Conceptual Design Report for the Upgrade of the ALICE ITS

The ALICE Collaboration*

– Version 2.3 –

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*See Appendix A for the list of collaboration members
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Chapter 1

Introduction

1.1 Background

ALICE (A Large Ion Collider Experiment) is a general-purpose, heavy-ion detector at the CERN LHC. It is designed to address the physics of strongly interacting matter, and in particular the properties of the Quark Gluon Plasma (QGP), using nucleus-nucleus collisions at high energies.

The ALICE detector consists of a central barrel and a forward muon spectrometer, allowing a comprehensive study of hadrons, electrons, muons, and photons produced in the collision of heavy Pb-Pb nuclei. The physics program also includes collisions with lighter ions at different energies. In order to vary the energy density and interaction volume, it also includes dedicated proton-nucleus runs.

Data taken during proton-proton runs provide reference data for the heavy-ion program and addresses a number of specific strong-interaction topics for which ALICE is complementary to the other LHC detectors. The ALICE scientific plans for the approved program are defined in the ALICE Physics Performance Report Vol I [1] (scientific program) and MoU [2] (the sharing of resources and responsibilities). An updated description of the ALICE detector can be found in [3].

Within its program to understand the properties of strongly interacting matter and after two years of operation with pp and Pb-Pb collisions, ALICE has demonstrated its excellent capabilities to measure high energy collisions at the LHC. The physics results produced by ALICE in pp and Pb-Pb have resulted in around 20 publications in peer reviewed journals [4]. Despite this success there are several frontiers for which the current experimental setup is not yet fully optimized. Detector upgrades could enhance the physics capabilities enormously, leading to further advancements.

The strategy for the upgrade of the central barrel detectors to achieve the ALICE long-term physics goals is discussed in [5]. The present document addresses the question of how to upgrade the Inner Tracking System (ITS) detector to comply with the new requirements set by the ALICE global upgrade strategy. In particular, this document will address the question of how to improve the performance for heavy-flavour detection.

It will be shown that it is possible to build a new silicon tracker with greatly improved features in terms of: determination of the distance of closest approach (dca) to the primary vertex, standalone tracking efficiency at low $p_t$, momentum resolution and readout rate capabilities. These potential improvements are a consequence of the spectacular progress made in the field of imaging sensors over the last ten years as well as the possibility to install a smaller radius beampipe. Moreover a tracker with the above features, in particular a high standalone tracking efficiency, creates an opportunity to perform, in combination with the TRD and TOF detectors, online event selection on the basis of topological and PID criteria.

Such a new silicon tracker will allow ALICE to measure charm and beauty production in Pb-Pb collisions.
with sufficient statistical accuracy down to very low transverse momentum, measure charm baryons and perform exclusive measurements of beauty production. These measurements are essential in order to understand the energy loss mechanism and thermalization of heavy quarks in the Quark-Gluon Plasma (QGP) state.

1.2 Scientific Scope of the Upgrade

The longterm goal of the ALICE experiment is to provide a characterization of the Quark-Gluon Plasma (QGP) state. A precise determination of its properties will be a major scientific achievement. These properties include initial temperature, degrees of freedom, speed of sound and general transport coefficients such as the shear viscosity over the entropy. Measuring such characteristics would go a long way towards a better understanding of QCD as a genuine multi-particle theory. To achieve this goal, high statistics measurements are required, as these will give access to the very rare physics channels needed to understand the dynamics of this condensed phase of QCD.

The general upgrade strategy for the ALICE central barrel has been conceived to deal with the challenge of expected Pb–Pb interaction rates of up to 50 kHz. A key aspect of the strategy pursued here is to develop methods by which 50 kHz Pb–Pb collisions can be inspected with the least possible bias. This implies shipping all data to the online systems either continuously or upon a minimum bias trigger. Full online calibration, event reconstruction and event data reduction will allow writing to tape a large fraction of the events, which will be selected on the basis of topological and pid criteria, one of the unique strengths of ALICE. Such an upgrade would provide an accumulated sample in the order of \(10 \text{ nb}^{-1}\), which is the minimum needed for the proposed physics program. As discussed in [5], in the central rapidity region the physics program will include the following main topics.

- Study of the thermalization of partons in the QGP, with focus on the massive charm and beauty quarks. Heavy-quark elliptic flow is especially sensitive to the partonic equation of state. Ultimately, heavy quarks might fully equilibrate and become part of the strongly-coupled medium.

- Study of the in-medium parton energy loss mechanism, that provides both a testing ground for the multi-particle aspects of QCD and a probe of the QGP density. The relevant observables are: jet structure, jet–jet and photon–jet correlations, jets and correlations with high-momentum identified hadrons plus heavy-flavour particle production. In particular, it is crucial to characterize the dependencies of energy loss on the parton species, mass, and energy.

- Study of the quarkonium dissociation and, possibly, regeneration pattern, as a probe of deconfinement and of the medium temperature.

- Study of the production of thermal photons and low-mass dileptons emitted by the QGP. This is to assess the initial temperature and degrees of freedom of the system, as well as the chiral nature of the phase transition.

The upgrade of the ITS to improve its resolution and readout rate capabilities is a fundamental cornerstone within such a physics program. The new measurements on charm and beauty production that will become possible with the ITS upgrade are listed below:

- Study of the thermalization of heavy quarks in the medium, in particular by measuring heavy flavour charmed and beauty baryons. The new improved silicon tracker at mid-rapidity will impact significantly the following measurements:
  - Charm down to zero \(p_t\) will be accessible for the first time.
– Charm and beauty baryons, $\Lambda_c$ and $\Lambda_b$. The latter will be measured via the decay $\Lambda_b \rightarrow \Lambda_c + X$ and this will be accessible for the first time.
– Baryon/meson ratios for charm ($\Lambda_c/D$) and for beauty ($\Lambda_b/B$), will also be accessible for the first time.
– The elliptic flow of charmed and beauty mesons and baryons down to low transverse momentum will also be accessible for the first time.
– Study of the quark mass dependence of in-medium energy loss. This is done by measuring the nuclear modification factors $R_{AA}$ of the $p_t$ distributions of D and B mesons separately. The new detector will dramatically improve or make accessible for the first time the following measurements in Pb–Pb collisions:
    – Measurement of beauty via displaced $D^0 \rightarrow K\pi$, which will be accessible for the first time.
    – Measurement of beauty via displaced $J/\psi \rightarrow ee$, which will also be accessible for the first time.
    – Improve measurement of single displaced electron.
    – Improve measurement of beauty decay vertex reconstruction, using any of the previous three channels plus an additional track.

In addition, the upgraded ITS will be extremely important for a detailed measurement of thermal electromagnetic radiation from the hot QGP, which is just in its infancy at the LHC. This will permit the ITS to characterize:

– Thermal radiation from the QGP.
– In-medium modifications of hadronic spectral functions as related to chiral symmetry restoration, in particular for the $\rho$ meson.

In order to address new high precision measurements in a thorough and systematic way, the following design goals have to be met:

1. Coverage in transverse momentum to be as complete as possible, in particular down to very low momenta.
2. Very accurate identification of secondary vertices from decaying charm or beauty ($D^0$, $J/\psi$, $\Lambda_c$, $\Lambda_b$).
3. High stand-alone tracking efficiency, which is fundamental to implement trigger capabilities based on the event topology. This is not currently possible in the current setup.

The recent progress in Si detector technology, an improved integration to reduce the distance between the interaction region and the first layer of the ITS and a minimized material budget make it possible for ALICE to improve the resolution on the charged track dca by a factor of three. This improves the sensitivity to charm by one order of magnitude or more, depending on the transverse momentum range. This in turn implies a better signal-to-background ratio. Therefore fully reconstructed rarely produced heavy-flavour hadrons (including charm-strange and beauty-charm mesons, which should be exceedingly sensitive to parton re-combination effects) will become accessible.

In pp collisions, there is also a need to improve the understanding of the flavour dependence of multiparticle production. The precise measurement of both the total charm and beauty production cross-sections,
down to zero $p_t$, will be possible for the first time. Furthermore, heavy-flavour jet tagging will also be significantly enhanced.

Moreover, the improved readout rate capabilities of the new detector will allow the inspection of 50 kHz Pb–Pb and 2 MHz pp interactions. The new readout strategy is to send the event related data of all interactions to the online systems (DAQ and HLT). These will then perform an event reconstruction and selection based only on the tracking and PID information of ITS, TRD and TOF. The selected data of all subdetectors are then processed in a second step for further selection based on the fully reconstructed events. Such an improvement will have a dramatic effect on the overall ALICE physics program at mid-rapidity. Examples of triggering for heavy flavour detection are discussed in 2.2.1. In order to achieve this, an upgrade of the Inner Tracking System (ITS) is necessary.

1.3 Current Detector Performance and Limitations

The present ALICE ITS consists of six cylindrical layers of silicon detectors placed coaxially around the beam pipe. They are located at radii between 39 mm and 430 mm and cover the pseudo-rapidity range $|\eta| < 0.9$ for vertices located within ±60 mm with respect to the nominal interaction point (i.e. ±1σ of the luminous region). Within the boundaries set by technological limitations and available funds, the number, position and segmentation of the layers were optimized to achieve a high precision in the determination of the charged particle dca to the primary vertex and efficient track finding in combination with the TPC. Therefore, the inner radius is the minimum allowed by the radius of the beam pipe. The outer radius is determined by the necessity to match tracks with those from the TPC.

As will be illustrated in chapter 3 optimizing the detector geometry to achieve the highest standalone tracking efficiency would lead to an alternative configuration including a larger number of layers and different radii. The first layer has a more extended pseudo-rapidity coverage ($|\eta| < 1.98$) which, together with the Forward Multiplicity Detectors (FMD), provides continuous coverage for the measurement of charged particle multiplicity.

As a result of the high particle density (the current system is designed for up to 100 particles per cm$^2$ for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV), and in order to achieve the required dca resolution, the first two layers of the ITS are made of Silicon Pixel Detectors (SPD) and the two middle ones are made of Silicon Drift Detectors (SDD). The two outer layers, where the track density has fallen to one particle per cm$^2$, are equipped with double-sided Silicon micro-Strip Detectors (SSD). 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. All detector elements were carefully optimized to minimize their radiation length, achieving 1.1%$X_0$ per layer, the lowest value among all the current LHC experiments.

The performance of the present ITS for tracking and identifying charged particles in pp and Pb-Pb collisions will be discussed in chapter 3. The capabilities for heavy flavor detection will be shortly reviewed in chapter 2. It will be shown in these that the precision of the present ITS in the determination of the track dca is adequate to study the production of charm mesons in exclusive decay channels (e.g. $D^0 \rightarrow K\pi$ and $D^+ \rightarrow K\pi\pi$) at values of transverse momentum above 2 GeV/c. At lower transverse momenta, however, the statistical significance of the measurement is insufficient.

The situation is even worse for charm baryons. The most abundantly produced charm baryon ($\Lambda_c$) has a mean proper decay length ($c\tau$) of only 60 μm. This is lower than the impact parameter resolution of the present ITS in the transverse momentum range of the majority of its daughter particles. Therefore, charm baryons are presently not accessible by ALICE in central Pb-Pb collisions. For the same reasons outlined above, the study of beauty mesons, beauty baryons, or of hadrons with more than one heavy quark are also beyond the capability of the current detector.

A crucial limitation of the present ITS detector is given by its poor readout rate capabilities. As it will be
illustrated in chapter 3, the ITS can run up to a maximum of 1 kHz (with 100% dead time) irrespective of the detector occupancy. This rate limitation restricts ALICE to use only a small fraction of the full Pb–Pb collision rate of 8 kHz that the LHC presently can deliver and prevents the collection of required reference data in pp collisions. Clearly the present ITS is totally inadequate to fulfill the required rate capabilities envisaged for the ALICE long-term plans discussed in the previous section.

Finally, the impossibility to access the present ITS detector for maintenance and repair interventions during the yearly LHC shutdowns represents a major limitation in sustaining a high data quality. In the context of an upgrade, the rapid accessibility to the detector will be set as a priority.

### 1.4 Detector Upgrade Concept

In this section, the key features of the ITS upgrade will be discussed and compared to the present ITS, following the considerations made in sections 1.2 and 1.3.

- **First detection layer closer to the beam line.** At present the radial distance of the first layer from the beamline is 39 mm. On the basis of the first studies done by the LHC Beampipe Working Group and the ALICE Technical Coordination, the installation of a new beampipe with an outer radius of 19.8 mm is considered a realistic possibility. This will be discussed in chapter 5. Installation of such a beampipe would enable the first detection layer to be located at a radius of about 22 mm. The baseline for the wall thickness of the beampipe in this document is 0.8 mm, although the possibility of a thinner wall (for example 0.5 mm) should be addressed with dedicated R&D.

- **Reduction of material budget.** Reducing the material budget of the first detection layer is particularly important for improving the impact parameter resolution. In general, reducing the overall material budget will allow the tracking performance and momentum resolution to be significantly improved. As will be shown in chapter 4, the use of Monolithic Active Pixel Sensors (MAPS) will allow the silicon material budget per layer to be reduced by a factor of 7 in comparison to the present ITS (50 µm instead of 350 µm). A careful optimization of the analogue front-end timing specifications and readout architecture will allow the power density to be reduced by a factor of 2. At the same time this will increase the pixel density by a factor of 50. The lower power consumption and a highly optimized scheme for the distribution of the electrical power and signals will allow the material budget of the electrical power and signal cables to be reduced by a factor of 5. Mechanics, cooling and other detector elements can also be slightly improved when compared to the present ITS design. Combining all these new elements together, it should be possible to build a detector with a radiation length of 0.3% \(X_0\) per layer or better. An example of the feasibility of such a design is represented by the STAR HFT detector [6]. Achieving such a low material budget is particularly critical for the first detection layer, since it affects strongly the impact parameter resolution at low \(p_t\) where the resolution is mainly determined by multiple Coulomb scattering.

As will be illustrated in chapter 4, hybrid pixels would allow the construction of detector layers with a slightly higher radiation length (0.5% \(X_0\)), but this would still represent a significant improvement of the performance as compared to the present ITS.

- **Geometry and segmentation.** The studies presented in this document are based on a detector consisting of seven concentric cylindrical layers covering a radial extension from 22 mm to 430 mm with respect to the beamline. The physics studies of the benchmark channels presented in chapter 2 are based on the assumption that all layers are segmented in pixels with dimensions of 20 × 20µm. However, as will be illustrated in chapter 3, the detector performance in terms of impact parameter resolution and standalone tracking efficiency will not change significantly, even
if the outermost four layers would have a much lower granularity as can be achieved for example with the Silicon micro-Strip Detectors presented in chapter 4.

- **Measurement of energy loss.** The new detector will preserve PID capabilities by measuring the ionization in the silicon layers. As will be discussed in chapter 3, in the case where all seven layers would be implemented with monolithic pixel technology, the performance of the detector would be slightly reduced with respect to the present one. Nevertheless it would maintain a $3\sigma$ separation power up to 600 MeV for pion to kaon and up to 1 GeV for proton to kaon.

- **Readout time.** As we have seen in section 1.3, the present ITS features a maximum readout rate of 1 kHz. The new detector aims to read the data related to each individual interaction up to a rate of 50 kHz for Pb-Pb collisions and 2 MHz for pp collisions. The readout architectures that allows such rates to be achieved are presented in chapter 4.

As will be shown in chapter 3 a new silicon tracker featuring the characteristics listed above will enable the track position resolution at the primary vertex to be improved by a factor of 3 or larger. The standalone tracking efficiency would be comparable to what can be presently achieved by combining the information of the ITS and the TPC. The relative momentum resolution of the silicon tracker standalone would be about 2% up to 2 GeV/c and remain below 3% up to 20 GeV/c.

In summary, the baseline idea for the layout of the ITS upgrade is to replace the existing ITS detector in its entirety with three inner layers of pixel detectors followed by four outer layers of silicon strips, or pixel detectors with lower granularity.

Two basic technology choices are considered for the ITS pixel detector: hybrid silicon pixel detectors and Monolithic Active Pixel Sensors (MAPS). In chapter 4 we demonstrate the key R&D areas for both pixel detector technologies, for the new Silicon micro-Strip Detector and for the system aspects. The new detector geometry, such as the number of layers, radial position, and segmentation, as well as the options of pixel or strips detectors for the outermost layers, are being evaluated with respect to their performance in terms of standalone tracking efficiency, momentum resolution and PID. However, other considerations related to space and integration issues, cost, etc., will also be taken into account in the definition of the layout of the new detector.

### 1.5 Physics Performance Studies

A detailed presentation of the performance studies for heavy-flavour detection with an upgraded ITS is the main topic of chapter 2. In this section we summarize the main results. We consider the following benchmark analyses:

- Charm meson production via $D^0 \rightarrow K^-\pi^+$;
- Charm baryon production via $\Lambda_c \rightarrow pK^-\pi^+$;
- Beauty production via $B \rightarrow D^0 (\rightarrow K^-\pi^+)$;
- Beauty production via $B \rightarrow J/\psi (\rightarrow e^+e^-)$;
- Beauty production via $B \rightarrow e^+$.

For such studies, a fast simulation scheme has been employed. It is based on existing Monte Carlo productions including the detailed geometry and response of the current ALICE detector setup. The impact of the ITS upgrade is obtained by recomputing reconstructed track parameters by means of a simple
scaling of the residuals of the impact parameters in $r\phi$ and $z$, as well as of the transverse momentum, with respect to their true values (MC). These are known from the generated particle kinematics.

For the performance studies, the following baseline configuration for the upgraded ITS (see detailed description in chapter 3) has been considered: 7 pixel layers with radii from 2.2 to 43 cm instrumented with pixel detectors with an intrinsic resolution $\sigma_{r\phi}, \sigma_z = (4, 4)$ $\mu$m, and with a radiation length of 0.3% $X_0$ per layer. Figure 2.14 shows the corresponding impact parameter resolutions for charged pions as a function of transverse momentum for the upgraded ITS compared to those of the current ITS.

### 1.5.1 Charm mesons: $D^0 \rightarrow K^- \pi^+$

The $D^0$ can be considered as a benchmark for all the $D$ meson studies. Its measurement is fundamental for understanding the charm energy-loss mechanisms in the hot and dense medium. Moreover, the good signal extraction and the possibility to have as a reference the present ITS performance based on real data, allows a realistic study of the benefits of an upgrade of the ITS.

Here we present a comparison of the performance achievable in Pb–Pb collisions with the current and upgraded ITS configurations. The comparison is made for the centrality class 0–20%, which is the same as was used for the first $R_{AA}$ measurement.

The right panel of figure 1.1 shows the significance normalized to the number of events for both the present and upgraded ITS. For $p_t < 2$ GeV/$c$ the significance is affected by the present uncertainties in the expected nuclear modification factor in Pb–Pb, and in the background as extrapolated from $p_t > 2$ GeV/$c$ while taking into account also the uncertainty in the pion nuclear modification factor. The error box takes into account such uncertainties.

Considering an integrated luminosity of 10 nb$^{-1}$, the number of central events in the centrality class of 0–20% would be $1.7 \times 10^{10}$. However, we consider a sample of $10^9$ events because, as it will be explained in section 2.2.1, the rate of events with a candidate $D^0$ might exceed what can be accommodated in the available bandwidth to tape. Therefore, the rate to tape of these events might be downscaled, possibly as function of $p_t$. Under these assumptions, the significance is several hundreds at any $p_t$. For comparison, the significance in the 2010 run with the present setup, corresponding to $3 \times 10^6$ central events, is 8-10 for $p_t > 2$ GeV/$c$ and negligible for $p_t < 2$ GeV/$c$ (see figure 1.1). At very low $p_t$, even considering the uncertainties in the nuclear modification factor and in the background which enter in the estimation of

![Figure 1.1: $D^0 \rightarrow K^- \pi^+$: comparison of the signal-to-background ratio (left) and significance (right) obtained for the current and upgraded ITS.](image)
the significance, the measurement will be quite precise.

We now summarize the benefits in the charm measurement from the $D$ meson.

An improved detector resolution will provide a better separation between signal and background on several selection variables, rejecting more background and allowing less stringent cuts to be used in order to keep more of the signal and therefore increasing the selection efficiency. The significant improvement of the measurement will come not from only the increased performance in terms of resolution but also from the much higher readout capabilities. This will allow, in particular, for the measurement of charm production down to zero transverse momentum. This is of crucial importance for testing the QCD-predicted colour-charge and mass dependencies of parton energy loss ($R_{AA}$ measurement), for assessing the degree of thermalization of charm quarks in the medium (flow measurement), and for disentangling the role of initial state effects ($p$–$Pb$ studies) and for studying the possible in medium production of $c\bar{c}$–pairs.

It is worth mentioning that the systematic uncertainties arising from an imprecise description of the detector properties (including alignment) and performance (for example vertex and track reconstruction precision) are reduced significantly even in the $p_t$ region where a measurement is presently possible. This is of particular importance because with the present setup and even decreasing the statistical error with higher collected statistics, the systematic errors will hardly decrease. For that reason it will remain difficult to fully discriminate between the different theoretical models.

In conclusion, the ITS upgrade setup will represent a substantial break-through for a high precision measurement of heavy-flavor energy loss in the full $p_t$ domain.

### 1.5.2 Charm baryons: $\Lambda_c \rightarrow pK^-\pi^+$

The physics motivation for the measurement of charm baryon production is briefly discussed at the beginning of this chapter and in more detail in section 2.1.1. The most promising measurement is the decay of the $\Lambda_c^+$ into three charged prongs ($p$, $K^-$ and $\pi^+$) with a B.R. of about 5.0% [7]. In order to identify the decay vertex, a very high resolution is needed because of the short mean proper decay length of the $\Lambda_c$ ($c\tau \approx 60$ $\mu$m [7]).

Presently a $\Lambda_c$ signal is visible in the $pK^-\pi^+$ invariant mass distribution obtained from a data sample of $1.9 \times 10^8$ proton–proton events at $\sqrt{s} = 7$ TeV collected with the ALICE minimum bias trigger. However, the significance is only $\sim 5$ due to the limited efficiency for background rejection with the current ITS.

For the performance study with the upgraded ITS by means of the Hybrid approach, $pp$ events produced with the PYTHIA generator were used. In this way for the ITS upgrade scenario we obtain for $\Lambda_c$ baryons with $p_t > 3$ GeV/$c$ a significance of about 12. The increase of the signal statistics is $\sim 50\%$ (less stringent cuts can be used for the upgrade case) and the increase of the signal-to-background ratio is greater than a factor of 5.

The most dramatic improvement is for Pb–Pb collisions. The $\Lambda_c$ signal could not be observed with the 2010 Pb–Pb data sample, because of the very large combinatorial background. In this case, the performance was studied using a dedicated simulation sample of about $10^4$ central (0–10%) Pb–Pb events at $\sqrt{s_{NN}} = 5.5$ TeV. In this Monte Carlo sample, the current ITS detector layout was considered without any inactive module (contrary to the simulations used for the $D^0$ study). The performance in non-central collisions was estimated by scaling the signal and background yields with centrality and evaluating then the signal-over-background ratio and the significance. The results, in terms of $S/B$ ratio and significance per event, are reported in figure 1.2 as a function of $p_t$ for different centrality classes and for minimum bias collisions. For the most central collisions, the signal-to-background improves by a factor 400 (in $2 < p_t < 4$ GeV/$c$) from current to ITS upgrade. The significance also improves by a factor 5–10 in all $p_t$ intervals above 2 GeV/$c$. The performance in peripheral collisions is better, in terms of significance,
by about a factor of 2. The signal-to-background ratio becomes quite large in peripheral collisions.

In the following we will consider an integrated luminosity of 10 nb$^{-1}$ which corresponds to $1.7 \times 10^{10}$ central events (using the centrality class 0–20%). For this event sample, the significance is $1.3 \times 10^{5}$ times the values reported in the figure: 7, 40 and 53 in the $p_t$ bins 2–4 GeV/$c$, 4–6 GeV/$c$ and 6–8 GeV/$c$ respectively. The signal-over-background ratio is expected to be very small - $\sim 10^{-4}$ in 2–4 GeV/$c$. However, the background level in the $\Lambda_c$ mass region will be determined very precisely using the information from the invariant mass side-bands. Therefore, we conclude that the $\Lambda_c$ production should be measurable down to a transverse momentum of $\sim 2$ GeV/$c$ in central collisions.

For the peripheral collisions the significance is 20 in $2 < p_t < 4$ GeV/$c$ for $1.7 \times 10^{10}$ events (in a centrality class like 70–90% or 60–80%).

Figure 1.3 shows the expected statistical uncertainties for the measurement of the $\Lambda_c/D^0$ ratio using $1.7 \times 10^{10}$ central Pb–Pb collisions (0–20%), corresponding to an integrated luminosity of 10 nb$^{-1}$. The points are drawn on a line that captures the trend and magnitude of the $\Lambda_c/K^0_S$ ratio.

Summarizing, the central-to-peripheral nuclear modification factor will be measured for $p_t > 2$ GeV/$c$.

In addition, with an integrated luminosity of 10 nb$^{-1}$, a measurement of the elliptic flow will be performed for $p_t > 4$ GeV/$c$ in semi-central collisions (e.g. 30–50%), as is illustrated in figure 2.24, and for $p_t > 2$ GeV/$c$ in peripheral collisions (e.g. 60–80%).

1.5.3 Prospects for beauty production measurements

As already mentioned, the high precision measurement of beauty production in nuclear collisions and its comparison to charm production is of great importance to assess the mechanisms of heavy flavour energy loss. Beauty can be accessed in three different ways:

1.5.3.1 $B$ meson production via displaced $D^0$

Most of the $B$ meson decay channels include a $D^0(D^0)$. The kaon and pion tracks coming from secondary $D^0$ decays are, on average, more displaced from the primary vertex than those coming from the decay of a prompt $D^0$. This is due to the relatively long lifetime of $B$ mesons ($c\tau \approx 460–490$ µm). Therefore, the
selection applied on reconstructed $D^0$ candidates, optimized to prefer secondary vertices displaced from the primary vertex, further enhances the secondary-to-prompt ratio of reconstructed $D^0$ up to typical values around 10% even for $p_t < 5$ GeV/c.

The fraction of prompt and displaced $D^0$ mesons can be measured by exploiting the different shapes of the impact parameter distributions of primary and secondary mesons. The left panel of figure 1.4 shows the impact parameter distribution for prompt and secondary $D^0$ in $2 < p_t < 3$ GeV/c as obtained from a heavy-flavour enriched MC simulation of pp collisions at $\sqrt{s} = 7$ TeV produced with the PYTHIA generator. For example, the probability to reconstruct an impact parameter of 100 $\mu$m for prompt $D^0$ decreases by a factor larger than 3 in the upgraded ITS case. This is when compared to the current ITS case. Such a decrease allows for a much better separation of the two components with smaller systematic uncertainties.

A first estimation of the performance for the measurement of beauty production in central Pb–Pb collisions using the fraction of non-prompt $D^0$ mesons was carried out, starting from the simulation results on the impact parameter resolution, the $D^0$ $S/B$ ratio, and the expected $D^0$ signal statistics (section 2.2.3). In the last case, we have considered a sample of $10^9$ events in the centrality class 0–20%. An additional input parameter of the study is the value of the fraction of non-prompt $D$ mesons, which we have taken as 0.15, independent of $p_t$. The relative statistical uncertainty on the fraction of $D^0$ mesons from $B$ decays is shown in the right panel of figure 1.4. Since the statistical uncertainty on the measurement of the total $D^0$ yields is expected to be of the order of 1%, the values shown in the figure coincide in practice with the relative statistical uncertainty on the measurement of beauty production. The results are very promising, with a statistical uncertainty of the order of 10% down to $p_t$ of 2 GeV/c. In particular, that will give access to $B$ mesons with $p_t$ down to 0.

### 1.5.3.2 $B$ meson production via displaced $J/\psi$

The measurement is performed by reconstructing the final charmonium state via its $e^+e^-$ decay, and finding a displaced secondary vertex with the two electrons attached. A combined fit of the pseudo-proper decay length $l_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_{t,J/\psi}$ and the $e^+e^-$ invariant mass distribution can be used to extract the non-prompt to prompt $J/\psi$ ratio. The measurement can be done down to very low transverse momentum, $p_t(J/\psi) \sim 1.3$ GeV/c, which is a unique capability of ALICE at the LHC. Figure 1.5 shows the
Figure 1.4: Left: $D^0$ from $B$ decays. Comparison of the impact parameter distributions for prompt and secondary $D^0$ obtained with the current and upgraded ITS configurations in the transverse momentum range $2 < p_t < 3$ GeV/c. Right: relative statistical uncertainty on the fraction of $D^0$ mesons from $B$ decays for $10^9$ central Pb–Pb collisions, with the upgraded ITS. The input fraction of non-prompt $D^0$ mesons is 0.15.

Figure 1.5: $J/\psi$ from $B$ decays. Pseudo-proper decay length resolution obtained with the current ITS compared to the resolution with the upgraded ITS for $p_t(J/\psi) > 1.3$ GeV/c.

pseudo-proper decay length distribution for reconstructed prompt $J/\psi$ with the present and upgraded ITS. This distribution is used in the combined fitting procedure as an estimate of the resolution of the pseudo-proper decay length variable because the $l_{J/\psi}$ distribution should be ideally peaked at zero, being prompt $J/\psi$ produced at the primary vertex. Its broadening is due to the resolution of the primary vertex and to the multiple scattering induced by the detector material on reconstructed tracks. The upgraded ITS scenario exhibits a significant enhancement in terms of pseudo-proper decay length resolution, which is a factor of 2 better than with the current ITS. Moreover, this resolution enhancement extends over the whole $J/\psi$ transverse momentum domain.

1.5.3.3 $B$ meson production via displaced electrons

This has been up to now the standard measurement in ALICE because beauty hadrons have substantial branching ratios ($\sim 10\%$) to single electrons or single muons, which give rise to a large signal-to-
background ratio using this channel, in particular at high $p_t$. Also in this case, one obtains a high-purity sample of electrons from beauty hadron decays by applying a cut on the impact parameter.

Figure 1.6 shows the signal-to-background ratio with the upgraded ITS divided by that with the current ITS, as a function of $p_t$. As shown in the figure, the improved resolution results in a very significant increase of the signal-to-background ratio in the low $p_t$ region. This is crucial to measure the total beauty cross section.

The resolution improvement by about a factor of 3 with the upgraded ITS is very effective in reducing the background contributions related to electrons coming from the primary interaction vertex (like Dalitz and di-electron decays). A further improvement comes from the reduction of photon conversions in the detector material (e.g., conversion of photons from the decay $\pi^0 \rightarrow \gamma\gamma$), which originate from displaced secondary vertices. This is not shown in the figure. The reduced material thickness of the beam pipe and of the ITS layers results in a decrease of such background.

In summary, the upgraded ITS will allow for a much more precise measurement of beauty production, in particular down to low transverse momentum. The latter feature is a distinctive aspect of ALICE and will be more elaborated on in section 1.6.

### 1.5.4 Prospects for low mass dilepton measurements

As discussed in section 1.2, low mass dileptons are important for the measurement of thermal radiation from the QGP, and in-medium modifications of vector mesons spectral functions related to the restoration of chiral symmetry. At the LHC, a significant increase of thermal radiation is expected due to the increased system lifetime and the $T^4$ dependence of the Stefan-Boltzmann law. This could be accessed at pair masses around $100 \text{ MeV}/c^2$ and pair transverse momenta down to 1 GeV/c.

Experimentally, the measurement of low-mass $e^+e^-$ pairs is challenging due to the large combinatorial background. This mainly comes from photon conversions and Dalitz decays. There is a necessity for a very low material budget before the first detection layer and excellent tracking and PID capabilities at low $p_t$, to allow for the active detection and rejection of conversions and Dalitz pairs.

As previously discussed for the single electron measurement, the upgraded ITS strongly improves the detector performance precisely in the direction required for the di-electron measurement. The perfor-
mance could even be enhanced by operating the experiment with a reduced magnetic field. The ITS will thus extend to low $p_t$ the excellent electron identification capabilities of ALICE provided by the TPC, TRD, TOF and calorimeters.

Finally, the low-mass dilepton measurement will strongly benefit from higher collision rates and increased data recording capability. In this case there is no obvious trigger scheme for low-mass lepton pairs in Pb-Pb due to the dominating combinatorial background.

1.6 Competitiveness and Uniqueness of ALICE with an Upgraded ITS

In this section we point out the aspects that will make unique the heavy flavour physics program that can be carried out with heavy-ion collisions at the top LHC energy by ALICE with an upgraded ITS detector.

1.6.1 With respect to STAR at RHIC

With its new silicon Heavy Flavour Tracker (HFT) [6], the STAR experiment at RHIC is going to address a heavy flavour physics program similar to the one we propose. This project intends to study heavy quark propagation and thermalization in the QGP formed in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. This will be mainly done via the measurement of the $D$ meson and $\Lambda_c$ baryon nuclear modification factor and elliptic flow, and via beauty-decay electron tagging.

Charm and beauty production cross sections are expected, on the basis of NLO pQCD calculations [8], to be about 10 and 100 times, respectively, larger at the top LHC energy than at the top RHIC energy. Therefore at the LHC, the kinematic range over which charm and beauty production can be measured extends to much larger transverse momenta. This presents a unique opportunity for the study of the predicted colour-charge and mass dependencies of the parton–medium interaction with high energy $c$ and $b$ quarks, using in particular prompt and non-prompt $D$ mesons, and non-prompt $J/\psi$ mesons.

The intriguing open questions on heavy quark thermalization in the QGP, and the coalescence-induced baryon/meson effect in the charm sector have to be addressed in the very different energy regimes accessible at RHIC and the LHC. Indeed, these effects could vary between $\sqrt{s_{NN}} = 200$ GeV and 5.5 TeV, and their comparison would provide crucial information for the characterization of the QGP properties and their excitation energy function. For instance, the first measurements of global system features in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by ALICE [9–11] indicate that the hot and dense system formed at the LHC has three times larger energy density and two times larger volume than at RHIC energies.

1.6.2 With respect to CMS and ATLAS at the LHC

The ATLAS and CMS experiments have excellent capabilities for lepton triggering and reconstruction over a broad $\eta$ acceptance. This is coupled to a precise track position and momentum measurement with silicon detectors in strong magnetic fields. Both these features make them ideally suited to study beauty production at high $p_t$ using displaced leptons and displaced $J/\psi$ mesons.

A comparison of the features of ALICE, ATLAS and CMS that are relevant for heavy-flavour measurements is presented in table 1.1.

An important advantage for ALICE in the low-momentum region is the small material budget of the silicon tracker, which with this ITS upgrade would become a factor 4 and 5 smaller than that of CMS and ATLAS respectively. This lower thickness results in substantially smaller multiple scattering for low-momentum particles and so a better impact parameter resolution and reconstruction efficiency. This is clearly crucial for low-$p_t$ charm and beauty measurements. This is the case in particular for $\Lambda_c$ reconstruction, where the decay protons have momenta well below 1 GeV/$c$ and are strongly affected by multiple scattering (larger for heavier particles, due to the $1/\beta$ dependence).
Table 1.1: Comparison of the features of the future ALICE, ATLAS and CMS trackers that are relevant for heavy-flavour measurements [12, 13]. The $p$ range of the ALICE PID reported here refers to the combined PID information of ITS, TPC and TOF. However, it does not include the TPC PID in the relativistic rise.

<table>
<thead>
<tr>
<th></th>
<th>current ALICE</th>
<th>ALICE upgrade</th>
<th>ATLAS upgrade</th>
<th>CMS upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>innermost point (mm)</td>
<td>39.0</td>
<td>22.0</td>
<td>25.7</td>
<td>30.0</td>
</tr>
<tr>
<td>$x/X_0$ (innermost layer)</td>
<td>1.14%</td>
<td>0.3%</td>
<td>1.54%</td>
<td>1.25%</td>
</tr>
<tr>
<td>$d_0$ res. $r\phi$ ($\mu$m) at 1 GeV/$c$</td>
<td>60</td>
<td>20</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>hadron ID $p$ range (GeV/$c$)</td>
<td>0.1−3</td>
<td>0.1−3</td>
<td>–</td>
<td>–</td>
</tr>
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</table>

Finally, hadron identification over a very broad momentum range, 0.1−3 GeV/$c$, will be preserved as one of the most unique features of ALICE and a very strong point in its competitiveness with respect to the other two large LHC experiments. This capability, provided by the TPC, the TOF, and the ITS, has already proven to be crucial for the measurement of $D$ meson production in Pb–Pb collisions, with background reduction of a factor 2−3 in the low momentum region. It has also been crucial for the observation of the $\Lambda_c$ signal in pp collisions. The simulation studies for $\Lambda_c \rightarrow pK\pi$ reported in section 1.5.2 indicate that more than 90% of the background is rejected by applying the $\pi/K/p$ identification from ITS, TPC and TOF. The study of charm meson and baryon production and flow at low momentum would not be possible without good hadron identification capability.

1.7 Upgrade Timeline

The ALICE ITS upgrade will require a long shutdown (LS) and, therefore, will naturally have to be in phase with the installation of upgrades for the other LHC experiments. These are planned as of today for the 2013/14 and 2017/2018 shutdowns. The ITS upgrade targets the long LHC shutdown period in 2017/2018 (LS2). The scope of the upgrade for the LS2 will be tailored to what can be reasonably designed, constructed and tested within the next five years and installed in 12-15 months while including a safety margin. The R&D efforts will continue until 2014, construction will take place in 2015/16 and then installation and commissioning by 2017/18.

