The ALICE 3 particle identification systems

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The ALICE 3 particle identification system

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The ALICE Collaboration has proposed a completely new apparatus, ALICE 3, for the LHC Runs 5 and 6. The experiment will enable novel studies of the quark-gluon plasma focusing on low-p_T heavy-flavour production, as well as on precise multi-differential measurements of dielectron emission to probe the mechanism of chiral-symmetry restoration and the time-evolution of the QGP temperature. The detector consists of a large pixel-based tracking system covering eight units of pseudorapidity and including a vertex detector mounted on a retractable structure inside the beam pipe. Moreover, it will be endowed with a comprehensive particle identification (PID) system, implementing silicon time-of-flight (TOF) detector, an aerogel-based ring-imaging Cherenkov (RICH) detector, a muon identification system, and an electromagnetic calorimeter.

This paper presents the conceptual design of the PID subsystems and technology options, as well as the expected performance from simulation studies and first results achieved in the ongoing R&D activities.

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1. Introduction

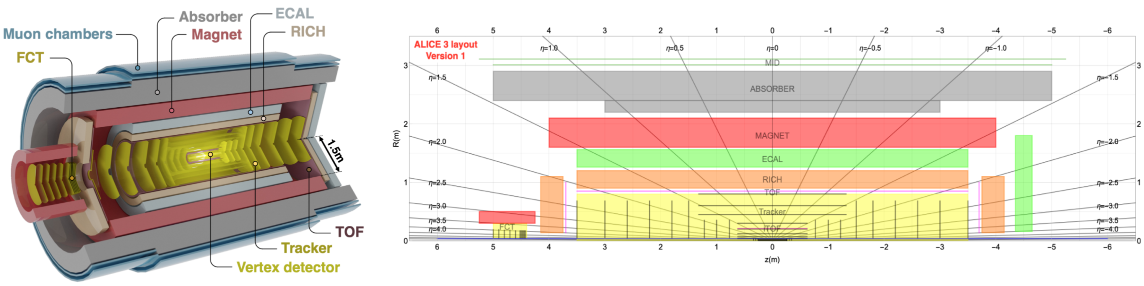
ALICE (A Large Ion Collider Experiment) is one of the four main experiments at the CERN Large Hadron Collider (LHC) devoted to the study of the properties of the quark-gluon plasma (QGP), a state of matter where quarks and gluons are deconfined, produced in ultra-relativistic heavy-ion collision. The ALICE Collaboration has proposed a next-generation heavy-ion experiment called ALICE 3, which will be installed during the Long Shutdown 4, in preparation for Run 5 (2035) and 6 [1]. The new apparatus will have a very large acceptance of 8 units of pseudorapidity for tracking and particle identification and unprecedented track impact parameter resolution.

2. ALICE 3 detector concept

The proposed ALICE 3 experiment combines excellent particle identification capabilities with a tracking system that has very low mass and unique pointing resolution, covering a much larger rapidity range than the current ALICE setup. The detector will measure the electromagnetic radiation produced by the QGP through a multi-differential approach, enabling the investigation of its early evolution. Additionally, it will provide an improved characterization of hadron production with heavy flavors down to very low transverse momenta. To this aim, an innovative detector concept is necessary (Figure 1a) where the key requirements are: a retractable vertex detector, a compact and lightweight all-silicon tracker combined with a superconducting magnet system, extensive particle identification, large pseudorapidity acceptance $|\eta| < 4$ (Figure 1b), and continuous readout combined with online processing.

Particle IDentification (PID) plays a key role in the proposed physics program and various PID systems will be essential: the Time of Flight (TOF), the Ring Imaging Cherenkov, an Electromagnetic Calorimeter, and the Muon identification (MID).

In the following, the main features of the different ALICE 3 detectors for particle identification are outlined and some of the corresponding ongoing R&D activities are presented, with special focus on the timing performance.



(a) (b)

Figure 1: Schematic view of ALICE 3 state-of-the-art detector concept (a). Longitudinal cross section of the ALICE 3 detector (b) [1].

3. Particle identification systems

The hadron and electron identification in the central barrel detector and the forward region is performed via Time-of-Flight and Cherenkov imaging techniques. Figure 2 summarises the PID capabilities of the proposed detector, emphasizing the $\eta - p_T$ regions where particle identification can achieve a separation better than 3σ. In general, combining the data from various detector systems enables high particle identification efficiencies across a wide momentum range.

