PROCEEDINGS OF SCIENCE

ALICE ITS2: performance and operational experience

Jiyoung Kim on behalf of the ALICE collaboration[a,b,*]

[a] *CERN,*
1, Esplanade des Particules, Meyrin, Switzerland
[b] *Department of Physics, Inha University,*
100 Inha-ro, Michuhol-gu, Incheon, South Korea

E-mail: jiyoung.kim@cern.ch

The Inner Tracking System (ITS2) is the innermost tracking detector of the ALICE experiment, upgraded for LHC Run 3, providing vertex reconstruction and tracking of charged particles. The detector consists of seven cylindrical layers of Monolithic Active Pixel Sensors covering 10 m^2 of active area and has been successfully operating since 2021. The ALPIDE sensors, manufactured using a 180 nm CMOS technology, feature 29 × 27 µm pixels with a spatial resolution of 5 µm. Thanks to a very light support structure and thinning down the chip thickness to 50 µm, the material budget was reduced to 0.36 % X_0 per layer in the Inner Barrel.

This contribution reports on three years of ITS2 operational experience during LHC Run 3. Performance results demonstrate excellent detector stability with fake-hit rates below 10^{-6}/pixel/event, detection efficiency exceeding 99 %, and stable threshold operation through occasional retuning. Beam-induced background effects observed in the 2023 heavy-ion run, affecting approximately 10 % of data before mitigation, are reported. Furthermore, the ITS *color run* campaign successfully demonstrated particle identification capabilities, achieving π/K/p separation through Time-over-Threshold measurements with modified front-end electronics settings and readout configurations.

33rd International Workshop on Vertex Detectors (VERTEX2025)
25-29 August 2025
University of Tennessee, Knoxville, USA

*Speaker

https://pos.sissa.it/

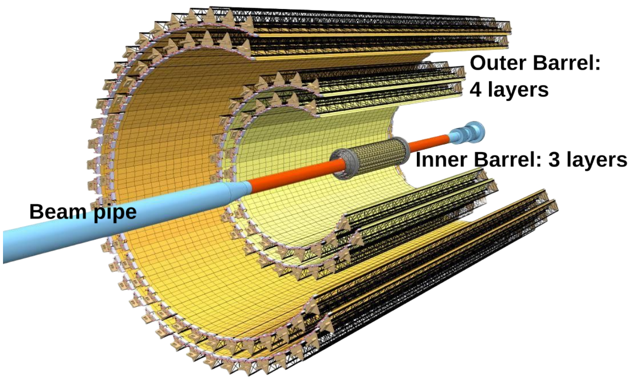
PoS(VERTEX2025)006

1. Introduction

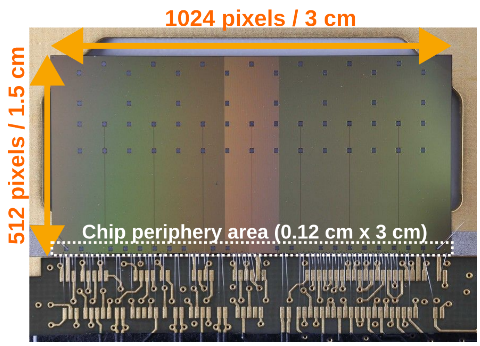
ALICE (A Large Ion Collider Experiment)[1] studies Quark-Gluon Plasma (QGP) in heavy-ion collisions at the Large Hadron Collider (LHC). High spatial resolution and a low-mass detector are essential for tracking low-p_T particles in this particle-rich environment. During LHC Runs 1 and 2, the Inner Tracking System (ITS1) employed pixel, strip, and drift silicon technologies. In Long Shutdown 2 (2019-2021), ITS1 was replaced by ITS2 [2], an all-pixel detector positioned at 22 mm from the collision point (previously 39 mm), enabling high-precision measurements of rare probes [3].

