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# The Upgrade of the ALICE Inner Tracking System

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ALICE is a general purpose experiment designed to investigate nucleus-nucleus collisions at the CERN Large Hadron Collider (LHC).
The Inner Tracking System (ITS) is a key ALICE detector for the study of heavy flavour production in pp and Pb-Pb collisions. Very important and original results have been obtained in the first three years of data taking. After the completion of the approved physics programme, ALICE will focus on precision measurements of the Quark-Gluon Plasma (QGP) properties. This requires improved tracking capabilities and a higher readout rate to exploit the increased luminosity expected to be delivered by LHC in the future.
During the second LHC Long Shutdown in 2018 a completely new ITS, based on today's frontier technologies, is planned to be installed. The new detector will greatly improve the current performance in terms of pointing resolution, low transverse momentum resolution, standalone tracking efficiency and fast readout capabilities.

The present contribution describes the ongoing developments and the expected physics performance of the new ITS.

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PoS(Vertex 2013)018

## 1. Introduction

ALICE (A Large Ion Collider Experiment) [1] is a general-purpose, heavy-ion detector at the CERN LHC. It focuses on the study of the properties of the Quark-Gluon Plasma (QGP) created in strongly interacting matter at extreme energy densities in high energy nucleus-nucleus collisions. This study is performed by means of various probes emerging from the collisions; in particular rare probes like charmed and beauty mesons and barions can give valuable information about the formation and evolution of the QGP state.

The ALICE detector consists of a central barrel part and a forward muon spectrometer, which are specifically designed to study Pb-Pb collisions, as well as pp and p-Pb collisions as reference. The central part measures and identifies mid-rapidity hadrons, electrons and photons produced in the interaction, reconstructing particles, included short-lived ones, in an environment with large multiplicity of charged particles. It covers the pseudo-rapidity range of $|\eta| < 0.9$ and is embedded in a large solenoid magnet. The main tracking devices in the central barrel are – going from the innermost outward – the Inner Tracking System (ITS), the Time Projection Chamber (TPC), the Transition Radiation Detector (TRD) and the Time Of Flight (TOF) system.

At central rapidity and down to transverse momenta as low as 2 GeV/c ALICE has unique particle identification (PID) capabilities and high tracking and vertexing precision. These allow for a detailed characterization of QGP: for example, the charged particle production in Pb-Pb collisions was determined using the nuclear modification factor ($R_{AA}$) and it was observed that the suppression of high-$p_T$ particles strongly depends on event centrality. A large enhancement in the strange baryon/meson ratio was observed. Suppression and elliptic flow of the $D$ mesons in Pb-Pb collisions have been measured down to $p_T = 2$ GeV/c for the first time [2]. In addition, several other measurements in the heavy-flavour sector have been performed. ALICE has thus confirmed the previous observations made by CERN SPS and BNL RHIC, observing the formation of hot hadronic matter at exceeding values of temperatures, densities and volumes, with a precision and in a kinematic range never attained for all significant probes of the QGP. These results were achieved by ALICE after only two years of Pb-Pb running and one p-Pb run.

Despite these important results, several frontier measurements, such as reaching lower transverse momentum values, seem to be precluded with the current experimental setup, not yet fully optimized. These measurements are characterized by a very small signal-to-noise ratio and large backgrounds, so calling for large statistics while making the use of trigger selection techniques not applicable or very inefficient. Moreover they require also a significant improvement of the vertexing and tracking efficiency. ALICE is therefore preparing a major upgrade of its detectors, planned for installation during the second Long LHC Shutdown (LS2) in the years 2017-2018.

In this presentation the upgrade strategy for the Inner Tracking System is presented.