1.8 Document Summary

The physics performance and limitations of the present ALICE detector in studying heavy flavour at mid-rapidity in Pb-Pb collisions, as well as the performance of the upgraded detector, are discussed in chapter 2. Chapter 3 deals with the detector functional requirements and performance in terms of tracking and identification of charged particles. Chapter 4 reviews the technologies that are being considered for the detector implementation, with a particular focus on the key R&D activities. The aspects related to the integration of the new detector, the support mechanics, the cooling and the services will be presented in chapter 5. Finally, chapter 6 will present the project organization, timeline and cost estimate.
Chapter 2

Physics Motivation

The main physics motivation for the upgrade of the Inner Tracking System of the ALICE experiment is to perform new measurements on charm and beauty production in heavy-ion collisions, which address important questions that cannot be answered with the present experimental setup. Namely:

- Study of the thermalization of heavy quarks in the medium, in particular by measuring the baryon to meson ratio for charm ($\Lambda_c/D$) and for beauty ($\Lambda_b/B$), the elliptic flow for charm mesons and baryons, and the possible in-medium thermal production of charm quarks.

- Study of the quark mass dependence of in-medium energy loss, by measuring the nuclear modification factors $R_{AA}$ of the $p_t$ distributions of D and B mesons separately.

This could be achieved by means of a silicon vertex tracker with improved resolution in the central rapidity region.

At present, at mid-rapidity $|\eta| < 1$, the capability of studying yields and spectra of particles containing heavy quarks is mainly provided by the Inner Tracking System (ITS). Charm production can be addressed through meson and baryon hadronic decays ($D^0 \to K\pi$, $D^+ \to K\pi\pi$, $D_s \to K\pi\pi$, $D^* \to D^0\pi$, $D^0 \to K\pi\pi\pi$, and $\Lambda_c \to pK\pi$) via topological selection of a secondary vertex. Particle identification is needed to reduce the very large backgrounds in heavy ion collisions. This is provided mainly by the TPC and TOF detectors. In addition, charm and beauty can be tagged in semi-leptonic decays $D, B \to e + X$. Electron identification is provided by the TPC, TOF, TRD and EMCAL detectors. However, a component of electrons from charm decays has to be subtracted statistically, implying a significant systematic uncertainty, especially in the low $p_t$ region (below 5 GeV/$c$). Important physics topics such as the study of beauty baryons or of hadrons with more than one heavy quark are beyond the capability of the current detector, and the performance for charm baryons will be much worse than for charm mesons, given that the most abundantly produced baryons ($\Lambda_c$) have a mean proper decay length ($c\tau$) of only $60 \, \mu m$, to be compared with the 100–300 $\mu m$ of D mesons.

It is important to stress that to address new high precision measurements in a thorough and systematic way, the following design goals have to be met:

1. Coverage in transverse momentum should be as complete as possible, in particular down to very low momenta.

2. Very accurate identification of secondary vertices from decaying charm or beauty particles (prompt $D, D$ and $J/\psi$ from $B$ decays, $\Lambda_c, \Lambda_b$).
3. High standalone tracking efficiency, which is essential to perform online event reconstruction and selection.

The online selection should be performed using the data of the ITS, in combination with the TRD and TOF detectors, from all interactions at a rate of 50 kHz. The events partially reconstructed, i.e. without TPC information, can be stored to tape at the interaction rate, for offline analysis, and also used online to elaborate a first level of event selection based on the tracking and PID information of ITS, TRD and TOF. In a second step, all data of the selected events will be processed for a further selection based on the fully reconstructed events.

A new vertex detector with the capabilities described above will place ALICE in a unique position in comparison to the other LHC experiments, since for a number of heavy-flavour measurements the other experiments can only explore momenta above a certain threshold of a few GeV/c.

2.1 Current experimental situation and impact of the ITS upgrade

2.1.1 Heavy flavour thermalization, coalescence, and possible thermal production: present status and further measurements

Given the very large energy of the collisions at LHC, an abundant production of $c\bar{c}$ and $b\bar{b}$ pairs is expected in the initial hard-scattering processes (about 80 and 3, respectively, per central Pb–Pb collision at $\sqrt{s_{NN}} = 5.5$ TeV, see table 2.1 on page 25).

Heavy quarks lose energy while traversing the hot and dense medium and, in particular at sufficiently low transverse momentum, they can thermalize in the medium itself. Reinteractions will reflect in the $p_t$ spectra and, in particular, in the elliptic flow in semi-central collisions.

Elliptic flow, measured in non-central collisions, provides the most direct evidence of the collective hydrodynamical behaviour of the medium. During the collision, the two nuclei overlap in an elliptically-shaped region, the short axis of which lies on the reaction plane. The expansion, under pressure gradients, translates the space asymmetry into a momentum asymmetry. This is detected by measuring the momentum-dependent azimuthal distribution $d^2N/dp_t d\Delta\phi$ of the produced particles with respect to the reaction plane. The parameter describing the asymmetry is $v_2$ (also called elliptic flow), which is the second coefficient of the Fourier expansion of the azimuthal distribution.

At RHIC $v_2(p_t)$ or $v_2(m_t - m_0)$ of identified particles scales with $m_t - m_0$ for relatively low $p_t < 2$ GeV/c [15]. The same behavior is observed also at LHC [16]. At higher $p_t$, $v_2$ seems to scale with the constituent quark number, so that $v_2/n_q$ scales with $p_t/n_q \approx m_t/n_q$. This is clearly visible in figure 2.1, where the $\Lambda$ and $K^0_S$ data extend up $p_t \approx 5$ GeV/c [14]. This observation suggests the presence of an initial partonic state. It can be naturally explained with a coalescence model [17] for hadronization, where the flow of constituent quarks add up, so that $v_2^{\text{meson}}(p_t) = 2v_2^q(p_t/2)$ and $v_2^{\text{baryon}}(p_t) = 3v_2^q(p_t/3)$.

A very stringent test would be to verify whether this universal scaling continues to hold also for heavy flavour mesons and baryons. This requires measuring the $D$ meson and $\Lambda_c$ elliptic flow in the range $2 < p_t < 5$ GeV/c, where the baryon/meson ($\Lambda_c/K$) separation at RHIC is most pronounced. A first measurement of the $D^0$ elliptic flow coefficient $v_2$ in 30–50% central Pb–Pb collisions was obtained by ALICE (see figure 2.2): the result is very intriguing, because it seems to indicate that $D$ mesons take part in the flow.

The production of charm and beauty baryons has also a particular interest to assess the thermalization of heavy flavours in the medium and to discriminate among different thermal or coalescence models, because it was predicted that their production could be significantly enhanced in nuclear collisions [22]. Indeed, the low non-photonic electron $R_{AA}$ measured at RHIC could be related to an enhancement in the charm baryon/meson ratio ($\Lambda_c/D$), considering the fact that charm baryons have lower branching
Constituent quark scaling of meson and baryon $v_2$ as measured by STAR in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [14]. Left: $v_2$ vs. $p_t$. Right: $v_2/n_q$ vs. $p_t/n_q$.

First measurement of $D^0 v_2$ in 30–50% Pb–Pb collisions at the LHC by ALICE [18].

ratio to electrons with respect to charm mesons [23, 24]. For light flavour and strange baryons, such an enhancement was indeed observed at intermediate transverse momenta at RHIC and at LHC [19, 20], as shown in figure 2.3.

Within thermal models, it is assumed that charm and beauty hadrons are produced during the QGP hadronization and they are in thermal equilibrium with the medium. Within coalescence models, partons produced in hard scatterings can combine with quarks and anti-quarks in the QGP to form hadrons. The resulting hadrons will have momenta between those from the independent fragmentation and from the hadronization of the QGP. In addition, contrary to thermal models, coalescence models consider also the possibility of recombination of a heavy quark with di-quarks present in the QGP. It was suggested that this could lead to a rather significant enhancement of the $\Lambda_c$ with respect to thermal models [22], where the relative abundance of particles depends only on their masses.

As an example of the size of the expected effect, we report in figure 2.4 the $\Lambda_c/D^0$ and $\Lambda_b/B^0$ enhancements as a function of transverse momentum for central Au–Au collisions at RHIC ($\sqrt{s_{NN}} = 200$ GeV) [21]. The enhancement is of up to 7–10 for both baryon/meson ratios, and it is maximum...
at $p_t \simeq 2$ GeV/c for charm and $p_t \simeq 4$ GeV/c for beauty. For strange quarks (figure 2.3) the position of the maximum is higher by about 1 GeV/c at LHC with respect to RHIC energy. Therefore, one can expect the maximum of $\Lambda_c/D^0$ to be at $p_t \simeq 3$ GeV/c at LHC energy. This demands for a measurement of $\Lambda_c$ production in central Pb–Pb collisions starting from $p_t \simeq 2–3$ GeV/c.

Actually, if coalescence occurs statistically at the hadronization temperature, there could be a chance that even two or three charm quarks coalesce together forming a multi-charm baryon. That can happen only if the quarks are close to thermalization because high momentum quarks will hadronize in general independently, unless two or three correlated quarks are close together in momentum from the hard process (which is much less likely to occur). Thus, also an enhanced production rate of multi-charm baryons is a distinctive feature of thermalization of the medium produced in heavy ion collisions. The enhancement predicted by statistical models in case of hadronization by coalescence can reach a factor $10^3$ for the $\Omega_{ccc}$ at LHC energies [25]. Thus, double and triple charmed baryons or charmed-beauty baryons could be observed (it has to be noted that states as the $\Omega_{ccc}$ are not yet observed even in elementary collisions).

From the experimental point of view, the main issue for the measurement of charmed baryons is their rather short lifetime: the $c\tau$ of the $\Lambda_c$ is a factor of 2 smaller than that of the $D^0$. Those measurements require a very precise tracking and impact parameter resolution, because the decay tracks typically have displacements of a few tens of microns ($\sim c\tau$) from the primary interaction vertex. Presently, the $\Lambda_c$ signal was observed by ALICE in the $pK^-\pi^+$ decay channel in pp collisions at $\sqrt{s} = 7$ TeV collected in

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Figure 2.3: Left: $\Lambda/K_S^0$ ratio vs. transverse momentum as measured by ALICE at LHC and by STAR at RHIC [19, 20].

Figure 2.4: Heavy flavour baryon/meson enhancement as a function of $p_t$ in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [21]. Left: $\Lambda_c/D^0$. Right: $\Lambda_b/B^0$. 
2010, as we show in one of the next sections. However, the signal is observed only at transverse momenta above 3 GeV/c and the statistical significance is relatively low (about 5 $\sigma$), as compared to the $D$ meson signals. In Pb–Pb collisions, in particular down to low transverse momenta, the $\Lambda_c$ measurement seems to be beyond the present setup capabilities. Figure 2.5 shows the impact parameter resolution as a function of $p_t$ in pp and Pb–Pb collisions. It is clear that to access the $\Lambda_c$ the impact parameter resolution should be improved by a factor of 2 at least.

If the initial temperature of the high-density system produced in central collisions is large enough, a thermal production of $c\bar{c}$ pairs may occur, leading to a measurable increase of the total production yields of charm particles [26–29].

For example, thermal charm production is studied at next-to-leading-order in QCD in Ref. [28]. It is found that the total yield of charm production may be enhanced by 30 (80)% if initial temperatures of 700 (750) MeV are considered and a charm quark mass value of 1.3 GeV/$c^2$ is used (see figure 2.6, left). On the other hand, the enhancement would be marginal if the initial temperature is of the order of 600 MeV or if the charm quark mass is 1.5 GeV/$c^2$ or higher.

In-medium $c\bar{c}$ production is studied within a partonic transport model in Ref. [29]. As shown in figure 2.6 (right), the relevance of the effect is found to depend strongly on the initial gluon density assumed for the deconfined system (initial conditions from PYTHIA, Color Glass Condensate or mini-jets) and on the charm quark mass value.

In conclusion, while the yield of possible thermal charm production depends on specific model parameters, it is clear that its observation would provide key information on the initial temperature and density of the deconfined plasma. From the experimental point of view, this effect has to be searched as an enhancement of the total $D$ meson production yields per binary collision in Pb–Pb with respect to pp collisions, or in central with respect to peripheral Pb–Pb collisions. It is, therefore, essential to reconstruct $D$ meson decays down to $p_t = 0$. In the comparison of pp and Pb–Pb, the initial-state modification has to be taken into account. This can be tackled using p–Pb collisions.

The measurement of the total charm production will also provide the natural normalization for the study of medium effects on charmonium production ($J/\psi$ and $\psi'$). The crucial advantage of this normalization being that the initial-state effects are mostly common between open charm and charmonium and, thus,
The ALICE Collaboration

Figure 2.6: Thermal charm production in Pb–Pb collisions at top LHC energy, as a function of the proper time, for two different models. Left: $c\bar{c}$ yields per unit of rapidity at mid-rapidity from [28]; total $c\bar{c}$ yields from [29].

cancel out in the ratio.

**Impact of the ITS upgrade and new measurements**

On the basis of the discussion in the previous section, a new improved silicon tracker at mid-rapidity will impact significantly the following measurements:

- Charm down to zero $p_t$. See simulation study in section 2.2.3.
- Charmed baryons - $\Lambda_c$. See simulation study in section 2.2.4.
- Beauty baryons - $\Lambda_b$. Once the $\Lambda_c$ can be experimentally tagged, then also the beauty baryon $\Lambda_b$ could be measured via the decay $\Lambda_b \to \Lambda_c + X$.
- Elliptic flow of charmed and beauty mesons and baryons down to low transverse momentum. The baryon sector will be made accessible for the first time.
- Multiple-heavy-flavour baryons like $\Xi_{bc}$ and $\Omega_{ccc}$. A possible approach to these searches is to use two or three displaced electrons produced in cascade semi-leptonic decays of the constituent heavy quarks. However, these measurements would be challenging even with an upgraded tracker.

2.1.2 Heavy flavour energy loss: present status and further measurements

One of the distinctive features of the hot and dense medium formed in heavy ion collisions is the strong energy loss induced on the hard partons that are produced in the initial hard scattering processes. Parton energy loss is thought to be dominated by gluon radiation, but also elastic collisions with the medium gluons would play an important role. The investigation of heavy flavour energy loss has a particular interest. Indeed, gluon radiation from heavy quarks is predicted to be suppressed, with respect to the case of light partons, at angles smaller than the quark energy-over-mass (dead cone effect) [30,31]. Moreover, light flavour hadrons are dominantly produced at LHC energies by hard fragmenting gluons, which lose more energy due to their stronger coupling to the medium. Thus, one has the prediction for the energy loss $\Delta E_g > \Delta E_c > \Delta E_b$. Experimentally, the energy loss in heavy ion collisions can be investigated as a function of transverse momentum via the nuclear modification factor $R_{AA} = dN_{AA}/dP_t/\langle N_{AA}\rangle d\sigma_{pp}/dP_t$.

Theoretical models based on perturbative QCD with the inclusion of radiative parton energy loss predict for charm mesons a suppression factor of 3–5 and a significantly smaller suppression for B mesons (see
ITS Upgrade CDR

Figure 2.7: Left: prediction for $R_{AA} vs p_t$ for $D$ mesons (blue) and $B$ mesons (red) in Pb–Pb collisions at the LHC, from radiative + collisions energy loss (DGHW) [32]. Right: mass dependence of $B$ meson $R_{AA}$ in Pb–Pb collisions at the LHC from radiative energy loss (ASW) [33].

Figure 2.8: Heavy-to-light $R_{AA}$ ratios as predicted by radiative energy (ASW) [33]. Left: $R_{AA}^D/R_{AA}^h$. Right: $R_{AA}^B/R_{AA}^h$.

left panel of figure 2.7 [32]). The mass dependence of energy loss is more pronounced for the beauty, as seen in the right panel of figure 2.7 [33]. Mass and colour charge dependence can be investigated experimentally with the ratio $R_{D/b} = R_{AA}^D(p_t)/R_{AA}^h(p_t)$ (see figure 2.8 [33]). The mass effect is more pronounced at moderately low transverse momenta. At sufficiently high $p_t$ (above $\sim 10$ GeV/$c$) the $c$ quark starts to behave essentially as a massless parton. However, the ratio should not tend to one since it becomes sensitive to the color charge dependence of energy loss.

Even more interesting is the ratio $R_{B/D} = R_{AA}^B(p_t)/R_{AA}^D(p_t)$, which is shown in the left panel of figure 2.9 [33]. Here, the ratio shows a strong deviation from one in particular at moderately low $p_t$, decreasing only rather slowly for increasing $p_t$. String theory models inspired by the AdS/CFT correspondence have been able to describe qualitatively a number of aspects of the heavy ion collisions phenomenology (see e.g. [35]). Predictions for the ratio $R_{D/B} = 1/R_{B/D}$ are shown in the right panel of figure 2.9 [34]. This ratio has also the advantage of magnifying the differences in the mass and $p_t$ dependence of pQCD and AdS/CFT models. While differences are present among pQCD models and among AdS/CFT models, the two classes of models yield largely different predictions irrespectively of
During the 2010 run, the LHC experiments collected data from Pb–Pb collisions at 2.76 TeV. ALICE performed the first measurement of the $D$ meson $R_{AA}$, which is shown in figure 2.10 (left) [36]. At the moment the analysis is restricted to $p_t > 2$ GeV/$c$. Presumably it will be possible to go down to $p_t \approx 1$ GeV/$c$ using higher-statistics data from the 2011 Pb–Pb run, but reaching zero transverse momentum seems to be precluded with the current setup, due to the huge background level. In addition, the present accuracy of the $R_{AA}$ measurement is limited to $\approx 30–40\%$ by the systematic uncertainties on the B feed-down correction, the signal yield extraction, and the efficiency evaluation. As it will be explained in sections 2.2.3 and 2.2.5.1, all these contributions could be substantially reduced with an upgraded vertex detector. The feed-down correction, currently based on pQCD predictions with an hypothesis on the unknown nuclear modification of beauty production, will become more accurate with the direct measurement of the non-prompt fraction of $D$ mesons. The systematic uncertainties on the yield extraction and efficiency correction will be reduced thanks to the higher statistics, that will allow for a better determination of the signal invariant mass shape and for the usage of less stringent selection cuts.

The other key measurement is a precision measurement of beauty energy loss via $R_{AA}$ with coverage down to low $p_t$. In ALICE, beauty production is accessed at mid-rapidity via $B \to e^+X$. In the present setup, this will be the only way to measure it. At low $p_t$, the component of electrons from charm decays has to be subtracted statistically, implying a significant systematic uncertainty.

The $R_{AA}$ for the electron spectrum measured at mid-rapidity is shown in figure 2.10 (right) [36] (this electron measurement is not fully background subtracted, but the $p_t$ spectra are expected to be dominated by heavy flavour semi-leptonic decays above 4–5 GeV/$c$).

Summarizing, with the current detector, beauty production measurement at mid-rapidity may be possible only via single electrons. However, at low $p_t$ the subtraction of the background contributions is problematic.

Another interesting possibility is to measure beauty via the $J/\psi$ decay tagging a secondary vertex with two leptons attached. This is a rather clean measurement. A first measurement in Pb–Pb was performed by the CMS Collaboration [37]. The left panel of figure 2.11 shows the $J/\psi$ pseudo-proper decay length ($L_{xy} = \frac{m_{J/\psi}}{p_t}$). $R_{AA}$ is shown in the right panel: the suppression is of about a factor 2.5. The CMS
Figure 2.10: Heavy-flavour nuclear modification factors at mid-rapidity in central Pb–Pb collisions at the LHC measured by ALICE [36]. Left: $D$ meson $R_{AA}$ compared to charged pions, at mid-rapidity. Right: $R_{AA}$ for the cocktail-subtracted electron spectrum, at mid-rapidity.

Figure 2.11: Left: $J/\psi$ pseudo-proper decay length measured in Pb–Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV measured by the CMS experiment [37]. Right: $R_{AA}$ of $J/\psi$ from $B$ decays.

measurement is limited to the region $J/\psi p_t > 6.5$ GeV/$c$, due to the large momentum cut on the decay muons. In the present ALICE setup, at mid-rapidity this measurement is severely limited by the lack of a triggering scheme, which prevents to collect a high-statistics sample. On the other hand, the low transverse momentum limit reaches $J/\psi p_t = 0$.

**Impact of the ITS upgrade and new measurements**

On the basis of the discussion in the previous section, a new improved silicon tracker at mid-rapidity would dramatically improve or make accessible for the first time the following measurements in Pb–Pb collisions:

- Beauty via displaced $D^0 \to K\pi$ will be accessible for the first time, with a reach down to $D p_t = 2$ GeV/$c$. See simulation study in section 2.2.5.1.
– Beauty via displaced $J/\psi \rightarrow ee$ will be accessible for the first time. See simulation study in section 2.2.5.2.

– Single displaced electron will be greatly improved. See simulation study in section 2.2.5.3.

– Beauty decay vertex reconstruction using any of the previous three channels plus an additional track will be greatly improved.

The electron measurement requires full tracking, but there would be a clear possibility to trigger on electrons with the TRD or EMCAL in conjunction with a topology trigger on tracks associated with a displaced vertex.

2.2 Physics performance studies for the ITS upgrade

2.2.1 Possible measurements and expected yields

In the second part of this chapter, we present the first performance studies for heavy flavour detection with an upgraded ITS. We consider the following benchmark analyses:

– Charm meson production via $D^0 \rightarrow K^-\pi^+$;

– Charm baryon production via $\Lambda_c \rightarrow pK^-\pi^+$;

– Beauty production via $B \rightarrow D^0 \rightarrow K^-\pi^+$;

– Beauty production via $B \rightarrow J/\psi \rightarrow e^+e^-$;

– Beauty production via $B \rightarrow e^+$.

The results on the expected impact of the upgrade are reported in the following sections. Here, we provide estimates on the possible statistics that could be collected in minimum-bias and central collisions (0–10% centrality class) during a Pb–Pb run at top LHC energy, $\sqrt{s_{\text{NN}}} = 5.5$ TeV. For this exercise, we consider the scenario envisaged for the LHC and for the ALICE central barrel conditions after the 2017-18 shutdown, as outlined in the “Upgrade Strategy for ALICE at High Rate” document [5]. Namely: an interaction rate of 50 kHz for Pb–Pb collisions; a central barrel readout rate to tape in the range 5–25 kHz; an online High Level Trigger that allows us to inspect all interactions [5].

We use the production yields predicted by perturbative QCD and we assume a Pb–Pb running and data taking scenario. For each analysis, we assume a value for the acceptance times efficiency, which we evaluated based on the currently ongoing analyses with ALICE data. The estimates require also an assumption on the High Level Trigger efficiency, which we set to be equal to the offline selection efficiency for this first exercise, and on the trigger purity, which we assign starting from the signal-to-background ratios that can be expected with the ITS upgrade based on the studies that will be presented in the next sections.

In table 2.1 we summarize the expected production yields for $c\bar{c}$ and $b\bar{b}$ pairs in central (0–10%) and minimum-bias (0–100%) Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.5$ TeV (and for other energies/systems for comparison). The numbers are obtained by applying binary $N_{\text{coll}}$ scaling to next-to-leading order perturbative QCD (pQCD) predictions from the HVQMN calculation [8]. The value of the charm and beauty quark masses and of the pQCD scales are set as: $m_c = 1.2$ GeV$/c^2$, $m_b = 4.75$ GeV$/c^2$, $\mu_R = \mu_F = 2m_c$ for charm and $\mu_R = \mu_F = m_b$ for beauty production. CTEQ6M parton distribution functions are used with the EPS09NLO [38] correction for nuclear shadowing. These predictions are affected by a theoretical uncertainty of a factor 2–3.
Table 2.1: Heavy quark production at the LHC as expected from pQCD calculations at NLO with nuclear shadowing corrections.

<table>
<thead>
<tr>
<th>System</th>
<th>Pb–Pb</th>
<th>Pb–Pb</th>
<th>pp</th>
<th>pp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s_{NN}}$ [TeV]</td>
<td>Pb–Pb</td>
<td>Pb–Pb</td>
<td>pp</td>
<td>pp</td>
</tr>
<tr>
<td>$N_{\text{tot}}^{c\bar{c}}$, min.bias, 0–10% central</td>
<td>2.1</td>
<td>3.4</td>
<td>6.9</td>
<td>11.2</td>
</tr>
<tr>
<td>$\sigma_{c\bar{c}}$ [mb]</td>
<td>12, 50</td>
<td>19, 80</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>$N_{\text{tot}}^{b\bar{b}}$, min.bias, 0–10% central</td>
<td>0.08</td>
<td>0.14</td>
<td>0.23</td>
<td>0.50</td>
</tr>
<tr>
<td>$\sigma_{b\bar{b}}$ [mb]</td>
<td>0.5, 1.9</td>
<td>0.8, 3.3</td>
<td>0.003</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 2.2: Expected production yields (total and per unit of rapidity and mid-rapidity) for charm and beauty particles (+ anti-particles) in minimum-bias and 0–10% central Pb–Pb collisions at 5.5 TeV, mean proper decay length, branching ratios to the relevant decay channels [7], and typical acceptance. The acceptance factor is defined such that: $N_{\text{acc}} = \frac{dN}{dy}|_{y=0} \cdot \text{B.R.} \cdot \text{Acc.}$

| Part. | Yield m.b., 0–10% | $dN/dy|_{y=0}$ m.b., 0–10% | $c\tau$ [\mu m] | decay channel | B.R. | Acc. |
|-------|------------------|-------------------------|----------------|----------------|------|------|
| $D^0$ | 23, 110 | 2.3, 11 | $\approx 120$ | $K^- \pi^+$ | 3.8% | 1 |
| $\Lambda_c$ | 2.9, 14 | 0.29, 1.4 | $\approx 60$ | $pK^-\pi^+$ | 5.0% | 1 |
| $B^+$ | 1.3, 6.2 | 0.2, 0.9 | $\approx 500$ | $J/\psi(\rightarrow \phi K^+ K^-)$ | $1.2\% \times 6\%$ | 1 |
| $B^0$ | 0.6, 2.7 | 0.1, 0.4 | $\approx 500$ | $J/\psi(\rightarrow ee)K^+$ | 0.1% $\times 6\%$ | 1 |
| $B^0_s$ | 0.2, 0.9 | 0.03, 0.13 | $\approx 500$ | $J/\psi(\rightarrow ee)\phi(\rightarrow KK)$ | $0.14\% \cdot 6\% \cdot 50\%$ | 1 |
| $\Lambda_b$ | 0.1, 0.5 | 0.015, 0.07 | $\approx 400$ | $\Lambda_c(\rightarrow pK^-\pi^+ + e^-)$ | 9.9% $\times 5\%$ | 1 |

In table 2.2 we report, for central Pb–Pb at 5.5 TeV, the corresponding yields for the production of $D^0$, $\Lambda_c$, $B$ ($B^0 + B^+ + B_s^+$), and $\Lambda_b$ particles (+ their anti-particles), using the branching fractions for c and b quarks as given by the PYTHIA event generator [39]. The mean proper decay lengths ($c\tau$), the relevant final states and their branching ratios are reported as well, along with the typical acceptance (for a tracking acceptance of $|\eta| < 0.9$).

We consider the following running scenario for Pb–Pb, as a working hypothesis:

- instantaneous luminosity: $6 \times 10^{27}$ cm$^{-2}$s$^{-1}$, which (using $\sigma_{\text{hadronic}}^\text{PbPb} = 8$ b) gives a hadronic interaction rate of 50 kHz (5 kHz in the 0–10% centrality class);

- sustainable rate of readout to tape: 5 kHz (worst case considered in the “Upgrade Strategy for ALICE at High Rate” document [5]);

- sustainable rate for the inspection of events with rare trigger algorithms: no limitation, in line with the proposed global strategy for the central barrel detectors, according to which the data related to all Pb–Pb interactions will be transmitted to the online system and the event selection (software trigger) will be done on the basis of fully reconstructed events.

We use the information given in table 2.2, along with the expected reconstruction and selection efficiencies, to estimate the yields of reconstructed decays per event ($S/\text{ev}$), in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. We then compute the estimated statistics per nb$^{-1}$ of integrated luminosity ($S/\text{nb}^{-1}$). The target Pb–Pb integrated luminosity for the ALICE upgrade program is 10 nb$^{-1}$. 
Table 2.3: Estimated signal statistics with online trigger, for minimum-bias Pb–Pb collisions at a hadronic interaction rate of 50 kHz.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Eff</th>
<th>S/ev</th>
<th>S/B</th>
<th>B/ev</th>
<th>trigger rate (Hz)</th>
<th>S/nb(^{-1}) with trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^0)</td>
<td>0.02</td>
<td>1.6 \times 10^{-3}</td>
<td>0.03</td>
<td>0.16</td>
<td>8 \times 10^{-3}</td>
<td>1.3 \times 10^{-7}</td>
</tr>
<tr>
<td>(\Lambda_c)</td>
<td>0.01</td>
<td>1.4 \times 10^{-4}</td>
<td>5 \times 10^{-5}</td>
<td>8</td>
<td>5 \times 10^{-4}</td>
<td>1.1 \times 10^{-6}</td>
</tr>
<tr>
<td>(B \rightarrow D^0(\rightarrow K^-\pi^+))</td>
<td>0.01</td>
<td>0.8 \times 10^{-4}</td>
<td>0.001</td>
<td>0.25</td>
<td>1.2 \times 10^{-4}</td>
<td>0.6 \times 10^{-6}</td>
</tr>
<tr>
<td>(B \rightarrow J/\psi(\rightarrow e^+e^-))</td>
<td>0.1</td>
<td>1.3 \times 10^{-5}</td>
<td>0.01</td>
<td>4 \times 10^{-3}</td>
<td>4 \times 10^{-2}</td>
<td>0.6 \times 10^{-6}</td>
</tr>
<tr>
<td>(B^+ \rightarrow J/\psi K^+)</td>
<td>0.01</td>
<td>0.5 \times 10^{-7}</td>
<td>0.01</td>
<td>1.5 \times 10^{-5}</td>
<td>7.5 \times 10^{-1}</td>
<td>4 \times 10^{-2}</td>
</tr>
<tr>
<td>(b \rightarrow J/\psi\phi)</td>
<td>0.01</td>
<td>1.1 \times 10^{-8}</td>
<td>0.01</td>
<td>3.3 \times 10^{-6}</td>
<td>1.6 \times 10^{-1}</td>
<td>9 \times 10^{-4}</td>
</tr>
<tr>
<td>(\Lambda_b(\rightarrow \Lambda_c + e^-))</td>
<td>0.01</td>
<td>0.7 \times 10^{-6}</td>
<td>0.01</td>
<td>2.1 \times 10^{-4}</td>
<td>10</td>
<td>5 \times 10^{-3}</td>
</tr>
<tr>
<td>(\Lambda_b(\rightarrow \Lambda_c + h^-))</td>
<td>0.01</td>
<td>0.7 \times 10^{-5}</td>
<td>0.01</td>
<td>2.1 \times 10^{-3}</td>
<td>1 \times 10^{-2}</td>
<td>5 \times 10^{-4}</td>
</tr>
</tbody>
</table>

We assume a trigger efficiency \(\epsilon_{\text{trigger}} = 100\%\). The trigger purity is instead related to the signal-to-background ratio \(S/B\) because also all the background candidates that pass the selections will fire the trigger; in particular, we have:

\[
\text{purity} = S/B' = S/B \times 1/3,
\]

where \(B'\) is the background in the broad invariant mass range (e.g. \(\pm 9\sigma\)) that is necessary to fit the invariant mass distribution. Thus, \(S/B' = 1/3 \cdot S/B\), where \(S/B\) is the signal-to-background in \( \pm 3\sigma \) of the invariant mass distribution. The probability that a collision fires the trigger will be:

\[
\text{triggers/ev} = (S/ev) / \text{purity} = (S/ev) / (S/B').
\]

The trigger rate in minimum-bias collisions is:

\[
\text{rate} = (S/ev) / \text{purity} \times 50 \text{ kHz} = (S/ev) \cdot 3 \cdot (B/S) \times 50 \text{ kHz}.
\]

The signal collected in triggered events is, per \(\text{nb}\)^{-1} of integrated luminosity:

\[
S/\text{nb}^{-1} \text{ with trigger} = (S/ev) \times \sigma_{\text{ PbPb}}^{\text{hadronic}} [\text{nb}] = (S/ev) \times 8 \times 10^9.
\]

The results are reported in table 2.3 for minimum-bias collisions. For the case of the \(\Lambda_c\), also considering a minimum \(p_t\) threshold at 2 GeV/c, due to the small \(S/B\) ratio, the trigger rate would be very large (12 kHz). This indicates that the \(\Lambda_c\) production measurement is the main use-case for a more aggressive scenario, outlined in the “Upgrade Strategy for ALICE at High Rate” document [5], in which reduced event information is written to tape at a rate of up to 25 kHz. In any case, the selection strategy used for the simulation studies reported in the following should be further optimized in order to achieve a higher \(S/B\) ratio.

In the near future these estimates will be repeated as a function of the trigger efficiency and of a minimum \(p_t\) threshold (\(p_t^{\text{min}}\)) for the trigger particle. For the moment, we present in figure 2.12, as an example, the \(D^0\) \(p_t^{\text{min}}\)-dependent (0 \(\leq p_t^{\text{min}} \leq 8\) GeV/c) figures for Pb–Pb collisions at a hadronic interaction rate of 50 kHz: the signal per triggered event (top-left), the trigger purity (top-centre), the fraction of triggered events (top-right), the trigger rate (bottom-left), and the signal per \(\text{nb}^{-1}\) in triggered events (bottom-right). The estimation was performed using the selection efficiency and the \(S/B\) resulting from the ITS-upgrade simulation study (see section 2.2.3). The amount of signal produced per Pb–Pb collision, for \(p_t^{\text{min}} \geq 2\) GeV/c, was computed based on the measured production yields in Pb–Pb data from 2010 (0–20% centrality class), applying a scaling factor \(\approx 0.3\) from the Glauber model to go to minimum bias collisions and a \(p_t\)-dependent scaling factor \(\approx 1.5–2.5\) from NLO pQCD to go from \(\sqrt{s_{\text{NN}}} = 2.76\) to 5.5 TeV. For \(p_t^{\text{min}} = 0\), the numbers correspond to those in table 2.3.
Figure 2.12: $D^0$ signal/event (top-left), trigger purity (top-centre), fraction of triggered events (top-right), trigger rate (bottom-left), and signal per nb^{-1} (bottom-right), as a function of $p_t^{\text{min}}$, in minimum-bias Pb–Pb collisions at a hadronic interaction rate of 50 kHz.

### 2.2.2 Simulation method

In order to quantify the possible improvement of an upgrade of the ITS, a fast simulation scheme is employed. It is based on existing Monte Carlo productions including the detailed geometry and response of the current ALICE detector setup. The impact of the new ITS is obtained by recomputing reconstructed track parameters according to the $p_t$ and particle species dependent scaling laws as obtained by the Fast Estimation Tool described in chapter 3. This is done by rescaling the difference to Monte Carlo, keeping any kind of intrinsic correlation of the parameters. The ALICE reference frame has the $z$ axis in the beam direction, the $x$ axis pointing to the centre of the LHC ring, and the $y$ axis pointing upward. In the rotated ALICE reference frame, where the $x$ coordinate is parallel to the track momentum near the origin, the improvement reads as follows:

$$
\begin{bmatrix}
  y \\
  z \\
  \sin \phi \\
  \tan \theta \\
  1/p_t
\end{bmatrix}' =
\begin{bmatrix}
  y_{\text{MC}} + \sigma_{d_{0z,\text{upgrade}}}^{\text{upgrade}}(p_t)/\sigma_{d_{0z,\text{current}}}(p_t) \cdot (y - y_{\text{MC}}) \\
  z_{\text{MC}} + \sigma_{d_{0z,\text{upgrade}}}^{\text{upgrade}}(p_t)/\sigma_{d_{0z,\text{current}}}(p_t) \cdot (z - z_{\text{MC}}) \\
  \sin \phi \\
  \tan \theta \\
  (1/p_t)_{\text{MC}} + \sigma_{1/p_t,\text{upgrade}}^{\text{upgrade}}(p_t)/\sigma_{1/p_t,\text{current}}(p_t) \cdot ((1/p_t) - (1/p_t)_{\text{MC}})
\end{bmatrix}
$$

(2.1)

Thus, it is a simple scaling of the residuals of the impact parameters in $r\phi$ and $z$, as well as of the
transverse momentum, with respect to their true values (MC), known from the generated particle kinematics. The scaling factors are the ratios of the upgrade/current resolutions on these variables. The track polar angle \( \theta \) remains unchanged and the inclination \( \phi \) is zero by the choice of the coordinate frame. This approach is called Hybrid, because it applies the detector performance of the upgraded ITS to full simulations of the current ITS. The corresponding analysis flow is shown in figure 2.13. A drawback of this approach is that it does not allow to study the effect of an extended pseudo-rapidity acceptance, a possibility that is actually being considered for the design of the upgraded ITS, to reach for example a coverage \( |\eta| < 1.5 \) or even larger, using end-caps. The impact of this extension on the physics performance is not assessed here, but it will be addressed in the near future with dedicated simulation studies.

For our performance studies we have considered as a baseline the configuration for the upgraded ITS that is described in chapter 3: 7 layers with radii of (2.2, 2.8, 3.6, 20.0, 22.0, 41.0, 43.0) cm, instrumented by pixel detectors with intrinsic resolution \((\sigma_\phi, \sigma_z) = (4, 4)\ \mu m\), and with a thickness of 0.3% radiation length \(X_0\) per layer. Figure 2.14 shows the corresponding charged pions impact parameter resolutions as a function of transverse momentum for the upgraded ITS compared to those of the current ITS. The scaling factors of the Hybrid approach are the ratios of these two resolutions. As an example, the resolutions on the reconstructed position of the \(D^0 \rightarrow K^-\pi^+\) decay vertex are shown in figure 2.15. Performance studies based on this approach will follow in the next sections, for \(D^0 \rightarrow K^-\pi^+\), \(\Lambda_c \rightarrow pK^-\pi^+\), \(B \rightarrow J/\psi(\rightarrow e^+e^-) + X\), and \(B \rightarrow e + X\).

