

UNIVERSITY OF GENOVA

SCHOOL OF MATHEMATICAL, PHYSICAL AND NATURAL SCIENCE

PHYSICS DEPARTMENT



**Università
di Genova**

Ph.D. IN PHYSICS AND NANOSCIENCES - XXXV CICLO

**Towards the construction of a new tracker for the
ATLAS detector at the HL-LHC**

Candidate:
Leonardo Vannoli

Supervisors:
Dr. Claudia Gemme
Professor Riccardo Ferrando

Academic year 2019-2020

So then, we are not anarchists, because sciences tell us to be: we are, instead, anarchists because, among other reasons, we want everyone to be able to enjoy the advantages and the joys that science can procure for us.

— Errico Malatesta, *Science and Social Reform*

Contents

Introduction	1
1 The Large Hadron Collider	4
1.1 Magnets and Machine Layout	6
1.2 Injection Chain and Bunch Structure	8
1.3 Run-2 Machine Performances	10
1.4 The High Luminosity LHC Program	12
2 The ATLAS Experiment	14
2.1 The ATLAS Coordinate System	14
2.2 ATLAS Detector Configuration for Run 3	15
2.2.1 The Inner Detector	16
2.2.2 The Calorimeters	22
2.2.3 The Muon Spectrometer	23
2.2.4 The Magnets System	25
2.2.5 Trigger and Data Acquisition	27
2.3 Physics with the ATLAS Experiment	29
2.3.1 The Higgs physics	29
2.3.2 W and Z physics	31
2.3.3 Supersymmetry Searches in ATLAS	32
3 Silicon Detectors for High Energy Physics	35
3.1 Introduction	35
3.2 Particles Interaction with Matter	36
3.2.1 Charged Particles	36
3.2.2 Photons	38
3.3 pn-junction	39
3.4 Silicon Detectors	42
4 The ATLAS Inner Tracker for Phase II	46
4.1 ATLAS Phase II Upgrade	46
4.1.1 The Inner Tracker Upgrade	46

4.1.2	The Calorimeter Upgrade	47
4.1.3	The Muon Spectrometer Upgrade	48
4.1.4	The Trigger and Data Acquisition Upgrade	48
4.2	The ITk Layout	50
4.3	ITk Expected Performance	55
4.3.1	Material Budget	55
4.3.2	Efficiency and Number of Tracks with ITk	56
4.3.3	Track Parameter Resolution	59
4.3.4	Jet Flavour Tagging	61
4.4	ITk Pixel Modules	64
4.4.1	3D Sensors	64
4.4.2	The Modules R&D: the RD53A Project	66
4.4.3	From R&D to Pre-Production: ITkPixV1.1	67
5	The ITk 3D Modules Qualification	71
5.1	Introduction	71
5.2	Module Test Procedure	73
5.2.1	The Sensor IV Scan	73
5.2.2	The Module Configuration	73
5.2.3	The Chip Scans and Tuning	74
5.3	Module Testing at Genova Laboratories	76
5.3.1	Test Setup	76
5.3.2	RD53A Results	79
5.4	Beam Test at DESY and CERN Facilities	83
5.4.1	Test Setup	83
5.4.2	Modules Irradiation	87
5.4.3	RD53A Modules Tested at DESY	92
5.4.4	ITkPixV1.1 Modules Tested at CERN	99
5.4.4.1	Unirradiated Modules	99
5.4.4.2	Irradiated Modules	107
6	The ITk Outer Endcap Local Support	120
6.1	The Outer Endcap Overview	120
6.2	ITk Outer Endcap Local Support	124
6.2.1	Local Support Structures	124
6.2.2	Local Support Manufacturing and Assembly	125
6.3	Foam Density Studies	130
6.3.1	Carbon Foam Machining	131
6.3.2	Lockheed Martin Density Analysis	131
6.3.3	Entegris Density Analysis	141
6.4	Local Support Metrology and Thermal Properties	144
6.4.1	Thermal Expansion Metrology Measurements	144
6.4.2	Thermal Conductivity Measurements	152

6.5	ITk Production Database	160
6.5.1	Outer Endcap Local Support Structure	160
6.5.2	ITk Production Database Components	162
6.5.3	Stages and Test	165
6.5.4	Serial Number, Batch Number, and Properties	166
6.5.5	Bare HR Assembly inside Production Database	169
6.6	The Impact of Misalignment on Tracking Performances	173
6.6.1	Introduction	173
6.6.2	Alignment Procedure	173
6.6.3	Misalignment Studies with ITk Layout	176
Conclusions		185
Appendices		189
A Appendix		190
A.1	The Beam Test Setup at CERN	190
A.2	Modules IV Scans Pre-irradiation	192
A.3	Modules IV Scans Post-irradiation	194
A.4	SCCs threshold vs noise scatter plots	196
A.5	SCC3 and SCC5 threshold and noise distrubution of the enabled and disabled pixel	198
A.6	W30-D9.5 RD53A module ToT with unexpected behavior	202

Introduction

Particle tracking is one of the most fundamental aspects of high-energy physics research. By tracking the path of charged particles produced in high-energy collisions, physicists can study the properties of the particles and gain insight into the fundamental forces and interactions that govern the behavior of matter at the smallest scales.

One of the most essential components of particle tracking is the interaction of charged particles with matter. When a charged particle passes through matter, it ionizes the atoms and molecules in its path, producing a trail of electrons and ions that can be detected and analyzed. Especially when dealing with high particle rates, semiconductor detectors are commonly used to detect the passage of ionizing particles, generating electrical signals that can be localized with high precision. By analyzing these signals, physicists can reconstruct the path of the particle and determine its properties.

The need for high-precision tracking detectors arose in the 1970s with the development of the first colliders and the discovery of short-lived particles. These colliders produced particles with extremely high energies, making it difficult to detect them with traditional detectors. To detect these particles, compact detectors had to be developed and placed as close as possible to the point of interaction. These requirements led to the development of semiconductor detectors.

Among semiconductor detectors, silicon detectors have become the most widely used tracking system in high-energy physics experiments. Silicons are ideal for tracking thanks to their low material cost and increasing industrial development in this material processing making them an attractive option for large-scale experiments. In particular, modern techniques have allowed the fabrication of pixel detectors which allow 3D spatial resolutions of the order of 10 μm . For these reasons, silicon pixel detectors are a standard choice in tracking systems in high-energy physics experiments.

Pixel detectors have played a crucial role in the advancement of high-energy physics research, and the ATLAS and CMS experiments at the Large Hadron Collider (LHC) are excellent examples of this application. The LHC is the world's largest and most powerful particle accelerator. Located at the European Organization for Nuclear Research (CERN) in Switzerland, it is designed to accelerate protons and heavy ions to nearly the speed of light and collide them at four experiment sites. The LHC is the culmination of decades of research and development, and its construction and operation represent an enormous technological

and scientific achievement. The discovery of the Higgs boson in 2012, a missing piece in the Standard Model particle puzzle, was made possible also thanks to the high-precision tracking capabilities of pixel detectors. However, with an upgrade of the LHC planned, the High-Luminosity LHC, the ATLAS detector needs to be updated to cope with the increase in luminosity, improve the sensitivity of analyses already carried out, and widen the possibility of discoveries. As part of this upgrade, a new all-silicon detector, ITk, will replace the current ATLAS tracking system during the Long Shutdown 3 (2026-2028). The ITk detector will consist of a Pixel detector at a small radius and a large area Strip detector surrounding it. The main challenge facing the ITk detector will be the harder radiation environment, where both the level of radiation in the detector and the number of particles per square centimeter will increase by about a factor of seven.

To address the radiation constraints, innovative high radiation-hard 3D pixel detectors will be used for the innermost layer of the ITk Pixel detector. The 3D sensor technology was used for the first time in HEP detectors in 2014 for the upgrade of the current ATLAS Pixel detector: a single layer (IBL) was partially equipped with 3D sensors for a surface of just 375 cm^2 . However, this first application paved the way for using 3D technology in future LHC detector upgrades. After several years of R&D, in 2020 ATLAS decided to use the 3D technology as baseline for the innermost pixel layer, with a cell size of $25 \times 100 \text{ }\mu\text{m}^2$ in the barrel and $50 \times 50 \text{ }\mu\text{m}^2$ in the forward region.

Despite the decision to use 3D technology in the ITk detector based on first prototype samples, there was the recommendation to continue with more prototypes and in pre-production the validation of the radiation hardness up to the ultimate fluence of $2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and ionizing dose of 10 MGy.

This Ph.D. thesis has been developed primarily inside the ITk Pixel project, focusing on two main specific aspects: the full qualification to the ultimate fluence of the 3D devices and the qualification of the local supports for the detector forward region. More specifically: Chapter 1 provides an overview of the LHC accelerator, including the machine performance in Run-2. Additionally, this chapter discusses the High Luminosity LHC program, which aims to upgrade the LHC to increase by almost one order of magnitude its collision rate luminosity. The ATLAS experiment is described in detail in Chapter 2, including the detector configuration for Run-3, and the various subsystems that make up the detector. This chapter also discusses the physics goals of the ATLAS experiment, including the Higgs physics, W and Z physics, and SuperSymmetry searches. Chapter 3 provides an introduction to silicon detectors for high-energy physics, including a discussion of particles' interactions with matter and the pn-junction. This chapter also explores the use of silicon detectors in particle physics experiments. Chapter 4 focuses on the ATLAS Inner Tracker for Phase II, which is part of the ATLAS upgrade program. This chapter also provides an overview of the Calorimeter, Muon Spectrometer, and Trigger and Data Acquisition systems upgrades. Additionally, this chapter discusses the ITk layout and its expected tracking performance. Chapter 5 explores the ITk 3D module qualification, both in Genova Laboratories and during the beam test campaigns carried out at Deutsches Elektronen-Synchrotron (DESY) and CERN. In the Genova laboratory standard measurements such as sensor IV and electron-

ics tuning and characterization are performed, while the main results from the test beam campaigns are the detector efficiencies measurements.

In particular, prototype modules, so-called RD53A, were tested in 2020 with an electron beam at DESY, obtaining an efficiency higher than 97% with both unirradiated and irradiated modules. In 2022 pre-production ITk 3D modules were tested with a protons beam at Proton Synchrotron (PS) at CERN, and nearly 99% efficiency was achieved with unirradiated modules, while at Super Proton Synchrotron (SPS) always at CERN, after irradiation the pre-production modules had shown the efficiency of 98.5% (99.9%) with modules placed perpendicularly (titled of 15 degrees) with respect to the beam. Therefore it is shown how the sensors meet the ITk requirement to have a mean efficiency higher than 96% (97%) in the perpendicular (tilted) configuration after irradiation. Chapter 6 focuses on various aspects of the ITk Outer Endcap Local Support structures. The section includes an overview of the Outer Endcap, details on the local support structures, and their manufacturing and assembly process. It also covers studies on foam density, metrology, and thermal properties, as well as information on the ITk Production Database, used to store all the results of the test done during the ITk detector construction. Finally, this section discusses the impact of detector active components misalignment on tracking performances, including the alignment procedure and misalignment studies with the ITk layout.

Chapter 1

The Large Hadron Collider

The Large Hadron Collider (LHC) [1], located at the European Organization for Nuclear Research (CERN) on the border between Switzerland and France, is a two-ring-superconducting-hadron accelerator and collider. With its 26.7 km circumference, the LHC is the largest particles accelerator currently operating. It is built into the same tunnel that was constructed between 1984 and 1989 for Large Electron-Positron Collider (LEP) machine [2], 100 m below ground.

Normally used to collide proton with proton (pp), LHC can also be run in heavy-ion configurations wherein proton-lead and also lead-lead collisions take place.

Protons accelerated in the LHC are nuclei of hydrogen atoms, taken from a bottle of hydrogen gas. Electrons are stripped off the atoms, leaving only protons. They are then injected in LINAC4 and subsequently passed into the Booster, the Proton Synchrotron (PS), and then the Super Proton Synchrotron (SPS). Finally, they enter the LHC where the adjacent oppositely moving beams of protons are each accelerated to the maximum energy, so far 6.8 TeV. Superconducting magnets and a series of resonant frequency cavities are used to guide the two hadrons beams along the circular path into separated pipes and accelerate them to very high energies. The parallel beams meet at four crossing points along the LHC where detectors are located. The protons collide at these interaction points with a center-of-mass energy that increased from 7 TeV (2010-2011) and 8 TeV (2012) during Run-1, to 13 TeV during Run-2 and 13.6 TeV during Run-3, started on 5th of July 2022. The four independent physics experiments, A Large Ion Collider Experiment (ALICE) [3], A Toroidal LHC ApparatuS (ATLAS) [4], the Compact Muon Solenoid (CMS) [5], and the Large Hadron Collider beauty (LHCb) [6] are positioned in the collision points as seen in Fig. 1.1.

