EPJ Web of Conferences **296**, 08002 (2024) https://doi.org/10.1051/epjconf/202429608002
Quark Matter 2023

Novel silicon detectors in ALICE at the LHC: The ITS3 and ALICE 3 upgrades

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Abstract. The ALICE experiment is preparing for the ITS3 upgrade, which is set to take place during the LHC Long Shutdown 3. The aim of this upgrade is to replace the three innermost tracking layers with truly cylindrical wafer-scale Monolithic Active Pixel Sensors (MAPS). By adopting this innovative technology, ALICE will further reduce the material budget and the distance from the interaction point, thus significantly improving its tracking and vertexing capabilities. The R&D program for ITS3 includes several advancements, such as operability of bent MAPS, validation of the 65 nm CMOS technology, and employment of the stitching process to produce wafer-scale sensors.
In addition to the ITS3 upgrade, ALICE is designing a completely new apparatus, ALICE 3, planned for LHC Runs 5 and 6. The detector consists of a large MAPS-based tracking system covering eight units of pseudorapidity, complemented by multiple systems for particle identification, including silicon time-of-flight layers, a ring-imaging Cherenkov detector, a muon identification system, and an electromagnetic calorimeter. The vertex detector is based on an evolution of the ITS3 concept aiming at a track pointing resolution of better than 10 μm for tranverse momenta above 200 MeV/c through the integration of the tracking layers in a retractable structure inside the beam pipe.
In this proceeding the detector concept of these upgrades is described, together with their physics motivations and R&D status and achievements.

1 Introduction

The ALICE experiment will undergo several upgrades on the next few years, which will be crucial for its operation in the Run 4 and beyond. During the LHC Long Shutdown 3 (2026-2028), the collaboration plans to upgrade the innermost layers of the current Inner Tracking System (ITS) detector with a novel vertex detector called ITS3 [1]. All the achievements and technology advancements that the ITS3 R&D will lead to, will also set the basis for the vertex detector of ALICE 3 [2]. ALICE 3 will consist of a completely new apparatus, planned to be built during the Long Shutdown 4.

The following sections will cover both the ITS3 upgrade and the plans for ALICE 3, highlighting the detector concept, the physics performance, and the status of novel sensor R&D. It will showcase the achievements already made and provide an outline of the future plans for advancing the detector technologies.

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2 Physics motivation

The ITS3 detector and ALICE 3 will enable novel studies of the quark-gluon plasma and open up important physics opportunities in other areas of QCD and beyond. Among the several physics motivations behind these upgrades, the measurements that will benefit more from the technology advancement are:

- Measurements of low-p_{T} heavy-flavour production, including beauty hadrons, multi-charm baryons and charm-charm correlations. The reduced radial distance between the interaction point and the innermost detector will make the direct tracking of multi-charm baryons accessible.
- Thermal emission of dileptons, to probe the mechanism of chiral-symmetry restoration and the time-evolution of the QGP temperature. The reduced material budget and the improved background suppression will enable not only the high-precision measurement of the temperature, but also its differential analysis in transverse momentum.

The main requirements to achieve these physics goals include: increased effective acceptance, enhanced particle identification capabilities, and an improved tracking and vertexing performance at low-p_{T} for background suppression.

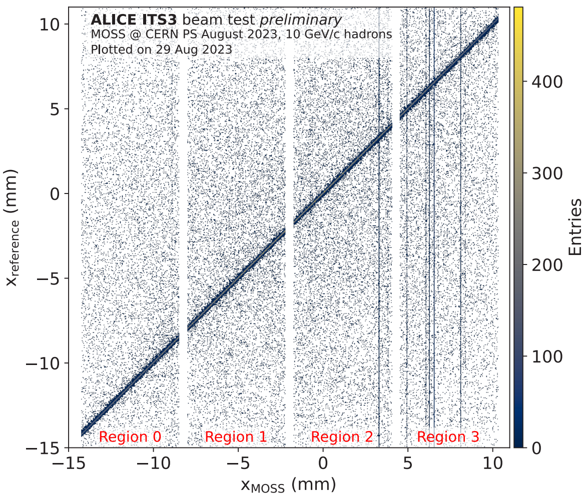
3 ITS3 upgrade

The ITS3 detector will be based on truly cylindrical ultra-thin ($\leq$50 μm) wafer-scale (280 mm × 94 mm) Monolithic Active Pixel Sensors (MAPS), fabricated in 65 nm CMOS imaging process. The advantage of this detector concept is, not only a reduced material budget (that will go from 0.35 % to 0.05 % per layer), but also a smaller distance to the interaction point (from 23 to 18 mm), which will result in an improved vertexing performance.

