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Title: New ALICE detectors for Run 3 and 4 at the CERN LHC

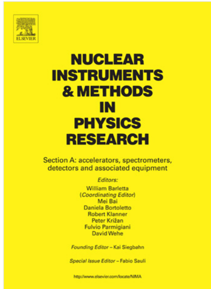
Year: 2020

Version: Accepted version (Final draft)

Please cite the original version:

Trzaska, W. (2020). New ALICE detectors for Run 3 and 4 at the CERN LHC. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 958, Article 162116. https://doi.org/10.1016/j.nima.2019.04.070

Accepted Manuscript



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PII: S0168-9002(19)30544-3
DOI: https://doi.org/10.1016/j.nima.2019.04.070
Reference: NIMA 62116

To appear in: *Nuclear Inst. and Methods in Physics Research, A*

Received date : 19 March 2019
Revised date : 3 April 2019
Accepted date : 17 April 2019

Please cite this article as: W.H. Trzaska, New ALICE detectors for Run 3 and 4 at the CERN LHC, *Nuclear Inst. and Methods in Physics Research, A* (2019), https://doi.org/10.1016/j.nima.2019.04.070

New ALICE detectors for Run 3 and 4 at the CERN LHC

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Abstract

Run 3 at the CERN LHC is scheduled to start in March 2021. In preparation for this new data taking period the ALICE experiment is making major modifications to its subsystems and is introducing three new detectors: the new Inner Tracking System, the Muon Forward Tracker, and the Fast Interaction Trigger. The new detectors will enhance tracking, especially at low transverse momenta, improve vertexing, provide the required triggering, fast timing, luminosity, and forward multiplicity functionality. For instance, it will be possible to measure beauty from displaced J/ψ vertices down to transverse momenta $p_{\mathrm{T}} \sim 0$ and improve precision for the $\psi(2S)$ measurements. The upgraded ALICE will be able to register ten-fold increase of Pb-Pb delivered luminosity in Run 3 and 4 as well as two orders of magnitude more minimum bias events at 50 kHz in Pb-Pb collisions.

Keywords: HL-LHC, ALICE upgrade, Inner Tracking System, Muon Forward Tracker, Fast Interaction Trigger

1. Introduction

ALICE (A Large Ion Collider Experiment) [1], sketched schematically in Fig. 1, is a general-purpose, heavy-ion detector at the CERN Large Hadron Collider (LHC). ALICE was designed to address the physics of strongly interacting matter and, in particular, the properties of the Quark-Gluon Plasma (QGP). In December 2018 the LHC has ended the four-year period of operation known as Run 2 and entered a two-year upgrade period referred to as the Long

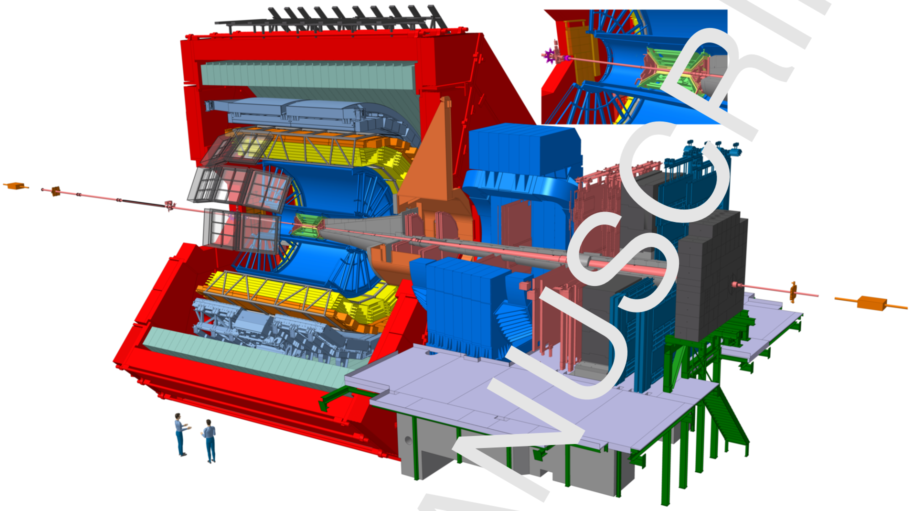

Figure 1: A simplified sketch of the ALICE setup.