### 2.2.3 \(D^0\) meson reconstruction as a benchmark for detector performance

As described in the first part of this chapter, the \(D\) meson \(R_{AA}\) was measured in Pb–Pb collisions at \(\sqrt{s_{NN}} = 2.76\ \text{TeV}\) via the reconstruction of the \(D^0 \rightarrow K^-\pi^+\) (BR=3.89%, \(c\tau \approx 123\ \mu m\)), \(D^{*+} \rightarrow K^-\pi^+\pi^+\) (via \(D^{*+} \rightarrow D^0\pi^+\), strong decay, BR=67.7%), and \(D^+ \rightarrow K^-\pi^+\pi^+\) (BR=9.4%, \(c\tau \approx 312\ \mu m\)) decay channels (see [7] for the decay properties quoted). All analyses are based on the reconstruction and selection of secondary vertex topologies with a few hundreds of microns separation from the primary vertex. Displaced tracks are selected and good alignment between the \(D\) meson momentum and the flight-line connecting the primary and decay vertex is required (i.e. small pointing angle, see the sketch of the \(D^0\) decay in figure 2.16). As shown in figure 2.16, due to the relativistic boost, the pion and kaon tracks have an intrinsic impact parameter in the transverse plane typically of the order of the \(D^0\) c\(\tau\) for sufficiently high \(D^0\) transverse momentum, thus they can be identified as displaced tracks if the track resolution in the vicinity of the vertex is of the order of tens of microns. The \(D^0 \rightarrow K^-\pi^+\) decay channel was reconstructed in Pb–Pb collisions in the transverse momentum range, \(2 < p_t < 12\ \text{GeV}/c\), and yielded the most precise \(R_{AA}\) measurement, with a statistical error of the order of 25% in the centrality range 0–20%. The possibility to have a direct reference of the performance on real data allows for a more realistic study of the benefits that would come from an upgrade of the ITS. Therefore, the \(D^0\) case can be considered as a benchmark for all the \(D\) meson analyses.

Here we present a comparison of the performance achievable in Pb–Pb collisions with the current and upgraded ITS configurations, considering the centrality class 0–20%, which is the same that was used for the first \(R_{AA}\) measurement. The Hybrid approach described in the previous section was applied to a

![Figure 2.13: Scheme of the Hybrid simulation approach for the ITS upgrade studies.](image)
**Figure 2.14:** Track impact parameter resolution in $r\phi$ and $z$ (current and upgrade).

**Figure 2.15:** $D^0 \rightarrow K^- \pi^+$ secondary vertex position resolutions for current and upgrade scenarios: $x$ (left) and $z$ (right) coordinates.

**Figure 2.16:** Schematic view of the $D^0$ decay in the $D^0 \rightarrow K^- \pi^+$ channel.
Monte Carlo simulation sample produced with the HIJING 1.36 event generator [40] and with additional heavy flavour particles added to each event using the PYTHIA 6.4.21 generator [39]. The HIJING generator yields a charged particle multiplicity in central collisions similar to the one measured at the LHC. The response of the full ALICE detector was included via the GEANT3 transport package and a detailed description of the geometry of the apparatus. The precision on the measurement of $D^0$ production performed with 2010 Pb–Pb data was taken as a reference: in the 0–20% centrality class the statistical significance was of the order of 8–10 in the $2 < p_t < 12$ GeV/$c$ interval and the statistical uncertainty (which approximately corresponds to the inverse of the statistical significance) was at the level of 10–15%. The simulation study was performed using the same cut values for the two ITS configurations, in order to single out the effect of the improved tracking resolutions. The cuts were fixed to values close to those used for the 2010 Pb–Pb data analysis\(^1\). The selected signal (raw) yield was obtained by multiplying the corrected $D^0$ $p_t$ spectrum, $dN/dp_t$ measured with the 2010 data, by the efficiency calculated from the simulation for the current or upgraded ITS configuration. The selected background yield in the $D^0$ mass region was scaled in the simulation so as to match, for the current ITS case, the value measured in the data. The same background scaling factor was then used also for the upgraded ITS case.

The main cut variables used to extract the $D^0$ signal are the product of decay track impact parameters, the cosine of the pointing angle, and the decay length. For the background, composed mainly of pairs of primary tracks, the distribution of the product of decay track impact parameters ($d_0^b \times d_0^b$) is symmetric and peaks at 0, the width being determined by the detector impact parameter resolution. For the $D$ meson signal, the distribution is asymmetric because the displacement of the secondary vertex induces a large tail at negative values of the product. The cosine of the pointing angle is peaked towards 1 for signal candidates, while it has a flatter distribution for the background. The decay length distribution of reconstructed $D^0$ meson is the convolution of the true decay length distribution and a resolution term, which characterizes the background distribution. The narrower the background distribution is, the better the signal and background shapes can be distinguished.

An improved detector resolution would provide a better separation between signal and background, thus the possibility to reject more background and use less stringent cuts in order to keep more signal, increasing the selection efficiency. Generally, this also allows one to reduce the systematic uncertainties arising from a not fully precise description of the detector properties (including alignment) and performance (e.g. vertex and track reconstruction precision). A comparison of the $d_0^b \times d_0^b$ distributions for background and signal is shown for $1 < p_t < 2$ GeV/$c$ and $4 < p_t < 5$ GeV/$c$ in figure 2.17 for the current and upgraded ITS configurations, in the upper and lower panels, respectively. The signal–background separation clearly improves in the ITS upgrade case.

The comparison of the cut efficiencies in the current and upgrade scenarios, reported\(^2\) in figure 2.18, shows that almost the same signal is selected in the two cases for $p_t > 2$ GeV/$c$. Conversely, the background rejection improves by a factor of 6 for $p_t > 2$ GeV/$c$. As shown in figure 2.19, this determines a large increase of the signal-to-background ratio (factor of 6) and of the statistical significance (factor of 2–3), here scaled by the square root of the sample size.

As an example, figure 2.20 (top) shows the comparison of the invariant mass distributions obtained in the current and upgraded ITS scenarios for $2 < p_t < 4$ GeV/$c$ from the heavy-flavour enriched MC simulation described above. Very importantly, in the range $0 < p_t < 2$ GeV/$c$ (bottom panel of the same figure) the background rejection improves by a factor of 25 allowing the extraction of a clear $D^0$ signal (with significance of about 9) that is not observed with the current ITS configuration. The production of $D$ mesons in central Pb–Pb collisions has never been measured in this $p_t$ range. Thus,

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\(^1\)Further improvement, in the upgrade case, can arise from a dedicated optimization of the cut values or from the introduction of additional cuts. This point is briefly discussed at the end of the section.

\(^2\)The figure shows also the efficiency for secondary $D^0$ from $B$ decays, which is relevant for the discussion in section 2.2.5.1.
Figure 2.17: $D^0 \rightarrow K^- \pi^+$: products of the decay tracks impact parameters for background and signal candidates for the current ITS configuration, in two different $p_t$ ranges. Upper panels: current ITS. Lower panels: Upgraded ITS.

Figure 2.18: $D^0 \rightarrow K^- \pi^+$: reconstruction and selection efficiency for prompt $D^0$ and $D^0$ coming from $B$ decays, in the current ITS and upgrade ITS cases. The same selection cuts are used for the two scenarios.
**Figure 2.19:** $D^0 \rightarrow K^- \pi^+$: comparison of the signal-to-background ratio (left) and significance per event (right) obtained for the current and upgraded ITS. A different procedure was used to estimate the expected signal and background for $p_t < 2$ GeV/$c$ and for $p_t > 2$ GeV/$c$ (see text for details).

**Figure 2.20:** $D^0 \rightarrow K^- \pi^+$. Top: comparison between the invariant mass distributions of $D^0$ candidates with $2 < p_t < 4$ GeV/$c$ obtained from the analysis of $\sim 3 \times 10^4$ central (0–20%) Pb–Pb events at $\sqrt{s_{NN}} = 2.76$ TeV (HIJING events enriched with charm signals) with the current and upgrade scenarios. Bottom: invariant mass distribution in $0 < p_t < 2$ GeV/$c$ obtained from the analysis of $\sim 1.5 \times 10^5$ central (0–20%) Pb–Pb events at $\sqrt{s_{NN}} = 2.76$ TeV (same as above) with the upgrade scenario.
some hypotheses on the expected signal and background levels were made. The spread obtained for the signal-to-background ratio and for the significance are displayed by the boxes in figure 2.19 (the markers represent the values obtained with $R_{AA}^{D^0} = 0.5$ and a global background scaling factor of 8.5 and $k = 0.7$, see footnote). Although the large uncertainty prevents firm conclusions, in most of the considered scenarios the expected performance allows for the measurement of the $D^0$ production down to $p_t \approx 0$ with a significance larger than 5, even considering only few $10^7$ central events (which correspond to the sample collected in the 2011 Pb–Pb run).

In order to quantify the expected significance for a new measurement with the upgraded ITS, we consider an integrated luminosity of $10 \text{ nb}^{-1}$, which would lead to $1.7 \times 10^{10}$ central events (0–20%). However, we consider a sample of $10^8$ events, because the trigger rate for $D^0$ selection is larger than 5 kHz (see table 2.3 on page 26), therefore this trigger should be somehow downscaled, possibly as a function of $p_t$. In these conditions, the $D^0$ significance is larger than one hundred at any $p_t$. For comparison, the significance in the 2010 run with the present setup, corresponding to $3 \times 10^8$ central events, is 8–10 for $p_t > 2 \text{ GeV}/c$ and negligible for $p_t < 2 \text{ GeV}/c$. At very low $p_t$, even considering the uncertainties in the nuclear modification factor and background which enter in the estimation of the significance, the measurement will be quite precise.

As discussed in the first part of this chapter, the measurement of charm production down to zero transverse momentum in heavy-ion collisions is of crucial importance for the testing the QCD-predicted colour-charge and mass dependencies of parton energy loss ($R_{AA}$ measurement), for assessing the degree of thermalization of charm quarks in the medium (flow measurement), and for disentangling the role of initial state effects (p–Pb studies).

For the comparison presented above, the same selection was applied in the simulation for both the current and upgrade scenarios. However, the better separation between signal and background in the upgrade case allows one to vary the values of the cuts in order to further increase: a) the statistical significance, thus reducing the statistical uncertainty; b) the signal-to-background ratio, enhancing the signal purity and the capability of “tagging” $D^0$ mesons, e.g. for correlation studies; c) the signal amount, thus the efficiency, providing a better control of the systematic uncertainties. Furthermore, the large improvement in the $z$ resolution will allow the exploitation of new variables to effectively reject the background. These studies will be carried out in detail in the near future.

2.2.4 Charm baryons: $Λ_c \to pK^-\pi^+$ as a benchmark case

The physics motivation for the measurement of charm baryon production was discussed in the first part of this chapter. The most promising measurement is the decay of the $Λ_c^+$ into three charged prongs ($p$, $K^-$, $\pi^+$) with the current ITS. Due to the extrapolation uncertainty this factor was varied between 7 and 10. Background pairs are composed mainly of primary pions. Therefore the background amount is sensitive to the pion nuclear modification factor, roughly as $B \propto (R_{AA}^{p})^2$. To account for the unknown $p_t$ dependence of the pion $R_{AA}^{p}$ for $p_t < 2 \text{ GeV}/c$ and for a possible discrepancy between the pion suppression in data and MC the scaled background was further varied by a factor $k = 0.5–1.7$.

### Footnote

In order to get a more realistic estimate of the achievable performance, the signal was estimated via a binary scaling of the FONLL prediction of $D^0$ meson production in pp collisions at 2.76 TeV [41] and using a range of hypotheses on its nuclear modification in Pb–Pb due to initial state and medium effects:

$$S = R_{AA}^{D^0} \times 2 \times \frac{d\sigma^{\text{FONLL}}}{dp_t} \times \Delta p_t \times \epsilon \times \langle T_{AA} \rangle \times N_{ev}. \quad (2.2)$$

In this formula $(T_{AA})$ is the average nuclear overlap function calculated via the Glauber model for the centrality range $0–20\%$. The nuclear modification factor, $R_{AA}^{D^0}$, was varied between 0.3 and 1 to account for both possible energy loss and nuclear shadowing effects. The factor 2 accounts for the fact that both particles and anti-particles are reconstructed, while the theoretical prediction refers to the particle only. The values shown in figure 2.18 for prompt $D^0$ mesons were used for the acceptance times efficiency factor, $\epsilon$. The signal $S$ was evaluated separately in the $p_t$ ranges (of width $\Delta p_t$) $0 < p_t < 0.5$, $0.5 < p_t < 1$, $1 < p_t < 2 \text{ GeV}/c$, and then summed. The background obtained from the heavy-flavour enriched MC simulation with the Hybrid method was scaled up by a factor 7–10. This was estimated by extrapolating to the range $0 < p_t < 2 \text{ GeV}/c$ the ratio of the background in data to that in the MC calculated for $p_t > 2 \text{ GeV}/c$ with the current ITS. Due to the extrapolation uncertainty this factor was varied between 7 and 10. Background pairs are composed mainly of primary pions. Therefore the background amount is sensitive to the pion nuclear modification factor, roughly as $B \propto (R_{AA}^{p})^2$. To account for the unknown $p_t$ dependence of the pion $R_{AA}^{p}$ for $p_t < 2 \text{ GeV}/c$ and for a possible discrepancy between the pion suppression in data and MC the scaled background was further varied by a factor $k = 0.5–1.7$. 
The total factor is simply the ratio of the sample sizes for the data and the simulation to match the features observed in data, as explained in the following. For the background, the scaling PYTHIA generator (with the Perugia-0 tune) by rescaling the signal and background yields, in order event statistics. This is obtained with the Hybrid approach and the upgraded configuration of the ITS. To discriminate the \( \Lambda_c \) signal against the background, which is made mostly of primary particles, a study of the cuts on kinematical and topological variables was carried out. The analysis cuts optimized to extract the signal in pp collision data at \( \sqrt{s} = 7 \) TeV were used as a starting point. However, these are not fully adequate for taking advantage of the ITS upgrade potential, because the increased impact parameter resolution provided by the new detector allows a better discrimination of the signal against the background, hence less stringent cuts allow one to still reject effectively the background but minimize the loss of the signal.

The optimization of the cuts with the ITS Upgrade layout has been performed by studying the distribution of the kinematical variables used to reject the background against the signal. A comparison has been done between the amount of signal and background rejected with the current analysis cuts and with the new ones: the new cuts represent a compromise between the maximization of the significance and the minimization of the signal loss.

The most effective cut variables are:

- The cosine of the pointing angle (\( \theta_p \)): the angle formed by the vector connecting the primary to the secondary vertex and the momentum of the \( \Lambda_c \), obtained as the sum of the momenta of its three decay tracks at the secondary vertex. The cut \( \cos \theta_p > 0.75 \) allows one to reduce significantly the background while only rejecting a very small amount of signal. In the current analysis with the present detector this cut is \( \cos \theta_p > 0 \).

- The \( \Lambda_c \) decay length (\( L \)): the distance between the primary and the secondary vertex. The current analysis uses \( L > 70 \) \( \mu m \); a further background rejection with the upgraded ITS is achievable by imposing \( L > 80 \) \( \mu m \) in pp and a tighter \( p_t \)-dependent cut in Pb–Pb (e.g. \( L > 200 \) \( \mu m \) at \( p_t = 4 \) GeV/c).

- The minimum \( p_t \) of the three decay tracks. This selection enables a very strong reduction of the combinatorial background in the low-\( p_t \) region. Also in this case, the cut value depends on \( \Lambda_c \) transverse momentum.

**Results for pp collisions.** In figure 2.21 (left) we show the invariant mass distribution of \( \Lambda_c \to pK^-\pi^+ \) candidates with \( p_t > 3 \) GeV/c, obtained from a data sample of \( 1.9 \times 10^8 \) proton–proton events, collected with the ALICE minimum bias trigger, at \( \sqrt{s} = 7 \) TeV (using the present ITS). The \( \Lambda_c \) is visible, however the significance is low, due to the limited efficiency for background rejection. In the right-hand panel of the same figure, we show the distribution as it is expected for the ITS upgrade case for the same event statistics. This is obtained with the Hybrid approach on a sample of pp events produced with the PYTHIA generator (with the Perugia-0 tune) by rescaling the signal and background yields, in order to match the features observed in data, as explained in the following. For the background, the scaling factor is simply the ratio of the sample sizes for the data and the simulation \( N_{data}/N_{MC} \) (1.9 \( \times 10^8 \)/1.3 \( \times 10^8 \)). For the signal, in addition to this factor, a 10% correction was included in order to equalize the total \( c\bar{c} \) cross section yielded by PYTHIA Perugia-0 to the one measured in ALICE, \( \sigma_{pp} = 7.73 \pm 0.54 \) \text{mb}. For the ITS upgrade scenario we obtain for \( \Lambda_c \) baryons with \( p_t > 3 \) GeV/c a significance of about 12, to be compared to the current value from data of
Significance (3 σ) 5 ± 1.2
S (3σ) 292 ± 69
B (3σ) 3002 ± 19

The signal-to-background ratio is more than a factor of 5.

Results for Pb–Pb collisions. The \( \Lambda_c \) signal could not be observed with the 2010 Pb–Pb data sample, because of the very large combinatorial background. Therefore, we do not have a baseline selection, nor a direct comparison with data. We have studied the selection strategy using a dedicated simulation sample of about 10 \(^4\) central (0–10\%) Pb–Pb events at \( \sqrt{s_{NN}} = 5.5\) TeV produced with the HIJING event generator. In each event, 20 \( \Lambda_c \rightarrow pK^-\pi^+ \) decays were added, in order to obtain a high-statistics signal sample allowing for the study of the selection cuts. The signal per event was then rescaled to the expected \( dN/dy = 1.4\) (see table 2.2 on page 25) and also the branching ratio (5\%) normalization was accounted for. A \( p_t \)-dependent weight was applied to each signal particle such that the shape of the \( p_t \) distribution of the simulated \( \Lambda_c \) matches the prediction of the FONLL pQCD calculation for \( D \) mesons at \( \sqrt{s} = 5.5\) TeV [41]. In this Monte Carlo sample the current ITS detector layout was simulated (without any inactive module, at variance with the simulations used for example for the \( D^0 \) study) and the effect of the ITS upgrade on the tracking precision was included a posteriori using the Hybrid approach.

Three different upgrade configurations were tested: the baseline configuration (same as used for the \( D^0 \) studies), and two other cases that represent variations of the layer thickness only (with respect to the baseline), for the innermost two layers to 0.1\% of radiation length and for all layers to 0.5\% of radiation length, respectively. A cut optimization study was carried out with the aim of maximizing the signal significance. It was found that the two most effective cuts for the ITS upgrade scenario are the \( \Lambda_c \) decay length and the minimum \( p_t \) of the decay tracks. The results, in terms of \( S/B \) ratio and significance per event, are reported in figure 2.22 as a function of \( p_t \). The signal-to-background improves by a factor 400 (in \( 2 < p_t < 4\) GeV/c) from current to ITS upgrade, while the significance improves by a factor 5–10 in all \( p_t \) intervals above 2 GeV/c. Considering an integrated luminosity of 10 \( \text{nb}^{-1} \), this would lead to \( 1.7 \times 10^{10} \) central events (using the centrality class 0–20\%). For this event sample, the significance is \( 1.3 \times 10^8 \) times the values reported in the figure, that is: 7 in 2–4 GeV/c, 40 in 4–6 GeV/c, 53 in 6–8 GeV/c. The signal-over-background ratio is expected to be very small (\( \sim 10^{-4} \)) in 2–4 GeV/c). However, the background level in the \( \Lambda_c \) mass region can be determined precisely using the information from the invariant mass side-bands, as well as the like-sign and event-mixing techniques, which are currently under study. Therefore, we conclude that the \( \Lambda_c \) production should be measurable down to a transverse momentum of 2 GeV/c in central collisions.

Figure 2.21: \( \Lambda_c \rightarrow pK^-\pi^+ \) candidates invariant mass distribution for \( p_t > 3\) GeV/c in pp collisions at 7 TeV (\( 1.9 \times 10^8 \) events). Left: pp collision data. Right: Hybrid simulation with the ITS upgrade configuration. The sample statistics in the simulation is the same as in the data, while the selection cuts were optimized specifically for the upgrade scenario.

About 5. The increase of the signal statistics is about 50\% (less stringent cuts are used for the upgrade case) and the increase of the signal-to-background ratio is more than a factor of 5.
Figure 2.22: $\Lambda_c \rightarrow p K^- \pi^+$ in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV: signal-to-background ratio (upper panel) and significance per event (lower panel) for current and upgraded ITS. For the upgrade, three different scenarios are considered: the baseline configuration is labeled “0.3%”; the cases labeled “0.1%” and “0.5%” represent variations of the layer thickness only (with respect to the baseline configuration), for the innermost two layers to 0.1% of radiation length and for all layers to 0.5% of radiation length, respectively.

Figure 2.23: Estimated statistical uncertainties on the measurement of the $\Lambda_c / D^0$ ratio using $1.7 \times 10^{10}$ central Pb–Pb collisions (0–20%), corresponding to an integrated luminosity of 10 nb$^{-1}$. The points are drawn on a line that captures the trend and magnitude of the $\Lambda / K^0_S$ ratio (see figure 2.3).

The performance in non-central collisions was estimated by scaling the signal and background yields with centrality and evaluating the signal-over-background ratio and the significance. The $\Lambda_c$ signal $S$ was scaled according the number of binary nucleon–nucleon collisions $N_{\text{coll}}$, using a constant scaling factor for all transverse momentum intervals $S_P = S_C \cdot (N_{\text{coll}}^P / N_{\text{coll}}^C)$, where $C$ and $P$ stand for central and peripheral collisions, respectively, $S_C$ being the signal resulting from the simulation study. The three-track combinatorial background was scaled according to $B_P = B_C \cdot (N_{\text{coll}}^P / N_{\text{coll}}^C)^3 / (R_{\text{charged}}^C)^3$, where $R_{\text{charged}}^C$ is the central-to-peripheral nuclear modification factor of charged hadrons. In principle, we should consider, for each background candidate, the $p_t$-dependent nuclear modification factors of the three decay particles, and use their product as a weight for that candidate. We use, instead, the aforementioned scaling with an $R_{\text{CP}}$ value constant with $p_t$ and conservatively chosen as the minimum value of the measured $R_{\text{CP}}(p_t)$ for charged hadrons. This minimum is close to the value of $R_{\text{CP}}$ for $p_t \rightarrow 0$. Therefore, this
collisions. This will allow for an accurate determination of the width of the torus for $10 \text{ nb}$.

Most of the $B$ meson production via displaced $D^0$ via meson decay channels include a $D^0(\bar{D}^0)^4$. According to the FONLL perturbative QCD calculations [41], in pp collisions at $\sqrt{s} = 7 \text{ TeV}$, the ratio of $D^0$ from $B$ decay and prompt $D^0$ increases with transverse momentum, from $\approx 5\%$ at $p_t \approx 1 \text{ GeV/c}$ to $\approx 20\%$ at $p_t \approx 20 \text{ GeV/c}$. As illustrated in figure 2.25, the kaon and pion tracks coming from secondary $D^0$ decays are, on average, more displaced from the primary vertex than those coming from the decay of a prompt $D^0$, due to the relatively long lifetime of $B$ mesons ($\tau \approx 460\text{–}490 \mu\text{m}$ [7]). Therefore, the selection applied on reconstructed $D^0$ candidates, optimized to prefer secondary vertices displaced from the primary vertex, further enhances the secondary-to-prompt ratio of reconstructed $D^0$ up to typical values around $10\%$ even for $p_t < 5 \text{ GeV/c}$.

The ALICE measurement of prompt $D$ meson production used FONLL prediction of beauty production

$\Lambda_c \rightarrow pK^-\pi^+$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5 \text{ TeV}$: signal-to-background ratio (left panel) and significance per event (right panel) for upgraded ITS with the baseline configuration with $0.3\%$ $x/X_0$ layer thickness. The results from the simulation for $0$–$5\%$ central collisions are scaled to minimum bias, semi-peripheral ($40$–$50\%$) and peripheral ($70$–$80\%$) collisions.

Figure 2.24 shows the significance and signal-over-background in three centrality classes ($0$–$5\%$, $40$–$50\%$, $70$–$80\%$) and in minimum-bias collisions (in this case the background was scaled using $\langle (dN_{ch}/d\eta)^3 \rangle$ instead of $\langle dN_{ch}/d\eta \rangle^3$). The performance in peripheral collisions is better, in terms of significance, by about a factor of 2 with respect to central collisions, with a significance of $20$ in $2 < p_t < 4 \text{ GeV/c}$ for $1.7 \times 10^{10}$ events (in a centrality class like $70$–$90\%$ or $60$–$80\%$, for an integrated luminosity of $10 \text{ nb}^{-1}$). This would allow for the measurement of the central-to-peripheral nuclear modification factor for $p_t > 2 \text{ GeV/c}$. In addition, the signal-to-background ratio becomes quite large in peripheral collisions. This will allow for an accurate determination of the width of the $\Lambda_c$ invariant mass signal, which can then be used as a constraint for the signal extraction in central collisions, where the signal-to-background ratio is very low. In semi-central Pb–Pb collisions (40–50% in figure 2.24), the significance is the same as in central collisions. With an integrated luminosity of $10 \text{ nb}^{-1}$, a measurement of the $\Lambda_c$ elliptic flow can be performed for $p_t > 4 \text{ GeV/c}$ in semi-central collisions (e.g. 30–50%) and for $p_t > 2 \text{ GeV/c}$ in peripheral collisions (e.g. 60–80%).

2.2.5 Prospects for $B$ mesons at central rapidity

2.2.5.1 $B$ meson production via displaced $D^0$

Most of the $B$ meson decay channels include a $D^0(\bar{D}^0)^4$. According to the FONLL perturbative QCD calculations [41], in pp collisions at $\sqrt{s} = 7 \text{ TeV}$, the ratio of $D^0$ from $B$ decay and prompt $D^0$ increases with transverse momentum, from $\approx 5\%$ at $p_t \approx 1 \text{ GeV/c}$ to $\approx 20\%$ at $p_t \approx 20 \text{ GeV/c}$. As illustrated in figure 2.25, the kaon and pion tracks coming from secondary $D^0$ decays are, on average, more displaced from the primary vertex than those coming from the decay of a prompt $D^0$, due to the relatively long lifetime of $B$ mesons ($\tau \approx 460\text{–}490 \mu\text{m}$ [7]). Therefore, the selection applied on reconstructed $D^0$ candidates, optimized to prefer secondary vertices displaced from the primary vertex, further enhances the secondary-to-prompt ratio of reconstructed $D^0$ up to typical values around $10\%$ even for $p_t < 5 \text{ GeV/c}$.

The ALICE measurement of prompt $D$ meson production used FONLL prediction of beauty production $^{4}\text{BR}(b_{\text{hadr}} \rightarrow D^0 + X) = 61.0 \pm 3.1\%$, for $B^\pm /B^0 /B^0 /b$ – baryon admixture [7].
to subtract the contribution of secondary $D$. The uncertainty of this contribution, evaluated by considering the spread of the predictions obtained by varying the parameters entering the theoretical calculation, ranges between 10% and 30% depending on $p_t$. In the measurement of the $D$ meson nuclear modification factors, the above uncertainty partially cancels in the ratio of Pb–Pb and pp spectra. However, the unknown $B$ meson $R_{AA}$ yields a further and relevant uncertainty (up to 25%) on the $D$ meson $R_{AA}$ [36].

A direct measurement of the fraction of prompt $D$ mesons would:

- avoid the usage of theoretical predictions and assumptions on beauty production and nuclear modification factor in the charm production measurements in pp and Pb–Pb;

- create the possibility to perform an inclusive measurement of the $B$ meson production and nuclear modification factor, via the $p_t$ spectra of $D$ mesons from $B$ decays.

The fraction of prompt $D^0$ mesons can be measured by exploiting the different shapes of the impact parameter distributions of primary and secondary mesons. This approach has been used already in pp (or p$ar{p}$) collisions by the CDF Collaboration [42] to measure the production of prompt $D$ mesons at $\sqrt{s} = 1.96$ TeV (p$ar{p}$) and by the LHCb Collaboration [43] to measure the production of $B$ mesons at $\sqrt{s} = 7$ TeV at forward rapidity. The limited statistics available for the ALICE measurements of $D$ meson production only allowed this approach to be used as a cross-check of the theory driven methods mentioned above. In this section the different factors that determine the performance of this method are discussed, in relation to the improvements achievable with the ITS upgrade.

The main factors determining the performance achievable with this method are the available statistics, the uncertainty deriving from the subtraction of the background impact parameter distribution, and the resolution of the $D$ meson impact parameter, which is directly related to the resolution of the track position in the vicinity of the primary vertex.

The Hybrid simulation approach was used to study the effect of the improved track position and $p_t$ resolutions for the ITS upgrade configuration. Figure 2.26 (left panel) shows the impact parameter distribution for prompt and secondary $D^0$ in $2 < p_t < 3$ GeV/$c$ as obtained from a heavy-flavour enriched MC simulation of pp collisions at $\sqrt{s} = 7$ TeV produced with the PYTHIA generator. For example, the probability to assign a 100 $\mu$m impact parameter to a prompt $D^0$ decreases by a factor of more than
3 in the upgraded ITS case, with respect to the current ITS case. The detector resolution function can be modeled with a Gaussian term plus exponential tails. In figure 2.26, right panel, the $\sigma_D$ parameter (Gaussian width), obtained by fitting the prompt $D^0$ impact parameter distribution with this functional form, is reported as a function of transverse momentum for the current and upgraded ITS scenarios. An improvement by a factor of around 2 is obtained in the latter case.

The side bands of the invariant mass distribution are used to model the impact parameter distribution of the background that is subtracted from the impact parameter distribution of $D^0$ candidates in the mass peak region. The uncertainties in the background shape, due to statistical fluctuations in the distribution, and on the amount of background, estimated from the fit to the invariant mass distribution, affect the performance of the fit. The large reduction of the background expected in the ITS upgrade scenario (section 2.2.3) should strongly reduce the impact of background subtraction uncertainties on the achievable performance.

A first estimation of the performance for the measurement of beauty production in central Pb–Pb collisions using the fraction of non-prompt $D^0$ mesons was carried out, starting from the simulation results on the impact parameter resolution (see figure 2.26), the $D^0$ $S/B$ ratio, and the expected $D^0$ signal statistics (section 2.2.3). For the last, we have considered a sample of $10^8$ events in the centrality class 0–20%. An additional input parameter of the study is the value of the fraction of non-prompt $D$ mesons, which we have taken as 0.15, independent of $p_t$. The relative statistical uncertainty on the fraction of $D^0$ mesons from $B$ decays is shown in figure 2.27 (left). Since the statistical uncertainty on the measurement of the total $D^0$ yields is expected to be of the order of 1%, the values shown in the figure coincide in practice with the relative statistical uncertainty on the measurement of beauty production. The results are very promising, with a statistical uncertainty of the order of 10% down to $D^0$ $p_t$ of 2 GeV/$c$. We note that this gives access to $B$ mesons with $p_t$ down to 0. As an example of the expected physics performance, we show in figure 2.27 (right) the corresponding estimated statistical uncertainties for the measurement of the heavy-to-light ratio $R_{AA}^{D_{from b}}/R_{AA}^{D_{from c}}$. Here, the following assumptions were made: a) the statistical uncertainty of $R_{AA}^{D_{from c}}$ is negligible with respect to that of $R_{AA}^{D_{from b}}$; b) the statistical uncertainty of

Figure 2.26: $D^0$ from $B$ decays. Left: comparison of the impact parameter distributions for prompt and secondary $D^0$ obtained with the current and upgrade ITS configurations in the transverse momentum range $2 < p_t < 3$ GeV/$c$. Right: sigma of the Gaussian term of the detector resolution function, representing the $D^0$ impact parameter resolution, for current and upgrade ITS scenarios.
Figure 2.28 shows the current ALICE performance for the measurement of the non-prompt $D^0$ mesons is 0.15. Right: estimated statistical uncertainties for the measurement of the heavy-to-light ratio $R_{AA}^{D_{from b}} / R_{AA}^{D_{from c}}$.

$R_{AA}^{D_{from b}}$ is $\sqrt{2}$ times the uncertainty in central Pb–Pb (shown in the left panel), i.e. the uncertainty on the pp measurement is the same as that for Pb–Pb. For illustration, the points were drawn on a curve that follows the radiative energy loss prediction from figure 2.9 (left).

2.2.5.2 $B$ meson production via displaced $J/\psi$

As mentioned in section 2.1.2, the study of the $B$ hadron semi-inclusive decay $B \rightarrow J/\psi + X$ is an interesting way to measure open beauty production. Such a measurement is particularly important for studying the strong parton energy loss induced by the medium produced in heavy ion collisions.

The measurement of open beauty via $J/\psi$ decay is feasible since $B$ hadrons are long-lived particles with a $\tau \approx 500$ $\mu$m, resulting in a final state $J/\psi$ which is displaced from the primary vertex. The measurement is performed, at mid-rapidity ($|y| < 0.9$), by reconstructing the final charmonium state via its $e^+e^-$ decay and finding a displaced secondary vertex with the two electrons attached. The $J/\psi$ displacement can be parametrized in terms of the $B$ hadron proper decay length $\lambda_B = L_{xy} / m_B / p_{t,B}$, where $L_{xy}$ is the distance between the $B$ hadron production and decay point in the transverse plane. Since the $B$ hadron is not completely reconstructed and its transverse momentum is not known, the $J/\psi$ mass and transverse momentum can be used by defining a pseudo-proper decay length $l_{J/\psi} = L_{xy} / m_{J/\psi} / p_{t,J/\psi}$. A combined fit of this variable and the $e^+e^-$ invariant mass distribution can be used to extract the non-prompt to prompt $J/\psi$ ratio. As mentioned in section 2.1.2, a first measurement in $\sqrt{s_{NN}} = 2.76$ TeV Pb–Pb collisions has been performed by the CMS Collaboration [37] in the rapidity region $|y| < 2.4$ using the $\mu^+\mu^-$ decay channel. However, the CMS measurement is limited by the large $p_{t,\text{num}}$ cut on the $J/\psi$ decay muons, which restricts the measurements to $J/\psi$ with $p_t > 6.5$ GeV/c. This implies a limitation on the $B$ hadron $p_t$ that is reachable of about 3 GeV/c, and prevents at present the beauty cross section measurement in the whole transverse momentum range.

Figure 2.28 shows the current ALICE performance for the measurement of the non-prompt $J/\psi$ fraction $F_B$ in $\sqrt{s} = 7$ TeV pp minimum-bias collisions, using the $e^+e^-$ channel in the mid-rapidity region ($|y| < 0.9$). The left panel of figure 2.28 shows the result of the combined fit projected over the $l_{J/\psi}$ variable. ALICE is currently able to extract the $F_B$ fraction down to $J/\psi$ $p_t \sim 1.3$ GeV/c, which is much lower than the CMS and ATLAS limits. This implies no restrictions on the $B$ hadron transverse momentum.
reach and the possibility to measure the beauty cross section down to $p_t = 0$. In this regard, ALICE has a unique capability at mid-rapidity with respect to other LHC experiments.

The right panel of figure 2.28 shows the pseudo-proper decay length distribution for reconstructed prompt $J/\psi$ simulated with PYTHIA. This distribution is used in the combined fitting procedure as an estimate of the resolution of the pseudo-proper decay length variable. Indeed, the $I_{J/\psi}$ distribution should be ideally peaked at zero since prompt $J/\psi$ are produced close to the primary vertex. However, it is broadened as an effect of the resolution of the primary vertex and the multiple scattering induced by the detector material on reconstructed tracks. In this regard, the upgraded ITS at mid-rapidity will impact significantly on the pseudo-proper decay length resolution. In the left panel of figure 2.29 the $I_{J/\psi}$ resolution that could be achieved with the upgraded ITS is compared to the resolution with the present ITS design. For the upgrade case, the Hybrid simulation approach was used to estimate the performance, considering the same scenario as used for the $D^0$ and $\Lambda_c$ studies. The upgraded ITS scenario exhibits a significant enhancement in terms of pseudo-proper decay length resolution, which is a factor of 2 better than with the current ITS. This resolution enhancement extends over the whole $J/\psi$ transverse momentum range, as shown in the right panel of figure 2.29, where the resolution function r.m.s. is presented as a function of the minimum $J/\psi$ transverse momentum.

Figure 2.28: $J/\psi$ from $B$ decays. Left: current ALICE performance for the non-prompt $J/\psi$ fraction ($F_B$) measurement using the likelihood fit approach with current ITS design, from pp data at $\sqrt{s} = 7$ TeV. Right: pseudo-proper decay length resolution obtained with current ITS design.

Figure 2.29: $J/\psi$ from $B$ decays. Left: pseudo-proper decay length resolution obtained with the current ITS compared to the resolution with the upgraded ITS. Right: resolution function R.M.S. vs. $J/\psi$ minimum $p_t$ for the current ITS, compared to the upgrade case.
In addition, the measurement of beauty via displaced $J/\psi$ from the 2010 data was severely limited at mid-rapidity by the lacking of a proper trigger scheme for electrons, which prevented the collection of a high-statistics sample. Such a trigger should fulfill two main requirements: enlarge the sample of electrons used in the analysis, and keep a low reach in $J/\psi$ transverse momentum of $\approx 1.3\text{–}1.5$ GeV/$c$, which means a minimum electron $p_t$ of about 2 GeV/$c$. In 2011 the EMCAL detector is being used for electron triggering, but the threshold of 4 GeV/$c$ on the electron transverse momentum limits significantly the sensitivity to low-$p_t$ $B$ production.