## 2. The present ITS

The present ITS consists of six cylindrical layers of silicon detectors: the *Silicon Pixel Detectors* (SPD), the *Silicon Drift Detectors* (SDD) and the *Silicon Strip Detectors* (SSD). Due to the high particle density and to achieve the required resolution, different techniques are exploited



PoS(Vertex 2013)018

**Table 1:** Dimensions of the present ITS subdetectors.

| Layer | Type | r [cm] | $\pm$z [cm] | Area [m$^2$] | Channels [M] | Resolution (r$\phi$ – z) [$\mu$m] |
|---|---|---|---|---|---|---|
| 1 | Pixel | 3.9 | 14.1 | 0.07 | 3.28 | 12 – 100 |
| 2 | Pixel | 7.6 | 14.1 | 0.14 | 6.55 | 12 – 100 |
| 3 | Drift | 15.0 | 22.2 | 0.42 | 0.04 | 35 – 25 |
| 4 | Drift | 23.9 | 29.7 | 0.89 | 0.09 | 35 – 25 |
| 5 | Strip | 38.0 | 43.1 | 2.20 | 1.15 | 20 – 830 |
| 6 | Strip | 43.0 | 48.9 | 2.80 | 1.46 | 20 – 830 |

to reconstruct in two dimensions the intersection point of a particle with each layer. The main parameters for the three subdetectors are listed in Table 1.

The number, position and segmentation of the layers are optimized for efficient track finding and high impact parameter resolution: in such a way the whole ITS allows to precisely reconstruct the trajectory of particles directly emerging from the interaction point. Moreover the four outer layers have analogue readout and therefore can be used for particle identification via $dE/dx$ measurement in the non-relativistic ($1/\beta^2$) region. The analogue readout has a dynamic range large enough to provide the $dE/dx$ measurement for low-momentum, highly ionising particles, down to the lowest momentum at which tracks can still be reconstructed. The outer layers of the ITS (SSD) are also crucial for the matching of tracks from the TPC to the ITS.

The SPD modules consist of a two-dimensional sensor matrix with 256160 cells of reverse-biased silicon detector diodes, 200 $\mu$m thick. Two modules are mounted together along the z direction to form a *half-stave*, and two mirrored half-staves are attached, head-to-head along the z direction, to a carbon-fiber-composite support sector. Each sector supports six staves: two on the inner layer and four on the outer layer. In total, the SPD includes 60 staves, consisting of 240 modules with 1200 readout chips. The read-out is based on a binary concept, where the full matrix is shifted out on a 32 bit bus. Each pixel chip generates a pulse whenever at least one pixel cell detects a particle signal above threshold. This pulse is used to implement a prompt trigger which contributes to the ALICE L0 trigger.

The SDD modules are mounted on linear structures called *ladders*, for a total of 260 modules. Ladders and modules are assembled in such a way to ensure full angular coverage. One SDD module consists of a drift detector and its front-end electronics. The sensitive area of a detector is split into two drift regions, where electrons move in opposite directions, by a central cathode kept to a nominal voltage of -1800 V. The SDD front-end electronics is based on three types of ASICs, two of them directly bonded to the sensor, and one located at each end of the ladder.

The SSD is optimized for low mass in order to minimise multiple scattering. The detection modules consist of one sensor each, connected to two hybrids with six chips each. Both outer layers use double sided Silicon Strip Detectors mounted on carbon-fiber support structures, with a strip pitch of 95 $\mu$m and a stereo angle of 35 mrad. Each module has 768 P- and 768 N-side strips. The modules are assembled on ladders: the SSD consists of 72 ladders, each one having 22 (34 ladders on layer 6) to 25 (38 ladders on layer 6) modules, resulting into 1698 modules.

The major contribution to the on-detector power dissipation is due to the front-end chips. SPD



