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Operation and Performance of the Upgraded ALICE Inner Tracking System

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The ALICE Experiment underwent a major upgrade during the Long Shutdown 2 of the Large Hadron Collider (LHC), which included the installation of a new Inner Tracking System (ITS2). The ITS2, consisting of a 7-layer, pixel-only tracker with 24,000 Monolithic Active Pixel Sensors (MAPS) and 12.5 billion pixels, represents the largest scale application of the MAPS technology in a high-energy physics experiment to date. It has been successfully commissioned for the LHC Run 3, started in July 2022 with proton–proton collisions at a center of mass energy of 13.6 TeV. To ensure stable operation and maintain high data quality, a regular calibration of the detector has to be performed, which consists in tuning and a subsequent measurement of pixel thresholds and determination of the noisy channels. The complexity of the calibration depends linearly on the number of pixels, making the ITS2 calibration an unprecedented challenge. This work offers an overview of the operational procedures required to maintain optimal detector performance, along with results obtained from calibration and the performance achieved during LHC Run 3. Furthermore, this contribution discusses the significant improvements brought by the ITS2 to the ALICE experiment, such as an impact parameter resolution of about 40 µm both in the $r\varphi$ and z coordinates at a transverse momentum of 500 MeV/c, a detection efficiency better than 99%, and the event readout-rate increased from 1 kHz up to 100 kHz in Pb–Pb collisions and 200 kHz in proton–proton collisions.

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1. The upgraded ALICE Inner Tracking System

ALICE (A Large Ion Collider Experiment) is one of the four large experiments at the Large Hadron Collider (LHC) at CERN, and it is dedicated to the study of strongly interacting matter. ALICE completed a major upgrade in 2022, aimed to fulfill the requirements of the Run 3 physics program of the LHC [1]. In particular, the Inner Tracking System (ITS) was entirely changed during the upgrade. It is the innermost detector of ALICE and its main purposes are the localization of primary and secondary vertices and the reconstruction of particle tracks. The ITS2 consists of 7 cylindrical layers of Monolithic Active Pixel Sensors (MAPS) named ALPIDE (ALice Pixel Detector) [2], with radial coverage from 2.2 cm to 39 cm. The 7 layers are divided into Inner Barrel (IB, layers 0–2) and Outer Barrel (OB, layers 3–6). Each layer is azimuthally segmented into units called staves, there are 192 staves in total. With a total of 24120 chips, each one measuring 15×30 mm^2, and an area of 10 m^2 covered by the detector, the ITS2 is the largest pixel-based detector in High-Energy Physics to date. The material budget of the new ITS is 0.36% X_0/layer for the IB and 1.1% X_0/layer for the OB. The IB has therefore significantly lower material budget w.r.t. the old ITS [3]. This allows the tracking performance to be significantly improved, especially for low-momentum particles, as the effect of Coulomb scattering on the tracking resolution in IB layers is reduced.

2. ALPIDE MAPS

The ALPIDE MAPS, developed on purpose by the ALICE Collaboration, is implemented in a 180 nm CMOS imaging process and fabricated on substrates with a 25 µm thick high-resistivity (>1 kΩ cm) p-type epitaxial layer. Its total power consumption is lower than 47 mW/cm^2. The signal-sensing elements are n-well diodes with a diameter of approximately 2 µm and an area typically 100 times smaller than the pixel cell area. The particular manufacturing process also provides a deep p-well layer that is exploited to implement the full CMOS circuitry in the active sensor area without compromising the charge collection by sensing-diodes. The ALPIDE chips include a matrix of 512 pixel rows in the $r\phi$ direction and 1024 pixel columns in the z direction, with every pixel cell having a pitch of 29.24×26.88 µm^2. The readout of pixel hit data is based on a circuit called Priority Encoder, which with its 512 instances (one per every two-pixel columns) provides the address of the fired pixels to the periphery. Analog biasing, control, readout, and interfacing functionalities are implemented in a peripheral region of 1.2×30 mm^2. The periphery of the chip contains fourteen 8-bit analog DACs (Digital-to-Analog Converters) for the biasing of the pixel front-ends. The pixel signal is amplified and digitized at the pixel level: each pixel cell contains a sensing diode, a pulse injection capacitor to inject a test charge, a front-end amplifier and shaping stage, a discriminator, a digital section with 3 hit registers, a pixel masking register, and the pulsing logic. Test beam results have shown that the sensor has an intrinsic spatial resolution of 5 µm [4] and fulfills the experimental requirement of a detection efficiency above 99% [4]. About 60 e^-/µm are generated in the epitaxial layer by a traversing Minimum-Ionizing Particle (MIP), which means that about 1500 e^- are generated for a MIP normal incidence in the 25 µm epitaxial layer. This charge is shared between adjacent pixels. The readout of the chips is achieved differently in the IB and in the OB because of the different occupancy in the inner and outer layers: in the IB every ALPIDE transmits data through a 1.2 Gb/s high-speed link, while in the OB a 400 Mb/s link is shared among every group of 7 ALPIDE chips.