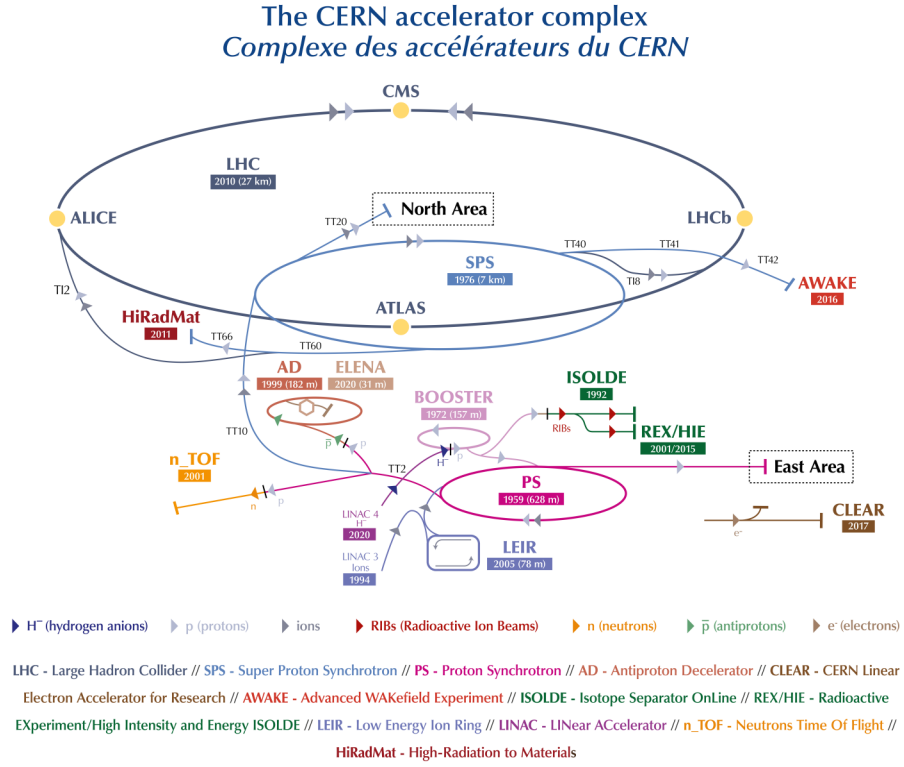


Figure 1.1: Diagram of the CERN accelerator complex, showing the flow of protons from LINAC4 through the PS and SPS into the Large Hadron Collider [7]. The main four experiments and facilities are also labeled.

1.1 Magnets and Machine Layout

In LHC there are two primary types of superconducting magnets: the dipoles (bending magnets) and the quadrupoles (focusing magnets). The whole LHC ring is filled by 1232 dipoles each 15 m long and 392 superconducting quadrupole magnets which bend and focus the beam around the collider. Furthermore, the proton beams are guided in a stable circular trajectory by 6,000 additional correcting magnets. Using copper-stabilized NbTi Rutherford cables or single strands, these superconducting magnets operate in superfluid helium at 1.9 K.

The superconducting dipoles are designed for a nominal operation current of about 11600 A for a central field of 8.3 T. The coils are of the twin type, as shown in Fig. 1.2, i.e. a unique collar for the two apertures and they are composed of poles of two layers each. Moreover, the magnets must be curved, with a sagitta of about 9 mm, corresponding to a radius of curvature of 2812.36 m. This curvature has a tolerance of ± 1 mm, with the exception of the extremities of the magnets where the tolerance is tighter, ± 0.3 mm (systematic), in order to keep 0.5 mm r.m.s. in the corrector magnets centered with respect to the beam tube, to avoid harmonic feed down [8].

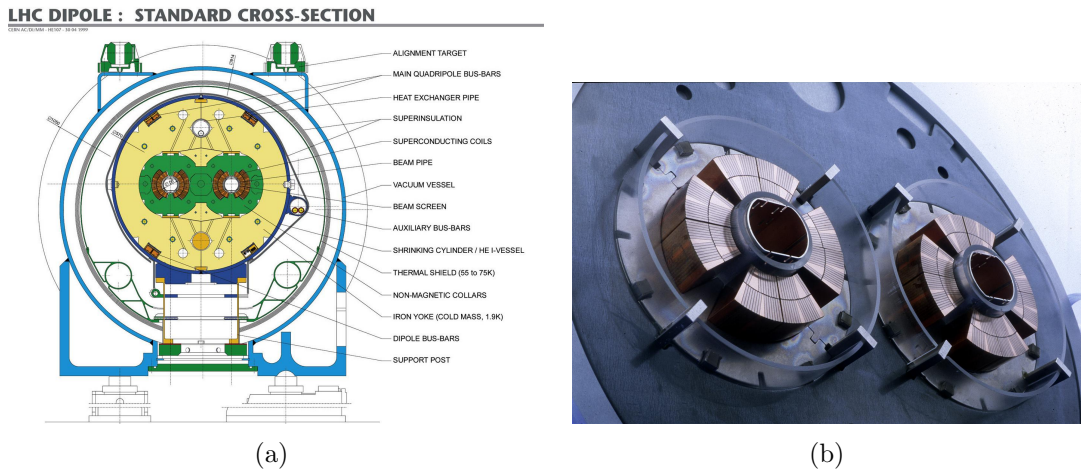


Figure 1.2: (a) Diagram showing the cross-section of an LHC dipole magnet with cold mass and vacuum chamber [9]. (b) Cross-section of a model of the superconducting quadrupole magnet [10].

A chain of LHC magnets is shown in Fig. 1.3 as it would be visible by visiting the tunnel that houses the accelerator at CERN. The characteristic blue color is mainly due to certain unwritten rules, such as the choice of bright colors that are clearly visible in a poorly lit environment such as that of the LHC tunnels. In fact, the familiar blue alternates with a gleaming white used for the vacuum vessels containing the LHC's quadrupole magnets and the deep red of the triplet quadrupole magnets.

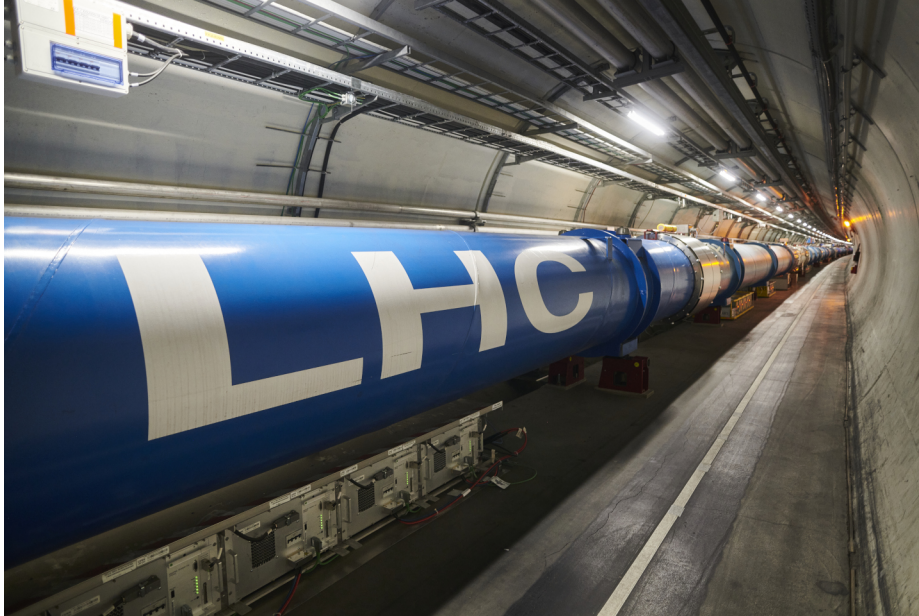


Figure 1.3: A chain of LHC dipole magnets inside the LHC tunnel, with its characteristic blue color [11].

These colors will be joined in a few years' time by the dark blue of the future High-Luminosity LHC's 11 Tesla magnets, which are currently undergoing tests. The darker shade is intended to reflect the magnet's stronger magnetic field than that of the regular LHC dipoles, which are lighter in color [12].

1.2 Injection Chain and Bunch Structure

The LHC relies on a series of pre-acceleration steps that bring initial low-energy protons to an energy of 450 GeV before they are injected into the LHC. These steps are referred to as the LHC injector chain and form the heart of the CERN accelerator complex illustrated in Fig. 1.1.

As already exposed in Sec. 1, the protons are initially sourced from hydrogen atoms which are released at the start of the linear accelerator LINAC where the protons are brought up to an energy of 50 MeV. This is followed by three circular accelerators of increasing radius, the PSB, the PS and the SPS, where the energy is brought to 1.4 GeV, 25 GeV and 450 GeV, respectively. The beams are then injected into the LHC at two points, one for the counter-clockwise beam, and one for the clockwise beam. A standard LHC fill takes about 31 minutes per ring (from SPS), and waits up to 20 minutes on the LHC 450 GeV injection plateau before the 21 minutes ramp to high energy and 10 minutes to squeeze [13].

The protons arrive at the LHC in bunches which are initially prepared in the injection chain and are then kept in their final bunch structure by the oscillations of the RF cavities. When the beam has reached the required energy, an ideally timed proton with exactly the right energy will not be further accelerated. By contrast, protons with slightly different energies arriving to the cavities earlier or later will be accelerated or decelerated so that they stay close to the desired energy.

The oscillation frequency of the RF cavities defines the boundaries in which proton bunches can lie. These boundaries are called RF buckets and, along with the circumference of the LHC, dictate the number of proton bunches that can potentially fit in the LHC. In principle, the 400 MHz Radio-Frequency (RF) allows for 35640 RF buckets along the LHC 26.7 km circumference, but in practice only a tenth of them are used. This is because the experiments are designed for a maximum bunch-crossing rate of 40 MHz and higher frequencies might result in too high radiation levels and difficulties in separating the data between the bunch crossings. Typically, the proton bunches are therefore filled with a spacing in time of 25 ns in the LHC. The position of a proton bunch along the ring with a 25 ns spacing is called the bunch-crossing identifier (BCID) and runs from 0 to 3563.

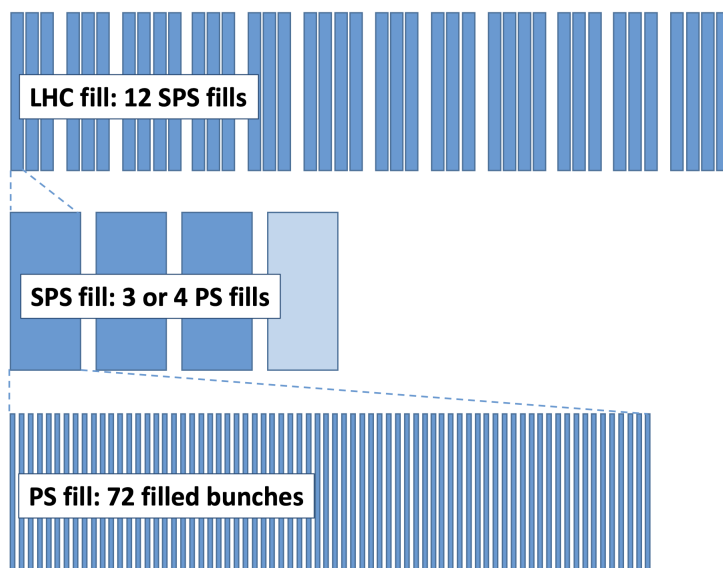


Figure 1.4: A schematic view of the 25 ns filling scheme of the LHC.

Proton bunches are filled in two main patterns into the LHC. The main pattern consists in bunch trains consisting of patterns of several bunches in consecutive 25 ns slots with longer gaps between these patterns. To fill an accelerator with proton bunches, several fills of the preceding accelerator in the injection chain are needed. The exact scheme in which the different accelerators are sequentially filled with proton bunches effectively determines the final bunch pattern in the LHC. When the PS is filled it holds 72 proton bunches and 12 empty bunches with a 25 ns spacing. An SPS fill then consists of three or four PS fills and the LHC typically consists of 12 of these variable-length SPS fills. This is illustrated in Fig. 1.4. The total number of bunches is always lower than the 3564 BCIDs potentially allow for. This is in part due to the non-trivial bunch-filling schemes used, but also because there must be a $3 \mu\text{s}$ abort gap without any filled BCIDs to allow the kicker magnets to ramp up when aborting the beam. There are also individual bunches where there are empty BCIDs before and after the filled bunch used for specific trigger or physics studies.

1.3 Run-2 Machine Performances

The number of pp collisions per second at the LHC is given by

$$\frac{dN}{dt} = \mathcal{L} \sigma_{pp}^{tot} \quad (1.1)$$

where σ_{pp}^{tot} is the total interaction cross-section. This quantity is measured in barn ($1 \text{ b} = 10^{-24} \text{ cm}^2$). The instantaneous luminosity $\mathcal{L}$ depends on the beam characteristics and can be expressed as

$$\mathcal{L} = f_{rev} n_b \frac{n_1 n_2}{4\pi \sigma_x \sigma_y} F \quad (1.2)$$

In the Eq. 1.2, n_1 and n_2 quantify the number of protons per bunch. The revolution frequency of the bunches is denoted as f_{rev} and the total number of bunches is referred to as n_b . Assuming as z the direction in which the beams travel, the beam size is assumed to be Gaussian in the transverse plane with widths $\sigma_{x/y}$. The factor F (that has a value < 1) quantifies the luminosity reduction due to a finite crossing angle of the bunches and their transverse displacement.

When the beam is accelerated, particles are confined by the magnetic field and tend to oscillate around the nominal propagation direction. The equation of motion in the transverse plane is given by a harmonic oscillator, whose amplitude is given by a parameter $\beta_{x(y)}$. These oscillations are reduced via triplet magnets, which are located near the interaction points, such that a higher luminosity is achieved where the collisions take place. In the interaction point, this parameter takes the name of β^* , and it has units of length. It is often more useful to consider the normalized emittance, η^* , which expresses the cross-sectional speeds in terms of a small angle regarding the direction of the beam and is proportional to the squared root of the energy (so the physical size of the beam will vary inversely to the square root of the energy). The relation between β^* and η^* is reported in Eq. 1.3:

$$\beta^* = \pi \sigma_x \sigma_y \epsilon^* \quad (1.3)$$

The amount of data collected, the integrated luminosity (Eq. 1.1) over a time period, is instead expressed in terms of the inverse of a cross-section, in barns. An overview of the performance of the LHC during Run-2, in terms of the quantities, introduced previously, is reported in Fig. 1.5. Further details are reported in [14].

