Muon Forward Tracker
Technical Design Report

for the

Muon Forward Tracker

The ALICE Collaboration*

Abstract

The ALICE [1, 2] physics programme after the second LHC Long Shutdown (LS2) is mostly devoted to high precision measurements of hard probes (heavy-flavour hadrons, quarkonia, photons and jets). The strategy for the detector upgrade is reported in the ALICE Upgrade Letter of Intent [3, 4]. The present Technical Design Report describes the Muon Forward Tracker (MFT), a new Si-tracking detector designed to add vertexing capabilities to the MUON spectrometer. The MFT will allow ALICE to extend the precision measurements of the QGP fundamental properties towards the forward rapidity region. The MFT will substantially improve the present performance of the MUON spectrometer and open the path to new measurements not accessible with the present apparatus (open charm/beauty separation, $\psi'$ in central Pb–Pb collisions and $J/\psi$ from $b$-hadron decays measurements). The MFT consists of two half-cones containing five detection half-disks placed along the beams axis between $-460$ mm and $-768$ mm away from the average position of the ALICE interaction point. The MFT covers the pseudo-rapidity domain $-3.6 < \eta < -2.45$. The basic detection element is a silicon pixel sensor, developed by the ALICE pixel groups for both ITS and MFT. The 896 silicon pixel sensors of the MFT will be assembled, using the same technology as for the new ITS, on 280 ladders of 1, 2, 3, 4 or 5 sensors each. ITS read-out electronics will be used for the MFT.

Copyright CERN, for the benefit of the ALICE Collaboration. This article is distributed under the terms of Creative Commence Attribution License (CC-BY-3.0), which permits any use provided the original author(s) and source are credited.

*see list of authors in App. C
# Contents

1 **Introduction** .................. 1
   1.1 Physics objectives .......................... 1
   1.2 MFT layout .................................. 2
   1.3 Experimental conditions ..................... 3
   1.4 Document summary ............................ 6

2 **Pixel sensor** .................. 7
   2.1 Pixel Sensor Developments for ALICE .................. 8
   2.2 Experimental Results ........................... 10
      2.2.1 The full-scale ALPIDE prototype ................. 10
      2.2.2 Radiation Tolerance ........................... 11
   2.3 Criteria for the Final Sensor Choice ................ 11

3 **Ladder and disk structure** .......... 13
   3.1 Ladder mechanical design ..................... 13
   3.2 Disk mechanical design ....................... 16
      3.2.1 Disk general structure ..................... 16
      3.2.2 Material budget of disks ................... 17
   3.3 Ladder assembly .............................. 20
      3.3.1 Ladder assembly procedure ................... 20
      3.3.2 Ladder quantity and assembly timing ........... 22
   3.4 Half-disk assembly ........................... 24
   3.5 Half-MFT assembly ............................ 24

4 **Global support structures, thermal studies, services and integration** ......... 27
   4.1 Services .................................... 27
      4.1.1 Power supply .............................. 27
      4.1.2 Input and output cables ..................... 28
      4.1.3 DCS cables ................................ 29
      4.1.4 Cooling .................................. 29
   4.2 MFT half-cone ............................... 30
   4.3 MFT half-barrel .............................. 32
   4.4 Thermal studies ............................. 34
      4.4.1 Water cooling option ....................... 34
      4.4.2 Air cooling option .......................... 35
      4.4.3 PCB cooling ............................... 37
   4.5 Installation and removal ...................... 37
   4.6 Survey and mechanical alignment ............... 39

5 **Readout architecture and electronics** .......... 41
   5.1 General readout architecture ................... 41
   5.2 Sensor data throughput ........................ 42
   5.3 Data transmission on Flexible Printed Circuit .... 45
   5.4 Half plane printed circuit boards ............... 47
## 5.5 FPGA based backend readout unit

### 6 Performance

6.1 Detector acceptance

6.2 Standalone track reconstruction in the MFT

6.2.1 Cellular Automaton algorithm

6.2.2 Linear Track Finder algorithm

6.2.3 Reducing the combinatorics: the fiducial interaction region

6.2.4 Parameters of the algorithms

6.3 Simulation frameworks

6.3.1 Simplified Monte Carlo simulations

6.3.2 AliRoot simulations

6.4 Standalone tracking performance

6.4.1 CA track finding performances

6.4.2 Momentum dependence of the track finding efficiency for LTF and CA

6.5 Matching between MUON and MFT tracks

6.6 Muon offset resolution

6.7 Physics case review and update

6.7.1 Open Heavy Flavours in the single muon channel

6.7.2 Beauty via non-prompt $J/\psi$

6.7.3 Summary of the other available performance studies

6.7.4 Ongoing and future physics performance studies

### 7 Organization, cost and schedule

7.1 Organisation

7.2 Cost assessment

7.2.1 Pixel sensor

7.2.2 Flex Printed Circuit

7.2.3 Hybrid Integrated Circuit and ladder assembly

7.2.4 Global assembly

7.2.5 Integration in ALICE

7.2.6 Readout electronics and cables

7.2.7 Services

7.3 MFT general schedule

### A Air cooling studies

A.1 Model description

A.2 Detailed partial thermo-fluid model

A.2.1 Temperature uniformity optimization

A.3 Detailed ladder calculations

A.3.1 Parametric studies

A.3.2 Summary of thermal studies

### B Glossary

### C The ALICE Collaboration

### Bibliography
1 Introduction

The primary purpose of ALICE (A Large Ion Collider Experiment) is to explore the physics of strongly interacting matter at high temperature and energy density [1]. Its fundamental goal consists of establishing how the properties of the Quark Gluon Plasma (QGP) emerge from the dynamics of the strong interaction. To address this programme, ALICE uses proton–proton, proton–nucleus and nucleus–nucleus collisions at the energies provided by the CERN LHC [2].

After the first Long Shutdown (LS1) in 2014, the upgraded LHC will operate at an energy of 13 TeV in proton–proton collisions and 5.1 TeV in Pb–Pb collisions. The next long shutdowns, LS2 and LS3, are scheduled to progressively increase the luminosity of both proton and Pb beams. During LS2 (2018–2019), the LHC upgrade aims to increase the instantaneous proton–proton and nucleus–nucleus luminosity to $L_{pp} = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and $L_{Pb-Pb} = 6 \times 10^{27}$ cm$^{-2}$s$^{-1}$. At such high luminosity, the Pb–Pb interaction rate will reach 50 kHz.

The upgrade strategy defined by the ALICE Collaboration aims at providing the capability to record all Pb–Pb interactions and at enhancing the track reconstruction performance of the apparatus. The goal is to accumulate an integrated luminosity of 10 nb$^{-1}$ minimum-bias Pb–Pb collisions, and 3 nb$^{-1}$ of integrated luminosity, in a dedicated low-magnetic-field run, for low-mass dielectron studies [3, 4]. The implementation of this upgrade programme includes: new readout electronics for most of the detectors enabling the high readout rate [5]; a new, high-resolution, low-material budget Inner Tracking System (ITS) [6]; the replacement of the Time Projection Chamber (TPC) readout wire chambers with micro-pattern gaseous readout detectors [7]; a new set of forward trigger detectors [5]; a new integrated online–offline system [3, 8]; the Muon Forward Tracker (MFT) presented in this document.

The MFT [4] is a Si-tracking detector designed to add vertexing capabilities to the MUON spectrometer. With the MFT, ALICE will gain access to new measurements currently out of reach with the MUON spectrometer alone and increase the sensitivity of several other measurements.

The MFT physics objectives are summarized in Sec. 1.1. An overview of the MFT layout is given in Sec. 1.2. The experimental conditions for the MFT operation are discussed in Sec. 1.3.

1.1 Physics objectives

QCD matter at high temperature and energy density is characterized by its equation of state and by thermodynamic properties such as transport coefficients, bulk and shear viscosity and speed of sound, which can be calculated from perturbative and/or lattice QCD. These properties can be derived from studying the in-medium hard probes dynamics, from production to hadronization, and thermal radiation from the various stages of the system evolution. Covering a wide rapidity range is crucial, as illustrated by the RHIC experiments, for a comprehensive understanding of the observed phenomena in nucleus–nucleus collisions and to constrain theoretical models. The MUON spectrometer together with the MFT addition extends the central barrel pseudo-rapidity coverage ($|\eta| < 0.9$) to large pseudo-rapidities ($-3.6 < \eta < -2.45$). In this respect, together with measurements down to zero transverse momentum, ALICE will be unique at the LHC. In addition, measurements at large rapidities will give access to the study of the gluon dynamics at small Bjorken-$x$ values, allowing to shed light on the initial state of the collisions. The extended
The physics programme, that comes within reach thanks to the MFT, will in particular address the study of the following key points:

- The in-medium charmonium dynamics and the competing mechanisms of dissociation and regeneration to probe the medium temperature and the quark interaction in a deconfined system; this study will involve measurements of prompt $J/\psi$ and $\psi(2S)$ production and nuclear modification factors $R_{AA}$ down to zero $p_T$.

- The thermalization of heavy quarks in the medium; this study will involve measurements of elliptic flow ($v_2$) for charm down to $p_T = 1$ GeV/$c$ (semi-muonic decays), beauty (semi-muonic and $J/\psi$ decays) and prompt charmonium down to zero $p_T$.

- The medium density and the mass dependence of in-medium parton energy loss; this study will involve measurements of charm (semi-muonic decays), beauty (semi-muonic and $J/\psi$ decays) $p_T$-differential production yields.

- The QCD phase transition and its chiral nature; this study will involve the measurement of the QGP thermal radiation and the spectral shape of low mass vector mesons.

The MFT will enable these measurements over a broad transverse momentum interval and with high statistical precision.

The new high-precision measurements accessible to ALICE thanks to the high-precision vertexing capabilities added by the MFT to the present MUON spectrometer are summarised in Table 1.1. The upgrade physics programme is further discussed in detail in the MFT letter of intent [4].

### Table 1.1: New physics measurements made possible by the MFT addition.

<table>
<thead>
<tr>
<th>Observable</th>
<th>$p_T$-coverage (GeV/$c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Charm</strong></td>
<td></td>
</tr>
<tr>
<td>Prompt $J/\psi - R_{AA}$ &amp; $v_2$</td>
<td>$p_T(J/\psi) &gt; 0$</td>
</tr>
<tr>
<td>$\psi(2S) - R_{AA}$</td>
<td>$p_T(\psi') &gt; 0$</td>
</tr>
<tr>
<td>$\mu$ from $c$-hadron decays - $R_{AA}$ &amp; $v_2$</td>
<td>$p_T(\mu) &gt; 1$</td>
</tr>
<tr>
<td><strong>Beauty</strong></td>
<td></td>
</tr>
<tr>
<td>Non-prompt $J/\psi - R_{AA}$ &amp; $v_2$</td>
<td>$p_T(J/\psi) &gt; 0$</td>
</tr>
<tr>
<td>$\mu$ from $b$-hadron decays - $R_{AA}$ &amp; $v_2$</td>
<td>$p_T(\mu) &gt; 3$</td>
</tr>
<tr>
<td><strong>Chiral symmetry and QGP temperature</strong></td>
<td></td>
</tr>
<tr>
<td>Light vector mesons spectral functions and QGP thermal radiation</td>
<td>$p_T(\mu\mu) &gt; 1$</td>
</tr>
</tbody>
</table>

### 1.2 MFT layout

The MFT role is to measure charged tracks with high spatial resolution in front of the MUON spectrometer and inside its acceptance. The MFT detector surrounds the vacuum beam-pipe, it

---

1 We are referring here to the $p_T$ of the decay product, the muon for semi-muonic decays and the $J/\psi$ for $B \to J/\psi + X$ decays.
is positioned inside the ITS outer barrel and along the beam axis between the ITS inner barrel and the front absorber of the MUON spectrometer (see Fig. 1.1).

The basic detection element of the MFT is a silicon pixel sensor, identical to that of the new ITS [6].

The MFT consists of two half-MFT cones (Fig. 1.1). Each half-MFT cone consists of 5 half-disks positioned along the beam axis, in the direction of the MUON spectrometer (C-side) at $z = -460, -493, -531, -687, -768$ mm from the nominal interaction point. The first two half-disks are identical (called Half-Disk-0 and 1), while the remaining three half-disks are all different and are called Half-Disk-2, Half-Disk-3 and Half-Disk-4 respectively. The MFT covers the pseudo-rapidity acceptance $-3.6 < \eta < -2.45$. In this range, the probability for a particle to hit at least four disks is greater than 90% if we consider a Gaussian distribution for the interaction vertex in the $z$-direction with $\sigma \approx 60$ mm \(^2\). A half-disk consists of a disk spacer, a disk support, two printed circuit boards (PCB disks) and the sensor ladders. The sensor ladder consists of 1, 2, 3, 4 or 5 silicon pixel sensors soldered to a Flex Printed Circuit (FPC) with aluminium strips. Geometrical parameters of the MFT and of each half-disk are reported in Tab. 1.2. The positioning of the sensors on the front and back planes of the half-disks is shown in Fig. 1.2. Special care has been taken in the selection of materials to minimise the material budget: it amounts to less than 0.6% of a radiation length per disk (Sec. 3.2.2).

1.3 Experimental conditions

The experimental conditions in terms of interaction rates and particle multiplicity, which have served as a basis for the definition of the detector specifications and simulation of its performance,
are presented in this section.

Table 1.3 summarises the expected maximum hit densities for primary and secondary charged particles. An additional contribution to the overall particle load comes from $e^+e^-$ pairs generated in the electromagnetic interaction of the crossing beam-ion bunches. These will be referred to as QED electrons. The latter contribution depends on the detector-electronics integration-time. The expected radiation doses and hadron fluences are computed for the following integrated luminosities:

- $8 \times 10^{10}$ nuclear Pb–Pb collisions ($10 \text{ nb}^{-1}$, $\sqrt{s_{\text{NN}}} = 5.5 \text{ TeV}$);
- $1 \times 10^{11}$ nuclear p–Pb collisions ($50 \text{ nb}^{-1}$, $\sqrt{s_{\text{NN}}} = 8.8 \text{ TeV}$);
- $4 \times 10^{11}$ inelastic proton–proton collisions ($6 \text{ pb}^{-1}$, $\sqrt{s} = 5.5 \text{ TeV}$);

A conservative safety factor of ten is further applied to take into account uncertainties in the beam background, possible beam losses, inefficiency in data taking and data quality requirements. The expected radiation levels corresponding to the sum of Pb–Pb, p–Pb and proton–proton integrated luminosities are summarised in Tab. 1.3. The pixel chip technology adopted by the MFT is not significantly degraded when exposed to these radiation levels even when operated at room temperature (see Chapter 2).
Table 1.2: Geometrical parameters of the MFT. Number of sensors and ladders per Half-Disk and for the full MFT.

<table>
<thead>
<tr>
<th>Half-Disk</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Full MFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius (mm)</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
<td>38.2</td>
<td>39.2</td>
<td>–</td>
</tr>
<tr>
<td>Outer radius (mm)</td>
<td>92.6</td>
<td>98.0</td>
<td>104.3</td>
<td>130.1</td>
<td>143.5</td>
<td>–</td>
</tr>
<tr>
<td>z-position (mm)</td>
<td>–460</td>
<td>–493</td>
<td>–531</td>
<td>–687</td>
<td>–768</td>
<td>–</td>
</tr>
</tbody>
</table>

No. sensors: 64 64 76 112 132 896

No. ladders with:

<table>
<thead>
<tr>
<th></th>
<th>1 sensor</th>
<th>2 sensors</th>
<th>3 sensors</th>
<th>4 sensors</th>
<th>5 sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sensor</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2 sensors</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3 sensors</td>
<td>18</td>
<td>18</td>
<td>14</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>4 sensors</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>5 sensors</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
</tbody>
</table>

No. ladders: 24 24 26 32 34 280

* Radius to reach $\eta = 2.5$ with a vertex position at $z = 100$ mm from the nominal IP position.

Table 1.3: Expected maximum hit densities and radiation levels in the MFT given at inner and outer radii of each disk. Values obtained from full AliRoot simulations using FLUKA and GEANT transport models and Pythia (Perugia 2011) as the MC event generator for pp collisions at $\sqrt{s} = 5.5$ TeV.

<table>
<thead>
<tr>
<th>Disk</th>
<th>Radius (mm)</th>
<th>Particles $^a$ (cm$^{-2}$)</th>
<th>QED electrons $^b$ (cm$^{-2}$)</th>
<th>NIEL $^c$ (1 MeV n$_{eq}$/cm$^2$)</th>
<th>TID $^d$ (krad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.0</td>
<td>12.7</td>
<td>8.9</td>
<td>$5.7 \times 10^{12}$</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>92.6</td>
<td>1.9</td>
<td>$6.9 \times 10^{-2}$</td>
<td>$1.1 \times 10^{12}$</td>
<td>52</td>
</tr>
<tr>
<td>1</td>
<td>25.0</td>
<td>12.9</td>
<td>8.6</td>
<td>$5.9 \times 10^{12}$</td>
<td>380</td>
</tr>
<tr>
<td></td>
<td>98.0</td>
<td>1.7</td>
<td>$6.0 \times 10^{-2}$</td>
<td>$1.1 \times 10^{12}$</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>25.0</td>
<td>12.6</td>
<td>8.6</td>
<td>$5.7 \times 10^{12}$</td>
<td>347</td>
</tr>
<tr>
<td></td>
<td>104.3</td>
<td>1.6</td>
<td>$4.8 \times 10^{-2}$</td>
<td>$1.1 \times 10^{12}$</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>38.2</td>
<td>11.9</td>
<td>3.4</td>
<td>$3.5 \times 10^{12}$</td>
<td>317</td>
</tr>
<tr>
<td></td>
<td>130.1</td>
<td>1.1</td>
<td>$2.7 \times 10^{-2}$</td>
<td>$1.1 \times 10^{12}$</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>39.2</td>
<td>12.9</td>
<td>3.1</td>
<td>$3.8 \times 10^{12}$</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>143.5</td>
<td>0.9</td>
<td>$2.2 \times 10^{-2}$</td>
<td>$1.3 \times 10^{12}$</td>
<td>29</td>
</tr>
</tbody>
</table>

$^a$ Average hit densities in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV (including secondaries produced in material).

$^b$ Integration time of 4 $\mu$s, and interaction rate of 100 kHz.


$^d$ Total Ionizing Dose. Including a safety factor 10.
1.4 Document summary

The same CMOS monolithic technology as that chosen for the new ITS [6] is adopted for the implementation of the MFT pixel sensor [4]. The common sensor is jointly developed by the MFT pixel group and the ITS pixel group. Therefore R&D activities on the pixel sensor are only briefly described in Chapter 2. Details can be found in the ITS Technical Design Report [6].

Chapter 3 describes the design of the main MFT detection elements: the ladders and the disks. The assembly of the silicon pixel detector with the FPC will use the same bonding technology as the one used by the ITS [6]. The main difference between the ITS inner-barrel FPC and the MFT FPC is the number of silicon pixel sensors per ladder, which in the case of the MFT varies between 1 and 5 sensors. The assembly of the MFT ladders on the disks and of the half-disk in the half-MFT is also described in this chapter.

The services and main mechanical structures, barrels and cones, of the MFT are described in Chapter 4. A cooling strategy based on water cooling through polyimide water-pipes in the disk spacer, similar to the solution adopted by ITS is discussed. A full thermal study based on air cooling of the pixel sensor is presented in Chapter 4 and appendix A. Finally, the MFT installation inside ALICE and the removal procedure are discussed together with the mechanical alignment procedure.

The complete read-out chain, from the silicon pixel sensor to the ALICE DAQ system, is discussed in Chapter 5. The MFT readout working group collaborates with the ITS readout working group to build a common readout electronics, following the strategy described in ITS Technical Design Report [6].

The detector performance and physics studies, based on Monte Carlo simulations including particle transport and a detailed geometrical model of the MFT detector, are presented in Chapter 6.

Chapter 7 presents the project time schedule, organisation, cost estimate and sharing of responsibilities among the participating institutes. Explanations and justifications of cost estimates for the main cost items and the work breakdown structure (WBS) and planning are detailed there.
2 Pixel sensor

To fulfill the requirement of high resolution track reconstruction in the environment of high multiplicity created in nucleus–nucleus collisions, a new pixel detector has been selected as the basic detection element of the MFT. The pixel detector is based on the CMOS monolithic pixel sensor technology (the same technology has been selected 2 years ago for the new ALICE ITS detector [6, Sec. 2.2]). The detection efficiency and the performance of track reconstruction depend on the spatial resolution of the sensor, the fake-hit rate induced by noise and the level of charge pile-up in the sensor. The high-multiplicity and confined environment in which the MFT will operate requires that the sensors are tolerant to radiation and power efficient to limit heat dissipation inside and outside of the detector. Specifications for the MFT sensors are summarized in Table 2.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>$\sim 5 \mu m$</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>$\sim 25 \mu m$</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>$&gt; 99.5 %$</td>
</tr>
<tr>
<td>Integration time</td>
<td>$&lt; 20 \mu s$</td>
</tr>
<tr>
<td>Sensor thickness</td>
<td>50 $\mu m$</td>
</tr>
<tr>
<td>Binary output</td>
<td>1-bit</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>$&lt; 150 \text{mW/cm}^2$</td>
</tr>
</tbody>
</table>
| Radiation tolerance*     | $\sim O(10^{13}) \text{neq/cm}^2$ (10-years operation) $\sim O(700) \text{krad}$

*The highest value between MFT (Tab. 1.3) and ITS [6] has been chosen.

The CMOS monolithic Pixel Sensor (CPS) technology, currently used in high energy physics experiments, is a well adapted technology for vertex detectors which allows the requirements of granularity, material budget, and power consumption to be met [9]. To improve further the performance, in terms of readout speed and radiation hardness, of existing CPS sensors, the 0.18 $\mu m$ CMOS Imaging Sensor (CIS) technology from TowerJazz that provides smaller feature size was selected. Availability of wafers with “thick” and high-resistivity epitaxial layer contributes in addition to the improvement of the radiation tolerance.

Since the end of 2011, an active R&D program is pursued by the MFT group – in close collaboration with the ITS group – with the goal to define the optimum sensing node, amplification and readout architecture. The next sections summarize the ASIC developments with the TowerJazz technology and the performances achieved. Finally, the criteria for selecting the most suitable CMOS pixel sensor for the MFT are addressed in the last section.
2.1 Pixel Sensor Developments with the TowerJazz Technology

The detector technology and architecture are fully described in [6, Sec. 2.2] and [4, Sec. 3.1] and will not be reiterated in this document.

During the R&D program, a series of multi-project wafer and engineering runs were realized. Following the prototyping phase, the pixel-design collaboration has validated the values of the key parameters such as the charge collection properties for several configurations varying pixel size, diode size and type, wafer resistivity, front-end electronics and digital signal processing [10, 11, 12, 13]. The main outcome is summarized in Section 2.2. Taking into account the MFT requirements in term of charge collection efficiency, fake hit rate and readout speed, a fully digital pixel with double-row simultaneous readout has been specifically developed [14] (Tab. 2.2) rather than the rolling shutter architecture of existing CPS designs with analogue pixels and single end-column discriminators [15].

