It features a novel asynchronous readout based on a custom designed oversampling of a 37-bit wide bus and low front end power consumption (<80 mW/cmˆ2). Coupled with radiation hardness up to 1x10ˆ15 neq x cmˆ2 (NIEL) and 80 Mrad (TID), MALTA is an interesting candidate for the inner radii tracking modules for HL-LHC and beyond.
MALTA has been extensively tested (both irradiated and un-irradiated samples) in the SPS CERN test beam and with radioactive sources in the lab. Over time, multiple iterations have taken place on the initial MALTA chip design. Results from these measurement campaigns will be presented and their implications on future chip design iterations will be discussed.

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TEST ONLY - Test for title - SI for FCC

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Here goes the content. Silicon tracking detectors for the FCC-hh require unprecedented radadiation hardness up to $10^{15}\mathrm{N}_{eq}$. We develop them with the help of TCAD simulations in 3D and CMOS technologies.

LGAD / 136

Spatial and temporal resolutions of sensors belonging to the second FBK RSD production

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The second production of resistive silicon detectors at FBK, RSD2, features several innovative designs of the electrode geometry aiming to maximize signal sharing among a well-defined number of pads. This talk presents the first results obtained with the "cross" geometry, where the metal of the pads is shaped like a cross.
This geometry is particularly well suited to maximize charge sharing among 4 pads while minimizing the spread over pads that are further away.

3D Sensors / 137

Investigation of the Time Resolution of LGADs and 3D sensors using a beta source and a laser system

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Collider experiments as the upcoming high-luminosity LHC or the future FCC will increase the demands of the detectors used for tracking. In the FCC, sensors will not only face fluences of up to $1 \cdot 10^{17}\ n_{\mathrm{eq}}/\mathrm{cm}^2$, but also high pile-up scenarios. Thus sensors are needed which have a high radiation tolerance, but also an excellent time resolution while still providing a good spatial resolution.

Currently Low Gain Avalanche Diodes (LGADs) are the prime candidate when it comes to timing, reaching a resolution of below 30 ps. However, 3D sensors are promising candidates as well, as they have not only a good time resolution but also a proven superior radiation hardness.
In this study, the time resolution of both LGADs and 3D sensors was investigated with measurements using a beta source, as well as measurements using a laser with infrared wavelength. These timing-TCT measurements allow the investigation of the position dependence of the time resolution. This is interesting especially for the 3D sensors, where the time walk component due to the more complex electric field structure influences the time resolution strongly.

LGAD / 138

Characterization of Trench-Isolated LGADs before and after irradiation

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Low Gain Avalanche Diodes (LGADs) are state-of-the-art silicon sensors for 4D tracking in high energy physics applications. A limitation of LGAD technology is the no-gain area (50-100µm) between adjacent pixels, which reduces the fill-factor (active area/total area) of the sensor. FBK proposed a novel strategy of LGAD-segmentation based on narrow trenches, that could potentially reduce the width of the inter-pixel region to 10µm or less. FBK produced within the RD50 collaboration a batch of Trench-Isolated LGADs (TI_LGADs), where a wide variety of trenches and fabrication parameters have been explored.
In this work, we will present the pixel-isolation tests performed with DC electrical characterization and TCT measurements. Moreover, for the first time, TI-LGADs irradiated with neutrons (up to 1.5E15 neq) and X-rays (up to 10 Mrad) have been tested, and we will present the preliminary results on their characterization.

LGAD / 139

Detailed process characterization of carbonated LGADs through Secondary Ion Mass Spectroscopy

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Using high resolution Secondary Ion Mass Spectroscopy (SIMS), the gain layer doping profiles of carbonated FBK UFSD 2 and CNM RUN 10478 LGADs are evaluated. A combination of $^{55}Cs^{-}$ and $^{16}O^{+}$ primary ion driven campaigns yield a high sensitivity in the order of 1.35×10^{14} $atoms/cm^3$ for Boron concentrations along with a precise depth estimation within ˜ 5 nm. For Carbon profile studies, a 62-hour Caesium pre-sputtering protocol is established which, combined with beam parameter optimization, result in an unprecedented sensitivity of 2 × 10^{15} $atoms/cm^3$. Through advanced analysis techniques, conclusions are extracted concerning the implantation dose, energy and activation for Boron and Carbon implants. The latter are validated though Monte-Carlo TCAD process simulations, while Boron de-activation on carbon co-implantation is discussed. Finally, using as input the measured dopant profiles, electrical simulations are presented and compared with previously reported laboratory data.

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Silicon Electron Multiplier (SiEM)

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Silicon sensors for the future generation of collider physics experiments will require high performances on spatial (< 10 μm) and time resolution ($20 - 50$ ps) with a radiation tolerance up to fluences of 10^{17} n_{eq}/cm^2. To meet these challenges, an innovative silicon sensor architecture is proposed, achieving internal gain without relying on doping, the Silicon Electron Multiplier (SiEM). The SiEM consist of a set of metallic electrodes buried within the silicon substrate which create a high electric field region close to the readout electrode. Such a geometry results in charge multiplication. Extensive studies of the SiEM behaviour through TCAD simulations demonstrating a gain in excess of a factor 10 are presented. The impact of the multiplication electrode geometry and biasing scheme on the gain and breakdown behaviour of the device is also discussed. Through transient simulations, the time structure and formation of the signal is presented for the various cases. Finally, possible fabrication processes are presented with a highlight on very first studies done with the Metal Assisted Chemical Etching technique.

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Characterisation of UFSD4 production by FBK

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In this contribution, I present the latest production of Ultra-Fast Silicon Detectors, UFSD4, manufactured by Fondazione Bruno Kessler. The production comprises of 18 wafers; on each wafer there are R&D structures and 12 full sensors prototypes for the Endcap Timing Layer of the CMS experiment at the High Luminosity LHC. Each of this 12 sensors has 16x16 1.3x1.3 mmˆ2 pads. The new batch has been tested on wafer at FBK and additional measurements are ongoing in Torino on diced structures, to perform both static and dynamic characterisation. Data have been analysed to study the production yield and the gain layer uniformity, with the aim of verifying that UFSD4 meets the requirements for the CMS sensors.