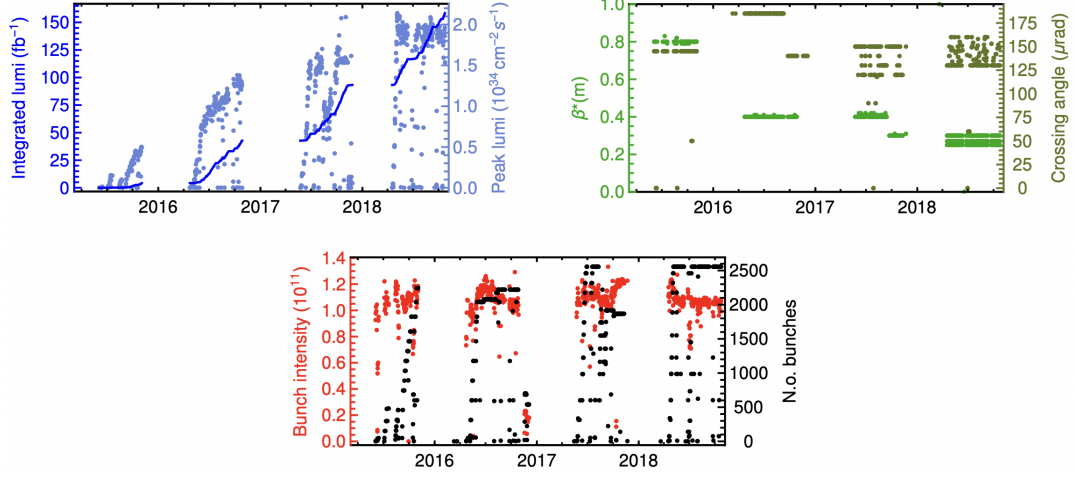


Figure 1.5: Run-2 LHC performances summary measured in IP1 and IP5. Top left: In this pad are reported the integrated and the instantaneous luminosity measured for each LHC fill. Top right: In this pad are reported the β^* and the crossing angle. Lower: In this pad are reported the parameters related to the proton bunches characteristics [14].

In each collision between the bunches, multiple pp interactions take place. From the Eq. 1.1 and 1.2 it can be derived the average collision number in each bunch crossing $\mu = dN/dt \times 25 \text{ ns}$ and how it depends on the instantaneous luminosity. For example, given the total pp inelastic cross-section at $\sqrt{s} = 13 \text{ TeV}$ which was measured to be $78.1 \pm 2.9 \text{ mb}$ by the ATLAS collaboration [15] in Run 2, μ was around 40, with long tails up to 60 interactions per crossing. The additional collisions cause pile-up to the hard scattering interactions and can be a limiting factor for precision measurements. There are two different types of pile-up: the in-time pileup, that is the one due to multiple collisions happening in the same bunch crossing, and the out-of-time pile-up, due to interactions in the previous crossings. The impact of the out-of-time pile-up is due to the fact that in particular detectors' electrical signals may last more than the time that separates two bunch crossings.

total length of more than 1.2 km of the modified machine and 1 km of additional technical services and equipment required by the new components [17].

A comparison between HL-LHC and LHC key parameters, bringing to the much higher luminosity, is presented in Tab. 1.1.

Parameter	Nominal LHC	High-Lumi LHC
Number of bunches	2400	2800
Beam Energy [TeV]	6.8	7
Average p-p collision ($\sim$)	30	200
Luminosity [$10^{34}cm^{-2}s^{-1}$]	2	5-7.5
Integrate Luminosity after 10 year [fb^{-1}]	450	4000
Particles per bunch [10^{11}]	1.2-1.8	2.2

Table 1.1: High Luminosity LHC performance comparison with LHC Run 3 [17].

Chapter 2

The ATLAS Experiment

ATLAS is one of the two general-purpose experiments operating at LHC. One of the largest scientific collaborations ever attempted, the ATLAS collaboration consists of about 6000 physicists, engineers, technicians, and students from about 180 institutions in 42 countries.

2.1 The ATLAS Coordinate System

The coordinate system and nomenclature used to describe the ATLAS detector and the particles emerging from the $p - p$ collisions are briefly summarised here since they are used repeatedly throughout this thesis. The nominal interaction point is defined as the origin of the coordinate system, while the beam direction defines the z -axis and the $x - y$ plane is transverse to the beam direction. The positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive y -axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z and side-C is that with negative z . The azimuthal angle ϕ is measured as usual around the beam axis, and the polar angle θ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln [\tan (\theta/2)]$. The transverse momentum p_T , the transverse energy E_T , and the missing transverse energy E_{miss} are defined in the $x - y$ plane unless stated otherwise. The transverse distance ΔR in the pseudorapidity-azimuthal angle space is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ [4].

2.2 ATLAS Detector Configuration for Run 3

The interaction point is forward-backward symmetric to the ATLAS detector. The detector measures 25 meters in height and 44 meters in length. Approximately 7000 tonnes are the detector's total weight. The magnet configuration consists of an inner-detector cavity-enclosing thin superconducting solenoid and three sizable superconducting toroids—one barrel and two end caps—arranged around the calorimeters in an eight-fold azimuthal symmetry [4]. The Inner Detector (ID), the Electromagnetic Calorimeter, the Hadronic Calorimeter, and the Muon Spectrometer (MS) are the sub-detectors that compose the ATLAS detector. Additionally, the Trigger and Data Acquisition System (TDAQ) and the Detector Control System support all of these sub-detectors (DCS).

The initial ATLAS detector is described in [4]. But, the ATLAS detector is subject to upgrades, implemented during the year-end technical stop (YETS) or during the Long-shutdown (LS). The following paragraphs will provide an overview of the individual sub-detectors of ATLAS updated for Run 3.

The Fig. 2.1 illustrates the Run 3 (July 2022) configuration of the ATLAS detector.

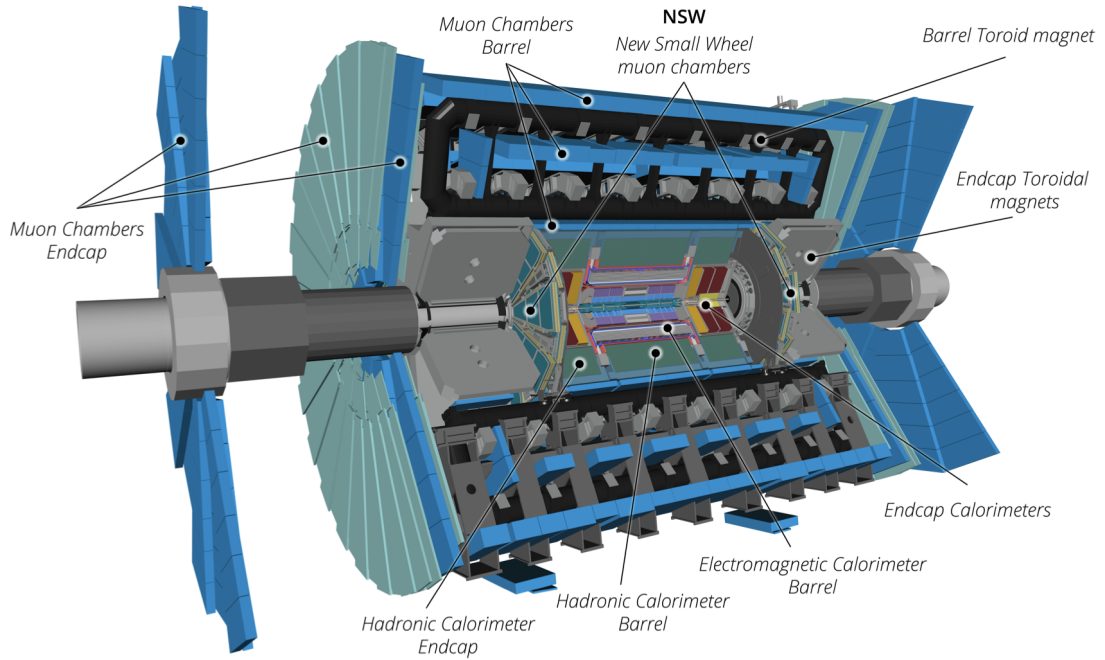


Figure 2.1: Cut-away view of the Run 3 configuration of the ATLAS detector. In figure the detector sub-systems are indicated.

2.2.1 The Inner Detector

The ATLAS Inner Detector (ID), sketched in Fig. 2.2 has been designed to provide hermetic and robust pattern recognition, excellent momentum resolution, and both primary and secondary vertex measurements for charged tracks within the pseudorapidity range $|\eta| < 2.5$. It is contained in a cylindrical envelope 2×3512 mm long and 1150 mm in radius, immersed in the 2 T field of a solenoidal magnet.

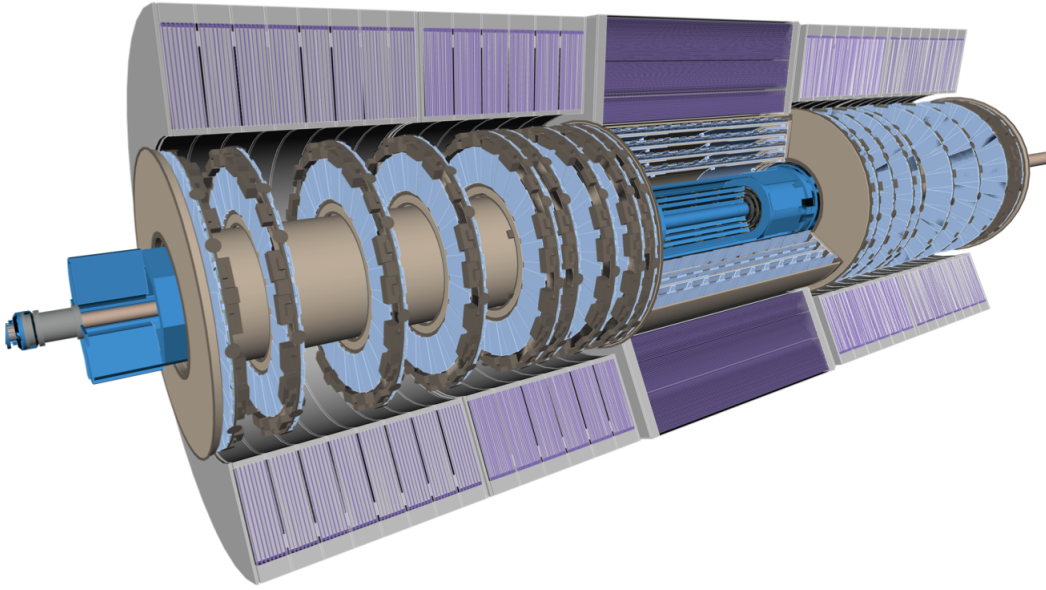


Figure 2.2: Cut-away view of the ATLAS Inner Detector, which is designed to provide a high-precision reconstruction of charged-particle trajectories. The ID covers the pseudorapidity range $|\eta| < 2.5$ and has full coverage in ϕ . It consists of a silicon Pixel detector at the innermost radii surrounded by a silicon microstrip detector the SCT, and a straw-tube detector, the TRT, that combines continuous tracking capabilities with particle identification based on transition radiation.

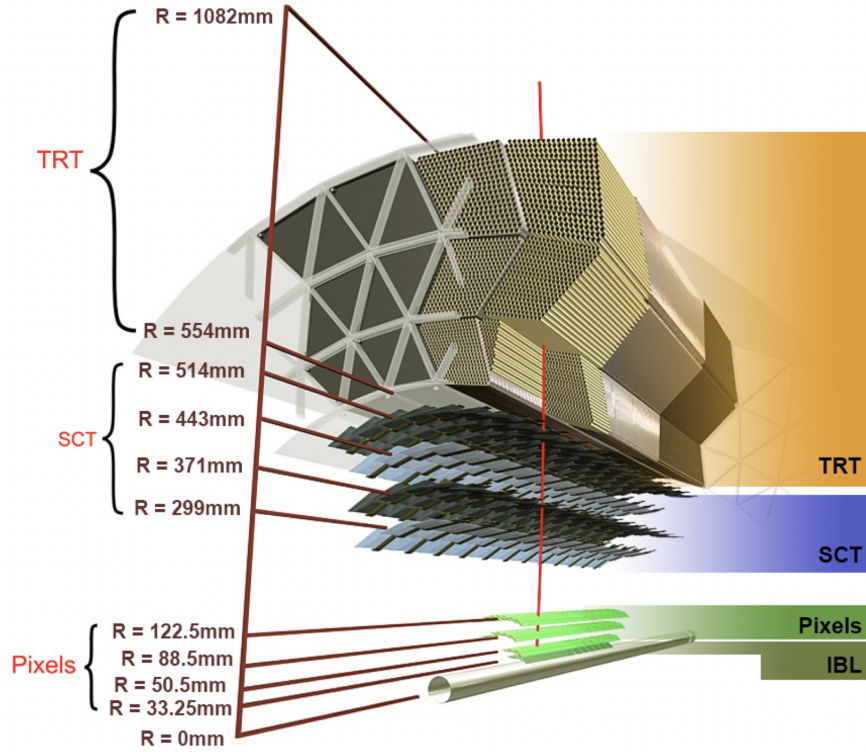


Figure 2.3: The ATLAS Inner Detector transversal layout with IBL, Pixel, SCT, and TRT subdetectors.

