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ALICE silicon tracker upgrades for LHC Run 4 and beyond

Luca Aglietta *, on behalf of the ALICE collaboration

Università degli Studi di Torino, Via P. Giuria 1, Torino, Italy
Istituto Nazionale di Fisica Nucleare (INFN) Sez. Torino, Via P. Giuria 1, Torino, Italy

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ABSTRACT

During the Long Shutdown 3 of the LHC (2026–2028) the ALICE experiment foresees an upgrade of the inner barrel of its Inner Tracking System: the ITS3.

This new vertex detector is based on Monolithic Active Pixel Sensors produced in a commercial 65 nm CMOS technology. Each half-layer is realized with a single stitched sensor of 26 cm long and less than $50\,\mu m$ thick, bent to form a half-cylinder, and held in place with carbon foam supports. The detector is air cooled allowing for an extremely low material budget of $0.09\,X/X_0$ per layer. With respect to the current ALICE vertex detector, ITS3 will improve the pointing resolution by 50% and the tracking efficiency by 30% for hadrons of low transverse momentum.

Parallelly, ALICE is designing a next generation heavy-ion experiment for LHC Run 5 and 6 (beyond 2035).

Its tracking system will be based on a vertex detector, integrated in a retractable structure inside the beam pipe to achieve the best possible pointing resolution, and a large-area outer tracker, surrounding the vertex detector and covering the pseudorapidity range $-4 < \eta < 4$. Both systems will be based on the same MAPS technology developed for ITS3 and will have to satisfy stringent requirements: the innermost vertex detector layer, placed at 5 mm from the interaction point, must withstand an integrated radiation load of 9×10^{15} $1\,\mathrm{MeV}\,n_{eq}/cm^2$ NIEL and $2.88\,\mathrm{MGy}$ TID; the outer tracker, extending from the beam pipe to a maximum radius of about 80 cm, covers almost $60\,m^2$ of area.

This proceeding will cover both the ITS3 upgrade and the projects for ALICE3 silicon tracker, highlighting their requirements, sensor specifications, mechanics and integration. It will showcase the results achieved during the ITS3 R&D and outline the challenges expected for the implementation of the ALICE 3 tracking system.

1. Introduction

The physics program of the ALICE experiment is devoted to the study of the properties of the Quark Gluon Plasma produced in ultra-relativistic heavy-ion collisions at the LHC. QGP is studied via several probes that benefit greatly from the precise reconstruction of displaced decay vertices, such as open heavy flavour hadrons or thermal dieleptons, in order to mitigate the massive combinatorial background of heavy-ion collisions.

To achieve this goal an inner tracker with excellent pointing resolution is needed. The resolution of a tracker, computed in [1] as the dispersion of the Distance of Closest Approach of prompt tracks from the primary vertex, can be parametrized as

$$\sigma_{DCA} \simeq A\sigma_{xyz} \oplus B\frac{r_0}{p_T}\sqrt{\frac{X}{Xo}}\cosh\eta. \tag{1}$$

Therefore, to achieve optimal impact parameter resolution, three key ingredients are needed:

- excellent spatial resolution (σ_{xyz}),
- minimal material budget ($\frac{X}{Xo}$, i.e. material thickness expressed in units of radiation-length), in particular before the first detection layer,
- minimal distance between the first sensing plane and the interaction point (r_0).

With the installation of its current Inner Tracking System (ITS2), the ALICE experiment has pioneered the use of Monolithic Active Pixel Sensors (MAPS) in High Energy Physics to pursue the best pointing resolution and tracking performance. The ITS2 is made of 7 layers of ALPIDE [2,3] chips for a total sensitive area of $10\,m^2$.

For LHC Run 4 and beyond the ALICE experiment is planning two major upgrades of its silicon tracker: for Run 4 (2029), the replacement of the inner barrel of the ITS2 with three truly cylindrical, wafer-scale MAPS layers with minimal support structures for an unprecedented

* Correspondence to: Università degli Studi di Torino, Via P. Giuria 1, Torino, Italy.
E-mail address: luca.aglietta@unito.it.

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Table 1
Evolution of ALICE silicon tracker form ITS2 to ALICE 3.