A possibility for the $B \to J/\psi \to e^+e^-$ analysis is to use the trigger on electrons that can be provided by the Transition Radiation Detector (TRD) in conjunction with a topological trigger on tracks associated to a displaced decay vertex. Such a trigger scheme would enable a fast selection of $B \to J/\psi \to e^+e^-$ candidates since it would not require the full tracking provided by the TPC; moreover, it would allow a clean sample selection by removing the prompt $J/\psi$ component on the basis of topological constraints.

### 2.2.5.3 $B$ meson production via displaced electrons

Beauty production can be measured by preferentially selecting the electrons from beauty hadron decays, which are displaced with respect to the primary interaction vertex. Beauty hadrons have substantial branching ratios ($\sim 10\%$) to single electrons, which gives rise to a large signal-to-background ratio using this channel, in particular at high $p_t$. In addition, beauty hadrons have an average decay length $c\tau \approx 500$ $\mu$m [7]. Therefore, we can obtain a high-purity sample of electrons from beauty hadron decays by applying a cut on the impact parameter. At present, the analysis was carried out for pp collisions at $\sqrt{s} = 7$ TeV, using a cut on the normalized transverse impact parameter, or impact parameter significance, $|d_0(r\phi)/\sigma_{d_0(r\phi)}| > 3$. The remaining contributions from background sources are subtracted from the electron $p_t$ spectrum. The main background sources are: electrons from Dalitz decays (e.g. $\pi^0 \to e^+e^\gamma$) and photon conversions in the detector material (e.g. conversion of photons from the decay $\pi^0 \to \gamma\gamma$), and charmed hadron semi-electronic decays. These contributions are estimated, respectively, on the basis of the ALICE measured $\pi^0$ meson production cross section and $D$ meson ($D^0$ and $D^+$) production cross section.

The benefit of the ITS upgrade for this measurement is two-fold:

1. the improved impact parameter resolution enables a better rejection of the background electrons that originated at the primary interaction vertex (like Dalitz decays):

2. the reduced material thickness of the beam pipe and of the ITS layers results in a decrease of the background electrons from photon conversions.

In the following, these two effects are discussed, and preliminary performance results are presented, for the case of proton–proton collisions at $\sqrt{s} = 7$ TeV. A simulation sample produced with the PYTHIA generator with Perugia-0 tuning was used, and the effect of the improved resolution was included using the Hybrid approach.

Since the impact parameter cut on electron candidates is applied to enrich the sample with electrons from $B$ meson decays, the resolution improvement by about a factor of 3 that is targeted with the ITS upgrade will reduce the background contributions related to electrons coming from the primary interaction vertex (like Dalitz and di-electron decays). The effect of the improved track position resolution for ITS upgraded configuration was studied using the Hybrid simulation approach.

Figure 2.30 shows the transverse impact parameter distribution (normalized to its uncertainty, i.e. an impact parameter significance), $d_0(r\phi)/\sigma_{d_0(r\phi)}$, for electrons from Dalitz/di-electron decays (left) and $B$ meson decays (right) with the current and upgraded ITS configurations, in the transverse momentum range $0.8 < p_t < 6$ GeV/$c$. The impact parameter significance distribution remains the same for the
electrons produced at the primary vertex, while it becomes broader for the electrons from displaced secondary vertices, due to the reduction of $\sigma_{d_0(r\phi)}$. As a consequence, the signal-to-background ratio increases for the upgraded ITS in the transverse momentum region dominated by electron backgrounds from light meson decays. Figure 2.31 (left) shows the signal-to-background ratio from the upgraded ITS divided by that from the current ITS, as a function of $p_t$. The cut on $|d_0(r\phi)/\sigma_{d_0(r\phi)}|$ was applied at $>3$ for the current setup (as is done currently on the pp data), while for the upgraded ITS scenario the cut was tightened to $>9$. This value was chosen in order to keep the same cut efficiency for the signal as in the case of the current ITS. As shown in the figure, the improved resolution determines an increase of the signal-to-background ratio in low $p_t$ region.

At low $p_t$ (below 2 GeV/c), the electrons from photon conversions become the dominant background source, since they originate from displaced secondary vertices, and the impact parameter cut suppresses...
them less compared to the electron backgrounds from the primary vertex (like electrons from Dalitz decays). The amount of photon conversion background depends on the amount and position of the material. Since in this analysis the electron candidate tracks are required to have an associated hit in the innermost pixel layer, all material further away from the collision vertex than this layer does not contribute to the electron spectrum. The effective thickness of the converter material is expressed in units of radiation length, $x/X_0$. This thickness determines the conversion probability for a photon (which, in principle, depends slightly on the photon energy). For the current ITS setup, the effective thickness of conversion material is calculated based on the known material budget, and it can also be measured directly from the data. We get for the effective converter thickness (including the beam pipe) a value of $x/X_0 = (0.73 \pm 0.05)\%$. With the upgrade of the ITS ($x/X_0 = 0.3\%$ per layer and beam-pipe thickness of 0.5–0.6 mm), the effective thickness of converter material would become $x/X_0 = 0.34\%$, i.e. one half of the current value.

The ratio of the conversion electron yield with the upgraded ITS to the one with the current ITS can be calculated as follows:

$$\frac{BR^{\gamma\gamma} \times 2 \times (1 - \exp(-\frac{7}{9} \times (\frac{x}{X_0})_{\text{upgrade}})) \times 2}{BR^{\gamma\gamma} \times 2 \times (1 - \exp(-\frac{7}{9} \times (\frac{x}{X_0})_{\text{current}})) \times 2}$$

For the upgraded ITS with a thickness of 0.3% radiation length $X_0$ and 0.5–0.6 mm of beam pipe, the ratio is equal to 0.46.

Figure 2.31 (right) shows the signal-to-background ratio from the upgraded ITS divided by that from the current ITS, as a function of $p_t$, with the $|d_0(r\phi)/\sigma_{d_0(r\phi)}| > 3$. Only the changes of material budget (thickness of 0.3% radiation length $X_0$ and 0.5–0.6 mm beam pipe thickness for the upgraded ITS configuration) are considered. For $p_t < 2$ GeV/$c$, the background contribution from light meson decays gets larger compared to the one from charmed hadron decays. Therefore, we observe an improvement by 30% in signal-to-background, in the low $p_t$ region, which is crucial in order to measure the total cross section of electrons from beauty hadron decays.

Together with the improvement due to the better impact parameter resolution, this plays an important role in the precise measurement of the total cross section of electrons from $B$ meson decays. In addition, it will reduce the systematic uncertainty on the nuclear modification factor of $B$ meson decay electrons in the transverse momentum region dominated by electron backgrounds from light meson decays.
Chapter 3

Detector Functional Requirements

3.1 Introduction

In this chapter we will discuss the functional requirements that an upgraded ITS detector should satisfy in order to achieve the physics performance which has been studied in the previous chapter. The ITS upgrade aims to (i) improve the resolution of the track impact parameter by a factor 3 or better (at $p_t = 1$ GeV/c) with respect to the present ITS, (ii) obtain an efficient stand-alone tracking capability with a momentum resolution of a few percents up to 20 GeV/c, and (iii) extend the trigger capabilities for enhancing the statistics of rare heavy flavour signals.

The tracking performance has been studied using two complementary methods: an analytical tool, referred to as the “Fast Estimation Tool” (FET) which has been further developed into a Fast Monte Carlo Tool (FMCT), and a Monte Carlo description based on a transport code (FullMC). The FET can provide accurate determination of the tracking resolution (both for the spatial and the momentum components) as a function of the detector configuration. It can also provide an estimate of the tracking efficiency. The FullMC, being intrinsically much slower, is used to obtain a better description for a few given detector configurations. At present, the two methods provide an overall good agreement in their estimates, but some discrepancies are still being observed. Work is currently in progress to optimize the tracking algorithm of the upgraded ITS configuration as described by the Monte Carlo simulation, and the remaining differences are attributed to that. The outcome of this study is the definition of a baseline new configuration, referred to as “upgraded ITS” in this document. The particle identification performance has been studied with an independent approach.

The robustness of the new layout will be discussed by studying how the key performance of the detector would be degraded in the event of a dramatic reduction of the detector efficiency (one dead layer). There will also be a discussion of the performance of a few different configurations, which are obtained from the baseline configuration by changing the material budget and/or the intrinsic resolution of the layers and properties of the beam pipe.

3.2 Performance of present ITS detector

The present ITS detector consists of six cylindrical layers of silicon detectors with three different technologies. Moving outwards from the interaction region, there are two layers of Silicon Pixel Detector (SPD), two layers of Silicon Drift Detector (SDD) and two layers of double sided Silicon Strip Detector (SSD). The geometrical parameters of the layers (radial position, length along beam axis, number of modules, spatial resolution) and material budget are summarized in table 3.1. The material budget reported in the table takes into account the $\phi$-averaged material (including the sensors, electronics, cabling, support structures and cooling) associated with radial paths through each layer. Another 1.30% of $X_0$
Table 3.1: Characteristics of the six ITS layers, the beam-pipe and the thermal shields

<table>
<thead>
<tr>
<th>Layer / Type</th>
<th>r [cm]</th>
<th>±z [cm]</th>
<th>Number of modules</th>
<th>Active area per module $r \phi \times z$ [mm$^2$]</th>
<th>Intrinsic resolution [µm] $r \phi \times z$</th>
<th>Material budget $X/X_0$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>2.94</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.22</td>
</tr>
<tr>
<td>1 / pixel</td>
<td>3.9</td>
<td>14.1</td>
<td>80</td>
<td>12.8 $\times$ 70.7</td>
<td>12 100</td>
<td>1.14</td>
</tr>
<tr>
<td>2 / pixel</td>
<td>7.6</td>
<td>14.1</td>
<td>160</td>
<td>12.8 $\times$ 70.7</td>
<td>12 100</td>
<td>1.14</td>
</tr>
<tr>
<td>Th. shield</td>
<td>11.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.65</td>
</tr>
<tr>
<td>3 / drift</td>
<td>15.0</td>
<td>22.2</td>
<td>84</td>
<td>70.2 $\times$ 75.3</td>
<td>35 25</td>
<td>1.13</td>
</tr>
<tr>
<td>4 / drift</td>
<td>23.9</td>
<td>29.7</td>
<td>176</td>
<td>70.2 $\times$ 75.3</td>
<td>35 25</td>
<td>1.26</td>
</tr>
<tr>
<td>Th. shield</td>
<td>31.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.65</td>
</tr>
<tr>
<td>5 / strip</td>
<td>38.0</td>
<td>43.1</td>
<td>748</td>
<td>73 $\times$ 40</td>
<td>20 830</td>
<td>0.83</td>
</tr>
<tr>
<td>6 / strip</td>
<td>43.0</td>
<td>48.9</td>
<td>950</td>
<td>73 $\times$ 40</td>
<td>20 830</td>
<td>0.83</td>
</tr>
</tbody>
</table>

comes from the thermal shields and supports installed between SPD and SDD barrels and between SDD and SSD barrels, thus making the total material budget for perpendicular tracks equal to 7.66 % of $X_0$.

Figure 3.1 shows the impact parameter resolution as a function of transverse momentum. The resolution in the bending plane ($r \phi$) which is mainly determined by the ITS, is plotted for ITS stand-alone tracks for Pb-Pb data and Monte Carlo simulations with realistic residual misalignment. The impact parameter resolution in the longitudinal direction (z), is plotted for the ITS stand-alone and ITS-TPC combined tracking. This also benefits from the TPC information.

Figure 3.1: Impact parameter resolution of present ITS versus $p_t$, for the $r \phi$ (left, Pb–Pb data and MC) and z (right, pp MC simulation [44]) components. Reconstructed tracks have been selected requiring successful refit in ITS and 6 ITS clusters per track.

In figure 3.2 the relative $p_t$ resolution is shown as a function of $p_t$ for ITS stand-alone and ITS-TPC combined tracks, which have been selected requiring 6 ITS clusters per track. The $p_t$ resolution provided by the ITS stand-alone is about 6 % for tracks with $p_t < 2$ GeV/c. Due to the smaller lever arm and the limited number of points, this is worse by about an order of magnitude with respect to the ITS-TPC combined tracks. In the ITS stand-alone mode the $p_t$ resolution reaches the 10 % value at $p_t = 10$ GeV/c.

In figure 3.3 the ITS stand-alone tracking efficiency is shown as a function of $p_t$ and $\eta$ for Monte Carlo Pb–Pb central collisions. The efficiency is defined as the number of “good” refitted tracks (i.e. tracks with $\geq 3$ associated clusters and without any fake associated cluster from another track) divided by the
number of “trackable” particles. A “trackable” particle has been defined as a particle with at least three reconstructed clusters on three different ITS layers and at least one of the reconstructed points on one of the three innermost layers in the case of the outward procedure. In the case of the inward procedure it must be found on one of the three outer layers. The definition of trackable particles using reconstructed clusters instead of potential hits, for example GEANT energy deposit, has been preferred in order to separate the algorithmic tracking efficiency from other inefficiency sources. In the plots of figure 3.3 the blue circles show the ideal case of the ITS detector with all modules 100 % efficient while the red squares show a typical configuration of the detector during the 2010 Pb–Pb run.

Figure 3.4 shows the efficiency in prolongating tracks from the TPC to the ITS detector as a function of $p_t$ for minimum bias Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The comparison to a Monte Carlo simulation is also shown in the same figure. The value of this efficiency, which is quite constant as a function of $p_t$, is mainly determined by the fraction of dead modules in the ITS. The largest inefficiency is due to 30 of the 120 SPD modules that cannot be operated due to problems related to the cooling system. This problem will be solved in the extended LHC shutdown planned for 2013-14.
The four layers equipped with drift and strip detectors provide a measurement of the specific energy loss, $dE/dx$, which can be used for particle identification. The energy loss measurement in each layer is corrected for the track length in the sensitive volume using the tracking information. In the case of SDD clusters, a linear correction is applied to account for the dependence of the reconstructed raw charge on the drift length due to the combined effect of charge diffusion and zero suppression. For each track, the $dE/dx$ is calculated using a truncated mean: the average of the lowest two points, in case four points are measured, or a weighted sum of the lowest (weight 1) and the second lowest point (weight 1/2), in case only three points are measured. Figure 3.5 shows the truncated mean $dE/dx$ for a sample of ITS stand-alone tracks along with a parametrization of the most probable value [45] based on the Bethe-Bloch formula.

Figure 3.5: Specific energy loss $dE/dx$ as a function of the momentum measured with the ITS stand-alone in Pb–Pb collisions. The solid lines are a parametrization of the detector response based on the Bethe-Bloch formula.
Table 3.2: Readout time and maximum rate, assuming 100% dead time, of the ITS sub-detectors.

<table>
<thead>
<tr>
<th>detector</th>
<th>R/O time (µs)</th>
<th>Max. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPD</td>
<td>296</td>
<td>3300</td>
</tr>
<tr>
<td>SDD</td>
<td>1023</td>
<td>985</td>
</tr>
<tr>
<td>SSD</td>
<td>310</td>
<td>3265</td>
</tr>
</tbody>
</table>

We conclude this section by reporting the performance of the ITS detectors in terms of readout rate capabilities. Table 3.2 lists the readout time and maximum event readout rate under the assumption of no back pressure from the DAQ network. It should be noted that the readout time of the three ITS detectors depends only marginally on the detector occupancy and, therefore, is very similar for p-p and Pb-Pb events.

3.3 Simulation conditions

Beam pipe: The present beam pipe is 4.82 m long with a central part made of a straight beryllium tube of length 3.95 m, with a wall thickness of 0.8 mm and an outer radius of 29.8 mm. For the ALICE upgrade, the baseline scenario will include the installation of a new beam pipe with a wall thickness of 0.8 mm and an outer radius of 19.8 mm. See section 5.4 for a detailed discussion.

Particle load: The charged particle density in central Pb–Pb collisions at the LHC energy determines the density of particles in the different detector layers. Consequently this determines the occupancy per layer and in the individual channels. A relevant contribution to the hit density in a given layer can come from secondary particles, which are mostly produced in the interaction of other particles with the material of the beam pipe and of the inner layers.

By extrapolating the measured charged particles in central Pb–Pb collisions at √s_{NN} = 2.76 TeV using the s_{0}^{0.15} scaling one obtains dN_{ch}/dη ≃ 1970 for central Pb–Pb collisions at √s_{NN} = 5.5 TeV. Based on a Monte Carlo simulation for central Pb–Pb collisions, which uses the HIJING generator tuned to such a charged particle multiplicity, the hit density of both primary and secondary charged particles has been estimated. The number of secondary particles depends on the actual material budget distribution, which for this study has been assumed to be the same as the present ITS. In figure 3.6(a) the total hit density due to the charged particles produced in a central Pb–Pb collision at the top LHC energy is shown as a function of r and z.

An additional contribution to the overall particle load comes from the electromagnetic interactions of the crossing ions, among which the dominant process in terms of cross section is the e⁺e⁻ pair production. These will be referred to as QED electrons. The cross section of single pair production (about 220 Kb) is about 98% of the total cross section. The flux of these electrons through the detectors which are close to the beam pipe can be rather high. The flux of QED electrons was estimated by means of a Monte Carlo generator implemented in the AliRoot framework. The results are illustrated in figure 3.6(b).

Table 3.3 summarizes the expected maximum hit densities for primaries, secondaries and QED electrons. The latter contribution depends on the detector integration time. The values reported in the table refer to the radial position of the layers for the ITS upgrade scenario under study (see section 3.6).

Detector acceptance: This study focuses on the central rapidity region and therefore the detector has been assumed to have a barrel geometry. The ITS acceptance has been determined based on its matching with the current external barrel detectors. For physics studies which require an extended coverage at forward rapidities, additional layers with an end-cap like geometry are more suited, in particular at large radii. This could take the form of disks placed perpendicularly to the z axis.

In figure 3.7 a cut view of the ALICE TPC, TOF, TRD and EMCAL detectors is shown with the polar angles of the lines from the nominal Interaction Point (IP) to the most external corners of these detectors.
Figure 3.6: Local hit and flux densities in Pb–Pb collisions at top LHC energy as a function of the radial distance $r$ and the longitudinal coordinate $z$ assuming the ALICE magnetic field of 0.5 T. The material budget distribution of the present beam pipe and ITS has been assumed.

Table 3.3: Expected hit densities in central Pb–Pb collisions (incl. secondaries produced in the material simulated assuming the current ITS setup) and QED electrons for different integration times. Interaction rates of 50 (and 8) kHz and a 0.5 T magnetic field have been assumed.

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>Primary and secondary particles per event (cm$^{-2}$)</th>
<th>QED electrons for $\tau=100$ ns (cm$^{-2}$) 8 kHz</th>
<th>QED electrons for $\tau=100$ ns (cm$^{-2}$) 50 kHz</th>
<th>QED electrons for $\tau=1$ $\mu$s (cm$^{-2}$) 8 kHz</th>
<th>QED electrons for $\tau=1$ $\mu$s (cm$^{-2}$) 50 kHz</th>
<th>QED electrons for $\tau=50$ $\mu$s (cm$^{-2}$) 8 kHz</th>
<th>QED electrons for $\tau=50$ $\mu$s (cm$^{-2}$) 50 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>74.05</td>
<td>0.022</td>
<td>0.137</td>
<td>0.220</td>
<td>1.374</td>
<td>10.99</td>
<td>68.71</td>
</tr>
<tr>
<td>2.8</td>
<td>45.71</td>
<td>0.014</td>
<td>0.085</td>
<td>0.136</td>
<td>0.848</td>
<td>6.79</td>
<td>42.42</td>
</tr>
<tr>
<td>3.6</td>
<td>27.65</td>
<td>0.008</td>
<td>0.051</td>
<td>0.082</td>
<td>0.513</td>
<td>4.11</td>
<td>25.66</td>
</tr>
<tr>
<td>20.0</td>
<td>0.90</td>
<td>0.000</td>
<td>0.002</td>
<td>0.003</td>
<td>0.017</td>
<td>0.13</td>
<td>0.83</td>
</tr>
<tr>
<td>22.0</td>
<td>0.074</td>
<td>0.000</td>
<td>0.001</td>
<td>0.002</td>
<td>0.014</td>
<td>0.11</td>
<td>0.69</td>
</tr>
<tr>
<td>41.0</td>
<td>0.21</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.004</td>
<td>0.03</td>
<td>0.20</td>
</tr>
<tr>
<td>43.0</td>
<td>0.19</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.004</td>
<td>0.03</td>
<td>0.18</td>
</tr>
</tbody>
</table>

indicated. The acceptance of the TPC, for tracks traversing its full radial extension, corresponds to $|\eta| < 0.92$. The TRD and TOF have the same acceptance as the TPC, while the EMCAL acceptance is smaller.

In figure 3.7, the line for tracks traversing half of the TPC radial extension is drawn, because the TPC can also reconstruct these tracks. In the latter case the acceptance of the TPC extends to $|\eta| < 1.22$. So far we have considered the acceptance for tracks emitted from the nominal IP. However, in the Pb–Pb interactions at $\sqrt{s_{NN}} = 5.5$ TeV the luminous region would spread around the nominal IP with a longitudinal Gaussian distribution with $\sigma_{z,\text{lumi}} = 5.61$ cm [52]. The requirement of accepting all tracks within a given $\eta$ range from this luminous region determines the longitudinal length of each ITS layer. In figure 3.8 we plot the half-length of the barrel as a function of the distance from the beam, assuming $|\eta| < 0.92$ or $|\eta| < 1.22$ for tracks originating from the nominal IP ($z_{\text{vtx}} = 0$) and from vertices within $z_{\text{vtx}} < \sigma_{z,\text{lumi}}$ and $|z_{\text{vtx}}| < 1.39\sigma_{z,\text{lumi}}$ (90% of the total). In the following sections, we assume for the acceptance of the upgraded ITS the condition corresponding to 90% of the luminous region and a pseudo-rapidity coverage of $|\eta| < 1.22$.

Number and radius of layers: The optimization of the detector parameters has been studied by con-
**Figure 3.7:** ALICE cut view along the $yz$-direction. The lines drawn from the nominal Interaction Point (IP) indicate the acceptance of the TPC for tracks traversing the whole ($45^\circ$) or half ($34^\circ$) of its radial extension. The EMCAL acceptance is also indicated.

**Figure 3.8:** Half-length of the barrel ($z_{\text{max}}$) versus the radial distance from the beam to provide acceptance in $\eta$ within 0.92 (in black) and 1.22 (in red) for tracks originating from the nominal IP (dotted lines), and for all events with vertices within $\pm \sigma_{z,\text{lumi}}$ (68.5% of the events, full lines) and $\pm 1.39 \sigma_{z,\text{lumi}}$ (90% of the events, dash-dotted lines).
sidering primarily the stand-alone performance and monitoring that the efficiency of the track matching from the TPC to the ITS stays at an excellent level in the ITS-TPC combined tracking mode.

The performance will be studied considering a 7-layer layout, made of a combination of pixel (hybrid and/or monolithic) and/or strip layers.

**Material budget:** A reduction of the material budget can be achieved by reducing the thickness of the electronic sensor, plus the material budget of the services (mechanical support, cooling system, read-out system). Based on the most recent developments in pixel detector technologies, which will be discussed in detail in the next chapter, we will show in section 3.5 the effect of the material budget of the first layer (varying $X/X_0$ between 0.3 and 0.9) on the pointing resolution. For the remaining layers the same material budget as in the current ITS (see table 3.1) will be assumed in this particular study.

**Detector segmentation:** The segmentation of the detector determines the intrinsic spatial resolution of the reconstructed track points. As an example, in the case of an ideal digital detector, the resolution in a given direction is given by $d/\sqrt{12}$, where $d$ is the size of the elementary cell in that direction. A small segmentation of the detector is also important to keep the occupancy at a low value. An excellent resolution of the first layer is fundamental for the resolution of the impact parameter at high $p_t$ where the effect of the multiple scattering becomes negligible. For the outer layers, a good resolution is also important to improve the $p_t$ resolution and the tracking efficiency in the ITS stand-alone mode. In our studies we have assumed an intrinsic spatial resolution of 4 $\mu$m in both $r\phi$ and $z$. For the outermost layers, the option of 20 (830) $\mu$m spatial resolution in $r\phi$ ($z$) is also considered.

### 3.4 Simulation Tools

Two independent tools were developed: a fast simulation (see section 3.4.1) and a detailed Monte Carlo (MC) method (see section 3.4.2) fully integrated within the AliRoot code [53]. A more detailed description of each tool can be found in [54].

These tools were validated against the performance of the current ITS design as well as against each other for an ITS upgrade scenario. Although the two tools are very different in terms of speed and complexity, they agree quantitatively in their predictions regarding the possible improvements in impact parameter resolution and transverse momentum resolution. The predictions for the tracking efficiency are qualitatively similar and the remaining discrepancy is attributed to the not yet optimized stand-alone tracking algorithm of the MC method.

#### 3.4.1 Fast simulations

The semi-analytical Fast-Estimation-Tool (FET) is based on a “Toy-Model” tool originally developed by the STAR HFT collaboration [6]. This enables a simple detector model to be built and to use the tracking method as proposed in [55]. The simplest model of a central barrel detector is a combination of cylindrical layers with the properties of radius $r$, radiation length $X/X_0$, and the intrinsic detector resolution in the $r\phi$ and $z$ components ($\sigma_{r\phi}$, $\sigma_z$).

The intrinsic (or cluster) resolution of a layer largely depends on the cell-size of the detection layer (segmentation of the cylinder). It is taken into account in the method by determining the magnitude of the covariance matrix elements at the various stages of the tracking. Furthermore, the traversed material and the cluster resolution depend on the inclination angle of the charged particle with respect to the layer normal (i.e., on the dip angle and rapidity of the track).

The original “Toy-Model” was extended and adapted in various ways in order to answer the key questions of the ITS upgrade proposal. These questions included the ITS upgrade stand-alone tracking capabilities. For example, the tracking code itself was exchanged for the Kalman technique [56] which is implemented...
in the standard ALICE software framework [53]. A detailed description of the method and its extensions can be found in [54].

An extension of this method, called the Fast Monte Carlo Tool (FMCT), allows the estimation of the tracking performance from the reconstruction of a probe particle embedded in the background as expected from collisions. In contrast with the FET, the FMCT is able to disentangle the performance of a detector layout from the efficiency of specific track-finding algorithms. This is done by accounting for the competition between the track candidates of different length and quality, and represents an approach much closer to that of the full MC based simulation and reconstruction.

Both methods have been validated against the pp and Pb–Pb data sample collected by ALICE. As an example, figure 3.9 shows the official ITS performance plots with superimposed results from the FET calculations using the current ITS layout (see table 3.1).

![Figure 3.9: Validation of the Fast-Estimation-Tool: comparison with the performance of the present ITS. Transverse ($r\phi$) impact parameter resolution for unidentified charged particles (top-left panel) and for different particle species (top-right panel), Longitudinal ($z$) impact parameter resolution (bottom-left panel) and $p_t$ resolution (bottom-right panel).](image)

### 3.4.2 Monte Carlo simulation

A more refined simulation tool, based on a Monte Carlo transport code (FullMC), has been developed for detailed performance studies on physics benchmark channels. The detector segmentation, the number of layers, their radii and material budgets can be set as external parameters of the simulation.
The tracking algorithm is developed from the stand-alone one of the current ITS [44]; the detailed description of the implementation of the Monte Carlo simulation can be found in [54]. Figure 3.10 shows the comparison between the MC predictions for the impact parameter resolution in the transverse plane. This assumes the current ITS layout, and the results of pp data at \( \sqrt{s} = 7 \) TeV, reconstructed in the ITS stand-alone mode. A good agreement is also found for the \( z \) component of the impact parameter and the \( p_t \) resolution.

The implementation of the ITS-TPC combined tracking algorithm is currently ongoing.

![Figure 3.10](image)

**Figure 3.10:** Transverse impact parameter resolution as a function of \( p_t \) in pp collisions at \( \sqrt{s} = 7 \) TeV with the ITS stand-alone compared to the predictions of the MC ITS Upgrade simulation, but using the current ITS layout.

### 3.4.3 Comparison

In figure 3.11 a comparison between the three methods, namely FET, FMCT and FullMC, is shown for the current and an “upgraded ITS” layout (the latter as described in section 3.6). The overall agreement is good and the remaining discrepancies observed for the FullMC are attributed to the tracking algorithm, whose optimization for the upgraded layout is ongoing.

### 3.5 Impact parameter resolution

The performance of a vertex detector, in particular its capability to separate secondary vertices of heavy flavour decays, is determined by the impact parameter resolution \( d_0 \). This is the convolution of the vertex resolution and the track pointing resolution. The impact parameter resolution mainly depends on the properties of the innermost layers. In the following we report the results of a dedicated study where an innermost layer (L0) has been added to the current ITS layout. The parameters of L0 which are varied are the radial distance, the material budget and the intrinsic spatial resolution.

**Radial distance:** Figure 3.12 shows the pointing resolution as a function of the transverse momentum for three values of the radial position of layer L0, the material budget and the spatial resolution being those of the current pixel detector. The results for the current ITS without L0 are also reported for comparison.

**Material budget:** In figure 3.13 the pointing resolution as a function of the transverse momentum is shown in the case of layer L0 placed at 2.2 cm and three values of its thickness in units of radiation length, \( X/X_0 \), assuming the spatial resolution of the current pixel detector. The results for the current ITS without L0 are also reported for comparison.
Figure 3.11: Comparison of the three simulation methods for the current ITS and the upgraded ITS.

Figure 3.12: $\phi$ (left) and $z$ (right) pointing resolutions of charged pions at the primary vertex versus transverse momentum $p_t$ for different radii of the layer L0 in ITS-TPC combined tracking mode.

Figure 3.13: $\phi$ (left) and $z$ (right) pointing resolution of charged pions at the primary vertex versus transverse momentum $p_t$ for different material budget of the layer L0 in ITS-TPC combined tracking mode.
Intrinsic spatial resolution: In figure 3.14 the pointing resolution as a function of the transverse momentum is shown in the case of layer L0 placed at 2.2 cm and $X/X_0 = 0.3\%$ and three values of the intrinsic spatial resolution. The results for the current ITS without L0 are reported for comparison.

In summary, the studies described in this section show that, by adding an innermost layer (L0) to the present ITS detector, the impact parameter resolution can be improved by a factor of 3 at 400 MeV/c. The parameters assumed for the additional L0 layer are a radial distance of 22 mm from the beamline, a radiation length of 0.3 % $X_0$ and a spatial resolution of 4 $\mu$m.

![Figure 3.14: $r\phi$ (left) and $z$ (right) pointing resolution of charged pions at the primary vertex versus transverse momentum $p_t$ for different values of the intrinsic spatial resolution of the layer L0 in ITS-TPC combined tracking mode.](image)

3.6 Upgrade scenario

In this section the baseline upgrade option, referred to as “upgraded ITS”, is described. The number and radial positions of the new layers have been optimized with the Fast-Estimation-Tool described in section 3.4.1. The longitudinal extensions of the new layers are determined by the condition described in section 3.3, corresponding to a pseudo-rapidity coverage of $|\eta| < 1.22$ over 90% of the luminous region. This study assumes an intrinsic resolution of 4 $\mu$m, both in $r\phi$ and $z$, and a material budget of 0.3 % of $X_0$, which can be achieved by detectors based on monolithic pixels as discussed in the following chapters.

The baseline scenario assumes a completely new ITS detector made of 7 layers of pixel and strip detectors based on the ongoing developments discussed in chapters 4 and 5. In table 3.4 this detector configuration is summarized. In the table the resolution and the material budget for the case where the outermost layers are equipped with microstrip detectors are indicated in brackets. The number of layers and their radial positions have been determined taking into account the available space between the new beam pipe and the outermost radius of the current ITS. The outcome of the simulations indicates that an improved tracking efficiency and $p_t$ resolution in stand-alone mode is obtained by grouping the layers in an innermost triplet, an intermediate pair and an outermost pair.

The performance of the upgraded ITS and the current ITS are compared in figures 3.15, 3.16, 3.17 and 3.18 for both ITS stand-alone and ITS-TPC combined tracking mode. Figure 3.15 shows the pointing resolution to the vertex for charged pions. Left and right panels show the ITS stand-alone and ITS-TPC combined tracking modes, respectively. Both the $r\phi$ and $z$ components are shown in the same plots for the only pixel and the combined pixel/strip configurations (see table 3.4). As an example, at a $p_t$ of about 400 MeV/c, an improvement of a factor 3 and 5 is achieved for the $r\phi$ and $z$ components, respectively. It should be noticed that for the present ALICE set-up the ITS-TPC combined tracking provides at high $p_t$ a sizeable improvement with respect to the ITS stand-alone tracking. Conversely, in the case of the
Table 3.4: Characteristics of the upgrade scenario. The numbers in brackets are, i.e. intrinsic resolution and material budget of microstrip detectors:

<table>
<thead>
<tr>
<th>Layer / Type</th>
<th>r [cm]</th>
<th>±z [cm]</th>
<th>Intrinsic resolution [μm]</th>
<th>Material budget X/X₀ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>0.22</td>
</tr>
<tr>
<td>1 / new pixel</td>
<td>2.2</td>
<td>11.2</td>
<td>4 4</td>
<td>0.30</td>
</tr>
<tr>
<td>2 / new pixel</td>
<td>2.8</td>
<td>12.1</td>
<td>4 4</td>
<td>0.30</td>
</tr>
<tr>
<td>3 / new pixel</td>
<td>3.6</td>
<td>13.4</td>
<td>4 4</td>
<td>0.30</td>
</tr>
<tr>
<td>4 / new pixel (strip)</td>
<td>20.0</td>
<td>39.0</td>
<td>4 (20) 4 (830)</td>
<td>0.30 (0.83)</td>
</tr>
<tr>
<td>5 / new pixel (strip)</td>
<td>22.0</td>
<td>41.8</td>
<td>4 (20) 4 (830)</td>
<td>0.30 (0.83)</td>
</tr>
<tr>
<td>6 / new pixel (strip)</td>
<td>41.0</td>
<td>71.2</td>
<td>4 (20) 4 (830)</td>
<td>0.30 (0.83)</td>
</tr>
<tr>
<td>7 / new pixel (strip)</td>
<td>43.0</td>
<td>74.3</td>
<td>4 (20) 4 (830)</td>
<td>0.30 (0.83)</td>
</tr>
</tbody>
</table>

Figure 3.15: Pointing resolution to the vertex of charged pions as a function of the transverse momentum for the current ITS and the upgraded ITS. Left panel: ITS stand-alone tracking; right panel: ITS-TPC combined tracking.

Figure 3.16: Pointing resolution to the vertex versus transverse momentum \( p_t \) for different particle species in the ITS stand-alone tracking mode for the current ITS (dotted lines) and the upgraded ITS (full lines). The \( r φ \) and \( z \) components are shown in the left and right panel, respectively.

upgraded ITS, adding the information from the TPC does not yield any further improvement. Similar results are obtained for the other particle species, as shown in figure 3.16.

Figure 3.17 illustrates the improvements in terms of the transverse momentum resolution. For the ITS stand-alone tracking mode, the upgraded ITS yields a dramatic improvement. It should be noted that the \( p_t \) resolution in the stand-alone mode benefits significantly from the intrinsic resolution of the outer...
**3.7 Particle Identification**

In this section we discuss the possibility to perform proton, kaon and pion identification by the specific energy loss ($dE/dx$) measurement in the $1/\beta^2$ region with the upgraded ITS.

### 3.7.1 Simulation tools

Two simulation approaches have been considered to study the PID capabilities of the ITS detectors: the “Truncated-Mean” and the “Bayesian”. These two methods were developed for the current ITS detector [57] and they have been adapted to the detector configurations under study. For this study, a 7 layer layout has been assumed. To account for the thin detectors assumed for the upgrade scenarios, a
dedicated Monte Carlo simulation has been developed to study the energy deposition per unit length for 15 and 100 \( \mu m \) thick detectors. These two values are plausible for an implementation of the detector with monolithic and hybrid pixels, respectively. In figure 3.19 the distributions of the specific energy-loss in 15 and 100 \( \mu m \) thick detectors are compared to that of the current 300 \( \mu m \) for pions of 500 MeV/c. The most probable energy-loss values are obtained by fitting the \( dE/dx \) distributions with a Landau function.

The diffusion, charge collecting inefficiency, noise and digitization of the detector response have been introduced in the simulation.

**Truncated Mean method.** This approach consists of computing a truncated mean of the charge values in the various layers crossed by the track. A single value of the \( dE/dx \), obtained after normalizing to the length of the track segment in the silicon volume, is assigned to each track. The truncated mean algorithm used in this analysis consists of computing the arithmetic mean of the \( n \) lowest \( dE/dx \) values among the ones of the clusters attached to the track. The number \( n \) of used \( dE/dx \) values is set to a fixed fraction \( f \) of the total number of clusters attached to the track. By default the value \( f = 1/2 \) is used. In case \( n \) is an odd number, the mean is computed using the \( (n - 1)/2 \) lowest \( dE/dx \) values, the \( (n - 1)/2 \) highest \( dE/dx \) values are not used, and the remaining cluster with intermediate \( dE/dx \) enters in the mean with a weight of 1/2.