<table>
<thead>
<tr>
<th>Prototype</th>
<th># Pixels (× 1000 pix)</th>
<th>Pitch (µm)</th>
<th>Main parameter tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>M32</td>
<td>32.8</td>
<td>20</td>
<td>First characterization of charge collection properties with simple pixels architecture</td>
</tr>
<tr>
<td>M32D</td>
<td>8.1</td>
<td>22</td>
<td>Pixel matrix with end-column discriminators</td>
</tr>
<tr>
<td>M32Ter</td>
<td>32.8</td>
<td>20</td>
<td>Matrix with in-pixel amplification</td>
</tr>
<tr>
<td>RSBPix1</td>
<td>2.3</td>
<td>25</td>
<td>Matrix with in-pixel discriminator</td>
</tr>
<tr>
<td>M32V4</td>
<td>32.8</td>
<td>20</td>
<td>Analogue signal processing optimization dedicated to digital pixel and RTS noise mitigation</td>
</tr>
<tr>
<td>RSBPix2</td>
<td>2.3</td>
<td>25</td>
<td>Matrix with in-pixel discriminator</td>
</tr>
<tr>
<td>M22THRB2</td>
<td>4.1</td>
<td>22</td>
<td>Pixel matrix with end-column discriminators; increase of readout speed by reading out 2 rows simultaneously</td>
</tr>
<tr>
<td>Pixam</td>
<td>73.7</td>
<td>25</td>
<td>1/3 of final sensor with full functionalities: digital pixels, clusters recognition, data sparsification, double read-out</td>
</tr>
</tbody>
</table>

*ASIC co-designed with IPHC group.

Four large prototypes with full functionalities have been realized by combining the previously tested prototypes into a Full Scale (FS) or Full Scale Building Block (FSBB: about 1/3 of the ASIC final size) pixel sensor with maximum functionalities approaching the final ones required for the MFT.

- **Pixam (FSBB)**

  *IRFU*

  The *Pixam_FSBB* sensor is based on the rolling shutter architecture with a digital pixel matrix (in-pixel discrimination) and pixel size of 25 µm leading to spatial resolution from the binary pixel of about 5 µm. The sensor allows simultaneous double-row readout giving an integration time of about 10 µs, when operated at the nominal 160 MHz frequency. Digital data are processed to reconstruct hit-pixel clusters providing a compression factor of 57 with respect to the full matrix readout as estimated for the anticipated multiplicity environment in which the MFT will operate [16]. The *Pixam_FS* ASIC could be built out of three *Pixam_FSBB* to constitute a 30 mm × 6.3 mm sensor for an estimated power
consumption of 150 mW/cm². The present ASIC design is adapted to be connected to the FPC by the wire bonding technique (all pads are gathered at the bottom of the chip, the six metal layers are used in the design).

- **Alpide (FS)**  
  CERN, INFN, CCNU, YONSEI  
  The \textit{pAlpide\_FS} prototype is a full scale sensor (≈ 30 mm × 15.3 mm) implementing a data-driven architecture [6, Chap. 2.6.4] which guarantees that only hit pixels are read out. With the benefit of an external trigger, the equivalent integration time is of the order of about 4 µs. Collected charges are digitized and sparsified within the 28 µm² pixel area with a low power front-end and an asynchronous readout leading to a power consumption of 50 mW/cm². The sensor was designed to be back biased with a negative power supply of a few volts in order to increase the charge collection and the radiation-hardness of the ASIC. The present ASIC design is adapted to be connected to the FPC by a laser soldering technique (pads are distributed on the ASIC surface using the two last metal layers, four metal layers remain available for the micro-electronic design).

- **Mistral (FSBB) / Astral (FSBB)**  
  IPHC  
  \textit{Mistral\_FSBB} [6, Chap. 2.6.1] and \textit{Astral\_FSBB} [6, Chap. 2.6.2] are dedicated sensors for the ITS inner-layers and outer-layers respectively. They are designed to be an element (1/3) of the final ∼ 30 × 16 mm² sensor. They both use the rolling shutter architecture and share common digital signal processing (zero suppression logic and cluster recognition) as well as readout circuits. The differences between the two sensors lie in the pixel matrix and digitization architecture process, as follows:

  The \textit{Mistral\_FSBB} sensor is optimized for spatial resolution with an analogue matrix of 22 × 33 µm² pixels. The expected spatial resolution is about 5 µm. The analogue signal is digitized by end-column discriminators (two per column). Two rows are read out simultaneously giving an integration time of about 40 µs. The power consumption for the \textit{Mistral\_FS} sensor is ∼ 200 mW/cm².

  The \textit{Astral\_FSBB} sensor is optimized for power consumption with a low power digital matrix with elongated pixels (pixel size 36 × 62.5 µm²). The foreseen spatial resolution is about 10 µm. The sensor performs a simultaneous double-row readout giving an integration time of about 20 µs. The power consumption expected for the \textit{Astral\_FS} sensor is about 100 mW/cm².

  Both Astral and Mistral architectures are adapted to be connected to the FPC by the wire bonding technique (all pads are gathered at the bottom of the chip, the six metal layers are used in the design). Design changes to be compatible with the laser soldering technique are under study for Mistral.

---

*Figure 2.1: Pictures of ALICE full scale CMOS pixel sensors.*
2.2 Experimental Results

The pixel sensor prototypes developed within the ITS and MFT projects are being qualified in the laboratory and with test beams. A comprehensive characterization campaign aiming at the qualification of the TowerJazz 0.18\,\mu m CMOS Imaging Sensor (CIS) process, as well as proving the feasibility of different readout architectures, is reported in [1, Chap. 2.7]. Both have been established by the use of small- and medium scale prototype chips (up to a few 10\,000 pixels). This in particular includes the possibility to add complex logic circuitry consisting of both NMOS and PMOS transistors into the pixel matrix, which is a special feature of this technology, and which allows for optimized readout schemes.

Given the positive results of the small-scale chips, the next generation of sensor prototypes, namely FS and FSBB prototypes of the different architectures have been designed and manufactured, and their performances are reported hereafter. It is worth noting that all sensors have to be operational at a temperature of $T \geq 30^\circ\text{C}$.

2.2.1 The full-scale ALPIDE prototype

The pALPIDE\,FS, which is a full-scale prototype, was tested at the CERN PS with a 6 GeV $\pi^-$ beam. The energy deposits equal those of minimum-ionizing particles within 10\%. The ASIC features an 18\,\mu m-thick, high-resistivity (\geq 1\,k\Omega\,cm) epitaxial layer as a sensitive volume, and is back-thinned down to 50\,\mu m. The ALPIDE architecture allows to apply reverse substrate bias, $V_{BB}$, to increase the total bias of the collection diode.

![Figure 2.2: pALPIDE\,FS performance results, measured at the CERN PS with 6 GeV $\pi^-$ beam for different neutron irradiation (NIEL) levels. The fake hit rate, the detection efficiency, the cluster multiplicity and the spatial resolution are drawn in function of the in-pixel discriminator threshold ($I_{thr}$).](image)

Figure 2.2 shows the key performance parameters of the sensor before and after irradiation. Measurements are performed at an ambient temperature between 22\,\degree C and 30\,\degree C and the bias set to $V_{BB} = -3\,\text{V}$. The chips were irradiated in two steps up to the required level of $1 \times 10^{13}$ 1 MeV n$_{eq}$ cm$^{-2}$ (NIEL).

With an operating point between 100\,pA and 200\,pA for the in-pixel discriminator threshold current, the results show an efficiency of above 99.5\%, while keeping the fake hit rate below $10^{-5}$ per pixel and event and yielding spatial resolution better than 5\,\mu m. After neutron irradiation, the fake hit rate increases while no effect is observed on the detection efficiency. The operational margins observed before irradiation provide enough room to operate the sensor according to requirements.
2.3 Criteria for the Final Sensor Choice

2.2.2 Radiation Tolerance

The radiation tolerance of the *TowerJazz* 0.18 µm technology has been assessed both for basic transistor and diode structures and for full sensor prototype circuits containing digital logic for data processing. The most noticeable results are:

- **TID:** NMOS and PMOS transistor structures have been irradiated with X-rays up to a dose of 10 Mrad. The most affected structures are minimum feature size (0.18 µm) transistors that show a shift in threshold voltage of a few 10 mV at maximum and an almost complete recovery after 24 h of annealing. The impact of TID on sensor prototypes has been measured in various test beam campaigns at CERN and at DESY, showing only a very marginal degradation of the charge collection properties after TID irradiation of 3 Mrad.

- **NIEL:** Full sensor prototypes have been characterized in the laboratory and in various test beams after irradiation with neutrons with a fluency of up to $1 \times 10^{13}$ 1 MeV $n_{eq}/cm^2$. An acceptable decrease of the SNR of about 10 % to 20 % and an increase of noise of up to 20 % was observed for most of the prototypes.

- **Single Event Effects (SEE):**
  - Single Event Upset (SEU): The SEU sensitivity of the *TowerJazz* technology has been measured using a dedicated memory chip (SEU,TJ180) consisting of a single port RAM, a dual port RAM and a shift register. The test structures were exposed to proton beams between 24 and 230 MeV/c and the bit flips were monitored as a function of exposure time and particle flux. Over the range of available proton energies, SEU cross sections between $5 \times 10^{-14}$ cm$^{-2}$ and $12 \times 10^{-14}$ cm$^{-2}$ were measured, indicating a mean error probability of better than $10^{-9}$ under the operational conditions of the ALICE ITS Upgrade.
  - Single Event Latchup (SEL): The latchup sensitivity of the *TowerJazz* technology has been measured using two different devices, a memory chip (SEU,TJ180), a full sensor prototype chip (*pAlpide_FS*), a chip periphery containing digital and analog blocks for chip operation and data processing. Both devices were exposed to heavy ion beams with a LET between 3.3 MeVcm$^2$/mg and 67.7 MeVcm$^2$/mg. The single port RAM of the memory chip started to show latchup from a LET of 6.4 MeVcm$^2$/mg, well within the LET range created by the particle spectrum in the LHC experiments. Dual port RAM and shift registers, however, were not sensitive to latchup up to a LET of 40 MeVcm$^2$/mg. The occurrence of latchup in the *pAlpide_FS*, consisting of dual port RAM and shift registers, but not of single port RAM, was consequently observed for a LET of 40 MeVcm$^2$/mg and higher. Using a collimating system, it was also found that the sensitivity to latchup almost entirely resides in the analog block of the *pAlpide_FS*.

2.3 Criteria for the Final Sensor Choice

With the constant concern to minimize cost, avoid unnecessary duplication of R&D, and make the best use out of the expert human resources available within the ALICE Collaboration, the MFT project will strictly monitor the developments around the new ITS detector and is collaborating closely with the ITS project.

This natural move is fully justified by the similarity between the requirements imposed on the ITS inner-barrel sensors and those imposed on the MFT sensors, in terms of particle flux, radiation dose, spatial resolution and readout speed. In addition, not only the sensors but also
the ladder production, assembly, readout electronics and qualification tests will largely benefit from a close collaboration between the two projects. The ITS final sensor architecture will be selected by the ITS project early 2015, following an internal review involving also the MFT project.

Currently, the Alpide architecture exhibits good performances for the MFT, namely the short readout time (about 4 $\mu$s) considerably reducing the pile-up probability.
3 Ladder and disk structure

The silicon pixel sensors, described in the previous chapter, are integrated on mechanical ladder structures which are assembled on the five disks that constitute the MFT. This chapter provides details on the ladders and the disks. The additional mechanical structures, such as the cone and the barrel, are described in the next chapter together with services and integration. The last sections of the present chapter describe the assembly procedure of all the elements of the MFT.

3.1 Ladder mechanical design

The MFT ladders are thin structural elements that hold the silicon pixel sensors and ensure electrical links between the sensors and the readout electronics. Ladders of various length are equipped with 1, 2, 3, 4 or 5 silicon pixel sensors (Fig. 3.1).

A typical ladder consists of the following elements (Fig. 3.2):

- the stiffener: a mechanical support made out of carbon fibre ensures the necessary stiffness. It is equipped with one pin to allow a precise isostatic positioning of the ladder on the half-disk support and is fixed on it by one screw.
- the silicon pixel sensors: from 1 to 5 sensors, depending on the ladder size (see Fig. 3.1 and Fig. 3.3).
- the Flexible Printed Circuit (FPC): a printed circuit made of polyimide with aluminium traces (a picture of a FPC prototype with copper wires for 5 silicon pixel sensors is shown in Fig. 3.4). The FPC is equipped with a connector at one end and SMD components (Surface Mounted Device) such as decoupling capacitors.

The Hybrid Integrated Circuit (HIC) consists of the sensors laser-soldered to the FPC, with a gap of 100 µm between sensors. The stiffener is fabricated out of composite material. In the detection area, the maximum thickness is 200 µm. Although the exact type of the composite material is not yet defined, a unidirectional High Modulus (HM) Carbon Fiber Reinforced Polymer (CFRP) is considered. In order to minimize the material budget, a simple layer of polyimide (30 µm thick) may be considered, its feature will be the protection of the sensors.

The FPC (Fig. 3.4) is composed of a 75 µm thick layer of polyimide and top and bottom aluminium layers, each 25 µm thick. It has been designed so that it can be precisely positioned during the ladder assembly (see Sec. 3.3) using the ear shaped extra parts. These parts are removed with a dedicated cutting tool once the assembly is completed.

A ladder prototype is presently being built (see Fig. 3.5, with the stiffener prototype) and a mechanical characterization of the ladder is being performed.
Figure 3.2: MFT ladder details (top exploded view and bottom view). The stiffener, located on the bottom side of a ladder, has not been represented.

Figure 3.3: MFT ladder dimensions.
3.1 Ladder mechanical design

Figure 3.4: Prototype of a FPC for a 5-sensor ladder fabricated by CERN facility with copper traces. This FPC is dedicated to assemble a mechanical ladder using dummy sensors with 50 contacts. The ear shaped parts are used to position the FPC during the laser soldering process. These parts are cut out before the assembly of ladders on the half-disks. The final version of the FPC will be fabricated with aluminium traces.

Figure 3.5: Prototype of a carbon fiber stiffener.
3.2 Disk mechanical design

3.2.1 Disk general structure

The MFT consists of five disks (Disk-0, Disk-1, Disk-2, Disk-3 and Disk-4). Disk-0 (Fig. 3.6) is the closest to the Interaction Point (IP). Each disk is subdivided in two half-disks (top and bottom one), corresponding to the upper and lower half of the MFT (Fig. 3.7). Half-disks have the same global design and Half-Disk-0 and Half-Disk-1 are identical. Each half-disk has two detection planes one on the front and one on the back side. The overlap between sensors of the back and front plane ensures the hermeticity of the half-disk. The pitch for ladders in a given plane is 17 mm (ladder width is 16 mm) optimising the detector acceptance around the beam-pipe and increasing the overlap of the detector: 50% of charged particles will hit both planes of the disk.

The half-disk spacer includes water polyimide pipes [6] ensuring cooling of the ladders (see Fig. 3.8). Additional water cooling pipes will be used to cool the DC-DC converters outside the acceptance. In addition, some air is circulating around the disks at the speed of about 0.5 m/s to homogenize the ambient temperature (between 20 °C and 22 °C) and also to cool down the beam pipe.

![Half-Disk-0 Diagram](image)

**Figure 3.6: Half-Disk-0.**

A half-disk consists of the following elements (see Fig. 3.8):

- Ladders are fixed on one edge with one screw for safety and glued all along their length on the half-disk spacer;
- Two Printed Circuit Boards (PCBs) located outside the acceptance. They are equipped with connectors (for the ladder connection and the signal cables), DC-DC converters (providing 1.8 V for the sensors) and other electronic components;
- One half-disk support located outside the acceptance. Its mechanical feature is to ensure the link between the different components of the half-disk and also between the half-disk
and the MFT half-cone. To limit the production of secondary particles plastic materials like PEEK are being considered;

- One half-disk spacer located inside the acceptance. Its main purpose is to add rigidity to the ladders in the acceptance area and to ensure their cooling (see Fig. 3.8). This part is fixed on the half-disk support. It is under consideration to build this part out of composite material with high rigidity (HM CFRP).

Fixing and positioning of the half-disks inside the MFT half-cone is done with two screws and two pins (one adjusted and one positioning). The same kind of positioning solution is used for the ladders. The manufacturing of a prototype of Half-Disk-0 is being perform to test the ladder assembly and half-disk integration.

### 3.2.2 Material budget of disks

The material budget of the disks has been evaluated. Several cooling methods have been considered. The baseline cooling is using water based on the studies performed by the ITS. For integration reasons, two scenarii are considered: water pipes running along the ladders, named *axial water cooling*, or perpendicularly to the ladders, named *perpendicular water cooling*. Fig. 3.9 shows an example of the spatial distribution of the fraction of $X_0$ of a half-disk for the two water cooling scenarii. The material budget has been also evaluated in the case of air cooling.

The mean material budget for each half-disk is reported in Tab. 3.1. Only the ladders and the

---

*Figure 3.7: Typical disk arrangement.*
half-disk support have been taken into account, the other elements being outside the acceptance. The maximum fraction of $X_0$ is 0.576 % below the value used for the performance studies (0.6 % of $X_0$).

Additional details are shown in Fig. 3.10 with the contribution to the material budget of each component, along the ladder direction ($X$) and along the orthogonal direction ($Y$). The $Cooling$ and $Spacer$ labels in Fig. 3.10 corresponds to the water pipes and the cold plates, and to the mechanical structure between the front and back plane ladders, respectively. As shown in Fig. 3.10, the ladders (pixel sensors, FPCs and stiffeners) are the largest contributors with 64 % of the total material budget.
3.2 Disk mechanical design

Figure 3.9: Distribution of radiation length for a half-disk for both water cooling scenarios (perpendicular and axial respectively). Note that there is a set of water pipes for each half-plane (front and back).

Figure 3.10: Mean contributions to the fraction of $X_0$ of the different elements of disk2 along X and Y directions. The top figures correspond to the perpendicular water cooling scenario and the bottom figures to the axial water cooling scenario.
3.3 Ladder assembly

3.3.1 Ladder assembly procedure

Wafer production, thinning, dicing and qualification tests of the sensors follow the procedure defined by the ITS upgrade project [6]. All the sensors received and qualified are considered ready for assembly on a ladder.

The ladders are assembled using the laser soldering bonding-technology developed for the ITS upgrade project [6]. The connection of the sensors to the FPC is done at a facility at CERN, where the ITS inner layers are assembled. Dedicated tooling for the MFT ladder assembly has been built and tested in February 2015 (see Fig. 3.11 from [17]). The key components are:

- A vacuum table, dedicated to hold the sensors and the FPC, installed on the semi-automatic industrial soldering machine;
- A lid with a quartz window to ensure the vacuum for the soldering;
- A frame to handle and to position the FPC precisely on top of the chips. This frame is aligned with the vacuum table and the FPC with the help of alignment pins;
- A soldering grid, made out of ceramic material, with an array of conical holes acting as a funnel to guide the soldering balls to the FPC holes. It is used as well to press the FPC against the sensors;
- A tool to pick up the soldering balls (possibly the same as the one used by ITS);
- A gluing tool for the assembly of the HIC and the stiffener;
- A cutting tool to remove the extra parts of the FPC dedicated to the positioning.

![Figure 3.11: Schematic view of the MFT worktable.](image)

The assembly is foreseen to proceed as follows (Fig. 3.12):

- The sensors (1 to 5) are placed and precisely aligned on the vacuum table with a gap of 100 µm between each;
• The FPC is precisely placed on top of the sensors with the dedicated frame and held in place with the vacuum table;

• The soldering grid is placed on top of the stack “sensor + FPC”;

• The solder balls are loaded in the soldering grid using the pick-up tool precisely aligned with the soldering grid;

• The lid is put on top and the vacuum applied;

• The soldering of each connection is done sequentially;

• The HIC is removed from the vacuum table using the FPC frame with the soldering grid fixed on top and placed on the test bench to check the quality of the HIC;

• The stiffener is placed in the gluing tool and a proper quantity of glue is applied on the stiffener;

• The HIC is placed on top of the stiffener, with the frame and the soldering grid;

• Once the glue is cured, the ladder is removed from the frame and placed on the cutting tool to remove the extra parts of the FPC;

• Quality tests of the ladders are performed.

Figure 3.12: MFT ladder assembly workflow
3.3.2 Ladder quantity and assembly timing

To allow to repair quickly the detector during a shutdown, a spare of each half-disk will be produced. This leads to the production of a half MFT. Another 20% of additional ladders will be as well produced to allow the reparation of the half-disks. So the total production will be one MFT, one half MFT and 20% of ladders (see Sec. 7.2.1 for more details). Table 3.2 summarizes the total number of ladders.

<table>
<thead>
<tr>
<th>Number of sensors</th>
<th>Quantity of ladders</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
</tr>
<tr>
<td>3</td>
<td>212</td>
</tr>
<tr>
<td>4</td>
<td>170</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>Total</td>
<td>504</td>
</tr>
</tbody>
</table>

A total quantity of 1614 sensors are needed. With an estimated 50% yield for all processing steps (wafer production, dicing, thinning, wafer post-processing) [6], a total of 3228 sensors have to be produced and qualified (see section 7.2.1).

The time to produce each type of ladder has been estimated based on the duration of the elementary task as reported by ITS Tab. 3.3. The resulting numbers, including a safety margin to perform each task, are given in Tab. 3.4.

To save time during the production, all soldering tasks up to the gluing are done in the morning and the first half of the afternoon. The gluing is done in the second half of the afternoon, to allow glue curing during night. Even if it takes 24 hours for a total curing of the glue at room temperature, the ladder can be manipulated gently after 7 to 8 hours. The ladder qualification tests can be performed in parallel with the HIC laser soldering and stiffener gluing processes. The ladder production time is thus mainly determined by the soldering process duration. A maximum of 6 ladders can be assembled in one day.

Assuming a standard rate of work, the time to assemble the ladders for each half-disk type, the half-MFT, the whole MFT and the spare ladders can be estimated (Tab. 3.5) with a manpower of two technicians and one physicist.
### 3.3 Ladder assembly

#### Table 3.3: Elementary task duration for the ladder soldering.

<table>
<thead>
<tr>
<th>Elementary task</th>
<th>Estimated duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection of chip</td>
<td>2'/chip</td>
</tr>
<tr>
<td>Transfer of chip from carrier to vacuum table</td>
<td>10''/chip</td>
</tr>
<tr>
<td>FPC placement</td>
<td>3'/ladder</td>
</tr>
<tr>
<td>Soldering mask placement</td>
<td>3'/ladder</td>
</tr>
<tr>
<td>Soldering balls placement per chip</td>
<td>3'/chip</td>
</tr>
<tr>
<td>Work table closing and vacuum pumping</td>
<td>10'/ladder</td>
</tr>
<tr>
<td>Laser soldering of one interconnection (displacement included)</td>
<td>13''/solder point (103 solder points/chip)</td>
</tr>
</tbody>
</table>

#### Table 3.4: Assembly duration per ladder type.

<table>
<thead>
<tr>
<th>Number of sensor</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44'</td>
</tr>
<tr>
<td>2</td>
<td>71'</td>
</tr>
<tr>
<td>3</td>
<td>99'</td>
</tr>
<tr>
<td>4</td>
<td>126'</td>
</tr>
<tr>
<td>5</td>
<td>154'</td>
</tr>
</tbody>
</table>

#### Table 3.5: Total ladder assembly duration

<table>
<thead>
<tr>
<th>Duration of Ladder Assembly</th>
<th>Hours</th>
<th>Days</th>
<th>Weeks</th>
<th>Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladders of half-disk0</td>
<td>36</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladders of half-disk1</td>
<td>36</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladders of half-disk2</td>
<td>42</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladders of half-disk3</td>
<td>63</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladders of half-disk4</td>
<td>70</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladders of whole MFT</td>
<td>84</td>
<td>21</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Ladders of spare half-disks</td>
<td>42</td>
<td>10.5</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Additional spare ladders</td>
<td>25</td>
<td>6.3</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Total ladder assembly time</td>
<td>151</td>
<td>37.8</td>
<td>9.4</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Half-disk assembly

The half-disk assembly procedure is shown in Fig. 3.14. The positioning of a ladder is determined by the position of the holes in the disk support and positioning pins on the ladder. Once all the ladders are mounted on the disk, disks are tested and qualified. Finally, the positions of all the sensors are measured looking through the FPC: it is designed with holes to allow visibility of the sensors reference markings/targets and to do a precise measurement of the position of each sensor.