2. Inner Tracking System 2 (ITS2)

ITS2 consists of seven cylindrical Monolithic Active Pixel Sensors (MAPS) layers with radii from 22 mm to 400 mm, divided into Inner Barrel (IB, layers 0-2) and Outer Barrel (OB, layers 3-6) as shown in Fig. 1a. IB has nine ALPIDE chips per stave, while OB uses Hybrid Integrated Circuits (HICs) with 2×7 chip arrays. Both use 180 nm CMOS ALPIDE sensors [4] with different thicknesses: 50 µm (IB) and 100 µm (OB). The detector operates at 20 °C to 25 °C with water cooling, achieving material budgets of 0.36 % X_0 and 1.1 % X_0 for the IB and OB, respectively.



(a) ITS2 detector layout



(b) ALPIDE sensor chip

Figure 1: (a) Three-dimensional view of the ALICE ITS2 detector consisting of seven cylindrical layers. The Inner Barrel (IB, layers 0-2) and Outer Barrel (OB, layers 3-6) are shown with the beam pipe at the center. (b) Photograph of a single ALPIDE chip showing the 15 mm × 30 mm size with wire bonding connections.

The ALPIDE chip contains 512 × 1024 pixels of 29 µm × 27 µm pitch in a 15 mm × 30 mm chip (Fig. 1b), achieving approximately 5 µm spatial resolution. Table 1 summarizes the main specifications. The pixel and chip implements complete CMOS circuitry for signal processing and zero-suppressed readout, with globally calibrated thresholds.

The raw data is read out by an FPGA-based Readout Unit (RU) via copper at 1.2 Gbps (IB, 1 chip/link) and 0.4 Gbps (OB, 7 chips/link) [5]. The readout electronics are located approximately 7 m away from the interaction point, where they are influenced by a 0.5 T magnetic field and a radiation exposure that was estimated to be less than 10 krad Total Ionizing Dose (TID). To minimize the radiation-induced impact on FPGAs on boards, such as Single Event Upset (SEU),

Table 1: Main characteristics of the ALPIDE pixel chip

Parameter	Value
Pixel pitch	29 μm × 27 μm
Spatial resolution	5 μm
Detection efficiency	> 99%
Fake-hit rate	<< 10^{-6} event^{-1} pixel^{-1}
Radiation tolerance	> 270 krad, $2.7{\times}10^{12}$ n_{eq}/cm^2

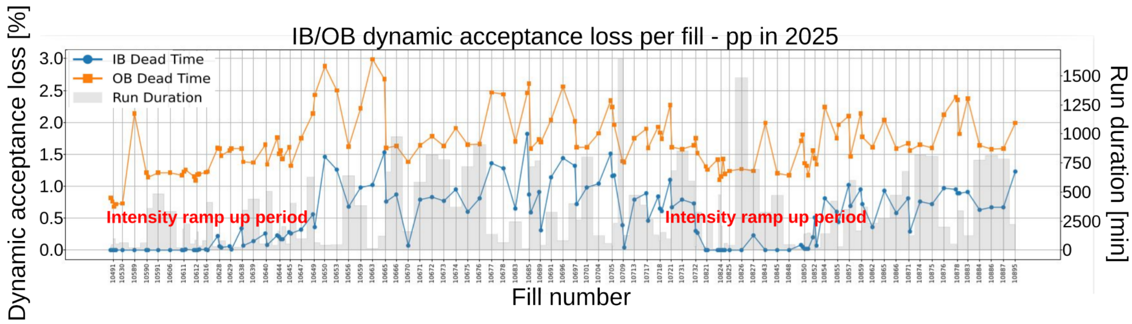


Figure 2: Dynamic acceptance loss for the Inner Barrel (IB) in blue and Outer Barrel (OB) in orange during pp collisions in 2025. Gray bars indicate the run duration in each fill.

regular scrubbing of the firmware and the triple modular redundancy (TMR) technique have been used as fault-tolerant methods.