The calibration of the PID algorithm is based on building the distribution of the \( dE/dx \) for the tracks of each hadron species in a given momentum interval. These distributions are fitted with Gaussian functions. The distribution of the mean values of the Gaussian fits as a function of their momentum is then fitted to a parametrized formula (taken from the PHOBOS experiment [45]):

\[
\frac{dE}{dx} = \frac{E_0}{\beta^2} \left( b + 2 \cdot \ln \gamma - \beta^2 \right) \tag{3.2}
\]

where \( E_0 \) and \( b \) are the free parameters. An example of this fit is shown in figure 3.20. The fitted mean value, for a given particle type \( i \), will be indicated with \( M_G[i] \). The sigma of the Gaussian fits \( \sigma_G[i] \), corresponding to the resolution, is found to be independent of the track momentum. With this

\(^1\)Alternatively, an approach based on a weighted mean has also been considered. In this case, the values of the energy deposit of all clusters attached to the track are used; a single \( dE/dx \) value is assigned to the track according to the following formula:

\[
\frac{dE}{dx} = \left[ \frac{1}{N_{\text{layers}}} \sum_{i=1}^{N_{\text{layers}}} \left( \frac{1}{dE/dx_i} \right)^2 \right]^{-1} \tag{3.1}
\]
method, the particle identity of a reconstructed track is assigned to the species \( i \) for which the quantity \( |dE/dx - M_G[i]|/\sigma_G[i] \) is lowest. The \( M_G[i] \) and \( \sigma_G[i] \) parameters are used to calculate the average separation in units of \( \sigma_G \) between the particle types as a function of the momentum, according to the following:

\[
x(\pi) = \frac{M_G[\pi] - M_G[K]}{\sigma_G[K]} \quad (3.3)
\]

\[
x(P) = \frac{M_G[P] - M_G[K]}{\sigma_G[K]} \quad (3.4)
\]

**Landau+Gauss method.** This method is based on computing for each layer a probability for the measured signal to be produced by an electron, pion, kaon or proton. The \( dE/dx \) distributions for tracks of each species in a given momentum interval are built for each layer. These distributions are then fitted with a convolution of a Landau and a Gaussian functions yielding 3 parameters, namely Most Probable Value (MPV), Landau sigma (\( \sigma_L \)) and Gaussian sigma (\( \sigma_G \)). The Landau function describes the particle energy loss and the Gaussian represents the smearing of the signal due to the detector response. Examples of such fits are reported in figure 3.21.

The dependence of these 3 parameters on the track momentum is fitted with ad hoc functions for each layer and for each particle species, which are used in the particle identification algorithm. An example of the MPV as a function of momentum for pions, kaons and protons is shown in figure 3.22. Using these functions it is possible to compute for each track the probability of the track being an electron, kaon, pion or proton starting from the measured track momentum and the energy deposition in each layer. The probabilities extracted from each layer are then multiplied, resulting in an array of 4 (electron, pion, proton, kaon) probabilities.
3.7.2 Results

The two methods provide similar results. Therefore in the following only those obtained with the Truncated-Mean method are discussed. Three detector configurations with different numbers and thicknesses of the layers providing PID information have been studied:

a) 4 layers $300 \, \mu m$ thick each. The performance of the present ITS in pp collisions was used to extract the specific energy loss information. A noise of 700 electrons and a charge collection efficiency of 95% were assumed in the simulation as well as an 11-bit ADC with a dynamic range of 20 MIP.

b) 7 layers $15 \, \mu m$ thick each. The dimension of the pixel is assumed to be $20 \times 20 \, \mu m^2$ and an analogue readout has been considered using an 8-bit ADC.

c) 3 layers $100 \, \mu m$ thick each + 4 layers $300 \, \mu m$ thick each. A Time-Over-Threshold (TOT) readout has been considered for the 3 layers of $100 \, \mu m$ thickness. It has been assumed a signal over noise ratio of 46, as reported in [58], and an 8-bit clock counter with a dynamic range of about 20 MIP, which implies a MIP signal of 325 ns for a 40 MHz clock. For the 4 layers of $300 \, \mu m$ thickness, the same readout as in case a) has been taken into account. For all layers the charge collection efficiency has been fixed at 95%.
**dE/dx resolution.** The dE/dx resolution as a function of the integrated thickness of the silicon layers is shown in figure 3.23. The resolution was evaluated as the ratio $\sigma_{G}[\pi]/M_{G}[\pi]$ for pions with a momentum $1.024 \text{ GeV}/c \leq p \leq 1.056 \text{ GeV}/c$. The dE/dx resolution goes from 20 % for 105 $\mu$m integrated thickness, corresponding to the configuration b), to about 9 % for 1.2 mm integrated thickness corresponding to the configuration a), and therefore to the present ITS.

**Particle species separation** The comparison of the three configurations for the particle species separation is reported in figure 3.24.

For the configuration with 4 layers of 300 $\mu$m it is possible to have a 3 sigma separation of kaons from protons with momentum lower than 1.2 GeV/c and pions with momentum lower than 0.7 GeV/c. This performance is very similar to the one obtained with configuration c). A worsening in the separation capabilities is found, as expected, using 7 layers of 15 $\mu$m silicon detector. The particle species separation for the b) configuration (monolithic) has also been studied assuming the detector performance of the MIMOSA chip [59]. In this simulation the charge sharing and the collection efficiency have been introduced. A threshold equal to 120 electrons and a Gaussian noise of 20 electrons have also been taken into account. It was found that the separation between the particle species is practically the same using a 6-bit or 8-bit ADC and it deteriorates significantly using a 4-bit ADC in the low momentum region.

![Figure 3.23: The dE/dx resolution as a function of the integrated thickness of the silicon layers used for the PID.](image)

![Figure 3.24: Pion to kaon separation (black circles) and proton to kaon separation (red triangles) in unit of sigma in the case of 4 layers of 300 $\mu$m (left panel), 7 layers of 15 $\mu$m (central panel) and 3 layers of 100 $\mu$m + 4 layers of 300 $\mu$m (right panel) silicon detectors. The horizontal lines correspond to a 3 sigma separation.](image)
the following, for the 7 layers of 15 µm silicon detector configuration, a readout based on an 8-bit ADC has been assumed.

**Efficiency and contamination.** In this study two data samples of different electron, pion, kaon and proton relative abundances have been generated: i) the relative abundances as extracted from 900 GeV pp data [60] and ii) from preliminary 2.76 TeV Pb–Pb data. The efficiency $\varepsilon(i;p)$ and the contamination $K(i;p)$ for the particle type $i$ (pions, kaons and protons) in each momentum bin $[p, p+\Delta p]$ are defined as follows:

$$
\varepsilon(i;p) = \frac{N_{\text{Good}}(i;p)}{N_{\text{True}}(i;p)}
$$

$$
K(i;p) = \frac{N_{\text{Fake}}(i;p)}{N_{\text{ID}}(i;p)}
$$

where $N_{\text{Good}}(i;p)$ is the number of particles of type $i$ correctly tagged as $i$, $N_{\text{True}}(i;p)$ is the number of generated particles of type $i$ in the momentum range $[p, p+\Delta p]$, $N_{\text{Fake}}(i;p)$ is the number of particles tagged as $i$ without being of type $i$ and $N_{\text{ID}}(i;p)$ is the total number of tracks identified as $i$ ($N_{\text{ID}}(i;p)=N_{\text{Good}}(i;p)+N_{\text{Fake}}(i;p)$).

The efficiency and the contamination in all detector configurations are shown in figure 3.25 and 3.26 for the two Monte Carlo samples with different $\pi^+$, $K^+$ and $p$ relative abundances. The results indicate that the PID performance that can be achieved with the hybrid configuration of c) is similar to that of the present ITS with 4 layers featuring analog readout, each of them 300 µm thick. With a 7 layer 15 µm thick detector configuration, the particle separation is still possible, although in a reduced momentum range.

**Figure 3.25:** Efficiency (closed symbols) and contamination (open symbols) as a function of the particle momentum assuming the relative abundances of $\pi^+$, $K^+$ and $p$ as extracted from pp data at $\sqrt{s} = 900$ GeV [60] for different configurations: 4 layers 300 µm thick (black circles), 3 layers 100 µm thick + 4 layers 300 µm thick each (red triangles) and 7 layers 15 µm thick silicon detectors (blue stars). Pions, kaons, and protons are shown in the left, middle and right panels, respectively. In all plots a line corresponding to a PID efficiency of 95 % is drawn as a reference.
The ALICE Collaboration

Figure 3.26: Efficiency (closed symbols) and contamination (open symbols) as a function of the particle momentum assuming the relative abundances of $\pi^+$, $K^+$ and $p$ as obtained from preliminary Pb–Pb data at $\sqrt{s_{NN}} = 2.76$ GeV for different configurations: 4 layers 300 $\mu$m thick (black circles), 3 layers 100 $\mu$m thick + 4 layers 300 $\mu$m thick each (red triangles) and 7 layers 15 $\mu$m thick silicon detectors (blue stars). Pions, kaons, and protons are shown in the left, middle and right panels, respectively. In all plots a line corresponding to a PID efficiency of 95% is drawn as a reference.

3.8 Timing requirements

The interaction rates assumed for the study described in this section are 2 MHz for pp and 50 KHz for Pb–Pb. These values may imply a significant pile-up rate in the detector, depending on the integration time of the readout, which has an impact on event reconstruction and analysis.

If the total occupancy from triggered and pile-up interactions significantly exceeds the occupancy of a central Pb-Pb collision, the reconstruction efficiency drops due to the ambiguity of the cluster to track association at inner layers. With 50 kHz interaction rate and 20 $\mu$s readout, on average one extra Pb-Pb collision will be read-out on top of the triggered event. With 50 $\mu$s readout time, one will 5 or more extra collisions in about 10% of the triggers. Figure 3.27 shows the degradation of reconstruction efficiency for triggered central Pb-Pb collisions piled up with five extra events, whose charged particle multiplicity is the average of the multiplicities in minimum bias Pb–Pb collisions.

To prevent the reconstruction efficiency loss, particularly at low $p_t$, one should improve the time resolution in the highest occupancy layers to a few $\mu$s (the same applies to layers with large extrapolation distances to others). Moreover, at least one additional low-occupancy outer layer should also have the same time resolution in order to provide the time-stamp for the cluster matching of the inner layers. Figure 3.27 also shows the reconstruction efficiency for pile-up events assuming that one or two innermost and one outer layers have a time resolution of 5 $\mu$s to be essentially free of the pile-up.

In pp collisions, where a very large pile-up is expected, the issue is the correct assignment of each track to its own interaction vertex. For primary tracks, assuming the vertexing and tracking capabilities of the upgraded ITS, the pile-up vertices should be separated from the triggered one by at least 1 mm in order to correctly reconstruct the triggered vertex. For the heavy flavour decay tracks, the $\sim$1 mm isolation should be enough for the short lived $\Lambda_{c}$, while for the B-mesons an isolation of $\sim$1 cm is required.

The left panel of figure 3.28 shows the fraction of isolated triggered pp vertices as a function of isolation distance to closest pile-up vertex and the number of integrated collisions per readout cycle. A Gaussian profile with $\sigma = 5$ cm is assumed for the luminous region along the beam direction.

Assuming a 2 MHz interaction rate and a 20 $\mu$s integration time (corresponding to 40 pile-up collisions),
Figure 3.27: Reconstruction efficiency of the upgraded ITS setup for triggered central Pb–Pb collision with (dotted line, in black) or without (full thick line, in black) the pile up of five extra events, whose multiplicity is the average one for minimum bias Pb–Pb collisions. The corresponding efficiencies for the cases where two or three detector layers have a time resolution of 5 µs are also shown, in particular for layers 2 and 3 (full thin line, in blue), layers 2 and 6 (dotted line, in red) and layers 2, 3 and 6 (dashed-dotted line, in green). In all cases 5% detection inefficiency per plane is assumed.

Figure 3.28: Left panel: Fraction of triggered vertices isolated from nearest pile-up vertex as a function of isolation distance and the number of integrated collisions per readout cycle in pp collisions. Right panel: overall gain in terms of triggered events that can be analyzed as a function of the isolation distance and the number of integrated collisions per readout cycle in pp collisions. Gaussian profile with \( \sigma = 5 \) cm is assumed for the luminous region along the beam.

approximately half of the triggered vertices will not be separated by 1 mm or more from those of the pile-up collisions, while for an analysis requiring \( \sim 1 \) cm vertex separation, less than 10% of triggered vertices can be used. The right panel shows the overall gain in terms of triggered events that can be analyzed as a function of the isolation distance and the number of integrated collisions per readout cycle.

The pile up ambiguities would be drastically reduced if at least one point for each track carries a precise time-stamp.

3.9 Radiation environment

Detailed studies have been done in the past for the expected dose in the ALICE detector according to the standard running scenario [61]. The dose values have been recently re-evaluated, as reported in [62]. The hadron flux values, which are given in 1 MeV neutron equivalent, are taken from [61] and
have been renormalized by a factor 0.94. The latter is the ratio between the dose values quoted in [62] and in [61]. Within these notes, the radiation is dominated by pp and high-luminosity Ar–Ar runs, the Pb–Pb collisions representing only about 1/6 of the time integrated radiation load [62]. The factor 1/6 is an overestimate because the computations were done taking into account the formerly expected higher multiplicity environment of ion collisions, corresponding to \(dN_{\text{ch}}/d\eta = 8000\) for central Pb–Pb collisions. Scaling down the formerly overestimated multiplicity, and at the same time scaling up the interaction rates (to 2 MHz for pp and 50 KHz for Pb–Pb, compare [5]), one obtains a final scaling factor of 4.99 with respect to the running scenario mentioned in the notes cited above.

In figure 3.29, the expected doses and hadron fluences as a function of the radial distance to the beams are shown for a 10 year running scenario at high interaction rates, corresponding to 2 MHz for pp and 50 KHz for Pb–Pb.

The expected radiation levels are also summarized in table 3.5 for the radial positions corresponding to the upgraded ITS. An extra safety factor of \(\approx 2\) has been included with respect to figure 3.29.

![Figure 3.29](image)

**Figure 3.29:** Integrated dose and hadron fluences (in 1 MeV neutron equivalent) for a 10-year running scenario of the LHC (with high interaction rate; 2 MHz for pp; 50 KHz for Pb–Pb) as a function of the radial distance to the beams.

**Table 3.5:** Expected radiation levels for the upgraded ITS (over 10 years at high interaction rates, see text for details) including a safety factor of \(\approx 2\).

<table>
<thead>
<tr>
<th>Radius [mm]</th>
<th>1 MeV n [cm(^{-2})]</th>
<th>TID [krad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>22</td>
<td>(1015 \times 10^{11})</td>
</tr>
<tr>
<td>Layer 2</td>
<td>28</td>
<td>(633 \times 10^{11})</td>
</tr>
<tr>
<td>Layer 3</td>
<td>36</td>
<td>(390 \times 10^{11})</td>
</tr>
<tr>
<td>Layer 4</td>
<td>200</td>
<td>(29 \times 10^{11})</td>
</tr>
<tr>
<td>Layer 5</td>
<td>220</td>
<td>(27 \times 10^{11})</td>
</tr>
<tr>
<td>Layer 6</td>
<td>410</td>
<td>(20 \times 10^{11})</td>
</tr>
<tr>
<td>Layer 7</td>
<td>430</td>
<td>(19 \times 10^{11})</td>
</tr>
</tbody>
</table>

### 3.10 Further studies

#### 3.10.1 Redundancy

This paragraph deals with the detector performance in the event of a dramatic reduction of the detector efficiency. In particular we compare the performances of the 7-layer upgrade scenario discussed in section 3.6, whose characteristics are summarized in table 3.4, with that of another configuration with 2 more
layers (9-layer configuration) with the same intrinsic resolution as the others. The positions of the two extra layers in this new configuration have been optimized to provide the best tracking efficiency in the event of one layer being completely dead. The results of the study suggest to have one extra layer between the most external doublet and the intermediate one and the other close to the innermost triplet. The radial positions of this optimized configuration are thus \( \{2.2, 2.8, 3.6, 4.2, 20.0, 22.0, 33.0, 41.0, 43.0\} \) cm. In figure 3.30 and 3.31 the efficiency and the momentum resolution as a function of \( p_t \) are shown for the two configurations with 7 and 9 layers, respectively, in the case of one dead layer. The standard case of all layers properly working is also shown as reference. The pointing resolution, which depends mainly on the first two layers, does not change. The result of this study proves that the configuration with 9 layers would prevent the drop of the tracking efficiency for those tracks where a hit in an intermediate layer has not been produced.

**Figure 3.30:** Tracking efficiency (left) and momentum resolution (right) for the 7-layer upgrade scenario defined in table 3.4. The radial distances of the layers are \( \{2.2, 2.8, 3.6, 20.0, 22.0, 33.0, 41.0, 43.0\} \) cm. The scenario where layer 3 at 3.6 cm (cyan) or layer 6 at 41.0 cm (green) is dead is compared to the case of all layers properly working.

**Figure 3.31:** Tracking efficiency (left) and momentum resolution (right) for the new configuration with two extra layers, see the text for details. The radial distances of the layers are \( \{2.2, 2.8, 3.6, 20.0, 22.0, 33.0, 41.0, 43.0\} \) cm. The scenario where layer 3 at 3.6 cm (cyan) or layer 7 at 33.0 cm (green) is dead is compared to the case of all layers properly working.

### 3.10.2 Performance of modified upgrade scenarios

In this paragraph we show how the performance of the upgraded detector would improve or worsen, by considering different values for the intrinsic precision and the material budget with respect to the baseline, i.e. 7 layers of 0.3 % \( X_0 \) and 4 \( \mu \)m intrinsic resolution. The effect of having the innermost
layer at an even smaller radius will be also discussed, which requires a beam pipe at a reduced radius. In particular, the following configurations have been considered:

- all layers presenting a larger material budget \( X/X_0 = 0.5\% \) and an intrinsic resolution of 6 \( \mu m \);
- the baseline configuration but the innermost layer (L0) having a smaller material budget of \( X/X_0 = 0.1\% \) and unchanged intrinsic resolution of 4 \( \mu m \);
- the previous configuration but assuming a beam-pipe thickness of 500 \( \mu m \) instead of 800 \( \mu m \);
- the previous configuration but the first layer at a radius of 1.9 cm instead of the baseline 2.2 cm, and a beam pipe of 1.67 cm radius and 500 \( \mu m \) thickness.

In the top panels of figure 3.32 the \( r\phi \) pointing resolution to the vertex as a function of \( p_t \) for these modified configurations is compared to that of the present detector and the upgrade baseline (upgraded ITS) configurations. The \( z \) pointing resolution is shown only for the present ITS detector, because for all upgrade scenarios it is very similar to the \( r\phi \) distribution of the corresponding configuration. The transverse momentum resolution as a function of \( p_t \) is shown in the bottom panels of figure 3.32 for the same configurations. At \( p_t \approx 0.4 \) GeV/c an additional factor 2 of improvement would be obtained for the pointing resolution, with respect to the baseline configuration, by considering the configuration with the innermost layer at a radius 1.9 cm.

![Graphs showing pointing resolution and transverse momentum resolution for different configurations of the ITS detector](image)

**Figure 3.32:** Top panels: pointing resolution to the vertex of charged pions as a function of the transverse momentum for the current ITS and different options of the upgraded detector, see text for details. Bottom panels: transverse momentum resolution for charged pions as a function of \( p_t \) for the current ITS and different options of the upgraded detector. Left and right panels show the ITS stand-alone and the ITS-TPC combined tracking, respectively.
### 3.10.3 Layer geometry

Mechanically, the layers can be assembled to form a barrel based on planar staves of finite width and, optionally, by introducing overlaps between adjacent layers to have good hermeticity. In particular for the innermost layer the specific assembly adopted can have an influence on the impact parameter resolution.

The overlaps in the azimuthal direction can be realized using either a “turbo-like” geometry or a “two-radii” geometry. Both options would introduce an azimuthal $\phi$ dependence of the impact parameter resolution due to the larger material budget in the directions of the overlaps. Apart from the overlaps, a modulation of the impact parameter resolution as a function of $\phi$ is also due to the non constant radial distance $r(\phi)$ of the points of each stave. On the one hand, this latter effect is less relevant for a stave of small width; on the other hand, the number of overlaps (equal to the number of staves) would be larger and therefore the average material budget and impact parameter resolution would increase.

In figure 3.33 the pointing resolution as a function of $\phi$ is shown for the turbo-like and two-radii geometry for the case of two stave widths, a “small” (about 1.45 cm) and a “large” (about 1.9 cm) one, assuming an overlap between adjacent staves of 0.2 cm. In this simulation, the upper part of each stave, corresponding to the region of the overlap, is assumed to be dead; therefore for tracks crossing the overlaps only one space point is produced, as for the regions without the overlaps. Given this hypothesis, for the turbo-like geometry it has been assumed that the insensitive region would be that of the border with larger $r$. In figure 3.33 the case of an ideal cylindrical layer is also shown for comparison.

![Figure 3.33: Pointing resolution to the vertex versus $\phi$ for charged pions with transverse momentum $p_t$ of 0.2 GeV/c. Two different layer geometries are considered: a “turbo-like” geometry (left panel) and a “two-radii” geometry (right panel). In all cases the minimum radius of the innermost layer is assumed to be $r_0 = 2.2$ cm and an overlap region of 0.2 cm is considered. The green curves show the case of staves of width equals to 1.5 cm and 1.4 cm for the turbo-like and two-radii geometry, respectively. The blue curves show the case of a larger stave width, in particular 2.0 cm and 1.8 cm for the turbo-like and two-radii geometry, respectively. The average values of the pointing resolution is indicated with the thick lines with the same colors. As a reference, also the ideal case of a perfect cylindrical geometry is shown in red.](image)

The dependence of the mean pointing resolution as a function of the stave width, in the two geometries, is shown in figure 3.34 for different values of the overlaps between adjacent staves, assuming the minimum radius of this innermost layer equals 2.2 cm. A minimum is observed at a width which depends on the size of the overlaps.

For the first layer two different cases have been considered in terms of azimuthal segmentation in staves, 12 and 14, for both layouts (turbo and two-radii). A dead area of 0.2 cm is assumed to be placed only on one side of each stave. The outcome of this study is presented in figure 3.35, which suggests that the turbo-like geometry is slightly better than the two-radii one, the mean pointing resolution being smaller...
Figure 3.34: Mean pointing resolutions to the vertex versus the width of the stave for charged pions with $p_t$ of 0.2 GeV/$c$, for different sizes of overlaps. The left panel shows the case of a turbo-like geometry, the right panel that of a two-radii geometry.

Figure 3.35: Pointing resolution to the vertex versus $\phi$ for pions with transverse momentum $p_t$ of 0.2 GeV/$c$. The turbo-like and two-radii geometries are compared in configurations with either 12 or 14 staves, see text for details.

by a few percent. The reason is that in the turbo-like geometry the dead part of all staves can be placed at the larger radius; therefore the tracks crossing an overlap would have the hit on the stave closer to the vertex and thus a better pointing resolution to the main vertex. No significant difference is observed between the 12 and 14 stave geometries.

In chapter 5 the various possible solutions for the mechanical assembly of the upgraded detector are discussed. The radii that can be obtained from the mechanical point of view with given assumptions in terms of clearance, dead area, chip dimension, etc. are slightly different from those of the simplified geometry used to define the baseline configuration of the upgraded ITS. However, the effect of these variations on the tracking performance is minor, as can be seen in figure 3.36.
Figure 3.36: Pointing resolution as a function of the azimuthal angle for charged pions with $p_t$ of 0.2 GeV (left panel) and efficiency versus $p_t$ (right panel) for the ideal geometry used to define the baseline upgraded ITS configuration (in red) and for a realistic turbo-like assembly with 10 staves for the innermost layer (in black). The horizontal black line in the left panel shows the average over $\phi$ of the realistic assembly.
Chapter 4

Detector Technical Implementation

4.1 Introduction

This chapter presents the different technical options under consideration for the upgrade of the ALICE ITS. A fully upgraded ITS will consist of at least 7 layers of silicon tracking detectors as described in chapter 3. The number of layouts under study has been reduced to two which follows an approach of the complexity of the system in terms of the number of different components and designs.

- **Layout 1**: The layers will be made entirely of silicon pixel detectors. All layers will provide the same accuracy in pointing resolution of 4 µm.

- **Layout 2**: The innermost 3 layers will be made of silicon pixel detectors, followed by 4 layers of double sided silicon strip detectors. This layout will provide an optimal particle identification.

Layout 2 takes into account that the spatial precision in rφ needed to optimize the tracking efficiency is comparable to the one provided by silicon strip detectors with a geometry similar to the current detector. The fake hit rate due to hit ambiguities in the strip layers will be less than 5%. At lower radii the high occupancy will limit the use of strip detectors. Layout 1 will provide an improved momentum resolution in ITS standalone tracking mode as is shown in figure 3.17 and a further improved tracking efficiency in the low momentum region (see figure 3.18).

A key requirement for both layouts is the need to minimize the material budget for the innermost layers. Furthermore, the expected radiation levels for those layers will require a careful validation of the different technologies in terms of radiation resistance. Both hybrid and monolithic pixels are under consideration for the innermost pixel layers, while, due to the high cost of bump bonding, the layers at larger radii can only be equipped with monolithic pixel detectors in the case of Layout 1 and with strips in the case of Layout 2.

In the following sections the technical requirements, the operating conditions and the constraints are presented. The different technologies and architectures under consideration are discussed and plans and first results from prototypes are reported.

4.2 Technical Specifications

The technical specifications are based on the requirements defined in chapter 3. The following table 4.1 summarizes the key technical specifications for pixel and strip detectors.
Table 4.1: Technical specification for the pixel and strip detectors for the ITS upgrade.

<table>
<thead>
<tr>
<th>Pixels:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size (rφ)</td>
<td>20-30 µm</td>
</tr>
<tr>
<td>Pixel size (z)</td>
<td>20-50 µm</td>
</tr>
<tr>
<td>Track density (inner layer)</td>
<td>up to 85 cm$^{-2}$</td>
</tr>
<tr>
<td>Material budget [% Xo]</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>Signal to noise ratio (1 MIP)</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Power density</td>
<td>0.25-0.5 W/cm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strips:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip pitch (rφ)</td>
<td>95 µm</td>
</tr>
<tr>
<td>Strip length (z)</td>
<td>20 mm</td>
</tr>
<tr>
<td>Stereo angle</td>
<td>35 mrad</td>
</tr>
<tr>
<td>Sensor thickness</td>
<td>300 µm</td>
</tr>
<tr>
<td>Power consumption</td>
<td>≤ 0.5 mW/channel</td>
</tr>
<tr>
<td>Noise</td>
<td>≤ 400 e⁻rms</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>≈ 10 bits</td>
</tr>
</tbody>
</table>

The reduction of the pixel size allows one to improve the pointing resolution and tracking efficiency in rφ and the background rejection capability by using a reduced pixel size in the z direction. The target pixel size is ≈ 20-30 µm in rφ and ≈ 20-50 µm in z depending on the technology choice.

The geometry of the strip detectors considered for the outer layers in layout 2 will require a strip pitch of about 95 µm and a small strip inclination with respect to z direction, resulting in a pointing resolution of about 20 µm in rφ and about 800 µm in z. The strip length is foreseen to be 2 cm to decrease the cell size and extend their use to lower radii.

The maximum track density expected for the first layer is about 100 tracks per cm². Applying a factor of two safety margin and considering a pixel of (20 × 20) µm, the event rate per pixel is ≈40 Hz at an interaction rate of 50 kHz. Therefore, pile-up at the pixel level is not a major concern and long shaping times on the order of µs can be considered. A pixel power budget of 0.3-0.5 W/cm² seems feasible to achieve using a deep or very deep sub micron CMOS technology and an optimized front-end architecture.

Recent developments in ADC design allow the development of a strip detector readout chip that incorporates a low power ADC with 10 bit resolution and a 40 Msample/s acquisition speed. The long shaping time of 1-2 µs will help to keep the power consumption low, aiming at a total of 0.5 mW/channel.

A readout time of 50 µs will result in average in a pile-up of 2.5 additional events for 50 kHz Pb–Pb collisions and 100 additional events for 2 MHz pp collisions. As shown in section 3.8, the pile-up has a marginal effect on the standalone reconstruction efficiency for Pb–Pb collisions, while, in order to separate primary and secondary vertices from different interactions, a time tagging of tracks with a resolution in the order of 2 µs is required. This time tagging information can either be provided by at least one dedicated ITS layer or by the TOF detector. However, only 80% of the ITS tracks with a p_t larger than 300 MeV/c are in the TOF acceptance.

The newly suggested scheme of a Fast Trigger Processor (FTP) for the ALICE upgrade uses the ITS as an input for the L1 trigger decision. The L1 latency of 10 µs for p-p collisions (20 µs for Pb-Pb collisions) requires fast signal processing and a custom designed trigger processing unit.
The data readout on reception of a L0/L1 trigger decision can then be used by the High Level Trigger (HLT) to form a L2 and L3 decision.

- **The material budget** is one of the most critical parameters for the innermost layers, where it defines the ultimate limit of the achievable pointing resolution. A material budget of 0.3% of \(X_0\) for monolithic and of 0.41% of \(X_0\) for hybrid pixel detectors is considered a challenging, but feasible limit. The contributions of the different components to the overall material budget are listed in table 4.2.

- For the inner layer, assuming 100 hits per \(\text{cm}^2\) and a 40 bit word per cluster for the digital information, a **transmission bandwidth** of \(\approx 80\ \text{Mbits}/(\text{s cm}^2)\) is needed. Assuming a \(1/r^2\)-dependency of the number of hits per \(\text{cm}^2\) the data throughput will therefore decrease for the layers at higher radii, reaching a value of only 0.2 Mbits/(s \(\text{cm}^2\)) for the outermost layer.

- The information on the signal amplitude will be preserved for the strip sensors, since charge interpolation will be used to improve the space resolution and the fake hit rejection well beyond the nominal strip pitch. Assuming a noise level of 400 electrons will allow to measure signals as low as 4000 electrons with an adequate S/N ratio. The ratio between the maximum expected signal (20 MIPS) and the noise yields a dynamic range of 10 bits. In case of a full monolithic implementation of the new ITS, the pixel sensors might be also equipped with high resolution charge read-out to maintain the **particle identification** capability.

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**Table 4.2:** Material budget goals for monolithic and hybrid silicon pixel detectors. The contribution of the support structure is expected to be on the order of 0.08% \(X_0\) (see chapter 5).

<table>
<thead>
<tr>
<th></th>
<th>Monolithic Pixels</th>
<th>Hybrid Pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Target</td>
<td>0.30% (X_0)</td>
<td>0.41% (X_0)</td>
</tr>
<tr>
<td>Silicon sensor</td>
<td>-</td>
<td>0.11% (X_0) (100 (\mu)m)</td>
</tr>
<tr>
<td>Silicon ASIC</td>
<td>0.053% (X_0) (50 (\mu)m)</td>
<td>0.053% (X_0) (50 (\mu)m)</td>
</tr>
<tr>
<td>Other components</td>
<td>0.25% (X_0)</td>
<td>0.25% (X_0)</td>
</tr>
</tbody>
</table>

---

**4.2.1 Radiation Effects**

With respect to the current detector, the innermost pixel layer will move about 17 mm closer to the interaction point. The yearly radiation levels as discussed in chapter 3 are summarized for the first layer in table 4.3. A safety factor of 2 has been included.

Radiation will induce damage both in the front-end electronics and in the sensors. The Total Ionizing Dose (TID) will cause charge trapping in the gate oxide of CMOS transistors and in the thick oxide employed for device and interconnect isolation. This will change the threshold voltage of both normal and parasitic devices and can give rise to leakage currents between drain and source of NMOS transistors and in between neighboring transistors. In the ASICs now in use in the LHC, which are implemented in a 0.25 \(\mu\)m CMOS process, a very high level of radiation tolerance was achieved through the systematic use of Enclosed Layout Transistors (ELT) and guard-rings. A reduction of the TID sensitivity has been observed moving to smaller technology nodes. This improvement is mostly attributed to the thinner gate

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**Table 4.3:** Expected yearly radiation levels for the first layer for a high interaction rate scenario (compare table 3.5).

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Radius [mm]</th>
<th>1 MeV n (\text{cm}^{-2})</th>
<th>TID [krad]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22</td>
<td>(1 \times 10^{15})</td>
<td>685</td>
</tr>
</tbody>
</table>
oxides. Measurements in 0.13 \( \mu m \) CMOS technologies [63] suggest that ELT transistors may no longer be needed. The target technology nodes for the ALICE ITS upgrade are described in subsection 4.3.1.

For hybrid pixel detectors the sensor is a separate chip produced on high resistivity silicon. In the case of monolithic silicon detectors the detection volume is implemented in the readout chip itself, either as a layer of epitaxial silicon of defined thickness or as the bulk material on which the readout circuitry is produced. In general the radiation induced damage to the silicon lattice will lead to a macroscopic degradation of the sensor characteristics. In hybrid pixel detectors this manifests itself as an increase in leakage current, a change in depletion voltage in case of a depleted operation and in trapping of the signal charge [64]. The leakage current will increase proportionally to the 1 MeV neutron equivalent fluence [64].

Current monolithic silicon pixel detectors produced in 0.35 \( \mu m \) CMOS technology can be operated to irradiation levels of some \( 10^{12} \text{ n}_{eq} \text{ cm}^{-2} \) and a few hundred krad [65]. While this is fully compatible with the radiation levels expected for the outer layers of the ITS, the requirements for the first two layers are more stringent. Novel technologies in 0.18 \( \mu m \) like the INMAPS technology (see section 4.5.2) or in 0.09 \( \mu m \) CMOS like LEPIX (see section 4.5.3) will very likely improve the radiation resistance and will allow the use of monolithic sensors even for the layers closest to the interaction point. A key issue here is also the choice of architecture which can improve the radiation resistance of a given circuit.

4.2.2 Further Reduction of the Material Budget of the first layer

First results from simulations show that a reduction of the material budget of the first layer to 0.1 \( \%X_0 \) will further enhance the sensitivity to decays like the \( \Lambda_c \). This goal can only be achieved considering monolithic pixel detectors thinned to at least \( \approx 50 \mu m \) and mounted on a very lightweight carbon fibre frame. To minimize the material due to interconnections a stitching technology has to be considered to connect power and signal lines from one die to the next, overcoming the limitations of the reticle size. This technology available in industry has to be validated to match with a design and architecture for the ALICE ITS upgrade but would provide the possibility to build an ultra-light tracking layer very close to the interaction point.

4.3 Technology Options for Pixel Detectors

A number of technologies - each representing a different level of maturity - could potentially fulfill the requirements of the inner ITS layers. The options can be divided into two groups: monolithic and hybrid silicon pixel detectors. A schematic view of both concepts is shown in figure 4.1. In the hybrid pixel detector concept the sensor and the front-end electronics are implemented in two separate silicon chips, while in the case of monolithic pixel detectors the sensing part is incorporated inside the ASIC.

Hybrid pixel detectors have been the choice for the current LHC experiments because they provide clean, time stamped, unambiguous 3-dimensional hit information and they are radiation tolerant. In the hybrid approach the front-end chip and the sensor are produced on two different wafers and then connected using bump bonds. Present bump bonding techniques are limited to pitches of 30-50 \( \mu m \). However, the recently introduced Cu-pillar technology may reduce substantially this limit in the near future. Currently, bump bonding represents one of the main cost factors for the production of hybrid pixel detectors and prevents their application to larger surfaces.

Monolithic pixel sensors use as the detection volume the p-type epitaxial layer grown on the highly p-doped silicon substrate during standard CMOS microelectronic processes. The epitaxial layer typically has a thickness of 10-18 \( \mu m \), thus the most probable signal generated by a MIP is of the order of \( \approx 10^3 \) electrons assuming an average production of 80 e-h pairs/\( \mu m \). In the standard monolithic sensor the epitaxial volume is un-depleted and the charge generated by an ionizing particle is collected through thermal diffusion by regularly implanted NWELLs. CMOS pixel sensors typically feature pixel dimensions of...
20×20 μm². Additionally, they allow the integration of the complex signal processing circuitry on the same substrate as the sensitive volume. Therefore they offer a significant reduction in cost since only CMOS wafers are used. The resistance of CMOS sensors to the radiation levels expected for the inner layers of the ITS upgrade needs to be proven and is under detailed study at the moment. In recent years CMOS sensor technology has reached an adequate level of maturity to be chosen to equip the vertex detectors of the STAR experiment [66] which is currently under construction.

4.3.1 Technology Node

CMOS 0.13 μm technology has become a standard for the design of front-end electronics. Complex ASICs like the FEI4 [69] for the ATLAS upgrade and MediPix [70] have been implemented in this process. A 0.13 μm CMOS process offers several advantages with respect to the 0.25 μm CMOS technology employed for most of the front-end chips instrumenting the present LHC detectors today. Firstly, the technology is inherently more radiation hard. Therefore, an adequate radiation tolerance can be achieved without the systematic use of Enclosed Layout Transistors (ELT). This favors a more compact layout, allowing in addition the use of commercial standard cells for the digital logic. Secondly, the smaller capacitance of the digital gates and the lower power supply voltage reduces the digital power consumption. Thirdly, the technology is equipped with several options (triple well transistors, deep moats, etc...) which allow an effective reduction of the interference of the digital blocks to the analogue ones. However, the 0.13 μm CMOS process presently used in the hybrid pixel developments does not offer a sufficiently thick epitaxial layer as required by the design of monolithic pixel detectors.

TOWER/JAZZ¹ offers a 0.18 μm CMOS process optimized for imaging applications. This technology offers two interesting options: a high resistivity epitaxial layer up to 18 μm thick and quadruple well transistors. The latter feature allows the fabrication of both PMOS and NMOS transistors inside the pixel area, thus making more complex in-pixel signal processing possible. This technology could also be considered for a hybrid front-end if it will be proven to be significantly cheaper than the 0.13 μm technology and radiation hard enough to avoid the burden of ELT usage.

¹TOWER/JAZZ, http://www.jazzsemi.com/
4.3.2 Pixel Front-End Architecture

The front-end architecture has to meet the requirements as outlined earlier in this chapter. For the strip detectors it is foreseen to follow the development of an ASIC that includes a 10-bit ADC with low power dissipation. Further details are described in section 4.7. The requirements for pixels are very demanding in terms of material budget, power budget and cell size. Several different pixel front-end architectures are being studied for the ALICE ITS upgrade:

- Rolling shutter architecture
- ORTHOPIX readout scheme
- Sub-matrix sparsified readout

The rolling shutter architecture is based on the concept that the pixel matrix is read periodically row by row. During the readout period, in this context also referred to as integration time, all the pixels remain sensitive and all the hits will be registered. This architecture is intrinsically dead-time free, but can generate event pile-up in case that the integration time is larger than the mean time between events. As discussed in section 3.8 an integration time of about 20 $\mu$s would fulfill the readout requirements for the Pb-Pb case, while an integration time of a few $\mu$s would be necessary for p-p running to unambiguously assign tracks to the different interactions. A possible implementation of the rolling shutter architecture is presented in section 4.5.1 which gives details on the proposed MISTRAL chip for ALICE.