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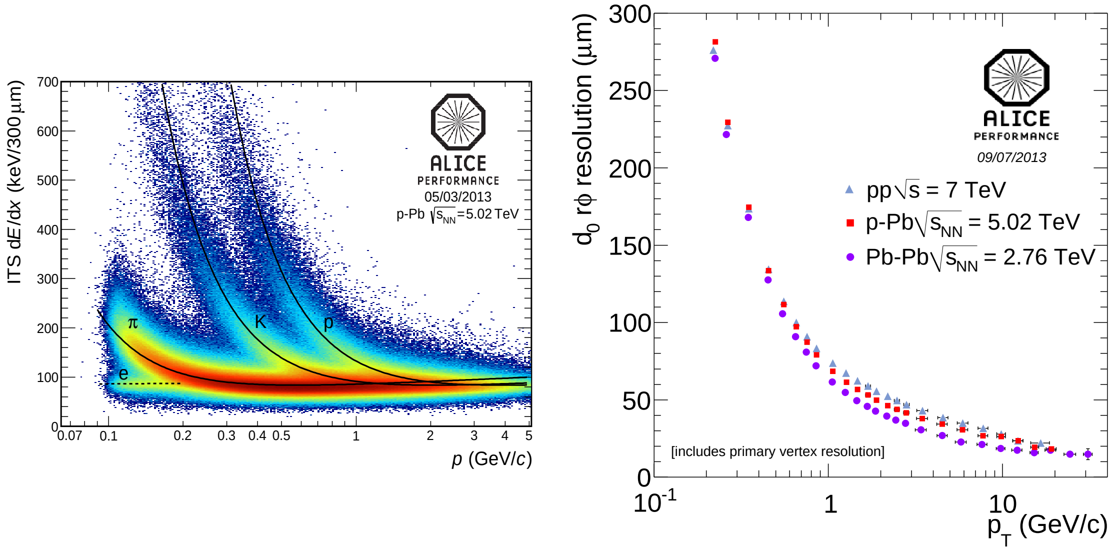


**Figure 1:** Example of ITS performances. Left panel: $dE/dx$ of charged particles vs their momentum for ITS pure standalone tracks measured in p-Pb collisions at 5.02 TeV. Right panel: Track impact parameter resolution in the transverse plane ($r\phi$) vs $p_T$ for charged particles.

uses an evaporative cooling system with $C_4F_{10}$ as coolant fluid, while for SDD and SSD a shared cooling system with underpressure demineralized-water circuits is used to take away the power dissipated by the front-end electronics and to maintain temperature stability. A dedicated interlock system constantly monitors pressure and flow to guarantee leak-safety and assure an adequate heat removal.

In Fig. 1 an example of the current ITS performances is shown. On the left panel the plot shows the $dE/dx$ of charged particles vs their momentum, both measured by the ITS alone (ITS pure standalone track) in p-Pb collisions at 5.02 TeV; the lines are a parametrization of the detector response based on the Bethe-Bloch formula. On the right panel the track impact parameter resolution in the transverse plane ($r\phi$) vs $p_T$ for charged particles is shown. The resolution includes the contribution from the primary vertex resolution, which improves from pp to p-Pb and Pb-Pb (with charged multiplicity).

## 3. General ALICE upgrade

At central rapidity and down to low transverse momentum ALICE has unique particle identification capabilities as well as high tracking and vertexing precision. These capabilities allow for a detailed characterization of the Quark-Gluon Plasma: after only two years of Pb-Pb running and one p-p run, ALICE confirmed the basic QGP picture, observing the creation of hot hadronic matter at unprecedented values of temperatures, densities and volumes, with an exceeding precision and kinematic reach, so demonstrating its excellent capabilities to measure high-energy nuclear collisions at LHC. Both the light quark and the heavy-flavour sectors are extensively studied by ALICE. For example, the charged particle production in Pb-Pb collisions was determined via the nuclear modification factor ($R_{AA}$) and it was observed that the suppression of high-$p_T$ particles strongly depends on event centrality. For the first time, higher harmonic anisotropic flow was measured for charged particles in Pb-Pb collisions, giving insight into initial spatial anisotropy and fluctuations, while a large enhancement in the strange baryon/meson-ratio was observed, which may be explained by coalescence models. Suppression and elliptic flow of D mesons in Pb-Pb at LHC energies were measured for the first time down to $p_T = 2$ GeV/c.

Despite these successful measurements, to achieve deeper insight, especially within the scope of rare heavy quark production, high-statistics precision measurements at very low $p_T$ are required, for which the current experimental setup is not yet fully optimized. The major scientific objective will be a precise determination of the QGP properties, including initial temperature, degrees of freedom, speed of sound and general transport coefficients. The study of thermalization and in-medium energy loss of partons in QGP, of quarkonium dissociation and possibly regeneration patterns, and of the production of thermal photons and low-mass dileptons are among the main topics of the ALICE physics program. These measurements in Pb-Pb collisions require a large statistics, due to the very small signal-over-background ratio. On the other hand the large background calls for unbiased trigger, since the application of trigger selections is impossible or very inefficient. Moreover a significant improvement of the vertexing and tracking efficiencies is also required.