Shutdown 2 (LS2). Improvements being implemented to the accelerator complex during the LS2 will boost the heavy-ion collision parameters of Run 3 and 4 to well beyond the specifications of the current ALICE setup. For instance, the Pb-Pb instantaneous luminosity during Run 3 will increase by a factor of 5 to 6 and the minimum-bias (MB) Pb-Pb interaction rate will reach $\sim$ 50 kHz, which is $\sim$ 50 times more than the rate recorded by ALICE with heavy-ion collisions during Run 2. To cope with such a drastic change in the running conditions and to achieve the proposed physics objectives, during the LS2 ALICE is implementing several improvements and installing three new detectors: the new Inner Tracking System (ITS), the new Muon Forward Tracker (MFT) and the new Fast Interaction Trigger (FIT).

2. Physics goals

The physics justification for the upgrade of ALICE is outlined in the Letter of Intent [2]. The main ALICE physics goals driving the upgrade requirements aim at extending the sensitivity down to very low transverse momenta (p_T) and collection of the minimum bias (MB) data at the highest possible rate.

For the study of quark-medium interaction mechanisms, heavy-flavour mesons and baryons should be measured down to very low p_{T} values. Further, ALICE will study charmonium states dissociation/regeneration as a tool to study deconfinment and medium temperature and employ high precision measurements of light and hyper-nuclei as a way to assess production mechanisms and collectivity. For an in-depth review of the future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams, see the recent review in the CERN Yellow Report [3].

3. Upgrade implementation

The main areas where the improvements to the ALICE setup have to be implemented to meet the proposed physics goals are: the ability to collect a large minimum-bias data sample, improvements in tracking efficiency and resolution at low p_{T} values, and the consolidation and speeding-up of the main particle identification (PID) detectors. The improvements are intended to increase the MB data sample by up to two orders of magnitude with respect to Run 2, to record all Pb-Pb interactions at the delivered collision rate of up to 50 kHz, to increase the tracking granularity, and to reduce the material budget and the distance of the sensors to the interaction point (IP). The technical aspects of the upgrade are described in the relevant Technical Design Reports (TDRs) [4, 5, 6, 7, 8]. In addition to the three new detectors shown in Fig. 2, the other important upgrades will include new Gas Electron Multiplier-based readout chambers for the Time Projection Chamber [9], and readout upgrades for the other detectors including the Time-Of-Flight (TOF), the Transition Radiation Detector (TRD), Muon chambers, Zero Degree Calorimeters (ZDC), and the other ALICE Calorimeters. In addition, an integrated Online-Offline system (O^2) [8] is being developed to record, compress and process the data.