The ORTHOPIX readout architecture is based on multiple projections in a pixel matrix beyond X and Y to deal with a given occupancy. The method compresses the hit information to a fixed data size and moves it to the periphery immediately (within one clock cycle), where it can be stored and used for triggering and readout. The method minimizes digital power consumption because distribution of the clock signal across the pixel matrix is no longer needed, and because the data compression significantly reduces the amount of data to be treated. The latter also reduces the area for the peripheral readout circuitry. The maximum occupancy sustainable without information loss and the compression ratio are dependent on the number of pixels included in one sub-matrix and on the number and the choice of the additional projections. The size of a sub-matrix can be made programmable on-chip to adapt and prevent information loss with sufficient margin for a given hit occupancy. Assuming a 50 kHz Pb-Pb interaction rate and a pixel size of $10 \times 10$ $\mu$m, a preliminary analysis indicates a data reduction to about 4 kb per event and per cm$^2$ for the inner pixel layer resulting in a data rate of 200 Mb/s/cm$^2$. The architecture has now been integrated in the ALICE simulation framework and will also be further studied within the LEPIX development as described in section 4.5.3.

The sub-matrix sparsified readout architecture follows an approach where the chip matrix is subdivided into a set of small sub-matrices. In each sub-matrix each pixel cell is connected to a priority encoder which registers the addresses of the hits in every clock cycle. The processing in each sub-matrix is carried out in parallel. All priority encoders of the full matrix are connected to the end-of-column electronics. This architecture allows a real sparsified readout in every sub-matrix which features a readout time that scales with the event multiplicity. If the size of the sub-matrices is defined such that the average number of hits per sub-matrix is one or less, such a readout scheme allows readout times well below 1 $\mu$s to be reached. Detailed studies are done to investigate if such an architecture can be implemented e.g. in the INMAPS process (see 4.5.2).

4.3.3 Overview of Different Technical Implementations

Monolithic pixels, implemented in standard CMOS processes, can only use NMOS transistors in the pixel cell. The NWELLs needed for PMOS transistors fabrication would act as competing charge collection
centers with respect to the main diode. Therefore, the front-end cell has to be kept very simple and a serial readout scheme is needed. The use of a deep PWELL underneath the PMOS devices acts as a shield for the generated charges and allows to implement more complex electronics in the pixel cell. Monolithic pixels with a hybrid-like front-end, embedding preamplifier, shaper and discriminator inside the pixel cell, have been recently demonstrated using the INMAPS process [68] at TOWER/JAZZ.

An emerging technology in the field of monolithic sensors consists of using standard very deep sub-micron CMOS processes fabricated on uniformly doped high resistivity wafers, called LEPIX. This opens the possibility of a substantial depletion of the sensing volume and of charge collection by drift, therefore increasing the signal-to-noise ratio and reducing the effects of radiation induced charge trapping.

All these different technical implementations described above will allow the achievement of the spatial resolution required for the ALICE ITS upgrade. A key requirement that needs detailed discussion is the material budget limitation for the innermost layers of 0.3-0.5% $X_0$. This aim is unprecedented in any of the presently operated pixel detectors. The current pixel layers in ALICE have achieved a total radiation length of 1.14% $X_0$ per layer. However, the STAR Heavy Flavor Tracker (HFT), now under construction and based on CMOS sensors, has a material budget of 0.37% $X_0$ per layer [66]. This shows that the target material budget for the ITS upgrade is within reach.

Monolithic sensors will have a reduced silicon contribution with respect to hybrids. At present CMOS sensors are regularly thinned down to 50 $\mu$m (0.05% $X_0$). Hybrid pixels have already achieved sensor thicknesses of 100 $\mu$m. First tests are currently ongoing to reduce the front-end chip thickness of hybrid pixel detectors to 50 $\mu$m so that a final radiation length of 0.16% $X_0$ for sensor and chip will be achieved. A sizable contribution to the overall material budget will in both cases originate from the support, cooling, and interconnection. Therefore, an optimized power management is a key issue.

The power consumption can be considered separately for the digital and analogue parts of the front-end ASIC. The power dissipation of the digital section depends on the data rate and on the processing architecture. Therefore, it will be of the same order for both monolithics and hybrids.

The analogue power consumption primarily depends on the needed Signal to Noise Ratio (SNR). For a fixed power budget, the series noise contribution of the front-end can be reduced by increasing the shaping time. Long integration times, on the other hand, increase the parallel noise. Therefore, a low leakage current even after irradiation is mandatory to obtain a good SNR with a low bias current. For a given shaping time and a fixed power budget, the series noise is limited by the sensor capacitance. Therefore, a good figure of merit to estimate the minimum power consumption achievable is the ratio between the charge generated in the sensor (Q) and the corresponding parasitic capacitance (C). For a 100 $\mu$m thick sensor a minimum ionizing particle generates approximately 8000 e$^-$-hole pairs, while the parasitic capacitance is about 30 fF. Thus the resulting Q/C is around 50 mV. In monolithic detectors with an epitaxial layer 15 $\mu$m thick and a parasitic capacitance of 3-5 fF, the Q/C amounts to 40-60 mV. Monolithic pixels with a depletion layer of the order of 50 $\mu$m would yield a Q/C ratio in the 200-300 mV range. Therefore they could offer a very favorable analogue power figure. For this reason and for its potential radiation hardness due to the charge collection by drift, the approach pursued by LEPIX is considered of significant interest even though it is still in a very early phase of development. Table 4.4 summarizes the main features of the technologies considered for the ALICE ITS upgrade.

### 4.4 Hybrid Pixel Detectors

Current state of the art pixel detectors used, for example, in the present LHC experiments are hybrid silicon pixel detectors. The silicon presents one of the main contributions to the material budget in the current detectors. The following table summarizes the silicon thicknesses used in the present LHC
Table 4.4: Key parameters for different pixel technologies under consideration for the ALICE ITS upgrade.

<table>
<thead>
<tr>
<th></th>
<th>Hybrid Pixels</th>
<th>Mon. Pixels (MAPS)</th>
<th>Mon. Pixels (LEPIX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maturity</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Pixel size</td>
<td>30µm</td>
<td>20µm</td>
<td>30µm</td>
</tr>
<tr>
<td>Material budget (Si)</td>
<td>≈0.16% X₀</td>
<td>≈0.05% X₀</td>
<td>≈0.05% X₀</td>
</tr>
<tr>
<td>SNR</td>
<td>&gt;50</td>
<td>≈40</td>
<td>&gt;50</td>
</tr>
<tr>
<td>L1 trigger</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Timestamp</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Cost/cm²</td>
<td>-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>&gt;10^{14}nₑq</td>
<td>≈10^{13}nₑq</td>
<td>&gt;10^{13}nₑq</td>
</tr>
</tbody>
</table>

experiments and the target values for an upgraded ITS. The target thickness of the front-end ASIC and the sensor is set to 50 µm and 100 µm, respectively. This will allow the achievement of a material budget contribution of 0.4-0.5% X₀ as required for an upgraded ITS. This goal represents a significant improvement compared to the present systems. However, as will be shown in the following paragraphs, it represents a realistic goal to be achieved. First results from prototypes are presented in subsection 4.4.2.

4.4.1 Sensor Technologies

The use of thin silicon sensors, with thicknesses in the range of 100 µm will require novel developments in terms of processing. The technical challenges to be met in this respect are the procurement of thin blank detector grade wafers and the processing of such thin wafers in the standard production lines.

The radiation environment expected for the innermost layers in ALICE is still relatively modest, compared to the pixel layers of ATLAS and CMS (see tables 4.3 and 4.5). It is therefore assumed that at the end of the operating time the sensors will not yet suffer from strong reverse annealing effects. The sensors of the innermost layers which are exposed to the highest fluences and doses will operate close to the type inversion region.

Table 4.5: Summary of thicknesses used in the current LHC hybrid pixel detectors and target values for a hybrid pixel detector for the ALICE ITS upgrade.

<table>
<thead>
<tr>
<th></th>
<th>ASIC thickness [µm]</th>
<th>Silicon sensor thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE pixel</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>ALICE ITS upgrade</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>ATLAS pixel</td>
<td>180</td>
<td>250</td>
</tr>
<tr>
<td>CMS pixel</td>
<td>180</td>
<td>285</td>
</tr>
</tbody>
</table>

Most silicon pixel sensors have a typical thickness of about 200-300 µm. The processing of thinner sensors increases the risk of damage, i.e. breakage of the wafer, during one of the processing steps. Therefore the aim of using silicon pixel sensors with 100 µm thickness as foreseen for the ALICE ITS upgrade is a new challenge in terms of processing and production. The use of support and carrier wafers to protect a thin wafer during processing is mandatory. The carrier wafers are attached to the sensor wafer either by means of oxide bonding or specific glues. An alternative to using carrier wafers is the use of epitaxial silicon sensor wafers. In this case the detection volume is the epitaxial layer on a low resistivity CZochralski (CZ) silicon wafer. The CZ wafer acts as a support wafer during bumping and can be thinned leaving only a very thin layer to provide the ohmic contact for the sensor back-side. First successful results from prototype tests of epitaxial silicon sensors are presented in the following section.

An additional aspect of the material budget contribution of the silicon sensor comes from the fact that standard pixel sensors use multiple guard rings to degrade the potential from the pixel matrix to the
dicing edge. In a p-in-n sensor the matrix which is connected to the electronics is held close to ground potential, while the edge is at the same potential as the sensor backplane. In the case of the current ALICE pixel detector the sensor is biased at 50 V. In order to degrade the potential to the edge and to achieve a high current stability of the sensor the guard rings and the edge region range from several hundred µm up to a mm. This region is inactive with respect to registering particles and causes gaps between neighboring sensors. In a tracker configuration this is partially recovered by placing the modules in an overlap configuration. The use of edgeless pixel sensors with very slim edges below 100 µm would allow the placement of sensors very close to each other with almost no dead zone in between and to reduce the overlap between modules. A schematic view of a sensor with a multi-guard structure and an edgeless sensor is shown in figure 4.2. Prototyping work on edgeless sensors has already started and is described in the following section.

![Schematic view of a sensor with multi-guard structure and of an edgeless sensor using an n⁺ edge implantation.](image)

**Figure 4.2:** Schematic view of a sensor with multi-guard structure and of an edgeless sensor using an n⁺ edge implantation.

### 4.4.2 Sensor Prototypes

A set of epitaxial wafers was purchased in 2010 to test the possibility to produce 100 µm thick sensors for the ALICE ITS upgrade. The wafers were processed at FBK² using the ALICE pixel layout. Earlier trials for the PANDA experiment [71] using epitaxial wafers have indicated that the processing of the sensors on the front-side and the thinning of the back-side after bump deposition is possible. However, in these first attempts the wafers could not be fully recovered at the end of the process. A modified procedure led to improvements in the processing and two full epitaxial wafers were bumped and successfully thinned to 110 µm with a 100 µm thick epitaxial layer and then flip chip bonded to existing ALICE pixel chips. Assemblies with 100 µm epitaxial sensors were then tested in the laboratory using radioactive sources and in a 350 GeV/c pion/proton beam at the CERN SPS in 2010. The tracking performance of the sensors was checked inside a pixel telescope at various threshold, bias and angle settings. Figure 4.3 shows a picture taken of the setup inside the CERN SPS beamline in November 2010.

A first analysis of the testbeam data shows a comparable performance of this novel thin sensor with 100 µm epitaxial thickness over a range of threshold and bias settings with respect to a sensor with standard thickness (200 µm) as installed in ALICE and a 300 µm thick sensor.

A new set of 100 µm sensors is currently in production by VTT³. These sensors are produced on standard high resistivity n-type wafers and supported by carrier wafers.

The layout foresees to produce these sensors as edgeless sensors. The dead region will thus be reduced to less than 100 µm. Delivery of these new sensors flip chip bonded to existing ALICE readout chips.

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²Fondazione Bruno Kessler, Trento, Italy, www.fbk.eu
³VTT Technical Research Centre of Finland, FI-02044 VTT, Finland
is foreseen for early 2012. Furthermore, a second run of epitaxial sensors with an edgeless layout is currently under production at FBK and will be delivered in 2012. Detailed tests will be carried out using electrical and source tests as well as irradiation tests and beamtests.

4.4.3 Front-End Chip Architecture

In hybrid pixel detectors, a relatively complex signal processing chain is accommodated in the pixel area. The pixel front-end cell includes preamplifier, shaper, discriminator, digital to analog converters for threshold tuning, registers for local hit storage and trigger matching logic. This architecture allows in-pixel hit detection and time-tagging with bunch crossing accuracy. It must be observed that a simpler read-out scheme with a few transistors per cell and a serial read-out like the rolling shutter routinely employed in CMOS sensors is also possible for hybrids. Such an approach can achieve smaller pixels and could be considered if it offers also a reduced power consumption. Conversely, one should note that most of the considerations made in this section on the front-end architecture for hybrid pixels apply also to the case of monolithic sensors with in-pixel discriminator described in [68].

The necessity of minimizing the radiation length calls for a significant reduction of the current drained by front-end chip. Reduction by a factor of two in the power density is considered an aggressive but realistic goal that can be met thanks to the improvements in microelectronics technologies and to the smaller sensor capacitance. In a hybrid pixel architecture, the minimum pixel size is primarily defined by the pitch of the bump bonding, which, at present, limits the pixel area to 30 $\mu$m $\times$ 30 $\mu$m. The considerations in the following are based on this size, since a larger cell will relax the constraints on the front-end electronics. Furthermore, significantly smaller cells are not achievable if a complete preamplifier-discriminator chain has to be fitted in the pixel. Assuming a target power density of 250 mW/cm$^2$ the average power consumption per pixel is 2.5 $\mu$W, to be compared with the 100 $\mu$W per channel of the present detector.

In the following discussion we assume a power supply voltage of 1.5 V, which implies an average current per channel of 1.6 $\mu$A. One third of the current is allocated to the front-end stage.

The use of thinner sensors to decrease the material budget implies lower signals. Therefore it is desirable to maintain or improve upon the present noise performance. For a sensor thickness of 100 $\mu$m, the most probable value for a minimum ionizing particle will be 8000 electrons. Taking into account Landau fluctuations and charge sharing, the smallest signals of interest will be around 1000 electrons. An rms noise of 50 electrons hence guarantees a signal-to-noise ratio of 20 for those signals. In order to combine low noise with very small power consumption, the front-end electronics should use long shaping time.
With these parameters, the optimal peaking time is 1.5 $\mu$s for a leakage current of 1 pA and longer for smaller values of leakage current. A 1.5 $\mu$s peaking time would not be optimal for the highest expected leakage current, but it would still guarantee a more than adequate performance also in this extreme condition.

With such a long peaking time, a bias current at the level of some hundreds of nanoamperes would be sufficient to bias the discriminator. Additionally, the use of a shaping time longer than the L0 trigger latency (1.2 $\mu$s) offers the opportunity of reducing further the power consumption of the pixel cell. In this case, in fact, the discriminator can be activated only when a trigger is received. Figure 4.4 shows a simplified schematic of the circuit. In this approach the front-end amplifier is continuously sensitive and shapes the input signal with a peaking time of 1.2 $\mu$s or longer. When a trigger signal is asserted the comparator is switched on. An offset compensation is firstly performed with dynamic techniques. This avoids the use of a threshold correction DAC in every channel, favoring a compact layout of the pixel cell. After the calibration, the front-end output is sensed and the detection of a hit is stored in a local flip-flop.

Assuming a duration of 200 ns for the calibration-comparison phase, a bias current of 1 $\mu$A, a power supply of 1.5 V and a trigger rate of 10 kHz, the discriminator average power consumption would be only 2 nW. The average current per cm$^2$ would be 200 $\mu$A. A capacitor of 1 $\mu$F per cm$^2$ reserved to the comparator power supply would be sufficient to guarantee a voltage drop of less than 20 mV during a single read-out cycle.

It is nevertheless clear that simultaneous enabling of all the discriminators will pose challenges to the design of the on-chip power supply network that should not be underestimated and must be adequately addressed with detailed studies and simulations.

### 4.4.4 Hybrid Pixel Detector Packaging

Through Silicon Vias (TSV) offer the possibility to fan out the contacts for a chip to the back side of the ASIC instead of routing them to the wire bonding pads located on the edges of the die. The vias are etched through the thickness of the chip, creating a vertical electrically conducting connection between the front and the back side of the chip. Wire bonding pad connections can thus be omitted. A back side redistribution layer can be used to bring the electrical contacts to a matrix of contacts big enough to accommodate BGAs. Other possibilities are the use of screen printing contacts to the back side pads of the TSVs to connect a flex cable which carries power and signal lines. TSVs allow for a very compact arrangement of ASICs or ASICs and interconnect structures such as flex cables without the extra space required for wire bonding connections. Specifically for hybrid silicon pixel detectors, the TSV technology is of high interest as it will allow the creation of very compact modules. For example a flip chip assembly with TSV connections on the ASIC side can be connected to a flex cable. The requirements of very thin ASICs for the ITS upgrade is fully in line with the needs of thin wafers for TSV formation. A schematic view of TSV connections in a hybrid silicon pixel detector is shown in...
Figure 4.5: Schematic view of a hybrid silicon pixel detector with TSVs.

First tests for the ALICE ITS upgrade are being carried out together with the MediPix collaboration to evaluate a novel TSV technology. The test-wafers for this trial are MediPix3 wafers and first prototypes are expected to be delivered in early 2012.

Typical bump bonding diameters in current detectors are on the order of 25 µm. The most common material choices for the bump bond are eutectic Pb-Sn, Sn-Ag or Indium, depending on the vendor and the environmental requirements. In the present ALICE SPD, bump bonds of eutectic Pb-Sn with a bump diameter of 25 µm have been used. The Pb-Sn bump is deposited on an Under Bump Metallisation (UBM) layer which provides the metallurgical connection to the Aluminum pad on the components and the wettable metal for the actual bump. The different metal layers are deposited in sputtering systems and electrolytic baths. Photolithographic steps are used to define the bump diameter. The minimum diameter of the bump defines also the possible pitch of the pixels. Current techniques are proven for pitches down to 50 µm and are believed to match still with pixel pitches of 30 µm. However, smaller pixel pitches will most likely require a change in bump technology. A first evaluation of the feasibility of making hybrid pixel detectors with a pitch of 30 µm for the ALICE ITS using current deposition technologies is foreseen using dummy components.

The wafers have to be thinned from native thickness to achieve the necessary thickness of the ASIC and in the case of hybrid detectors also of the sensor. The handling and processing of very thin wafers requires the use of support wafers that are attached to the actual wafer. In the special case of epitaxial sensor wafers the support is provided by the Czochralski base material of the sensor, which is thinned and metalized after processing to provide the back plane contact. The ASIC wafers in both cases, monolithic and hybrid, have to be attached either by specific glues or tapes or similar means to mechanical support wafers. In the case of hybrid detectors this process step has to be integrated into the bumping process flow.

The thickness requirements of 50 µm for the ASICs and 100 µm for the sensor is unprecedented in other experiments and necessitates a detailed study of the thinning process. A first trial using specially produced dummy components with the layout of the actual ALICE pixels has been started successfully with IZM. Single chip assemblies and multi-chip assemblies with 5 ASICs connected to a 70 mm long sensor tile with the final thicknesses of 50 and 100 µm, respectively, have been produced. Figure 4.6 shows a schematic view of the cross-section of an assembly before glass carrier removal and the corresponding

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5Frauenhofer Institute for Reliability and Microintegration (IZM), Dept. High Density Interconnect and Wafer Level Packaging, Gustav-Meyer-Allee 25, D-13355 Berlin
4.5 Monolithic Pixel Detectors

In the following section, the different types of monolithic pixel detectors which are under consideration for the ALICE ITS upgrade are discussed. The technology, the architecture and results or plans for prototype developments are presented. Further types of monolithic silicon pixel detectors, such as the DEPFET or SOI pixel detectors may also have potential interest for the ALICE ITS upgrade. However, no detailed investigations have yet been carried out.

4.5.1 Monolithic CMOS sensors with Rolling-Shutter Read-Out

A sensor with an extension of the rolling shutter, low power, architecture of the ULTIMATE sensor for STAR (see figure 4.7) is under development for the ITS upgrade. This new sensor, called MISTRAL (standing for "MIMOSA Sensor for the TRacker of ALICE"), is intended to increase the read-out speed by a factor of at least four and to improve the radiation tolerance by one order of magnitude. While the read-out speed improvement does not present any particular difficulty, the targeted radiation tolerance at room temperature necessitates switching to a smaller feature size fabrication process. The development of the MISTRAL chip will therefore incorporate the exploration of a 0.18 μm CMOS technology, which is significantly more powerful than the 0.35 μm process used for MIMOSA sensors up to now.

4.5.1.1 Architecture

With the rolling shutter architecture the charge collection inside a pixel is continuous, and the pixel matrix is read periodically row by row. This architecture results in a low power consumption, since only one row is being read out and powered at a time. In the present MIMOSA sensors the power consumption corresponds to 150-250 mW/cm² depending on the number of columns per surface unit and on their length.

In order to guarantee the small pixel size, the logic inside each pixel is kept to a minimum, as shown in figure 4.8. A pixel cell contains only the sensing element, a preamplifier, a clamping node and the row selector.

The first element after the collecting diode is the preamplifier. Its feed-back loop also provides the bias voltage of the pixel, with the advantage of a continuous leakage current compensation. A row selector activates one row at a time, and connects the pixels to the discriminators placed at the end of column,
where the signal is digitized after a Correlated Double Sampling (CDS) that compensates the pixel-to-pixel offset. A sparsification algorithm is implemented on the digitized data, that identifies and encodes pattern of hits on one line of pixels, retaining only the information of the column address of the first pixel hit and the number of contiguous hits. With the processing of the matrix row by row, the sparsification and zero suppression algorithm will generate output states at a Poisson-distributed rate, going from zero states to a maximum number that depends on the chip occupancy. To equalize the output data rate and limit the data bandwidth, a buffer will be implemented, in the form of memory blocks. For the existing MIMOSA26 sensors [59], two memories are implemented and they are alternatively selected: when one memory is being written, the other is read, and vice versa.

The MIMOSA family has a trigger-less architecture, meaning that once the readout of the pixel matrix is started, the frames are sent out continuously at a fixed frequency, independently from the collisions. Studies are on-going on a micro-circuit that will be implemented inside the MISTRAL sensor to select only those frames that correspond to a collision that has activated the ALICE L0 trigger; this will reduce the chip power consumption and the output bandwidth, since not all the frames will be sent out. To reduce even more the data bandwidth, the ALICE L1 trigger could be applied at the output of the memory stage.

### 4.5.1.2 Prototype development

The development of a new sensor with a rolling-shutter architecture is advancing using as a reference the MIMOSA26 sensor [59] developed at IPHC and the ULTIMATE sensor [66] developed for STAR, but adopting a 0.18 μm CMOS technology featuring a quadruple well allowing the use of both types of transistors inside the pixel cell as described in section 4.5.2. The sensor area will increase to $1.5 \times 3 \, \text{cm}^2$ or $2 \times 3 \, \text{cm}^2$ (depending on the layer concerned) and the two options of a single sided or double sided
readout are under study. With a double sided readout, the readout time of the matrix will halve, but the power consumption of the chip will double since more rows will be active at the same time. Since the sensor will be elongated in one direction, a modular design is under study; the smaller modules will ease the prototype evaluation, because they could work independently of the other modules and only a common part to combine together the modules output will be needed.

A first prototype circuit has been submitted in autumn 2011 to Tower/Jazz. This circuit, MIMOSA32, contains a series of smaller blocks such as various diodes and amplifiers for charge collection and radiation hardness studies and discriminators equipped with 64 rows of pixels. Figures 4.9 shows a picture of the MIMOSA32 prototype.

![Figure 4.9: Picture of a MIMOSA32 prototype. The picture is composed of several images taken with a visual inspection system.](image)

Two test prototypes will be submitted in 0.18 $\mu$m CMOS technology in 2012: one will integrate the pixel matrix and the discriminators and it will be used to investigate the radiation tolerance of the technology, while the other will feature the zero suppression architecture and the memory design and will allow the SEU sensitivity to be tested. Other submissions and iterations will be needed before obtaining the final sensor layout: the pixel matrix and the digital blocks will be first integrated inside a basic module and then the full size chip will be prepared.

4.5.2 CMOS sensors with in-pixel hit discrimination

In standard monolithic active pixel sensors (MAPS) (see figure 4.10, left) [68], the detecting element is formed by a reverse bias diode whose terminals are an NWELL and the substrate. The NWELL acts as the collecting electrode and the diode capacitance converts the signal charge into a voltage, usually read-out with a source follower. In this approach only NMOS transistors can be located into the pixel. PMOS transistors, in fact, would need their own NWELLS, which would act as competing electrodes in the collection of the charge. One possibility to circumvent the problem consists in using a deep PWELL placed underneath the PMOS NWELLS. The deep PWELL screens these NWELLS, so that the charge is focused towards the collecting electrode. Shown in figure 4.10 (right), this approach is called INMAPS or quadruple well. The possibility of embedding PMOS transistors close to the sensors makes it possible to design more conventional pixel cells with preamplifier-shaper-discriminator chains, as demonstrated in [68].

4.5.2.1 Architecture

Using a quadruple well approach, one can develop an architecture identical to the one discussed in the hybrid pixel sensor section and shown in figure 4.4. In a monolithic implementation the detection layer is much thinner than in a hybrid approach. With doped epitaxial substrates, a detection thickness of 18 $\mu$m can be achieved, so a minimum signal down to 100 electrons can be measured. The much reduced sensor capacitance (on the order of a few fF) offers the opportunity of a good signal-to-noise ratio even at very low power consumption. As an example, figure 4.11 shows the noise as a function of the peaking time for a monolithic implementation with conventional read-out. In the calculation, a CR-RC shaping
Figure 4.10: Standard monolithic approach (left) and quadruple well technology (right).

Figure 4.11: Noise evaluation for monolithic sensors read out with a CR-RC chain.

function is assumed. In the plot, three curves corresponding to different value of sensor leakage current are shown. The total input capacitance is supposed to be 10 fF and the transconductance of the input device 2.5 µS, which corresponds to a bias current of 100 nA.

The figure shows the potential of achieving a noise below 10 electrons for a low to moderate value of leakage current, while reasonable performance is still maintained for currents corresponding to the end of lifetime of the detector.

In a monolithic implementation, the pixel size will not be limited by the pitch of the bump bonding, but by the space necessary to accommodate the processing electronics. A pixel size of (30 × 30) µm should be achievable in a 0.18 µm CMOS process. An architecture with local processing allows significant power saving compared to a pure rolling shutter scheme. In fact, the matrix will not be read-out periodically, but only upon a trigger request. The power saving will be greater at lower trigger rates. For instance, the power needed to extract the data from the matrix would be one half at a 10 kHz trigger rate when compared to a rolling shutter scheme in which a complete scan is performed every 50 µs. However, if the trigger rate is 1 kHz, the power would be cut by a factor 20. This estimate is limited to the fraction of the power necessary to drain the data out of the matrix. Assuming a hit density of 100 hits/cm² per interaction and that, because of charge sharing, every hit is determined by a cluster of eight pixels, the occupancy will be 0.8%. A further reduction in power could be achieved with a sparsified read-out, identifying the pixel with an address and reading out only those with a hit. This requires some extra logic to store and extract the address and hence some extra area for the pixel cell, but this is a penalty which is probably worth paying. More detailed studies will be done during the design of the first prototypes.
Prototype developments

Prototype sensors for particle tracking, the CHERWELL sensor, and calorimetry, the TPAC sensor, have been designed and manufactured by the UK ARACHNID Collaboration using quadruple well technology in the 0.18 µm CMOS process from TOWER/JAZZ. The characterisation of the sensors is now underway. Crucially, the radiation hardness to the level required by ALICE remains to be demonstrated. This statement applies only to the innermost layers of the ITS and in particular to a new inner layer made possible by a smaller beam pipe, where 1.4 Mrad of total ionizing dose is expected. The radiation resistance achieved [72] by today’s monolithic technologies would be already adequate for the external layers which in the present ITS are instrumented with Silicon Drift and Strip sensors.

Evaluation of the radiation tolerance is ongoing using both the CHERWELL and TPAC sensors as well as prototype structures designed by RAL (UK). Figure 4.12 shows a photograph of the RAL test structure which contains different transistors (PMOS and NMOS) and capacitors.

![Figure 4.12: Picture of a test structure designed by RAL and produced by Tower/Jazz. Different PMOS and NMOS transistors as well as accumulation capacitors and other test elements are contained in this structure.](image)

The qualification of the radiation hardness has three critical aspects. First, one must assess the radiation damage of the sensor itself. Here, in particular, the bulk damage due to non- ionizing energy loss may lead to charge collection inefficiencies and high leakage currents that could compromise the signal to noise ratio and the detection efficiency. A second aspect of the radiation damage is the leakage current induced by the total dose effect on the CMOS transistors. The baseline process used in the quadruple well technology is 0.18 µm. Here one should clarify if the technology has an adequate radiation resistance without the systematic use of ELTs, as is the case of the 0.13 µm. The need for an enclosed geometry in the transistor layout would require the development of a custom digital library. More importantly, the extra area required may push up significantly the minimum pixel size achievable. Finally, one should check the susceptibility to single event upsets. In particular, the use of high-resistivity epitaxial substrates, which are beneficial from the sensor point of view, could lead to an increased sensitivity to latch-up phenomena triggered by heavily ionizing particles.

In 2012, prototype sensor designs that can fulfill the specifications of the ALICE ITS upgrade will be made in this quadruple well (INMAPS), 0.18 µm technology and submitted for manufacture. This is intended to validate the choice of this technology. If the quadruple well approach is chosen, it is foreseen to implement first a reduced-scale matrix that will incorporate the final read-out scheme and the ancillary
blocks. Although most of the critical properties can be explored in the laboratory with the use of infrared lasers and radioactive sources, a test beam will be needed to provide the final validation of the sensor concept. For this reason, the matrix should incorporate a reasonable number of pixels (64 × 64 pixels).

4.5.3 Drift Based Monolithic Sensors in Very Deep Submicron CMOS

The LEPIX project explores the possibility of fabricating monolithic CMOS sensors using deep submicron CMOS technologies ported on moderate to high resistivity wafers. In these devices, a relatively large depletion region (several tens of microns) could be reached with a moderate bias voltage (less than 100 V) and the charge will be collected by drift. This should minimize the impact of bulk damage due to non-ionizing radiation which still plagues standard monolithic sensors. The use of a drift field will help in controlling the charge sharing among different pixels, and will also improve the speed of charge collection. Combined with a relatively thick depletion layer, this might allow the use of such devices in applications in which particle identification is required. The LEPIX development will therefore be followed closely, since such kinds of sensors could be of great interest to ALICE if the technology reaches a sufficient maturity.

4.5.3.1 Sensor principles

The detector matrix (see figure 4.13) is formed by a two-dimensional array of NWELL diffusions into a P-type substrate of moderate resistivity (well above a few 100 Ωcm). Each of these NWELL diffusions forms the charge collection electrode of one pixel, and contains the local readout circuitry for the pixel. The local readout circuit is connected to the periphery where the remainder of the readout electronics is located in an NWELL. The NMOS transistors are systematically placed in a PWELL inside the NWELL (use of triple well technology). Charge collection electrodes and readout circuit are biased near ground (a power supply of ≈1 V) with the P-type substrate negatively biased to several tens of volts. To sustain the reverse substrate voltage the readout circuitry and the detector matrix are surrounded by a guard ring structure. By applying a sufficient reverse substrate bias a bath-tub shaped depletion layer should be formed. This layer is continuous underneath the readout and detector matrix. It ends near the outer edge of the guard ring and has a thickness D of several tens of microns. Some of the design challenges are that the significant reverse bias has to be sustained in a technology which has been developed for 1 V operation, the electrostatic discharge protection structures have to be modified to no longer be connected to the substrate (which is not anymore at ground). Layer density rules have to be respected for manufacturability, which is particularly challenging especially for the polysilicon and active areas.

Figure 4.13: Schematic overview of the detector structure for drift based monolithic pixel detectors.
4.5.3.2 Architecture

To reduce analog power consumption it is important to reduce the capacitance of the charge collection electrode as much as possible. In principle it is possible to use the triple well structure to add readout circuitry local to the pixel, but the additional capacitance that would so be introduced would strongly penalize the power-performance ratio of the device. Therefore the local readout circuit was reduced to a very few PMOS transistors only while carrying the analog signal immediately to the periphery, where it is further treated for readout. This has the additional advantage that the clock distribution can be limited to the periphery only instead of covering the full matrix. This will reduce digital power consumption as well as crosstalk from digital circuitry into the detector matrix.

In the periphery the triple well structure with NMOS transistors is used. In fact, all NMOS transistors need to be located in a triple well structure to shield them from the severely reverse biased substrate. The approach of carrying the analog signal to the periphery immediately requires very dense interconnect over the pixel matrix, which is why a 90 nm technology was chosen for the initial development. This technology offers low-K dielectrics in the metal stack and hence provides dense interconnect with reduced (capacitive) parasitics. Using this approach we have indications from first measurements that the capacitance seen at the collection electrode is at the 1 fF level or below. Combined with a depletion layer thickness of several tens of microns, a minimum ionizing particle should develop a signal on the collection electrode of several hundred mV. This should allow an analog power consumption per pixel of well below the microwatt, but creates the demand for a readout circuit which properly takes advantage of such a large signal. The leakage current in the detecting element will be a determining parameter in the design of such a readout circuit. In principle, in the LEPIX approach each pixel cell has its own front-end electronics at the periphery of the matrix. To reduce the dead space and take advantage of the cluster nature of the events, pixels could be grouped in a small sub-matrix sharing the same very front-end electronics. Detailed studies on different architectures for smart data extraction are in progress.

Since the analog signal is immediately transferred to the periphery of the matrix, this architecture is very well suited for generating fast trigger information. If analog information is required, a time over threshold scheme could also be implemented.

4.5.3.3 Prototype developments

A first pilot submission was carried out in the spring of 2010 on two lots, one on standard silicon, and the other on a higher resistivity substrate. It contained several test matrices, a large test diode to evaluate the substrate material, transistor test structures, and a structure allowing a study of the breakdown voltage as a function of the detailed pixel geometry. Unfortunately, a short was created in the guard ring due to a mask generation problem causing the guard ring to be heavily implanted with boron over its entire surface. As soon as this was discovered the lot on standard resistivity, was put on hold. A correction on six masks has been submitted recently to successfully complete the higher resistivity lot.

Despite the guard ring problem, it was possible to verify the correct functionality of the circuitry and to extract the following encouraging measurement results from the lot on standard resistivity:

- The pixel breakdown voltage was measured to be larger than 30 V on standard silicon, and it is expected to be even larger on the higher resistivity substrate. In fact, this value is not very far from the breakdown voltage for an ideal planar junction. This indicates that it is likely we will reach a depletion region of around 50 µm.

- Injecting a pulse over a 1 fF injection capacitor yields a pulse of over 70% of the amplitude at the pixel input. Since this 70% ratio is governed by capacitive division the pixel amplifier is an open loop amplifier. This indicates that the pixel capacitance seen at the input apart from the injection
The combination of a large depletion zone with a very small collection capacitance, if confirmed on the high resistivity lot, will allow for a signal-to-noise ratio of unprecedented quality for a monolithic detector.

4.5.3.4 Design and qualification for radiation hardness

The CMOS circuitry is normally sensitive to ionizing radiation but it is well known that with the decreasing oxide thicknesses for deeper submicron CMOS technologies, the transistors become increasingly resistant to ionizing radiation. This has been confirmed by a recent measurement result where the prototype on standard resistivity (with the short in the guard ring, but with the functional readout circuit) was subject to an irradiation with 10 keV X-ray up to a dose of 10 Mrad. The circuit was continuously biased and readout regularly during the irradiation, and remained functional throughout. Some important pixel level shifts (a few 100 mV in the analog output) were observed immediately after irradiation (the full 10 Mrad dose was given in a few hours). These shifts are currently not fully understood but they were largely reduced after a 68 hour room temperature anneal. This measurement confirms the intrinsic radiation tolerance provided by very deep submicron processes.

4.6 Pixel Module and Interconnection

A conceptual description of the module integration is given in chapter 5. One module for the innermost layer will cover approximately 22 cm along z and will thus be composed of several pixel chips. The reticle size of the 0.18 µm and 0.09 µm CMOS processes will enable the production of chips with typical sizes of 2-3 cm along z and 1-2 cm along rφ direction. Current CMOS technologies also provide the possibility of stitching, thus connecting the lines of neighboring ASICs on the wafer level. In this case sensors which are larger than the reticle size can be produced.

In the case of hybrid silicon pixel detectors a silicon sensor will be connected to the readout chip via flip chip bonding. Current experiments at LHC connect between 5 and 16 ASICs to one sensor. In order to maintain a high bumping yield individual chips which fail after the bump bonding need to be reworked. Reworking describes a procedure which detaches the ASIC from the sensor while maintaining enough bump metal on the pads to allow for bonding of a new ASIC. Hybrid assemblies with less readout chips will thus result in a higher bump bonding yield figure.