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Sensitivity analysis of parameters characterizing the bulk radiation damage on silicon devices

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The "Perugia 2019 Surface"radiation damage model is a Synopsys Sentaurus Technology CAD (TCAD) numerical model which accounts for surface damage effects induced by radiation on silicon particle detectors. In order to get a complete picture of the phenomena taking place in the volume of the irradiated silicon detectors, the non-ionizing effects, referred to as bulk damage, also need to be taken into account in the description of a more inclusive "New University of Perugia"model. These non-ionizing effects are responsible for the increase of the leakage current in silicon sensors, the changes in the effective space charge concentration and the charge collection efficiency. In this work, the impact of the variation of some input parameters of the model, such as the electron/hole cross sections and acceptor/donor introduction rates on the changes in the leakage current, the full depletion voltage, the charge collection efficiency and the damage constant α (a figure of merit of an irradiated device) of a PIN diode and/or a Low-Gain Avalanche Detector (LGAD) is investigated.

LGAD / 143

Present and future development of thin silicon sensors for extreme fluences

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In this contribution, we present a new development of radiation-resistant silicon sensors. This innovative sensor design exploits the recently observed saturation of radiation damage effects on silicon, together with the usage of thin substrates, intrinsically less affected by radiation. The internal multiplication of the charge carriers will be used to overcome the small signals coming from thin substrates.
At the end of 2020, the Fondazione Bruno Kessler (Italy) delivered Low-Gain Avalanche Diodes (LGAD) produced on 25 and 35 μm thick p-type epitaxial substrates, namely the EXFLU0 production: I-V and C-V characterisation of the sensors has been performed before and after irradiation up to 1E17 n$_{eq}$/cm^2, together with signal analysis from an infrared laser and beta stimulus.
The outcome of the laboratory tests will be implemented in the EXFLU1 production, in which optimisation of the sensor peripheries and the gain layer responsible for internal multiplication will be pursued. The goal is to pave the way for a new design of silicon sensors that can efficiently operate above fluences of 1E17 n$_{eq}$/cm^2.

LGAD / 144

Development of AC-LGADs for large-scale high-precision time and position measurements

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Low Gain Avalanche Detectors (LGADs) are thin silicon detectors with moderate internal signal amplification. LGADs can provide time resolution as good as 17 pico-seconds for minimum ionizing particles. In addition, the fast rise time and short full charge collection time (as low as 1 ns) of LGADs are suitable for high repetition rate measurements in photon science and other fields. However the current major limiting factor in granularity is due to structures preventing breakdown caused by high electric fields in near-by segmented implants. As a result, the granularity of LGAD sensors is currently limited to the mm scale.

In this contribution, we present measurements on AC-LGADs (also named Resistive Silicon Detectors RSD), a version of LGAD which has shown to provide spatial resolution on the few 10‘s of micrometer scale. This is achieved by un-segmented (p-type) gain layer and (n-type) N-layer, and a di-electric layer separating the metal readout pads. The high spatial precision is achieved by using the information from multiple pads, exploiting the intrinsic charge sharing capabilities of the AC-LGAD provided by the common N-layer. The response depends on the location, the pitch and size of the pads.

Using a focused IR-Laser scans directed both at the readout side on the front and the bias side on the back of the sensor, the following detector parameters have been investigated in RSD produced by FBK with the scope of optimizing the sensor design: sheet resistance and termination resistance of the n-layer, thickness of the isolation di-electric, doping profile of the gain layer, and pitch and size of the readout pads. Furthermore the electrical characterization (capacitance over voltage) of the sensors with different connection configurations will be shown. Finally, charge sharing distributions produced with data taken at the Fermilab test beam facility in the spring of 2021 will be shown. The data will be used to recommend a base-line sensor for near-future large-scale application like the Electron-Ion Collider where simultaneous precision timing and position resolution is required in the tracking detectors.

3D Sensors / 145

Single cell 3D timing: Time resolution assessment and Landau contribution evaluation via test-beam and laboratory measurements

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The proven potential of 3D geometries at higher than 10^{16} n_{eq}/cm^2 radiation fluences, in combination with a small cell approach, makes them an excellent choice for a combined precision timing tracker. In this study, the timing resolution of a single 50 x 50 μm 3D pixel cell is presented in various temperatures through charge collection measurements with discrete electronics in a laboratory setting. The series is complemented by an extensive test-beam campaign with 160 GeV SPS pions, using a multi-plane timing telescope with an integrated pixelated matrix. Through a varied incidence angle study, field uniformity, Landau contribution and collected charge are treated at incidence angles of +/- 12^o. Using state of the art numerical methods, the choice of instrumentation on signal composition and induced bias on results is also evaluated.

Simulations / 146

Dynamic characterization of the ARCADIA passive pixel arrays: a comparison between simulation and experimental data

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Recently, an increasing interest towards the development of novel Monolithic Active Pixel Sensors (MAPS) based on CMOS technology has spread inside the radiation detector community. The ARCADIA project aims at the development of an innovative platform for the design of MAPS exploiting a production process which is fully compatible with commercial 110nm CMOS technology. A first engineering run, including both active sensors with integrated electronics and passive test structures, has been completed in 2021. The designed sensors are fabricated on low doped n-type silicon substrates with thicknesses equal to 100 and 200 μm or, alternatively, on n-type epitaxial layers with an active thickness of 48 μm, grown on p-type silicon. The sensor is composed of a n-type collection electrode located at the pixel centre. P-type regions (pwells and deep pwells) are formed at the pixel periphery, where the front-end electronics can be hosted.
In order to select the optimal pixel layout in terms of charge collection speed, capacitance and operating voltage range, parametric simulations have been performed with a TCAD tool, focusing on the pixel layout i.e. on the dimensions of the frontside p- and n-type implants. Transient simulations on single pixel 3D domains have been used to reproduce the sensor response to an external infrared (IR) and red laser, which illuminates the devices from the backside with an unfocused light spot. Passive pixel arrays with different pixel pitches (50, 25 and 10 μm) and different pixel layouts have been tested at a probe station as well as in an optical setup employing an IR or, alternatively, a red laser.
An excellent agreement has been obtained comparing the data extracted from measurements and simulations and thus proving the reliability of the adopted device models.
We will present the obtained results from this characterization activity, focusing on the comparison between experimental and simulated characteristics and on the dynamic performance of the different pixel layouts.