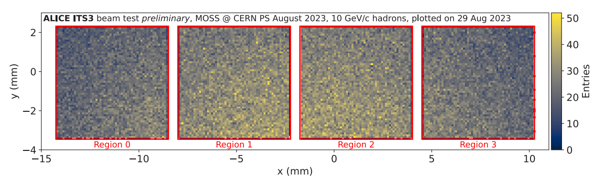
The R&D fields of study are several, but the most innovative developments, introduced for the first time in high-energy physics by ALICE, are:

- Bending: the idea is to thin down sensors in order to make them flexible, and bend them to the target radii and mechanically hold them in place by carbon foam spacers. The bending procedure was tested in several conditions and at different radii on ITS2 ALPIDEs and no degradation was observed compared to flat chips [3]. Similar studies also started for smaller 65 nm technology prototypes and new results are coming soon.
- Stitching: a technology used to overcome the limit of reticle size in standard CMOS manufacturing, fundamental to produce wafer-scale sensors. A first stitched unit, called MOnolithic Stitched Sensor (MOSS) was tested with wafer probing and systematic lab tests verifying all basic functionalities. The prototype performance underwent beam tests as well, and the analysis is ongoing. The setup consisted in a telescope of ALPIDEs with the MOSS prototype (DUT) in the middle. The hits position correlations between ALPIDEs and the DUT, together with the associated hitmaps are depicted in Fig. 1.
- Technology validation: the Tower Partners Semiconductors (TPSCo) 65 nm CMOS imaging technology was chosen as baseline due to its higher integration density and production on larger wafers (300 mm vs 200 mm). The development of MAPS in this technology is done together with CERN EP R&D and it was validated in terms of charge collection efficiency, detection efficiency and radiation hardness. Several pixel variants were tested both in laboratory and in beam tests, and a detection efficiency higher than 99 % was reached while preserving a fake-hit rate below 10 pixel^{-1}s^{-1}. This result was obtained not only for the non irradiated sensors but also for levels of irradiation higher than the ITS3 radiation hardness requirement (10 kGy + 1×10^{13} 1 MeV $\mathrm{n_{eq}}$ cm^{-2}) [4]. Furthermore, these results

were achieved at room temperature, but for irradiated chips an improvement in performance is expected when operating the sensors at lower temperatures.



(a)



(b)

Figure 1. This figure depicts the results obtained during a test beam at PS at CERN. On top (a) the hits position correlation in X direction between ALPIDEs and the DUT is clearly visible for different regions of the chip. The bottom plot (b) shows the associated hitmap of each region.

4 ALICE 3

The ALICE 3 apparatus will exploit various innovative technologies. The key ingredients that are behind the concept of this upgrade can be summarized as: a compact and lightweight all-silicon tracker (p_T resolution ~1−2 % over large acceptance), a retractable vertex detector with excellent pointing resolution (3−4 µm at 1 GeV/c), a large acceptance ($-4 < \eta < 4$, p_T>0.02 GeV/c), e/π/K/p particle identification over large acceptance, a Muon Identification system, a large-area ECal for photons and jets, a Forward Conversion Tracker for ultra-soft photons, a 2T superconducting magnet system, and a continuous readout and online processing.

The vertex detector of ALICE 3 will consist of 3 layers of wafer-size, ultra-thin, curved, CMOS MAPS inside the beam pipe in secondary vacuum. Its main feature is a retractable configuration that is possible thanks to its movable petals allowing the transition from innermost radius of 5 mm during data taking, to 16 mm during beam injection. A schematic of these two configurations is shown in Fig. 2. This approach aims at achieving an unprecedented spatial resolution (σ_{pos}~2.5 µm) and an extremely low material budget.

The main challenge will be the radiation tolerance (300 Mrad + 1×10^{16} 1 MeV n_{eq} cm^{-2}), but considering that ITS3 prototypes already achieved a good performance for a radiation dose up to 1×10^{15} 1 MeV n_{eq} cm^{-2} at room temperature, an improvement on the forthcoming designs seems achievable.

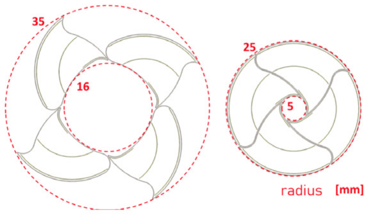


Figure 2. A schematic of the two different configurations that the vertex detector of ALICE 3 can undertake. One during beam injection at a radial distance from the beam axis of 16 mm (left), and the other during data taking at a radial distance of 5 mm (right).

The tracker includes 8+2x9 tracking layers (barrel + disks) for a total of 60 m^2 silicon pixel detector based on CMOS MAPS technology. The module integration and material budget represents the main challenges, due to its dimensions (outer radius of 80 cm). It will ensure a large coverage and a position resolution of 10 μm for a pixel pitch of 50 μm.

The particle identification of ALICE 3 is based on two systems, which complement each other, and together will guarantee an high p_T and η coverage: the Time of Flight (TOF) and the Ring-Imaging Cherenkov (RICH) detectors.

The first one will be based on silicon timing sensors, for a total area of 45 m^2, with the aim of achieving a time resolution of 20 ps. The effort is focused on testing many technologies for timing purposes, such as LGADs and CMOS with gain layer. Preliminary results are already approaching the required resolution value.

The RICH is based on alternating an aerogel radiator coupled with SiPMs, for a total area of 40 m^2. A big effort is devoted to the R&D on monolithic silicon photon sensors. Beam tests on first prototypes are being planned and new results will come soon.

5 Conclusions

ALICE is planning a very ambitious program of upgrades. For what concerns ITS3, the R&D is progressing and showing excellent results, with the technology ingredients already established and validated.

Also the R&D for ALICE 3 started on several strategic areas, following a clear plan on future activities.

Besides making new observables accessible for low-mass dileptons and heavy flavour particles in ALICE, these upgrades will also pioneer R&D directions that can have a broad impact on future high-energy physics experiments.

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