In both the hybrid and monolithic cases, very thin assemblies and chips, respectively, will be used to construct the module. The use of TSV (see section 4.4.4) and BGA type contacts to establish the connection between the chip and a flex cable could be used in order to reduce the insensitive areas at the edges of the module (i.e. the ASIC control part and wire bonding pads). The flex cable will consist of one or more thin Kapton and Aluminum layers to stay within the material budget design goals. A schematic view of a hybrid and a monolithic pixel module is shown in figure 4.14.

Prototypes of the Kapton cable are being designed using 25 µm thick layers of kapton with metal traces of Aluminium. Various interconnection types will be tested to ensure a good electrical contact to the chip while maintaining a low material budget. First prototypes will become available in spring 2012 and can be connected to dummy silicon tiles to form first dummy modules.

4.7 Technology Options for Strip Detectors

The present ITS strip detector design is optimized for the present LHC conditions and ALICE physics goals. Although the available strip detector technologies are rather mature, the construction of a new
strip detector will benefit from past experience, leading to better reliability and uniformity of several components and thus to a significantly improved overall performance in real operating conditions. In addition, appropriate modifications made on each component design will allow the requirements suggested by the new physics aims, the expected experimental conditions and the position of the detector in the new tracker to be met. At smaller radii with respect to the present position, the strip detector will probably face an occupancy problem that requires a redefinition of its geometric characteristics. Moreover, since the low-momentum particle identification performed by the silicon tracker appears to be a relevant physics item and requires a wide input dynamic range, the development of the strip detector will take into account this need.

### 4.7.1 Sensor Design

The upgraded strip detector will be based on 300 μm thick, double-sided micro-strip sensors with a small stereo angle between the strips on opposite sides, in order to keep an acceptable rate of ambiguities in track reconstruction. Given the prospect of a smaller distance between the strip layers and the interaction vertex and taking into account the increased particle multiplicity foreseen at the nominal LHC energy, we considered a redesign of the current SSD sensor with a decrease in the cell size in order to keep the occupancy low.

The simplest way to do this is to halve the strip length while keeping the same sensor dimensions: each sensor-side accommodates two arrays of 768 20 mm long strips, for a total number of 3072 strips per sensor. The strips are cut in half by inserting a narrow gap (a few micrometer wide) between them. This gives no efficiency loss for particle hit detection. The sensor layout appears as in figure 4.15.

This layout modification results in a factor of two lower occupancy, better ghost hit rejection and lower strip capacitance, which has a beneficial effect on the signal-to-noise ratio. Dedicated simulations suggest the feasibility of using strip detectors to build the intermediate layers of the ITS, keeping the occupancy, the efficiency and the purity at the present level, or better, even in increased multiplicity conditions. On the other hand, the new design doubles the readout channel density, with important effects on the global power dissipation and on the requirements of the cooling system. It also makes the sensor to front-end chip connection and the module assembly more challenging. A set of sensor mock-ups with the new design has been ordered from FBK\(^6\) in autumn 2011; the submitted masks include also a series of dummy chips with compatible layouts. The manufactured components will be used to define and test the assembly procedure of the new strip module.

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\(^6\) Fondazione Bruno Kessler, Trento, Italy, www.fbk.eu
4.7.2 Front-End Electronics Development

A new front-end chip for Silicon Strip Sensors will incorporate on board the analog to digital conversion, today performed outside the front-end ASIC. The ASIC will deliver to the back-end electronics digitized data serialized on a few high speed differential links. To accommodate more channels on chip, one could explore the use of commercial flip chip technologies as an alternative to standard wire bonding. The front-end chip will be designed in the same process (0.13 $\mu$m or 0.18 $\mu$m) chosen for the pixel sensors. This will minimize the use of different technologies in the project and will favor expertise exchange and building block re-use among the different subsystems.

4.7.2.1 Requirements

The requirements for the front-end ASIC for the strips are reported in Table 4.6. The key difference between a new chip and the existing HAL25 will be the data digitization directly on chip. The requirements on total dose are easily accommodated by modern CMOS technologies without enclosed layout transistors. A Single Event Upset tolerant design will be adopted in the control path.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>HAL25 (present SSD)</th>
<th>Upgrade chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASIC spec</td>
<td>80 $\mu$m</td>
<td>44 $\mu$m</td>
</tr>
<tr>
<td>ASIC size</td>
<td>(3.65 x 11.90) mm</td>
<td>(6 x 6) mm</td>
</tr>
<tr>
<td>Noise (5 pF load)</td>
<td>400 e$^-$</td>
<td>400 e$^-$</td>
</tr>
<tr>
<td>Peaking time</td>
<td>1.4 - 2.2 $\mu$s</td>
<td>1 - 2 $\mu$s</td>
</tr>
<tr>
<td>Power per channel</td>
<td>500 $\mu$W</td>
<td>500 $\mu$W</td>
</tr>
<tr>
<td>Total number of channels</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Digitization</td>
<td>Off chip</td>
<td>On chip</td>
</tr>
<tr>
<td>Radiation level</td>
<td>30 krad</td>
<td>30 krad</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS 0.25 $\mu$m</td>
<td>CMOS 0.13 - 0.18 $\mu$m</td>
</tr>
</tbody>
</table>
4.7.2.2 ASIC architecture

The front-end ASIC will interface to the outside world with fully differential digital I/O (LVDS or SLVS). Several approaches can be used for the on-chip digitization of the analogue information. The spectacular progress recently made in the domain of analog to digital converters allows a design of an extremely low power and fast ADC. Successive approximation converters with 40 Msamples per second, 2 mW of power, 0.04 mm$^2$ of area and resolution of 10 bits are today state of the art. If one can integrate one ADC per channel, the input capacitance of the ADC will serve also as the sampling element. As in the HAL25, the peaking time could be used also to accommodate the trigger latency. L0 will trigger the sampling and the digitization, a process that can be done simultaneously on all channels in less than 100 ns. The digitized data are then stored in output buffers and sent to the readout electronics. Four output drivers working at 40 MHz will allow the transmission of non-zero suppressed data in 10 µs. In this case the common mode correction and the zero suppression will be performed by the first stages of the readout electronics, that will be based on FPGAs. This solution requires more transmission bandwidth on the chip side, but it allows the quick upgrade of the processing algorithms by reprogramming the FPGAs. Another alternative is to implement the common mode correction and signal feature extraction on a digital signal processor embedded on the front-end chip. The sharing of the ADC among different channels is also possible. In this case the amplifier output will be stored on a local capacitor and several channels will be read in sequence by the ADC.

The use of shorter strips and the consequent reduction of the input capacitance will offer margins for power saving in the front-end.

A transconductance of 1 mS (achievable with a current smaller than 100 µA) and a sensor capacitance of 5 pF are assumed. Since for the strips the power and the space for the front-end electronic are not as constrained as for the pixels, a more elaborate shaper (CR-RC$^4$) was considered, which offer better noise performance for the same pulse width with respect to the simple CR-RC. With this configuration, a noise below 300 electrons for a peaking time above 1.2 µs is achieved up to a leakage current of 5 nA per strip.

As for the pixels, the ASIC will incorporate on board the service and slow control components (voltage regulation, temperature monitoring, etc.).

4.7.2.3 Development program

The design of the front-end chip will start only after a final decision on the use of the strip sensors will be made. It is foreseen to have a short period (3-4 months) of behavioral simulations to choose the most suitable architecture before starting the design of the circuit. After that the design of a small prototype will be undertaken. This first ASIC will contain already the full processing chain, but only a limited number to reduce the development costs. After this first step, one will proceed with the design of the final circuit. The full development cycle of the ASIC is expected to last two years.

4.7.3 Module concept and assembly

The present SSD module uses low-mass Kapton-based cables with aluminum conductors for the electrical connections between the sensor and the front-end chip. This technology is still considered the most suitable for this kind of detector layout, thanks to its greater flexibility with respect to the standard wire bonding technique. It allows the positioning of both hybrid circuits (reading p and n-sides) on the same side of the sensor, by folding around the sensor edge the microcables connected to the opposite side.

In the present SSD, cables made of 10 µm polyimide foil with 14 µm thick aluminium traces are used to connect the front-end chip to the sensor on the input side and to the hybrid circuit on the output side. The length of the input traces connecting the chip to the detector is 11 mm, with a fan-out to adapt the input layout (128 input pads in one row with 80 µm pitch) to the sensor pitch (95 µm). The trace width
is 36 µm. The recent technology development offers now the possibility to realize cables with a smaller inter-trace pitch, down to 42.5 µm, and to connect and read-out a doubled number of strips arranged on two separated rows, preserving the low material budget and a compact detector layout. First prototypes of (10+10) µm thick kapton-aluminum cables, with minimum inter-trace pitch of 44 µm and trace width of about 25 µm have been manufactured. The geometrical characteristics for the sample designed to connect the p- and n-side of the sensor, with the corresponding two different dimensions, are listed in table 4.7. The traces are arranged in order to match two rows of bonding pads with a pitch of 95 µm on the sensor side (contacting two groups of 64 half-length strips), and the two staggered rows of pads on the front-end chip, each with a pitch of 88 µm. Since the single-point Tape Automatic Bonding (TAB) technique becomes extremely challenging at small trace width and pitch, a set of dummy components with the proposed geometric characteristics are being fabricated in order to test and verify the possible solutions for module interconnection and assembly. Bonding tests and quality assessment procedures are planned for spring 2012.

Table 4.7: Microcable dimensions and arrangement

<table>
<thead>
<tr>
<th>Cable area</th>
<th>to-hybrid (output pads)</th>
<th>to-chip (input pads)</th>
<th>transmitting area</th>
<th>to-sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trace pitch [µm]</td>
<td>136</td>
<td>136</td>
<td>44</td>
<td>47.5</td>
</tr>
<tr>
<td>Trace width [µm]</td>
<td>~ 80</td>
<td>~ 50</td>
<td>~ 30</td>
<td>~ 22</td>
</tr>
<tr>
<td>Trace quantity</td>
<td>43</td>
<td>43</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Bonding pad placement</td>
<td>one row</td>
<td>one row</td>
<td>two rows (staggered)</td>
<td>-</td>
</tr>
</tbody>
</table>

In parallel, the hybrid circuit used to accommodate the chips, drive out the signals and provide the services is being designed with the same aluminum-polymide cable technology as used in the present SSD, in two symmetric layouts corresponding to the two sides of the sensor. The power and interconnecting cable (also called flex) will be glued onto a stiffener, made of five-layer carbon-fibre material. The flex is a two-layer bus used for power, digital i/o and analog outputs. The interconnections between the two layers are made by TAB bonded vias.

The front-end module of the upgraded strip detector is shaped in a very compact layout in order to guarantee a continuous sensitive area once integrated in the tracker layers. The flexibility of the interconnections should allow the arrangement of the front-end electronics of the whole module on the downstream side with respect to the incident particles, leaving sufficient space to accommodate the supports and the cooling services. Different options for the module layout are being studied. Figure 4.16 shows a possible arrangement of the cables and the hybrids, before and after folding them on the sensor. At present, this option seems to allow the simplest assembly procedure and the most comfortable placement of the chips, optimizing at the same time the cable dimensions and the hybrid layout.

A specific programme of test and quality control will be organized to carry out a complete static characterization of the sensors. The assembly procedure will foresee electrical and functionality tests at each

Figure 4.16: Schematic view of the strip module, in the open (top) and folded (bottom) configurations.
processing step, allowing faulty component rejection and possible reworking before the final integration in the complete module.

First strip module prototypes will be tested with beam particles to study the performance, the efficiency and the spatial resolution of the strip detector once the full chain is integrated in the module.

### 4.8 Readout, trigger and control electronics

The upgrade of the ALICE ITS will require the development of a new readout, trigger and control system. The readout system has to provide sufficient data bandwidth upstream (detector to counting room) and downstream for control. On-detector readout components have to be low mass, consume low power and be compatible with the radiation environment. The architecture should be cost effective and reliable.

A first schematic view of a possible scheme for the readout, trigger and control part is shown in figure 4.17. The electronics located at the detector is connected via optical fibres to FPGA (Field Programmable Gate Arrays) based readout and trigger boards in the control room. These implement the interface to the central systems in ALICE, such as the CTP (Central Trigger Processor), the DCS (Detector Control System), the DAQ (Data Acquisition) and the HLT (High Level Trigger). Data and trigger information arriving from the detector are processed in these boards and forwarded to the CTP and DAQ/HLT respectively. The DCS interfaces via the readout boards in the control room with the detector. The detailed choice of the type of optical connection between the detector and the boards in the control room is still to be made. However, either bi-directional links which carry data, control and trigger information or a combination of uni- and bi-directional links to ensure the correct transmission of all signals are possible choices. Neither would present technical limitations.

![Figure 4.17: Illustration of an architecture for the upgraded ITS trigger and readout electronics (R/O). The connections to the central services (CTP-Central Trigger Processor, DCS-Detector Control System, DAQ-Data Acquisition, HLT-High Level Trigger) are indicated schematically.](image)

At this early stage the different technologies and architectures for the detector are under study. Consequently a detailed scheme for the readout, trigger and control electronics will develop in parallel with these studies and will be presented at a later stage. However, considerations on basic requirements such as the expected data throughput can already be made. They are discussed in the next section, followed by initial considerations on powering.
4.8.1 Expected data throughput

The expected data throughput is one of the main considerations when designing the readout system. The transmission bandwidth has to be adapted to the data throughput requirements and the number of links needed has to be defined. Several recent developments, such as the GBT and Versatile Link projects [73, 74] target the development of ASICs and optical links satisfying the common requirements for high bandwidth readout and tolerance to radiation of large scale high energy physics experiments. These developments are in line with the requirements for the ITS upgrade and it is foreseen to include them in its layout.

The expected Pb-Pb interaction rate will amount to 50 kHz, thus requiring a readout time of about 10 µs to avoid pile-up. Assuming that for every cluster a 50-bit word\(^7\) is generated the expected data throughput for the innermost layer is about 80 Gbit/s. An estimate for the data throughput for each of the layers is summarized in table 4.8.

Table 4.8: Required data throughput estimations for the different layers of the ITS assuming a 50 kHz interaction rate and a 50-bit word per cluster (compare table 3.3).

| Layer | Radius \((|\eta|\leq 1.2)\) [mm] | Length [mm] | Layer surface [cm\(^2\)] | Hit density Pb-Pb plus QED \([50\text{ kHz}]/\text{cm}\(^2\)] | Data throughput [50 kHz] [Gbit/s] |
|-------|-----------------|-------------|-----------------|-------------------|------------------|
| L1    | 22              | 224         | 310             | 101.53            | 78.7             |
| L2    | 28              | 242         | 425             | 62.68             | 66.5             |
| L3    | 36              | 268         | 605             | 37.91             | 57.4             |
| L4    | 200             | 780         | 9800            | 1.23              | 30.1             |
| L5    | 220             | 836         | 11550           | 1.02              | 29.3             |
| L6    | 410             | 1424        | 36670           | 0.29              | 26.6             |
| L7    | 430             | 1486        | 40130           | 0.26              | 26.2             |

The number of data links has to match the required bandwidth as well as the detector segmentation. Under the assumption of a conservative figure of 3.3 Gbit/s per link the number of links required for L0 amounts to about 25 for a 50 kHz interaction rate. With increasing radius the number of links per layer will further decrease. The technical implementation could foresee either one link per module, even if the full bandwidth is not used, or group several modules together using one common link.

An alternative option being considered is the use of electrical links as the first transmission medium from the modules, carrying the signals to a location sufficiently far away from the detector, where the electrical to optical conversion would take place.

The design will depend on module and detector integration constraints as well as on operating considerations, such as the impact on efficiency of a link failure.

4.8.2 Powering

The high power, low voltage supply needs of the latest generation of front-end ASICs present a challenge for the power distribution. DC-DC converters and serial powering [75] schemes tackle this issue. In the case of DC-DC converters power is delivered with a voltage of the order of 12 V and currents that are lower with respect to the case of directly supplying the voltages needed by the ASICs (typically in a range from 1.2 V to 3.3 V). This reduces the losses over the cables, the voltage drops and thus the amount of copper required to distribute the electrical power. The voltage applied to the ASICs is regulated to

\(^7\)Assuming an 18-bit cluster address and 32-bit cluster shape information.
the desired values using DC-DC converters located close to the detector. Recent developments include radiation hard DC-DC converters [76] that work also in magnetic fields up to 5 T.

Serial powering offers an alternative option to reduce the cable mass in the active area [75]. In this approach, a given number of modules is connected in series and is served by the same bias current. In each module, a shunt regulator generates locally the needed voltage supply level. Figure 4.18 shows the difference between the serial and the parallel powering schemes. With serial powering, the current flowing in the cable is substantially reduced, thus allowing the use of cables with a smaller cross section. A detailed comparison [75] shows that serial powering would allow the material budget due to cabling to be reduced by almost a factor of two with respect to a scheme based on DC-DC converters. However, the use of serial powering entails also critical issues, like the design of the shunt regulators and the implementation of proper bias-bypass circuits to avoid the loss of the full chain in case of a fault in one of the modules connected in series. Both powering schemes are currently considered for the ALICE ITS upgrade.

The upgrade of the ITS aims to significantly reduce the power needed for the pixel layers by optimizing the design layout of the front-end chips. For a pixel size of $20 \times 20 \, \mu\text{m}^2$ the aim is to reach a power density of $250 \, \text{mW/cm}^2$. A first estimate of the power requirements is given in table 4.9, assuming pixels in all layers. The total expected power dissipated in the ITS upgrade amounts to about 24 kW. Using a general 12 V supply with on-detector DC-DC regulation would result in a total current of about 2 kA.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Radius [mm]</th>
<th>Surface [cm$^2$]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>22</td>
<td>310</td>
<td>80</td>
</tr>
<tr>
<td>L2</td>
<td>28</td>
<td>425</td>
<td>100</td>
</tr>
<tr>
<td>L3</td>
<td>36</td>
<td>605</td>
<td>150</td>
</tr>
<tr>
<td>L4</td>
<td>200</td>
<td>9800</td>
<td>2400</td>
</tr>
<tr>
<td>L5</td>
<td>220</td>
<td>11550</td>
<td>2900</td>
</tr>
<tr>
<td>L6</td>
<td>410</td>
<td>36670</td>
<td>9100</td>
</tr>
<tr>
<td>L7</td>
<td>430</td>
<td>40130</td>
<td>10000</td>
</tr>
</tbody>
</table>

### 4.9 Irradiation Plans

The radiation levels expected for the innermost layers of the ALICE ITS upgrade will lead to radiation induced damage in the front-end electronics and the sensor parts as described in section 4.2.1.
Irradiation tests have started in 2011 and will be continued in order to investigate if the different technology options are sufficiently radiation resistant for the ALICE ITS upgrade. The tests are carried out to the respective radiation levels as described in table 3.5. A detailed annealing scenario is currently in preparation and will be based on the expected operating temperature (i.e. room temperature) and the foreseen accelerator operation schedule.

Two types of irradiation tests can be distinguished: X-ray irradiation tests and hadron irradiation tests. While it is expected that the TID delivered during X-ray irradiation tests will lead to radiation induced damage mainly in the electronics parts, the Non Ionizing Energy Loss (NIEL) delivered by the hadrons will lead to lattice damage which manifests itself in the degradation of the sensor characteristics. Furthermore, during an irradiation with charged hadrons (i.e. protons), there will additional TID effects. It is therefore necessary to carry out both types of irradiation tests to simulate the radiation environment in the ALICE experiment and to disentangle the radiation induced effects on the different components.

4.10 Testbeam Plans

The performance of the detector prototypes will be evaluated in dedicated beam test runs at the CERN SPS and PS. In addition to the electrical characterization, tests with sources and the irradiation measurements, the tracking performance of the detector prototypes being developed for the ITS upgrade will be evaluated by exposing them to high momentum particle beams. Intrinsic pointing resolution, track resolution and dE/dx capability will be evaluated for monolithic and hybrid pixel detectors as well as micro-strip detector prototypes. It is also foreseen to study the detector performance in a high multiplicity environment by exploiting the ion beam availability at the CERN SPS.

As described in section 4.4.2, a first beam test was carried out at the CERN SPS in autumn 2010 with the aim of studying the performance of a thin hybrid pixel detector based on the ALICE layout. A 110 µm thick sensor was flip-chip bonded to the existing ALICE pixel front-end chip and tested in the high momentum pion-proton beam. In 2012 we plan to test hybrid pixel detectors based on active edge sensors and first prototypes of monolithic pixel detectors. In order to study the physics performance of the detector prototypes, two tracking telescopes are available: one is based on the existing ALICE pixel detector modules, which can provide a tracking accuracy of the order of 10 µm and was used in the 2010 beam test, and the EUDET telescope, based on the MIMOSA26 sensors, which can provide a resolution of the order of a few µm.

In the following two years the beam tests will be used to validate the design and implementation of the detectors, to study in detail the performance with the final geometry and to verify the functionalities of the system components. The preparation of a detailed plan for test beam requirements for the next years is in progress.

4.11 Discussion and Summary

The silicon strip detectors will follow the design of the present ALICE silicon strips with a reduced strip length to cope with the expected occupancy levels at smaller radii. Similarly to the present system the new strips will provide precise particle identification information. The technical implementation will be similar to the present one and does present a challenging but feasible task.

The pixel detectors considered for an upgraded ITS on the contrary aim for new technologies coupled with stringent requirements. One of the most stringent requirement for the pixel detectors is a target material budget of 0.3-0.5% $X_0$ per layer. An intense R&D program has been carried out to achieve the lowest material budget contribution of all LHC pixel detectors for the present ALICE SPD corresponding to 1.14% $X_0$. The work of the ALICE ITS upgrade will build on this knowledge and expertise. The following list summarizes the average contributions to the material budget on the individual module level
for the monolithic and hybrid pixel detector option. A discussion of the contribution from mechanics and cooling is presented in chapter 5.

- **Silicon**: The basic scenario foresees an ASIC thickness of 50 µm to which, in the case of hybrid pixels, the sensor sensor thickness of 100 µm has to be added. This amounts to 0.053 and 0.16% $X_0$.

- **Flex-cable**: A flex-cable will connect the data and control signals and the power lines from a patch panel outside of the detector acceptance to each individual ASIC. The cable will consist of one or two layers of Kapton (each 25 µm) and aluminum lines (25 µm). The material contribution will thus range from about 0.037 % $X_0$ for a single layer Kapton with 25 µm Al to approximately 0.074% $X_0$ for a two layer flex cable.

- **Contacts**: A compact layout of the module will avoid wire bonds along z and reduce the insensitive area of the ASIC. The contacts have to be re-routed and distributed over the ASIC surface. In the case of monolithic pixels this can be achieved using BGA type contact pads on the ASIC front-side. For hybrid silicon pixel detectors a dedicated study of TSV connections which bring the contacts to the ASIC back-side is ongoing. Standard BGA contacts with a diameter of 200 µm present a local accumulation of material exceeding the requirements of the new ITS. Alternatively the use of BGA balls with plastic core is under study. A very different approach is to replace the BGA balls by depositing aluminium though a large via on the flex cable. This approach presents a low local increase of the material (about 25 µm Al) and will be studied using dummy components.

The pixel size in r-phi and z will be reduced to increase the impact parameter resolution and to enhance the background rejection capability in z. Monolithic pixel detectors with a rolling shutter architecture have already proven that pixel sizes of (20 × 20) µm can be achieved. In the case of hybrid pixel detectors the current bump bonding technology limits the pixel size to approximately 30 µm. However, the slightly larger size will also allow to include more functionality into each cell, such as Time-over-Threshold or Time-of-Arrival measurement. Consequently, also (slightly) larger pixel sizes are being studied for the ALICE upgrade.

A readout time of 50 µs will result in average in a pile-up of 2.5 additional events for 50 kHz Pb–Pb collisions and 100 additional events for 2 MHz pp collisions. As shown in section 3.8, the pile-up has a marginal effect on the standalone reconstruction efficiency for Pb–Pb collisions, while, in order to separate primary and secondary vertices from different interactions, a time tagging of tracks with a resolution in the order of 2 µs is required. This time tagging information can either be provided by at least one dedicated ITS layer or by the TOF detector. However, only 80% of the ITS tracks with a $p_t$ larger than 300 MeV/c are in the TOF acceptance.

The requirement of a power consumption of 0.25-0.5 W/cm² is within reach for thos architectures presented earlier in this chapter.

The different technological options and implementations are being studied and their compatibility with the ALICE requirements is being evaluated in the course of 2012.
Chapter 5

Mechanical layout, services and integration

5.1 Introduction and System Overview

This section contains some basic considerations about the mechanical and geometrical requirements for the ITS upgrade. In section 5.1.1, the present ALICE layout is briefly described together with some considerations on how to improve the accessibility to the new detector. The principle of the new installation procedure allows the insertion of the detector inside the TPC from the Mini Frame, and will not require moving the TPC to its parking position. This results in a much faster and “lighter” intervention inside the experiment that can be carried out in a winter shutdown. The mechanical requirements of this structure for the ITS upgrade are summarized in section section 5.1.2.

5.1.1 ALICE layout and ITS accessibility

The present layout of the ALICE central barrel, with the TPC and ITS detectors, is shown in figure 5.1. The location of the four patch-panels (PP1 to PP4) for the ITS services (power cables, cooling pipes and data links) is also shown in this figure. The ITS is connected to both A and C sides: the services coming from the A-side (from PP1 to PP2) are housed in the service-chariot (SC) while those coming from the C-side (from PP4 to PP3) are routed in cable-trays placed along the front absorber (FA). The layout of the present ITS detector is shown in figure 5.2.

The ITS is made of two distinct parts: the SPD and the SDD-SSD barrel. These two parts are installed separately and attached together via the cones which are also used to hold the services in place. The SDD-SSD and the SPD services (not shown) are routed respectively outside and inside the SPD cone. The ITS is fixed to the inner aperture of the TPC by two hooks which are located at the top of the SDD-SSD cones and two guiding points at the bottom. FMD-2 and FMD-3 are attached to the ITS, while V0 and T0 are supported on the front-absorber and beampipe respectively. The beampipe is attached to FMD-2 and FMD-3. The central valve (visible in figure 5.1) sits on a table attached to the TPC service support wheel and faces the Mini Frame1 (MNF). As a result, the beampipe and the entire ITS, including FMD-2 and 3, are mechanically linked to the TPC.

Since the ITS has services coming from both the A and C sides, and because of the way the beampipe is held in place, it cannot be extracted from the A-side. With the present layout, any access to the ITS requires a series of lengthy operations inside ALICE (see section 5.5). These include: removal of shieldings2; removal of the MNF and of the beampipe on the MNF; the displacement of the TPC towards the A-side.

---

1The Mini Frame (MNF) provides the support for the TPC and ITS services on the A-side. It also houses the A-side beam-pipe and the compensator magnet. Contrary to what its name suggests, it is a large object, weighing about 14 tons.
2The PX24 plug and the shielding in front of the L3 magnet, around the Mini Frame.
The ALICE Collaboration

Figure 5.1: Side view of the present ALICE layout, including the TPC and ITS detectors. The ITS is fixed to the inner wall of the TPC. The location of the four patch-panels PP1-PP4 for the ITS services is shown. The service-chariot (SC) and front-absorber (FA) are also shown. The central valve of the beampipe is also visible (left), which is sitting on a table attached to the TPC service support wheel.

Figure 5.2: Side view of the current ITS barrel: (1) SPD, (2) SDD, (3) SSD, (4) FMD-2, (5) T0, (6) FMD-3, (7) V0, (8) SPD cones, (9) SDD and SSD cones, (10) front-absorber and (11) hinges for the connection to the TPC.

the A-side (to its parking position: IP + 4800 mm).

The time estimated to carry out this sequence of operations is about three months. It would take six-to-seven months to get access to the ITS and to restore the original configuration of detectors and services. Additionally, at least four more weeks are required to get access to the SPD, and there will be more time required for maintenance and repairs. It should be noted that the re-connection of the services and re-commissioning of the TPC and ITS are delicate operations that take several weeks.

This program would therefore require a long shutdown of several months. In order to guarantee a fast insertion and removal of the upgraded ITS, it should be conceived so that it can be inserted and extracted from the A-side without moving the MNF and the TPC. This implies that the upgraded ITS must be assembled away from the IP and slide along the beampipe to reach its nominal position. This solution would be feasible during a winter shutdown, which lasts typically between 2 and 3 months.

This concept of a pluggable detector has important implications for the ITS services and the beampipe...
Table 5.1: Requirements for the ITS upgrade

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Inner Barrel</th>
<th>Outer Barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beampipe outer radius (mm)</td>
<td>19.8</td>
<td>-</td>
</tr>
<tr>
<td>Detector Technology</td>
<td>Pixel</td>
<td>Pixel–Strip</td>
</tr>
<tr>
<td>Number layers</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Mean radial positions (mm)</td>
<td>22, 28, 36</td>
<td>200, 220, 410, 430</td>
</tr>
<tr>
<td>Stave length in z (mm)</td>
<td>224, 242, 268</td>
<td>780, 836, 1424, 1486</td>
</tr>
<tr>
<td>Power consumption (W/cm²)</td>
<td>0.3 ÷ 0.5</td>
<td>≤ 0.5 mW/strip</td>
</tr>
<tr>
<td>Total material budget per layer</td>
<td>X/X₀ (%)</td>
<td>≤ 0.5</td>
</tr>
<tr>
<td>Working temperature (°C)</td>
<td>≈ 30</td>
<td>≈ 30</td>
</tr>
<tr>
<td>Deviation from nominal shape</td>
<td>few hundreds</td>
<td>few hundreds</td>
</tr>
</tbody>
</table>

support elements. The PP2 should be removed, as this patch-panel is not accessible when the TPC is in place. As a consequence the detector will be inserted together with its services from PP1 and since all the services are routed on side A, the patch panels on side C (PP3 and PP4) are not needed anymore. The support structure for the beampipe has to ensure the perfect alignment of the ITS, TPC and beampipe. Additionally it also has to allow the insertion of the detector without moving the TPC.

5.1.2 Upgrade requirements

At the moment two different options for the ITS upgrade are under discussion. The first option is the replacement of the full ITS with a new detector based on 3 layers of pixel detectors and 4 layers of strip detectors. The second option consists of 7 layers of pixel detectors. Concerning the beampipe we are assuming to have an outer radius of 19.8 mm instead of the current 29.8 mm. This will allow the first sensitive layer to be placed closer to the interaction point.

The main design parameters considered for the ITS upgrade are summarized in table 5.1. The radial positions of all layers are optimized to reach the maximum pointing resolution, tracking efficiency and momentum resolution in the available space between the beampipe and TPC. The longitudinal extension of each layer is determined by the requirements (see section 3.3) of a pseudo-rapidity coverage of |η| < 1.22 over 90 % of the luminous region. Values of the radiation length lower than 0.5% of X₀ per layer are very important for the first layers to reduce the multiple scattering effect which would degrade the pointing resolution performance for low momenta particles. The projected radiation load and the corresponding degradation of the sensor performance are not high enough to justify the operation of the detector at cryogenic temperatures. Because of this, we assume the working temperature to be at around 30°C. This requirement softens the constraint for the Coefficient of Thermal Expansion (CTE) mismatch between the different components used in the structure. The detector support structures have to be sufficiently stiff to avoid possible mechanical interference with the surrounding mechanical structures (for example the beampipe) and minimize the mechanical stress on the sensors. As a compromise between material budget and structure stiffness we can accept deformations up to few hundred microns.

Different support and cooling structures are under study (see section 5.3). In all these studies we are assuming values of power consumption ranging from 0.3 to 0.5 W/cm².

5.2 Conceptual design, integration and mechanics

The ITS upgrade is conceived as a two-barrel structure: Inner Barrel and Outer Barrel. Due to the more stringent requirements of material budget for the first layers, the possibility to have several solutions for cooling and mechanical support will be considered. The request of having all the services on one side would permit the detector installation and removal without moving the TPC. As a preliminary approach we will ensure this requirement for both barrels although it is strictly only needed for the first layers if detector technologies with moderate radiation tolerance are considered.
5.2.1 Inner Barrel

The conceptual design of the Inner Barrel is based on a 3-layer structure equipped with independent modules (staves) held at the two extremities on carbon fiber wheels. This solution has the advantage that each stave is fully characterizable from the electrical and cooling point of view before being mounted on the barrel structure.

The stave is the smallest operable part of the detector. The sketch of the stave assembly is shown in figure 5.3. It is formed by a support structure with embedded cooling ducts, pixel detector modules, flex cable bus and data links. The pixel modules and the flex cable are glued on top of the support structure as a sandwich. The electrical connections between the FEE chip pads and the flex cable are made through wire-bonding (same strategy used for the present SPD half-stave module [77]) or with Through Silicon Vias (TSV) connections if hybrid pixel detectors will be used. In the case of monolithic pixel detectors, the pixel chips will be flip-chip bump bonded directly on the flexible bus. In this general concept, the electrical component that performs the data read-out and data transfer to the off-detector electronics is not shown. This could be either mounted on the stave, at its edge, or on an independent unit connected to one or more staves via electrical cables.

An estimate of the material budget of the main stave’s components is listed in table 5.2. Depending on the different assumptions for the pixel module thickness, the total material budget ranges from about 0.25 % to 0.36 % of $X_0$. The contribution of the support structure and cooling, which are not taken into account in this table, ranges from 0.08 % to 0.34 % of $X_0$. This will be further discussed in section 5.3.

Table 5.2: Estimation of the main contribution to the stave material budget.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material budget</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support structure</td>
<td>–</td>
<td>see section 5.3</td>
</tr>
<tr>
<td>Glue</td>
<td>0.045</td>
<td>two layers of glue, 100 $\mu$m thick each</td>
</tr>
<tr>
<td>Pixel module</td>
<td>0.053 – 0.16</td>
<td>Monolithic (50 $\mu$m thick) – hybrid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(150 $\mu$m thick)</td>
</tr>
<tr>
<td>Flex bus</td>
<td>0.15</td>
<td>reasonable for single-sided flex bus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(studies are on-going)</td>
</tr>
<tr>
<td>Total</td>
<td>0.25 – 0.36</td>
<td></td>
</tr>
</tbody>
</table>
The low material budget and the position of the staves forming the first layer, are the most important requirements to improve the pointing resolution. A dedicated simulation has been performed to optimize the sensor width ($r\phi$) and the staves arrangement around the beampipe (section 3.10.3). In this simulation the overlap regions have also been taken into account. The outcome of the simulation and the generic stave layout previously discussed has been considered in the conceptual design shown in figure 5.4. The 3-layer barrel is equipped with 10, 14 and 18 staves mounted on the 2 support wheels. Each stave is to be 16.7 mm wide with 2 mm of dead area placed on one side. The full azimuthal coverage plus 200 $\mu$m of additional overlap in the sensitive area has been guaranteed in the mechanical layout. No overlap along the z direction has been foreseen to simplify the structure as done for the present SPD. The possibility to avoid the overlap in $r\phi$ for the first layer is still considered if this would significantly improve the mean radii and it would allow a further reduction of material budget. The clearance between the staves mounted on the same layer is $\approx 1$ mm, and this clearance will increase for the two consecutive layers. The mean radii obtained with these assumptions are 22.2, 31.4 and 40.5 mm respectively. These radii are slightly different from the requested ones but, accordingly with the results of the fast simulation tool, neither the pointing resolution nor the tracking efficiency are significantly affected by this. The full structure will be further optimized once a better definition of the components is reached.

The full barrel is divided in two halves, which are mounted around the beampipe, outside the TPC. The clearance between the beampipe and the first pixel layer is 2 mm. This is needed to allow the insertion along the beampipe towards the final position. A carbon fiber cylindrical foil, placed outside the third layer, connects the 2 wheels to avoid torsion in the structure. Considerations on the installation and removal procedure are discussed in section 5.5.2.

**Ultra light structure**

In chapter 2 the need to further improve the pointing resolution, e.g. for a better $\Lambda_c$ reconstruction, is discussed. This requirement has an important impact on the design of the innermost layer. With the fast simulation tool (see section 3.10.2) it has been estimated that an improvement by a factor of 2 can be obtained if the first sensitive detector is located at a mean radius of $\approx 20$ mm with a total material budget of $\approx 0.1 \%$ of $X_0$.

The only possibility to have a first layer closer to the interaction point is with a smaller beampipe radius. In section 5.4.2 the feasibility of having a beampipe with an outside radius of 17.0 mm is shown.
second requirement which has to be fulfilled is the material budget. The only possibility to reach an overall material budget of \( \approx 0.1 \% \) of \( X_0 \) is by simplifying the stave design and mechanical structure as much as possible. The mechanical support could be a carbon fiber structure with openings along the sensitive region (see figure 5.5). The structure could consist of two halves fixed on wheels at the two ends which are also used to link the first layer to the outermost ones (not shown in figure).

The chosen cooling option should have almost no extra material along the sensitive area. Air cooling in this respect would be the best option especially if the detector power consumption is on the order of 0.3 W/cm\(^2\) or lower. This ultra-light mechanical support with the stave concept shown in figure 5.3 would still exceed 0.1 % of \( X_0 \). The target of 0.1 % of \( X_0 \) would only be feasible if we use monolithic pixel technology on a large silicon surface thinned to 50 \( \mu \)m and with an integrated bus capable of bringing the signals to the periphery. We can connect the services for the power and the data extraction at one extremities as shown in figure 5.5. Basic informations on the technology that could be used to build such a structure are discussed in chapter 4.

![Figure 5.5: Sketch of a ultra-light mechanical structure (left) equipped with staves and services (right) to form the innermost layer of the upgraded ITS.](image)

### 5.2.2 Outer Barrel

The Outer Barrel is a four-layer structure. At the moment we are investigating two options: the first is based on a modular concept in which group of staves, arranged in sectors, are extractable from a fixed frame structure. The second foresees the extraction of the complete barrel. A conceptual sketch for the second option is shown in figure 5.6. The mechanical layout support for the four detector layers is composed of two separate barrels, each one supporting two detector layers (not shown). Three tubes of diameter 50 mm and 0.5 mm thick are fixed permanently to the inner part of the external barrel and serve both to increase the rigidity of the structure and to support/guide the inner barrel.

