Upgrade of the ALICE Inner Tracking System

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Abstract. ALICE detector was constructed to study the properties of hot and dense hadronic matter formed in relativistic nuclear collisions. During the second long LHC shutdown in 2019-2020, the collaboration plans to upgrade the current vertex detector, the Inner Tracking System (ITS), in order to increase the reconstruction accuracy of secondary vertices and to lower the threshold of particle transverse momentum measurement. The upgrade strategy of ITS is based on the application of new Monolithic Active Pixel Sensors (MAPS) designed in 0.18 μm CMOS technology. The 50 μm thick chip consists of a single silicon die incorporating a 0.18 μm high-resistivity silicon epitaxial layer (sensor active volume) and matrix of charge collection diodes (pixels) with readout electronics. Radiation hardness of the upgraded ITS is one of the crucial moments in the overall performance of the system. A wide set of MAPS structures with different read-out circuits was produced and is being studied by the ALICE collaboration to optimize the pixel sensor functionality. An overview of the ALICE ITS upgrade and the expected performance improvement will be presented together with selected results from a campaign that includes several irradiation and beam tests.

1. General ALICE upgrade
ALICE [1] is an experiment designed to study properties of the Quark-Gluon Plasma using nucleus-nucleus, proton-nucleus and proton-proton collisions at the CERN Large Hadron Collider. ALICE has confirmed the existence of the quark-gluon plasma and extended the precision and kinematic reach of many significant probes measured previously at RHIC and at the SPS. After the second long shutdown of the LHC in 2019–2020, ALICE will focus on the measurement of heavy-flavor hadrons, quarkonia and low-mass dileptons at low transverse momenta [2]. This requires high-precision measurements at low transverse momentum $p_T$ resulting in the need of recording large samples of minimum-bias events. In order to achieve this, ALICE plans to read out all Pb–Pb collisions delivered by the LHC, which corresponds to a maximum collision rate of 50 kHz. The upgraded detector will record an integrated luminosity of 10 nb\textsuperscript{−1} in Pb–Pb collisions which means a factor 100 more compared to the data that will be recorded up to 2018. The ALICE upgrade strategy includes several projects [2]. Two new detectors will be installed: a high resolution, low material budget Inner Tracking System and a Muon Forward Telescope. They will be surrounding a new beampipe with a smaller radius, which will allow the first layer of the ITS to be moved closer to the interaction point resulting in better track impact parameter determination. The readout chambers of the Time Projection Chamber will be replaced by Gas Electron Multiplier detectors and its readout electronics will be upgraded together with the readout electronics of the Transition Radiation Detector, the

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Time Of Flight detector and the Muon Spectrometer. The forward trigger detectors, the online system and the offline reconstruction and analysis framework will also be upgraded.

2. The new Inner Tracking System
The goals of the ITS upgrade [3] are to improve the track impact parameter resolution (by at least a factor of 5 in $z$ direction and by a factor of 3 in $r\phi$ direction), the tracking efficiency and the transverse momentum resolution at very low $p_T$. In order to achieve these improvements the first layer of silicon detectors will be placed closer to the interaction point (figure 1). The reduction of the beam pipe diameter in the center of ALICE will allow the first ITS layer to moved as close 22 mm to the interaction point instead of the present 39 mm. The spatial resolution and the tracking performances will gain from a reduction of the material budget, in particular in the inner layers. The use of MAPS, the optimization of the front-end electronics, and the consequent reduction of the power and signal cables will reduce the total material budget $X/X_0$ per layer from the present 1.14% to as low as 0.3% for the three innermost layers and to $\sim 0.8$% for the outer layers. Both track impact parameter and momentum resolutions will improved by increasing the detector granularity. The current design assumes that all layers are segmented in pixels with dimensions of 28 $\mu$m $\times$ 28 $\mu$m. Finally, the tracking efficiency and $p_T$ resolution will also be improved by increasing the number of layers (from present 6 to 7). The seven layers of the new ITS will cover an area of around 10 m$^2$ and will consist of around $1.25 \times 10^{16}$ pixels. The layers will be grouped according to the following: the three innermost layers make up the Inner Barrel and the four outermost layers the Outer Barrel (figure 1). All the layers will be segmented into elements called staves which extend the full length of the detector in the direction of the beam. A stave is the smallest operable unit of the detector and has a slightly different design in the case of the Inner and Outer Barrel. In addition it will be possible to remove the detector for maintenance and replace faulty modules during yearly shutdowns. The new ITS will not measure the ionization in the silicon layers. For what concerns the environment in which the new ITS will operate, recent simulations have shown that the overall dose expected for the innermost layer can reach up to 2.7 Mrad (TID) and $1.7 \times 10^{13}$ 1 MeV $\text{eq}/\text{cm}^2$ (NIEL), including a safety factor of 10, for the full integrated luminosity. The present ITS runs up to a maximum of 1 kHz. The upgraded ITS aims to read out data up to a rate of 50 kHz in Pb–Pb collisions and 400 kHz in pp collisions, with a dead time of about 10%.