CMOS / 147

Upgrade to the Belle II Vertex Detector with CMOS pixel sensors

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The success of the Belle II experiment at KEK (Japan) relies on the very high instantaneous luminosity, close to 6x10ˆ35 cmˆ-2 sˆ-1, expected from the SuperKEKB collider. The beam conditions to reach such luminosity levels generate a large rate of background particles in the inner detection layers of Belle II, which exceeds by far the rate of particles stemming from elementary collisions. This beam-induced background creates stringent constraints on the vertex detector, in addition to the requirements coming from the physics performance needed.

The current Belle II vertex detector (VXD) has been operating very satisfactorily since the experiment started full operation in 2019. While efforts are still ongoing to mitigate beam-induced backgrounds, current prospects for the related occupancy rates in the VXD layers at full luminosity fall close to the acceptable limits of the employed technologies.
In this context, the Belle II collaboration is considering the possibility to install an upgraded VXD system on the time scale around 2026 and R&D activities on fully depleted CMOS sensors have started. Such an upgrade should provide a sufficient safety factor with respect to the background rate expected at the nominal luminosity and possibly enhance performances for tracking and vertexing.

New CMOS monolithic technologies for pixel sensors offer a combination of granularity, speed, low material budget and radiation tolerance matching well Belle II requirements and could be exploited to design a fully pixelated VXD, also benefiting from significant developments made in recent years for other experiments.

This talk will review the context of the proposed VXD upgrade with monolithic technologies in Belle II, providing details of the technological proposal and discussing performance expectations from simulations. Especially, recent progresses on integration system to achieve the requested exquisite low material budget will be presented.

Planar Sensors / 148

New test beam results of HPK planar pixel sensors for the CMS Ph2 upgrade

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The new Inner Tracker CMS pixel detector for the High-Lumi upgrade of LHC will be designed to sustain and collect till to 1 MeV neutron equivalent fluence (ϕ_{eq}) of up to 2.3 x 10^{16} cm^{-2} for more than 3000 fb^{-1} of integrated luminosity. Various solutions are being evaluated in terms of pixel pitch, sensor designs, and vendors.

Planar n^{+}-p sensors produced by Hamamatsu Photonics (HPK) with an active thickness of 150 μm and pixel pitches of 25 x 100 and 50 x 50 μm^2 are among these proposals. In 2017 a first production was characterized and in 2019 a new set of improved prototypes was produced. Sensors were coupled to the RD53A chips and the modules were irradiated at different fluences up to 2 x 10^{16} cm^{-2} and extensively tested in the DESY II test beam facility in the last 2 years.

This talk will present an overview of all the results obtained for this new production in terms of spatial resolution, hit efficiency, cluster breaking frequency at shallow angles and noise studies, together with a detailed comparison between the two main sensor designs available for that production (bricked and bitten).

3D Sensors / 149

Test Beam results of FBK 3D pixel sensors interconnected to RD53A readout chip after high irradiation

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Columnar pixel sensors, also known as 3D sensors, are considered for the innermost layers of the tracking detectors of the CERN Large Hadron Collider High Luminosity upgrade (HL-LHC). In the case of the CMS experiment, the first layer of pixel detectors will be installed at about 3cm distance from the beam pipe; it will be exposed to unprecedented fluences of up to 2E16 neq/cm2 (1MeV equivalent neutrons). In addition, in order to cope with the extremely track dense environment, the area of a single pixel cell will be 2500 μm2 with an active thickness of 150 μm. In this presentation results obtained in beam test experiments with 3D pixel sensors interconnected to the RD53A readout chip are reported. RD53A is the prototype, in 65nm technology, issued from RD53 collaboration for the future readout chip to be used in the upgraded pixel detectors. The irradiations of the interconnected detectors were performed at different irradiation sites up to a maximum fluence of about 2E16 neq/cm2. The sensors were produced in the FBK foundry in Trento, Italy, and their development was done in collaboration with INFN (Istituto Nazionale di Fisica Nucleare, Italy). The performance of the irradiated detectors was measured at different beam facilities (SPS-CERN and DESY II). The analysis of collected data shows very high hit detection efficiencies and good spatial resolutions as measured after irradiation. Analysis of most recently collected data is still underway; an overview of the up-to-date results, together with details of the pixel sensors, will be shown. All the results which make the object of this presentation are obtained in the framework of the CMS experiment R&D activities.

Electronics and ASICs / 150

MONOLITH - picosecond time stamping capabilities in fully monolithic highly granular silicon pixel detectors

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Monolithic silicon pixel detectors are attractive candidates for future large-area trackers in particle physics due to their advantages, for instance to reduce the production effort and material budget. State of the art monolithic silicon pixel detectors can reach high spatial precision. Integrating picosecond time resolution in such devices would significantly improve their performance and further widen their range of applications.

The MONOLITH ERC advanced project aims at achieving this by using SiGe BiCMOS electronics and a novel sensor concept, the Picosecond Avalanche Detector (PicoAD). Standard SiGe BiCMOS processes give access to ultra fast, high gain, low noise, low power frontend, implemented in a large collection electrode monolithic design. Using high-resistivity epitaxial layer material in combination with a continuous deep and thin gain layer, the novel PicoAD sensor concept permits to achieve a picosecond precise detector response over the full pixel cell. Placing the gain layer away from the pixel junctions additionally allows for a small pixel pitch and high spatial precision.

Several prototypes of this technology have been produced and investigated in simulations, laboratory and test-beam measurements. This presentation gives an overview of the novel sensor concept and the designed front end, and discusses the first preliminary results of the project.