The stave structure which will be used to equip each layer is not yet defined since the technology for the implementation of the sensor has not been defined yet. In case the outermost layers would be equipped with double-sided micro-strip sensors, a mechanical structure similar to the one used for the present ITS could be used to hold the sensors [3, 78]. Some considerations on the micro-strip sensor layout and cabling can be found in section 4.7.

### 5.3 Cooling studies, R&D and prototyping

The cooling system is a crucial part of the detector, and represents an engineering challenge due to the very demanding requirements in terms of material budget. Because temperature variations can occur extremely fast, a reliable and efficient cooling system is needed to avoid spots of high temperature. This section presents different cooling options for the inner barrel: using air, water and per-fluorocarbons as the cooling medium. An air cooling system, compared to the other implementations, has the advantage of not introducing any extra material (i.e. ducts and liquid) in the detector sensitive volume. Some basic
considerations referred to a simplified geometry are reported in the air cooling section. One viable air cooling implementation and first prototypes are presented in [79]. Concerning the liquid cooling, several options are illustrated in this section. For each option the analytical results are provided, together with the status of the relevant R&D activities and future plans. For all these studies, the cooling efficiency has been evaluated by numerical simulations for power consumption values ranging from 0.3 to 0.5 W/cm$^2$. These options are based on different materials to transfer the heat: carbon foam, polyimide and silicon. In addition to them, another solution has recently been proposed by the EN-CV-DC section at CERN, based on high thermal conductivity plates [80]. Their extremely high thermal coefficient, together with a very low mass, make them promising for these kind of applications.

5.3.1 Air cooling

In this section we report some basic considerations for the option of cooling the pixel detector (inner barrel) by an air-cooling system [81]. It is important to notice that this solution is adopted for the Heavy Flavor Tracker in the STAR Experiment which is currently under construction [66, 82]. With respect to other implementations based on liquid or two-phase coolants, air-cooling features very low material budget. Since the mechanical stresses and vibrations can be important at high air velocity, a rough estimation on the minimum air velocity required to cool the detector is provided here.

In order to simplify the analysis, the three pixel layers are described as cylindrical surfaces (i.e. cylinder0, cylinder1 and cylinder2), with dimensions given by table 5.1 and no thickness. Air is assumed to flow inside the gap between the concentric tubes enclosed between the beampipe and the cylinders, from one side to the other, without any air leakage between the layers. The heat flux density $q$ on the pixel detector is considered to range from $q = 0.3$ W/cm$^{-2}$ up to $q = 0.5$ W/cm$^{-2}$ and it is thought of as uniformly distributed on the cylindrical surfaces. It is also assumed that each detector surface is uniformly cooled by air at both sides (i.e. inner and outer), therefore the heat flux required on each side is $q/2$. It is important to note that, in order to achieve this, some air must also flow on the outside surface of cylinder2.
The required heat transfer coefficient $h$ can be computed as follows:

$$q/2 = h(T_s - T_a)$$  \hspace{1cm} (5.1)$$

where $T_s$ and $T_a$ are the detector surface and air temperature respectively. The sensor temperature should not exceed 35°C. By reducing the air temperature the heat transfer coefficient required to cool the detector is reduced (hence also the required air velocity). Under the assumptions of $T_a = 7°C$ and $T_s = 35°C$, $h$ can be calculated for two values of $q$:

$q = 0.3 \text{ W/cm}^2 \Rightarrow h \approx 50 \text{ W m}^{-2} \text{K}^{-1}$ \hspace{1cm} (5.2)$$

and:

$q = 0.5 \text{ W/cm}^2 \Rightarrow h \approx 90 \text{ W m}^{-2} \text{K}^{-1}$ \hspace{1cm} (5.3)$$

The hydraulic diameter has been computed for the three gaps between concentric tubes: between beam-pipe and layer 0, layer 0 and layer 1, and layer 1 and layer 2; then, the hydraulic diameter has been used in the Gnielinski [83] correlation to provide a rough estimation of the heat transfer coefficient which is plotted versus air velocity in figure 5.7. It should be considered that with the real geometry the heat transfer coefficient is expected to be higher, since the air would leak between the staves, achieving a more turbulent flow. The plot gives us an idea of the order of magnitude of the air velocity required to cool-down the staves. For the case of $q = 0.3 \text{ W cm}^{-2}$ and $T_a = 7°C$, the air velocity should be $\approx 10 \text{ m s}^{-1}$. For $q = 0.5 \text{ W cm}^{-2}$ and $T_a = 7°C$ a speed of $\approx 20 \text{ m s}^{-1}$ would be required.

The mechanical support used for the HFT in STAR [66, 82] is quite similar to the SPD carbon fiber support. This design provides good rigidity with low material budget, additional heat transfer surface and it also works as conducting air duct. A similar approach would allow the reduction of the required heat transfer coefficient and air velocity.

In the case of air flowing from one side of the pixel detector to the other and neglecting thermal entrance effects and the positive influence of axial thermal conduction along the staves, the axial temperature rise of the detector is the same as the air temperature rise from inlet to outlet, which can be computed as follows:

$$(T_a^{\text{OUT}} - T_a^{\text{IN}}) = Q/(mc_p)$$  \hspace{1cm} (5.4)$$

where $Q$ is the heat flow rate to be dissipated, $m$ is the air mass flow rate and $c_p$ is the specific heat of air. The air temperature rise versus air velocity is reported in figure 5.8. As a general conclusion, if air flow from one side to the other of the pixel detector is chosen, very high velocities are needed to ensure
Figure 5.8: Air temperature rise from inlet to outlet. Design detector heat flux $q = 0.1\, \text{W cm}^{-2}$, $q = 0.3\, \text{W cm}^{-2}$ and $q = 0.5\, \text{W cm}^{-2}$.

an inlet/outlet air temperature rise below $5\text{K}$. It is important to note that this constraint is less demanding than the constraint regarding the heat transfer coefficient. Alternatively, inverting the direction of the flow in order to have both the air inlet and outlet on the same side, would allow one to keep the temperature non-uniformity on the stave lower than the air temperature rise.

These thermal studies have to be improved once the mechanical design is more advanced as well as the analysis of mechanical vibrations and stresses due to the air flow. Therefore a CFD thermal analysis is planned for a more comprehensive study of the problems.

5.3.2 Liquid cooling with carbon foam structure

In this section the proposal of a leakless water cooling system will be discussed. The support and cooling structure used in the simulations is shown in figure 5.9. It consists of a cooling tube with a 2 mm outer diameter and $80\, \mu\text{m}$ wall, embedded in the Omega carbon fiber structure. The Omega structure is composed of two plies of unidirectional material, properly oriented to guarantee a good rigidity. The Omega and the tube are glued to the 1 mm thick carbon foam and the pixel module (assumed to be

Figure 5.9: The FEM model consists of the cooling tube embedded in an omega structure, glued to a carbon foam. The detectors are glued to the carbon foam by a second layer of glue.
150 \mu m thick in these simulations) is glued on the top of the carbon foam. The 2 layers of glue considered in this scheme are 100 \mu m thick each. The Omega structure guarantees the rigidity and stiffness of the system, while, owing to its good thermal conductivity, the carbon foam improves the power dissipation. A similar structure has been studied and tested for the Micro Vertex Detector (MVD) in the PANDA Experiment [84, 85] and for the Insertable B-Layer (IBL) in the ATLAS Experiment [12]. In the Finite Element Method (FEM) analysis conducted with the described model, the following assumptions have been made:

1. inlet water cooling temperature 18°C
2. flow rate 0.3 l/min
3. no natural convection with the ambient air
4. ideal contacts between surfaces
5. Carbon foam isotropic thermal conductivity 50 W/mK (as measured in the lab [84])
6. Glue thermal conductivity (1 W/mK)
7. Omega carbon fiber M55J 200 \mu m thick.

The preliminary FEM results are shown in figure 5.10 and 5.11. In the figures we are comparing the behavior of the same structure with two different cooling tube, the MP35N - metal and PEEK, and for two power consumption values, 0.5 W/cm² and 0.3 W/cm². The simulations show that the cooling performance obtained with the metal tube is slightly better: the maximum temperature obtained with the higher power consumption is \approx 29°C for the metal tube, while it is \approx 35°C in the other case. On the contrary the metal tube has a bigger material budget. Preliminary estimation of material budget ranges from \approx 0.22 to \approx 0.34\% of X₀ for the mechanical structure and the coolant in the case of PEEK or metal tube respectively. This simulation shows that the proposed cooling system is adequate to operate a stave according to the ITS upgrade requirements, although some optimizations are still needed:

- structure rigidity with the minimal material budget
- cooling tube characteristics (i.e. diameter, wall thickness and material)
- hydraulic optimization to work in leakless regime
- glue selection and qualification (i.e. thermal conductivity, curing properties and adequate thickness).

Some prototypes will be produced to prove the feasibility, to study the mechanical properties and to validate the cooling performance.

5.3.3 Liquid cooling with polyimide micro-channels structure

Polyimide based Micro-Channels Heat Sink (MCHS) [86] represents an interesting possibility to cool down the pixel stave using single phase cooling. Figure 5.12 shows a schematic view of the pixel stave (top) and the MCHS cross section (bottom). The MCHS is a multilayer polyimide composite made with a layer of Pyralux LF110 [87, 88] in the bottom, a Photoimageable PC 1020 [88, 89] layer in the middle and a Pyralux LF7001 [87, 88] layer glued on the top. The multilayer PC 1020, which is 200 \mu m thick, is glued on the LF110. The rectangular pattern which defines the channels is created with a
photolithography process at 180°C and the foil of LF7001 is hot pressed on the top of the substrate to cover the channels. The full structure is then thermally cured at 180°C for 10 hours in order to achieve its ultimate end-use properties. The MCHS structure is glued on a carbon-fiber chassis which is used to rigidify the stave and to support it onto the two carbon-fiber wheels. The chassis has an opening below the detector in order to minimize the total material budget in the active area. The advantage of the polyimide substrate is the high radiation length (29 cm). The estimated mean material budget ranges from 0.085% of $X_0$ to 0.13% of $X_0$ if water or $C_6F_{14}$ is used as coolant respectively. This estimation doesn’t include the carbon fiber chassis.

An analytical thermo-fluid dynamic study has been carried out to find the best MCHS geometry fulfilling the operational requirements, and exhibited reasonable values for local and distributed pressure drops. This issue has been addressed using a simplified configuration with inlet and outlet at the opposite sides. The analysis is based on the correlation of Nusselt number for fully-developed laminar flow and quoted by Shah and London [90]. The assumptions include constant thermo physical properties of the fluid and uniform laminar flow across the micro-channels. All the heat is assumed to be dissipated uniformly through the top of the chip to the heat sink base. Heat losses from the chip through the substrate to the ambient, and through the cover plate to the surrounding air have been neglected. The total area being cooled corresponds to $W \cdot L$ (figure 5.13-a) with individual micro-channel flow passage dimensions of $a \cdot c$ (figure 5.13-b). The wall separating two channels is of thickness $b$.

Figure 5.14 shows the pressure drop localized across the stave versus the channel width for water and $C_6F_{14}$ in the case of a heat flux $q=0.5$ W/cm² and a total length of 200 mm.
Figure 5.12: Sketch of the stave concept with the polyimide micro-channel support and the carbon fiber chassis (top). Cross section of the polyimide micro-channels structure (bottom).

Figure 5.13: Assonometric view a) and b) of the optimized polyimide micro-channels structure.

The maximum temperature $\Delta T$ was set to $5^\circ$C. The values of height $c$ and pitch $b$ have been fixed to 200 $\mu$m, which are reasonable values considering the fabrication process. The pressure drop decreases asymptotically with the channel width $a$. The optimal value found is 800 $\mu$m: wider channels don’t exhibit a significantly lower pressure drop, while they make the structure weaker. In order to verify that the micro-channels cooling performance meet the design requirements, CFD simulations have been carried out using Fluent 6.0 [91]. The boundary conditions used for the analysis are:

- Constant heat flux on the top: 0.5 and 0.3 W/cm$^2$;
Figure 5.14: Pressure drop versus channel width for a heat load of 0.5 W/cm\(^2\) and micro-channel length of 200 mm using C\(_6\)F\(_{14}\) and water.

- Coolant inlet temperature: 288.15 K;
- \(t_{\text{max}}\) coolant inlet-outlet;
- Inlet and outlet on the opposite side;
- Symmetry conditions on both side (left and right) of the computational domain;
- Adiabatic condition on the bottom surface.

Numerical simulations using water and C\(_6\)F\(_{14}\) were carried out. The temperature distribution on the heated surface and along the micro-channel cross section are shown in figure 5.15, which includes water and C\(_6\)F\(_{14}\) and the maximum heat load (0.5 W/cm\(^2\)). As expected, the temperature rises along the flow direction in the solid and the fluid regions of the micro-channel in both cases and the highest temperature point is located at the heated surface of the channel in the region of the outlet. From the comparison between the two temperature profiles, the water use is more efficient in cooling (the top surface reaches the maximum temperature of \(\approx 21^\circ\text{C}\) instead of \(\approx 26^\circ\text{C}\) with C\(_6\)F\(_{14}\)) although both solutions would fit the requirements.

One of the first prototypes produced is shown in figure 5.16. An home made support frame has been manufactured to plug the cooling tubes to the polyimide structure (see figure 5.17) and a series of tests have been performed to validate the structure tightness, the compatibility with water and the structure’s thermo fluid dynamics with the C\(_6\)F\(_{14}\). Details on the first series of tests which have been performed can be found in reference [86].

5.3.4 Evaporative cooling with silicon micro-channels structure

The solution of micro-channels etched on a silicon substrate is described in this section. This is actually an option considered for the NA62 Experiment at CERN [92]. This cooling technique [93] is being studied within the framework of the Cooling Project of the PH-DT group at CERN, in cooperation with the Microsystems Laboratory of EPFL [94] in Lausanne and CSEM [95] in Neuchatel. Since the detector and the micro-channels are both silicon structures, one of the main advantages of this solution is to reduce the mechanical stress due to the thermal stress. The silicon micro-channel plates optimized for the NA62 experiment are based on a 4-inch wafer (101.6 mm). This means that at least two plates would be required to equip each stave. Silicon cooling plates of suitable dimensions can be manufactured with standard 8-inch wafers. Partners such as CEA-LETI [96], can provide this technology. The goal is now
Figure 5.15: Temperature profile of a single micro-channel considering a power consumption of 0.5 W/cm$^2$: a) top view, b) side view and c) outlet cross section. The results with water are shown on the left and the ones with C$_6$F$_{14}$ on the right.

Figure 5.16: Picture of a polyimide micro-channel heat sink prototype: The micro-channels dimensions are 800 µm wide, 200 µm deep, 20 cm long, the wall thickness is 200 µm.

Figure 5.17: Picture of the MCHS support frame used for this tests (left). Leak and water compatibility test set up (right).
Two solutions are currently being considered in conjunction with evaporative cooling:

- **Distributed micro-channels:**
  A silicon substrate 150 $\mu$m thick that covers the full stave surface. The micro-channels are etched into a 130 $\mu$m thick silicon wafer. The proposed micro-channel dimensions are $(100 \times 200) \mu$m and a 20 $\mu$m thick cover-layer is fusion-bonded on top of the silicon substrate.

- **Sideline micro-channels:**
  A silicon substrate 250 $\mu$m thick that covers only the 2 sides of the stave where the dead area is supposed to be located. The micro-channels are etched into a 200 $\mu$m thick silicon wafer. The proposed dimensions are $(100 \times 200) \mu$m and a 50 $\mu$m thick cover-layer is fusion-bonded to the silicon substrate.

In both solutions a carbon fiber chassis placed at the edges of the silicon substrate is needed to increase the stave rigidity and to provide the support needed to fix the stave on the carbon fiber wheels (see figure 5.18 and figure 5.12). The sideline micro-channel option has a thicker substrate, but the material is concentrated in the dead area zone. The mean value of the estimated material budget for the silicon structure is 0.11% of $X_0$ in the case of the distributed option and 0.07% of $X_0$ in the sideline option. In the latter case, the silicon that is concentrated in the 2 sides is 0.21% of $X_0$ and covers one third of the full structure.

The connection to the cooling pipes could be made in PEEK to assure excellent resistance to high pressures with reduced impact on the material budget. Silicon micro-connectors could also be considered. A first contact with CSEM which is interested in micro-connectors for silicon micro-channels has been established. The manifolds and micro-channels optimization strongly depends on the coolant option and working regime which will be simulated and compared with the test campaign which will start in the next months.

The preliminary criteria adopted to choose the size of the silicon micro-channels are based on the studies published by Prof. J. Thomes from the EPFL in Lausanne [97]. The models used to reproduce the evaporative regime in macro-channels are not easily applicable in the case of micro-channels. Due to the importance of scale effects the models that are valid for macro-channels may be useless for micro-channels. The same is true for the models used to calculate the pressure drop which, for micro-channels,
are based on two possible approaches: the homogeneous and the separated flow models [98]. Tests on prototype structures are therefore important to validate the analytical results and to extract the system parameters such as the heat transfer coefficient, void fraction, pressure drop etc. The void fraction of the vapor phase in the cross-section of the flow channel is the most critical parameter in two-phase flow systems. Several analytical theories have been presented for two-phase flows in macro-channels, especially for the bubble, slug, annular and stratified flow regimes [98–100].

The first prototypes of low material budget micro-fabricated silicon cooling plates have been built in the class 100 clean-room of the Center of MicroNanoTechnology [94] at EPFL in Lausanne. This is achieved in cooperation with the Microsystems Laboratory and CSEM [95]. The process is carried out on a Czochralski silicon wafer polished on both sides. The main characteristics of the substrate are: 4 inches diameter, 380 $\mu$m thickness and 0.1 - 0.5 $\Omega$·cm p-type.

The micro-channels are covered with a silicon layer 20-30 $\mu$m thick. The two silicon layers are pressed at room temperature and afterwards annealed at high temperature.

Figure 5.19 displays the results of the simulations of the mechanical resistance of the fusion bonding process versus the thickness of the silicon cover and the width of the inlet manifold. The calculations show that for 50 $\mu$m thick silicon covers, a 0.5 mm wide manifold can stand up to 30 bar. To make it withstand higher pressures it is necessary to reduce its size or to thicken the fusion bonded silicon layer (the maximum yield strength for silicon is 165 Mpa). The first prototypes of a sideline micro-channel structure have been recently produced at EPFL (see figure 5.20) following the aforementioned procedure, including the extra etching step needed to create the opening in the structure. The prototypes are based on a simplified geometry with the inlet and outlet manifolds placed at opposite sides (see figure 5.20). The prototypes have been manufactured on 4-inch silicon wafers, which will also be used to tune the fabrication parameters. In a second stage, the process will be transferred to 8-inch silicon wafers. Additionally, a dedicated R&D program is being carried-out with CSEM to develop in-plane silicon microfluidic connectors which will allow the production of cooling frames as long as the pixel staves.

### 5.4 Beampipe design

#### 5.4.1 Length and wall thickness

Presently the beampipe central section, has an outside diameter of 59.6±0.10 mm, a thickness of 0.8 mm and a length of 4820±2 mm. The length of the new pipe should be approximately 5.5 m in order to have
sufficient room for the installation of the new ITS on the A side. To have a beampipe with a thickness of 500 µm will require an R&D effort, as there are concerns over porosity and related vacuum tightness issues. Since there is very little experience with such a thin wall thickness, prototypes will have to be built and measured in order to assess the feasibility. Such a 'non standard' item will also have to be analyzed in terms of the risks to the LHC operation.

5.4.2 Diameter

All the numbers used in this section are from the LMC presentation by Massimo Giovannozzi from 2/2/2011 [101]. The nominal required aperture was originally quoted as $n_1 \leq 7 \sigma$. Since it turned out that the aperture is in reality $n_1 \leq 10 \sigma$, this value is quoted as the new aperture limit for normal (squeezed) LHC operation. The current beampipes radius of 29 mm for ALICE, ATLAS and CMS results in an aperture of $\leq 26.4 \sigma$ assuming an alignment tolerance of 11 mm. ATLAS and CMS are currently considering beampipe radii of 22.5 mm, which results in an aperture of $11.8 \sigma$ for an alignment tolerance of 11 mm, and is officially accepted for their new beampipes to be installed in LS1 (2013/2014 shutdown). The ALICE request of a beampipe with an internal diameter of 38 mm (e.g. radius 19 mm) together with an 11 mm alignment tolerance would result in an aperture of only $4.2 \sigma$.

Table 5.3 shows the budget for the alignment and fabrication tolerances for the beampipe, including mechanical fabrication, installation and concentricity tolerances. By summing linearly all these contributions, corresponding to considering the most unfavorable case, a total alignment tolerance of 6 mm is obtained. With this value for the tolerance, and with the number of $2.36 \sigma$/mm for ALICE, it would mean that a beampipe with internal diameter of 38 mm (e.g. 19 mm radius) would result in an aperture of $16 \sigma$ and this option should be considered as the baseline. As a second option, in order to get the same aperture of $11.8 \sigma$ as ATLAS and CMS, we are considering a beampipe with internal diameter of 34.4 mm.

As a third option, we consider the case of a smaller mechanical and adjustment precision (1 mm instead of 2 mm). This is an extremely demanding case, and the total tolerance would drop to 5 mm. In this case, a beampipe with internal diameter of 32.4 mm would be needed to have an aperture of $11.8 \sigma$. These three options are summarized in table 5.4.

There are additional factors to be considered:

1. There are second order corrections to be applied to this line of reasoning because ALICE is in the T12 injection region, so the machine protection (experiment protection) issues of the smaller beampipe must be separately considered.
Table 5.3: Summary of ALICE beampipe tolerances, for a length of 4820 mm. All numbers assumed for 2 $\sigma$.

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<th>Quantity</th>
<th>Estimate</th>
<th>Comments</th>
</tr>
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<tr>
<td>Fabrication tolerance</td>
<td>0.5 mm</td>
<td>CMS quotes 0.4 mm</td>
</tr>
<tr>
<td>Sag</td>
<td>0.5 mm</td>
<td>Unsupported length 4335 mm + counterweight</td>
</tr>
<tr>
<td>Mechanical adjustment precision</td>
<td>2.0 mm</td>
<td></td>
</tr>
<tr>
<td>Survey to beamline uncertainty</td>
<td>1.5 mm</td>
<td>Provided by survey (could be improved)</td>
</tr>
<tr>
<td>Quad fiducial to beamline uncertainty</td>
<td>0.5 mm</td>
<td></td>
</tr>
<tr>
<td>L3 movement</td>
<td>$\leq$ 0.5 mm</td>
<td></td>
</tr>
<tr>
<td>B field movement</td>
<td>$\leq$ 0.5 mm</td>
<td>Measured value</td>
</tr>
<tr>
<td>Linear sum</td>
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<td></td>
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</table>

Table 5.4: Summary table for the new central beryllium beampipe. The first option is the baseline considered in this document.

<table>
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<tr>
<th>Options</th>
<th>$R_i/R_0$ (mm)/(mm)</th>
<th>Tolerance (mm)</th>
<th>$n_1$ ($\sigma$)</th>
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<tr>
<td>1)</td>
<td>19 / 19.8</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>2)</td>
<td>17.2 / 18.0</td>
<td>6</td>
<td>11.8</td>
</tr>
<tr>
<td>3)</td>
<td>16.2 / 17.0</td>
<td>5</td>
<td>11.8</td>
</tr>
</tbody>
</table>

2. Vacuum issues: specifically vacuum impedance issues, must be considered by the VAC group.

3. The beam impedance issues concerning the transition to the 100 mm diameter Miniframe beampipe and the Front Absorber beampipe must be studied. Maybe some tapering or conical part must be introduced.

4. All these optics discussions refer to the nominal machine. In the context of HL-LHC (considered to start after LS3, e.g. 2022) all these numbers, including beampipe diameters must be revisited. ATLAS and CMS are installing the new beampipes in LS1, so they will run with them for the next 10 years. Since ALICE wants to install the new beampipe in LS2 only, this has to be carefully considered. A first idea about HL-LHC optics should exist by 2013/14, so on this timescale it may be possible for ALICE to confirm whether the new ALICE beampipe will also be fine for the HL-LHC era.

5. There are more factors to be taken into account when high beta optics are considered. In ATLAS and CMS there is the TAS that protects the triplet magnets from interaction point debris, which could quench the magnets. ALICE doesn’t have a TAS. For high beta optics with $\beta^*$ on the order of or larger than the cavern dimension the beam is essentially a ‘cylinder’ parallel to the beam axis, so by staying in the shadow of the TAS, ATLAS and CMS can be convinced that the central beampipe can never become the aperture limit - but it is always the TAS. Since ALICE doesn’t have this, this may take the form of a special setting of the TCTs that will guarantee that there is no danger for the beampipe. Since the TCTs are however at quite some distance from the IP there will be some optics transfer between them and the IP, so it will not be a simple ‘shadow’ argument like in ATLAS or CMS. This needs special study. It has to be kept in mind that for a $\beta^* \geq 90$ m, a change of hardware has to be done for the magnets.

5.4.3 Deformation

The current beampipe is supported on three points. The three supporting points are connected to the TPC, and so the relative displacement between the beampipe and the ITS does not change when the position...
of the TPC is adjusted in the Space Frame (e.g. operation potentially needed after the insertion of TRD and TOF modules, which has the effect of loading the Space Frame). In this way a constant alignment is realized between the beampipe and the ALICE tracking detectors.

One option which is being considered for the new beampipe is to have only two supports, for example removing the central support located on FMD-2. This solution has two advantages:

1. the installation of the new ITS from the A-side would not require the disconnection of the central support and
2. the risk of having excessive stress along the pipe is eliminated (no more hyper-static situation).

The latter point is quite important, considering that in the present configuration the stresses on the beampipe are a matter of great concern, especially when detectors are moved in and out along the space frame. With three supports the beampipe is over-constrained. In order to keep the sag in the pipe to acceptable levels, accurate monitoring of the forces in the cables, which hold the beryllium beampipe in place is realized. Custom-made strain gauges [102], located in the central support, are used for this purpose.

The new 5.5 m long pipe would therefore be supported only at the two extremities, resulting in an increased sag. Given the 2 mm clearance with the innermost silicon layer, it is very important to calculate the sag of the pipe to avoid damaging the detector during its installation.

As an example, the sag for a 5 m long pipe supported on two rotation points has been plotted in figure 5.21. The calculation refers to an 800 $\mu$m wall thickness, and inner radius of 19.2 mm. The max deflection, located in the center of the pipe, is 2.7 mm. Since this is an unacceptable value, a way to reduce the sag should be implemented.

Pre-bending the pipe would be very challenging. Applying a torsional force on one end of the pipe could be used as a very simple way to reduced the sag. For example, the sag is reduced from 2.7 mm to 0.4 mm by applying a moment of 8.73 Nm on the left hand support. The moment could be easily obtained by placing a ‘counter weight’ at a given distance from the support such as a force of 4.4 kg at a distance of 0.5 m. This technique has also the advantage that the maximum stresses in the beampipe stays within a certain value, e.g. $\leq 6$ MPa in the example (everything below 15 MPa should considered no problem at all).

For the realization of the counter-weight we could design a vacuum chamber with an in-built counterbalance, or change the layout of the valve and pumping group such that it gives us the correct offset.

![Figure 5.21: Calculated sag for a 5 m long beampipe with 800 $\mu$m thick walls (purple curve). The sag is reduced from 2.7 mm to 0.4 mm by applying a moment of 8.73 Nm on the left support (blue curve).](image-url)
5.5 Detector and beam-pipe installation

The target date for the ITS upgrade is the long shutdown of 2017-18 (LS2). A long shutdown is in fact needed to replace the central beampipe. This section contains some basic considerations about the installation of the new beampipe and the ITS upgrade.

5.5.1 Installation of the new beam-pipe

The sequence in order to remove the existing beampipe is the following:

1. Remove Mini Space Frame and install Delphi Frame
2. Install temporary rails
3. Move TPC to parking position and displace SDD-SSD
4. Remove SPD, forward detectors and beampipe

Once the L3 doors are open and the Mini Space Frame is removed, the Delphi Frame (DF) is put in front of the Space Frame and is used for the installation and removal of the TPC. The temporary rails (also called ITS rails) are inserted in the TPC hole and they are held on the ITS table (inside the DF) and on the Front Absorber (FA). They are guided through the TPC by a series of brackets attached to the TPC. Before moving the TPC, the beampipe flange on the A-side is transferred to the temporary rails, and the beampipe table is dismantled. The ITS is also transferred to the rails. Once the TPC is moved to the parking position (e.g. located at IP + 4800 mm), both PP2 and PP3 are disconnected, FMD-2 is removed (together with the beampipe support), the SPD services on the A-side (PP2) are made horizontal and the SDD-SSD can be moved away from the SPD. The SPD is then taken out.

After removing the beampipe support on the C-side and the forward detectors (FMD-3, T0-C and V0-C), the central beampipe can be removed. Figure 5.22 represents the situation at this point. The ITS is removed at this stage. The installation of the new beampipe will most probably not differ from the installation of the present pipe [46]. Once in its final position, the C-side flange is connected to the flange on the absorber side, and the beampipe is baked-out and refilled with pure Neon. After the bakeout, the C-side forward detectors are re-installed and cabled. They are temporarily supported on the ITS rails. Then the beampipe is attached to FMD-3 (figure 5.23). Before moving the TPC to the IP, it is very important to be sure that the ITS will be perfectly centered around the beampipe. If the ITS is installed when the TPC is in the parking position (e.g. “old” scenario), this is possible because the detectors (ITS and FMD-3) are still accessible (thus adjustable) after their installation. However, in the proposed installation scenario the ITS is inserted when the TPC is in place: at that point no further alignment is possible. Therefore, there should be a way to ensure the alignment before the TPC is moved.

One possibility would be to align the beampipe to the outer ITS barrel. For this barrel we are currently looking into two possible solutions: 1) a fixed frame with the different sectors individually insert-able (like the Space-Frame), or 2) a barrel which is inserted and removed from the MNF (like for the inner barrel). In the former case, the frame is installed on the ITS rails before moving the TPC, therefore it could be aligned with FMD-3, resulting in a perfect alignment between the beampipe and the ITS. In the latter case a frame would be anyway installed before moving the TPC. In this case the outer ITS barrel will engage with this frame during its installation.

At this point the TPC is finally moved to the IP. The beampipe flange on the A-side is then transferred to the TPC SSW, and the beampipe is aligned on the A-side. The DF is removed and the Mini Space Frame re-installed and connected.

5.5.2 Installation of the new ITS

The ITS consists of two distinct barrels, therefore the installation of the outer and inner barrel will be dealt with individually.
Figure 5.22: Configuration before beampipe re-installation. Only the central part of the TPC is shown.

Figure 5.23: Beampipe support on FMD-3. Before being coupled with the ITS, FMD-3 is hold and aligned through a temporary support, which is demounted once the FMD-3 load has been transferred to the ITS.
Outer barrel installation

More conceptual studies have been carried out for the second of the two outer barrel solutions which have been previously mentioned. The baseline solution for the installation of the outer barrel consists of using the present ITS rails. This solution has proven to work for the present ITS and is therefore valid also for the upgrade. The rails are inserted from the miniframe, where the outer barrel is assembled and pushed to the IP, where it engages with the TPC. This option should be studied in details.

An alternative solution consists in using fixed support tubes, attached inside the TPC. In order to be assembled around the beampipe, the entire structure is split in four half barrels (two inner and two outer). Figure 5.24 shows a schematic view of the detector, after the installation at the IP. Three tubes (approximately 2750 mm long, $\varnothing$ 60 mm, 0.5 mm thick) provide the support for the external barrel. Two cones, attached to the inner aperture of the TPC, permanently hold these tubes. They are made of carbon composite. The installation sequence, assuming that the cones have already been attached to the TPC, is the following:

1. the two outer half barrels (fitted already with the detector modules) are assembled around the beampipe, and sit on three tubes, the prolongation of those inside the TPC. To hold the tubes, a suitable support is installed on the MNF;
2. the two inner half barrels are assembled inside the outside barrel. Figure 5.25 shows the two barrels ready to be inserted inside the TPC;
3. the two concentric barrels are pushed inside the TPC to the IP;
4. the extended tubes and the MNF support are removed.

It is worth noting that, for either solution, the service chariot must be entirely redesigned. In fact, it is not possible to leave the services floating during the insertion and then to re-arrange them afterwards. The service chariot should therefore “come-out” together with the detector. In any case, PP2 would be removed.

Inner barrel installation

In order to install the inner barrel structure, a set of temporary rails is installed inside the TPC aperture. The idea is to re-use the present ITS rails, however a new table (“SPD-table”) should replace the ITS table, which is too big to fit inside the Mini Space Frame. The SPD table should be designed in order to make a comfortable access to the detector during the assembly and insertion phases. The accessibility during the installation of inner barrel structure should be further studied. It will be installed together with the A-side cone and services to reach PP1. Given the tight clearance between the innermost layer and the beampipe (2 mm), the detector should be perfectly aligned to the beampipe before starting the insertion. This alignment should be maintained along the whole distance that has to be covered to reach the IP. In order to do this, two options are currently considered: 1) aligning the ITS rails (or a new set of SPD rails) with respect to the beampipe or 2) making a self-adjustable support which carries the detector along the z-axis. The interface with the outer barrel must be still studied. The preliminary idea is to engage the inner barrel cone inside the outer barrel, and eventually foresee an additional support on the C-side.
Figure 5.24: Schematic view of the ITS upgrade after the installation at the IP. In the bottom part the cutout view is shown.
Figure 5.25: Conceptual drawing of the assembly of the two barrels outside the TPC. The yellow structure is used to attach the three carbon composite tubes, which hold the detector during the insertion.
Chapter 6

Project Management and Organization, Participating Institutes, Cost Estimate and Time Schedule

6.1 Project Management and Organization

The ALICE Silicon Tracker Project, referred as AST in the following, is the proposed upgrade of the current ITS. It is organized according to the ALICE Collaboration rules and constitution and is part of the current ALICE ITS Project. In addition to the Institutes already members of the ITS Project, several new Institutes have joined the ITS Collaboration to participate in the development and construction of the AST detector and are actively participating to the R&D studies. Conversely, a few Institutes who are currently members of the ITS project will not participate in the AST although they have confirmed their commitments to the maintenance and operation of the present ITS. The Institutes that intend to contribute to the AST are listed in Table 6.1. The contributions and responsibilities of the participating Institutes, as well as the manpower and funding resources, are being discussed and will be defined in the MoU that will be set up at the time of the Technical Design Report which is planned for mid 2013. Some Funding Agencies have already in 2011 allocated relevant resources for the R&D activities and have committed themselves for 2012.

6.2 Participating Institutes

All Institutes taking part in the AST project have specific expertise and past experience in the development, construction and running of silicon trackers. The INFN groups and CERN have well renowned expertise in ASIC design, construction of detector ladder and support mechanics, manufacturing of composite materials, integration and characterization of hybrid pixel and microstrip detectors. Strasbourg and RAL are among the world leading experts for the development of monolithic pixel detectors. The Kharkov group has in-house capability of producing micro-cables.

6.3 Cost Estimate

At the present stage several technologies are being considered for the implementation of the AST detector. The technology that will be adopted for the implementation of the different detector layers, will be chosen to best suit the detector requirements within the boundaries set by the available funds and the project time line. In terms of performance and cost the use of monolithic pixel would be envisageable for all layers, while the hybrid pixels may become prohibitive as the radius increases due to the cost of
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<tr>
<td>Trieste</td>
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the bump-bonding. However, a limitation to the use of monolithic pixels for the innermost layers may arise from the level of radiation that can be tolerated by the selected technology. Moreover, it could turn out that a few microstrip layers at large radii is mandatory for particle identification if the charge signal delivered by the thin sensor layer of monolithic pixels does not provide enough resolution. Following the above considerations it can be reasonably assumed that the AST will be based at most on two silicon detector technologies.

In the following we give a cost estimate for the two design options under study:

1. 7 layers of monolithic pixel detectors, which would provide excellent standalone tracking efficiency and $p_t$ resolution, but limited PID capability, and

2. a combination of 3 innermost layers of hybrid pixel detectors and 4 outermost layers of strip detectors, which would provide a better PID capability but worse standalone tracking efficiency and momentum resolution.

The cost estimate for the two detectors options is reported in table 6.2. In future other detector options might also be considered (e.g. 4 layers of monolithic pixels and 3 layers of strips), but their cost can be reasonably assumed to be between that of options a) and b).

**Table 6.2:** Cost estimate for two detector configurations. Option 1): 7 layers of monolithic pixels. Option 2): 3 innermost layers of hybrid pixels and 4 outermost layers of strips.

<table>
<thead>
<tr>
<th>Detector configuration</th>
<th>R&amp;D (kCHF)</th>
<th>Construction and Installation (kCHF)</th>
<th>Total (kCHF)</th>
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</thead>
<tbody>
<tr>
<td>Option 1)</td>
<td>4000</td>
<td>10000</td>
<td>14000</td>
</tr>
<tr>
<td>Option 2)</td>
<td>4000</td>
<td>16000</td>
<td>20000</td>
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The target for the ITS Upgrade is the second long LHC shutdown (LS2), which is at the moment planned for 2017-2018. The schedule of the AST project covers the full upgrade program from the ongoing R&D phase and prototyping to the installation and commissioning in ALICE.

The main blocks of the AST project can be schematically identified as follows:

  - The detector technologies will be selected during 2012 and by the end of 2013 the detector layout and the system components will be finalized and optimized. This process will be based on the outcome of laboratory, irradiation and beam tests. The R&D activities for the auxiliary components may extend until 2014 following the detector specifications defined in 2012-2013.

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