3. Performance of ITS2 in LHC Run 3

Since the start of LHC Run 3 on July 5, 2022, until Nov 13, 2025, ALICE collected 132.3 pb^{-1} in pp and 3.3 nb^{-1} in Pb–Pb collisions, increasing statistics by factors of 3000 and 60, respectively, compared to Run 2. ALICE also operated in 2025 light-nuclei runs (Oxygen, Neon), collecting 5.01 nb^{-1} in O–O collisions.

Figure 2 shows the ITS2 acceptance loss (dead time) during 2025 pp runs. Both IB and OB show losses below 3 %, with improved performance during beam intensity ramp-up period. This beam-intensity dependence indicates background effects (Sec. 3.3). OB exhibits higher losses because its larger volume results in longer recovery times. This acceptance loss data, recorded at 1 Hz, is used for MC efficiency corrections.

3.1 Threshold Stability and Monitoring

For stable operation, the ITS2 charge threshold is regularly monitored and optimized via threshold scans and tunings, respectively. The detailed procedure for the threshold scan is described in [6]. The threshold scan of all the 12.5 billion pixels in ITS2 is time-consuming. Therefore, for regular monitoring, a representative subset of pixels is monitored by executing the scans between LHC fills roughly once or twice per day. Figure 3 shows the measured average chip threshold value time evolution since April 2023. The overall threshold stability is very high during the three-year

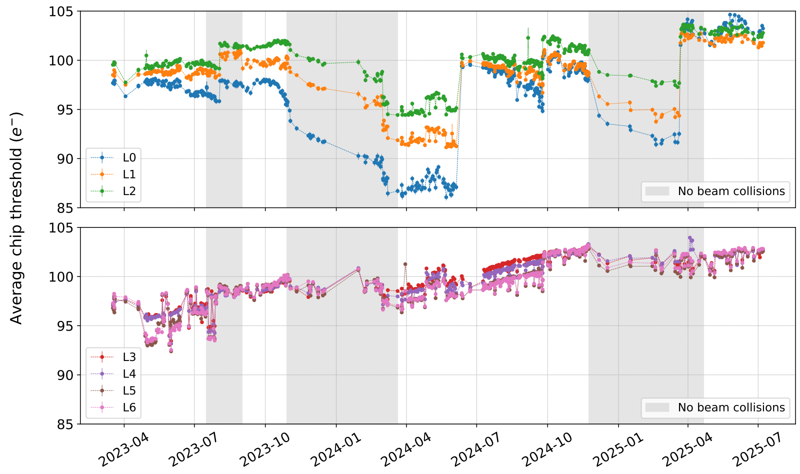


Figure 3: Average chip threshold per layer, measured from March 2023 to July 2025. Periods without beam at the LHC are marked in gray.

operations, as shown by a maximum deviation of about only 15 electrons from the nominal set value of 100 electrons.

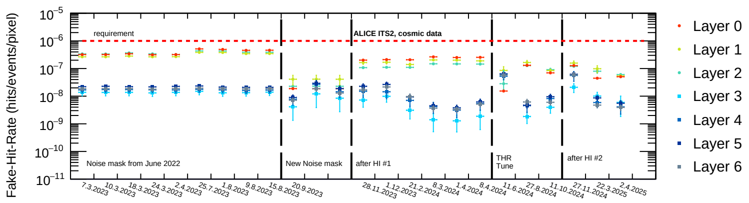
Since the threshold value is sensitive to changes in the analog supply voltage, the average threshold value changed in August 2023 and March 2024 due to modifications to the detector powering. Accumulated radiation dose on the detector also affects thresholds. Depending on the level of irradiation, IB and OB exhibit different trends in threshold changes. The OB layers show a slow increase in threshold attributed to the radiation effect. IB, which is expected to receive a much higher radiation dose due to its closer distance to the interaction point, shows the opposite trend, decreasing progressively toward the innermost layer. Laboratory tests confirmed that ALPIDE thresholds increase up to a radiation dose of 10 krad before decreasing at higher doses, explaining the different behaviors observed in OB and IB layers [6].

