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ALICE ITS3: the first truly cylindrical inner tracker

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During the next LHC Long Shutdown 3 in 2026–2028, the ALICE Collaboration plans to replace the three innermost layers of the current Inner Tracking System (ITS) with truly cylindrical layers, made of wafer-scale, thin (< 50 µm), and bent Monolithic Active Pixel Sensors (MAPS) that will be produced with the 65 nm CMOS imaging process. To fabricate the wafer-scale sensors, a technology, called stitching, is utilized to "stitch" small reticles and build sensors up to 300 mm in length in a single wafer. The upgrade aims to decrease the material budget of the innermost layers from the present 0.35% of X_0/layer to 0.05% of X_0/layer, essentially reducing it to the silicon contribution only. The upgraded ITS will improve the pointing resolution in the transverse plane by a factor of 2 and increase the reconstruction efficiency for low-p_{T} tracks. The construction of this detector encompasses many cutting-edge R&D efforts, for instance, production and characterization of the MAPS in the 65 nm CMOS process, fabrication of the stitched wafer-scale MAPS, and development of an ultra-light detector mechanics and a new air cooling system. This contribution provides a brief overview of the ALICE ITS3 detector and the R&D achievements, mentioned above.

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1. Introduction

Before Run 3 of the LHC, the ALICE experiment underwent a significant upgrade. A crucial part of the upgrade was the installation of a new silicon vertex tracker, called the Inner Tracking System (ITS2) [1]. The upgraded ITS detector allows for precise measurements of various observables, including low-p_T heavy-flavor hadrons, anti-nuclei, and hypernuclei. The ITS detector consists of 7 layers of Monolithic Active Pixel Sensors produced using the 180 nm CMOS process. The first three layers form the so-called Inner Barrel, where the innermost layer is located at a radial distance of 22 mm from the interaction point. The layers of the Inner Barrel have a material budget of 0.35% X_0/layer. Figure 1 shows the material distribution of the first Inner Barrel layer as a function of the azimuthal angle. Note that, to a large extent, the material budget is formed by

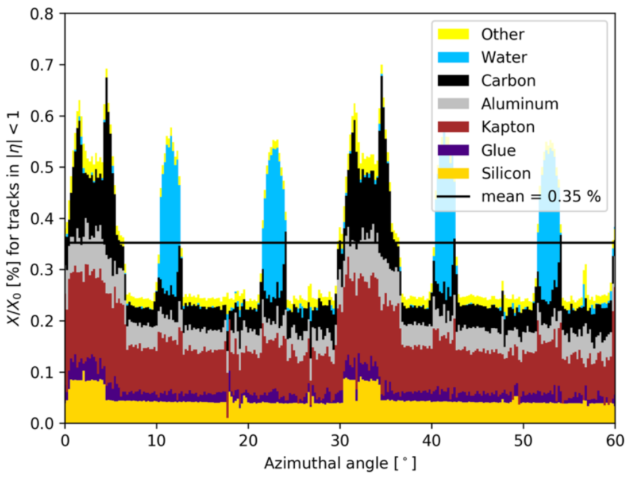

Figure 1: Material distribution in the first layer of the ITS2 detector. Taken from Ref. [2].

passive components, such as water cooling, carbon support structures, and flexible printed circuits. Silicon chips make up only about 1/7 of the material budget.

The passive material worsens the reconstruction of the decay vertex of low-p_T heavy-flavor hadrons because it increases the rate of multiple scattering. To further improve the precision of the ALICE measurements in Run 4, the ALICE Collaboration proposed to replace the Inner Barrel of the ITS with a new detector that will be formed by truly-cylindrical, wafer-scale sensors [2]. This upgrade will result in a significant reduction in the material budget from 0.35% to 0.05% X_0 per layer. The construction of the new detector requires:

- integration of the power and data buses into a silicon chip such that the circuit board can be removed;
- replacement of the water cooling system by air cooling, and reduction of the power consumption with respect to the present ITS;
- development of the technology for the production of large-area bent sensors, which require less mechanical support.