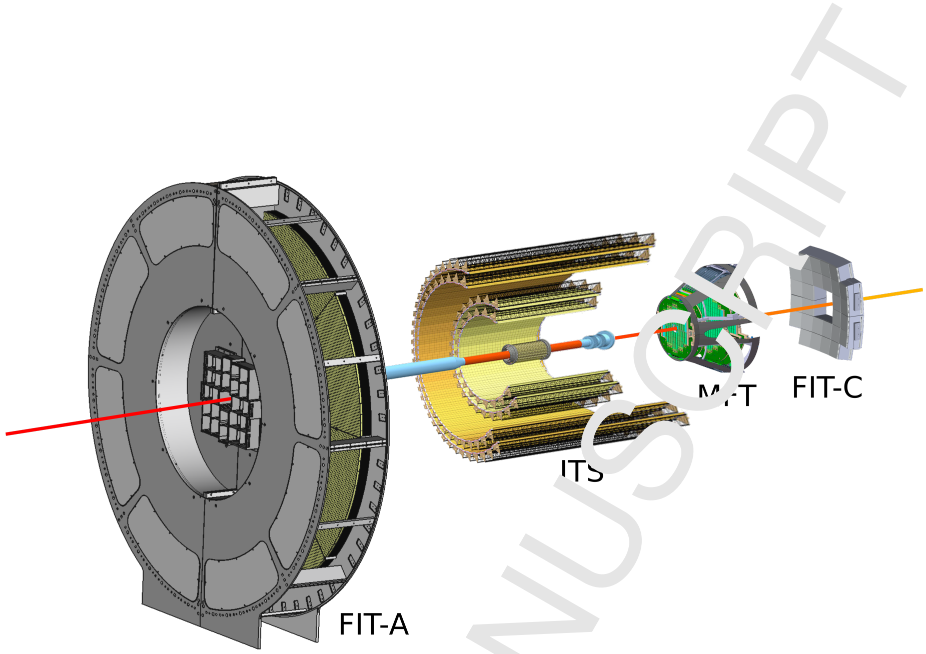

Figure 2: The new ALICE detectors for Run 3. From the left: FIT-A consisting of a large scintillator disk with a central part supplemented with an array of Cherenkov detectors, the new ITS – placed around the interaction point, the new MFT, and FIT-C – the second Cherenkov array.

4. ALPIDE sensor

The core of the upgrade of the ALICE silicon trackers is the new ALPIDE sensor [10, 11]. This is a CMOS Monolithic Active Pixel Sensor specifically developed for the upgrade of the ITS and for the MFT detector. The chip is implemented with a 180 nm CMOS Imaging Process using substrates with a high-resistivity (over 1 kΩ cm) p-type epitaxial layer, 25 µm thick, on a p-type substrate. Each sensor measures 15×30 mm^2 and contains a matrix of 512×1024 pixels with in-pixel amplification, shaping, discrimination and multi-event buffering. The presence of full CMOS circuitry within the active area eliminated the need for external electronics to be bonded to the chip. Due to the small diameter (2 µm) of the n-well diode covering just $\sim$ 1% of the pixel surface, the input capacitance was reduced to $\sim$ 5 pF. The power density is below 40 mW/cm^2, the maximum particle rate $\sim$ 100 MHz/cm^2 and the maximum particle readout rate (bandwidth) is $\sim$ 10 MHz/cm^2. The other advantage of the small capacitance is a large signal-over-noise ratio of S/N

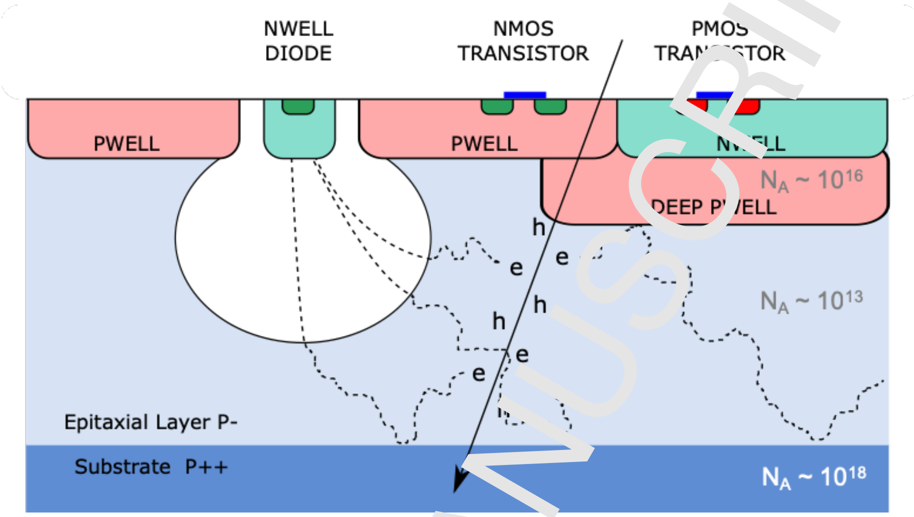

Figure 3: Schematic view of the well-structure used for ALPIDE and the corresponding charge collection. The picture is taken from [2].

> 100. A Minimum Ionizing Particle (MIP) traversing the sensor induces the collection of a charge of $\sim 1500\ e^-$ resulting in the signal amplitude of ~ 40 mV. A small reverse voltage of no more than -6 V is applied to the substrate to increase the depletion zone around the n-well collection diode. A schematic view of the well-structure used for ALPIDE is shown in Fig. 3.

While the n-wells are spaced on a 28 µm$\times$28 µm grid, the achievable position resolution, using a 200 e^- threshold, is typically 5 µm $\times$ 5 µm [12]. The performance of ALPIDE was tested with the total ionizing dose (TID) and neutron fluence (NIEL) up to 500 kRad and 1.7×10^{13} (1 MeV n_{eq}/cm^2), i.e., the dose exceeding 10 years of ALICE operation. There was practically no difference [12] between the irradiated and non-irradiated sensors in terms of resolution/pixel size, detection efficiency and fake-hit rate. The latter remained at the rate below 2×10^{-11} pixel/event. The number of masked pixels stayed at the level of 0.002%.