After the second LHC Long Shutdown (LS2) in 2018–2019 the increased LHC luminosity in Pb-Pb collisions (up to $6 \times 10^{27}$ cm$^{-2}$s$^{-1}$) will correspond to an interaction rate of about 50 kHz. Accordingly, an important part of the ALICE upgrade is the enhancement of the readout capabilities to be able to record Pb-Pb collisions at such a collision rate. The ALICE upgrade strategy includes several projects [3]:

1. Installation of a thinner beam pipe with a smaller diameter (from the present value of 29.8 mm down to 20.0 mm). This new beam pipe will allow to place the first tracking layer closer to the interaction point, and will reduce the multiple scattering.

2. Installation of a new Inner Tracking System, featuring an higher resolution, a lower material budget and increased rate capabilities (from current 1 kHz to 50 kHz).

3. Upgrade of the TPC readout electronics, replacing the present wire chambers with GEM detectors and installing a new pipelined electronics to cope with the high readout rate.

4. Upgrade of the readout electronics of the Transition Radiation Detector, the Time-Of-Flight, the Photon Spectrometer, the Electromagnetic Calorimeter and the Muon Spectrometer. Installation of a new Muon Forward Tracker.

5. Upgrade of the forward trigger detectors and of the Zero Degree Calorimeter.

6. Upgrade of the DAQ system, the High Level Trigger and the Offline framework, to be able to handle the new data volume.

The plans for the ITS Upgrade will be detailed in the following sections.

## 4. Objectives of the New ITS

The goals of the ITS Upgrade are to improve the impact parameter resolution (of at least a factor $\approx 5$ in the $z$ direction, i.e. along the beam axis, and $\approx 3$ in the $r\varphi$ direction), the tracking



PoS(Vertex 2013)018

efficiency, the transverse momentum resolution at very low (nearly zero) $p_T$ values, and the readout capabilities.

In order to achieve these improvements the first layer of silicon detectors will be placed closer to the interaction point: the reduction of the beam pipe diameter in the center of ALICE will allow to go down from the present 39 mm of the SPD Layer 1 to 22 mm. The spatial resolution and the tracking performances will certainly gain from a reduction of the material budget, in particular in the inner layers: the use of Monolithic Active Pixel Sensors (MAPS), the optimization of the front-end electronics, and the consequent reduction of the power and signal cables will reduce the total material budget $X/X_0$ per layer from the present 1.14% to as low as 0.3% for the three innermost layers and to $\sim$ 0.8% for the outer layers. Both impact parameter and momentum resolutions will improve by increasing the detector segmentation: the current design assumes that all layers are segmented in pixels with dimensions of $30\mu$m $\times$ $30\mu$m, to be compared with the values listed in Table 1 for the present ITS. Finally the tracking efficiency and $p_T$ resolution will also be improved by increasing the number of layers (from present 6 to 7).

The new ITS will not measure the ionization in the silicon layers. Detailed studies on the benchmark measurements of the ALICE upgrade physics program have shown that there would be only a marginal improvement if the new ITS would preserve the same particle identification capabilities as the present detector. So the current design assumes only a binary readout without any information on the charge amplitude.

For what concerns the environment in which the new ITS will operate, recent simulations have shown that the overall dose expected for the innermost layer can reach up to 700 kRad (TID) and $1.1 \times 10^{13}$ 1 MeV $n_{eq}/cm^2$ (NIEL), including a safety factor of 10, for the full integrated luminosity. The present ITS can run up to a maximum of 1 kHz with dead time close to 100% . The upgraded ITS aims to read out data up to a rate of 100 kHz in Pb-Pb collisions and 400 kHz in pp collisions, with a dead time of about 10% (at 50 kHz Pb-Pb interaction rate). In addition it will be possible to quickly insert or remove the detector for maintenance, so allowing for rapid accessibility and the possibility of replacing faulty modules during yearly shutdowns.

## 5. Design of the new ITS

The upgraded ITS [4] will be made of 7 layers grouped in two separate barrels, the *Inner Barrel* (IB) consisting of the three innermost layers and the *Outer Barrel* (OB) with the four outermost layers. The layers are segmented in units named *Staves*, which are mechanically independent and fixed on a support structure.