Simulations / 151

DC-coupled resistive silicon detectors for 4-D tracking

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In this work, we introduce a new design concept: the DC-Coupled Resistive Silicon Detectors, based on the LGAD technology. This new approach intends to address a few known features of the first generation of AC-Coupled Resistive Silicon Detectors (RSD). Our simulation exploits a fast hybrid approach based on a combination of two packages, Weightfield2 and LTSpice. It demonstrates that the key features of the RSD design are maintained, yielding excellent timing and spatial resolutions: a few tens of ps and a few microns. In the presentation, we will outline the optimization methodology and the results of the simulation. We will present detailed studies on the effect of changing the ratio between the n+ resistivity and the low-resistivity ring, on the effect of noise, and on the achievable temporal and spatial resolution.

3D Sensors / 152

SINTEF 3D pixel sensor pre-production for the ATLAS ITk.

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SINTEF MiNaLab recently completed its sixth fabrication run of 3D pixel detectors as pre-production for the ATLAS ITk upgrade. The common sensor layout for RD53B sensors in 50x50 (1E) configuration was used. In addition, sensors compatible with RD53A readout as well as 3D diodes and 3D strips were included in the wafer layout. In this iteration of the technology, the active-edge was removed and replaced with the standard slim-edge termination with ohmic columns. Sensors were fabricated on 6", Si-Si bonded wafers, with a device layer thickness of 150µm, using a single-sided processing approach. The temporary metal layer was deposited, and the electrical characterisation was completed in December 2021. In this presentation, we will focus on the measurement results from standard planar test structures, 3D diodes and 3D pixel detectors. The fabrication process and its challenges will be discussed together with some numerical simulation results.

Planar Sensors / 153

Process quality control of silicon sensors for the Phase-2 upgrade of the CMS Outer Tracker for the HL-LHC

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After the current running period Run 3 the LHC will undergo a major upgrade with the instantaneous luminosity reaching at $7.5 \times 10^{34}\ cm^{-2}\ s^{-1}$. In order to maintain or improve the physics performance of the CMS detector in this challenging conditions of the HL-LHC, the entire tracking system must be replaced with new detectors with higher radiation tolerance and improved tracking capabilities. The upgraded CMS Outer Tracker will consist of 26592 new silicon sensors. CMS has developed a systematic quality assurance plan in order to have continuous information about the quality of sensors during the long production period and to ensure that the sensors meet the specifications. Process quality control is one of the main procedures for characterizing the sensors along with the sensor quality control and it is performed on dedicated test structures fabricated on the same wafer with the sensor, allowing quick and easy access to the stability of the fabrication procedure and the quality of the materials. The process quality control procedure includes measurements on MOS, diodes, gated diodes, FETs, and Van Der Pauw structures. In this work, the experimental apparatus of the process quality control is described along with the extraction procedure of the relevant process parameters. Examples of experimental results from various wafers are presented as well.

LGAD / 154

Quantum efficiency measurements of FBK silicon planar sensors with optimized entrance window for soft X-Rays.

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Single photon detection of X-rays in the energy range of 250 eV to 1 keV for hybrid detectors is difficult due to the low quantum efficiency (QE) and to the low signal-to-noise ratio (SNR). The low QE is caused by the absorption of soft X-rays in the insensitive layers of the silicon sensor (entrance window). The entrance window is typically from a few hundred nanometers to a couple of micrometers thick and is comparable to the absorption depth of soft X-rays photons (e.g., the attenuation length of 250 eV X-ray photons is ˜ 100 nm in silicon). The low SNR is mainly caused by the small signal amplitude (e.g, ca. 70 electrons for 250 eV X-ray photons in silicon) with respect to the electronic noise.
In order to cope with these challenges, the QE should be improved by optimizing the entrance window to minimize the absorption of soft X-rays in the passivation layer, and to reduce charge recombination in the silicon/oxide interface and in the highly doped implants. To increase the SNR, and thus achieve single photon resolution, the noise of the readout electronics needs to be reduced. However, even with JUNGFRAU 1.1 (32 electrons r.m.s equivalent noise charge for the very high gain stage) we obtain single photon resolution only down to ca. 600 eV. Low Gain Avalanche Diodes (LGADs) with a multiplication factor between 5-10 increase the signal amplitude and therefore improve the SNR for soft X-rays. Combining LGADs technology with an optimized QE technology can thus allow hybrid detectors to become a useful tool also for soft X-ray detection.
In the present work, the QE of backside illuminated single pad silicon p-i-n diodes with 9 different entrance window variations is studied. The sensors are characterized at the Surface Interfaces Microscopy (SIM) beamline of the Swiss Light Source (SLS) using soft X-rays ranging from 200 eV to 1250 eV. From the investigation, a QE of 62.5% at 250 eV is obtained with one of the variations and further optimization is planned based on this study.
In addition, the QE of the inverse LGADs (iLGAD) with a thin entrance window has also been investigated. The first measurements show similar QE values as the optimized QE technology for p-on-n sensors without multiplication, thus proven the feasibility of implementing optimized QE technology into LGAD technology. Further studies on the iLGADs optimized for soft X-rays, in particular their gain variation as a function of the photon absorption depth, will follow the next months.

Experiments, Applications, Systems / 155

The 100μPET project: a small-animal PET scanner for ultra-high-resolution molecular imaging with monolithic silicon pixel sensors

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Recent developments in semiconductor pixel detectors allow for a new generation of positron-emission tomography (PET) scanners that, in combination with advanced image reconstruction algorithms, will allow for a few hundred microns spatial resolutions. Such novel scanners will pioneer ultra-high-resolution molecular imaging, a field that is expected to have an enormous impact in several medical domains, neurology among others.

The University of Geneva, the Hôpitaux Universitaires de Genève, and the École Polytechnique Fédérale de Lausanne have launched the 100μPET project that aims to produce a small-animal PET scanner with ultra-high resolution. This prototype, which will use a stack of 60 monolithic silicon pixel sensors as a detection medium, will provide volumetric spatial resolution one order of magnitude better than today's best operating PET scanners.