The ID consists of three sub-detectors, arranged in a barrel, coaxial to the beam line, and endcap parts, perpendicular to the beam axes. From inside out the detectors are: a high-resolution silicon Pixel detector [18], the Semi-Conductor Tracker (SCT) [19] relying on stereo micro-strips, the Transition Radiation Tracker ID end-plate (TRT) [20] comprising several layers of gaseous straw tubes interleaved with transition radiation material.

Fig. 2.3 shows the transversal layout of the upgraded ATLAS ID during Run 2 and Run 3. In Tab. 2.1 the main dimensions of the Inner Detector system are presented.

The tracking performance of the ATLAS experiment depends critically on the innermost layer of the Pixel detector. For this reason, at the beginning of 2013, during LS1, the detector underwent a major upgrade. During this period a fourth pixel layer partially based on a new technology, the Insertable B-Layer (IBL) [21,22], was added to the Pixel detector between a new, narrower beryllium beam-pipe and the previously existing innermost pixel layer (Pixel B-Layer). Fig. 2.3 shows the transversal layout of the upgraded ATLAS ID during Run 2 and Run 3. In Tab. 2.1 the dimensions of the Inner Detector system are presented.

Sub-System	Radial Extension (mm)	Length (mm)
Overall ID envelope	$0 < r < 1150$	$0 < z < 3512$
Beam-pipe	$23.5 < r < 30$	
Pixel (IBL included) - Barrel	$31 < r < 242$	$0 < z < 400.5$
Pixel (IBL included) - Endcap	$88.8 < r < 149.6$	$495 < z < 650$
SCT - Barrel	$255 < r < 549$	$0 < z < 805$
SCT - Endcap	$251 < r < 610$	$810 < z < 2797$
TRT	$554 < r < 1082$	$0 < z < 780$
TRT	$617 < r < 1106$	$0 < z < 2744$

Table 2.1: The ATLAS Inner Detector system dimensions. The z direction is along the beam axis. The radial distance from the beam axis is indicated as " r ".

The Insertable B-Layer (IBL)

The driving motivation for the IBL detector was the consolidation and enhancement of the ID tracking performance in high luminosity scenarios. IBL provides an additional hit closer to the primary interaction, at 3.3 cm, and its pixel longitudinal pitch is smaller ($400\ \mu\text{m}$ for the Pixel Detector vs $250\ \mu\text{m}$ for the IBL): it thus enhances the vertex reconstruction and b-tagging performance of the tracking system. Moreover, the additional layer of highly segmented pixel sensors helps to compensate for inefficiencies of the Pixel detector caused by irreparable module failures or by overall radiation damage, in particular in the B-Layer (the B-Layer was intended to be replaced) and reduces the occurrence of ghost tracks induced by high pile-up backgrounds.

IBL Layout The IBL layout consists of a single layer of pixel sensors pre-assembled to their readout chips (modules) and arranged on 14 longitudinal supports (staves) directly fastened onto a high precision carbon fiber tubular structure, the Inner Positioning Tube (IPT), via the stave support ring. The detector surrounds a 23.5 mm-radius beryllium beam pipe. The outer envelope is defined by a second carbon fiber cylinder, the Inner Support Tube (IST), fastened to the Pixel detector support structure. The staves are tilted by 14° in a classic turbine design in order to ensure complete azimuthal coverage for high p_T tracks and compensate for the Lorentz angle shift affecting the charges drifting in the sensors. Each stave hosts 20 active modules aligned along the beam axis (z -direction): 12 two-chip modules covering the central part and eight single-chip modules, extending the coverage up to $|\eta| = 2.58$. The main layout parameters of the IBL are presented in Tab. 2.2.

Item	Value
Number of staves	14
Number of physical modules per stave	20 (12 planar, 8 3D)
Number of front-end chips per stave	32
Coverage in $ \eta $ - no vertex spread	$ \eta < 3.0$
Coverage in $ \eta $ - 2σ (122 mm) vertex spread	$ \eta < 2.58$
Active z stave length	330.15 mm
Stave tilt in ϕ	14°
Overlap in ϕ	1.82°
Center of the sensor radius	33.5 mm

Table 2.2: Main layout parameters of the IBL. The nominal η coverage of the detector (assuming no spread on the longitudinal position of the interaction point) is $|\eta| < 3.0$ but a spread of the vertex position on the z -coordinate reduces the detector coverage down to $|\eta| < 2.58$.

Cooling is achieved by means of a CO₂ two-phase system where the coolant is circulated within titanium pipes embedded in the stave structure, in order to optimize the thermal contact between the active components and the pipes. This cooling system, together with other optimizations, has allowed to minimize the thickness of the IBL layer equivalent to 1.88 % of a radiation length, thus improving performance for reconstructing low momentum tracks.

Sensors Two sensor technologies are used in the IBL: an improved version of the ATLAS Run 1 Pixel planar sensors, able to cope with unprecedented operational conditions and reduced inactive edges, and an innovative design of 3D devices [23] a first-ever application in high energy physics. The two sensor implementations share a common footprint in order to be interfaced to the same readout chip, called FEI4 [24], with two-chip planar sensor tiles having an equal longitudinal dimension of two single-chip 3D sensors in order to fit a common mechanical layout. Both technologies are characterized by the same granularity, with $250\ \mu\text{m} \times 50\ \mu\text{m}$ pixels organized in 80×336 arrays (to be compared with the 18×160 matrix configuration of $400\ \mu\text{m} \times 50\ \mu\text{m}$ pixels of the three outermost Pixel layers).

The Pixel Detector

Thanks to the Pixel Detector's three layers, the system offers three measurements over the entire tracker acceptance. The central portion of the Pixel Detector is comprised of three barrel layers with radii of approximately 5 cm, 9 cm, and 12 cm. On either side are three

disks with radii between 9 and 15 cm. Tab. 2.1 provides a summary of the overall design, while in Tab. 2.3 a summary of the principal technical characteristics of the Pixel Detector are shown and compared to the newest IBL detector. The entire detector is made up of 1744 hybrid modules (22.4 mm wide and 62.4 mm long), for a total of 80 million readout channels and an active area of 1.7 m².

Technical characteristics		Pixel	IBL
Active surface	(m ²)	1.73	0.15
Number of channels	(x 10 ⁶)	80.36	12.04
Pixel size	(μm ²)	50 x 400	50×250
Active surface fraction	(%)	74	89
Sensor type		planar	planar / 3D
Sensor thickness	(μm)	250	200 / 230
Layer thickness	(%X ₀)	2.8	1.88

Table 2.3: Main features of the Pixel Detector, compared to the IBL layer.

A layer of the pixel detector's thickness is equivalent to 2.8% of a radiation length. Space point resolutions of $\sigma_{R-\phi} = 12 \mu\text{m}$ and $\sigma_z = 66 \mu\text{m}$ in the barrel region and $\sigma_z = 77 \mu\text{m}$ in the disks are provided by individual silicon modules. The size of a sensor pixel cell is 50 by 400 μm², with some exceptions to improve the acceptance in the area between the readout chips. Fig. 2.4 shows the whole inner detector.

The Semiconductur Tracker (SCT)

In the intermediate range of the Inner Detector, the Semi-Conductor Tracker (SCT) [19] is designed to provide four accurate measurements per track. the SCT is made by silicon microstrip. To achieve the coverage to $|\eta| < 2.5$, it consists of four barrel layers with radii of 300, 373, 447, and 520 mm and nine wheels on each side with a slightly different radius. Two strip detectors, one for each side, make up each module. A heat transfer plate separates the two devices, which are glued back-to-back at a 40 mrad angle to improve the spatial resolution, with the electronics mounted on a hybrid above the detectors. The detector has 6.2 million readout channels.

The spatial resolution along z , σ_z , and along the transverse plane, $\sigma_{R-\phi}$, are 580 μm 16 μm respectively. Fig. 2.4 illustrates a section of the SCT.

The Transition Radiation Tracker (TRT)

The TRT [20] is the outermost of the three tracking subsystems of the ID, and comprises several layers of gaseous straw tubes interleaved with transition radiation material. The

300000 thin-walled proportional-mode drift tubes provide on average 30 two-dimensional space points with $130\ \mu\text{m}$ resolution for charged particle tracks with $|\eta| < 2$ and $p_T > 0.5\ \text{GeV}$, contributing to the combined tracking system p_T resolution.

The TRT detector contains in the barrel 52544 straws and covers a radial range from 56 to 107 cm in the Barrel, while the end-caps consist of several wheels on each side for a total of 320 thousand straws. Along with continuous tracking, the TRT provides electron identification capability through the detection of transition radiation X-ray photons.

A section of the Inner Detector with the TRT endcap is shown in Fig. 2.4.

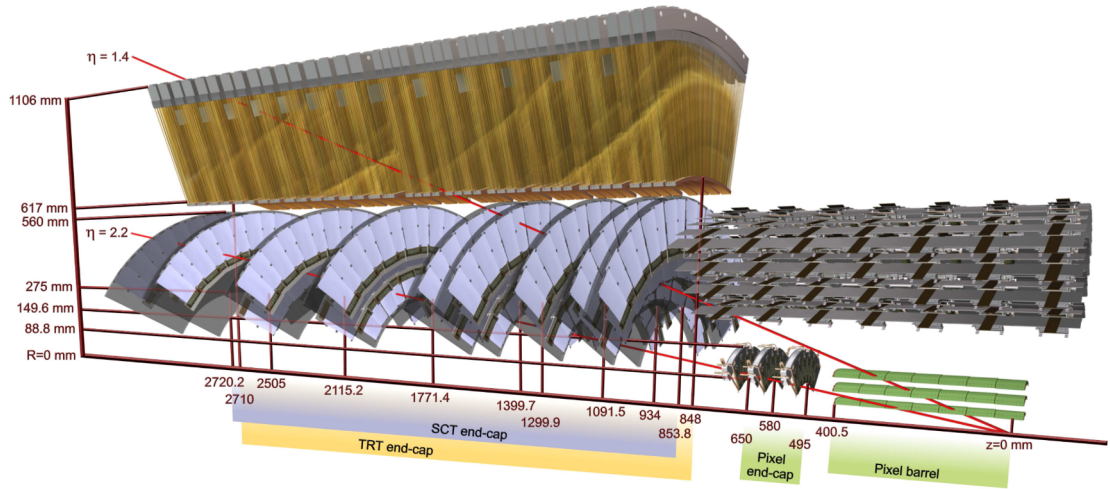


Figure 2.4: Layout of Pixel, SCT, and TRT endcap detectors.

2.2.2 The Calorimeters

In the ATLAS Experiment, the calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/Liquid Argon (LAr) calorimeters [25], with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadron calorimetry is provided by the steel/scintillator-tile calorimeter [26], segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadron endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic energy measurements respectively.

In Fig. 2.5 a sketch of the ATLAS Calorimeter system is shown.

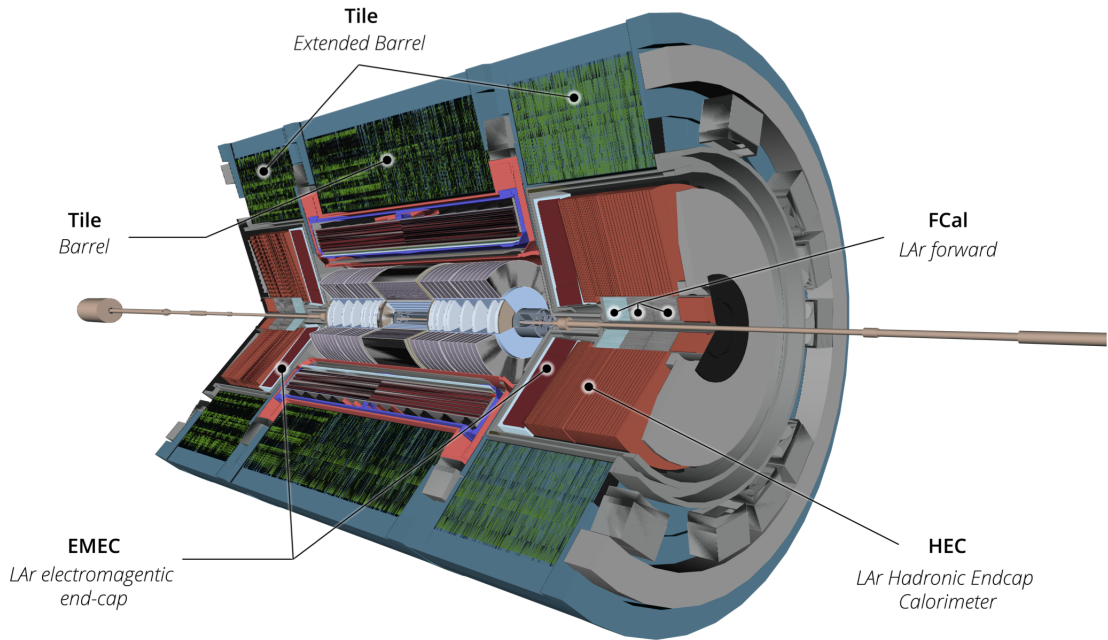


Figure 2.5: Cut-away view of the ATLAS calorimeter system that measures the energies and positions of charged and neutral particles through interleaved absorber and active layers out to $|\eta| < 4.9$. LAr is used as the active medium for the electromagnetic calorimeters and all of the endcap and forward calorimeters; scintillating Tiles are used for hadron calorimetry in the central region.