The positioning, the connection and electrical tests of one half-disk can be made within one week. Another week is necessary to perform the measurement of the sensor positioning and a third week for the qualification tests of a half-disk. This qualification consists of operating all the sensors of the half-disk with part of the MFT readout system and includes tests of the cooling performance.

Disk assembly can start about 2 to 3 weeks after the beginning of the ladder assembly, as soon as the first batch of ladders for one half-disk is ready.

MFT half disk assembly scenario

3.5 Half-MFT assembly

The assembly of the half-MFT (Fig. 3.15) proceeds in two steps: first the assembly inside the MFT cone, then the assembly of the MFT cone inside the barrel. Each step starts with servicing the cone/barrel with cables (signals and power), pipes (water and air) followed by a pressure test to detect any leakage before the insertion of the detection elements.

The cone assembly starts with Disk-0, the closest to the interaction point, to be able to route all the cables from each half-disk to a patch panel located at the back-end of the cone. An
3.5 Half-MFT assembly

electrical and leak test is performed for each half-disk installed in the cone. Once all 5 half-disks are installed, a qualification test is performed (including cooling test) for about one week. Then, the survey of the disks is done.

The assembly of the MFT cone and the barrel consists of the mechanical fixation of the MFT half-cone inside the barrel. Then the cables and the cooling tubes of the cone and the barrel are connected to the MFT readout board, LV supplies and cooling plant and a qualification test of the global assembly is performed for at least 3 months. A survey of the half-MFT is also performed.

The half-MFT assembly takes place at CERN in a clean room.

The time needed for the half-MFT assembly is estimated to be one week for the servicing and test of the cone, one week for the servicing and test of the barrel, one week for the cone assembly, one week for the cone qualification test, one week for the survey, one week for the the MFT cone and the barrel assembly. Three months are needed for qualification tests at surface and a about two months for check-out tests in the cavern (see the schedule of the project in Chap. 7).

**Half MFT assembly scenario**

Figure 3.15: Half-MFT assembly workflow.
4 Global support structures, thermal studies, services and integration

The design and assembly procedures for the MFT halves have been described in the previous chapter. In the following, the services and the integration of the MFT in the ALICE environment are presented. The results of the thermal studies are discussed. Finally, the survey and the mechanical alignment procedures are presented.

4.1 Services

In this section, services to operate the MFT detector are described, including the power supply, the cooling and the cables to drive data and slow control.

4.1.1 Power supply

The sensors have to be powered with a 1.8 V voltage for both their analog and digital parts. In the conservative hypothesis of a power consumption of 50 mW/cm$^2$, each sensor produces 225 mW of heat, leading to a total current for the whole MFT of 112 A. In order to minimize the voltage drop between the power supplies located outside the ALICE solenoid (about 6 m away from the MFT) and the sensors, DC-DC converters [18] are implemented on the PCBs of disks adopting the solution foreseen for the ITS upgrade. These components act also as voltage regulators.

According to the datasheet of the FEASTMP DC-DC converter [19], the input voltage should be in the range of 5–12 V, the maximum output current is 4 A and the conversion efficiency is 72.5% for a temperature of 18°C. This device has been tested with the input and output voltages set to 12 V and 1.8 V respectively and loaded with a 0.5 Ω resistor drawing 3.6 A. The part of the DC-DC converter that has to be cooled was in contact with a copper plate with an air circulation. Two series of tests were performed: with and without air circulation. Table 4.1 gives the results of these tests at room temperature of about 25°C. These values were stable during the six test days. The 70% efficiency is close to the one given in the datasheet (72.5%) [19] under the same conditions but with a cooling plate at 18°C. In conclusion, the FEASTMP DC-DC converter can be used on the MFT disks to power the sensors and cooling constraints are not stringent.

As the DC-DC converters are cooled down and the ambient air is planned to be about 22°C, the efficiency of these items is considered to be 70% in this document.

Taking into account the number of sensors (see Tab. 1.2) and under the assumption of a sensor power consumption of 50 mW/cm$^2$, Tab. 4.2 reports the number of DC-DC converters required per half-plane assuming a maximum output current of 3 A. It implies a total power (sensors plus DC-DC converters) of about 300 W to be dissipated.

The power is brought from A-side to the MFT through the MFT barrel by means of aluminium bus bars. The constraint to dimension these bus bars is an average voltage drop of 0.1 V. This value has been chosen to avoid the need to cool inside the MFT barrel; the heat produced by the bus bars is evaluated to 2.5 W. The length of the bus bars was estimated to be 6 m with a thickness of 1 mm. There are two bus bars, one for +V$\text{CC} = 12$ V and one for the ground...
Table 4.1: Performance test results of the DC-DC converter versus the cooling conditions. The room temperature was 25°C.

<table>
<thead>
<tr>
<th>Air cooling</th>
<th>$T_{\text{plate}}$ (°C)</th>
<th>$T_{\text{DC-DC}}$ (°C)</th>
<th>$V_{\text{out}}$ (V)</th>
<th>$P_{\text{in}}$ (W)</th>
<th>$P_{\text{out}}$ (W)</th>
<th>$P_{\text{dis}}$ (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off</td>
<td>36.0</td>
<td>45</td>
<td>1.777</td>
<td>9</td>
<td>6.31</td>
<td>2.69</td>
<td>70</td>
</tr>
<tr>
<td>On</td>
<td>30.6</td>
<td>40</td>
<td>1.775</td>
<td>9</td>
<td>6.30</td>
<td>2.70</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 4.2: Power supply for each MFT disk assuming sensors with a power dissipation of 50 mW/cm².

<table>
<thead>
<tr>
<th>Half-Plane of Half-Disk</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Full-MFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb. Sensors</td>
<td>32</td>
<td>32</td>
<td>38</td>
<td>56</td>
<td>66</td>
<td>896</td>
</tr>
<tr>
<td>$P_{\text{sensors}}$ (W)</td>
<td>7.20</td>
<td>7.20</td>
<td>8.55</td>
<td>12.60</td>
<td>14.85</td>
<td>201.60</td>
</tr>
<tr>
<td>Nb. DC-DC converters</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>48</td>
</tr>
<tr>
<td>$P_{\text{dissipation}}$ (W)</td>
<td>3.09</td>
<td>3.09</td>
<td>3.66</td>
<td>5.40</td>
<td>6.36</td>
<td>86.40</td>
</tr>
<tr>
<td>Total surface of bus bars (mm²)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>80</td>
</tr>
</tbody>
</table>

for half plane. Table 4.2 shows that the total cross section of bus bars to power the MFT is 80 mm².

4.1.2 Input and output cables

According to the readout scheme of the MFT (Chapter 5), each sensor needs one Low Voltage Differential Signaling (LVDS) cable for their data output. The clock is distributed through a multi-drop bus and the slow control communication through a bi-directional bus on the FPCs. Consequently, the total amount of LVDS cables is 1456 (see Sec. 5.1 for details). As the MFT is developing a common readout system with ITS, Samtec AWG30 Twinax “Firefly” [6] cables have been selected. Their capability to transmit signals at 1.2 Gb/s has been validated up to 4 m and tests for 6 m long cables are in progress. Those lengths correspond to the distances from the sensors to the backend concentrator boards.

From the specifications of the Twinax “Firefly” cables, the mean fraction of radiation lengths has been evaluated to be 2.5% along the long dimension and 3.8% along the short one (Fig. 4.1 and Fig. 4.2). Considering the space available in the MFT barrel (Sec. 4.3) and the dimensions of the Twinax cable, it is not possible to feed through all the cables in only one layer. Two layers of cables is adding 5% of $X_0$ over half of the acceptance of the TPC. Another possibility is to bundle the cables which results in about 40% of radiation length over about 20 cm (about 6% of the perimeter). These amounts of material passing between the ITS and the TPC are not tolerable as it would degrade the physics performances of ALICE at mid-rapidity. Consequently, the input/output cables must be fed through on the C-side along the front absorber of the MUON spectrometer.
4.1 Services

Figure 4.1: Distribution of radiation length in the Twinax “Firefly” cable section. Blue corresponds to copper, orange to the dielectric and red to the jacket.

Figure 4.2: Distributions of radiation length of the Twinax “Firefly” cables along the long (left) and short (right) dimensions. The dashed lines correspond to the mean values: 2.5% along the long dimension and 3.8% along the short one.

4.1.3 DCS cables

For the monitoring and the safety of the detector, the temperature, the current and the voltage outputs are measured. In the MFT cone, 20 temperature sensors (one per half-plane), 48 current sensors and 48 voltage sensors (one per FEASTMP DC-DC converter) are used, requiring the installation of 116 cables (232 wires). These wires are connected to the MFT Backend Readout Unit (BRU) to be added to the data flow sent the the Common Readout Unit (CRU) (see Fig. 5.2). The temperature, voltage and current information is then extracted to be sent to the Detector Control System (DCS) to monitor the status of the MFT and to prevent any damages.

An interlock system based on the monitoring of the cooling plants and the output of the power supplies is also foreseen.

4.1.4 Cooling

As seen in Sec. 4.1.1, the power to be extracted from the MFT cone is about 300 W (sensors and FEASTMP DC-DC converters). The MFT is planning to use a leak-less water-cooling plant like
ITS. Assuming an overall increase of the water temperature of 2 K, a water velocity of 1 m/s to limit the pressure loss of the leak-less system, the power dissipation system of the MFT would require four pipes of 5 mm of inner diameter (one inlet and one outlet pipe per half-MFT). In order to have redundancy in case of failure, eight pipes should be utilized. This rough estimation assumes that all the heat is extracted by water. Based on the developments made by the ITS collaboration, the water-cooling solution is robust and viable for the MFT.

To reduce to a minimum inhomogeneities of material budget due to water pipes in the MFT acceptance, an air cooling solution is an appealing alternative and, therefore, it has been studied (see Sec. 4.4). In this back-up solution, the MFT would require an air cooling plant to control the temperature, the flow and the humidity. With a cross-section of about 220 cm$^2$ available, the MFT half-barrels themselves could be used as air-ducts to bring and to extract air inside the MFT cone. The routing of air-cooling services in the MFT barrel is not considered as an issue.

4.2 MFT half-cone

The MFT half-cone is the element which contains the 5 half disks. Two MFT half-cones (called top half-cone and bottom half-cone) both having an identical design compose the MFT. The complete design of this MFT half-cone is shown in Fig. 4.3.

The back half-cone window, named back window, is built out of composite material and closed with kapton films. The main part of the half-cone, exhibiting a conical shape and named half-cone structure, supports the 5 disks as well as all the services described above. This element is made out of CFRP with local metallic inserts used for positioning and fixing of all the half-cone parts.

The choice of the MFT readout architecture imposes the routing of about 750 electrical links through the MFT half-cones. A mock-up of the service integration inside the cone has demonstrated that there is enough space inside the cone for all services. As outlined in the previous chapter, fixation and positioning of the half-disks is achieved with screws and positioning pins.
4.2 MFT half-cone

Figure 4.3: General layout of the MFT Half-Cone.
4.3 MFT half-barrel

Similarly to the MFT cone and disks, the MFT barrel is separated into two halves, called top MFT half-barrel and bottom MFT half-barrel. The functionalities of each MFT half-barrel are:

- Support and positioning of the half-MFT (and the Fast Interaction Trigger detector (FIT)) inside ALICE (see Fig. 4.4);
- Distribution of all the half-MFT (and FIT) services coming from the A-side;
- Insertion, and removal of the half-MFT and to attach the FIT detectors inside the ALICE TPC from A-side.

The MFT half-barrel is composed of the following elements (see Fig. 4.5):

- A patch panel on the back part to distribute services coming from A and C-sides, to assemble the MFT half-cone and the FIT to the inner barrel;
- An inner shell to fix and center the patch panel and to guide services coming from the A-side around the ITS;
- An outer shell to distribute services from the ALICE mini-frame to the inner barrel;
- Wheels to guide the barrel during the insertion operations and to position and fix the MFT in its nominal position.

The MFT is inserted, positioned and fixed exactly in the same way as the ITS, thanks to the same rails installed inside the ALICE cage. The top and bottom barrels have similar design concept. A main semi-cylindrical structure made of a sandwich composite structure supports the loads applied on the barrel. A group of connectors will be defined and located on the patch panel. The electrical link readout cables, exiting from the MFT cone, are also routed along the patch panel toward the C-side.
4.3 MFT half-barrel

Figure 4.4: General layout of the MFT half-barrel and its environment.

Figure 4.5: The MFT half-barrel elements.
4.4 Thermal studies

The MFT thermal studies aim at designing a cooling system able to keep the temperature gradient along a ladder below 5°C and below a temperature 30°C. Water cooling is the base-line option. The ITS collaboration has shown it is a robust solution for this kind of detector. Their constraints are similar to the MFT ones. Nevertheless, the MFT collaboration also studied the air-cooling option as a back-up solution.

4.4.1 Water cooling option

A power consumption of the silicon pixel sensors of 300 mW/cm² has been assumed for the inner barrel and 100 mW/cm² for the outer barrel of the ITS. However, recent results indicate that the ALPIDE power consumption is at most 50 mW/cm² [20]. A water cooling option has been studied for the MFT, using a similar strategy as the one developed for the ITS [6].

The design is based on a Cold Plate (CP) concept: a sheet of High-Thermal Conductivity (HTC) carbon fibre with embedded polyimide cooling pipes, with minimum diameter and wall thickness. The CP is in thermal contact with the pixel sensors, through the ladder stiffener, so as to remove the generated heat. While in the ITS Inner Barrel one CP for each stave is used (an ITS stave is equivalent to an MFT ladder), in the MFT one single CP cools the entire half-disk plane.

Two designs are under investigations. The first one, called axial water cooling consists on one cooling pipe running under the digital part of each sensor (heat generated mainly in this area). It implies that the water pipes are making a U-turn at the extremity of the ladders (see Fig. 3.9-right). In the second design, called perpendicular water cooling, the water pipes are running perpendicularly to the ladders (see Fig. 3.9-left). This design is more appealing because the material budget is lower (see Sec. 3.2.2) and the connection to the water manifold is easier.

In Tab. 4.3, a comparative analysis with the ITS inner barrel water cooling performances[6] is reported, assuming that MFT uses the same CP, water polyimide pipes and thermal contacts. In addition, a security factor of two has been assumed to define the total water pipes length in the half-disk spacers.

<table>
<thead>
<tr>
<th>ITS Inner Barrel Ladder</th>
<th>MFT Half-Disk0 Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sensors</td>
<td>9</td>
</tr>
<tr>
<td>Power consumption</td>
<td>12 W</td>
</tr>
<tr>
<td>Length of water pipes</td>
<td>54 cm</td>
</tr>
</tbody>
</table>

(64 cm with security factor)

Table 4.3: Comparative analysis of the ITS Inner-Barrel and MFT Half-Disk0 cooling parameters. Note that, in the calculation of the power consumption, a value of 300 mW/cm² was considered in the TDR of ITS[6]. Since, this value has been reevaluated to 50 mW/cm².
4.4 Thermal studies

confirms that the water pipes should be centered in respect to the sensors for a better cooling. The effect of the thermal conductances between the different layers (sensor, stiffener, cold plate and water pipe) has been studied. The results show that the thermal requirements can be fulfilled with the foreseen materials (HTC carbon fibres, glues). The water temperature should not exceed \( 17 \, ^\circ C \) to keep the sensor temperature below \( 30 \, ^\circ C \) (see Fig. 4.8) but does not have any effect on the temperature gradient.

The results of these simulations will be tested and checked by measurements on mock-ups of ladder and half-disk which are planned to be built in the coming months.

![Diagram of preliminary design with water cooling pipes](image)

*Figure 4.6: Preliminary design with water cooling pipes.*

### 4.4.2 Air cooling option

With a low power consumption of sensors at the level of 50 mW/cm\(^2\), air cooling could be an adequate option for the MFT detector and would, at the same time, allow to increase the uniformity of the material budget distribution.

Simulation studies have been performed in order to evaluate the performance of such a cooling system. Several layouts of the air inlet/outlet size and position, the air inlet velocity and temperature have been studied.

Figure 4.9 present the results of the calculation using a design with two inlets and one outlet per disk, with an inlet air velocity of only 3 m/s. A good heat transfer coefficient uniformity is achieved with an average value of 25 W/m\(^2\)-K. A maximal on-sensor temperature of 305 K is obtained with an on-sensor temperature gradient of about 6 K.

In addition more detailed studies have been carried out in order to improve the thermal behaviour of ladders. It showed that thermal conductivity of the carbon stiffener is a crucial parameter to reduce the on-sensor temperature gradient. For example, using a bi-directional carbon fiber, instead of an unidirectional one allows the reduction of the on-sensor temperature gradient by 1.0 to 1.5 K.
These calculations show that under conservative assumptions, air-cooling can be a suitable option for MFT. Thermal constraints imposed for the CMOS sensor operation have been mostly met: on-sensor temperature gradient $\Delta T \sim 6$ K (goal is 5 K under conservative assumptions); on-sensor maximal temperature $T_{\text{max}} \sim 305$ K; on-sensor air velocity < 5 m/s. A detail description of the air-cooling studies can be found in Appendix A.
4.5 Installation and removal

The MFT installation scheme is driven by the necessity of rapid access during the yearly LHC winter shutdown lasting 3-4 months. It foresees the insertion of the MFT detector together with all its services along the z-axis, with the beam pipe installed and baked.

The MFT is moved to its final position from the parking location, where it is mounted around the beam pipe outside of the TPC, over a distance of about 3 m.

One half-barrel at a time is inserted. The half-cone is fixed at one side of the half-barrel which conducts the services out to the opposite A-side. These services include the electrical power cables for the sensors and front-end electronics bias, the cooling lines and the DCS cables (voltage and temperature senses). The cables for the slow control and data transfer are directed towards the C-side to reduce material budget in the central rapidity region.

Prior to the installation, the FIT detector is attached to the back of the MFT half-cone and the FIT cables are grouped together with the MFT signal cables into bundles fixed at the front of the MFT. During the detector insertion, these bundles are pulled through the cage, routed in the gap between the front absorber and the TPC, and finally fixed on the service-wheel of the TPC.

When the MFT is in its final position, the cable bundles are secured to the MFT at one side, on ad hoc brackets, and to the TPC service-wheel at the opposite side, two meters apart. The distance between the two support points and the slack of the bundles in between avoids introducing a rigid mechanical link, through the cables, between the MFT and the TPC. Such a rigid link has to be avoided to allow relative displacements between the TPC and the MFT in case the MFT position needs to be realigned with respect to the TPC.

As for the ITS, the MFT half-barrels are inserted to the final position, separately and are positioned by means of wheels guided by the rails which are part of the detector cage (see

---

**Figure 4.9:** Heat transfer coefficient, velocity, and flow stream lines with the 2 inlets model.

4.4.3 PCB cooling

Various electronic components generating heat are implemented on the PCB around the sensitive area. DC/DC converters are the elements dissipating the largest amount of heat (2 W each, see Tab. 4.2). Additional power is dissipated by further integrated electronics components. As the PCB is outside the sensitive area, the heat can easily be extracted by water-cooling using pipes embedded between the two PCBs of each detection plane of a given disk. Thermal tests have been performed on DC/DC converters (see Sec. 4.1.1) and showed that cooling constraints of this component are not stringent.
Fig. 4.4 and Fig. 4.5). The detector cage is a stiff cylindrical shell made out of a light composite sandwich, which is fixed inside the TPC bore and provides a common support for the ITS and MFT barrels and the beam pipe. The cage provides the precise guiding rails needed for the insertion of the MFT service half-barrels (see Fig. 4.10). The rails are in CFRP, directly engraved in the composite sandwich structure that constitutes the cage side wall. During insertion, the half-barrels move on wheels guided by the rails. The rail design is such as to keep the MFT disks at a safe distance from the beam pipe and its support. Clearance reaches the minimum design value only a few centimetres before the final position when the half-barrel approaches the beam pipe with a radial movement. The accurate positioning of the half-barrels in $z$ is provided by precise mechanical stops located at the end of the translation route.

*Figure 4.10: Installation and removal of the MFT detector from its parking location until its final position in the experiment.*
4.6 Survey and mechanical alignment

The position of the MFT silicon pixel sensors and their stability in time during operation have to be known with an accuracy of less than 10 µm.

As for the ITS detector [6], the mechanical structure of the MFT has to be designed to provide precision and stability with the required level of accuracy. Several factors may influence the uncertainty of the position of the detectors:

- The manufacturing accuracy of all components;
- The tolerance after assembly of the components in the barrel;
- The deformation of the components under load;
- The global positioning uncertainties related to the installation procedure;
- Thermal expansion of the components;
- Other long-term effects such as the settling of different parts of the MFT structure and surrounding ALICE interfaces.

The required precision of the final position of the MFT silicon pixel sensors can only be ensured if the position of the components relative to each other is measured during each step of the assembly process.

On the top surface of each silicon pixel sensor, reference markers are implemented at the four corners and along the edges which are very accurately related to the pixel matrix (see Fig. 4.11). In the present layout, the marker starts 15 µm from the nominal edge and the distance of the central point of the cross to the nominal edge is 50 µm [17]. The FPC is equipped by holes allowing the visual access of the reference markers of each silicon pixel sensor of a ladder. By using a 3-dimensional Control Measuring Machine (CMM), equipped with an optical probe, the reference marks allows the determination of the relative positions of the silicon pixel sensor and their positions is known with respect to external reference markers on the MFT half-disks.

![Reference markers on silicon pixel sensor](image)

Figure 4.11: Magnified picture of the reference markers at one corner (left) and along one edge (right) of the silicon pixel sensors [17].

Next, the relative position of the half-disks in the MFT half-cone and with respect to its reference markers is precisely measured. Finally the relative position of the half-cone are determined with respect the half-barrel with reference markers that are visually accessible from the A-side, after the installation of the MFT in its final position. The MFT half-barrel is then positioned with respect to the ALICE global system. The precision of the measured position of
the detectors in the global ALICE coordinate system is determined by the accumulation of the measurement errors in each of the steps described above. The precision on the position of the sensors is expected to be 300 $\mu m$.

To achieve the 10 $\mu m$ precision, final alignment of the MFT detector is performed using track reconstruction during data taking. MFT tracks, matching high transverse momentum tracks measured in the MUON spectrometer, have to be reconstructed as straight tracks in the MFT region, since the effect of the ALICE central and dipole magnetic fields on the track bending is negligible (less than ten microns). The high counting rate foreseen after LS2 is sufficient to perform an alignment per physics run or even for a sub-run period, if necessary.
5 Readout architecture and electronics

5.1 General readout architecture

As described in Sec. 1.2, the MFT is composed of 5 detection disks of various radii located on both sides of the beam pipe. The \( z \)-positions and environment of the MFT disks are illustrated in Fig. 5.1. The readout architecture system is compatible with the CMOS pixel sensor architecture for the data throughput on one side and with the ALICE Common Readout Unit (CRU) on the other side. One of the constraints for the readout architecture is the radiation environment of 50 krad at the outer radius of the MFT acceptance (see Table 1.2 and Table 1.3). This constraint necessitates the use of active electronic components in a safer area where the TID is below few krad. Another constraint is the tight space available for MFT services in general between the MFT cone which contains the half-disks and the neighbouring ITS and MUON Absorber. The space used for the readout cable path is shown in Fig. 5.1.

![Figure 5.1: General layout of MFT: readout cables path and MFT disks environment.](image)

![Figure 5.2: General readout scheme of the MFT for 100 kHz Pb-Pb minimum bias collision rate.](image)
Figure 5.2 illustrates the general readout scheme of the MFT. Common ITS/MFT CMOS monolithic pixel sensor equips the whole sensitive surface of the MFT (see Chap. 2). As described in more details in Chap. 3, pixel sensors will be soldered on custom-made Flexible Printed Circuits (FPC) and mechanically stiffened to form a ladder. Each ladder will be electrically linked to a Printed Circuit Board (PCB, one per half-plane and per front/back side, see Sec. 5.4) in order to ensure the transmission of upstream and downstream signals as well as the power supply distribution up to the sensors.