	ITS2	ITS3	ALICE 3
Technology	180 nm	65 nm	65 nm
n Layers	7	7	11 + 2 × 12
$r(L_0)$	24 mm	19 mm	$\simeq$5 mm
$r(L_n)$	40 cm	40 cm	$\simeq$80 cm
pixel pitch	29 µm	22 µm(IB) 29 µm(OB)	10 µm(VD) 50 µm(OT)
X/X_0 (L_0)	0.35%	0.09%	$\simeq$0.1%
σ_{DCA}@1 GeV/c	40 µm	20 µm	$\simeq$4 µm

material budget (ITS3). Then, for Run 5 and 6 (beyond 2035), the realization of a $60\,m^2$ silicon tracker, entirely made of MAPS, with the first sensing layer inside the beampipe, as part of the ALICE 3 upgrade [4]. An overview of the specifications of the 3 versions of the ALICE silicon tracker are reported in Table 1 where the following abbreviations have been used: IB and OB for the ITS3 Inner and Outer Barrel, VD and OT for the ALICE 3 Vertex Detector and Outer Tracker, respectively.

The following sections will cover both the ITS3 upgrade and the plans for the ALICE 3 silicon tracker, showing the R&D status of both projects and highlighting the major results achieved so far and the challenges still ahead.

2. ITS3 upgrade

The ITS3 upgrade was first proposed in 2019 in an Expression of Interest [5], followed up by a Letter of Intent [6] later the same year. It consists in the replacement of the inner barrel of the ITS2 with three layers of bent, wafer-scale MAPS fabricated in the TPSCo 65 nm CMOS technology, with a single sensor used to form each half-layer of the detector. The realization of wafer-scale sensors is made possible thanks to the stitching technique that consist in the precise abutting of several exposures of sub-regions of the photolitographic mask in a predefined pattern.

This solution allows the inclusion in the silicon sensor design of all the lines necessary for powering and data transfer removing the need of an external FPC (Flex Printed Circuit). This, in combination with minimal carbon foam support structures and the adoption of air cooling, makes possible to achieve a material budget value of $0.09\,X/X_0$ per layer.

The realization of the ITS3 required an extensive R&D as described in the next paragraphs.

2.1. Technology qualification

The TPSCo 65 nm technology has been qualified for the first time for High Energy Physics applications with an extensive characterization campaign on test structures, produced as part of the MLR1 (Multi-Layer-Reticle run 1) submission to the foundry, starting from the end of 2020.

The MLR1 submission included a variety of prototype circuits, functional blocks and prototypes of pixel arrays. The characterization of the transistor test structures proved the selected 65 nm technology suitable for the realization of radiation hard circuits up to tens of MGy of total ionizing dose, demonstrating similar performance to other technologies with the same feature size that have been previously validated for applications in particle detection.

The pixel test structures produced in MLR1 feature process optimization techniques to accelerate the charge collection that were introduced for the first time in the previous generation of sensors realized in the 180 nm TowerJazz process [7]. The characterization of the Digital Pixel Test Structure (DPTS) allowed the qualification of the full pixel functionalities (charge collection, analogue and digital domain of the front-end electronics) up to the expected radiation level of ITS3 of 1×10^{13} $1\,\text{MeV}\,n_{eq}/cm^2$ NIEL (Non Ionizing Energy Loss) and 10 kGy TID (Total Ionizing Dose) [8].

Results from measurements on a family of Analogue Pixel Test Structures (APTS) demonstrated that the pixels preserve full efficiency at room temperature up to 1×10^{15} $1\,\text{MeV}\,n_{eq}/cm^2$ NIEL [9].

Moreover, an APTS variant, featuring a fast output buffer (APTS-OA), reached a time resolutions lower than 70 ps with 4.8 V of applied reverse bias voltage, see Fig. 1.

2.2. Bending

Silicon sensors with a thickness of 50 µm can be bent to a radius smaller than the target 19 mm before breaking. Test beam measurements on curved ALPIDE sensors show that the sensor performance is unaffected by the bending process [10].

The characterization of bent MLR1 pixel test structures confirm this result.

2.3. Stitching

The first prototypes of stitched sensors have been produced in 2023 as part of the 'Engineering Run 1' submission to the foundry. The largest prototype, the Monolithic Stitched Sensor (MOSS), is made by ten Repeated Sensor Units (RSUs) stitched together plus two smaller end-cap regions on the sides. The results from the characterization show the chip to be functional and with an efficiency higher than 99%.

The yield of the stitched sensor is being currently being assessed. Some faults caused by inter metal shorts, which prevent some chips to be powered, have been observed and will be mitigated by changes in the metal layers spacing in the next submission to the foundry.

2.4. Thermo-mechanical validation

In order to keep the material budget as low as possible, the ITS3 needs to be air cooled and assembled with minimal support structures. The detector will be held in place by two carbon-foam half rings at the endcaps and two longerons along the long sides of each half layer. The mechanical assembly has been exercised with engineering models using 50 µm dummy silicon planes in place of the sensors, see Fig. 2.