In Tab. 2.4 the energy resolution and the η coverage of the ATLAS calorimeter system are reported.

	Energy Resolution	$ \eta $ coverage
Electromagnetic calorimeter	$\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$	$\eta < 3.2$
Hadronic calorimeter		
Barrel/Endcap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$\eta < 3.2$
Forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$

Table 2.4: Energy resolution and η coverage of the ATLAS calorimeter system.

2.2.3 The Muon Spectrometer

The Muon Spectrometer (MS) is made by two different detector types: trigger detector and high-precision tracking chambers. The muons tracking is done by measuring the deflection of the particles in a magnetic field generated by the superconducting air-core toroidal magnets. The magnet field of the toroids is between 2.0 and 6.0 Tm across most of the muon detector.

The MS comprises a barrel, consisting of three concentric, roughly cylindrical, stations, and two endcaps, each consisting of three discs in planes perpendicular to the beam axis, referred to as inner, middle, and outer “wheels”. The anticipated high level of particle flux has had a major impact on the choice and design of the spectrometer instrumentation and its upgrade, affecting performance parameters such as rate capability, granularity, ageing properties, and radiation hardness.

The MS, shown in Fig. 2.6, can be schematized as follows: three stations of precision chambers, each consisting of layers of Monitored Drift Tubes (MDTs), cover the region $|\eta| < 2.7$, except in the innermost station of the endcaps, in the range $|\eta| < 1.3$, where the detectors used in Runs 1 and 2 have been replaced by the NSWs, described below. The muon trigger system covers the range $|\eta| < 2.4$ with Resistive Plate Chambers (RPCs) in the barrel, and Thin Gap Chambers (TGCs) in the endcap regions [4].

The majority of the barrel detectors are unchanged from the original Run 1 configuration described in [27]. In the barrel, the inner wheels (often nicknamed “small wheels”) have been the main focus of the Phase-I upgrade. These wheels sit between the calorimeters and the endcap toroid cryostats, inside the barrel toroids. These Small Wheels have been completely replaced by New Small Wheels (NSW) occupying the same position and providing tracking over the same polar angle range: $1.3 < |\eta| < 2.7$. The NSWs use two chamber technologies: sTGCs optimized primarily for Level-1 trigger functionality, and MICRO MESH Gaseous Structure (Micromegas) detectors optimized for precision tracking. These NSWs allow for improved p_T resolution in the trigger and increased background rejection, allowing for a low muon p_T threshold and manageable Level-1 trigger rate, thus maintaining the acceptance for many interesting physics processes.

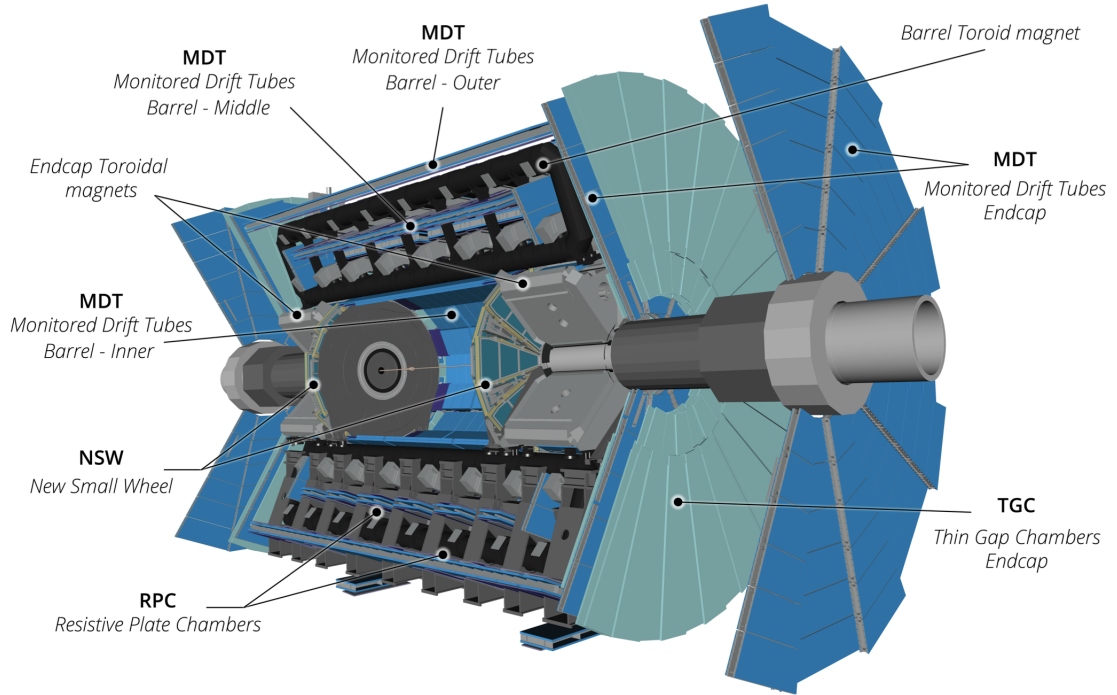


Figure 2.6: Cut-away view of the ATLAS muon system that detects charged particles exiting the barrel and endcap calorimeters and measures their momentum in the pseudorapidity range $|\eta| < 2.7$. The muon system is built around an air-core toroidal magnet system. The main muon detector components upgraded for Run 3 (e.g., the NSWs) are visible.

2.2.4 The Magnets System

The ATLAS Magnet System [28] consists of 4 superconducting magnets:

- a Central Solenoid (CS),
- a Barrel Toroid (BT)
- two End-Cap Toroids (ECT).

The arrangement of the bare windings of the coils is illustrated in Fig. 2.7.

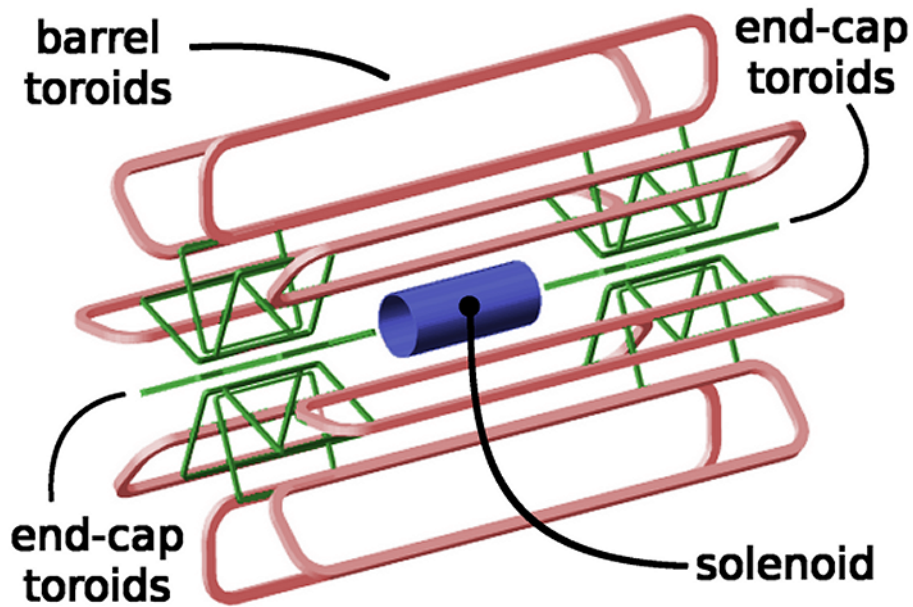


Figure 2.7: Sketch of the spatial arrangement of the ATLAS Magnet System with the central solenoid and the three toroids.

The Central Solenoid provides the magnetic field for the Inner Detector while the three Barrel and End-Cap Toroids generate the magnetic field for the muon detectors in the outer and forward directions respectively. The toroidal field is perpendicular to the solenoid field, the solenoid is magnetically de-coupled from the toroids.

Each of the three toroids consists of 8 coils (flat pancake type) assembled radially and symmetrically around the beam axis. The ECT coil system is rotated by 22.5 with respect to the BT coil system to allow for radial overlap and to optimize the bending power in the interface regions of both coil systems.

The weight of the coils and the Lorentz forces require a mechanical structure enclosing the

windings and a supporting structure between the coils. As the coils are superconducting, cooling circuits and cryostats for optimum thermal insulation of the coils are a necessity. The overall dimensions of the Magnet System are determined by the huge Barrel Toroid that extends over a length of 26 m and an outer diameter of 20 m.

The type of conductor used in all coils is a composite of a flat NbTi/Cu Rutherford cable positioned in the centre of an aluminum stabilizer with a rectangular cross-section. The size of the cables are matched to the peak field in the coils and to the stored energy respectively. In the case of the BT and ECT the cables are about 26 mm wide. This dimension is a factor 2 larger than the usual 10-16 mm wide cables commonly used in accelerator dipole magnets. For the BT and ECT conductors, the stabilizer is high-purity aluminum while in the case of the CS conductor, special cold-worked and (Ni) doped aluminum is applied that provides increased mechanical strength. The main design parameters of the ATLAS Magnets are shown in Tab. 2.5.

property		Barrel Toroid	End-Cap Toroids	Central Solenoid
Overall dimensions:				
Inner diameter	[m]	9.4	1.65	2.46
Outer diameter	[m]	20.1	10.7	2.63
Axial Length	[m]	25.3	5	5.3
Number of coils		8	2×8	1
Mass				
Conductor	[Mg]	118	2×20.5	3.8
Cold Mass	[Mg]	370	2×160	5.4
Total Assembly	[Mg]	830	2×239	5.7
Coils				
Turns/coil		120	116	1173
Nominal Current	[kA]	20.5	20.0	7.6
Magnet stored energy	[GJ]	1.08	2×0.25	0.04
Peak Field	[T]	3.9	4.1	2.6

Table 2.5: Main design parameters of the ATLAS magnets [29].

2.2.5 Trigger and Data Acquisition

The ATLAS Trigger and Data Acquisition (TDAQ) system selects events with distinguishing characteristics (such as the presence of energetic leptons, photons, clusters of particles called “jets”, or large missing energy) that make them interesting for physics analyses, and reads them out for further offline processing. It is based on a two-level event selection system: the Level-1 (L1) system, which consists of custom-built electronics, and the High-Level Trigger (HLT), which is a software-based system implemented on commercial computers. Interwoven with these levels is the Data Acquisition (DAQ) system, responsible for acquire data from custom subdetector electronics and save it for offline processing, according to the decisions made by the trigger. A diagram of the complete TDAQ system in Run 3 is shown in Fig. 2.8.

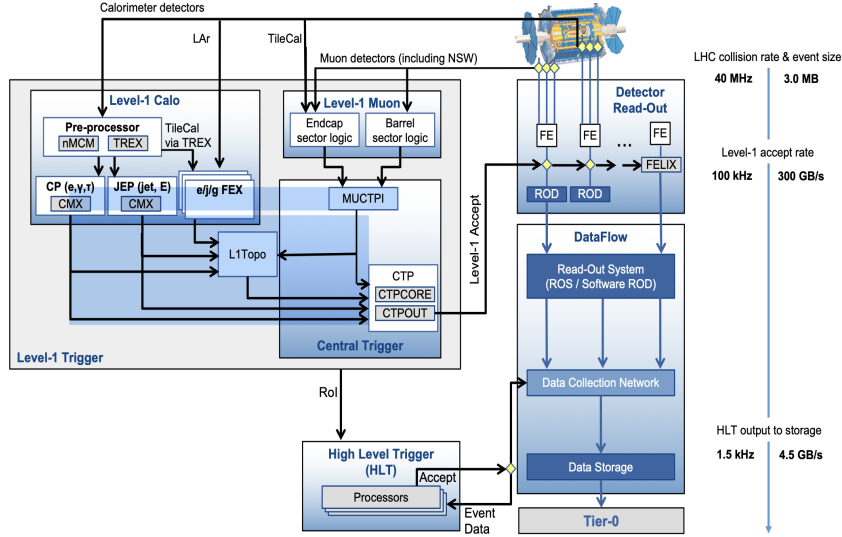


Figure 2.8: Schematic overview of the Trigger and DAQ system at the beginning of Run 3.

The L1 trigger uses reduced-granularity information from the calorimeters and muon system to search for signatures from a variety of “physics objects”: high- p_T muons, electrons, photons, jets, and τ -leptons decaying into hadrons, as well as events with large missing transverse energy or large total transverse energy.

The maximum L1 accept rate supported by the detector readout systems is 100 kHz, and the Trigger menu is tuned to allocate a share of this rate budget to each underlying physics object according to the physics goals of ATLAS. The L1 trigger has a latency of $2.5 \mu\text{s}$. This is the time window permitted by the on-detectors electronics that store the raw data waiting for a L1 decision.

The ATLAS High Level Trigger (HLT) software is designed to reproduce the offline

selection as closely as possible, a philosophy that will be taken one step further in Run 3 through the use of AthenaMT, the upgrade of the ATLAS software framework Athena, for the many-core world with multithreading [30].