The Stave is the basic detector unit: it includes the silicon sensitive chips, the polyimide printed circuit boards, the cooling units and the carbon fiber mechanical support. The OB Staves are further segmented in azimuth in two half-staves, and segmented longitudinally in modules; each module consists of a number of pixel chips bonded on a flexible printed circuit. The overall characteristics are summarized in Table 2. The intrinsic resolution is $5\mu$m in both $z$ and $r\varphi$ for the IB and $10\mu$m for the OB.

### 5.1 Inner Barrel design

Each IB stave consists of a single module containing 9 pixel chips ($15 \times 30$ mm$^2$ and 50

**Table 2:** Design parameters of the upgraded ITS.

| Layer | r [mm] | z [cm] | Number of Staves | Number of Chips | % $X/X_0$ | Throughput [Mbit/s/chip] |
|---|---|---|---|---|---|---|
| Beam pipe | 20.0 | - | - | - | 0.22 | - |
| 0 | 24.55 | 27.1 | 12 | 108 | 0.3 | 284 |
| 1 | 32.35 | 27.1 | 16 | 144 | 0.3 | 174 |
| 2 | 39.95 | 27.1 | 20 | 180 | 0.3 | 121 |
| 3 | 196.05 | 84.3 | 24 | 2688 | 0.8 | 14 |
| 4 | 245.45 | 84.3 | 30 | 3360 | 0.8 | 12 |
| 5 | 343.85 | 147.5 | 42 | 8232 | 0.8 | 11 |
| 6 | 393.35 | 147.5 | 48 | 9408 | 0.8 | 10 |

$\mu$m thick) in a row, connected with laser soldering or chip embedding to a polyimide Flex Printed Circuit (FPC) bringing data in/out and distributing power. The cable with the chips is then glued on the carbon fiber support in direct contact with a cold plate which embeds the water cooling pipes. A flex extension is under study to implement an interface to electrical and cooling services, which will be provided from the A-side only. At the two ends of the stave a connector is used for mechanical fixation and alignment. In the left panel of Fig. 2 a schematic view of a IB stave is shown. First prototypes of the Inner Barrel and staves have been produced at CERN in 2012 proving the technical feasibility of this design.

### 5.2 Outer Barrel design

The design studies for the Outer Barrel are still in progress. The larger surface of an OB stave requires to split it in several modules, whose size is to be adapted so as to have an integer number of modules along the stave length. The OB module accommodates 2 rows of 7 chips each. The module stiffness is ensured by a thin carbon fiber support plate. The 7 chips in a row are readout in daisy chain, which extends over the corresponding rows of all modules in a stave. The analogue and digital power for all modules are provided by a power bus running along all modules. A space frame derived from the ladders of the current ITS will support the modules, which are attached to two cold plates. The half-staves of Layers 3 and 4 are equipped with 4 modules each, while the half-staves of Layers 5 and 6 are equipped with 7 modules each. A schematic view of a OB stave is shown in the right panel of Fig. 2. Several components of an OB stave have been already prototyped.

### 5.3 Pixel chips

The active sensors and the associated readout electronics have very demanding requirements in terms of granularity, material thickness, readout speed, power consumption and radiation hardness. An intrinsic spatial resolution of 5 $\mu$m for the innermost layer requires a pixel pitch of $\sim 30$ $\mu$m. A significant reduction of the material budget, in particular for the innermost layers, to reduce the multiple Coulomb scattering leads to a Silicon thickness of 50 $\mu$m at maximum. The same material budget issue puts severe limitations on the amount of material that can be used to deliver power