The R&D on the optimisation of the monolithic pixel ASIC, the readout system and the mechanics, as well as the simulation of the scanner performance, will be presented.

Electronics and ASICs / 156

First tracks and initial timing results with Timepix4 ASIC

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A single arm beam telescope based on the Timepix4 ASIC was built in order to
perform first tests of synchronous readout and track reconstruction.
The telescope is composed of four planes with n-on-p silicon sensors.
Two of these planes are instrumented with 300 μm thick sensors tilted with respect to the beam, to provide high quality spatial measurements, while the remaining two have
100 μm thick sensors to achieve a better timing response.
Each detector assembly (sensor + Timepix4 ASIC) is readout with SPIDR4 system developed by Nikhef and ASI.
They are cooled by a 3D printed titanium blocks directly attached to the test PCB, through which a cooling fluid is circulated.
Both the cooling block and PCB have a circular cut-out to minimise the amount of material traversed by incident particles.
In this presentation, the initial results of the timing and spatial resolution of this telescope will be shown.

Electronics and ASICs / 157

A monolithic ASIC for the very high precision pre-shower detector of the FASER experiment at the LHC

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The design of a monolithic silicon pixel detector for the preshower of the FASER experiment at LHC is in progress, with the purpose of measuring and discriminating electromagnetic showers generated by photons with O(TeV) energies and separation down to 200 µm.
The new detector requires the development of a monolithic silicon pixel sensor with hexagonal pixels of 65 µm side, an extended dynamic range for the charge measurement and the capability to store the charge information for thousands of pixels per event. The ASIC will integrate a fast front-end electronics and analog memories inside the pixel area to allow for a frame-based event readout with minimum dead area and O(100) ps time resolution. A description of the architecture and design solution of the monolithic ASIC will be presented.

CMOS / 158

Performance Evaluation of Stitched Passive CMOS Strip Sensors

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Future particle physics experiments are motivated by the increase in luminosity and thus the need for intelligent tracking detectors providing fast track and momentum information to select events of interest. The next generation tracking detectors are mostly all silicon detectors and thus finding a cost effective solution to maximise the output is important. Commercial CMOS technology for silicon strip sensors is a prime candidate, which allows the use of large and high-resistive wafers and also provides the advantage of widely established industrial production processes.

The passive CMOS silicon strip sensors presented in this contribution is processed by a European foundry, in a 150 nm CMOS technology. The sensor have three different strip design to study in two different lengths and are formed by stitching of individual reticles. This study presents the probe station measurement and test beam results of the sensors before and after irradiation.

CMOS / 159

Depleted Monolithic Active Pixel Sensors (DMAPS) in 180 nm TowerJazz and 150 nm LFoundry Technology for High Radiation and High Rate Environments

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Monolithic active pixel sensors with depleted substrates are a promising option for pixel tracker detectors in high radiation environments. Exploiting high resistivity silicon substrate and high bias voltages in commercial CMOS technologies allows to enhance the radiation tolerance to levels of high radiation environments. As part of the DMAPS development, two full-size prototypes with the same column-drain readout architecture are currently tested and characterized in Bonn.

LF-Monopix2 is designed in 150 nm LFoundry CMOS technology employing a large charge collection electrode in which each pixel's digital electronics are integrated. This generally results in short drift paths and a homogeneous electric field across the sensor. Optimization of the pixel layout minimizes potential cross talk from the digital circuitry into the sensor node compared to its predecessor while reducing the pixel size to 50x150 um². The 180 nm TowerJazz CMOS technology used for TJ-Monopix2 features a small charge collection electrode with separated readout electronics. An additional n-type implant ensures full depletion of the sensitive volume. A smaller pixel size and low detector capacitance are benefits of this design resulting in lower noise.

In this talk results of the ongoing characterization of both prototype DMAPS are presented. Latest measurements for both Monopix chips as well as their predecessors are shown. Furthermore, upcoming plans and preliminary results of the testbeam campaign for both Monopix2 chips are discussed.

Miscellaneous / 160

Radiation damage studies of new p-n junction SiC detectors

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Silicon Carbide is one of the most promising materials for radiation detectors due to the high resistance to radiation damage. In this work we present the study of the radiation damage of a new large, p-n junctions silicon carbide device developed by SiCILIA collaboration. Several devices under test were irradiated in different experimental conditions with different beams in order to study its general performance as a function of fluence.

LGAD / 161

Defect spectroscopy studies on irradiated LGADs

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Si-based sensors, like Low Gain Avalanche Detectors (LGAD), operated in the high radiation environment of the CERN-LHC, undergo a degradation in performance that is significantly determined by defects formed during particle-interaction with the Si-crystal. In p-type Si a deactivation of active boron is observed –the so-called "acceptor removal effect"(ARE). One explanation of the ARE is the radiation induced formation of boron-interstitial oxygen-interstitial (BiOi) defects, that create donor-type energy levels which induce positive space charge. In the highly boron-doped LGAD multiplication layer the ARE can result in a complete disappearance of the gain at fluences higher than 2E+15 cm-2. However, assuming BiOi being the major ARE relevant defect cannot fully explain the boron-deactivation in LGADs. Therefore, to investigate the defect formation in LGAD gain-layers we performed defects spectroscopy studies using Deep Level Transient Spectroscopy (DLTS) and Thermally Stimulated Current technique (TSC) that we will present and discuss in comparison to defect studies made on irradiated standard p-type Si-diodes.