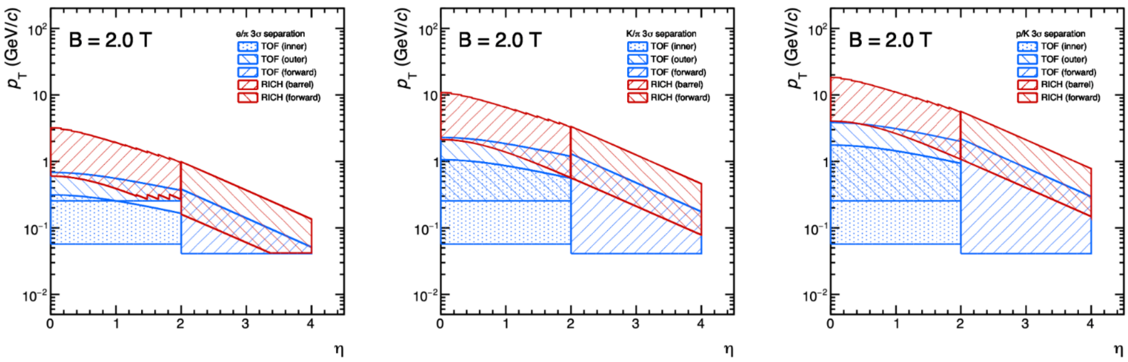


Figure 2: Expected coverage of $\eta - p_T$ regions in which particles can be separated by at least 3σ with the ALICE 3 TOF and RICH systems. e/π, π/K and K/p separation plots are shown from left to right.

The muon identification in ALICE 3 is based on the correlation of the information from the tracker and the muon identifier detector.

In addition, an electromagnetic calorimeter is planned to cover the full barrel acceptance and one forward region enabling a variety of measurements, including those of photon-jet correlations and radiative decays of χ_c and D^{*0}. It will be instrumented with a Pb-scintillator sampling calorimeter, while a fraction of the central barrel will be covered by the existing $PbWO_4$ crystals with SiPM readout.

3.1 Time of Flight system

The Time-of-Flight system enables particle identification over the entire acceptance range ($|\eta| < 4$). It consists of an inner layer (iTOF) at a radius of 20 cm and an outer TOF layer (oTOF) at a radius of 85 cm from the beam pipe, and two forward disks (fTOF) positioned on both sides of the interaction point at ±3.70 m. The detector ensures the separation of e/π, π/K, and K/p up to a transverse momentum of 500 MeV/c, 2 GeV/c, and 4 GeV/c respectively. This values refer to $|\eta| = 0$ (see Figure 2). In total, the TOF system will be devised as a silicon surface of about 45 m^2, a large detector area that has not ever been built before. To reach the target PID performance, a time resolution of 20 ps r.m.s. together with a low material budget of $1 - 3\%$ X_0 and a power density of 50 $\mathrm{mW/cm}^2$ are required.
Three sensor technologies are being evaluated as candidates for dedicated R&D: fully depleted CMOS sensors, Low-Gain Avalanche Diodes (LGAD) and Single Photon Avalanche Diodes (SPAD).

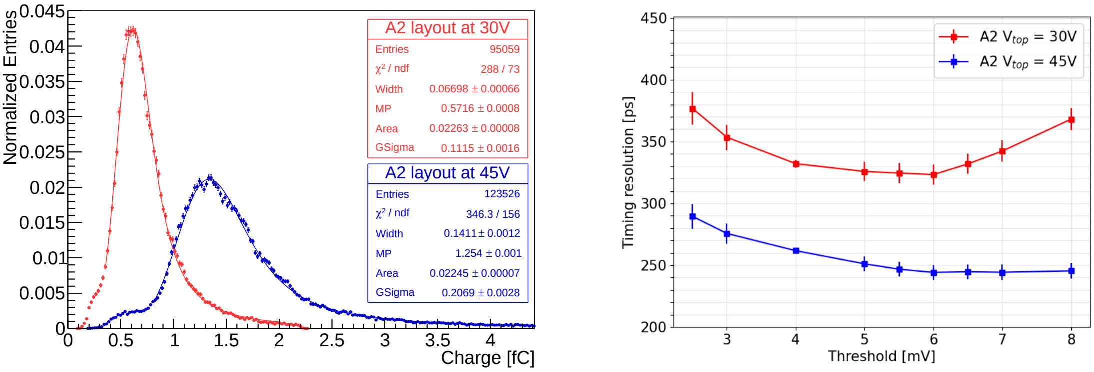
- ***LGADs***: LGADs, referred to as Ultra Fast Silicon Detectors (UFSDs) [2], have been deeply studied in recent years, making them one of the most advanced silicon technologies for timing applications. They achieve outstanding timing performance by introducing a controlled doped gain layer beneath the p-n junction, which creates a high electric field responsible for charge multiplication. The resulting moderate internal gain enhances the Signal-to-Noise Ratio (SNR) and ensures excellent timing performance. The LGAD technology has been selected for the timing layers in the ATLAS and CMS Phase II upgrades for the High-Luminosity LHC (2026) and is also a strong candidate for the ALICE 3 Time-of-Flight (TOF) system. In recent years LGAD sensors have been produced by different manufacturers with different doping levels, active thickness, pad sizes, and inter-pad gaps. Latest results on time resolution of LGADs with different thickness show that a device with 50 μm thickness can achieve a resolution of about 34 ps; while decreasing the thickness of the device the time resolution improves further [3].