3. Data readout

Each detector stave is connected to an FPGA-based Readout Unit (RU), which provides control, power, trigger, and monitoring. The 192 RUs are then connected to a set of 22 Common Readout Units (CRUs), hosted in 13 First Level Processors (FLPs). The CRUs aggregate the data received from the different RUs and forward it to the Event Processing Nodes (EPNs), which consist of 340 servers, each with 2 AMD Rome 32 core CPUs, 512 GB RAM, 8 AMD MI50 GPUs with 32 GB memory each, as well as a network interface. Here data are stored, reconstructed, and processed online. The offline processing of data is also possible on the EPNs when the detector is not taking data. All the data readout and processing are managed by the O2 framework [6], the ALICE computing system for Run 3. During data taking, quality control tasks developed inside the O2 are also available to monitor in a synchronous way detector data related to hit occupancy, clusters, tracks, decoding errors, etc. The detector can operate both in triggered and continuous readout mode. The standard operational mode is the continuous mode, in which the RUs internally generate periodic triggers to the sensors with a minimal gap between sent strobes [5].

4. ITS2 calibration procedure

A regular monitoring of the detector calibration is performed to ensure stable operation and high data quality. A general ITS calibration procedure involves tuning of pixel thresholds and masking of noisy pixels, nevertheless other scans are also available for detector studies. The ITS2 configuration, together with the calibration-scans control and execution, are managed by the ITS Detector Control System (DCS), while the data readout and subsequent processing are integrated into the ALICE O2. With a total of 24120 chips and more than 12.5 billion pixels, the huge number of channels that need to be calibrated makes the calibration of the ITS2 an unprecedented challenge: a threshold scan of the whole detector produces approximately 60 TB of event data, collected in approximately 1.5 hours, using 40 EPNs out of 340, which are in total available for all subdetectors. To limit the amount of time and computing resources spent in calibration, a scan of the full detector is generally used only as a reference and not performed on daily basis.

4.1 Threshold tuning

The purpose of the threshold tuning is to set the operating point of the detector by adjusting the setting of the DACs VCASN and ITHR, which change respectively the baseline and the shape of the pulse and consequentially influence the threshold: an increase of VCASN produces an exponential decrease of the threshold, while an increase of ITHR produces a linear increase of the threshold. The target value chosen for the threshold setting is 100 e^-, resulting from a compromise between having a good detection efficiency and a low fake-hit rate (FHR). Each of the two DACs is tuned by injecting an analog pulse with the fixed amplitude of 100 e^- and measuring the number of hits registered in the pixels. Then the DAC setting is changed and the injection of the fixed charge and the hit counting are repeated. This process is repeated 50 times for each DAC setting. The

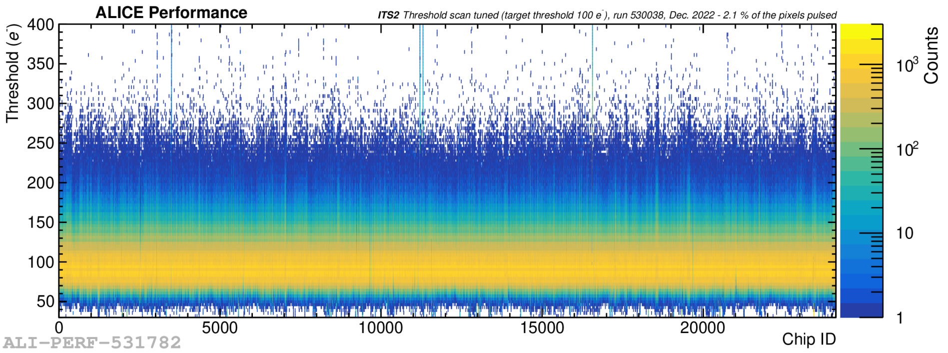


Figure 1: Threshold distribution as a function of the chip ID for the full ITS2, after the threshold tuning to 100 e^-.

