Proposal for PhD activities

“Characterization of first prototypes of ultra-thin bended silicon pixel sensors using wafers of the ALPIDE chip”

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Introduction:
In recent years, a tremendous achievement in silicon detectors has been the development of the CMOS Monolithic Active Pixel Sensors (MAPS), with the sensor matrix and readout integrated in a single chip. Presently, the state of the art is the ALPIDE (Alice Pixel Detector) developed for the ALICE upgrades to be finalized during the second long LHC shutdown (LS2). One of the key components of the ALICE upgrade programme is in fact the replacement of the current Inner Tracking System (ITS) with an entirely new one (ITS2) with increased vertexing and tracking performance, especially for particles with low transverse momentum (Pt<1 GeV/c). The new ITS consist of seven approximately cylindrical detector layers based on CMOS MAPS, the basic silicon chip is the ALPIDE and the full detector covers a 10 m² area with about 12.5 billion pixels. The ALPIDE chip contains approximately 5x10⁵ pixels, each measuring about 27µm X 29µm, arranged in 512 rows and 1024 columns, for a total active area of 30mm X 15mm and thickness of 50µm.

The aim of the current report is to present the proposal for a PhD project related with the characterization of first prototypes of ultra-thin bended silicon pixel sensors using wafers of the ALPIDE chip, taking as an important aspect, the applicability of the work in some fields like Particle Physics and Medicine.

Motivation:
Despite the high performance reached with the ALPIDE in terms of signal/noise ratio, spatial resolution, material budget and readout speed, there is still a lot that can be done to further improve MAPS. In this aspect, a proposal for the replacing of the three innermost layers of the ITS2 during the future LS3 has been presented. The related improvements are, radius and thickness reduction of the beam-pipe (inner radius from 18.2mm to 16mm and thickness from 800µm to 500µm); first detection layer positioned closed to the interaction point (from 23mm to 18mm) and impressive reduction of material budget (from 0.358% X₀ to 0,05% X₀ per layer). The new detector is referred to as ITS3.

These new features in a vertex detector will reduce to a minimum the multiple scattering in the beam pipe and in the first detection layers. With special interest in central Pb-Pb collisions with interaction rate of 50 kHz, the tracking and vertexing performance, which have been studied using Monte Carlo simulation tools, will be also improved, due the decreasing of tracking uncertainties because the reduction of multiple scattering inside the material of layers and the reduction of the inner radius. Figure 1 shows the comparison of the impact parameter resolution and tracking efficiency for ITS2 and ITS3 for pions at typical pseudorapidity η=0.5. The track impact-parameter resolution, which is defined as the dispersion of the distribution of the Distance of Closest Approach (DCA) of the reconstructed (primary) tracks to the interaction vertex, is the parameter that defines the capability of a vertex detector to separate secondary vertices of heavy-flavour decays from the interaction vertex. In all simulated cases the impact parameter resolution of ITS3 is significantly better than that of ITS2 and also the efficiency is grater for ITS3 at low Pt.
Figure 1. Impact parameter resolution (left) and tracking efficiency (right) for primary charged pions at typical pseudorapidity $\eta=0.5$ in central Pb-Pb collisions ($\sqrt{s_{NN}}=5.5$ TeV) as function of transverse momentum for the ITS2 and two different ITS3 detector configurations.

Reducing material thickness and bending sensors:

Currently, the Silicon sensor, which has a thickness of 50µm represents only 15% of the total material, the rest being due to the material of the electrical substrate (Flexible Printed Circuit) (50%), the cooling circuit (20%) and the carbon spaceframe (15%). In order to improve the material budget, the cooling circuit could be removed with the possibility of using a low-speed (<2ms$^{-1}$) air flow, which is a viable option for sensors with a power density below 20 mW cm$^{-2}$ (Only 7 mWcm$^{-2}$ of the total power density of ALPIDE chip 40 mWcm$^{-2}$ is dissipated in the pixel matrix); the pixel sensor digital periphery could be placed at the edge of the detector and the mechanical support could be also removed due the higher Si stiffness. In this way all the unneeded materials could be removed, remaining only the Silicon with 0.05% $X_0$ of material budget.