On average, the event processing time at the HLT in 2018 was approximately 400 ms for runs with a peak luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The mean HLT event processing time in Run 3 is expected to be larger due to the widespread use of full-detector HLT track reconstruction for hadronic signatures. Upgrades to the HLT farm and algorithmic improvements to tracking will keep the HLT resource usage within the limits of the deployed system. The HLT reduces the event rate from 100 kHz after the L1 selection to approximately 3 kHz (averaged over the course of an LHC fill), which is then stored for offline analysis.

The Data Acquisition System (DAQ) system has also undergone an upgrade in order to read out the full detector during Run 3. The ReadOut System (ROS) must support the L1 accept rate of 100 kHz plus 20% contingency. The throughput of the ROS will increase in Run 3 due to the increased request rate at which the HLT will request data and a 30% increase in the average event size (the event size at $\mu \approx 60$ is 2.1 MB). The system must accommodate an average rate of 1 kHz of physics events to mass storage with the flexibility to handle variations in such rate. At $\mu \approx 60$, assuming a maximum physics rate to the disk of 3 kHz and the above event size, the system is required to support a throughput of 6.3 GB/s. This represents nearly a factor of two increases in the required performance compared to Run 2. In order to store the raw data volume for continuous operation at 3 kHz average output, guaranteeing 24 hours of storage in case of downtime of the CERN mass storage services, the contribution of file transfer and deletion latencies, and the margin needed to guarantee the required file system throughput characteristics, at least 1.4 PB of the effective storage volume is available at Point 1.

2.3 Physics with the ATLAS Experiment

Studies of the Electroweak Standard Model, with a focus on the Higgs boson, the W/Z bosons, and the top quark, as well as searches for new physics phenomena BSM, flavor physics associated with the beauty and charm quarks, and tests of Quantum Chromodynamics, are the main objectives of the ATLAS experiment. In the following paragraphs, some of the main findings by the ATLAS collaboration's analysis with Run 1 and Run 2 data are illustrated:

2.3.1 The Higgs physics

Using the Run 2 dataset, which was collected with a centre of mass energy of $\sqrt{s} = 13$ TeV, more accurate measurements have been made following the announcement of the Higgs boson discovery by the ATLAS and CMS experiments in July 2012. A summary of the Higgs boson mass measurements from the individual and combined investigations carried out by ATLAS is shown in Fig. 2.9.

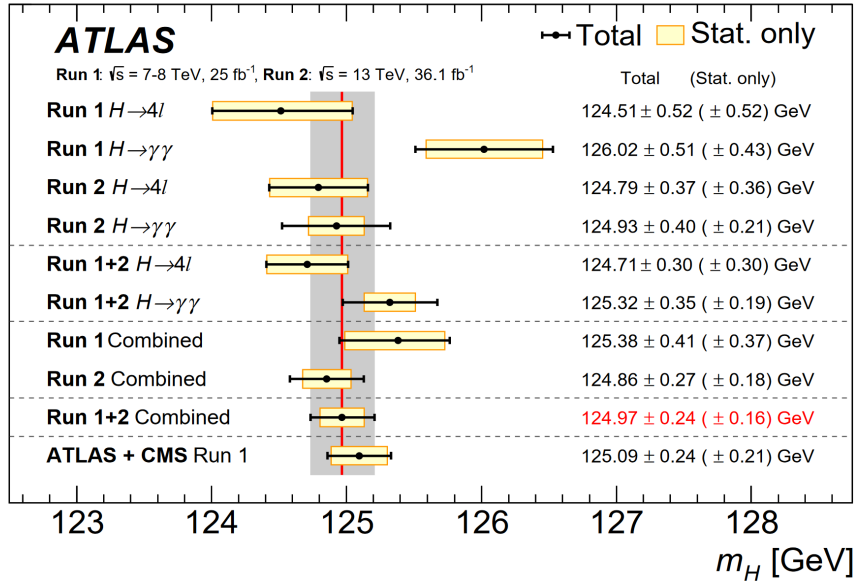


Figure 2.9: Summary of the Higgs boson mass measurements performed by ATLAS, compared with the combined Run 1 measurement by ATLAS and CMS. The (red) vertical line and corresponding (grey) shaded column indicate the central value and the total uncertainty of the combined ATLAS Run 1 + Run 2 measurement, respectively [31].

As shown in Fig. 2.9, so far the best estimate of the Higgs boson mass is:

$$m_H = 125.09 \pm 0.24 (\pm 0.21) \text{ GeV} \quad (2.1)$$

The analysis of the combined ATLAS and CMS Run 1 and Run 2 datasets produced this result. Furthermore, coupling characteristics of the Higgs boson to other SM particles, such as its production cross sections in p-p collisions and decay branching fractions, may be precisely estimated within the SM given the value of the Higgs boson mass. Gluon-gluon fusion (ggF), vector boson fusion (VBF), production associated with a vector boson (WH or ZH), and production associated with a top quark (tH) or a few top anti-top quarks (ttH) are the key steps in the production of the Higgs boson. Recent findings on the Higgs production cross section have been made by utilizing proton-proton collision data up to 139 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$, collected with the ATLAS detector. Fig. 2.10 shows the cross-section for each decay channel normalized to its SM value. The degree of agreement between the measurement and the SM prediction is indicated by the p-value $p_{\text{SM}} = 63\%$ [32].

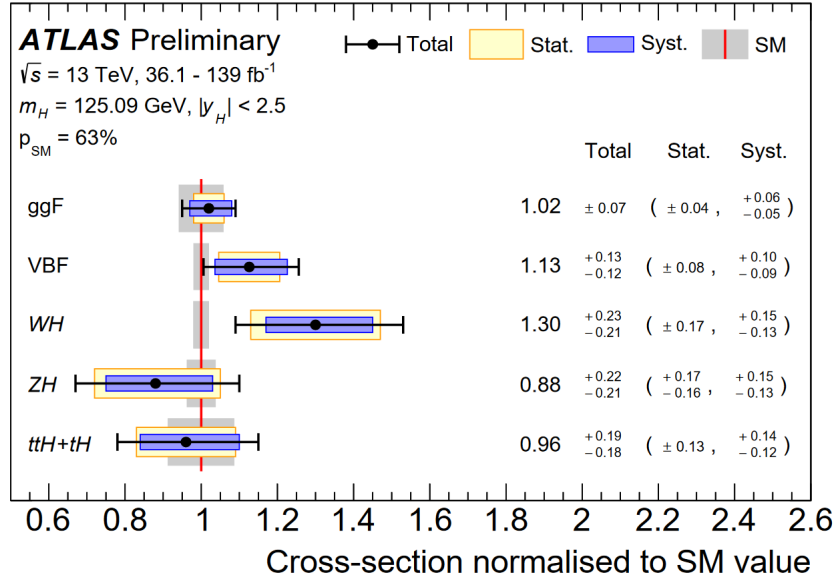


Figure 2.10: Cross sections for ggF, VBF, WH, ZH, and ttH + tH production modes. The cross sections are normalized to their SM predictions, measured assuming SM values for the decay branching fractions. The black error bars, blue boxes, and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The gray bands indicate the theory uncertainties on the SM cross-section predictions. The level of compatibility between the measurement and the SM prediction corresponds to a p -value of $p_{\text{SM}} = 63\%$ [32].

In addition, by taking into account the products $(\sigma \times B)_{if}$ of the cross-section σ in the production process i and branching fraction B to a final state f , a description of both the production and decay mechanisms of the Higgs boson is obtained. The decay modes that are being considered are $H \rightarrow \gamma\gamma$ as well as $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, $H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$, and $H \rightarrow \mu\mu$. Since there are not enough statistics to discriminate between WH and ZH processes, they

are combined into the same production modes as those mentioned above. The amount of consistency between the measurements and the SM predictions equates to a p-value of $p_{SM} = 79\%$. Fig. 2.11 presents the analysis findings.

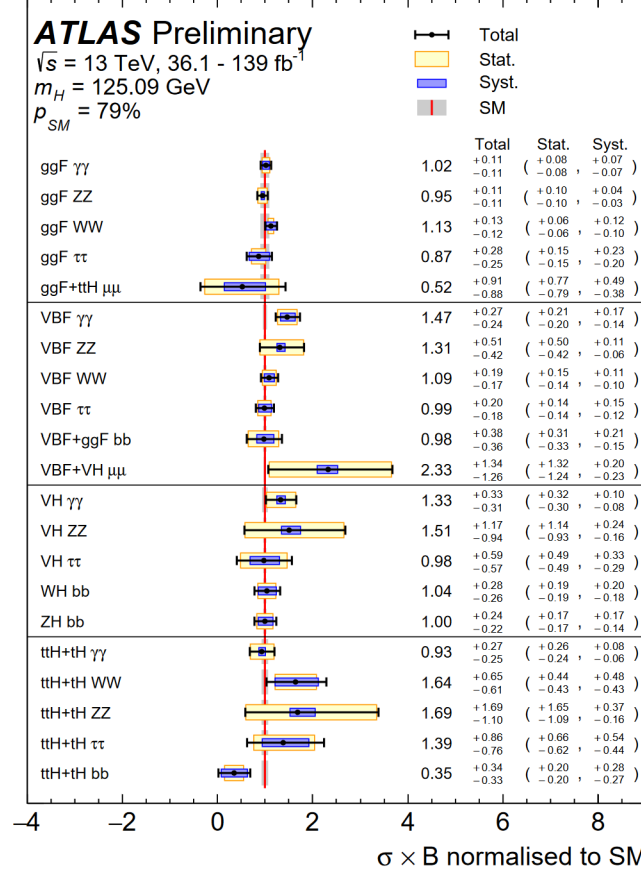


Figure 2.11: Cross sections times branching fraction for ggF, VBF, VH, and $t\bar{t}H + tH$ production modes production in each relevant decay mode, normalized to their SM predictions. The values are obtained from a simultaneous fit to all channels. The black error bars, blue boxes, and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The gray bands show the theory uncertainties on the predictions. The level of compatibility between the measurement and the SM prediction corresponds to a p-value of $p_{SM} = 79\%$ [32].

2.3.2 W and Z physics

Hadron collider measurements of the production of electroweak vector bosons provide as a baseline for understanding both electroweak (EW) and quantum chromodynamic (QCD) processes. The ATLAS collaboration measured the W boson mass in 2018. The mass was

estimated using template fits to the reconstructed distributions of the charged lepton transverse momentum and the W boson transverse mass in the electron and muon decay channels. This produced the following results: $m_W = 80370 \pm 7$ (stat.) ± 11 (exp. syst.) ± 14 (mod. syst.) MeV [33]. The comparison between ATLAS measurement of the W mass with the previous measurements (Tevatron, D0 II, and LEP combination) and the last measurements (LHCb and CDF II) is shown in Fig. 2.12. The CDF II measurement caused no small stir, reopening the debate about the actual value of the W boson's mass.

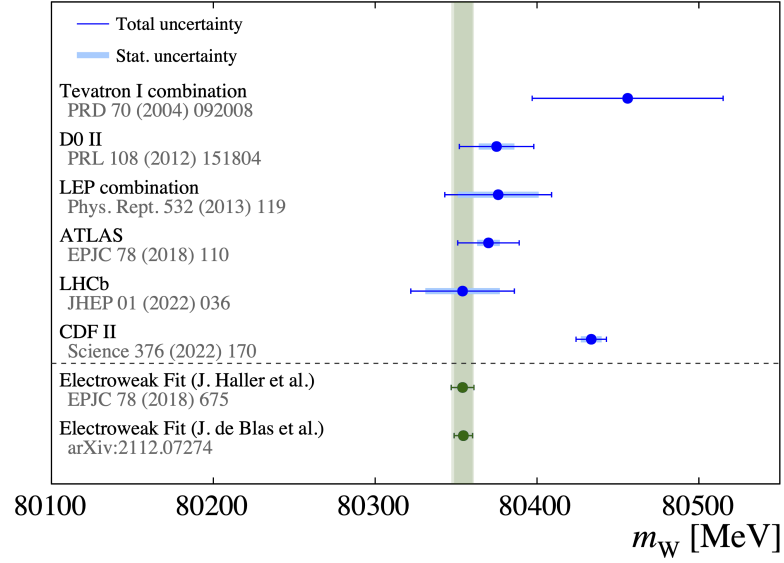


Figure 2.12: The new CDF measurement of the W mass along with other Tevatron results, the LEP experiments, ATLAS, and LHCb, showing the total (dark blue) and statistical (light-blue band) uncertainties. The Standard Model prediction is shown in green [34].

The W and Z cross-section predictions are sensitive to the underlying dynamics of highly interacting particles since they also rely on the Parton Distribution Functions (PDFs). As a result, measurements of the production of W and Z bosons present a rare chance to evaluate parton dynamics models. The $W \rightarrow l\nu$ and $Z \rightarrow l^+l^-$ channels were subjected to measurements. Both ratios and absolute cross-sections were measured. The fiducial and total cross sections are found to agree with theoretical calculations based on NNLO QCD with NLO EW corrections [35].