The MFT is powered through aluminium bus bars (see Sec. 4.1.1 for details). The upstream (slow control) and downstream (data) signals are transmitted by twinax cables from the MFT cone to an external backend concentrator board equipped with active components for data concentration (outside of the MFT detector acceptance). Table 5.1 summarizes for each half-disk the number of twinax cables needed to transmit the data (HSDATA), the clock (DCLK) and the slow control (DCTRL) signals, giving a total of 1456 twinax cables for the entire MFT readout. Then, from the backend readout unit board, data are transferred to the CRU using radiation-hard optical components.

<table>
<thead>
<tr>
<th>Signal Name</th>
<th>Number of Electrical Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Half-Disk 0</td>
</tr>
<tr>
<td>HSDATA</td>
<td>64</td>
</tr>
<tr>
<td>DCLK</td>
<td>24</td>
</tr>
<tr>
<td>DCTRL</td>
<td>24</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>112</strong></td>
</tr>
</tbody>
</table>

728 for Half-MFT / 1456 for whole MFT

5.2 Sensor data throughput

As shown in Tab. 1.3, the particle hit density on the sensors closest to the beam pipe is of the same order of magnitude (6.9 Mhit/s) as the particle hit density in the ITS inner layers [6, Tab. 1.2]. Therefore, the same readout scheme as the one used for the ITS inner layers is applied.

Physics simulations provide an estimate of the number of hits (crossing particles) for each pixel recorded per hadronic interaction including the low energy $e^+e^-$ pairs from QED processes. In addition to crossing particles, the fake hit rate from the electronic noise was evaluated to be $10^{-5}$/pixel/frame (integration time 4 $\mu$s). The scenario assumed to calculate the average data throughput involves the number of hits relative to a Minimum-Bias (MB) Pb–Pb collision event at 5.5 TeV, the QED electron background and fake hits from electronic noise.

The average data throughput for each sensor is shown in Fig. 5.3 taking the design parameters specified in Tab. 5.2 into account.

The fluctuations of the data throughput with respect to the average value will result from the intrinsic distribution of the Pb–Pb collision centrality, the Poisson distribution of Pb–Pb collision pile-up and the Gaussian distribution of the fake hit rate. Rare collision patterns, like pile-up of central Pb–Pb collisions, will create large fluctuations in the data throughput. The most central collisions will exhibit 3 times larger size than the average MB Pb–Pb collisions.
5.2 Sensor data throughput

Consequently an additional safety factor is applied between the average data throughput and the readout bandwidth.

In order to derandomize the data throughput, the Alpide sensor includes two digital memories: in-pixel memories with a 3-buffer depth and embedded SRAM at the end of the pixel matrix. Both memory stages are dimensioned to minimize the dead-time induced by instantaneous data throughput exceeding the bandwidth of the readout architecture.

<table>
<thead>
<tr>
<th>Table 5.2: Inputs to calculate the data throughput.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision Rate</td>
</tr>
<tr>
<td>Integration Time</td>
</tr>
<tr>
<td>Fake Hit Rate</td>
</tr>
<tr>
<td>Average Hit Encoding</td>
</tr>
</tbody>
</table>

The general data frame structure of the Alpide sensor serial output consists of 16-bit data words encoding: one event header, one chip header, event data words and one event trailer. The Alpide event data word format follows its internal 32-region segmentation. For each event, the sensor sends out the data from the different regions sequentially. The event data for each region is made of two 16-bit words containing region number, region event length, cluster size and X-Y address.

Assuming a Poisson distribution of hits in the Pixel Matrix, a mean 35.2 bits per cluster (including protocol overhead) is expected [22].

As expected, Figure 5.3 shows that sensors located nearest the beam pipe have the highest data throughput. A maximum of 242.7 Mb/s is calculated for a sensor located near the beam pipe on disk 0. One should note that an hadronic collision rate of 100 kHz is considered.

In the scenario of one central collision, the QED effect and the same $10^{-5}$ fake hit rate is considered, the maximum data throughput reaches 553.1 Mb/s, showing that the 1.28 Gb/s high-speed line data rate with 960 Mb/s useful bandwidth of the ITS/MFT sensor fulfills the required data throughput for the MFT.
Figure 5.3: Data throughput (Mb/s) per sensor (see text for details).
5.3 Data transmission on Flexible Printed Circuit

The design of the Flexible Printed Circuit (FPC) is done in collaboration with the ITS project. Table 5.3 and Fig. 5.4 summarize the electrical signals carried on the FPC. In order to ensure signal integrity at such high speed, the FPC routing shall correspond to the characteristic impedance of ALPIDE’s output (100 Ω differential), and in particular minimize impedance breaks, especially coming from connectors. In addition, special care shall be taken to the crosstalk between the high-speed signals involved. Fig. 5.5 shows a prototype designed with a double layer printed circuit using copper wires produced by the manufacturer ATLANTEC. The vertical extensions, "wings", are made for manipulation only and will be removed after assembly.

For the MFT FPC final design, aluminium traces will be implemented for material budget improvement.

![Diagram of FPC electrical layout](image)

Figure 5.4: FPC electrical layout (power distribution not drawn).

Table 5.3: Electrical wires on the FPC.

<table>
<thead>
<tr>
<th>Signal Name</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSDATA 0...4</td>
<td>Point to Point</td>
</tr>
<tr>
<td>Hits detected by Sensor</td>
<td>1 High-speed 1.28 Gb/s LVDS pair / sensor</td>
</tr>
<tr>
<td>Slow Control</td>
<td></td>
</tr>
<tr>
<td>Clock</td>
<td>40 MHz MLVDS multi-drop</td>
</tr>
<tr>
<td>Control Port</td>
<td>40 Mb/s bidirectional LVDS</td>
</tr>
<tr>
<td>Power Supply</td>
<td></td>
</tr>
<tr>
<td>1.8V, GND</td>
<td>225 mW / sensor</td>
</tr>
</tbody>
</table>

The connectors from the FPC to the PCB are HIROSE DF40C-70DP-0.4C(51) [Digikey H116630CT-ND] and DF40C-70DS-0.4C(51) [Digikey H116631CT-ND], soldered on the FPC and the PCB (Fig. 5.6) respectively.
Figure 5.5: FPC prototype (Cu trace version).

Figure 5.6: Ladder to PCN Connectors: PCB side (left), FPC/ladder side (center) and connector size (right).

Table 5.4: Technology constraints for aluminium FPC [23].

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Constraint Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium thickness</td>
<td>25 $\mu$m</td>
</tr>
<tr>
<td>Minimum aluminium width</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Minimum isolation width</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Microvia drill (non stacked vias)</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Hole drill (final hole)</td>
<td>220 ±10 $\mu$m</td>
</tr>
<tr>
<td>Polymide thickness</td>
<td>75 $\mu$m</td>
</tr>
<tr>
<td>Clearance without conducting metal all around FPC</td>
<td>$\geq$300 $\mu$m</td>
</tr>
</tbody>
</table>
5.4 Half plane printed circuit boards

As shown in Fig. 3.2, the equipped ladders (of front or back half-plane) are fixed on a rigid support structure and linked to a half-crown shaped Printed Circuit Board (PCB). There are 2 PCBs per half-plane, one per side (front and back side), separated by a gap of 14 mm. The purpose of these 10 half-crown shaped PCBs is to distribute configuration, readout signals (Tab. 5.1) and also power supply to the sensors (through the FPC). Due to the power consumption of the whole MFT (201.6 W, see Tab. 4.2), and in order to limit the cross-section of the power supply cables, it is necessary to include DC/DC converters on these PCBs.

The PCB and all its components (DC/DC converters, line drivers/receivers, optional data concentrators), located at a distance from the beam of 50 cm, shall withstand a $\sim 50$ kRad and $1.4 \times 10^{12}$ n$_{eq}$/cm$^2$ (1 MeV neutron equivalent fluence) radiation environment. The CERN DC/DC converter has been specifically designed to withstand radiation levels and magnetic fields exceeding by far those expected for the MFT. In addition, to ease the maintenance operations during MFT life cycle, these PCBs (associated to the ladders) will be removable from the MFT cone structure.

As shown in Sec. 5.2, a total of 1456 twinax cables are needed for the entire MFT readout. Tests with a Samtec AWG30 Twinax “Firefly” cable assembly have shown that the sensor is able to drive such a high speed link over 4 m (the FPC was not taken into account in this measurement)[24]. Fig. 5.8 shows cable performance in terms of insertion and return loss [25] which matches with Samtec data.

**Figure 5.7**: Samtec Twinax cables pair (left), laminated assembly (center) and connector assembly (right).

**Figure 5.8**: Samtec AWG 30 Twinax “Firefly” cable performances [25]: insertion loss (left), return loss (right).

The twinax cables are mounted onto the half-crowned shaped PCB using a dedicated Samtec “Firefly” connector system including UEC5 and UCC8 series connectors [26] and a small PCB about 10 mm wide which can host 11 electrical pairs (see Fig. 5.7).
5.5 FPGA based backend readout unit

As the data throughput among pixel sensors is not homogenous over the whole MFT (see Fig. 5.3) a data concentrator allows to optimize the number of high speed data links going to the CRU as shown in the readout schematic (Fig. 5.2).

An FPGA-based solution is foreseen to concentrate the 1.28 Gb/s electrical links from four sensors into one 4.96 Gb/s link, which plugs into a Versatile Twin-Transmitter (VTTx). The candidate FPGA must be radiation tolerant to a level depending on the actual location of the FPGAs in ALICE. This radiation level for the backend readout unit is expected to be between 5 and 10 kRad (see Table 1.3). This FPGA embeds high-speed transceivers to be able to cope with the high-speed downstream and upstream links.

Table 5.5 shows pros and cons of the different FPGA candidates which have been investigated. Installing the FPGA on the MFT PCB has been discarded as it is clear that no FPGA candidate is able to fulfill all the criteria (TID up to 50 kRad, high-speed transceivers and cost). The FPGA back-end concentrator would have to be located off-detector in a reduced TID environment, as shown in the readout schematic (Fig. 5.2). It is foreseen to use the same FPGA for both ITS and MFT projects. Future developments will be done in collaboration between ITS and MFT R&D teams.

Three different FPGA grades can be found, commercial grade, military grade and space grade. Due to the high cost of the last two ones, only commercial FPGAs are affordable. In these conditions the best candidates are the IGLOO2 or SmartFusion2 Flash based FPGAs from Microsemi.

<table>
<thead>
<tr>
<th>FPGA Type</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SRAM FPGAs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xilinx SPARTAN 3 (commercial FPGA)</td>
<td>TID several krad</td>
<td>No high-speed transceivers</td>
</tr>
<tr>
<td>Xilinx Virtex-5QV XQR5VFX130 (Space grade, 65 nm)</td>
<td>TID over 1 Mrad</td>
<td>Price and availability</td>
</tr>
<tr>
<td>Atmel ATF280 (Space grade, 0.18 µm)</td>
<td>TID over 300 krad</td>
<td>No high-speed transceivers</td>
</tr>
<tr>
<td><strong>Flash FPGAs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microsemi IGLOO2 &amp; SmartFusion2 (Commercial grade, 90 nm)</td>
<td>High-speed transceivers</td>
<td>TID few kRad</td>
</tr>
<tr>
<td>Microsemi RTAX (rad-hard grade)</td>
<td>TID 400 kRad</td>
<td>No high-speed transceivers</td>
</tr>
</tbody>
</table>
6 Performance

A first discussion of the MFT performance, with an emphasis on the impact of the detector on the physics programme of ALICE, has been presented in the ALICE Upgrade LoI [4]. In this Chapter, an update of the MFT performance studies is given, based on the more recent and accurate description of the detector setup considered in the present report.

In the first part (Sec. 6.1), the detector acceptance is discussed, especially in terms of the pseudo-rapidity coverage resulting from the ladder spatial positioning, constrained both by the dimensions of the chosen chip and by the required clearance around the beam vacuum tube.

In the second part (Sec. 6.2 to Sec. 6.5), the expected tracking performance of the MFT is reviewed. Special attention is given to the characterization of the MFT standalone tracking, with a detailed description of the algorithms under study and the discussion of their performance, a subject which was not covered in the ALICE Upgrade LoI. The analysis of the performance of the matching between MFT and MUON tracks, presented in the ALICE Upgrade LoI addendum, is updated.

In the last part (Sec. 6.7) the results of the performance studies for the physics channels considered in the ALICE Upgrade LoI addendum are summarized. New results concerning the definition and the implementation of the analysis strategy are presented, for the study of heavy flavor production in the single muon and the non-prompt $J/\psi$ channels.

Pile-up effects, related to the expected 20% pile-up probability\(^1\), may have an impact on the MFT performances due to the fact that, when more than one hadronic interaction is occurring during the readout time of the MFT sensors, the association of each reconstructed track to its primary vertex may be ambiguous. This problem, however, can be overcome in the measurements of interest for the muon physics thanks to the precise time tagging (to the level of few ns) of the muon tracks in the chambers of the Muon Identifier (currently serving as trigger detector for the MUON spectrometer), which could match the time tagging of the primary vertices reconstructed in the central barrel. On the contrary, no time tagging will be available for the MFT standalone tracks: however, in this case, events affected by pile-up effects could be simply discarded from the analyses, since the MFT standalone measurements (such as charged particle multiplicity and other global observables) will not require the exploitation of the full expected integrated luminosity.

6.1 Detector acceptance

During the design phase of the MFT, a fast Monte Carlo simulation has been used to compute the geometrical acceptance of the MFT, which allows the study of its dependence on parameters such as the size of the chip, the overlap between chips or the number of disks. The choice of the geometrical configuration of the MFT is based on these studies. The results for the final configuration of the detector are shown here, and the corresponding parameters are reported in Tab. 6.1.

The mechanical margin represents the imposed distance between the minimum allowed radial position around the beam pipe and the starting radial position of the active area. This margin takes into account the kapton film of a half-cone and the distance between the edge of a ladder and the first column of pixels. The outer radius to position sensors has been fixed in order to

\(^1\) Corresponding to a sensor readout time of 4 µs and an expected interaction rate of 50 kHz.
accept particles with a pseudo-rapidity up to $-2.5$ (upper limit of the acceptance of the MUON spectrometer) for primary vertices in the interval $-100 < z < 100$ mm.

The ladder positions on the disks can be deduced from the parameters reported in Tab. 6.1. An example is given by Fig. 6.1. Each rectangle of this figure represents the sensitive area of the sensors for disk 4. The red arcs correspond to the limits of the nominal acceptance area. The inner arc is given by the minimum allowed distance from the beam pipe extended by the mechanical margin of 1.2 mm. The outer arc corresponds to a pseudo-rapidity of $-2.5$ for a primary vertex at $z = +100$ mm (see Tab. 6.1).

For a given configuration, the geometrical acceptance of the MFT was computed considering straight tracks, having flat distributions in pseudo-rapidity ($\eta$) and azimuth angle ($\phi$) and the $z$-position of the origin distributed around $z = 0$ according to a Gaussian with $\sigma_z = 56.1$ mm [6]. Figure 6.2 (left) shows the resulting distribution of the number of hits per track in the MFT. A 98% detection efficiency of the sensors has been taken into account. The average number of hits per track is 7.1 within the acceptance defined by $-3.6 < \eta < -2.5$. The most probable values are 7 and 8, meaning that, in most of the cases, the tracks pass through at least one sensor per

---

### Table 6.1: Parameters used for the determination of the geometrical acceptance of the MFT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of a chip</td>
<td>30 mm</td>
</tr>
<tr>
<td>Width of the sensitive part of a chip</td>
<td>13 mm</td>
</tr>
<tr>
<td>Width of a ladder</td>
<td>17 mm</td>
</tr>
<tr>
<td>Overlap between sensitive zones</td>
<td>5 mm</td>
</tr>
<tr>
<td>Mechanical margin</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Maximum $\eta$ for a primary vertex at $z = +100$ mm</td>
<td>$-2.5$</td>
</tr>
</tbody>
</table>
6.2 Standalone track reconstruction in the MFT

The track reconstruction for the charged particles passing through the MFT is done in two steps: the track finding, where the clusters identified in the sensitive volumes of the detector are grouped into track candidates according to some criteria (track model); and the track fitting, where the candidate tracks are passed to a track-fitter, which computes the kinematic parameters and their covariance matrix. While the Kalman filter [27] could be used for both tasks, in this case only the track fitting part of it will be used.

The track finding in the MFT has to deal with a high density of clusters\(^2\), coming both from the charged particles produced in the hadronic interaction and from background particles like the low energy QED electrons [28]. On top of that, fake clusters also have to be accounted for, produced by the pixel electronic noise above the threshold used by the readout.

Two methods have been developed for track finding in the MFT: one is based on a Cellular Automaton (CA) [29] adaptation; the second method — implementing a Linear Tracking Finder (LTF) — is a plain search for “straight-line aligned” clusters on the MFT planes, starting from a seed connecting two clusters from the outer planes. The hypothesis assumed in the second method is that, due to the small radial extension of the MFT and its forward kinematic coverage, the curvature introduced on the tracks by the ALICE solenoid magnet can be neglected.

6.2.1 Cellular Automaton algorithm

When using a Cellular Automaton approach, the detector clusters are preliminarily paired in small units called cells. In our case, a cell is defined as a segment connecting two clusters from

\(^2\) We use the term cluster to indicate the reconstructed object corresponding to a generated hit.
two consecutive disks of the MFT. The cells must point to the primary vertex within some angular limits.

The CA then considers one given cell and, starting from the first MFT disk, proceeds in the direction of propagation of the particles stepping from one MFT disk to the next. In doing this, conditions of track continuity are applied in terms of breaking angle between cells. The cell status, initially at one, increases by one each time another compatible cell is attached to its end.

From the large number of cells, some particular cell chains will be singled out, with the more downstream cell having a status equal to four (see Fig. 6.3). Track candidates will be built starting from such chains of cell.

The CA method for track finding has been applied in several experiments, in particular for the vertex detector of HERA-B [30], whose detector geometry is similar to the one of the MFT. More recently, the CA was implemented in the track finder algorithms of the TPCs of the STAR and ALICE detectors [31]; its implementation is also foreseen in the CBM experiment at GSI as well as in the upgraded ITS of ALICE [32, 33].

6.2.2 Linear Track Finder algorithm

The use of an LTF method is justified by the specific experimental conditions for the standalone tracking in the MFT, especially because of the weak effect of the magnetic field of the ALICE solenoid in the forward acceptance of the detector. In the LTF, contrary to the CA approach, one imposes in a single pass that all clusters should minimize their distance to a straight line, see Fig. 6.4. This seeding line is obtained from combinations of clusters in the last disks of the MFT. The information on the vertex position is used in order to minimize the number of found seeds.

The main advantage of the LTF is the reduced computing time, the number of cluster combinations being smaller than in the case of the CA. However, the efficiency of the LTF is expected to be sensitive to the amount of scattering suffered by the particles when passing through the MFT disks, more than the CA approach which is using only local conditions of vicinity. In the low momentum and large pseudo-rapidity range, in addition, a further limit to the efficiency of the LTF comes from the finite track curvature in the magnetic field of the ALICE solenoid.

6.2.3 Reducing the combinatorics: the fiducial interaction region

The knowledge of the position of the interaction vertex reduces considerably the computing time by imposing constraints when building cells and seeds in the CA and LTF methods. While a
precise measurement of the interaction vertex in ALICE is provided by the ITS, the MFT would still be able to provide a standalone, rough estimation of the primary vertex position. This is possible by building the cells between the first two disks of the detector, then extrapolating them to the beam axis to compute the closest approach $z$-position: the peak corresponding to cells produced by the primary tracks is well distinguishable from the background of combinatorial cell prolongations. The example shown in Fig. 6.5 is obtained with a full AliRoot simulation of one event with 1000 primary tracks (expected for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV with centrality close to the 20th percentile) and the background from electronic noise and QED.

This method allows to identify the vertex position with a precision (the RMS of the residuals with respect to the true position is $\sim 2$ mm assuming $x = y = 0$ for the vertex position in the transverse plane) sufficient to guide the track finder methods to a fiducial interaction region even in case the ITS information is not available.

This estimation can be used, however, only for sufficiently large multiplicities of primary tracks ($N_{\text{tracks}}^{\text{min}} \approx 200$, expected for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV with centrality close to the 50th percentile), in order to let the peak from primary tracks exceed the background fluctuations. This limitation also depends on the considered background levels from the electronic noise and the QED electrons.
6.2.4 Parameters of the algorithms

CA parameters

The track finding using the CA is driven by a set of options and parameters, listed here together with their default choices or values:

- Using the vertex from an external source (default) or as estimated by the CA using cells between the first two disks.
- Maximum $\theta$ angle of a cell (default value is $\theta_{\text{max}} = 15^\circ$). This cut takes into account the dispersion in $z$ of the collision vertex.
- Maximum deviation $\Delta \theta_{\text{vertex-cell}}$ of a cell direction from the initial track direction (default value is $0.3^\circ$ for all disks, although it may slightly increase with the number of crossed disks due to multiple scattering, see Fig. 6.6 (a)).
- Maximum breaking angle between two neighbouring cells $\Delta \theta_{2-\text{cells}}$ (default value is $0.1^\circ$, see Fig. 6.6 (b)).
- Minimum track length expressed in number of clusters (by default 4 out of 5 disks).

![Figure 6.6: Angular cuts for building cells with respect to the vertex region (a) and for connecting compatible cells sharing a common cluster (b).](image)

LTF parameters

The LTF method depends on a single adjustable parameter: the radius $R_{\text{cut}}$ around the seed position at a given plane, defining the search zone for the clusters (by default two times the pixel size, see Fig. 6.4).

6.3 Simulation frameworks

6.3.1 Simplified Monte Carlo simulations

The study of the track finding was first done on fast simulations using a simplified Monte Carlo description for the detector and the track propagation, developed within the ROOT framework (Fig. 6.7).
6.4 Standalone tracking performance

Each disk of the MFT is represented by a single plane at the average position in $z$, ignoring the division in sensitive volumes (ladders). The multiple scattering is simulated when crossing the detector planes, the beam pipe and the beam pipe support, according to the average material budget traversed. The energy loss and the magnetic field are not considered in this simple model.

The electronic noise is simulated as uncorrelated and uniformly distributed firing pixels, which are all considered as valid clusters in the track finding. Clusters from QED electrons are also added, whose radial distributions are parameterised on the basis of full AliRoot simulations. Tracks corresponding to the main hadronic event are generated sampling the kinematic distributions of primary tracks given by HIJING. No specific particle identity is imposed on the generated tracks, and no decay is simulated. The $z$ position of the vertex is extracted from a Gaussian distribution centred on $z = 0$, with $\sigma_z = 4$ cm and limited to $[-10 \text{ cm}, +10 \text{ cm}]$.

The advantage of this simple Monte Carlo framework is that the MFT geometry can easily be varied by adjusting various characteristics of the detector such as (the default values are indicated in parenthesis): position of the disks along the $z$-axis; material budget per disk (0.6% of the $X_0$ per disk); single disk detection efficiency (98%); electronic noise probability ($10^{-5}$ per pixel); QED cluster yield corresponding to the peak hadronic interaction rate (100 kHz) and the CMOS integration time (4 $\mu$s), see Tab. 1.3.

6.3.2 AliRoot simulations

The simplified Monte Carlo simulations have been used in order to tune the track finding algorithms and to study different arrangements of the MFT planes and their material budget. In a second step, the track finder was also tested with an external input created from the clusters produced in separate full AliRoot simulations. This approach has the advantage of using the detailed detector geometry, the magnetic field and the description of the particle transport implemented in GEANT3 [34]. The generator used in the full AliRoot simulation is still a parametrization of pions and kaons, but the simulations include in this case all the decays and the secondary particle production, not present in the simplified Monte Carlo.