To compensate for this irradiation effect, threshold tuning has been performed once or twice per year, requiring a threshold scan of the entire detector. Occasional threshold tuning to 100 e^- was done in June, October 2024, and March 2025. The thresholds demonstrate good overall stability, with good uniformity across the chips, within a few electrons.

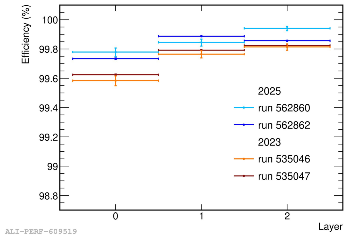
3.2 Noise Performance and Detection Efficiency

The noise level has also been regularly monitored and is well under control with a fake-hit rate lower than 10^{-6} per pixel per event since the beginning of the ITS2 operation, as shown in Fig. 4a. Masking noisy pixels enables controlling the noise level across the entire detector, and a dedicated noise scan is performed to identify the noisy pixels. Two different cut values for noisy pixels are used for IB and OB, firing occupancies of 10^{-2} and 10^{-6}, respectively. IB uses a relatively loose cut to prioritize detection efficiency, while OB uses a stricter cut due to limited readout bandwidth. In the end, only 0.15 % of the total pixels are found to be noisy and masked.

The detection efficiency has also been confirmed with the measured data in pp collisions. To confirm the detection efficiency of the installed sensors in ITS2, only tracks traversing the adjacent area between different staves are analyzed, enabling us to get reference tracks based on hits on other staves. Figure 4b shows the detection efficiency of the IB layers. The detection efficiency in all three layers is higher than 99 % and no degradation was observed over time.



(a) Fake-hit rate



(b) Detection efficiency

Figure 4: Performance plots showing (a) averaged per-layer fake-hit rate over the operational time, and (b) detection efficiency in Inner Barrel (IB) driven by measured data in pp collisions.

3.3 Beam background

Beam remnants circulating off-trajectory interact with accelerator elements, such as magnets and collimators, producing particle showers. These showers can lead to occupancies in the detector which are orders of magnitude above the ones in nominal operation. This leads to significant perturbation of the operation.

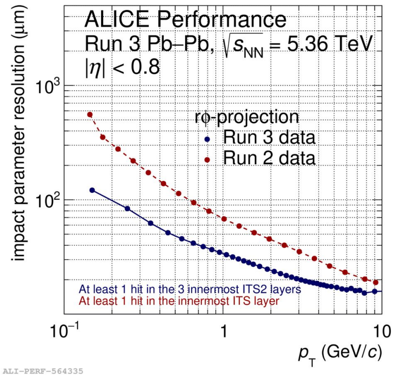
Such a beam background was first observed in ITS2 during Pb–Pb collisions in 2023, resulting in severe acceptance loss in the IB layers around $\varphi = 2.4$ rad. The primary source of the background in 2023 was identified as an interplay between the Pb beam and a collimator located 120 m away before the ALICE interaction point. As the background mitigation was applied quickly in collaboration with the LHC accelerator team, only 10 % of the Pb–Pb datasets in 2023 were affected by this issue.

At a smaller level, various beam backgrounds have still been observed across different collision systems and varying beam parameters. Therefore, continuous monitoring and simulation studies are ongoing to support the stable operation of ITS2 and to further the understanding and future vertex detector design.

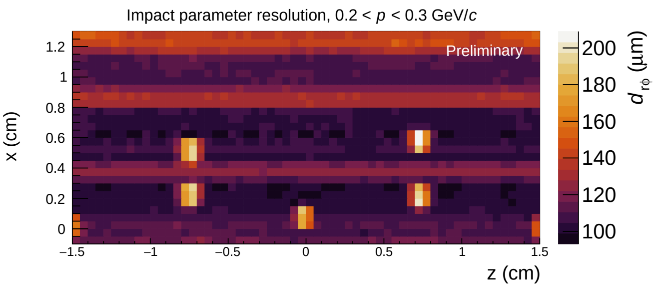
3.4 Detector performance

The ALICE impact parameter resolution was significantly improved with the installation of ITS2, as represented in Fig. 5a. A comparison with Run 2 data shows about a factor of 2 improvement for 1 GeV/c tracks. This improved resolution allows us to observe the material impact on the impact parameter resolution as well.