One of the features offered by CMOS imaging sensor technologies is the stitching. In standard CMOS manufacturing, the maximum size of a chip is limited to the reticle area defined by the field of view of the photolithographic steps, which is typically a few centimeters in both directions, the reticle is just stepped and repeated across the wafers to create multiple identical images of the same circuit or group of circuits. Stitching technology allows a fabrication of an image sensor that is larger than the field of view of the lithographic equipment, the reticles which fit into the field of view of that equipment are placed on the wafer with high precision, achieving a well-defined overlap, in this way, wafer-scale sensors can be produced. Figure 2 shows a large area sensor for X-Ray applications produced by stitching with the Tower Semiconductor 0.18/0.35 µm dual gate process.
The first step towards the final large area chip for the ITS3 would be to develop a new circuit (Fig. 3) of size 15mm x 14mm. The columns run along the short side of the sensor and have the same length as in the ALPIDE sensor. Data are extracted from the matrix as in the ALPIDE chip with hit-driven circuitry based on priority-encoder addressing scheme. Groups of 16 double columns are read out sequentially and data are transmitted from the bottom of the columns along one long side of the sensor to the periphery, which contains the control logic to steer the priority encoders, the interface for the configuration of the chip and the serial data transmitters. A flexible PCB, placed only under the digital periphery of the chip, will provide power to the sensor.

Sensor material could be reduced even more reducing the epitaxial layer from 25 to 18–20 µm by mechanical thinning. As below 50 µm Si becomes flexible and remains with good stability, the possibility to bend and operate curved sensors would be opened, then cylindrical layer of silicon-only sensors may be constructed. By reducing the beam pipe radius, a silicon layer could be placed at unprecedented small distances from the interaction point.

**ITS3 layout:**

Based on these ideas, the ITS3 will have a completely new Inner Barrel consisting of the three innermost layers (Layer 0 to Layer 2) that replaces the current Inner Barrel of ITS2. The ITS3 IB will consist of two halves, named half-barrels, to allow the detector to be mounted around the beam pipe. Each half-barrel will consist of three half-layers. Each half-layer is segmented...
longitudinally (at z = 0) in two halves, named quarter-layers. Each quarter-layer consists of a single large pixel chip, which is curved to a cylindrical shape. Ultra-lightweight half-wheel spacers are inserted between layers to define their relative radial position (Fig. 4).

Figure 4. Layout of the ITS3 Inner Barrel. The figure shows the two half-barrels mounted around the beam pipe.

**Activities:**

The activities proposed for this PhD will be focused on the characterization of first prototypes of ultra-thin bended silicon pixel sensors using wafers of the ALPIDE chip. It will be a preliminary feasibility study to demonstrate that full functionality is preserved upon bending the sensor, with the aim of applying this new detection system, not only in the field of High Energy Physics, but in others like Medicine. The test program will include measurements of electrical properties, this is, charge collection efficiency, cluster multiplicity, signal-to-noise ratio, equivalent noise charge, detection efficiency, single point space accuracy, noise occupancy and temporal noise. Verifying these features is of importance because the strain applied to the material when it is bended could damage the micro-circuitry of the chip (realized in the lithographic process in the plane geometry) or even produce tensions between atoms and planes in certain points of the crystal structure and this could lightly modify the semiconductor properties in some areas of the wafer, compromising the response of the sensor.

These experimental activities will take place in one of the department laboratories that it is conditioned like clean room, the laboratory will be reorganized according to the needs and requirements for the future measurements.