6.4 Standalone tracking performance

A detailed evaluation of the MFT standalone tracking performance for the CA algorithm, which has a rather complex set of parameters (see Sec. 6.2.4), is presented in Sec. 6.4.1. A comparison
between the performance of the LTF and the CA methods is then presented in Sec. 6.4.2. A short discussion of the offset resolution attainable with the MFT standalone tracking is finally presented in Sec. 6.6.

### 6.4.1 CA track finding performances

The CA track finding performance has been studied using the fast simulation framework described in the previous Section, implementing a simplified Monte Carlo description of the detector geometry and track propagation. All the simulations take into account the background sources from QED — assuming 100 kHz of hadronic interaction rate and a CMOS integration time of 4 µs — as well as the electronic pixel noise — unless stated otherwise.

#### CA CPU time performance

For the case of the fast Monte Carlo simulations, Fig. 6.8 shows the trend of the computing time per event as a function of the track multiplicity, for various sets of CA parameters and different background scenarios. The CA algorithm was tested up to very high multiplicities (3000 tracks per event), corresponding to the ones expected in the 5% most central Pb–Pb interactions at \( \sqrt{s_{NN}} = 5.5 \) TeV (neglecting any pile-up effects). As it is shown in the panel on the left, a relevant increase of the CA CPU time is observed when considering looser cuts on \( \Delta \theta_2\)-cells. The same figure shows that the differences between the CPU time for the various sets of cuts become more important at high event multiplicity: this suggests that different reconstruction parameters could be used for proton–proton runs — where events are characterized by low average multiplicities — and Pb–Pb runs where much larger multiplicities are expected. The panel on the right shows that — for a given choice of the tracking parameters — the performance of the algorithm is weakly dependent on the level of background from noisy pixels and QED electrons. Further studies are being carried out, aiming at an optimisation of the absolute computing time for the set of tracking parameters showing the best relative performance.

---

Figure 6.8: Left: relative CPU time performances for the CA track finder, as a function of the track multiplicity, for different cuts on \( \Delta \theta_2\)-cells (estimated using the fast Monte Carlo simulations). The bands account for the variation between the extreme values of the CPU time obtained in the simulations. Right: relative CPU time performances corresponding to a given choice of the tracking parameters, for various scenarios of the background level from noisy pixels and QED electrons.

---

\(^3\) The absolute CPU time depends of course on the processor used. Results were obtained on an Intel Xeon E5420 CPU at 2.50 GHz. Fig. 6.8 shows only relatives changes between setups and multiplicities. The smaller overall hit density in MFT compared to ITS and the much simpler track pattern (almost straight tracks) will make the track finding absolute CPU time a fraction of the ITS one.
6.4 Standalone tracking performance

CA track finding efficiency The total efficiency of the CA track finder, defined as the total number of found tracks normalized to the number of generated tracks in the MFT acceptance\(^4\), increases with looser cuts on \(\Delta \theta_{\text{vertex-cell}}\) and \(\Delta \theta_{\text{2-cells}}\). However, this is largely due to the fact that the CA algorithm finds more fake tracks, containing one or more background cluster or the clusters produced by different particles, as the event multiplicity increases, see Fig. 6.9 for the case of the fast Monte Carlo simulations. The optimal choice for the tracking parameters is thus a trade-off between having a large tracking efficiency for clean tracks — whose clusters all belong to the same generated track — and keeping a negligible contamination from fake tracks. From this point of view, a comparison between the two panels of Fig. 6.9 shows that the choice of the default cut \(\Delta \theta_{\text{2-cells}} < 0.1^\circ\) (\(\Delta \theta_{\text{vertex-cell}} < 0.3^\circ\) being also applied by default) is the most appropriate one. This choice guarantees a satisfactory track finder efficiency for clean tracks down to low transverse momenta, as it can be seen in Fig. 6.10.

![Track finder eff. vs track multiplicity](image)

**Figure 6.9:** Number of clean and fake tracks found by the CA track finder, normalised to the number of generated tracks, for two sets of cuts on \(\Delta \theta_{\text{2-cells}}\) and \(\Delta \theta_{\text{2-cells}}\) (default at left), as a function of the track multiplicity per event, integrated over the track \(p_T\). Fast Monte Carlo simulations have been used, with the single MFT plane efficiency set to 98%.

CA optimisation for candidate muon tracks The \(\Delta \theta_{\text{vertex-cell}}\) and \(\Delta \theta_{\text{2-cells}}\) deviations are induced by multiple scattering occurring inside the traversed volumes in each plane. Since this effect is less important for higher momentum tracks than for the lower momentum ones, it is possible to adjust the cut in order to optimise the CA tracking performance at larger momenta by reducing the combinatorics from soft tracks. This could be useful, for instance, when looking for MFT track candidates matching the extrapolated MUON tracks measured in the MUON spectrometer, where the presence of the hadron absorber and the muon filter imposes a minimum total momentum of about 4 GeV/c.

Several sets of cuts were then tested, and it was found that the one optimising the tracking performance for momenta larger than 4 GeV/c corresponds to \(\Delta \theta_{\text{2-cells}} = 0.07^\circ\) for all the 5 MFT disks. Indeed, as it can be seen from the panels in Fig. 6.11, this optimised cut preserves the tracking efficiency for tracks with \(p > 4\) GeV/c (left panel), reducing at the same time the fake track contamination (right panel). This last effect accounts for a reduction by a factor \(\sim 2\) of the fake track contamination, with respect to the default cut, independently of the multiplicity of tracks in the event.

Another way to reduce the fake track contamination for larger momenta is to impose a cut on the \(\chi^2/\text{ndf}\) of the tracks. Indeed, as shown in Fig. 6.12, a \(\chi^2/\text{ndf} < 6\) cut would have a negligible impact on the tracking efficiency for clean tracks of total momenta larger than

\(^4\) Fast Monte Carlo simulations have been used for this study, with the single MFT plane efficiency set to 98%.
Figure 6.10: Number of clean tracks found by the CA track finder, normalised to the number of generated tracks, for the default cut $\Delta \theta_{2\text{-cells}} < 0.10^\circ$ as a function of the transverse momentum, for all event track multiplicities. Fast Monte Carlo simulations have been used, with the single MFT plane efficiency set to 98%.

Figure 6.11: CA track finder performance. Left: clean track efficiency without (full line) and with (dashed line) an optimised $\Delta \theta_{2\text{-cells}}$ cut as a function of the track momentum. Right: fake track contamination without (full line) and with (dashed line) an optimised cut for six values of the track multiplicity.

4 GeV/c (left-panel), reducing at the same time the contamination from fake tracks by a factor $\sim 3$ (right-panel).

6.4.2 Momentum dependence of the track finding efficiency for LTF and CA

Figure 6.13 shows the comparison between the track finding efficiency of the CA and LTF methods as a function of the transverse and the total momentum, using input from full AliRoot simulations. As it can be seen, the LTF has the same tracking efficiency as the CA for tracks of total momentum larger than 8 GeV/c, and the efficiency loss with respect to the CA stays...
within 10% for tracks of total momentum down to 4 GeV/c.

Both track finder algorithms have advantages and disadvantages: the LTF is significantly faster compared to the CA but is less efficient in finding tracks at low $p_T$, for which the L3 induced curvature cannot be neglected anymore; the CA, on the other side, implies a combinatorial procedure which makes it much slower for higher multiplicities. The final track finding procedure will profit from the advantages of both algorithms by first performing the LTF to find the higher $p_T$ tracks. Then, the clusters attached to those tracks will be removed for the second step where the CA will find lower $p_T$ tracks. The hit density reduction will directly benefit the CA CPU time (see Fig. 6.8). This hybrid track finding procedure will ensure an optimal performance both for the muon physics — where the presence of the hadron absorber and the muon filter imposes a minimum total momentum of about 4 GeV/c — and for the measurement of global event properties like the charged particle multiplicity in the MFT acceptance — where the highest tracking efficiency as possible is needed down to low $p_T$. 

Figure 6.12: CA track finder performance. Left: clean track efficiencies without (full line) and with (dashed line) an optimized $\chi^2/\text{ndf}$ cut as a function of the track momentum. Right: fake track contamination without (black line) and with (red line) an optimized $\chi^2/\text{ndf}$ cut as a function of the track multiplicity per event.
6.5 Matching between MUON and MFT tracks

Track matching between the MFT and the MUON spectrometer (in the following referred to as MUON, as in the usual ALICE terminology) was studied in the highest detector occupancy conditions, corresponding to the 5% most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.5$ TeV. On average, 3000 particles are produced in such collisions in the MFT acceptance.

Two different approaches can be considered when performing the matching between MUON and MFT. The first one has been developed for the MFT Letter of Intent [4, Section 2.3]. It consists in performing a global tracking starting from the track reconstructed in the MUON spectrometer, extrapolating it throughout the MFT toward the primary vertex taking into account multiple scattering and energy loss corrections, and adding the MFT clusters to the track using the Kalman filter. If more than one track candidate is found, the one with the best $\chi^2$ is kept. The disadvantage of this method is that when attaching MFT clusters, the algorithm has no way to distinguish clusters from primary particles from clusters produced by the low energy QED background or by the electronic noise. This results in a reduction of the correct matching rate especially for pseudo-rapidity close to $-3.5$ (where the QED cluster density is larger, see Tab. 1.3) and for low $p_T$ muons (for which the search area has to be large, because of multiple scattering).

The second method uses the standalone MFT tracking described above and performs a matching between the MFT tracks and the muon tracks measured in the MUON spectrometer. This global tracking is made in stages, see Fig. 6.14 (left). The cluster finding, standalone track finding and fitting stages are first performed separately both in the MFT and the MUON spectrometer. The output of the first stages are arrays of MFT and MUON tracks. The MUON tracks are then extrapolated throughout the absorber toward the primary vertex taking into account multiple scattering and energy loss corrections. The extrapolation route is then evaluated at the last MFT plane (the one closest to the hadron absorber). Based on the MUON track parameters, a fiducial zone is defined in both angle and position spaces in which the MFT track search is performed, see Fig. 6.14 (right). The radius of the search area and the opening angle of the search cone are calculated using the covariance matrix elements of the track parameter.
after the track extrapolation to the last MFT plane. Three times the errors in both position and direction are chosen to define the search cone. A matching quality parameter is built comparing the positions of the MFT and MUON tracks on the last MFT plane, as well as their slopes. The MFT track candidate providing the best matching quality is then chosen.

In order to increase the correct matching efficiency one would optimally need to measure the track momentum in MFT and perform a matching in both position and momentum spaces. Unfortunately the transverse component of the L3 field in the MFT region is too small to have a sufficient momentum resolution to do so. But studies are on-going to quantify the capacity of the MFT to measure the sign of the charge particles which will already reduce by a factor 2 the number of MFT track candidates. The deviation induced by the L3 field is mainly a $\phi$ rotation in the $(r, \phi)$ plane. For $p = 10$ GeV/c muons ($p_T \simeq 1$ GeV/c), $\delta \phi$ between the first and the last MFT plane is about 250 $\mu$rad and about 100 $\mu$rad for 20 GeV/c muons ($p_T \simeq 2$ GeV/c). The MFT should indeed be very efficient in the sign determination for those lower $p_T$ (< 2 GeV/c) muons, reducing the number of candidate and therefore increasing the correct MFT/MUON matching efficiency. Detailed studies will be conducted in that direction to quantify the performances.

The final step consists in a global fit of the track combining the MUON and the MFT clusters, with the use of a Kalman filter. In the study presented below, the LTF method was used as MFT track finding algorithm, whose performances are similar to CA algorithm in the momentum range $p > 4$ GeV/c involved here for the MUON/MFT matching.

Both methods always find at least one final extrapolation candidate for each track reconstructed in the MUON spectrometer. However, the rate of correct MUON/MFT matching is found to depend on the track kinematics, with a strong dependence on $p_T$ and a weaker one on the rapidity.

Figure 6.15 shows the correct matching rate between MFT and MUON tracks as a function of the muon transverse momentum in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, and the performances from the two matching criteria described above are compared. Muons from prompt and displaced signal sources have been considered for this evaluation. For $p_T > 2$ GeV/c the correct matching rate is found to be larger than 90%, decreasing for lower momenta, but still being $\sim 65\%$ at $p_T = 1$ GeV/c (Fig. 6.15 left). As it was already noticed in the LoI [4, Fig. 2.6], the matching efficiency is lower for higher rapidity (Fig. 6.15 right), which can be explained by
As it can be seen in the left-panel of Figure 6.15, below $p_T \sim 2$ GeV/c the correct matching rate is slightly better for the track-matching approach compared to the cluster-matching considered in the LoI [4, Fig. 2.6]. While this difference probably reflects a different level of optimisation of the two methods, a residual advantage for the tracking-matching method may still come from the fact that in this approach some of the MFT clusters are eliminated in the preliminary standalone tracking stage, while in the cluster-matching approach all the clusters have to be tested, increasing the probability that a wrong one is associated to the extrapolated MUON track.

The track-matching approach may have some residual advantage also in the case of hadronic interaction pile-up, when the correct matching rate given by the cluster-matching approach decreases by about 20–30% for $p_T \sim 1–2$ GeV/c as shown in [4, Fig. 2.6]. In this case, thanks to the preliminary standalone tracking stage, the track-matching approach could automatically discard the MFT tracks not pointing to the main interaction vertex region, still allowing the needed tolerance for muons from decays of heavy-flavor hadrons.

Finally, we note that the fraction of fake MUON/MFT matching, complementary to the correct matching rate discussed above, can be significantly reduced by applying specific quality cuts within the various analyses, as discussed in [4].

### 6.6 Muon offset resolution

The MFT capability to identify muons coming from secondary vertices is measured by the experimental resolution on the muon track offset to the primary vertex, defined as the width of the Gaussian-parametrised offset distribution.

This resolution was determined in the transverse $(x, y)$ plane considering various scenarios for the material budget per disk, accounting respectively to 0.6%, 0.8% and 1.0% of the $X_0$, see left panel of Fig. 6.16. Full global tracking, with a Kalman fit performed on the ensemble of the MUON and MFT clusters, is used here on a simulation of prompt muons generated with flat $p_T$ and rapidity distributions with no underlying event environment. An additional misalignment of 15 $\mu$m is imposed on the transverse position of the MFT clusters, the displacement with respect to the true position being randomly chosen independently for each disk. This should be considered as a very conservative assumption, accounting for a significant degradation of the 10 $\mu$m misalignment expected for the MFT disks.
As it can be seen, at high $p_T$ (above 6 GeV/c) the offset resolution loosely depends on the assumed scenario for the material budget, converging to an intrinsic resolution of $\sigma \approx 30 \, \mu m$ defined by the imposed residual misalignment on the MFT clusters.

In the low-$p_T$ region, more sensitive to the multiple scattering effects, the difference between the material budget scenarios comes out to be more important. The offset resolution crosses the limit of 100 $\mu m$ — needed to perform a reliable separation of muons from charmed ($c\tau \sim 150 \, \mu m$) and beauty ($c\tau \sim 500 \, \mu m$) hadron decays in the transverse plane — around $p_T \approx 1$ GeV/c (the standard cut imposed on single muons in the analysis of heavy flavour observables). In particular, requesting that the resolution stays below 100 $\mu m$ at $p_T = 1$ GeV/c, imposes the material budget per disk to stay below 0.8% of the $X_0$. This allows to keep a safety margin with respect to the scenario considered for the present document (0.6% of the $X_0$ per disk) to accommodate possible additional constraints in the disk design. The relative degradation of the offset resolution between the 0.6% and the 0.8% of the $X_0$ scenarios is explicitly shown in the right panel of Fig. 6.16, where the fit function is an exponential on top of a constant $c = 1$.

**Figure 6.16**: Left: offset resolution in the transverse plane as a function of the muon transverse momentum for three scenarios of material budget per disk. Right: relative degradation between the 0.6% and the 0.8% of $X_0$ scenarios.
6.7 Physics case review and update

The ALICE capabilities for detecting muons at forward rapidity will be significantly enhanced by the presence of the MFT detector. Firstly, thanks to the prompt/displaced $J/\psi$ identification and to the charm/beauty separation in the single muon and dimuon channels, new observables become accessible down to very low transverse momenta. Secondly, the quality of already performed measurements can be improved, especially thanks to a stronger rejection of background muons from $\pi$ and $K$ decays. It should also be noted that, with the addition of the MFT, ALICE will be the only experiment performing these measurements for rapidities larger than 2.5 at the LHC in Pb–Pb collisions.

In this Section we discuss the expected performance of the ALICE MUON spectrometer upgraded with the addition of the MFT in the pseudo-rapidity range $3.6 < \eta < -2.5$. Special emphasis is given to the measurements for which new performance studies have been performed after the preparation of the ALICE Upgrade LoI, namely the measurement of open charm and beauty production in the single muon channel and the measurement of beauty production via displaced $J/\psi$. The other studies presented in the ALICE Upgrade LoI addendum [4] will be also summarised. It should be remarked that the physics cases discussed here and in the ALICE Upgrade LoI do not cover the whole set of physics cases of interest for the MFT, see Section 6.7.4. They still span and encompass, however, a broad range of the physics objectives of the ALICE muon physics after the MFT upgrade.

In all the physics performance studies performed so far, 0-10% Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.5$ TeV are simulated, with the final results extrapolated to the expected integrated luminosity of 10 nb$^{-1}$. A full description of the upgraded ITS, MFT and MUON spectrometer is considered, the global tracking of the muons being based on a MUON/MFT cluster-matching (the first of the two methods described in Section 6.5).

6.7.1 Open Heavy Flavours in the single muon channel

The MFT will contribute to the study of heavy flavour production both in the single muon and the dimuon channels, thanks to the possibility to discriminate muons from charm and beauty decays down to low $p_T$ even in central Pb–Pb collisions. It should be remarked that performing these measurements at the lowest $p_T$ is crucial in order to extract the total charm and beauty cross sections with the smallest possible dependence on models. In particular, as the charmonium regeneration models are very sensitive to the charm production cross section, its precise measurement is of great interest for the understanding of the charmonium measurements in the same rapidity range.

A separate measurement of charm and beauty production, in addition, allows to investigate the expected difference in the energy loss of charm and beauty quarks [35, 36, 37] which reflects in the hierarchy of the nuclear modification factors of charmed and beauty hadrons: $R_{AA}^{D} < R_{AA}^{B}$.

Updated results from new MC simulation studies are presented in the following, with a specific focus on the performance in the single muon channel already discussed in detail in [4].

**Signal and background definition**

For the present analysis, the signal is defined by the muons coming from the semi-muonic decay of heavy flavour hadrons, generated via the AliGenCorrHF generator [38] based on a parameterisation of the PYTHIA generator [39]. The $p_T$ distributions of the generated $c$ and $b$ quarks are consistent with the NLO calculations [40, 41]. Two categories have been identified for these muons: (i) muons from $b$ or $c$ “direct” decays, indicating muons that are produced directly from $B$ or $D$ hadron decays, and (ii) muons from $b$-chains, indicating muons produced at the end of the decay chain $\mu \leftarrow D \leftarrow B$. 
Background muons are defined as the muons coming from the decay of particles produced by the underlaying event, simulated with the HIJING generator [42]. Other categories have been identified as background for this study: (i) muons from resonances are muons with a resonance as a direct mother, (ii) muons from decay are those muons coming from light hadrons (mainly $\pi$ and $K$) decay, (iii) muons from secondary are muons coming from light hadrons produced inside the front absorber, (iv) muons from $c$-chains like $\mu \rightarrow \pi D$, (v) hadrons that punch through the front absorber and are misidentified as muon. The last category includes the noise from fake tracks, not representing physical particles.

![Figure 6.17: Left: $p_T$ distribution of the reconstructed single muons without any track selection. Right: $p_T$ distribution of reconstructed tracks after all requirements. Normalisations are relative to $L_{\text{int}} = 10 \text{ nb}^{-1}$, while uncertainties reflect the available Monte Carlo statistics.](image)

The left panel in Figure 6.17 shows the $p_T$ distribution of the reconstructed single muons available from the simulation. The only request here is that the reconstructed muon tracks have associated clusters both in the muon spectrometer and the MFT. As one can see, the most important contribution to the background at low-$p_T$ are muons from light hadron decays, while at high-$p_T$ the dominant source of background is the noise from fake tracks.

**Track selection**

The first track selection applied in the analysis, requires that reconstructed tracks fall within the geometrical acceptance of the MFT ($-3.6 < \eta < -2.5$). The second selection criterion imposes that all reconstructed tracks must be matched to a tracklet in the MUON-ID chambers at the end of the Muon Spectrometer: this requirement eliminates the 96% of the hadrons and the 81% of the fake tracks. Due to the $p_T$ cut implied by the matching with the MUON-ID chambers, a 61% of the muons from light hadron decays having passed the pseudorapidity cut, is also rejected. The third track selection is a quality cut on the $\chi^2/\text{ndf}$. By selecting tracks with $\chi^2/\text{ndf} < 3$ (evaluated considering the full MUON-MFT tracking information) it is possible to reject 99% of the remaining fake tracks and 64% of the remaining hadrons, while less than 8% of the signal is rejected.

The right panel in Figure 6.17 presents the $p_T$ distribution of the reconstructed tracks after the track selections described above. The most important source of background are now the muons from light hadron decays in the full $p_T$ range from 0 to 10 GeV/$c$.

The lower $p_T$ limit considered for the analysis is imposed at 0.5 GeV/$c$ by the presence of the hadron absorber and the iron wall in the setup of the Muon Spectrometer. However, in order to further improve the correct MUON-MFT matching rate for the final sample of analysed tracks and reduce the corresponding systematics, this threshold was set at 1 GeV/$c$. The upper limit
(\textit{p}_\text{T} = 6 \text{ GeV/c}) is imposed by the lack of statistics on the background generated by \textsc{Hijing}. The \textit{p}_\text{T} intervals considered in the present study are finally: 1 < \textit{p}_\text{T} < 1.5 \text{ GeV/c}, 1.5 < \textit{p}_\text{T} < 2 \text{ GeV/c}, 2 < \textit{p}_\text{T} < 3 \text{ GeV/c}, 3 < \textit{p}_\text{T} < 4 \text{ GeV/c} and 4 < \textit{p}_\text{T} < 6 \text{ GeV/c}.

### Analysis of the offset distributions

The analysis strategy for the measurement of the charm and beauty yields in the single muon channel, is based on the fit of the total offset distribution. In this case the offset is defined as:

\[
\Delta = \sqrt{(x_V - x_{\text{Extrap}})^2 + (y_V - y_{\text{Extrap}})^2},
\]  

(6.1)

where \((x_V, y_V)\) are the transverse coordinates of the primary vertex measured by the Inner Tracking System (ITS) and \((x_{\text{Extrap}}, y_{\text{Extrap}})\) are the coordinates in the plane transverse to the beam line of the extrapolated track evaluated at the \(z\) of the primary vertex.

For each \textit{p}_\text{T} bin, the offset distributions of the signals and the background are then evaluated via the Monte Carlo simulations and parametrised with a variable-width Gaussian function, with the width described as a polynomial function of the offset \(\Delta\):

\[
\sigma(\Delta) = \begin{cases} 
\sigma_0^L + \sigma_1^L(\mu - \Delta) + \ldots + \sigma_5^L(\mu - \Delta)^5 & \text{for } \Delta \leq \mu \\
\sigma_0^R + \sigma_1^R(\Delta - \mu) + \ldots + \sigma_6^R(\Delta - \mu)^6 & \text{for } \Delta > \mu 
\end{cases}
\]

where \(\mu\) is the mean value of the Gaussian. These parameterisations define the reference Monte Carlo templates that are sampled to build the offset distributions for signals and background corresponding to the expected statistics in a \(L_{\text{int}} = 10 \text{ nb}^{-1}\) scenario (for the charm and beauty, evaluated scaling the FONLL predictions by the number of binary collisions, with the nuclear modification factors set to 1; for the background, evaluated directly extrapolating the yield given by the \textsc{Hijing} generator. See Section 2.5.3 of [4]). In this way, the rest of the analysis will not suffer from the limited statistics of the original Monte Carlo samples. The total offset distribution is built, in each \textit{p}_\text{T} bin, by adding the open charm, open beauty and background offset distributions properly normalised to their expected contributions. These total distributions are then decomposed back to the three components, via a fit with the function:

\[
f(\Delta) = C \cdot f_c(\Delta) + B \cdot f_b(\Delta) + D \cdot f_d(\Delta)
\]

(6.2)

where \(f_c(\Delta), f_b(\Delta)\) and \(f_d(\Delta)\) are the Monte Carlo templates for charm, beauty and background, respectively. \(B, C\) and \(D\) are the free parameters corresponding to the normalisation of the three components.