The project of the Inner Barrel upgrade is called ITS3. The new Inner Barrel will also have 3 layers, each consisting of only two wafer-scale MAPS sensors bent to form a half-cylindrical shape. The sensors will be as large as 26×9 cm^2, and their thickness will be less than 50 µm. The innermost layer will be located at a radial distance of 18 mm from the interaction point. The layers will be held in place relative to each other with light carbon foam spacers.

The wafer-scale MAPS sensors will be produced on 300 mm wafers using the 65 nm CMOS imaging process with one-dimensional stitching technology. The spatial resolution of the future sensors is required to be about 5 µm. As the first layer of the ITS3 will be closer to the interaction point, the ITS3 sensors will have to cope with higher radiation loads when compared to the present ITS sensors. The project requires that the future sensors should be radiation hard at least up to 10^{13} 1 MeV $\mathrm{n_{eq}/cm^2}$ (NIEL) and 10 kGy (TID).

The substantially reduced material budget of the ITS3 and its closer location to the interaction point will improve the pointing resolution of reconstructed tracks in the transverse plane by a factor of 2. Moreover, the proposed design will also increase the reconstruction efficiency for tracks with transverse momentum less than 200 MeV/c. These improvements will enhance the ALICE capabilities to reconstruct open-heavy-flavor hadrons. For instance, the simulated significance of the signal from the decay of $\mathrm{B_s^0} \rightarrow \mathrm{D_s^-} + \pi^+$ measured with the ITS3 in 0–10% central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV is 1.4 times higher at $p_{\mathrm{T}} = 10$ GeV/c than for the ITS2. Moreover, the ITS3 extends this measurement to lower p_{T} region, which is unattainable for the ITS2. The performance of the detector is discussed in more detail in Ref. [3].

2. ITS3 R&D status

The roadmap of the ITS3 R&D is split into several parallel activities, namely the characterization of bent sensors, the development of detector mechanics and air cooling system, and the design of new sensors and their characterization. Each of the activities will be briefly discussed below.

2.1 Characterization of bent sensors

The sensors are bent to a half-cylindrical shape of a given radius using a mandrel. To prove the concept of operating bent sensors, the ALICE Collaboration built and tested a setup, called µITS3, see the left photo in Fig. 2. The setup consists of 6 ALPIDE monolithic active pixel sensors with a thickness of 50 µm [4], bent to the target radii of the ITS3. The right plot in Fig. 2 shows the detection inefficiency of the bent ALPIDE sensors for minimum ionizing particles as a function of the charge threshold. The project requires the detection inefficiency to be less than 10^{-2} (in other words, detection efficiency to be greater than 99%). One can see that at the nominal operating point of 100 electrons, the inefficiency is less than 10^{-4}. Furthermore, the detection inefficiency does not depend on the sensor curvature. The obtained results are consistent with the performance of a flat ALPIDE sensor. Complementary studies also showed that the bending does not affect the spatial resolution of the sensors. Similar studies were also carried out with a single bent ALPIDE sensor, see details in Ref [5].

2.2 Detector mechanics

The shape of the ITS3 half-cylindrical layers will be fixed by carbon-foam half-rings and carbon-foam longerons that will be glued to the sensors. There are two types of proposed carbon-foam materials, which differ primarily in density and thermal conductivity. The half-rings are made