With a breadboard model hosting a copper serpentine to simulate the sensor thermal load, it has been verified that an airflow of 8 m/s will be adequate to keep the sensor temperature within the operational range when the power consumption is kept below $40\,mW/cm^2$ in the matrix area. The amplitude of vibration induced by the airflow have been measured at the same time to be below 1 µm peak to peak, well within specifications.

With the precious inputs from the sensor characterization campaign, the design of the definitive full-scale and full functionality prototypes is being finalized for the ER2 submission to the foundry expected for fall 2024.

The results of the R&D efforts have been collected in the Technical Design Report [11] that has been reviewed by the LHCC and approved by the LHC Research Board in 2024. The ITS3 project is on track for its installation inside the ALICE experiment during the Long Shutdown 3 (2026–2028).

3. ALICE 3 upgrade

For LHC Runs 5 and 6 ALICE is planning to replace its entire experimental apparatus with a novel detector that makes use of the most advanced silicon sensors both for tracking and PID purposes. ALICE 3 will cover 8 units of pseudorapidity $-4 < \eta < 4$ and will feature a 2 T superconducting magnet. At its core there will be a large area silicon tracker entirely made of MAPS, complemented by three Time Of Flight layers, with a time resolution 20 ps, and Ring Imaging Cherenkov detectors for particle identification. A large acceptance electromagnetic calorimeter, a muon identification system, and a Forward Conversion Tracker (FCT) for ultra-soft photons, complete the apparatus.

A rendering of the ALICE 3 layout is represented in Fig. 3.

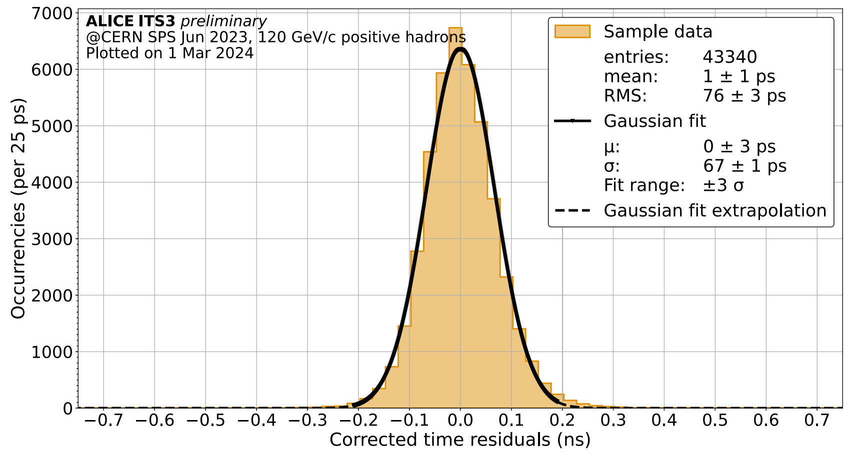

Fig. 1. Time residuals distribution for the APTS-OA test structure operated at V_{sub}=−4.8 V after time walk correction. The timing plane contribution of 30 ps has not been subtracted from the time resolution.

Fig. 2. The ITS3 Engineering Model 2.

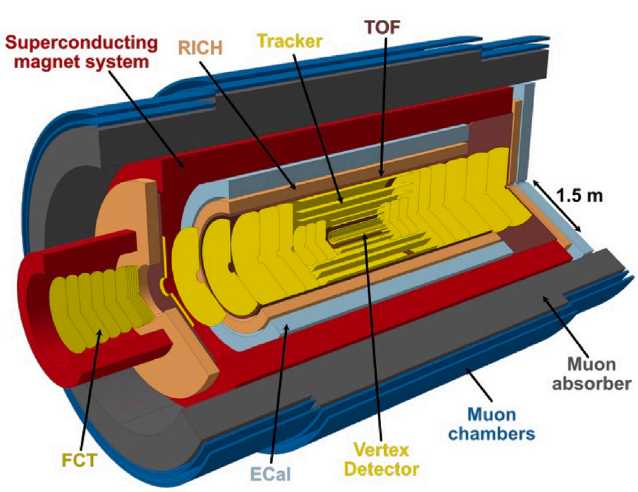

Fig. 3. Layout of the ALICE3 detector.