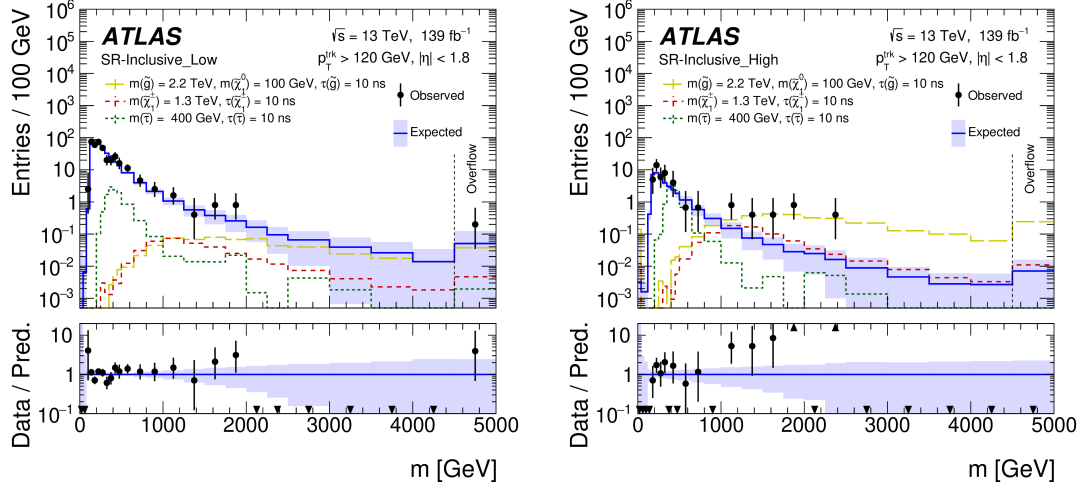
2.3.3 Supersymmetry Searches in ATLAS

The ATLAS collaboration is also involved in Supersymmetry searches exploiting a variety of signatures. As an example, in the following paragraph it is reported a search that exploits the pixel detector ionization as a key parameter [36]. A summary overview of hypothetical

massive, charged, long-lived particles search with the ATLAS detector is reported in this paragraph. The analysis was performed using an integrated luminosity of 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13 \text{ TeV}$, which corresponds to Run2 data of LHC, collected from 2015 to 2018.

These particles should be distinguishable by their high transverse momenta and anomalously large specific ionization losses, dE/dx , as they are predicted to move considerably slower than the speed of light. Particles with lifetimes as low as 1 ns and masses measured using the Bethe-Bloch relation ranging from 100 GeV to 3 TeV can be detected using only the inner tracking system and a dE/dx measurement in the pixel detector layers. Considering scenarios of Supersymmetry that are compatible with these particles having long lifetimes, interpretations for pair production of R -hadrons, charginos, and staus are given, with mass limits that go well beyond those from previous searches in a broad range of lifetime.

Fig. 2.13a and 2.13b compare the mass distributions in each of the *SR-Inclusive.Low* and *SR-Inclusive.High* bins (dE/dx between 1.8 and $2.4 \text{ MeVg}^{-1}\text{cm}^2$ and dE/dx higher than $2.4 \text{ MeVg}^{-1}\text{cm}^2$, respectively) with the expected background yields and several representative signal points. In the window *SR-Inclusive.High* bin in the high mass range the largest significance of 3.6σ is observed for a mass window $[1.1, 2.8] \text{ TeV}$ in high- dE/dx SR: in this window, 0.7 ± 0.4 events are expected and 7 events are observed with a global significance: 3.3σ . Elsewhere, the observed event distribution generally agrees well with the expected background distribution in these variables within the estimated uncertainties.



(a) *SR-Inclusive_Low*.

(b) *SR-Inclusive_High*.

Figure 2.13: The observed mass distribution in the Inclusive signal-region bins. The band on the expected background indicates the total uncertainty of the estimation. Several representative signal models are overlaid. Events outside the shown range are accumulated in the rightmost bin indicated as ‘Overflow’. Downward triangle markers at the bottom of the panels indicate that no events are observed in the corresponding mass bin, while the upward triangle markers at the top of the lower panel in (b) indicate that the observed data is beyond the range [36].

Chapter 3

Silicon Detectors for High Energy Physics

3.1 Introduction

In particle physics experiments, special detectors are often used to track the paths of charged particles. These are known as tracking detectors and when they are specifically designed to identify points where multiple particle tracks intersect, which can indicate the creation or destruction of particles, they are referred to as vertex detectors.

Particularly, in particle physics experiments, tracking detectors are used to identify and measure the trajectories of charged particles. These detectors are specifically designed to detect secondary vertices, which often indicate the presence of heavy particles such as hadrons with charm or bottom quarks or tau leptons. They also help to determine the momentum of particles by measuring the curvature of tracks in a magnetic field, and the sign of the curvature allows for the identification of the charge of the particle. Tracking detectors also measure the impact parameter, or the distance between tracks, and can indicate the presence of neutral intermediate particles that have not been directly observed. Additionally, by reconstructing the path from the production point to the decay point, tracking detectors can measure particle lifetimes, which can aid in identifying tau leptons or hadrons containing quarks. The information obtained from tracking detectors can also be used to trigger events of particular interest in the experiment [37].

For more than 50 years, silicon detectors have been utilized in the field of elementary particle physics. In 2005, the LHC experiments, such as ATLAS, CMS, LHCb, and ALICE, implemented the use of pixel pattern and strip detectors on a large scale, making them the current industry standard.

3.2 Particles Interaction with Matter

3.2.1 Charged Particles

For the purpose of understanding the operation of silicon detectors in particle physics experiments, it is important to have a basic understanding of how charged particles interact with matter. The two main mechanisms that are relevant to the construction of silicon tracking detectors are energy loss by ionization and multiple scattering. This information is primarily derived from reference [38–40].

To be detected by any detector, a particle or radiation must interact with it. During this interaction, a portion of the energy released by the particle is converted into electrical signals in the form of electron-hole pairs.

Charged particles deposit energy through multiple scattering with the electrons in the material they pass through along their path. This process is most pronounced for heavier particles, typically those that are heavier than electrons. It is described by the Bethe-Bloch formula in Eq. 3.1.

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \times \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right) \right]. \quad (3.1)$$

with:

- $\frac{dE}{dx}$ is the mean energy loss of the particle per unit path length,
- N_A is the Avogadro's number,
- r_e is the classical electron radius,
- m_e is the electron mass,
- c is the speed of light,
- z is the charge of the traversing particle in units of electron charge,
- Z is the atomic number of absorption medium,
- A is the atomic mass of absorption medium,
- $\beta = \frac{v}{c}$,
- $\gamma = 1/\sqrt{1 - \beta^2}$ is the Lorentz factor,
- I is the mean excitation energy,
- $T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$. This is the maximum kinetic energy which can be imparted to a free electron in a single collision,
- $\delta(\gamma)$ is the density correction effect.

For low energies the $1/\beta^2$ term in the Eq. 3.1 is dominant, with the stopping power decreasing with increasing energy. At a particle's velocity β of about 0.96 ($\beta\gamma \approx 3$) a minimum is reached, as shown in Fig. 3.1. At higher energies the logarithmic term leads to a slow rise again, which is canceled by the density correction. A particle with an energy loss in the minimum of the Bethe-Bloch formula is called a *minimum ionizing particle* (MIP). Note that the Bethe-Bloch formula predicts the average value of the energy deposition distribution per unit length, but it can not describe the behaviour of a single particle because of the stochastic nature of energy loss. Due to the flatness of the curve, the Bethe-Bloch expression is often also applied to all particles with $\beta > 0.96$ ($\beta\gamma > 3$). The value of the minimum depends on the square of the particle charge but very weakly on the particle mass.

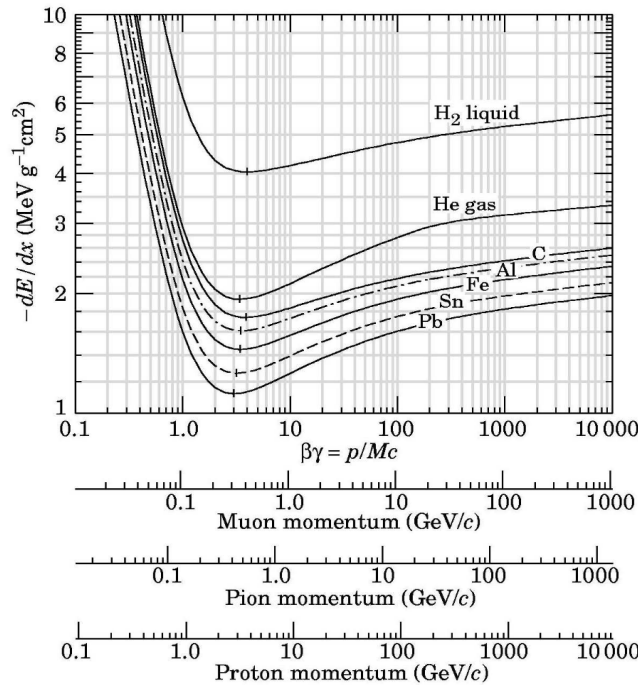


Figure 3.1: Bethe-Bloch energy loss for different particles in different materials as a function of their energy.

The distribution of the single energy loss is well described by the Landau distribution, which also includes the rare but important effect of the so-called δ -electrons generation which obtains enough energy by the interaction to become ionizing particles themselves. These δ -electrons are responsible for a long tail toward high energies in the energy loss distribution therefore, the Most Probable Value (MPV) of the Landau distribution is about 30% below the average value.

The average energy needed to create an electron-hole pair in silicon is 3.6 eV, three times larger than the Si band gap (1.2 eV): this difference of energy generates phonons. The

generated phonons are also needed to promote electrons in the conduction band in an indirect gap semiconductor, such as silicon. Phonons in the end will be degraded into thermal energy. The average number of electrons generated by a MIP is about 110 electrons/ μm , therefore for a MIP in silicon the MPV is about 80 electrons/ μm .

In addition to colliding elastically with atomic electrons, charged particles that travel through matter also experience multiple elastic collisions with nuclei, although with a much lower probability. The angle of scattering, after multiple interactions, generally follows a Gaussian distribution with an RMS value of:

$$\theta_{RMS} = \frac{13.6 \text{ MeV}}{\beta pc} z \sqrt{\frac{x}{X_0}} [1 + 0.038 \ln(\frac{x}{X_0})] \quad (3.2)$$

Where in the Eq. 3.2, θ represents the angle in radians, p represents the momentum of the particle in MeV, β represents the velocity of the particle in natural units, and z represents the charge number of the particle. To improve the resolution of a tracking detector, it is important to minimize the x/X_0 , which represents the thickness of the absorption medium in units of radiation length. The radiation length of silicon is 9.36 cm. This can be achieved by constructing a detector that is as lightweight as possible.

3.2.2 Photons

Photons interact with matter mainly via these three processes: the photoelectric effect, the Compton scattering, and via pair production.

A monochromatic photon beam penetrating through material is therefore not changed in energy but attenuated in intensity according to:

$$I = I_0 e^{-x/\mu} \quad (3.3)$$

where I is the intensity of the beam after passing through a material of thickness x , I_0 is the initial intensity of the beam, and μ is the linear attenuation coefficient, which depends on the properties of the material and the energy of the photon. As the photon beam passes through a material, some of its energy is absorbed, leading to a decrease in the intensity, or attenuation, of the beam. This effect is described by the exponential attenuation law.

3.3 pn-junction

Silicon is a type of crystal that has a specific energy band structure. There are two bands present in the material: a valence band where electrons are bound and a conduction band where the electrons are free. The two bands are separated by an energy gap that does not have any energy levels. The energy gap is determined by the distance between the atoms in the lattice and it can change based on temperature and pressure.

In the lowest energy state, all the electrons in the valence band participate in covalent bonding between the atoms in the lattice. However, thermal energy can excite an electron from the valence band into the conduction band, leaving a hole in its original position. This hole acts as a positive charge carrier in the valence band, and the free electrons in the conduction band act as negative charge carriers. Some of the electron-hole pairs generated by thermal energy will recombine and the equilibrium concentrations will be the same. The concentration n_i of electron-hole pairs is described by the Eq. 3.4:

$$n_i = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2k_B T}\right) = A T^{3/2} \exp\left(\frac{-E_g}{2k_B T}\right), \quad (3.4)$$

where N_c is the number of states in the conduction band, N_v is the number of states in the valence band, E_g is the energy gap at 0 K. The Fermi statistic shows that N_c and N_v are proportional to $T^{3/2}$ and the proportionality constant A is independent of the temperature. In pure silicon the intrinsic carrier concentration is about $1.5 \cdot 10^{10} \text{ cm}^{-3}$ at 300 K.

To construct an efficient silicon detector, it is important to compare the number of intrinsic carriers to the number of electron-hole pairs generated by a charged particle. For example, if a MIP passes through a thickness of 300 micrometers of silicon with an area of 1 square centimeter at 300 Kelvin, the mean ionization energy of silicon is 3.6 eV and the mean energy loss of a MIP is 3.87 MeV/cm. This results in a signal charge of 3.2×10^4 electron-hole pairs and an intrinsic charge of 4.35×10^8 electron-hole pairs, which is 4 orders of magnitude greater than the signal. To reduce the intrinsic carrier charge, a reverse-biased pn-junction can be formed and possibly cooled.