The results of the combined fits for the lowest (1 < \textit{p}_\text{T} < 1.5 \text{ GeV/c}) and highest (4 < \textit{p}_\text{T} < 6 \text{ GeV/c}) \textit{p}_\text{T} bins are displayed in the left and right panels, respectively, of Figure 6.18. At low-\textit{p}_\text{T} muons from background are the most important contribution at large offset, one order of magnitude over the beauty component, while at small offset similar yields are expected for the charm and background components. At high-\textit{p}_\text{T} charm-decay muons are dominant for small offsets and beauty-decay muons are dominant for large offsets.

### Estimation of uncertainties and physics performance

In the \(L_{\text{int}} = 10 \text{ nb}^{-1}\) integrated luminosity scenario of interest for the ALICE upgrade, the statistical uncertainties on the charm and beauty yield extraction in the single muon channel will represent a negligible fraction of the total uncertainty of the measurements. In the specific \textit{p}_\text{T} interval considered in the studies reported here, in particular, statistical uncertainties are expected to stay below the 0.5% level.
Non-negligible systematic uncertainties, on the other hand, are expected to rise in a realistic experimental scenario due to the limited knowledge of the Monte Carlo templates of each component. Three different sources of systematic uncertainty have been identified and considered in the evaluation of the physics performance.

The first source of systematic uncertainty is related to the residual misalignment between the MFT and the ITS, the latter being used to measure the primary vertex considered for the estimation of the muon offset. This effect was taken into account by increasing or decreasing the nominal \((x_V, y_V)\) by a fixed quantity \((10 \mu m)\): a set of biased offset distributions are then computed with these modified coordinates for each muon source.

The second source of systematic uncertainty reflects the dependence of the offset templates on the Monte Carlo \(p_T\) distributions of the parent hadrons. The observation of a weak dependence on the parent hadron \(p_T\) for the mean value of the muon offset distributions, confirms the fact that this systematic effect cannot be neglected, suggesting at the same time that only a limited impact can be expected on the final results. This effect has thus been estimated by varying the assumed \(R_{AA}(p_T)\) considered for the parent hadrons, applied on top of the FONLL predictions (for charm and beauty hadrons) or the HIJING \(p_T\) distributions (for the parent hadrons of the background muons, mainly charged pions and kaons). In the case of the charm and beauty hadrons, the alternative hypotheses have been chosen among the models which describe the current ALICE data \([43, 44]\). For the background, two simple linear hypotheses have been considered, with the light meson \(R_{AA}(p_T)\) slope set at \(+0.1\) and \(-0.1\), respectively, within the \(0 < p_T < 10\) GeV/c range of interest here. It should be noted that, in this systematic test, only the variation of the \(p_T\) hypothesis for the charm and beauty hadrons resulted in an appreciable contribution to the total uncertainty.

The third source of systematic uncertainty is related to the residual uncertainty on the pointing resolution of the MFT. This effect was taken into account by randomly smearing the measured \(x\) and \(y\) components of the measured offset: a Gaussian smearing was considered, with a \(p_T\)-dependent width representing a 10% of the nominal pointing resolution.

For each of these three systematic sources, the ratio between the biased and the reference offset distributions quantifies the distortion due to the considered effect. These distortion patterns were then parameterised and used to deform the reference Monte Carlo templates separately for each \(p_T\) bin. The deformed templates were in turn used to fit, via equation 6.2, the total, nominal offset distributions. The systematic uncertainty is defined as the absolute difference between the normalisations of the signal optimised by the fit, in the two cases in which the total offset distribution is fitted with the deformed and the reference templates.
An additional source for the systematics, due to the uncertainty on the tracking efficiency of the Muon Spectrometer, has been also considered: this contribution has conservatively estimated to 2.5% for the single muons, independent of $p_T$. The statistical and systematic uncertainties on the evaluation of the charm and beauty yields in the single muon channel are compiled in Table 6.2 and Table 6.3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 1.5</td>
<td>0.01%</td>
<td>2%</td>
<td>4%</td>
<td>10%</td>
<td>2.5%</td>
<td>11%</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>0.01%</td>
<td>1%</td>
<td>1%</td>
<td>3%</td>
<td>2.5%</td>
<td>4%</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.01%</td>
<td>0.4%</td>
<td>2%</td>
<td>1%</td>
<td>2.5%</td>
<td>3%</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.02%</td>
<td>0.3%</td>
<td>4%</td>
<td>0.1%</td>
<td>2.5%</td>
<td>4%</td>
</tr>
<tr>
<td>4 - 6</td>
<td>0.03%</td>
<td>0.6%</td>
<td>7%</td>
<td>0.3%</td>
<td>2.5%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Table 6.2: Expected statistical and systematic uncertainties on the evaluation of the muon yields from open charm decays, for 0-10 % central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV and $L_{\text{int}} = 10$ nb$^{-1}$.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 1.5</td>
<td>0.37%</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1.5 - 2</td>
<td>0.14%</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.07%</td>
<td>13%</td>
<td>8%</td>
<td>39%</td>
<td>2.5%</td>
<td>42%</td>
</tr>
<tr>
<td>3 - 4</td>
<td>0.04%</td>
<td>5%</td>
<td>3%</td>
<td>5%</td>
<td>2.5%</td>
<td>8%</td>
</tr>
<tr>
<td>4 - 6</td>
<td>0.03%</td>
<td>4%</td>
<td>3%</td>
<td>3%</td>
<td>2.5%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 6.3: Expected statistical and systematic uncertainties on the evaluation of the muon yields from open beauty decays, for 0-10 % central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV and $L_{\text{int}} = 10$ nb$^{-1}$.

The total systematic uncertainty, obtained combining quadratically the uncertainties from the considered sources, is shown in Figure 6.19. Present results indicate that it will be possible to measure the open charm yield in the semimuonic decay channel down to $p_T = 1$ GeV/c, with total uncertainties within 10%. For the open beauty yield, in the single muon channel, robust enough measurements will only be possible for $p_T > 3$ GeV/c.

### 6.7.2 Beauty via non-prompt $J/\psi$

The measurement of non-prompt $J/\psi$ production from displaced vertices is a well-established tool for the beauty meson production study in high-energy nuclear collisions. The statistical separation of displaced $J/\psi$ production is based on the measurement of the distance between the primary vertex and the secondary vertex corresponding to the decay of the $b$-hadron. The order of magnitude of such a distance being of 500 $\mu$m — corresponding to the $c\tau$ of the $b$-hadrons
which gives a significant contribution to this channel — the measurement needs a dedicated vertex tracker. Without such a vertex tracker, no measurement of displaced $J/\psi$ production is currently possible in ALICE in the dimuon channel. This possibility will be given by the presence of the MFT, opening the way to the measurement of beauty production at forward rapidity.

**Characterization of the $B \rightarrow J/\psi + X$ decay**

Among the beauty hadrons presenting a decay channel involving a $J/\psi$, the ones giving the most significant contribution are the $B^0$, the $B^+$, the $B_s$ and the $\Lambda_b$, whose mean proper decay lengths range between 420 and 490 $\mu$m. Since the $J/\psi$ partners in these decays will not be identified at forward rapidity, the measurement of the beauty cross section will be based on the knowledge of the weighted branching ratio for the $B \rightarrow J/\psi + X$ decay, where the branching ratios into $J/\psi + X$ of the cited hadrons will be weighted by the relative yields of the hadrons themselves. Such a combined branching ratio can be estimated, in absence of specific final-state effects, with phenomenological models like PYTHIA.

Given the mass difference between the beauty hadrons and the measured $J/\psi$ through which the $B \rightarrow J/\psi + X$ decay is accessed, the correlation between the kinematics of the parent and daughter particles is not trivial. This point is relevant here, since the physics goal of the measurement involved here is the study of the production cross section of the parent hadrons down to zero-$p_T$, while the experimental measurement and all the related limitations concern the $J/\psi$.

Of particular interest is the correlation between the $p_T$ of the parent hadron and the $p_T$ of the $J/\psi$, shown in the left of Fig. 6.20 as obtained from a simulation of the most relevant $B \rightarrow J/\psi + X$ decays with PYTHIA. The analysis of the shape of the correlation shows that two regions can be distinguished. The first region corresponds to a $p_T$ of the $J/\psi$ larger than $\sim 2$ GeV/$c$, where a (loose) direct correlation can be seen between the $p_T$ of the $J/\psi$ and that of the parent hadron. The second region corresponds to $p_T$ values of the $J/\psi$ smaller than $\sim 2$ GeV/$c$: here, we can observe the presence of a strong anti-correlation between the $p_T$ of the two particles. Such an anti-correlation is understandable when considering that a zero-$p_T$ beauty hadron will produce a $J/\psi$ with finite $p_T$, due to the presence of the $J/\psi$ partners and to the large invariant mass imbalance between the initial and the final state in the $B \rightarrow J/\psi + X$ decays. Thanks to this kinematic effect, we can access the beauty hadron production cross section down to zero-$p_T$ by measuring displaced $J/\psi$ down to $p_T \sim 1.5$ GeV/$c$ (note that the MFT/MUON apparatus can measure $J/\psi$ down to zero $p_T$).
Figure 6.20: Left: correlation between the $p_T$ of the beauty hadron and the measured $J/\psi$ in a $B \to J/\psi + X$ decay, as estimated with PYTHIA. Right: schematic picture showing the production of a prompt and a displaced $J/\psi$.

Optimisation of the method for prompt/displaced $J/\psi$ separation

Since it is not possible to identify a single $J/\psi$ as a “prompt” $J/\psi$ coming from the primary vertex or a “displaced” $J/\psi$ coming from a secondary vertex (see right panel in Fig. 6.20), prompt and displaced $J/\psi$ samples have to be statistically separated, exploiting the difference in the shape of their distribution of $L$, the distance between the primary vertex and the production vertex of the $J/\psi$ (coinciding with the vertex where the $J/\psi$ decays into a pair of muons, due to the short decay time of the resonance).

Ideally, correcting $L/c$ by the $\gamma$ factor of the beauty hadron, an estimation of the proper decay time of the hadron could be obtained. However, since the $\gamma$ factor of the beauty hadron can only be approximated to the one of the daughter $J/\psi$, the resulting quantity is typically called pseudo-proper decay time:

$$t = \frac{|\vec{r}_{J/\psi} - \vec{r}_{vtx}|}{p} \cdot M_{J/\psi},$$

(6.3)

where $p$ is the total momentum of the $J/\psi$, and $|\vec{r}_{J/\psi} - \vec{r}_{vtx}|$ the distance between the $J/\psi$ production vertex and the primary vertex of the collision. By the definition of prompt and displaced $J/\psi$ (see Fig. 6.20 right), one can expect that the distribution of the $t$ variable for the prompt $J/\psi$ will be peaked around zero with a width depending on the experimental resolution on the distance $|\vec{r}_{J/\psi} - \vec{r}_{vtx}|$, while the distribution for the displaced $J/\psi$ will present a tail reflecting the physics distribution of the decay times for a $b$-hadron.

In practice, the above definition is never used in the form given by Eq. 6.3. It turns out, in fact, that when projecting the transverse or the longitudinal components of the decay kinematics, a better separation is obtained between prompt and displaced $J/\psi$ samples, respectively when performing measurements at mid-rapidity or at forward rapidity:

$$t_{xy} = \frac{\sqrt{(x_{J/\psi} - x_{vtx})^2 + (y_{J/\psi} - y_{vtx})^2} \cdot M_{J/\psi}}{p_T},$$

$$t_z = \frac{(z_{J/\psi} - z_{vtx}) \cdot M_{J/\psi}}{p_z}.$$  

(6.4)

The transverse and longitudinal definition of the pseudo-proper decay time have been used respectively by the CMS and LHCb Collaborations in their measurements of beauty production via displaced $J/\psi$. The transverse projection is also used for the measurements in the ALICE central barrel. A definition based on the transverse degree of freedom of the decay was also
considered for the performances studies of the prompt/displaced $J/\psi$ separation with the MFT\(^5\), reported in the ALICE Upgrade LoI [4]. This choice is not optimal, given the forward rapidity range covered by the ALICE MUON spectrometer: for this reason, the numbers summarized in [4, Table 2.5] significantly underestimate the real performance of the prompt/displaced $J/\psi$ separation with the MFT.

In the current version of the analysis strategy for the measurement of the $J/\psi$ displaced/prompt ratio with the MFT, the transverse variable $t_{xy}$ has thus been replaced with the longitudinal $t_z$. This motivated and imposed a detailed re-evaluation of the uncertainties expected for the measurement.

**Measurement of the non-prompt $J/\psi$ fraction for $p_T < 3$ GeV/c**

As it was done for the studies reported in [4], the prompt $J/\psi$ signal is simulated by means of a parametric generator, while displaced $J/\psi$ production from $b$-hadrons decays is simulated using PYTHIA with the “Perugia0” tune. Simulations of complete HIJING events are used to estimate the background sources with their appropriate yields and kinematic distributions: every possible muon pair is considered, event by event, disregarding the origin of the muons (with the exception of the muons coming from neutral resonances – i.e. the signal we are interested in – which are discarded when building the background pairs). The normalisation of the prompt $J/\psi$ signal is obtained scaling the expected cross section in pp by the number of binary collisions and assuming a nuclear modification factor of 0.7, as explained in Section 2.4.4 of [4]. The ratio between the displaced and prompt $J/\psi$ components in the rapidity range of the Muon Spectrometer is taken from the LHCb measurement of $J/\psi$ in pp collisions at $\sqrt{s} = 7$ TeV [45]. The background normalisation is determined by scaling the yield of background dimuons per event, estimated by means of the HIJING simulations, to the expected number of events.

The general strategy for the statistical separation of the prompt/displaced $J/\psi$ contributions is the same as in [4], with $t_{xy}$ replaced by $t_z$; no variation, in particular, has been considered concerning quality cuts and selections on single muons and dimuon. The measurement implies a double (possibly simultaneous) fit on the dimuon invariant mass spectrum and the $t_z$ distribution of the dimuons falling within the $J/\psi$ mass window.

The fit on the invariant mass spectrum allows a precise and robust evaluation of the normalisation for the background contribution, easily identifiable thanks to its exponential-like falling shape, on top of which the inclusive $J/\psi$ peak stays clearly visible even in the most central Pb-Pb collisions (see right panel of Figure 2.12 in [4]). From the results of this first fit, the normalisation of the background in any mass window centered on the $J/\psi$ peak can be extracted, with a systematic uncertainty which can be estimated to be around 1% — estimation based on the present $J/\psi$ measurements with the Muon Spectrometer. To minimise the impact of this uncertainty on the extraction of the prompt/displaced $J/\psi$, an appropriate mass window should be chosen when building the $t_z$ distribution to be considered in the second fit, in order to improve the signal/background ratio without degrading too much the statistics for the signal. In the following, the mass window $3.0 < m_{\mu\mu} < 3.2$ GeV/c\(^2\) has been considered (see Table 2.4 of [4]), resulting in signal/background ratios between 1.2 and 3 in the $p_T$ range from 0 to 3 GeV/c for the inclusive $J/\psi$.

The second fit is based on the decomposition of the total $t_z$ distribution into the three components corresponding to the background, the prompt and the displaced $J/\psi$. The $t_z$ templates of the three components are estimated via Monte Carlo simulations, using a variable-width

\(^5\) In that case, the variable was expressed in terms of pseudo-proper decay length.
Gaussian parameterisation of the original distributions, with the width given by:

\[ \sigma(t_z) = \begin{cases} 
\sigma_0 \left( 1 + \alpha_L \cdot (\bar{t}_z - t_z) \beta_L \cdot \gamma_L \sqrt{\bar{t}_z - t_z} \right) & \text{for } t_z \leq \bar{t}_z \\
\sigma_0 \left( 1 + \alpha_R \cdot (t_z - \bar{t}_z) \beta_R \cdot \gamma_R \sqrt{t_z - \bar{t}_z} \right) & \text{for } t_z > \bar{t}_z
\end{cases} \]

where \( \bar{t}_z \) is the mean value of the Gaussian distribution (for the prompt \( J/\psi \) component the parameterisation is imposed to be symmetric with respect to \( \bar{t}_z \), as justified by the shape of the reconstructed distribution). The normalisation of the background being fixed from the fit on the invariant mass spectrum, the inclusive \( J/\psi \) normalisation and the prompt/displaced \( J/\psi \) ratio are left as the only free parameters. The robustness of the prompt/displaced \( J/\psi \) ratio measurement will thus only depend on the difference in the shape of the \( t_z \) distributions of the prompt and displaced \( J/\psi \). In Figure 6.21 the fit on the \( t_z \) distribution is shown in three \( p_T \) intervals from 0 to 3 GeV/c. The dramatic improvement in the prompt/displaced \( J/\psi \) separation with respect to the analysis based on the \( t_{xy} \) variable can be immediately appreciated by directly comparing these plots with the ones in Figure 2.17 of [4], the \( t_z \) distribution of the non-prompt \( J/\psi \) appearing now strongly asymmetric with respect to the distribution of the prompt \( J/\psi \), the exponential shape of the right tail reflecting the life time distribution of the beauty hadrons. The asymmetry of the background \( t_z \) distribution results from the fact that a significant fraction of the muons composing the combinatorial pairs are produced at finite distances from the primary vertex, in the direction of the Muon Spectrometer.

Figure 6.21: Fit on the total \( t_z \) distribution in the \( J/\psi \) mass window \( 3.0 < m_{\mu\mu} < 3.2 \text{ GeV}/c^2 \), in three \( p_T \) bins down to zero \( p_T \) (cfr Figure 2.17 of [4]).

**Estimation of uncertainties and physics performance**

The statistical uncertainties expected for the measurement of the non-prompt \( J/\psi \) fraction range from 0.8\% to 1.5\% in the \( 0 < p_T < 3 \text{ GeV}/c \) range considered for the present study. The values, reported in Table 6.4, include the propagation of the statistical errors in the background subtraction.

Two main sources of systematic uncertainty have been identified for the measurement of the prompt/displaced \( J/\psi \) ratio:

- the 1\% uncertainty on the normalisation of the background component;
- the uncertainty on the shape of the \( t_z \) templates.

The contribution to the systematic uncertainty coming from the first of these two sources has been estimated by repeating several times the fit on the \( t_z \), each time fixing a different normalisation of the background, spanning the cited 1\% uncertainty range. The difference between the
6.7 Physics case review and update

extreme values obtained for the prompt/displaced ratio is taken as the systematic uncertainty corresponding to this first source.

In order to study in detail the second source of systematic uncertainty, the discrepancy between the true and the Monte Carlo $t_z$ templates has been represented in terms of a Gaussian smearing of the $t_z$ distribution. The nominal $t_z$ templates have thus been replaced by modified templates in which the effect of the experimental $t_z$ resolution was artificially increased/decreased by up to 10%. In this case, too, the difference between the extreme values obtained for the prompt/displaced ratio is taken as the systematic uncertainty corresponding to this systematic source.

In practice, the impact of this second source of systematic uncertainty can be strongly reduced by leaving the experimental $t_z$ resolution to be optimised by the fit routine itself\(^6\). This can be done by expressing each $t_z$ Monte Carlo template as the convolution of a template describing the ideal detector response, and a Gaussian smearing representing the real detector response (non-Gaussian parameterisations of the detector-induced $t_z$ smearing can possibly be considered). By letting the fit optimise the width of this Gaussian smearing, the residual discrepancies between the Monte Carlo and the real $t_z$ templates can be reduced by a large extent. For this reason, we refer to this procedure as “σ recovering”. The final values considered in the following have been estimated by applying this “σ recovering” procedure.

The systematic bias given by the specific choice of the Monte Carlo $p_T$ distribution for the beauty hadrons, having an impact on the shape of the $t_z$ distribution for the displaced $J/\psi$ component, has also been studied. As in the case of the single muon analysis, several models have been considered for the $R_{AA}(p_T)$, among those which describe the current ALICE data [44]. In this case, however, no significant variation in the shape of the $t_z$ variable has been observed and no additional systematic uncertainty was thus propagated to the final results.

The values of the statistical and systematic uncertainties expected for the measurement of the prompt/displaced $J/\psi$ ratio are summarised in Table 6.4. As it can be noticed, the measurement of the statistical separation of prompt and displaced $J/\psi$ will be possible down to zero-$p_T$ with total uncertainties safely below 5%. The values are also represented as uncertainty bands in the left plot of Figure 6.22, where the expected performance for the measurement of the displaced/prompt $J/\psi$ ratio is shown. For the sake of completeness, in the last column of Table 6.4 we also report the systematic uncertainties due to the limited knowledge of the $t_z$ templates, when the “σ recovering” procedure is not applied.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>1.5 %</td>
<td>3 %</td>
<td>2 %</td>
<td>14%</td>
<td>3%</td>
</tr>
<tr>
<td>1 - 2</td>
<td>0.9 %</td>
<td>1 %</td>
<td>1 %</td>
<td>11%</td>
<td>2%</td>
</tr>
<tr>
<td>2 - 3</td>
<td>0.8 %</td>
<td>1 %</td>
<td>1 %</td>
<td>9%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table 6.4: Expected statistical and systematic uncertainties on the evaluation of the non-prompt $J/\psi$ fraction.

\(^6\) In addition, it should be mentioned that a tuning of the $t_z$ resolution in the Monte Carlo may be possible considering the $t_z$ distribution of prompt dimuon sources, like the dimuons of the $\Upsilon$ resonances. For the $t_z$ distribution of the background, furthermore, a cross-check between the mixed-event and the side-band techniques will also be possible.
Performance for the measurement of the non-prompt $J/\psi$ $R_{AA}$

A proper estimation of the displaced/prompt $J/\psi$ ratio represents the key ingredient in the measurement of the $R_{AA}$ of the beauty via displaced $J/\psi$. The statistical and systematic uncertainties summarised in Table 6.4 will thus enter in the evaluation of the uncertainty on the beauty $R_{AA}$, together with the uncertainties on the needed pp reference.

In order to obtain a full estimation of the performance expected for the measurement of the beauty $R_{AA}$, the uncertainties coming from the pp reference have thus been estimated. This has been done scaling the signal to the expected integrated luminosity of $6\text{ pb}^{-1}$ (representing the official requirement for the ALICE pp programme at $\sqrt{s} = 5.5\text{ TeV}$ serving as a reference for the Pb-Pb measurements, see [3]) and performing the $t_z$ fits in the limit of a negligible background contamination (the pointing resolution of the MFT and the almost 100\% MFT/MUON correct matching rate expected in low-occupancy conditions will allow an efficient rejection of muons from non-prompt sources, representing the bulk of the combinatorial background within the $J/\psi$ mass window). This allowed the statistical uncertainties to be properly estimated; as for the systematic ones, they were assumed to be comparable to the uncertainties on the description of the $t_z$ template found in the Pb-Pb analysis (see Table 6.4).

As in the case of the measurement of charm and beauty production in the single muon channel, an additional source for the systematics has also been considered, due to the uncertainty on the tracking efficiency of the Muon Spectrometer, at the high-occupancy conditions expected in central Pb-Pb collisions: this contribution, which cancels out in the measurement of the non-prompt over prompt $J/\psi$ ratio, must be taken into account when the non-prompt or the prompt components are considered separately (no cancellation occurs when dividing by the pp reference, due to the different data taking conditions), and has conservatively been estimated to 5\%, independent of $p_T$.