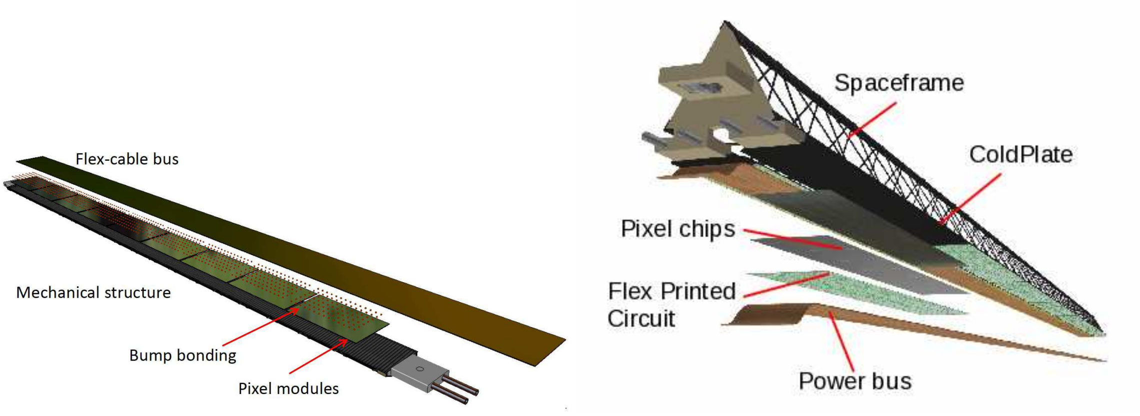


**Figure 2:** Schematic view of an Inner Barrel (left) and of an Outer Barrel (right) stave.

and cool down the system. According to the thermal studies that were carried out on prototype mechanics the power density on the sensor should not exceed 300 mW/cm$^2$. In order to cope with the assumed interaction rates and dead time in Pb-Pb and pp collisions, the maximum acceptable sensor integration time is $\sim$ 30 $\mu$s in order to limit the event pile-up. Finally the pixel detectors have to be tolerant against the radiation levels expected in the ITS environment.

Based also on the STAR Pixel experience, the monolithic CMOS MAPS technology has been chosen for the pixel detector [5]. A dedicated and intense research and development activity was carried out in order to evaluate the final chip design. Following the laboratory and beam tests, the 0.18 $\mu$m CMOS technology by TowerJazz has been selected for the implementation of pixel chip for all layers of the new ITS. Due to the small feature size, this process is expected to be more robust to the total ionizing dose than other technologies employed so far. The same feature size and the number of metals available are adequate to implement high density, low power digital circuits, so minimizing the dead area and making the power extraction more efficient. This technology allows the production of chips on wafers with a resistivity of $1 \div 5$ k$\Omega$cm$^{-2}$: in this way a substantial part of the epitaxial layer is already depleted at the reverse bias voltage applied to the collection diodes in the CMOS sensors, so increasing the signal-to-noise ratio and improving the resistance to non-ionizing radiation. Finally the availability of a quadruple-well option allows for significant enhanced functionality, a unique feature of this process that can enable low power readout electronics, in particular the possibility to include the discriminator inside the pixel and have a fast readout topology based on the binary information.

The R&D activity is still in progress for the design of the final chip architecture. The main challenge is to satisfy at the same time the stringent requirements on the spatial resolution, the readout speed and the power consumption. The PICSEL group of IPHC (Strasbourg) is working on two possible chips. The first one, called MISTRAL, based on the MIMOSA chip, uses a classical rolling shutter with parallel column readout; it features a pixel size of 22 $\times$ 33.3 $\mu$m, an integration time of $\sim$ 30 $\mu$s and power consumption of $\sim$ 200 mW/cm$^2$. The second, more advanced chip, called ASTRAL, has discriminators incorporated in each pixel that would allow an integration time of $\sim$ 20 $\mu$s; the binary readout is still based on the rolling shutter scheme. Two pixel sizes are under study, 24 $\times$ 31 $\mu$m with a power consumption of $\sim$ 85 mW/cm$^2$, and 36 $\times$ 31 $\mu$m with a power consumption of $\sim$ 60 mW/cm$^2$. The RAL group (UK) is working on a chip where 128 pixels are organized in so-called *strixels*, each one with its own discriminator, all readout in the parallel rolling shutter mode; in this case the pixel size is 20 $\times$ 20 $\mu$m, the integration time $\sim$ 30 $\mu$s and the power consumption $\sim$ 90 mW/cm$^2$. Finally the CERN-INFN-Wuan group is working on a prototype, called EXPLORER/ALPIDE, with an in-pixel amplifier and comparator; in this case the readout is data driven using the priority encoder technique. The pixel size is 28 $\times$ 28 $\mu$m, the overall readout time $\sim$ 4 $\mu$s and the power consumption $<$ 50 mW/cm$^2$.