**Examples of applications in Particle Physics:**

**Measurement of $\Lambda_c$ production in hadronic collisions (pp, p-Pb and Pb-Pb):**

The measurement of the production yields and flow of charm and beauty baryons is of particular interest to study the thermalisation and the mechanism of hadronisation of c and b quarks in the QCD medium. In particular, if in Pb–Pb collisions heavy quarks can thermalise and hadronise via recombination with light-flavour quarks present inside the Quark-Gluon Plasma (QGP) or at the QGP phase boundary, the production of charm and beauty baryons is expected to be significantly enhanced in the low and intermediate momentum region, say below 3 GeV/c. A precise measurement in the charm sector would provide crucial information on the charm quark thermalisation an hadronisation in the QGP. Particularly, at low moment, the study of the elliptic flux and the azimuthal anisotropy coefficient ($v_2$) for charmed baryons and mesons, can provide direct evidence of the collective behavior of the medium. More in general, recent measurements at the LHC indicate a large enhancement of the baryon-to-meson ratio $\Lambda_c/D^0$ in p-p with respect
to \( e^+ e^- \) collisions. This ratio is thus significantly underestimated by several Monte Carlo generators (tuned to the results in \( e^+ e^- \) collisions) implementing different charm quark fragmentation processes, suggesting that the fragmentation functions to charm quarks into different hadronics states are non-universal with respect to collision system and energies.

From the experimental point of view, the main issue for the measurement of charmed baryons is their short lifetime, the \( c\tau \) of the \( \Lambda_c \) is about 59 µm, a factor of 2 smaller than that of the \( D^0 \) meson.

One of the most convenient decay channels is \( \Lambda_c^+ \rightarrow p K^-\pi^+ \), which has a large three-prong combinational background. The measurement require very precise tracking and impact parameter resolution, because the decay tracks are typically displaced from the main interaction vertex by only a few tens of microns (\( \sim c\tau \)). This makes the measurement of the \( \Lambda_c \) a powerful benchmark to assess the improvement of the detector in terms of physics performance for heavy-flavour.

**Measurement of thermal dielectrons:**

Electromagnetic radiation produced by the high-temperature system formed in heavy-ion collisions can be detected using real direct photons with very low momentum or virtual photons yielding low invariant-mass dilepton pairs. The measurement using dielectron pairs in the ALICE central barrel, implies electron detection down to \( P_t < 100\text{MeV}/c \). Since the production rate of thermal dileptons is small, very good electron identification is mandatory to suppress the combinatorial background in which one of the particles of the pair is a hadron misidentified as an electron. Moreover, electrons from \( \pi^0 \) Dalitz decays and photon conversions (mainly from \( \pi^0 \rightarrow \gamma\gamma \)) produce a large combinatorial background.

In general, the reduction of material budget of the beam pipe and the inner barrel layer will reduce conversions by a factor of 3. The enhanced low- \( P_t \) capability will improve the reconstruction efficiency of photon conversions and the improved pointing resolution will enable efficient tagging of electrons from semi-leptonic charm decays.

**Applications in Medicine:**

**Radio-Guided Surgery (RGS) with \( \beta^- \) emitting radio-tracers:**

The process for the RGS consist of the administration of specific pharmaceuticals linked to a radio-nuclide, called radio-tracers, such pharmaceuticals are preferentially absorbed by tumors rather than healthy tissues and the radiation emitted reveals the portion of tissue affected. With an intra operative probe, the complete tumor extraction and presence of residuals during the operation is verified.

\( \beta^- \) emitting radio-tracers have a range of approximately 5 mm in body for 1 MeV electrons. An interesting application is related with \( \beta^- \) emitting radio-tracers as \( ^{18}\text{F-FDG} \) (fluorodeoxyglucose). Here, a \( \gamma/\beta \) detection ratio as low as possible is required in order to reduce the photon background from positron annihilation, achieving a clean and precise localization of small tumoral masses. With a sensitive layer of only \( \approx 25\mu m \), it is indeed expected that already the ALPIDE chip be almost transparent, hence insensitive, to \( \gamma \) radiation with energies in the order of few hundred keV, including photons produced from positron annihilation. Additionally, having also a detector with curved shape during a surgery could provide a better detection coverage of the radioactive volume.

**Positron Emission Tomography (PET):**

The Positron Emission Tomography is also an interesting application in the field of Medicine for the ALPIDE sensor. Having the possibility to replace conventional detectors in the cylindrical
scans (Fig. 5) with large curved sensitive silicon layers, would be an advantage in terms of larger area for detection and higher spatial resolution for the imaging purposes. Because of the transparency of the chip to γ radiation, a material deposit acting as a converter needs to be deposited as part of the assembly.

Figure 5. Image of the equipment with a cylindrical scan used for Positron Emission Tomography.