Figure 5b shows the impact parameter resolution as a function of the hit location on the x and z planes of ITS2 chips in the given low momentum tracks between 0.2 and 0.3 GeV/c. In the resolution map, one can clearly identify that the degraded spots are aligned with the locations of the capacitors on the Flexible Printed Circuit (FPC), placed on top of the chips. Furthermore, the cooling tubes, shown as two lines in the central region, and the overlapping area between adjacent staves on the upper edge, also show a slight degradation in resolution. This detailed study is also used to improve the detector response description in the simulations.



(a) Impact parameter resolution

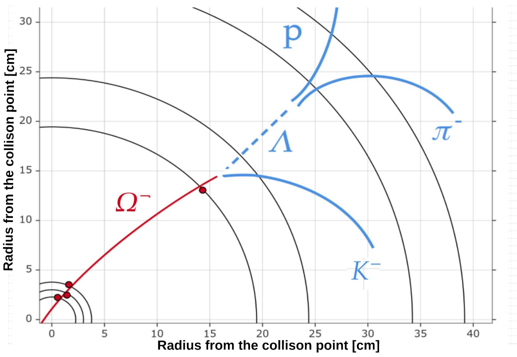


(b) Impact parameter resolution depending on hit locations in x and z planes

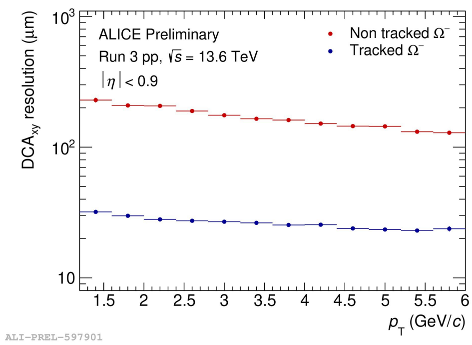
Figure 5: Impact parameter resolution measured in Pb–Pb collisions

A novel method, which became possible with ITS2, is the so-called strangeness tracking, in which particles are tracked prior to their weak decays. ITS2 enables this method due to the increased granularity close to the interaction point. In this tracking algorithm, one can look for a cascade-decay topology reconstructed in the outer ITS2 layers and match it to track segments detected only in the inner ITS2 layer, as illustrated in Fig. 6a.

Ω^- is a good observable to test this method because its track can be reconstructed in the ITS IB due to the decay length of around 4 cm. As shown in Fig. 6b, the pointing resolution (DCA_{xy}) of Ω^- is improved by a factor of 7 through this method. The significant improvement in the pointing resolution enables distinguishing between prompt and non-prompt Ω^- and measuring the fraction of Ω^-s originating from Ω_c^0 decays, which was not accessible with the previous detector.



(a) Sketch of a Ω^- decay in the ITS2 layers



(b) Pointing resolution of Ω^- with and without the strangeness tracking

Figure 6: Schematics and performance plot about the strangeness tracking algorithm

3.5 Particle identification studies: ITS *color run*

By operating the detector in a non-standard configuration for special data-taking, ITS performed energy-loss measurements to demonstrate the feasibility of performing particle identification with