5. Inner Tracking System

The new ITS [12] represents a decisive improvement over the silicon tracker used during the Run 1 and 2. The number of sensor layers surrounding the IP will be increased from 6 to 7 with the innermost layer at the radius of $\sim$ 23 mm from the beam axis – considerably closer than in the old system that has the inner radius of 39 mm. The material budget, especially for the innermost layers, will be reduced, in terms of the radiation length, from $\sim 1.1\%$ X_0 down to $\sim 0.35\%$ X_0 allowing for increased tracking efficiency, especially at low p_{T} values. The pseudorapidity coverage of the tracker will be increased from $-1 \leq \eta \leq 1$ to $-1.5 \leq \eta \leq 1.5$. The active silicon area will reach 10 m^2 as compared to 6 m^2 for the old ITS. Thanks to the ALPIDE properties, the spatial resolution will reach 5×5 µm^2. The old ITS utilized three detector technologies: pixel detectors for the two innermost layers, drift detectors for the two middle layers, and strip detectors for the two outer layers. The spatial resolution was 12×100 µm^2, 35×25 µm^2 and 20×830 µm^2, correspondingly. The reduction of the pixel size will improve the pointing resolution along the beam direction by a factor of 5 and by a factor of 3 in the $r\,\varphi$ direction reaching $\sim$ 40 µm at $p_{\mathrm{T}} = 500$ MeV$/c$. The maximum readout rate for the old ITS was only 1 kHz. Now it will be increased up to 100 kHz for Pb-Pb collisions and up

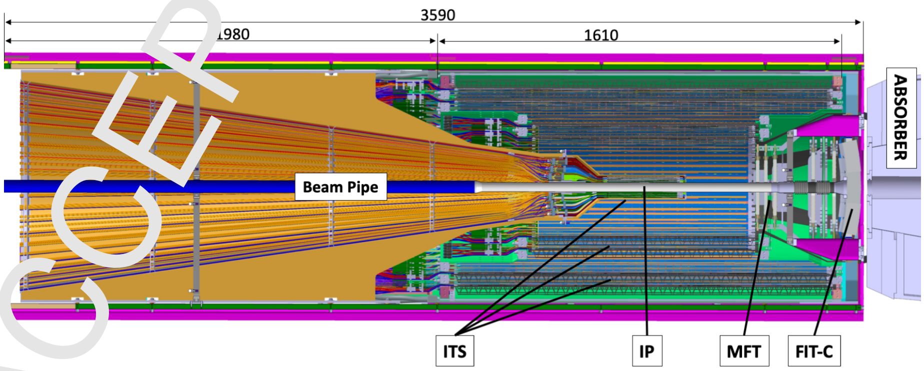

Figure 4: ALICE central detectors. The position of the IP, the three layers of ITS, MFT, FIT-C and of the absorber is indicated on the drawing.

to 1 MHz for pp. The position and integration of the ITS, MFT and FIT-C is presented in Fig. 4.

6. Muon Forward Tracker

The main objective for the Muon Forward Tracker [7] is to add vertexing capabilities to the ALICE Muon Spectrometer. As seen in Fig. 1, the muon chambers are located at the distance of several meters from the IP and separated from it by a massive absorber. Consequently, even with perfectly operating muon chambers, the pointing accuracy cannot reach the submillimeter level required, for instance, to identify displaced J/ψ vertices from the decay of a beauty hadron. The development of the ALPIDE sensors provided the needed technology to add five double-layers of detectors into the congested area (Fig. 4 and 5) surrounding the beam pipe between the ITS and the front of the absorber. In fact, the outer barrels of the ITS, the MFT and FIT-C will share the same support structure and will be installed as two elements: the lower and the upper half.