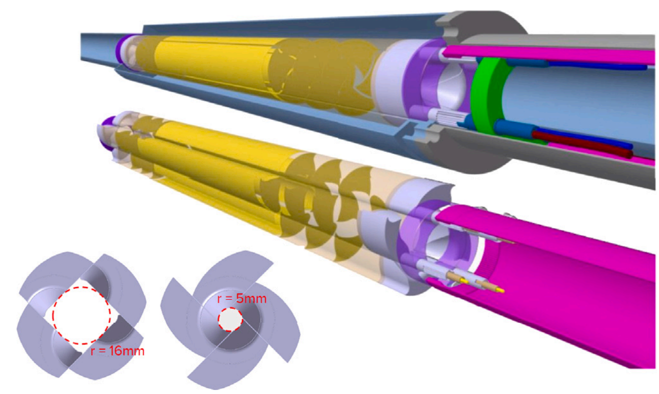

Fig. 4. Layout of the ALICE3 Vertex Detector. Top: configuration for stable beam, bottom: during beam injection. The variable aperture of the Iris Trackers arranged in the retractable structure inside the beam pipe is highlighted in the bottom left corner.

3.1. Outer tracker

The outer tracker of ALICE 3 consists of 8 cylindrical barrel layers and 9 forward discs on either side of the interaction point arranged in a compact design with $3.5\,\mathrm{cm} < R < 80\,\mathrm{cm}$ and $|z| < 4\,\mathrm{m}$. With each of the layers contributing about 1% of a radiation length, the total material budget of the entire tracker will be $< 10\%$ X/X_0. It will be the largest pixel detector ever built with almost $60\,\mathrm{m}^2$ of silicon surface and more than 20 billion pixels.

The sensors will be reticle-size MAPS with pixel pitch $40\,\mu\mathrm{m}$, arranged in modules of around $13 \times 5\,\mathrm{cm}^2$ and mounted on carbon space frames to form staves closely resembling those of ITS2. The power consumption will be limited to about $20\,\mathrm{mW/cm}^2$.

The main challenge of the R&D will be the design of the modules for large-scale industrialization.

3.2. Vertex detector

The vertex detector of ALICE 3 consists of 3 layers and 3 pairs of discs of wafer-size, ultra-thin, curved, MAPS mounted inside the beam pipe in secondary vacuum. Its main feature is a retractable iris structure made of four movable petals that allow the detector to move from an innermost radius of 5 mm during data taking, to 16 mm during beam injection, see Fig. 4.

In order to fully profit from the reduced distance from the interaction point, the pixel pitch needs to be as small as $10\,\mu\mathrm{m}$ and the material budget extremely low, around 0.1% X/X_0 per layer.

The expected pointing resolution for electrons should be better than $4\,\mu m$ for p_T larger than $1\,GeV/c$. Moreover, the reduced distance from the interaction point will allow direct tracking of strange hadrons, that will improve drastically the reconstruction of multi-charm baryons [4].

The main challenge for the vertex detector development will be the improvement of the radiation tolerance of the MAPS to 9×10^{15} $1\,MeV\,n_{eq}/cm^2$ NIEL and $2.88\,MGy$ TID. By cooling the detector to -25 °C, and by further improving the pixel design, in continuation of the ITS3 R&D, this result seems within reach.

4. Conclusions

This contribution described the ambitious program of ALICE upgrades for LHC Run 4 and beyond for what concerns its silicon tracking detectors.

For Run 4 (starting in 2029), with the ITS3 project, ALICE is going to replace the inner barrel of the ITS2 with true cylindrical sensing layers, removing most of the electrical, mechanical and cooling components from the active volume. The R&D stage for ITS3 has been completed with the publication and approval of the TDR [11] earlier this year. The selected 65 nm process has been qualified for HEP applications, the performance of curved maps have been demonstrated not to be affected by the bending process and the feasibility of ITS3 mechanical integration has been validated with full scale mechanical prototypes.

The realization of the MOSS prototype in the ER1 submission has been the first exercise of the realization of stitched MAPS for particle detection and showed encouraging results, that will lead to the production of full scale prototypes of the final sensors later this year.

The ITS3 project is on track to be installed in the ALICE experiment during the Long Shutdown 3 as planned.

For Run 5 and 6 (2035 and beyond), ALICE will replace its entire experimental apparatus as part of the ALICE 3 upgrade that will include the installation of a $60\,m^2$ silicon tracker with the first detection layer located inside the beampipe in secondary vacuum. The R&D for ALICE 3 started within several strategic areas, and, for what concerns the sensor to be used in the tracker, will be in direct continuation with the ITS3 developments.

The scoping document for ALICE 3 is being edited and will be submitted to the LHCC later this year.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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