A summary of the statistical and systematic uncertainties entering the measurement of the beauty $R_{AA}$ via displaced $J/\psi$ is presented in Table 6.5. The quadratic sum of all the reported uncertainties, separately for each considered $p_T$ bin, is then represented as a full box in the right panel of Figure 6.22. In this figure, the absolute position of the simulated data points follows the trend indicated by the BAMPS model [46] when describing the $R_{AA}$ of displaced $J/\psi$ in Pb-Pb at $\sqrt{s_{NN}} = 2.76\text{ TeV}$. The points corresponding to the expected performance of the upgraded ALICE ITS in the measurement of beauty via displaced $D^0$ are also shown, taken from the left panel of Figure 8.19 of [5]. As it can be clearly seen, the measurement of non-prompt $J/\psi$ in the dimuon channel at forward rapidity, considered in the present study, represents a key tool for the measurement of beauty down to zero $p_T$ in Pb-Pb collisions, in ALICE and more generally at the LHC.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>4%</td>
<td>1.3%</td>
<td>1.9%</td>
<td>5%</td>
<td>6%</td>
</tr>
<tr>
<td>1 - 2</td>
<td>2%</td>
<td>1.1%</td>
<td>1.1%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>2 - 3</td>
<td>2%</td>
<td>0.9%</td>
<td>1.3%</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Table 6.5: Expected uncertainties for the evaluation of the $R_{AA}$ of non-prompt $J/\psi$.

6.7.3 Summary of the other available performance studies

The contribution of the MFT to the ALICE muon physics is expected to be crucial in at least two other key-measurements: the observation of the $\psi(2S)$ down to zero $p_T$ even in central Pb–
Pb collisions, and the precision measurement of low-mass dimuon production down to low $p_T$. For these physics studies, we shortly review in this Section the main results already discussed in the ALICE Upgrade LoI addendum [4].

**ψ(2S) measurement**

The MFT tracking capabilities allow for a significant reduction of the combinatorial background coming from the semi-muonic decay of light hadrons, mainly pions and kaons, and from non-prompt correlated sources like open charm and open beauty processes. This background reduction is important for all signals, but is of major interest for the study of the $\psi(2S)$ in central Pb–Pb collisions, for which the signal-over-background ratio improves by a factor up to about 10 depending on the $p_T$ range. The very low signal-over-background ratio obtained with the current MUON spectrometer makes the $\psi(2S)$ extraction in the most central Pb–Pb collisions very difficult. The addition of the MFT, conversely, will allow the $\psi(2S)$ signal to be extracted with uncertainties as low as ~10% down to zero $p_T$ [4]. A precise measurement of the $\psi(2S)$, combined with the one of prompt $J/\psi$ production, will offer an important tool to discriminate between different models of charmonium regeneration in the QGP.

**Low-mass dimuon measurements**

The measurement of prompt dimuon sources in the low-mass region (below ~1.2 GeV/$c^2$) will strongly benefit from the addition of the MFT to the MUON spectrometer. A dramatic improvement, up to a factor of about 4, is expected for the mass resolution of the narrow $\omega$ and $\phi$ resonances, for which resolutions of ~15 MeV/$c^2$ are expected: this will translate into a significant improvement of the measurements involving these particles, allowing at the same time a reliable identification of the underlying thermal dimuon continuum and the measurement of the in-medium modified line shape of the short-lived $\rho$ meson. A precision of about 20% is
expected for the observation of these sources, currently not feasible due to the very small signal-
over-background ratio affecting the measurement with the present MUON spectrometer [4].

6.7.4 Ongoing and future physics performance studies

The results of the MFT physics performance studies, discussed in the ALICE Upgrade LoI [4] and reviewed in the previous Sections, naturally open the way to a more comprehensive exploration of the ALICE muon physics horizons after the LHC LS2. Investigations on possible improvements of the analysis strategies for the physics cases considered in the present studies are thus ongoing. In parallel, an intense effort is being undertaken to investigate and quantify the MFT contribution to an additional set of physics items, not covered by the currently available performance studies.

A first subject of primary interest is the improvement of the performances in the measurement of charm and beauty production in the single muon channel. Currently based on the decomposition of the transverse offset distributions of single muons with respect to the primary vertex, this analysis could profit of the introduction of a new discriminating variable, offering a better resolution power in separating charm from beauty, and both signals from background. Following what was done for the analysis of the displaced $J/\psi$ production, new definitions of the distance between muon tracks and primary vertex are being tested, based on the $z$-projection of the muon kinematics.

Coming to the currently uncovered items of the MFT physics, we should cite the measurement of the elliptic flow of prompt and displaced charmonia, allowing to understand the coupling of the charm and beauty quarks, respectively, to the deconfined medium. As these measurements are performed in semi-central Pb–Pb collisions, they will profit from a better signal-over-background ratio than the most central collisions considered in the available MFT performance studies. At the same time, the lower occupancy of the MFT disks will translate into a lower contamination from fake matches between the MUON and the MFT information, improving the spatial resolution of the extrapolated tracks to the primary vertex and the prompt/displaced $J/\psi$ discrimination.

Elliptic flow studies could also be performed on single muons from charmed and beauty hadrons. In this case, too, a more favorable signal-over-background ratio and a more reliable charm/beauty separation are expected with respect to the performances estimated in the most central Pb–Pb collisions, thanks to the cleaner environment of the semi-central Pb–Pb collisions. Azimuthal anisotropies of light neutral meson production could also be studied, giving precious informations about the participation of light quarks to the flow of the deconfined medium at forward rapidity.

Another measurement which could greatly profit from the presence of the MFT is the study of prompt dimuon production at intermediate (between the $\phi$ and $J/\psi$ masses) and high (between charmonia and bottomonia regions) invariant masses. The possibility to apply a strong $p_T$ cut on the muons involved in this measurement is expected to guarantee a powerful resolution in discriminating prompt sources from the correlated and uncorrelated non-prompt background, preserving at the same time the coverage down to zero-$p_T$. At intermediate masses, this measurement should allow the identification of the thermal dimuon radiation from QGP, giving information about the temperature of the deconfined medium. At higher masses, a study of the Drell-Yan dimuon production should be possible.

The possibility to perform a reliable standalone tracking in the MFT, finally, could allow a certain number of measurements beyond the realm of the ALICE muon physics. Among them, we can cite: (i) the measurement of the charged particle multiplicity at large rapidity; (ii) an estimation of the azimuthal symmetry planes (e.g. the so-called event plane corresponding to the 2$^{\text{nd}}$ harmonic of the Fourier decomposition of the azimuthal distribution of particles) complementing the measurements at mid-rapidity done using the central barrel detectors and
the estimates based on the other forward rapidity detectors, namely the FIT system [5]; (iii) the study of long-range correlations exploiting the complementary pseudorapidity acceptances of the ITS and MFT.
7 Organization, cost and schedule

The ALICE upgrade is planned to be in operation after Long Shutdown 2 (LS2) and has a programme that will extend into the HL-LHC era after Long Shutdown 3 (LS3). The current LHC schedule foresees LS2 to take place from July 2018 until December 2019. The installation and commissioning of the MFT is foreseen in parallel with the ITS over a period of three months end of the LS2 [6]. The main project activities and milestones are shown in the Gantt chart in Fig. 7.2, 7.3, 7.4 and 7.5.

The MFT project is managed in coordination with the ITS upgrade project for many aspects: i) the technology chosen for the MFT, CMOS Monolithic Active Pixel Sensors, is the same as for the new ALICE ITS detector [6]; ii) the only difference of the MFT Flexible Printed Circuit (FPC) with respect to that of ITS inner barrel, is the number of sensors; iii) the bonding technique for the Hybrid Integrated Circuit (HIC) is the same as the one developed by the ITS project; iv) the read-out electronic architecture will be identical for both projects and v) MFT shares the infrastructure for services of the ITS upgrade project. The physics cases of the MFT is directly linked to the one of the MUON spectrometer upgrade project [5], therefore, global tracking and physics performances studies are performed in a joint effort by the two projects.

7.1 Organisation

The Project Leader (PL) heads the Muon Forward Tracker Project. He is assisted by the MFT Deputy Project Leader (DPL) and the MFT Technical Coordinator (TC). The MFT PL, DPL and TC are all members of the ALICE Technical Board and thus can ensure the coherence of the project within the ALICE experiment. Issues of a financial, managerial and organizational nature are discussed and decided by the MFT Institute Board. This board also endorses technical matters recommended by the MFT Technical Board (see below) and proposed by the MFT Project Leader. All institutes participating in the MFT Upgrade Project, shown in Tab. 7.1, are represented by their Team Leader in the Institute Board. The Project Leader, Deputy Project Leader and Technical Coordinator are ex-officio members of the Institute Board. As shown in Fig. 7.1, the MFT Upgrade Project is organised into eight Working Groups, which work in close collaboration with the corresponding working groups of either the ITS or MUON projects. In particular, the WG1 (physics simulations) is a common working group with the Muon Spectrometer project, while WG2 (simulation and reconstruction), WG4 (CMOS pixel sensors and FPCs), WG6 (readout electronics) and part of WG8 (services and detector control system) are in common with the ITS project. The other working groups will work in synergy with the Muon Spectrometer (WG3: standalone and global tracking) or ITS (WG5: sensors production and assembly and WG7: Mechanics and thermal studies) projects. The Working Group Coordinators are nominated by the Project Leader and endorsed by the MFT Institute Board. They are members of the MFT Technical Board. The Project Leader, Deputy Project leader and Technical Coordinator are members of the MFT Technical Board.

The MFT construction will be distributed among the participating Institutes. This organisation allows institutional manpower to be engaged at their home institutes and thus reduces labour and some external associated costs.

The MFT construction will take place in close synergy with the ITS project [6, 47]:

79
• Pixel sensors will be the same as for ITS project and the final design will be done commonly by ITS and MFT microelectronics designers. The CMOS sensors manufacturing will be done by Tower Jazz company, which is one of the world leaders in the field of CMOS imaging sensors.

• Flexible Printed Circuits are planned to be manufactured in the same site than the ITS inner barrel FPCs.

• The soldering of the pixel sensors with the FPCs will be performed using the automatic machine developed by the ITS group (laser soldering technique). The MFT ladders assembly will be performed at CERN, thus benefiting of the ITS infrastructures and expertise. The MFT consists of 896 pixel sensors assembled in 280 HICs of different lengths from 1 to 5 sensors each. For comparison ITS inner barrel consists of 432 pixel sensors assembled in 48 staves, 9 pixel sensors each [47].

• The MFT read-out electronic architecture will be identical to that of ITS upgrade project [6]. The corresponding ITS and MFT WGs will work together to develop a data concentrator card that will comply the specifications of both detectors.

• Finally the infrastructure for services (cooling plant, power supply) will be shared between the ITS and MFT detectors.
Table 7.1: Institutes participating or planning to participate in the MFT Project.

<table>
<thead>
<tr>
<th>Country</th>
<th>City</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Wuhan</td>
<td>Central China Normal University (CCNU)</td>
</tr>
<tr>
<td>France</td>
<td>Clermont-Ferrand</td>
<td>Laboratoire de Physique Corpusculaire (LPC), Clermont Université,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Université Blaise Pascal, CNRS/IN2P3</td>
</tr>
<tr>
<td>France</td>
<td>Nantes</td>
<td>SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS/IN2P3</td>
</tr>
<tr>
<td>France</td>
<td>Saclay</td>
<td>Commissariat à l’Energie Atomique, IRFU</td>
</tr>
<tr>
<td>France</td>
<td>Villeurbanne</td>
<td>Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon</td>
</tr>
<tr>
<td>India</td>
<td>Kolkata, Aligarh</td>
<td>Saha Institute of Nuclear Physics and Aligarh Muslim University</td>
</tr>
<tr>
<td>Japan</td>
<td>Hiroshima</td>
<td>Hiroshima University</td>
</tr>
<tr>
<td>South Korea</td>
<td>Pusan, Incheon, Yonsei</td>
<td>Pusan National, Inha University and Yonsei Universities</td>
</tr>
<tr>
<td>Spain</td>
<td>Valencia</td>
<td>Instituto de Física Corpuscular</td>
</tr>
<tr>
<td>Peru</td>
<td>Lima</td>
<td>Pontificia Universidad Católica del Perú</td>
</tr>
<tr>
<td>Russia</td>
<td>Gatchina</td>
<td>Petersburg Nuclear Physics Institute</td>
</tr>
<tr>
<td>Thailand</td>
<td>Nakhon</td>
<td>Suranaree University of Technology and Thai Microelectronics Center</td>
</tr>
<tr>
<td></td>
<td>Ratchasima, Chachoengsao</td>
<td></td>
</tr>
</tbody>
</table>

7.2 Cost assessment

This section points out some design choices and their possible impact on the global project cost. The costs for R&D are not included in the assessment, neither the personnel cost, nor basic infrastructures of the participating institutes. A summary of the major tasks responsibilities sharing and cost assessment of the MFT detector is shown in Tab. 7.2. A foreseen spending profile, according to the project schedule, is given on Tab. 7.3. It is important to notice that the currency rates [47] are as follows: 1 EUR = 1.23 CHF and 1 USD = 0.9 CHF.

7.2.1 Pixel sensor

The chosen process for the pixels sensor is a 0.18 µm CIS (CMOS Imaging Sensor) process offered by TowerJazz. This process has been used intensively during the R&D phase and TowerJazz demonstrates its capacity to realize the Silicon sensors both for the ITS and MFT projects. The cost for the pixel sensors manufacturing consists of the mask cost plus the production cost per wafer. In the money matrix of the MFT project, a financial contribution to the mask is foreseen and the cost for the needed wafers. A financial contribution to the pre-production run is also taken into account in the global amount. In addition to the 896 sensors needed for the MFT, it is planned to build 20% of spare sensors plus an additional half-MFT. With a production yield of 50%, the total number of sensor to be produced is 3228. The number of sensors per wafer being about 45, it is planned to order 72 wafers.

7.2.2 Flex Printed Circuit

The Flexible Printed Circuits of the MFT will have similar design in terms of materials and strips lines than the one of ITS inner-barrel, except the length, which varies for the from 1 up to 5 CMOS sensors. The unit price is based on the offered obtained for ITS [47]. The quantity for MFT takes into account the half MFT spare and 20% spare in case of not satisfying circuits according to our quality criteria. This leads to a total number of 504 FPCs.
Table 7.2: Cost estimate and sharing of technical activities and responsibilities in the MFT Project. Laboratories in bold italics are coordinators of the corresponding item.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (kCHF)</th>
<th>Participating Institutes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>3345.2</td>
<td></td>
</tr>
<tr>
<td><strong>Pixel Sensors</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMOS wafers</td>
<td>310.8</td>
<td>IRFU, Thai Microelectronics Center, in synergy with ITS</td>
</tr>
<tr>
<td>Thinning &amp; dicing</td>
<td>44.3</td>
<td>IRFU, Thai Microelectronics Center, in synergy with ITS</td>
</tr>
<tr>
<td>Series tests</td>
<td>128.3</td>
<td>Pusan National University, Inha University and Yonsei University, IRFU, in synergy with ITS</td>
</tr>
<tr>
<td><strong>Ladders</strong></td>
<td>837.3</td>
<td></td>
</tr>
<tr>
<td>FPCs manufacturing &amp; tests</td>
<td>82.4</td>
<td>SUBATECH</td>
</tr>
<tr>
<td>FPCs electronic components &amp; tests</td>
<td>12.3</td>
<td>SUBATECH</td>
</tr>
<tr>
<td>Automatic assembly system for HICs</td>
<td>258.3</td>
<td>SUBATECH, IRFU, in synergy with ITS</td>
</tr>
<tr>
<td>Stiffeners manufacturing</td>
<td>93.0</td>
<td>SUBATECH</td>
</tr>
<tr>
<td>HICs and ladders assembly &amp; tests</td>
<td>163.9</td>
<td>IRFU, SUBATECH, AMU, IPNL, LPC CL, PNPI, SAHA in synergy with ITS</td>
</tr>
<tr>
<td>Ladders qualification tests</td>
<td>227.4</td>
<td>IRFU, IPNL, LPC CL, SAHA, HIROSHIMA, LIMA</td>
</tr>
<tr>
<td><strong>Disks</strong></td>
<td>371.5</td>
<td></td>
</tr>
<tr>
<td>Disk Spacers, support manufacturing</td>
<td>172.2</td>
<td>SUBATECH</td>
</tr>
<tr>
<td>Disks Assembly</td>
<td>84.3</td>
<td>SUBATECH, IPNL, IRFU, AMU, LPC CL, PNPI, SAHA</td>
</tr>
<tr>
<td>Disks Tests</td>
<td>84.3</td>
<td>IRFU, IPNL, LPC CL, SAHA, HIROSHIMA, LIMA</td>
</tr>
<tr>
<td>Shipments</td>
<td>30.7</td>
<td>SUBATECH</td>
</tr>
<tr>
<td><strong>Global assembly</strong></td>
<td>296.0</td>
<td></td>
</tr>
<tr>
<td>Cone manufacturing</td>
<td>61.5</td>
<td>SUBATECH</td>
</tr>
<tr>
<td>Half MFT Assembly &amp; test</td>
<td>93.5</td>
<td>SUBATECH, IRFU, SAHA, IPNL, PNPI, HIROSHIMA, LIMA</td>
</tr>
<tr>
<td>Services barrel, connections</td>
<td>141.0</td>
<td>IPNL</td>
</tr>
<tr>
<td><strong>Integration in ALICE</strong></td>
<td>324.6</td>
<td></td>
</tr>
<tr>
<td>Insertion Tools</td>
<td>36.9</td>
<td>IPNL, SUBATECH</td>
</tr>
<tr>
<td>Barrel manufacturing</td>
<td>61.5</td>
<td>IPNL</td>
</tr>
<tr>
<td>Check-out in surface</td>
<td>113.1</td>
<td>IPNL, IRFU, SUBATECH, PNPI</td>
</tr>
<tr>
<td>Installation in cavern</td>
<td>113.1</td>
<td>IPNL, IRFU, SAHA, SUBATECH, PNPI</td>
</tr>
<tr>
<td><strong>Readout electronics</strong></td>
<td>490.8</td>
<td></td>
</tr>
<tr>
<td>Printed Circuit Boards</td>
<td>49.2</td>
<td>IPNL, CCNU, IFIC</td>
</tr>
<tr>
<td>Data e-links</td>
<td>34.8</td>
<td>IRFU, IPNL, in synergy with ITS</td>
</tr>
<tr>
<td>Patch Panels equipped</td>
<td>47.4</td>
<td>IPNL</td>
</tr>
<tr>
<td>Optical fibers</td>
<td>64.8</td>
<td>SAHA, IPNL</td>
</tr>
<tr>
<td>Readout Units</td>
<td>121.5</td>
<td>AMU, SAHA, IRFU, IPNL, in synergy with ITS</td>
</tr>
<tr>
<td>Common Readout Units</td>
<td>173.0</td>
<td>AMU, SAHA in synergy with ITS and ALICE Electronics coordination</td>
</tr>
<tr>
<td><strong>Services</strong></td>
<td>541.6</td>
<td></td>
</tr>
<tr>
<td>Power Distribution</td>
<td>123.7</td>
<td>SUBATECH, in synergy with ITS</td>
</tr>
<tr>
<td>Power Supplies</td>
<td>173.8</td>
<td>SUBATECH, in synergy with ITS</td>
</tr>
<tr>
<td>Power Regulations</td>
<td>36.9</td>
<td>SUBATECH, in synergy with ITS</td>
</tr>
<tr>
<td>Cooling &amp; Ventilation Plants</td>
<td>89.1</td>
<td>PNPI, in synergy with ITS</td>
</tr>
<tr>
<td>DCS</td>
<td>118.1</td>
<td>PNPI, in synergy with ITS</td>
</tr>
</tbody>
</table>
7.2 Cost assessment

Table 7.3: Spending profile proposal for the MFT Project.

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expenses (kCHF)</td>
<td>86.1</td>
<td>1078.6</td>
<td>1544.1</td>
<td>525.7</td>
<td>110.7</td>
<td>3345.2</td>
</tr>
</tbody>
</table>

7.2.3 Hybrid Integrated Circuit and ladder assembly

The assembly of the CMOS pixel sensors with the FPC and test assembly will be done at CERN, using the same automatic assembly system foreseen for ITS inner barrel. It is planned that MFT will be equipped with its own automatic machine, avoiding a bottle neck with ITS inner-layers during production phase. This activity requires at least three persons permanently at CERN (one engineer as supervisor and two mechanical technicians) for the duration of one year. The MFT ladder assembly will be shared between several MFT institutes: IPNL, IRFU, LPCC, PNPI, SAHA and SUBATECH. The cost takes into account the realization of the HICs, plus the carbon stiffeners, a complete set of automatic assembly system with dedicated tools for MFT, consumables (glue, gloves,...).

7.2.4 Global assembly

This item summarizes the estimated cost for the realization of the two MFT cone structures, the half-MFT assembly, the connections between services barrel and cone (tooling, manpower).

7.2.5 Integration in ALICE

This item summarizes the estimated cost for the MFT barrel structure, the insertion tools necessary for the installation of the two half-MFT in the ALICE experiment. Some extra-manpower cost for installation and tests is included in this item.

7.2.6 Readout electronics and cables

The MFT disks are connected with a total of 1456 electrical links (896 downstream electrical links for data from each sensor and 560 electrical links for upstream Clock and Slow Control signals - see Sec. 5.4). Patch panels equipped with data concentrators FPGAs, Readout Units and Common Readout Units are taken into account in the cost estimation, based on ITS costing. Radiation hard optical fibers are used for data transmission and are the same than the ones chosen for ITS.

7.2.7 Services

Cooling

The cost estimate is based on the assumption that the MFT cooling system can be connected to the ITS Cooling and Humidity plants. A contribution of 10 % to the global cost is taken into account in the table. Another possible option, where MFT will have its own separate plants, has to be studied in more details and will be certainly more cost effective.