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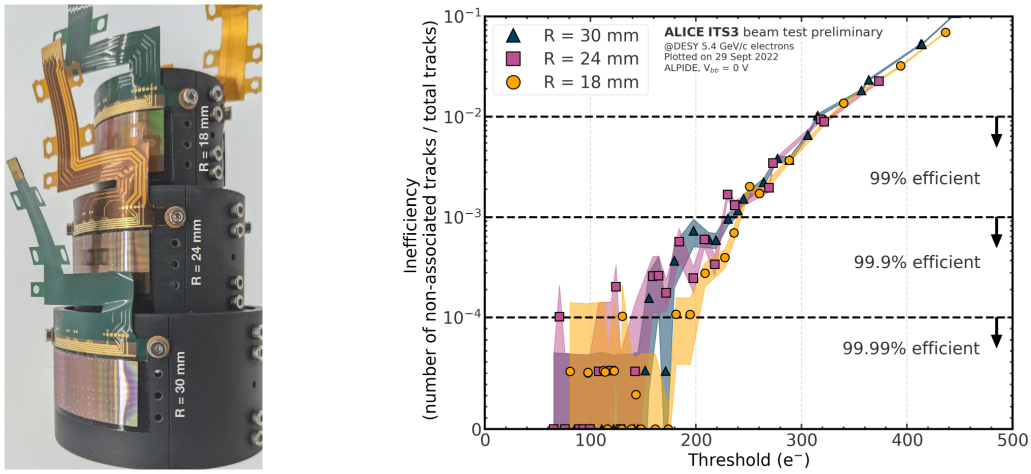

Figure 2: Left: μITS3 setup. Right: Inefficiency to detect a minimum ionizing particle by the ALPIDE sensors, bent to different radii, as a function of the charge threshold.

of carbon foam with high density (0.2–0.26 kg/dm^3) and high thermal conductivity (> 17 W/m/K) since it is expected that most of the heat will be produced at the sensor endcaps. Thus, in addition to providing a mechanical support, the half-rings act as a heat sink. In contrast, the longerons are made of carbon foam with low density ($\approx$ 0.045 kg/dm^3) to reduce the material budget and low thermal conductivity (> 0.033 W/m/K) since the sensor matrix generates a small amount of heat. Figure 3 shows a full-size breadboard model of the ITS3, assembled from dummy silicon wafers.

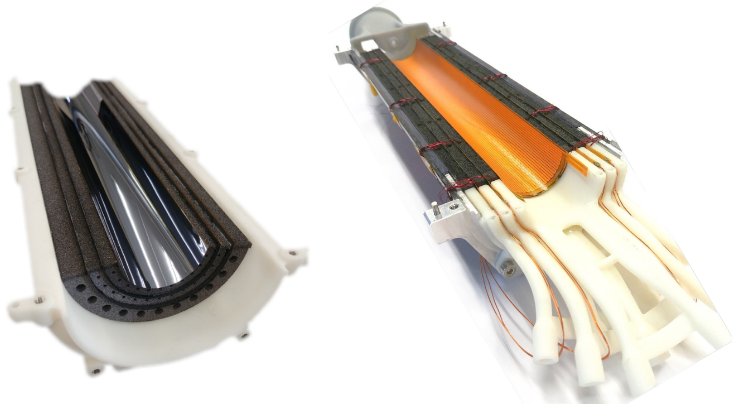

Figure 3: Left: One of the ITS3 breadboard models for mechanical studies. Right: The breadboard model equipped with an air distributor and thermal heater for mechanical and thermal tests in a wind tunnel.

2.3 Air cooling system

Various breadboard models, similar to the one in Fig. 3, equipped with flow distributors and sensors for temperature and displacement measurements, are used in tests with a custom wind tunnel to determine their thermal and mechanical properties. The project requires an air cooling system that can keep the operating temperature of the sensors below 30 °C. It was shown that in order to achieve the stated performance, the airflow of 8 m/s is sufficient. Measurements of mechanical vibrations caused by the airflow showed that the sensor displacement is within 0.5 µm. This level of vibrations is negligible when compared to the expected spatial resolution of the sensor. It is expected that the level of vibrations can be further reduced by optimizing the geometry of holes in the carbon-foam half-rings.