LGAD / 162

Readout development of a LGAD-based Hybrid Detector for Microdosimetry (HDM)

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Clinical outcomes collected over the past three decades have suggested that ion therapy has the potential to be a treatment modality superior to conventional radiation for several types of cancer, including recurrences, as well as for other diseases. Although the results have been encouraging, numerous treatment uncertainties remain a major obstacle to the full exploitation of particle radiotherapy.
To overcome therapy uncertainties optimizing treatment outcome, the best possible radiation quality description is of paramount importance linking radiation physical dose to biological effects.
Microdosimetry was developed as a tool to improve the description of radiation quality. By recording the energy deposition at the micrometric scale (the typical size of a cell nucleus), this approach takes into account the non-deterministic nature of atomic and nuclear processes, and creates a direct link between the dose deposited by radiation and the biological effect induced. Microdosimeters measure the spectrum of lineal energy y, defined as the energy deposition in the detector divided by most probable track length travelled by radiation. The latter is provided by the so-called "Mean Chord Length"(MCL) approximation, and it is related to the detector geometry.
To improve the characterization of the radiation field quality, we define a new quantity replacing the MCL with the actual particle track length inside the microdosimeter. In order to measure this new quantity, we propose a two-stage detector consisting of a commercial Tissue Equivalent Proportional Counter (TEPC) and 4 layers of Low Gain Avalanche Detectors (LGADs) strips. The TEPC detector records the energy deposition in a region equivalent to 2 um of tissue, while the LGADs are very suitable for particle tracking, because of the thickness thinnable down to tens of micrometers and fast response to ionizing radiation.
The concept of HDM has been investigated and validated with Monte Carlo simulations. Currently, a dedicated readout is under development. This two stages detector will require two different systems to join complementary information for each event: energy deposition in the TEPC and respective track length recorded by LGADs tracker. This challenge is being addressed by implementing SoC (System on Chip) technology, relying on Field Programmable Gated Arrays (FPGAs) based on the Zynq architecture. TEPC readout consists of three different signal amplification legs and is carried out thanks to 3 ADCs mounted on a FPGA board. LGADs activated strip signal is processed thanks to dedicated chips, and finally, the activated strip is stored relying again on FPGA-based solutions.
In this work, we will provide a detailed description of HDM geometry and the SoC solutions that we are implementing for the readout.

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Study of Irradiated CNM 3D Sensors

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For the high luminosity upgrade of the LHC, the CMS experiment is considering implementing the innermost layers of its inner tracker with 3D pixels. This technology should allow the detector to operate safely at unprecedented fluences that can be as high as O(2e16 Neq/cm2). In this study we present results of pixelated 3D sensors fabricated at IMB-CNM and interconnected to the RD53A demonstrator readout chip. The sensor plus chip ensembles were irradiated at the Fermilab irradiation test area with protons of momentum 400 MeV to fluences of approximately 1.3-2.0e16 and measured in a test beam of 120 GeV protons. We show some preliminary results of the sensor performance, including the hit detection efficiency and position resolution as a function of bias voltage and angle. Sensor characterization measurements also include the IV curve and the charge collection profiles inside a pixel cell for orthogonal incidence at full depletion.

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ATLAS ITk Pixel quad module test beam results

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As the module production for the ATLAS ITk Pixel detector approaches, prototype modules are scrutinised with test-beam particles to measure their properties. First results are presented of the reconstruction and analysis of these test-beam data for modules built with four front-end chips attached to a single sensor, called quad modules. The challenges of analysing data from quad modules are highlighted and a comparison with data from single chip modules is given.

LGAD / 165

TCAD Investigation of AC-LGAD

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Low Gain Avalanche Diode (LGAD) detectors are entering the mainstream as sensors planned for use in future particle detectors. However, their granularity is limited due to the need to isolate separate segments (strips or pixels) of the detector through the gain layer, limiting the granularity scale to approximately 1 mm. However, AC-coupled LGADs (AC-LGADs), also known as resistive silicon detectors (RSDs), provide solution to this limitation by reading out the detected particles through capacitive (AC) coupling through a thin passivation layer. The signal is collected temporarily under

the surface electrodes through the use of a resistive n+ junction layer. In this way precise timing is maintained, while precise position resolution is obtained through a combination of higher granularity and charge sharing between neighboring segments. In this work, we share the results of parametric investigation of strip AC-LGADs using two independent Technology Computer Aided Design (TCAD) tools: SilvacoTM Victory DeviceTM and SynopsysTM SentaurusTM. Results on the signal size and delay as a function of distance from the strip center are presented, and compared between each other as well as with test-beam data taken with a high-energy proton beam. Conclusions are drawn about the suitability of the use of TCAD simulation tools in the refinement of the design of AC-LGAD sensors.

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Influence of the ionization density on LGAD gain as measured with TCT, TPA-TCT and a beta source

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Low Gain Avalanche Diodes (LGADs) is one of the most promising sensing technologies for future 4D-tracking applications and has recently been qualified to be used in the ATLAS and CMS timing detectors for the HL-LHC upgrade. LGADs achieve an excellent timing performance due to the presence of an internal gain that improves the signal-to-noise ratio.
These detectors are designed to exhibit a moderate gain with an increase of the reverse voltage. However, the value of the gain strongly depends on the temperature. Thus, operation voltage and temperature must be kept under control in the experiments to maintain the gain within the required values. A reduction in the reverse bias or an increase in the temperature will reduce the gain significantly.
A further mechanism impacting on the gain was recently observed in LGADs. The gain measured in these devices highly depends on the charge density generated by a laser or particle in the bulk. Measurements performed with different detectors under different conditions showed that ionizing processes that induce less charge density in the detector bulk lead to an increase in the detector's measured gain.
Measurements were already conducted with IR-laser and Sr-90 in the lab confirming this mechanism. In this talk, we will present new measurements performed with a table-top Two Photon Absorption TCT system in a 300 um thick LGAD. Using this technique, very high charge carrier densities can be created inside the detector bulk at different depths that lead to different signal gain values. We present a model describing the observed data.

CMOS / 167

Timing properties of the RD50-MPW2 CMOS detector

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The CERN-RD50 collaboration has been developing High Voltage CMOS detector prototypes for high radiation environment based on high resistivity substrate and large collection electrode. In this contribution we will present timing properties of the RD50-MPW2 chip manufactured in LFoundry 150 nm process, which features an active 8 x 8 matrix of pixels with an analog front end and discriminator circuit. The time resolution and time walk of the detector were evaluated before and after neutron irradiation. Charge in the sensor was generated by laser TCT with light injection from the edge and back side.