In total, MFT will employ 920 silicon pixel sensors with the active surface of 0.4 m^2. The first double-disk (Disk 0) will be at $z = -46$ cm from the IP. The last (Disk 4) at -76.8 cm from the IP. According to the ALICE naming convention, the positive direction along the beam line is from the CMS (hence the C-Side) towards the ATLAS experiment (hence the A-Side). Zero is located at the IP. The pseudorapidity coverage will be $-3.6 \leq \eta \leq -2.45$. Simulations indicate that with the chosen MFT design the offset resolution will go below 40 μm for p_{T} values above 3 GeV/c [13]. This improvement will enable ALICE to measure beauty down to $p_{\mathrm{T}} \sim 0$ from displaced J/ψ vertices and to have an improved precision for the ψ(2S) measurement. It will also add high-granularity data to the forward multiplicity information acquired by FIT.

7. Fast Interaction Trigger

The new Fast Interaction Trigger [13, 14] was designed to provide input for the new ALICE Central Trigger Processor [5], to monitor luminosity, determine the collision time, and to provide an unbiased sample of forward multiplicity needed to extract the centrality and the reaction plane needed in the analysis of heavy-ion collisions. The required functionality mandated the need to secure both a pico-second time resolution and a large acceptance. To accommodate these demands and to conform with the stringent space restrictions around the central detector barrel while maintaining a reasonable cost, a hybrid design was chosen. The excellent timing properties are assured by the two Cherenkov arrays on the opposite sides of IP. On the very congested C-Side (Fig. 4 and 5) there is space for only 28 elements. Due to the proximity to the IP, FIT-C forms a concave structure (Fig. 6) with the front surface of each element facing directly towards the IP and maintaining the same distance from it equal 82

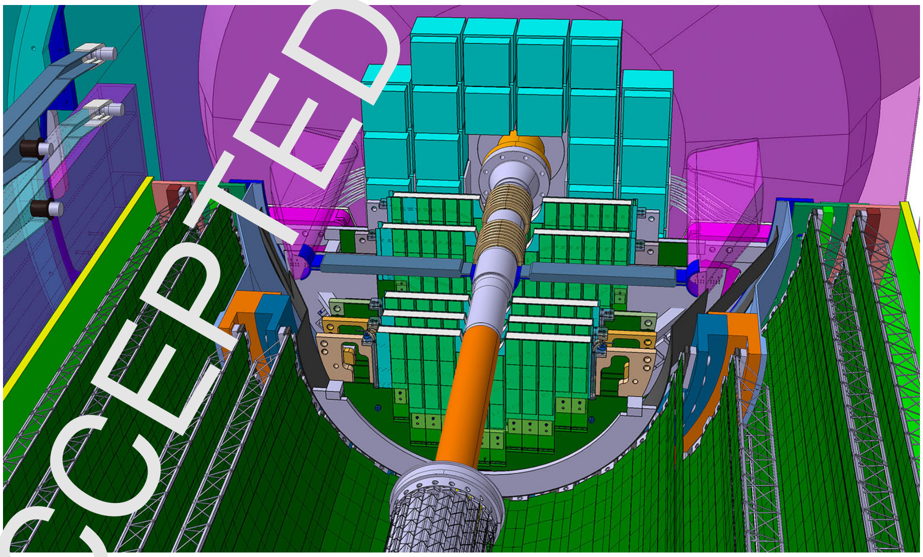

Figure 5: The five double-layers of the MFT and the 28 sensors of the FIT-C are located in the space between the ITS and the absorber (depicted in magenta). For clarity all the cabling has been omitted from the drawing and only the lower half of the MFT and of the outer ITS barrel is shown.