first DAC tuned is VCASN, which provides a coarse tuning of the threshold. Then the ITHR tuning is performed to fine-adjust the threshold. For each tuning, the pixel response is fitted with an error function to extract the 50% point, which corresponds to the DAC value that yields the desired threshold of 100 e^-. The threshold tuning is performed at chip level, since the parameter of interest is the average threshold per chip and the setting of VCASN and ITHR can only be made for the entire chip. Moreover, since running the tuning on all the pixels of the ITS2 is a long and resource-intensive procedure, the scan is performed on only about 1% of pixels of each chip, for a total ~98 million pixels selected uniformly in the whole detector. Based on the experience acquired during the commissioning of the detector, this small fraction of pixels is enough to have complete information for the whole detector.

4.2 Threshold scan

The threshold scan is performed to measure the threshold of the pixels of each chip of the detector. This measurement is performed by injecting analog pulses ranging from 0 to 500 electrons into the pixels keeping the VCASN and ITHR values fixed. The pixel response will result in an error function that can be fitted to extract the 50% point (threshold) and the σ (ENC noise). To save time and computing resources, a daily scan is done only for 11 rows selected uniformly on each chip, resulting in about 2% of pixels of the entire detector. The distribution of the in-pixel tuned threshold for each chip of the detector is shown in Figure 1. The average of every chip aligns with the target threshold of 100 e^- at which the ALPIDE chips are known to have an efficiency higher than 99% [4], with an RMS of about 20 e^-. Figure 2 shows the evolution of the average threshold per layer in several months of 2023, keeping always the same tuning. The average remained constant at around 100 e^- during the entire period, with only minor fluctuations due to modifications in the automatic voltage drop correction procedure. Those small fluctuations are of the order of 1–2 electrons and do not influence the operations of the detector. The decrease at the end of 2023 data-taking period is due to the effect of the Total Ionizing Dose (TID) on the chip front-end transistor, already observed during test beams [7]. The threshold value of 100 electrons can be reestablished by re-tuning the detector.

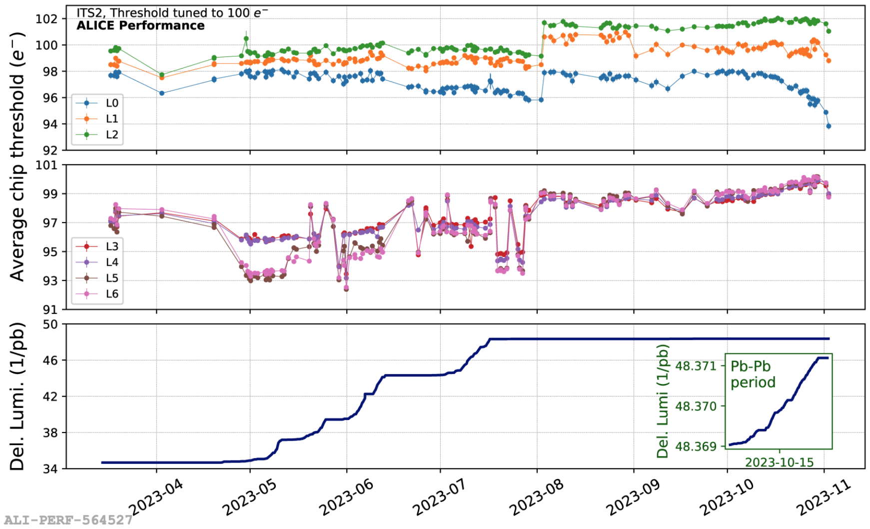


Figure 2: Evolution of the average in-pixel discriminating threshold per layer, compared with the luminosity delivered to ALICE, from March 2023 to November 2023.