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Development of a backside biased HV-CMOS sensor in a 150 nm process node for particle detection

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High Voltage-CMOS (HV-CMOS) sensors are an attractive option for tracking applications due to their high-performance and cost-efectiveness. However, to meet the challenging specifications required by future physics experiments in terms of radiation tolerance, time resolution and granularity, further R&D is needed to boost the performance of these sensors. UKRI-MPW0 is a new HV-CMOS sensor prototype, developed in the 150 nm process technology from LFoundry, aimed at addressing some of these specifications.

This contribution presents the main design aspects and preliminary laboratory evaluation results of UKRI-MPW0. The prototype implements a novel sensor cross-section optimised for backside biasing at unprecedented high voltages and targeting a large improvement in radiation tolerance. The chip uses a 1.9 kΩ·cm high resistivity substrate, and samples have been thinned to 280 µm and backside processed following two different techniques, namely plasma immersion ion implantation with laser annealing and beamline implantation with rapid thermal annealing. The chip has two large active matrices, several test structures consisting of small passive matrices with different pixel sizes (from 40 µm x 40 µm to 70 µm x 70 µm) to characterise the sensor depletion region, and of linear and circular transistors to study their radiation tolerance. One of the active matrices uses linear transistors only, whereas the other active matrix uses circular transistors. Each matrix has 20 rows and 29 columns of pixels. The pixels are 60 µm x 60 µm and integrate analogue readout electronics inside the collecting electrode. Each matrix has three different pixel flavours, which are continuous reset, switched reset and modulated feedback, to study and improve the sensor time resolution. The chip has a total area of 5 mm x 3.5 mm.

Preliminary measurements before and after neutron irradiation have shown the chip is able to sustain high bias voltages much beyond other state-of-the-art HV-CMOS detectors. We are in the process of measuring the active matrices with the Caribou readout system. The measurements shown at the workshop will focus on diode and transistor I-Vs, and active matrix characterisation.
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Electronics and ASICs / 169

Study of the charge carrier properties GaAs:Cr with Timepix3

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Recent advantages in crystal growth have facilitated the production of high resistivity (HR) chromium compensated gallium arsenide (GaAs:Cr), which has become an alternative to silicon especially in X- and gammas-ray detection and imaging, where such sensors profit from their higher absorption efficiency. To explore charge transport properties of the material we measured the dependence of the electrons and holes drift velocity on the electric field and the dependence of the diffusion coefficient on the electric field. It became possible by analyzing the detector response to charged particles entering the detector at grazing angle. The holes lifetime and their mobility was measured using the drift time information for the first time for HR GaAs:Cr material to be τ_{h} = 4.5±0.5 ns, μ_{h} = 320±10 cm2/V/s at 300 V. The measured parameters were validated by comparison of the measured and the simulated data for various X- and gammas-ray sources in the energy range of 6 –60 keV, protons of 125 MeV, and pions of 120 GeV/c. The sufficient lifetime of electrons (˜30 ns) and their higher mobility (> 3000 cm2/V/s) in comparison with silicon make the GaAs:Cr sensors interesting tools to fully exploit the timing precision of Timepix3 (i.e. 1.6 ns) in particle tracking applications or for characterization of pulsed X-ray sources.

Miscellaneous / 170

Silicon Detectors Beyond LHC –RD50 Status Report

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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 LHC-Phase-II trackers. While these trackers are now entering their construction phase, RD50 is continuing to study silicon sensors for particle tracking, but shifting the focus to applications beyond the LHC. The next generation of collision experiments, such as the FCC, require unprecedented radiation hardness in the range of a few $10^{17} N_{eq}$ as well as time resolutions of the order of 10ps. Another challenge is to move the sensor technology away from traditional planar and passive float-zone sensors that from large parts of the LHC-Phase-II trackers to sensor technologies such as CMOS where front-end electronics can be integrated, and where a wide availability promises cost advantages.
Key areas of recent RD50 research also include technologies such as Low Gain Avalanche Detectors (LGADs), where a dedicated multiplication layer to create a high field region is built into the sensor, resulting in time resolutions of a few tens of ps. Another strong activity is the development of sensor types like 3D silicon detectors.We also seek for a deeper understanding of the connection between macroscopic sensor properties such as radiation-induced increase of leakage current, doping concentration and trapping, and the microscopic properties at the defect level. A new measurement tool available within RD50 are the Two-Photon-Absorption (TPA) TCT systems, which allow position-resolved measurements down to a few μm.

Planar Sensors / 171

Characterisation of the silicon oxide quality in HGCAL sensor prototypes

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The quality of the silicon oxide layer in 8" sensor prototypes for the CMS High Granularity Calorimeter (HGCAL) is studied by means of X-ray irradiation of dedicated test structures at the CERN ObeliX facility. A fully automated irradiation and measurement setup called AXIOM (Automated X-ray Irradiation and Oxide Measurements) has been developed at CERN for this purpose.

Different oxide variants provided by Hamamatsu are characterised and compared to the results obtained with HGCAL 6" prototypes and sensors of the CMS outer tracker. A clear preference has emerged from these studies, and the oxide type with the best performance has been irradiated up to a dose of 3 MGy, the expected absorbed dose in the forward region of the detector at the end of the High-Luminosity LHC run. The findings of this measurement campaign have contributed to the choice of the oxide type for the next version of the HGCAL sensor prototypes, which will undergo larger scale testing.