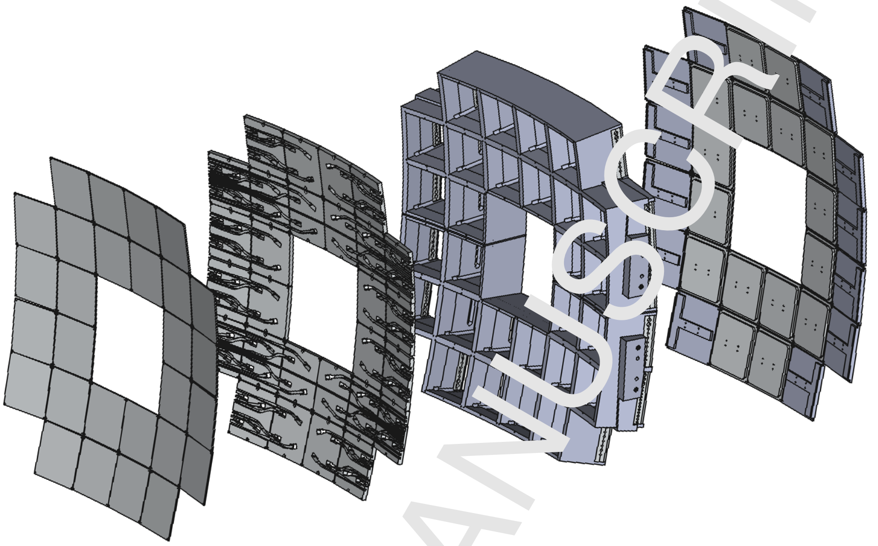

Figure 6: Elements of the concave support structure for the Cherenkov modules of FIT-C: 28 light-tight front plates, 28 plates with grooves to support optical fibres and mini prisms to shine the light from the calibration laser onto each quadrant of the photocathode, the top and bottom half of the support structure, and 28 back-plates.

cm. The elements of the Cherenkov array are based on a modified Planacon XP85012 MCP-PMT [14]. The 64 anodes of XP85012 were connected into 4 groups. Each group collects the charge induced by the Cherenkov light produced by the traversing minimum ionizing particles (MIPs) in a 2 cm thick quartz radiator. Just like the anode, the radiators were also divided into optically separated quadrants. In this arrangement each Planacon operates like 4 independent detector pixels.

The in-beam tests [15] of the Cherenkov modules operating inside of the ALICE setup during Run 2 have shown that it is possible to maintain a single-MIP time resolution of $\sim$ 24 ps. During the heavy-ion runs of Run 3 the charged particle multiplicity will be considerably higher, thus improving the time resolution down to $\sim$ 7 ps.

FIT-A, in addition to an array of 24 Cherenkov modules analogue to FIT-C, has also a 1.48 cm diameter, 4 cm thick scintillator disk. A Cherenkov-based detector of this size would be considerably more expensive. The disk, located 3.3 m from the IP, is divided into 45-degree sections. The octants are further subdivided into 5 rings of progressively increasing radii so that each ring has equal pseudo-rapidity coverage. In total there are 40 optically isolated sectors read-out by 48 photosensors. Studies based on Monte Carlo simulations indicate [13] that this division provides adequate granularity and acceptance to match the centrality resolution provided by the V0 detector [16] during Run 1 and Run 2.

The surface of the 4 cm thick EJ-204 plastic scintillator is viewed from the rear side by clear Ashai fibres arranged on a 5 mm XY grid (Fig. 7). To assure even spacing and a proper optical contact, the fibres are held by a thin acrylic plate with drilled holes. After the fibres are glued into the holes, the surface and the protruding fibre-ends are machined to form a smooth, flat surface to be optically coupled to the scintillator. At the other end the fibres are collected into equal-length bundles and are viewed by Hamamatsu H6614-70-Y001 micro-mesh PMTs. This light collection scheme produces a very uniform detection efficiency across the surface of the scintillator and allows for a single-MIP time resolution of 200 ps.

8. Summary

Run 3 at the CERN LHC is scheduled to start in March 2021. In preparation for this new data taking period the ALICE Collaboration is preparing major modifications to the experimental apparatus and is introducing three new detectors. The new ITS and the MFT will enhance tracking and vertexing performance while the FIT will provide the required triggering, fast timing, luminosity and forward multiplicity functionality. The new trackers are based on ALPIDE (ALICE Pixel Detector) – a custom designed sensor characterized by high-granularity and low material budget of the non-active elements. The new sensor will improve the performance of ALICE especially at low p_{T} values. The use of ALPIDE by the Muon Forward Tracker will allow ALICE to measure

Figure 7: Photograph of a full-size prototype of one octant of the scintillator rings on FIT-A.

beauty down to $p_{\mathrm{T}} \sim 0$ from displaced J/ψ vertices and to have an improved precision for the ψ(2S) measurement. It will also add high-granularity data to the forward multiplicity information acquired by FIT. The upgraded ALICE will be able to register tenfold increase of Pb-Pb delivered luminosity in Run 3 and 4 as well as two orders of magnitude more minimum bias events at 50 kHz in Pb-Pb collisions.

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