DCS

The DCS monitors in real time all parameters of the detectors such as the LV power value, temperature, water and air flow of the disks. In addition, DCS will have a set of different interlocks to avoid damage of detectors in case of abnormal situation (current overflow, water leaks, excessive temperature). For the cost estimate, a scaling from the ITS staves has been done, taking into account that MFT has 280 ladders equipped and reducing the number of boards and modules, compare to ITS case.
LV power

This service includes the LV power supplies (crates and boards), the cables, connectors, patch panels and the power regulation (including DC-DC converters). As for ITS, the CAEN modular LV system is proposed. Prices are based on an offer made for ITS and adapted to MFT. A separation of channels for the Analog and Digital power is necessary. It leads to a total of 212 channels. 30 boards will be necessary (including 10% spare), and consequently 5 main frames are taken into account with 3 Power Supplies per main frame. In the global cost, some installation cost is also taken into account.
7.3 MFT general schedule

The schedule of the project is presented on Fig. 7.2 to Fig. 7.5. The working time is assumed to be 5 days per week and 8 hours per day. Holidays are taken into account. The present critical path of the project is going through the sensors production and qualification tests activities and then impacting the ladders assembly activity till the end of the project. Nevertheless, a second critical path, very close to the first one (with 2 months of margin left), is the preparation of the assembly site activity with the organization of the ladders production and also the FPCs realization activity.
Figure 7.2: MFT Schedule - October 2014 version (part 1).
Figure 7.3: MFT Schedule - October 2014 version (part 2).
### Figure 7.4: MFT Schedule - October 2014 version (part 3)

<table>
<thead>
<tr>
<th>No.</th>
<th>Activity Description</th>
<th>Start Date</th>
<th>Finish Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>Design Phase</td>
<td>Jun 05/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>116</td>
<td>Very preliminary (mechanical and thermal) for Lot 1</td>
<td>Jun 05/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>117</td>
<td>Details mechanical design</td>
<td>Jun 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>118</td>
<td>Mechanical design</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>119</td>
<td>Mechanical design</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>120</td>
<td>Mechanical design</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>121</td>
<td>Intermediate mechanical detailed design with solutions for</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>122</td>
<td>Mechanical detailed design (compilation)</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>123</td>
<td>Detailed drawings</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>124</td>
<td>Completion of mechanical studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>125</td>
<td>Thermal studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>126</td>
<td>Intermediate working solution of thermal studies for TDR</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>127</td>
<td>Finalization of thermal studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>128</td>
<td>Completion of thermal studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>129</td>
<td>Completion of mechanical and thermal studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>130</td>
<td>Production Phase</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>131</td>
<td>Call for tender for jigs</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>132</td>
<td>Notification of the contract</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>133</td>
<td>Manufacturing of parts of the series incl. spacer part + P</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>134</td>
<td>PCB part cabling and tests control</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>135</td>
<td>Data of series delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>136</td>
<td>Data transfer to electronics assembly site</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>137</td>
<td>Assembly site readiness</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>138</td>
<td>Assembly site ready</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>139</td>
<td>Assembly of ladders on data</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>140</td>
<td>Visual inspections and test of ladders</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>141</td>
<td>Data of series delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>142</td>
<td>Target survey of all the series on data</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>143</td>
<td>shipment of equipment to electronics assembly site</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>144</td>
<td>Readout Electronics (from sensors to CBB)</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>145</td>
<td>Design studies incl. PCB</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>146</td>
<td>Compilation of studies with working solutions for MFT</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>147</td>
<td>Prototype realization (CRK)</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>148</td>
<td>Prototype tests in lab</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>149</td>
<td>Proof of principle validated w/ GET or other concentration</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>150</td>
<td>Design studies of final system</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>151</td>
<td>Components procurement for the series</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>152</td>
<td>Components delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>153</td>
<td>Shipment of components on PCBs to data assembly site</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>154</td>
<td>Design of other components for MFT commencing in series</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>155</td>
<td>Services</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>156</td>
<td>Cooling unit and piping design</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>157</td>
<td>Cooling unit and piping procurement</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>158</td>
<td>Cooling unit and piping delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>159</td>
<td>LV Power supplies studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>160</td>
<td>LV Power supplies choice</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>161</td>
<td>LV Power supplies procurement</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>162</td>
<td>LV Power supplies delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>163</td>
<td>LV Cabling and connectors studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>164</td>
<td>LV Cabling and connectors choice</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>165</td>
<td>LV Cabling and connectors procurement</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>166</td>
<td>LV Cabling delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>167</td>
<td>Optical fibers studies</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>168</td>
<td>Optical fibers choice</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>169</td>
<td>Optical fibers procurement</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>170</td>
<td>Optical fibers delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>171</td>
<td>DCS design</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>172</td>
<td>DCS components, cabling and connectors choices</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>173</td>
<td>DCS procurement</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>174</td>
<td>DCS delivery</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
<tr>
<td>175</td>
<td>All services ready to be installed in caverns</td>
<td>Mar 20/13</td>
<td>Mar 25/13</td>
</tr>
</tbody>
</table>
Figure 7.5: MFT Schedule - October 2014 version (part 4).
A  Air cooling studies

This appendix reports the full studies of the air cooling designed for the MFT. The section 4.4.2 contains a summary of it.

A.1 Model description

Preliminary calculations considering an air-cooling system have been performed for a global half-MFT model to evaluate the global dimensioning of air flow and to study the inlet/outlet design. The model includes the external cone, the PCBs, the sensor disks and the cooling system. Inlets are located at one side of the disks whereas outlets are located at the opposite side, as shown in Fig. A.1. Air inlet velocity and temperature are set to 10 m/s and 295 K respectively. The air outlet is simulated by a free pressure condition on a pipe along the face of the cone (no aspiration in that model). These studies indicate that an equilibrated flow along the sensors can be obtained by using thin air-inlets (2 mm) with a length corresponding to the disk radius. A 6 m/s average air velocity is obtained almost uniform along the sensors (Fig. A.1).

![Air velocity on half-MFT model. Inlets are located on the bottom part of the picture and outlets on the top part.](image)

A.2 Detailed partial thermo-fluid model

To improve the precision of the results, a more detailed model has been elaborated. It includes the first two Half-Disks (Half-Disk-01) and the first detection plane of Half-Disk-2. In addition to the air inlets on the external faces of sensors, internal cooling is included with air inlets inside
the 10 mm gap\textsuperscript{1} between two detection planes of a disk. The air inlet length is 35 mm. The 10 mm disk spacer has been designed with internal blades to divide and guide internal air flow on the whole sensor surface.

The on-sensor power dissipation is modelled by a power density uniform on the entire sensor surface (225 mW/sensor, 50 mW/cm\textsuperscript{2}). The power is equally distributed on each sensor side. Power dissipation surfaces are as first approximation modelled as constant walls (and not as layer of material), i.e. no inside conduction and dissipation.

In this simulation, a total power of 32 W (14 W for Half-Disk 0 and 1, and 4 W for Half-Disk 2) needs to be extracted. The total air flow is 0.0175 kg/s, i.e. 0.015 m\textsuperscript{3}/s. Figure A.2 shows the results of this simulation: temperature, heat transfer coefficient and velocity maps, streamlines diagram. Table A.1 gives the average and range of temperature and heat transfer coefficient on the sensors.

<table>
<thead>
<tr>
<th></th>
<th>(&lt;T&gt;) (K)</th>
<th>(T_{\text{min}}/T_{\text{max}})</th>
<th>(&lt;h&gt;) (W/m\textsuperscript{2}·K)</th>
<th>(h_{\text{min}}/h_{\text{max}}) (W/m\textsuperscript{2}·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External face</td>
<td>303.3</td>
<td>297/310</td>
<td>40.6</td>
<td>15/85</td>
</tr>
<tr>
<td>Internal face</td>
<td>304.0</td>
<td>298/310</td>
<td>33.1</td>
<td>15/65</td>
</tr>
</tbody>
</table>

Differences amounting to a few degrees K have been found by comparing models with and without internal blades inside the disk interspace. The maximum difference in sensor temperature over the disk reaches about 10 K. However, the temperature difference at the level of ladders and sensors does not exceed 6 K. The reason is that the heat transfer coefficient varies as expected from higher values near the inlets to lower values near the outlets. Acceptable air velocity uniformity has been obtained, with an average on-sensor velocity of about 6 m/s. The velocity is larger (about 10 m/s) close to the inlets and outlets. The inlet/outlet design (size and position) will be optimized to decrease the air velocity further.

A.2.1 Temperature uniformity optimization

The design was further optimized to improve the uniformity of the temperature, heat transfer coefficient and air velocity on the entire disk surfaces. A design using two air inlets was investigated. In that case, the inlets are located at each side of the half-disk and the outlet pipe in the center of the cone (orthogonally to the two inlet flows) as shown in Fig. A.3. To reduce the air velocity at the level of the sensors, the inlets have been moved away from the disks.

Figure A.3 and Tab. A.2 present the results of the calculation using this 2-inlets per disk design. The heat transfer coefficient is more uniform but on average lower than with the previous design. With the same average temperature as obtained with the previous model, the 2-inlets design gives a much better temperature gradient on the sensors (of the order of 5 K) which is the required value for the sensor operation. The air velocity is also reduced down to 3 m/s (and lower). As the total air flow is doubled, the design of an additional (and bigger) outlet pipe in the PCB area is required.

\textsuperscript{1}Initial value of the gap. The gap increase to 14 mm securing the disk support stiffness improves in fact the cooling performance.
Figure A.2: Temperature, heat transfer coefficient, velocity and flow streamlines.

Figure A.3: Heat transfer coefficient, velocity, and flow streamlines with the 2 inlets model.
Table A.2: Averages and ranges of the on-sensor temperature (T) and heat transfer coefficient (h) obtained with the 2-inlet per disk design.

<table>
<thead>
<tr>
<th></th>
<th>⟨T⟩ (K)</th>
<th>T_{min}/T_{max}</th>
<th>⟨h⟩ (W/m²·K)</th>
<th>h_{min}/h_{max} (W/m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External face</td>
<td>304.6</td>
<td>300/305</td>
<td>27.4</td>
<td>20/40</td>
</tr>
<tr>
<td>Internal face</td>
<td>305.6</td>
<td>300/307</td>
<td>25.2</td>
<td>20/30</td>
</tr>
</tbody>
</table>

A.3 Detailed ladder calculations

A detailed calculation has been performed at the level of the ladder using as input the heat transfer coefficient at the level of the disk obtained from the previous study. The 3-sensor ladder case has been examined as it is the most used type of ladder (see Tab. 1.2). For the thermal definition of the FPC, an equivalent conductivity coefficient (k_{eq} = 0.4 W/m.K) is assumed for the sake of simplicity.

Since sensors are soldered on the FPC, the contact between the FPC and the sensors is assumed to be a perfect thermal contact. The contact between the sensor and the stiffener is assumed to be a perfect thermal contact as well taking into account the glue thermal property used for this contact.

The power dissipation on the sensor is not uniform anymore and follows the volumetric dissipation of the CMOS sensor: 112.5 × 10^6 W/m³ on active part and 2.7 × 10^6 W/m³ on passive part of the sensor for a total power of 225 mW. Therefore in the ladder model, 75% of the power is deposited on 1 mm of the sensor height and 25% on the remaining 14 mm. The thermal conductivity of silicon has been taken into account. It has a small effect on the homogenisation of the temperature because the thickness of the sensor is small and the heat produced by the two parts have the same order of magnitude (168 mW for the active part and 57 mW for the passive part).

Table A.3 summarizes the main results of the detailed ladder calculation using the single and the double inlet design. A clear temperature gradient is now visible on the sensors (see Fig. A.4), due to the non-uniform power dissipation scheme. The low thermal conductivity of both the FPC and the stiffener prevents the achievement of a uniform temperature on the sensors, even with the higher heat transfer coefficients of the single inlet design.

Table A.3: Results of the detailed ladder calculation using a single or a double inlet design.

<table>
<thead>
<tr>
<th>Model</th>
<th>Double inlets</th>
<th>Single inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>h_{int} (W/m²·K)</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>h_{ext} (W/m²·K)</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>T_{max} (°C)</td>
<td>306.2</td>
<td>303.7</td>
</tr>
<tr>
<td>ΔT inner sensor (°C)</td>
<td>3.97</td>
<td>3.77</td>
</tr>
<tr>
<td>ΔT outer sensor (°C)</td>
<td>6.22</td>
<td>5.5</td>
</tr>
</tbody>
</table>
A.3 Detailed ladder calculations

A.3.1 Parametric studies

The study of the effect of several parameters that could improve the thermal behaviour of ladders has been carried out. Higher convection coefficients (obtained by optimizing air flow and blades) will mainly reduce the global maximum temperature of the ladder with smaller changes on the on-sensor $\Delta T$. Changes in the glue thickness as well as the thermal conductivity of glue and FPC material have been studied, but their thermal insulating properties remain dominant and only small changes are obtained on the sensor temperatures. A lower power dissipation assumption of 135 mW/sensor has been tested. It results in a reduction of the temperature gradient and of the maximum temperature by a factor 1.7 ($T_{\text{max}} < 29^\circ C$ and $\Delta T$ outer sensor $< 4^\circ C$).

Increasing the thermal conductivity of the carbon stiffener can be an interesting option. For example, using a bi-directional carbon fiber, instead of an unidirectional one (i.e. with transverse conductivity equal to the longitudinal at 35 W/m.K), allows the reduction of the on-sensor temperature gradient by 1.0 to 1.5 K. Moreover, with a carbon fiber having higher conductivity coefficient, an additional reduction of the on-sensor temperature gradient can be obtained (up to 2 K for about 150 W/m.K).

Simulations performed with 1-sensor and 5-sensor ladders show equivalent behaviour as the 3-sensor ladder (see Fig. A.5).
A.3.2 Summary of thermal studies

These calculations show that under conservative assumptions (air-cooling with moderate heat transfer coefficient, upper value of power dissipation and material thermal characteristics), thermal constraints imposed for the CMOS sensor operation have been mostly met:

- On-sensor temperature gradient $\Delta T \sim 6$ K. The goal is 5 K under conservative assumptions;
- On-sensor maximal temperature $T_{\text{max}} \sim 305$ K;
- On-sensor air velocity $< 5$ m/s.

Optimizations on stiffener material (for transverse conductivity coefficient) and guiding blades (for heat transfer coefficient) remain possible.
### B Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>A Large Ion Collider Experiment</td>
</tr>
<tr>
<td>ALPIDE</td>
<td>ALICE PIxel DEtector</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application Specific Integrated Circuit</td>
</tr>
<tr>
<td>ASTRAL</td>
<td>Arom Sensor for the inner TRacker of ALICE</td>
</tr>
<tr>
<td>BP</td>
<td>Beam Pipe</td>
</tr>
<tr>
<td>BRU</td>
<td>Backend Readout Unit</td>
</tr>
<tr>
<td>CA</td>
<td>Cellular Automaton</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Polymer</td>
</tr>
<tr>
<td>CIS</td>
<td>CMOS Imaging Sensor</td>
</tr>
<tr>
<td>CMM</td>
<td>Control Measuring Machine</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>CP</td>
<td>Cold Plate</td>
</tr>
<tr>
<td>CPS</td>
<td>CMOS monolithic Pixel Sensor</td>
</tr>
<tr>
<td>CPU</td>
<td>Central Processing Unit</td>
</tr>
<tr>
<td>CRU</td>
<td>Common Readout Unit</td>
</tr>
<tr>
<td>DCS</td>
<td>Detector Control System</td>
</tr>
<tr>
<td>DPL</td>
<td>Deputy Project Leader</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FIT</td>
<td>Fast Interaction Trigger</td>
</tr>
<tr>
<td>FPC</td>
<td>Flexible Printed Circuit</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>FS</td>
<td>Full Scale</td>
</tr>
<tr>
<td>FSBB</td>
<td>Full Scale Building Block</td>
</tr>
<tr>
<td>HIC</td>
<td>Hybrid Integrated Circuit</td>
</tr>
<tr>
<td>HM</td>
<td>High Modulus</td>
</tr>
<tr>
<td>HTC</td>
<td>High-Thermal Conductivity</td>
</tr>
<tr>
<td>IP</td>
<td>Interaction Point</td>
</tr>
<tr>
<td>ITS</td>
<td>Inner Tracking System</td>
</tr>
<tr>
<td>LET</td>
<td>Linear Energy Transfer</td>
</tr>
<tr>
<td>LTF</td>
<td>Linear Track Finder</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>LVDS</td>
<td>Low Voltage Differential Signaling</td>
</tr>
<tr>
<td>LS(1,2,3)</td>
<td>Long Shutdown</td>
</tr>
<tr>
<td>MB</td>
<td>Minimum Bias</td>
</tr>
<tr>
<td>MFT</td>
<td>Muon Forward Tracker</td>
</tr>
<tr>
<td>MISTRAL</td>
<td>MImosa Sensor for the inner TRacker of ALICE</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>NIEL</td>
<td>Non Ionizing Energy Loss</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PIXIAM</td>
<td>PIXel sensor for ALICE Muon spectrometer</td>
</tr>
<tr>
<td>PL</td>
<td>Project Leader</td>
</tr>
<tr>
<td>QCD</td>
<td>Quantum ChromoDynamics</td>
</tr>
<tr>
<td>QED</td>
<td>Quantum ElectroDynamics</td>
</tr>
<tr>
<td>QGP</td>
<td>Quark Gluon Plasma</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>RHIC</td>
<td>Relativistic Heavy Ion Collider</td>
</tr>
<tr>
<td>SEE</td>
<td>Single Event Effect</td>
</tr>
<tr>
<td>SEL</td>
<td>Single Event Latch-up</td>
</tr>
<tr>
<td>SEU</td>
<td>Single Event Upset</td>
</tr>
<tr>
<td>SMD</td>
<td>Surface Mounted Device</td>
</tr>
<tr>
<td>SRAM</td>
<td>Static Random Access Memory</td>
</tr>
<tr>
<td>TC</td>
<td>Technical Coordinator</td>
</tr>
<tr>
<td>TID</td>
<td>Total Ionizing Dose</td>
</tr>
<tr>
<td>TPC</td>
<td>Time Projection Chamber</td>
</tr>
<tr>
<td>VTTx</td>
<td>Versatile Twin Transmitter</td>
</tr>
<tr>
<td>WG</td>
<td>Working Group</td>
</tr>
</tbody>
</table>
C The ALICE Collaboration

Author List

M.B. Zimmermann\textsuperscript{33,36}, G. Zinovjev\textsuperscript{3}, M. Zyzak\textsuperscript{42}

**Affiliation notes**

\textsuperscript{1} Deceased

\textsuperscript{ii} Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

\textsuperscript{iii} Also at: University of Belgrade, Faculty of Physics and "Vinča" Institute of Nuclear Sciences, Belgrade, Serbia

\textsuperscript{iv} Permanent Address: Konkuk University, Seoul, Korea

\textsuperscript{v} Also at: Institute of Theoretical Physics, University of Wroclaw, Wroclaw, Poland

\textsuperscript{vi} Also at: University of Kansas, Lawrence, KS, United States

**Collaboration Institutes**

\textsuperscript{1} A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia

\textsuperscript{2} Benemérita Universidad Autónoma de Puebla, Puebla, Mexico

\textsuperscript{3} Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine

\textsuperscript{4} Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India

\textsuperscript{5} Budker Institute for Nuclear Physics, Novosibirsk, Russia

\textsuperscript{6} California Polytechnic State University, San Luis Obispo, CA, United States

\textsuperscript{7} Central China Normal University, Wuhan, China

\textsuperscript{8} Centre de Calcul de l’IN2P3, Villeurbanne, France

\textsuperscript{9} Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba

\textsuperscript{10} Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

\textsuperscript{11} Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico

\textsuperscript{12} Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Rome, Italy

\textsuperscript{13} Chicago State University, Chicago, USA

\textsuperscript{14} China Institute of Atomic Energy, Beijing, China

\textsuperscript{15} Commissariat à l’Energie Atomique, IRFU, Saclay, France

\textsuperscript{16} COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan

\textsuperscript{17} Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain

\textsuperscript{18} Department of Physics and Technology, University of Bergen, Bergen, Norway

\textsuperscript{19} Department of Physics, Aligarh Muslim University, Aligarh, India

\textsuperscript{20} Department of Physics, Ohio State University, Columbus, OH, United States

\textsuperscript{21} Department of Physics, Sejong University, Seoul, South Korea

\textsuperscript{22} Department of Physics, University of Oslo, Oslo, Norway

\textsuperscript{23} Dipartimento di Elettrotecnica ed Elettronica del Politecnico, Bari, Italy

\textsuperscript{24} Dipartimento di Fisica dell’Università ‘La Sapienza’ and Sezione INFN Rome, Italy

\textsuperscript{25} Dipartimento di Fisica dell’Università and Sezione INFN, Cagliari, Italy

\textsuperscript{26} Dipartimento di Fisica dell’Università and Sezione INFN, Trieste, Italy

\textsuperscript{27} Dipartimento di Fisica dell’Università and Sezione INFN, Turin, Italy

\textsuperscript{28} Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Bologna, Italy

\textsuperscript{29} Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Catania, Italy

\textsuperscript{30} Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Padova, Italy
Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università and Gruppo Collegato INFN, Salerno, Italy
Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
Eberhard Karls Universität Tübingen, Tübingen, Germany
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Faculty of Engineering, Bergen University College, Bergen, Norway
Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
Faculty of Science, P.J. Safářík University, Košice, Slovakia
Faculty of Technology, Buskerud and Vestfold University College, Vestfold, Norway
Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
Gangneung-Wonju National University, Gangneung, South Korea
Gauhati University, Department of Physics, Guwahati, India
Helsinki Institute of Physics (HIP), Helsinki, Finland
Hiroshima University, Hiroshima, Japan
Indian Institute of Technology Bombay (IIT), Mumbai, India
Indian Institute of Technology Indore, Indore (IITI), India
Inha University, Incheon, South Korea
Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
Institute for Theoretical and Experimental Physics, Moscow, Russia
Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
Institute of Physics, Bhubaneswar, India
Institute of Space Science (ISS), Bucharest, Romania
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
iThemba LABS, National Research Foundation, Somerset West, South Africa
Joint Institute for Nuclear Research (JINR), Dubna, Russia
Konguk University, Seoul, South Korea
Korea Institute of Science and Technology Information, Daejeon, South Korea
KTO Karatay University, Konya, Turkey
Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-
IN2P3, Grenoble, France
71 Laboratori Nazionali di Frascati, INFN, Frascati, Italy
72 Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
73 Lawrence Berkeley National Laboratory, Berkeley, CA, United States
74 Lawrence Livermore National Laboratory, Livermore, CA, United States
75 Moscow Engineering Physics Institute, Moscow, Russia
76 National Centre for Nuclear Studies, Warsaw, Poland
77 National Institute for Physics and Nuclear Engineering, Bucharest, Romania
78 National Institute of Science Education and Research, Bhubaneswar, India
79 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
80 Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
81 Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
82 Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
83 Oak Ridge National Laboratory, Oak Ridge, TN, United States
84 Petersburg Nuclear Physics Institute, Gatchina, Russia
85 Physics Department, Creighton University, Omaha, NE, United States
86 Physics Department, Panjab University, Chandigarh, India
87 Physics Department, University of Athens, Athens, Greece
88 Physics Department, University of Cape Town, Cape Town, South Africa
89 Physics Department, University of Jammu, Jammu, India
90 Physics Department, University of Rajasthan, Jaipur, India
91 Physik Department, Technische Universität München, Munich, Germany
92 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
93 Politecnico di Torino, Turin, Italy
94 Purdue University, West Lafayette, IN, United States
95 Pusan National University, Pusan, South Korea
96 Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
97 Rudjer Bošković Institute, Zagreb, Croatia
98 Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
99 Russian Research Centre Kurchatov Institute, Moscow, Russia
100 Saha Institute of Nuclear Physics, Kolkata, India
101 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
102 Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
103 Sezione INFN, Bari, Italy
104 Sezione INFN, Bologna, Italy
105 Sezione INFN, Cagliari, Italy
106 Sezione INFN, Catania, Italy
107 Sezione INFN, Padova, Italy
108 Sezione INFN, Rome, Italy
109 Sezione INFN, Trieste, Italy
110 Sezione INFN, Turin, Italy
111 SSC IHEP of NRC Kurchatov institute, Protvino, Russia
112 SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
113 Suranaree University of Technology, Nakhon Ratchasima, Thailand
114 Technical University of Split FESB, Split, Croatia
115 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences,
C The ALICE Collaboration

Cracow, Poland

The University of Texas at Austin, Physics Department, Austin, TX, USA

Universidad Autónoma de Sinaloa, Culiacán, Mexico

Universidade de São Paulo (USP), São Paulo, Brazil

Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil

University of Houston, Houston, TX, United States

University of Jyväskylä, Jyväskylä, Finland

University of Liverpool, Liverpool, United Kingdom

University of Tennessee, Knoxville, TN, United States

University of the Witwatersrand, Johannesburg, South Africa

University of Tokyo, Tokyo, Japan

University of Tsukuba, Tsukuba, Japan

University of Zagreb, Zagreb, Croatia

Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France

V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia

Variable Energy Cyclotron Centre, Kolkata, India

Warsaw University of Technology, Warsaw, Poland

Wayne State University, Detroit, MI, United States

Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary

Yale University, New Haven, CT, United States

Yonsei University, Seoul, South Korea

Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany

Thai Microelectronics Center, Chachoengsao, Thailand

Faculty of Electrical Engineering and Informatics, Technical University, Košice, Slovakia

Ukrainian Academy of Sciences (KIPT-KFTI), Kharkov, Ukraine

Rutherford Appleton Laboratory, Chilton, United Kingdom
Bibliography


[19] DCDC-team at CERN, FEASTMP datasheet - rev 1.0, DCDC team web page at CERN.