LGAD / 172

Development of Low Gain Avalanche Detectors at Teledyne e2v

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Low Gain Avalanche Detectors (LGADs) are a novel silicon sensor technology being developed to design full 4D trackers able to measure precisely both spatial and temporal coordinates. The first deployment of this technology will be in the ATLAS and CMS timing layers at the High Luminosity LHC where, by adding fast timing information to each crossing track, they will allow to better separate overlapping events.
Further developments of this technology will be pursued in anticipation of their use at future collider experiments where 4D tracking detector systems will be needed to cope with an unprecedented number of pile-up and beam background events through the addition of precise timing information to each point along the track. In this context, the University of Birmingham, University of Oxford, Rutherford Appleton Laboratory and Open University are working with the UK foundry Teledyne e2v to establish their processing line for LGAD production. The addition of Te2v to the currently established LGAD manufacturers will significantly increase LGAD production volume capabilities.
This talk will present updates on the ongoing characterisation of the first batch of LGAD sensors produced by Te2v, designed to match the specifications of the ATLAS and CMS timing layers. IV and CV measurements have been completed on a set of wafers that allows to compare the performance of the devices for different energy and dose of the gain layer implant. Diced structures from one of the wafers have undergone full characterisation including gain and timing measurements. We will present results from a set of un-irradiated devices and possibly first results after irradiation. Studies are also ongoing to evaluate the jitter component of the timing resolution. Finally, we will present plans for the design of the structures for the second batch of LGAD production at Te2v.

LGAD / 173

High-injection carrier dynamics generated by MeV ions and fs-laser, impacting the LGAD's limiting response: SEB and Gain suppression

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LGAD's failure due to Single Burnout Event and charge collection insufficiency (gain suppression) received a lot of attention recently,
Those radiation and high injection effects have some features in common, both deals with high density of generated charge but what distinguishes them seems to be the main triggering mechanism for another. While SEB induces a localized high-current state, gain suppression is charge cloud screening and gain polarization effect. While impact ionization by the holes seems to be suppressed during "gain suppression", their participation is crucial for self-sustaining of SEB.

SEB events have been investigated at ELI Beamlines in fs-laser tests, while the gain suppression presented here is investigated in IBIC tests at RBI and at ELI Beamlines. Through the use of different ion species at RBI and their respective energies, measurable charge signals give an insight into carrier transport properties in a wide range of detector depths. This also allows us to investigate the roles of two dominate phases of charge collection: the diffusion-dominated expansion phase of a charged cloud and the bipolar phase where the external field penetrates the clouds resulting in rapid charge injection into gain layer. The "transition" between those two phases can be seen as the "gain peak", more pronounced for more penetrating protons and carbons and at lower voltages. Gain suppression in SEB events was also investigated.

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Penetrating Particle Analyser (PAN). Silicon tracker development. Beamtest results

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Penetrating particle Analyzer (PAN) is an instrument designed to be used in deep space and interplanetary missions. It can precisely measure and monitor the flux, composition, and direction of highly penetrating particles in the effective range between 100 MeV/nucleon and 10 GeV/nucleon. It is a versatile device, which can potentially have an application in cosmic ray physics, solar physics,

space weather and space travel. PAN is a compact magnetic spectrometer (less than 20 kg of mass) with relatively low power budget (around 20 W). These features allow the spectrometer to potentially become one of the standard onboard devices accompanying future deep space human travel. The device consists of permanent magnet sections, high resolution silicon strip detectors, scintillating detectors and silicon pixel detectors. At the current stage of the device R&D, a first prototype, called MiniPAN, was built. The MiniPAN is a reduced version of PAN designed to estimate the capabilities and performance of a full-scale device - PAN. The MiniPAN consists of an aluminum supporting structure, 2 sections of permanent magnets, 6 silicon strip detectors measuring a single coordinate of a particle trajectory (X coordinate layers called StripX) and readout electronics. The StripX was designed as thin (150 ⊠m) layer of long silicon strips with a fine pitch (25 ⊠m) and 2048 readout channels in order to push the limit of a position resolution up to 2 ⊠m and provide the best momentum resolution for penetrating particles within the effective energy range.
In the second half of 2021 the beamtests were performed at CERN (Geneva) to demonstrate the performance (signal/noise ⊠ 8), the quality of the production of both single StripX layers and the MiniPAN protortype with 6 StripX layers (with/out magnets installed). The preliminary position resolution values obtained for 10 GeV/c negative pion beam are 6.4 ⊠ 0.64 ⊠m for the inner StripX module of the MiniPAN. The reconstructed momentum resolution studies are still ongoing and the data taking is continued using a cosmic ray setup built in the laboratory of the Department of Nuclear and Particle Physics of the University of Geneva. We will present current status of the hardware and the preliminary results from the beamtest and cosmic rays data.

LGAD / 175

Stability of irradiated LGAD sensors in the Fermilab high-rate proton beam facility

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Low Gain Avalanche Diodes (LGADs) will be employed in the CMS MTD and ATLAS HGTD upgrades to mitigate the high levels of pileup expected in the High Luminosity phase of the LHC. Over the last several years, much attention has focused on the development of radiation tolerant gain implants that successfully provide gain even after the fluences expected at the HL-LHC, in excess of 1 x 10ˆ15 neq/cmˆ2. However, it has been observed that highly-irradiated sensors operated at large bias voltage can be susceptible to single event burnout (SEB) when exposed to highly ionizing particles. The SEB mechanism has previously been studied in detail by CMS using the low-rate proton beam at Fermilab. We present the results of a new campaign using a high-intensity proton beam that demonstrates the successful operation of irradiated LGADs exposed to an extreme charged particle flux comparable a year at the HL-LHC. We find that the SEB mechanism is mitigated by a slight reduction in bias voltage, with little to no impact on the CMS MTD performance.

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Study of bulk damage induced by gamma irradiation in n-in-p silicon diodes

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The main goal of the presentation is to show the dependence of the leakage current and full depletion voltage on TID. Whereas the measured I-V characteristics show a linear dependence on TID, the full depletion voltage and thus also the effective doping concentration significantly decreases with higher gamma irradiation. The gradual decrease of the effective doping concentration with higher TID can be associated with acceptor removal or donor introduction.
The study was performed on $8 \times 8\,\mathrm{mm}^2$ n-in-p diodes fabricated on standard float zone silicon wafers with the initial resistivity of about $3\,\mathrm{k}\ \cdot \mathrm{cm}$. These diodes were irradiated in the range of $(10-564)\ \mathrm{MRad}$ by ^{60}Co gamma rays in an approximate charge particle equilibrium. An important feature of these samples is the presence of contact pads on the guard ring, which enables us to separate the bulk current from the total leakage current by grounding the guard ring during I-V and C-V measurements.