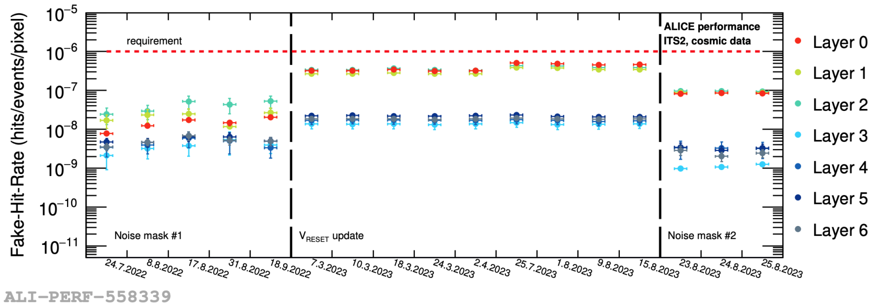


Figure 3: ITS2 average FHR trend as a function of date after masking 0.004% of pixels of the entire detector. Each point shows a separate run from Run 3.

4.3 Noise calibration

The purpose of the noise calibration is to tag and mask the noisy pixels. The noisy pixels are searched for after the threshold is tuned. A noise calibration run consists in a standard data-taking run without the beam presence. Pixel tagged as noisy are the ones exceeding 10^{-2} hits/event/pixel for the IB and 10^{-6} hits/event/pixel for the OB. They are subsequently masked. The difference between the two values of Fake-hit Rate (FHR) is driven by the choice to avoid efficiency losses in the Inner Barrel. Moreover, considering the lower occupancy of OB layers, the number of hits registered in the OB would be dominated by the noise if such a strict cut would not be applied. With these requirements, the number of pixels tagged as noisy and masked in the entire detector is around 0.004% out of 12.5 billion pixels, and they mostly come from the OB. Figure 3 shows the average FHR for each layer after applying the mask. The overall value on average is stable over time and remains around 10^{-8} hits/event/pixel for the OB and around 10^{-7} hits/event/pixel for the IB, below the 10^{-6} hits/event/pixel imposed by design to achieve a good track reconstruction performance [1].

4.4 Further monitoring scans

In addition to the main calibration scans discussed above, a few other scans are available for monitoring and detector studies, for example, to detect chip performance degradation due to radiation. A DAC scan is available to monitor the 14 on-chip DAC outputs and verify the linearity between the digital input and the analog output. The scan is done by providing at the input of each DAC a digital value between 0 and 255 and reading the analog output. A $\mathrm{V_{RESETD}}$ scan is available to monitor the optimal operational chip range: the reset voltage of the pixel-charge-collecting node is influenced by radiation, and in turn, it influences the discriminating threshold of the pixels. With the $\mathrm{V_{RESETD}}$ scan, a threshold scan is performed for different values of the $\mathrm{V_{RESETD}}$ DAC, and this allows us to find the optimal $\mathrm{V_{RESETD}}$ parameter to be set in order to have the optimal threshold of 100 electrons. A pulse-shape scan is available to sample the shape of a pixel signal. It is done by removing the signal clipping and applying a long pulse to the pixel, then multiple charge injections for a wide charge range are done every 250 ns: the signal is sampled with different strobe delays with respect to the pulse, and it is possible to obtain the shape of the signal. This scan is a part of an ongoing proof-of-concept study aimed at proving the possibility of performing time-over-threshold measurements with MAPS detectors and also verifying the possibility of obtaining PID with only the ITS2, after calibrating the time-over-threshold measured with the charge collected in each pixel.