## 6. Expected performances

Two different MonteCarlo simulation tools have been used to study the detector performances in different configurations.

The tracking performance was initially studied using an analytical method, the Fast Estimation Tool (FET). Based on a code originally developed by the STAR HFT collaboration, it allows a simplified description of the detector layout and tracking. The original code was extended and adapted to the need of the ITS upgrade, e.g. adding the ITS stand-alone tracking. This code further evolved into a Fast MonteCarlo Tool (FMCT), which allows the estimation of the tracking performance from the reconstruction of probing particles embedded in the background expected from collisions, so disentangling the performance of a given detector layout from the efficiency of a specific tracking algorithm. Both FET and FMCT were used to optimize the number of layers, their radial position, the material budget and the detector resolution [4].

The results of FET and FMCT simulations were confirmed (within $\sim$ 5% accuracy) by a full MonteCarlo based on the GEANT transport code and a detailed description of the geometry. Also the pixel response was properly taken into account. Despite the current pixel design alternatives differ in the readout architecture, common characteristics, such as the average pixel noise distribution, the fake pixel rate and the charge spread function, can be obtained from test beam measurements and used as input to the simulation. These three factors were extracted from test beam data collected with various kinds of pixel design, operating temperature and irradiation levels.

Fig. 3 shows an example of the performance study: the impact parameter resolution in $z$ (left panel) and $r\varphi$ direction (right panel) are both shown as a function of the transverse momentum, for the new ITS compared to the current ITS. It is clear that the upgraded ITS will permit to gain at least an order of magnitude in the low-end momentum range, allowing a good resolution and efficiency down to 0.2-0.1 GeV/c. In Fig. 4 the momentum resolution as a function of $p_T$ is shown for the upgraded ITS with standalone tracking and the ITS+TPC tracking.

## 7. Conclusions

The ALICE experiment proved outstanding performances in studying strongly interacting matter. For deeper understanding of, among the others, heavy flavours at very low $p_T$, thermalization of heavy quarks, azimuthal anisotropy and in-medium hadronization, a new, high-resolution, low-material ITS will be installed during the second LHC Long Shutdown. It will improve the ALICE performances in particular with an increased impact parameter resolution



PoS(Vertex 2013)018

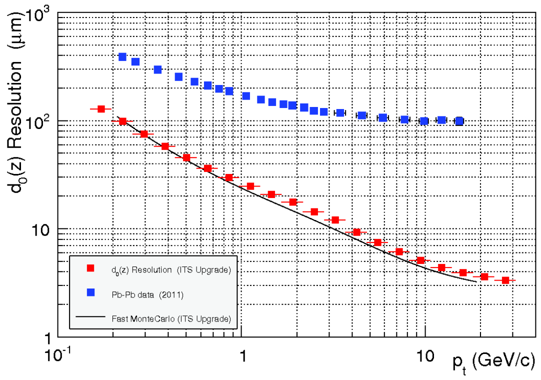


**Figure 3:** Impact parameter resolution in $z$ (left) and $r\varphi$ (right) direction as a function of the transverse momentum for the present and the new ITS.

and higher tracking efficiency. Its key features are a low material budget an increased number of layers, a greater radial extension, with a first layer nearer to the interaction point, and a smaller pixel size. The pixel sensors will employ the CMOS MAPS produced with the 0.18 $\mu$m TowerJazz technique. An intense R&D activity is still in progress on the pixel architecture.

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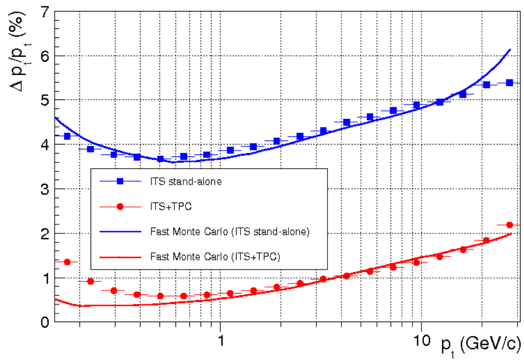


**Figure 4:** Momentum resolution as a function of the transverse momentum for ITS standalone and ITS+TPC.