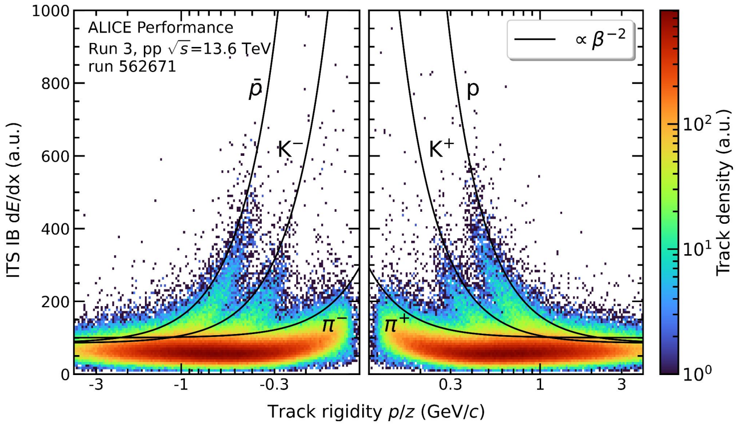


Figure 7: ITS dE/dx distribution versus track rigidity (p/z) measured with the ITS2 Inner Barrel layers in pp collisions with a 4 kHz interaction rate at $\sqrt{s_{\rm NN}}$ = 13.6 TeV

MAPS, despite their thin sensing volume and binary output. During these measurements, called *color runs*, the chips are configured to provide a pulse length proportional to the collected charge by deactivating the signal clipping mechanism in the pixel front-end circuit. Moreover, the readout frame rate of the innermost layers is increased to 2.2 MHz instead of 202 kHz. This allows to measure the Time-over-Threshold (ToT) as a proxy for the energy loss in the sensing volume. Such a mode of operation is not possible during nominal data taking but only at very low interaction rates of about 1-4 kHz pp collisions, as the long front-end pulses combined with the high framing rate require a very large bandwidth.

Figure 7 shows the *color run* results as measured in pp collisions at 4 kHz interaction rate. For reference, a parameterization of the energy loss as a function of $\beta^{-2} = (p/E)^{-2}$ for different particle species is overlaid on the plot. The *color run* results demonstrate the particle identification performance of ITS2, showing a distinct separation between particle species.

4. Summary and outlook

ITS2 has demonstrated excellent performance and stable operation since 2022 as the largest MAPS-based detector ever deployed in a high-energy physics experiment. A high detection efficiency above 99 % and a low fake-hit rate below 10^{-6} per pixel per event were maintained for over 3 years of operations. Thanks to its enhanced spatial resolution and closer proximity to the interaction point, it is possible to study in detail the detector material budget effects and the beam background physics. As a consequence of the detector performance improvements, the ITS2 has significantly enhanced the precision of weak-decay particle reconstruction across all collision systems, enabling the development of a strangeness-tracking algorithm and contributing to the study of previously inaccessible decay channels like Ω_c^0 to Ω^- and π^+. The particle identification capability using Time-over-Threshold information is being explored with the ITS *color run* campaign. The knowledge and experience gained from the operation of ITS2 have been employed to guide the research and development of the next-generation upgrade, ITS3, planned for installation during the next LHC Long Shutdown in 2026-2029 [7].

References

[1] The ALICE Collaboration, "The ALICE experiment at the CERN LHC," JINST **3**, S08002 (2008). DOI: 10.1088/1748-0221/3/08/S08002

[2] The ALICE Collaboration, "Technical design report for the upgrade of the ALICE inner tracking system," J. Phys. G **41**, 087002 (2014). DOI: 10.1088/0954-3899/41/8/087002

[3] The ALICE Collaboration, "ALICE upgrades during the LHC Long Shutdown 2," JINST **19**, P05062 (2024). DOI: 10.1088/1748-0221/19/05/P05062

[4] G. Aglieri Rinella, "The ALPIDE pixel sensor chip for the upgrade of the ALICE Inner Tracking System," Nucl. Instrum. Methods A **845**, 583 (2017). DOI: 10.1016/j.nima.2016.05.016

[5] F. Reidt *et al.*, "Upgrade of the ALICE ITS detector," Nucl. Instrum. Methods A **1032**, 166632 (2022). DOI: 10.1016/j.nima.2022.166632

[6] D. Agguiaro *et al.*, "Sensor operating point calibration and monitoring of the ALICE Inner Tracking System during LHC Run 3," arXiv:2510.27592 [physics.ins-det] (2025), https://arxiv.org/abs/2510.27592.

[7] The ALICE Collaboration, "Technical Design report for the ALICE Inner Tracking System 3," CERN-LHCC-2024-003 (2024). `https://cds.cern.ch/record/2890181`