2.4 65 nm sensor design and characterization

The design of the pixels for the ITS3 introduced a new feature, a low-dose n-type implant layer with a gap [8], which allows complete depletion of the sensitive volume and increases the radiation hardness of the sensors. The development of ITS3 sensor prototypes commenced with the production of digital and analogue test structures, DPTS and APTS, respectively. To optimize the new sensor design for better particle-detection performance, the sensors were manufactured in 4 process splits [6]. The DPTS sensor has a 32×32 pixel matrix with an amplifier and a discriminator in each pixel and digital readout with time encoding [7]. The DPTS sensors were characterized in terms of charge collection efficiency, detection efficiency for minimum ionizing particles, fake-hit rate, and radiation hardness [7]. The published results showed that the DPTS sensor, irradiated to the radiation levels expected for the ITS3, has a detection efficiency above 99% with a low but measurable fake-hit rate.

In 2023, the ITS3 project got the first two stitched-sensor prototypes: MOnolithic Stitched Sensor (MOSS) and MOnolithic Stitched sensor with Timing (MOST). The MOSS is a 6.7-megapixel sensor, measuring 1.4×25.9 cm^2, see Fig. 4. It is made of ten repeated sensor units (RSUs), which are basically the largest individual sensors that could fit in the design reticle and which are stitched together. Each RSU comprises two half-units (HUs), labelled top and bottom. Each half-unit contains four matrices, also referred to as regions, with a pixel pitch of 22.5 µm at the top and 18 µm at the bottom. The corresponding number of pixels in each of the top/bottom regions is $256 \times 256/320 \times 320$. The different pitch sizes for the top and bottom half-units are used to test two designs of pixel architecture. The MOST chip is 0.25 cm wide and 25.9 cm long with a pitch size of 18 µm. Currently, both MOSS and MOST chips are studied in a laboratory and testbeams in order to investigate the stitching process.

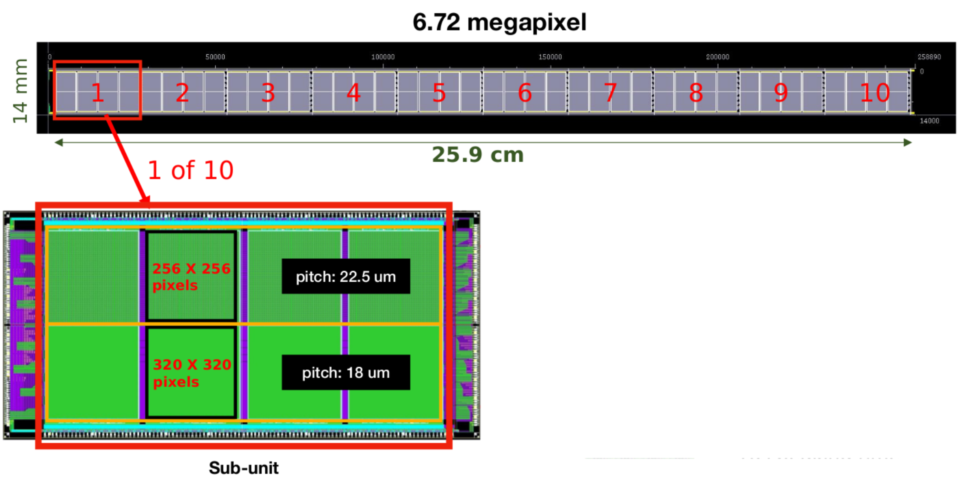

Figure 4: Structure of the MOSS chip. The numerated rectangles represent the repeated sensor units (RSU).

3. Summary

The future upgrade of the ITS detector will replace the Inner Barrel layers of the ITS2 with truly cylindrical wafer-scale monolithic active pixel sensors fabricated in the 65 nm CMOS process utilizing the stitching technology. The possibility of operating bent silicon sensors without loss of their performance was confirmed in the tests with bent ALPIDE chips [5]. The new 65 nm sensors demonstrate sufficient radiation hardness to meet the requirements of the ITS3 project. Currently, the R&D activities focus on the characterization of the stitched sensors, design of the final sensors, and improvement of the detector mechanics and air cooling system.

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