- ***Fully Depleted Monolithic Active Pixel Sensor (FD-MAPS)***: Contrarily to traditional LGADs, which are produced on sensor-grade wafers and require dedicated readout electronics, monolithic sensors can decrease the production costs, the material budget and simplify the complex assembly procedures characterising the hybrid devices. The FD-MAPS developed in the ARCADIA project [4] exploits a fully depleted technology to have a fast charge collection by drift, but the current time resolution is still too low ($\sim ns$) due to the low SNR. A promising solution to suppress the effect of noise increasing the SNR has been found by implanting a gain layer below the collection electrode. The electric field in the gain region becomes high enough to trigger the onset of the charge multiplication through the impact ionization mechanism. In this way, the LGAD technology has been integrated into the FD-MAPS devices in the first prototype produced with a commercial 110 nm CMOS Image Sensor (CIS) process provided by LFoundry [5].

  The first test beam campaign on these devices was carried out at the Proton Synchrotron at CERN (T10 beamline) in October 2023, where a beam composed of a mixture of protons and pions with a momentum of 10 GeV/c was provided. Starting from the analog waveforms, the collected charge distribution could be extrapolated and the results are reported in Figure 3a. The distributions presented for different collection electrode voltages, i.e. 30 V and 45 V, show the Most Probable Value (MPV) of the curves increases by a factor of ~2.2, which confirms the activation of the gain. Moreover, the time resolution obtained with the fixed threshold algorithm is shown in Figure 3b as a function of different applied thresholds. The best time resolution obtained with this method combined with the time walk correction was 244 ± 6 ps. This result is too low compared to the one required from the experiment, but in this production, a gain lower than the one expected (10 – 20) was found. New monolithic devices with higher gain will be tested soon with beams.

- ***SPADs***: The last candidates for the TOF timing layer are the Silicon PhotoMultipliers (SiPMs) whose cells (SPADs) are fired when a photon, produced by a charged particle in a resin layer, crosses them. Recently, several R&D studies have been carried on, and new prototypes with different protection layers have been measured [6].

  The time resolution of SiPMs with protection resin improves as the number of fired SPADs increases, achieving a result better than 20 ps for a number of SPADs larger than 5. These



(a) (b)

Figure 3: Distribution of the collected charge for two different top bias voltages: 30 V in red and 45 V in blue (a). Time resolution as a function of the applied threshold at two different top bias voltages (b) [5].

results confirm the importance of a protection layer and the Cherenkov light to enhance the timing response of SiPMs to a traversing charged particle. This is promising in terms of a possible combination of the TOF and RICH techniques.

3.2 RICH system

The TOF system is complemented by a barrel Ring-Imaging Cherenkov (RICH) layer (bRICH) with an inner radius of 90 cm and two forward RICH disks (fRICH) positioned at ±4.05 m from the interaction point. This setup utilizes a 2 cm thick aerogel radiator with a refractive index of 1.03 and a SiPM-based photodetector. The aim of the ALICE 3 RICH is to extend the PID range of the outer TOF to higher momentum. Thanks to a Cherenkov angle resolution better than 1 mrad, it improves the separation of e/π, π/K, and $K/$p above 2, 10, and 16 GeV/c, respectively, as illustrated in Figure 2. The main R&D challenge includes the possibility of merging the oTOF and bRICH systems using a common SiPM layer coupled to a thin radiator window to exploit the Cherenkov radiation and extend the particle identification capabilities. To test this integrated concept, a first small-scale prototype was successfully tested on beam where several 8x8 SiPM matrices and different radiator windows were measured. The estimated angular resolution is consistent with the detector specifications [7].

3.3 Muon identifier system

For the identification of muons down to $p_T \approx 1.5$ GeV/c and a pseudorapidity coverage up to $|\eta| < 1.3$ a dedicated Muon Identification system (MID) will be built and it will provide muon tagging for particles reconstructed in the tracker. It will consist of a cylindrical shape iron absorber with a thickness of 70 cm at $|\eta| = 0$, that would be installed outside the magnet, and dedicated muon chambers around the absorber itself. For the chambers, the use of plastic scintillator bars equipped with wavelength shifting fibers (WLS) and silicon photomultipliers is considered the baseline option due to their simplicity. Alternative options, such as well-known technologies like Multi-Wire Proportional Chambers (MWPCs) and Resistive Plate Chambers (RPCs) are also under study. In the last test beam performed in July 2023 the compatibility of different MWPC structures and scintillator bars with the MID requirements was verified [8]. The efficiency, defined as the probability of finding a valid hit in a given chamber, as a function of the estimated beam intensity was measured, and it resulted above 95% and constant for intensities up to 100 Hz/cm^2, well above the rate density of few Hz/cm^2 expected for the ALICE 3 MID in Pb-Pb collisions.

4. Conclusions

This contribution has described the ambitious program of ALICE 3, a next-generation multipurpose detector at the LHC, proposed as a follow-up to the present ALICE experiment. To fulfill this rich physics program, an innovative detector concept is needed to ensure high-precision measurements of heavy-flavour hadrons and electromagnetic probes that will remain inaccessible during Runs 3 and 4. ALICE 3 is being designed with excellent PID capability exploiting several PID techniques. In this paper the requirements of the PID systems and several ongoing novel detector R&D have been presented, with a broad impact on future high-energy and nuclear physics experiments. The start of data taking with ALICE 3 is planned for LHC Run 5, currently scheduled in 2035, thus by the end of the next year the selection of technologies and small-scale proof of concept prototypes must be performed.

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