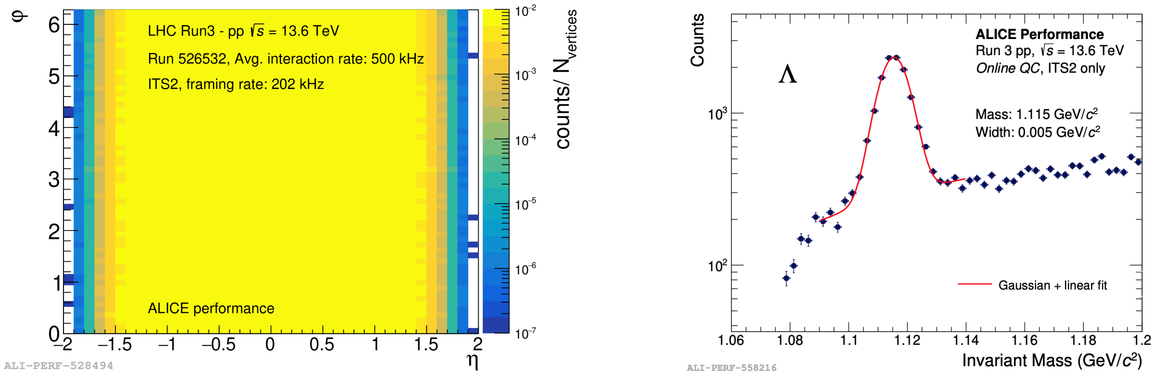
5. LHC Run3 performance overview

From the start of the LHC Run 3 in July 2022 until November 2023, a luminosity of about 28 $\mathrm{pb^{-1}}$ has been integrated by the ALICE detector in pp collisions at $\sqrt{s}$ = 13.6 TeV and of about 2 $\mathrm{nb^{-1}}$ in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV. The nominal ITS framing rate during pp collisions has been set to 200 kHz, for the nominal 500 kHz interaction rate of proton bunches in LHC. In the past, the ITS2 was successfully tested up to 4 MHz interaction rate with proton beam. The corresponding data rate was approximately 50 GB/s. During the Pb–Pb run the recorded Pb–Pb interaction rate reached 47 kHz, with a default framing rate of 67 kHz.

The tracking performance, wich was achieved by the ITS2 during the proton–proton period in Run 3, is illustrated in Figure 4. Figure 4a shows the distribution of tracks as a function of azimuthal angle and pseudorapidity as obtained from the online tracking task for quick QA of the data. In can be seen that tracks are uniformly distributed over the whole acceptance. In the online-quality-control framework, it is also possible to obtain physics performance results such as the invariant-mass peaks of Λ and K^0_s using only ITS standalone tracks, reconstructed matching positive and negative particle tracks in the ITS layers. An example of the invariant-mass peak for the Λ is shown in Figure 4b.
Moreover, the impact parameter resolution has been measured with Run 3 pp collisions data, using global tracks with at least 1 hit in the Inner Barrel. Figure 5 shows that the impact-parameter resolution in Run 3 improved by a factor of 2–2.5 with respect Run 2.

6. Conclusions

The calibration of the ITS2 consists of tuning and measuring the in-pixel threshold and spotting and masking the noisy pixels. This procedure is very challenging because of the large number of



(a) **(b)**

Figure 4:
4a Distribution of tracks measured by ITS2 as a function of pseudorapidity (η) and azimuth (φ) in pp collisions at $\sqrt{s} = 13.6$ TeV.
4b Invariant-mass peaks of $\Lambda(\rightarrow p\pi)$ obtained with ITS2-only tracks synchronously reconstructed in pp collisions at $\sqrt{s} = 13.6$ TeV.

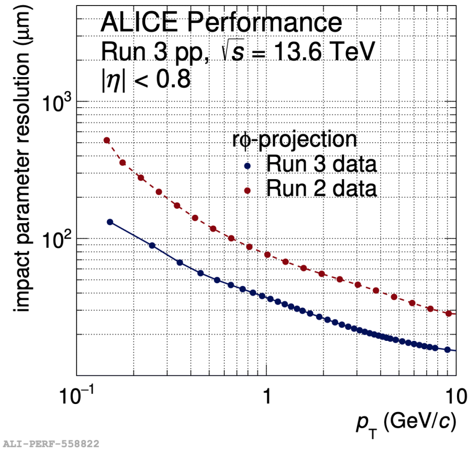


Figure 5: Impact parameter resolution evaluated at the primary vertex in $r\varphi$ vs. p_T in pp collisions at $\sqrt{s} = 13.6$ TeV in Run 3 compared with the same quantity measured in pp collisions at $\sqrt{s} = 13$ TeV in Run 2.

channels that have to be calibrated: a threshold scan of the full detector results in about 60 TB of raw hit data. A regular monitoring of the detector calibration is performed to ensure stable operation and high data quality. Obtained results show excellent stability of threshold and noise over time: the threshold remains stable around 100 e^- and the fake hit rate is stable around 10^{-8} hits/event/pixel in the Outer Barrel and around 10^{-7} hits/event/pixel in the Inner Barrel, masking only 0.004% of noisy pixels. The ITS2 was successfully tested up to 4 MHz interaction rate of proton bunches, which produces a data rate of approximately 50 GB/s. Studies performed during Run 3 show an improvement in the impact-parameter resolution with respect to Run 2 and an excellent quality of the ITS2 tracking.

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