3. Pixel chips
The active sensors and the readout electronics have very demanding requirements in terms of granularity, material thickness, readout speed, power consumption and radiation hardness. An intrinsic spatial resolution of 5 $\mu$m for the innermost layer requires a pixel pitch of $\sim 30$ $\mu$m. A significant reduction of the material budget, in particular for the innermost layers, to reduce
the multiple Coulomb scattering, leads to a silicon thickness of 50 μm at maximum. According to the thermal studies that were carried out on prototype mechanics the power density on the sensor should not exceed 300 mW/cm². In order to cope with the assumed interaction rates and dead time in Pb–Pb and pp collisions, the maximum acceptable sensor integration time is ∼ 30 μs to limit the event pile-up. Finally, the pixel detectors have to be tolerant against the radiation levels expected in the ITS environment. Based also on the STAR Pixel experience [4], the monolithic CMOS MAPS technology has been chosen for the pixel detectors. The 0.18 μm CMOS technology by TowerJazz has been selected for the implementation of pixel chip for all layers of the new ITS. Due to the small feature size, it is expected to be more robust to the total ionizing dose than other technologies employed so far. The same feature size and the number of metals available are adequate to implement high density, low power digital circuits, minimizing thus the dead area and making the power extraction more efficient. This technology allows the production of chips on wafers with a resistivity of 1 ÷ 5 kΩ·cm. In this way a substantial part of the epitaxial layer is already depleted at the reverse bias voltage applied to the collection diodes in the CMOS sensors. This will increase the signal-to-noise ratio and improve the resistance to non-ionizing radiation.

4. Performance of the pALPIDEs
There are two parallel chip developments ongoing for the ITS upgrade, the ALPIDE and the MISTRAL-O. Here we focus on the ALPIDE architecture. It has 512 × 1024 digital pixels with the size of 28 μm × 28 μm. It is read out using an asynchronous priority encoder network, thanks to which only hit pixels are read out resulting in very fast acquisition of the data from the full matrix. The chip is organized in four sub-matrices consisting of different types of pixels (figure 2). Several prototypes of the ALPIDE family have been designed by the ITS group. These prototypes have been characterized in several test beam campaigns at different test beam facilities (PS, SPS, DESY, BTF Frascati and PAL Pohang). The beam energy at these facilities range is from 60 MeV to 120 GeV and the particles used are electrons, positrons and pions. The following results were obtained at the PS using a 6 GeV negative pion beam. A telescope consisting of seven pALPIDE chips where the outer six chips are the tracking planes and the middle chip is being tested. Here we present the selected results of pALPIDE-2 with 25 μm
Figure 4. Position resolution and cluster size before and after irradiation level of $1.7 \times 10^{13}$ 1 MeV neq/cm$^2$. Lines, connecting points, are a guide to the eye.

epitaxial layer and -6 V back bias voltage, before and after irradiation. For data analysis EUrTelescope software package is used [5]. Figure 3 represents the particle detection efficiency, that is better than 99% for different threshold currents. At the same time fake hit rate is less than $10^{-5}$ hits/event/pixel. ITS project goals are thus fulfilled at a wide operating range of the threshold current. The good performance is also observed for chips that were irradiated with $10^{13}$ 1 MeV neq/cm$^2$. In figure 4 the resolution stays below 5 $\mu$m, which fulfills the project goal, and cluster size is only slightly affected by irradiation to expected NIEL of $1.7 \times 10^{13}$ 1 MeV neq/cm$^2$.

5. Conclusion
The Inner Tracking System of ALICE will be upgraded during the second long LHC shutdown to fulfill the ALICE physics requirements. Its key features are low material budget, an increased number of layers, a greater radial extension with a first layer closer to the interaction point, and a smaller pixel size. The pixel sensors will employ the CMOS MAPS produced using the 0.18 $\mu$m TowerJazz technology. First full scale prototypes show a good performance and large operational margin.

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