The conductivity of silicon is generally low, but it can be increased through the introduction of impurities, such as elements from the III Group, like Boron, or elements from the V Group, like Phosphorus or Arsenic. These impurities are known as *acceptors* and *donors*, respectively. To construct a pn-junction, a combination of p-type and n-type silicon is used, as illustrated in Fig. 3.2

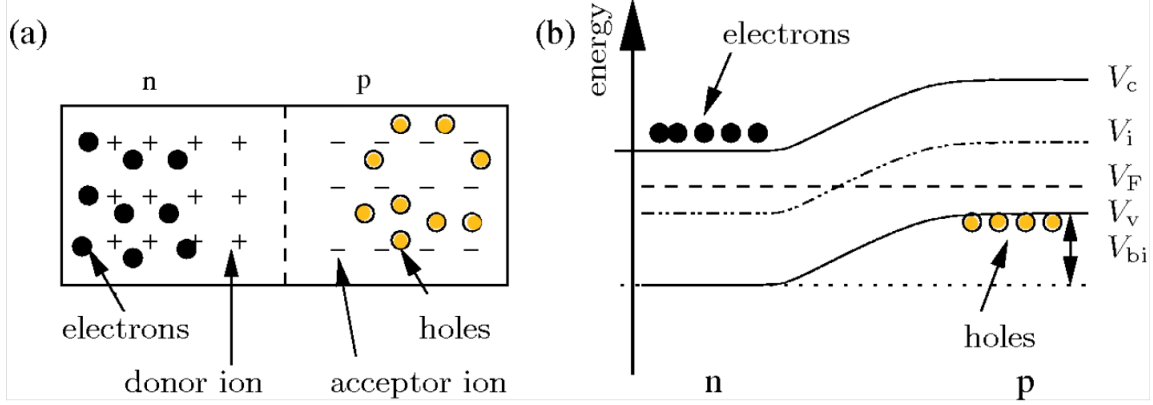


Figure 3.2: Schematic illustration of a pn -junction (a) and its band diagram to illustrate the formation of the built-in voltage (b).

When a p-type and n-type doped silicon are combined, a region near the interface called the depletion region forms. This region is depleted of free charge carriers and is caused by the recombination of majority charge carriers that diffuse from one side to the other. In this region, donor and acceptor ions are left without their balancing charges, which leads to the formation of an electric potential known as the built-in voltage (V_{bi}). The Eq. 3.5 characterize the V_{bi}

$$V_{bi} = \frac{k_B T}{e} \ln \left(\frac{N_A N_D}{n_i^2} \right), \quad (3.5)$$

where N_D and N_A are the concentrations of donors and acceptors.

The width of the depletion region (W) and the electric field can be calculated using a one-dimensional Poisson equation (Eq. 3.6, which depends on factors such as V_{bias} , V_{bi} , N_D , and N_A). When a negative potential, known as V_{bias} , is applied to the p-side of the pn-junction, it becomes reverse-biased, and a current, known as leakage current, begins to flow. The reverse bias causes the majority of carriers from either side to be further removed, thereby extending the depletion region.

$$W = x_p + x_n = \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_{bias} + V_{bi})}, \quad (3.6)$$

where x_p and x_n are the extensions of the depletion region on the n and p sides, respectively.

Silicon detectors are typically built with pn-junctions formed by low-doped material ($N_A \sim 10^{12} \text{ cm}^{-3}$) and highly doped electrodes ($N_D > 10^{18} \text{ cm}^{-3}$). When a p-type bulk material is used, it is possible to neglect the term $1/N_D$ in the equation. Additionally, since V_{bi} is in the order of 0.5 V, which is relatively small compared to typical operation V_{bias} values of 10-100 V, the equation can be simplified:

$$W \simeq \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{eN_A}V_{bias}} \quad (3.7)$$

The maximum electric field value inside the typical pn-junction device can be estimated as:

$$E_{max} = \frac{2V_{bias}}{W} = \sqrt{\frac{2N_A e V_{bias}}{\epsilon_0 \epsilon_{Si}}} \quad (3.8)$$

The plot of the leakage current in the function of the voltage bias is known as *IV curve*. The leakage current is therefore the result of the volume-generated current, the surface-generated one, and the avalanche breakdown contribution, as shown in Fig. 3.3. This avalanche effect will lead to a large increase in the leakage current of the device. A free electron, accelerated to a very high speed by the strong electric field, is able to break its bond with the lattice by colliding with another electron, generating a second free electron. For V_{bias} values exceeding this limit, the so-called avalanche effect starts. The voltage bias value at which the electric field at the junction will reach critical values (i.e. E_{max} , whose formal expression is given by the Eq.3.8) is the so-called breakdown voltage (V_{bd}).

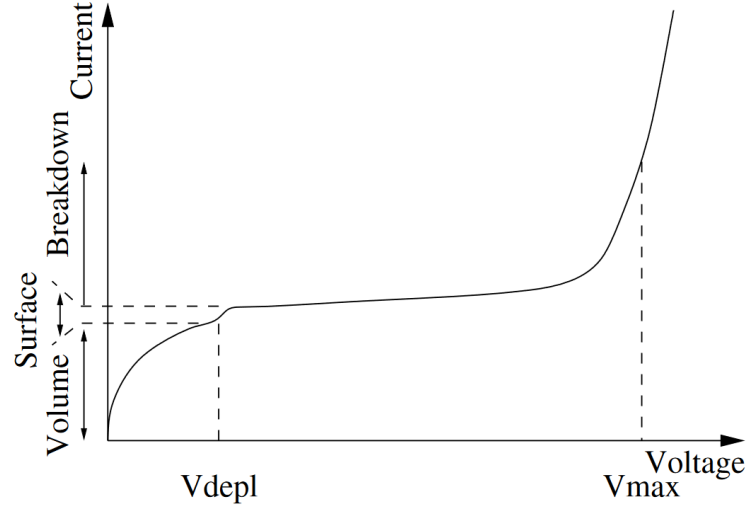


Figure 3.3: Typical shape of a silicon sensor IV curve with indication of the origin of different current contributions [38].

3.4 Silicon Detectors

The pn-junction as Detector

A reversely biased pn-junction is the fundamental component of silicon sensors, such as pixel sensors. It utilizes the lack of intrinsic charge carriers in the depletion zone to achieve a high signal-to-noise ratio (S/N) during the passage of a particle. To collect the charges generated by radiation, electrodes must be placed on both sides of the junction. To prevent the formation of a rectifying junction with an extended depletion zone in silicon, a layer of heavily doped n-type and p-type material is used between silicon and the metal leads. A pre-amplifier of the charge-sensitive type is typically used to collect the charge signal from the detector. Due to the low level of the signal, this pre-amplifier must have low-noise characteristics. Signal processing after the pre-amplifier also requires pulse shaping to achieve the best signal-to-noise characteristics [38].

The Radiation damage in tracking devices commonly found in the central regions of collider experiments is caused by the high density and high rate of particles, which can degrade the performance of silicon crystals. These effects can be divided into two categories: bulk defects, which are caused by the displacement of crystal atoms, and surface defects, which include all effects on covering dielectrics and the interface region, as cited in [38]. The primary impact of radiation damage includes the increasing of the leakage current, the change of the space charge in the depleted region (such as the type inversion), and the subsequent increase of the full depletion voltage and the charge trapping effect, which makes it more difficult to collect the signal.

A silicon diode with only two electrodes can be used to detect the presence of a particle, but it does not provide information on the particle's location. To obtain this additional information, two sensor design options can be considered. These designs, known as strip geometry and pixel geometry, are illustrated in Fig. 3.4.

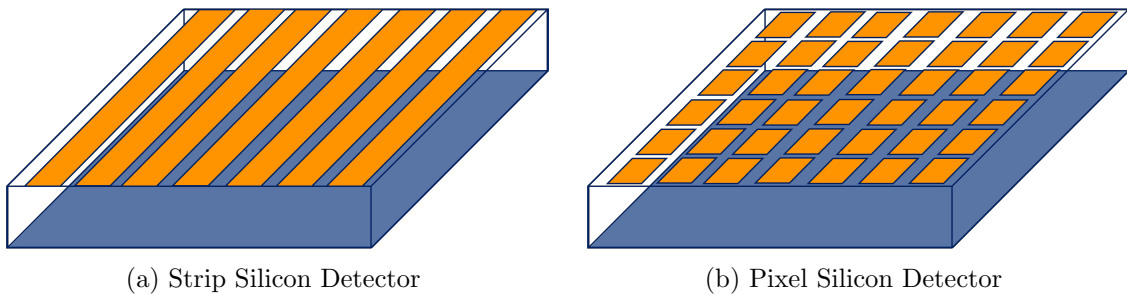


Figure 3.4: (a) Is shown a sketch of a strip silicon detector while a sketch of a pixel silicon detector is shown in (b)

Strip Silicon Detectors Design

A strip detector is a collection of strip-shaped implants that act as electrodes for collecting the charge. When these implants are placed on a low-doped, fully depleted silicon wafer,

they form an array of diodes in a one-dimensional pattern. By connecting each strip to a charge amplifier, a 1D position-sensitive detector is created. To make a 2D position-sensitive detector, a second array of strip-like implants can be added on the backside of the silicon wafer, as seen in Fig. 3.5.

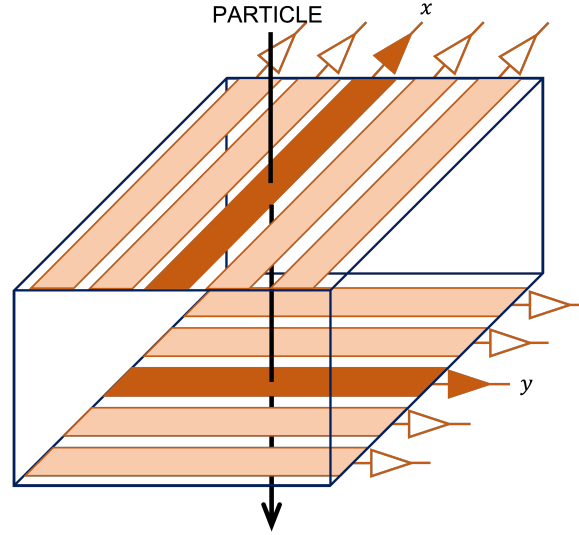


Figure 3.5: Sketch of a double side segmentation strip silicon detector is shown.

The configuration shown in Fig. 3.5 is useful for detecting two coordinates and is relatively simple, but it can lead to issues when the detector is used at high hit densities. Each hit generates both an x and y coordinate. If n hits occur in a short period of time, n pairs of coordinates will be generated, simulating a total of n^2 hits, $n^2 - n$ of which are fake. To overcome this problem, a small stereo angle α between opposite side strips can be used instead of 90° . If the angle α is very small the capture area is reduced but the disadvantage of this solution affects the longitudinal resolution negatively.

Pixel Silicon Detectors Design

order to mitigate position ambiguities caused by high particle fluxes, electrodes in detectors need to be segmented in both directions. This particular geometry is employed in pixel detectors. The sensor pixels are connected to the read-out chip (Front-end) through small solder bumps, as depicted in Fig. 3.6. This configuration is referred to as a hybrid pixel detector. Alternatively, it is possible to integrate portions or the entirety of the front-end electronics within the sensor itself, resulting in a monolithic pixel detector. The primary constraint on pixel size typically arises from the electronics, as a considerable amount of circuitry needs to be accommodated within a single read-out pixel. The complexity of the electronics varies depending on the type of read-out employed.

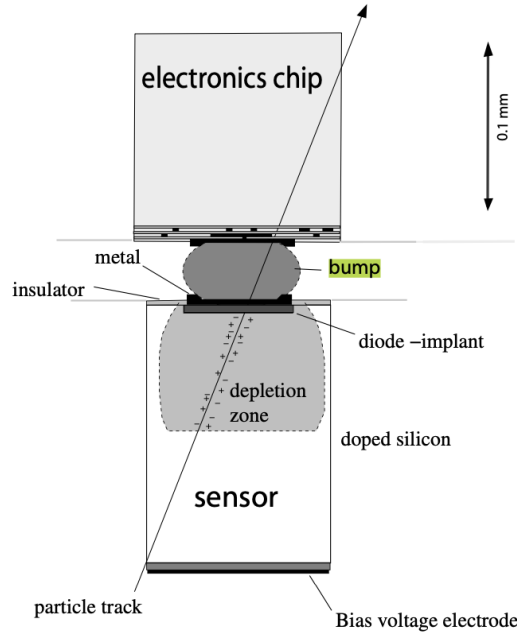


Figure 3.6: The hybrid pixel detector is composed of a basic building block called pixel cells. This schematic view illustrates one pixel cell. When an ionizing particle passes through the sensor, it generates charges that move in the depletion region under the influence of an electric field and produce signals. These signals are amplified, and the electronics identify and store the hit pixels. The thickness of the sensitive part of the detector, known as the depletion zone, is determined by the bias voltage and sensor parameter.

The main limitation on the pixel cell size comes from the electronics because a large amount of circuitry needs to be fitted in a single read-out cell. In the case of binary read-out, the pixel spatial resolution can be simply related to the pixel pitch as:

$$\sigma_{pixel} = \frac{pitch}{\sqrt{12}} \quad (3.9)$$

Modern pixels can reach a spatial resolution of about $5 \mu\text{m}$.

Two main types of pixel sensors are used for high-energy physics experiments, as shown in Fig. 3.7: planar sensors and 3D sensors. Planar sensors typically consist of an n-type or p-type low-doped bulk of the same wafer thickness (or even less if the sensor is thinned) with high-doped electrodes deposited on the surface using precision masks. On the other hand, in 3D sensors, the electrodes are implanted vertically inside the bulk material using Deep Reactive Ion Etching lithography processes. The 3D design preserves the bulk thickness for charge generation and allows reducing the distance between the electrodes. This reduced distance results in a shorter drift length for charge carriers, reducing the loss of charge by trapping along the path, and a much-decreased depletion voltage. For these reasons, 3D

sensors are more radiation tolerant than planar ones.

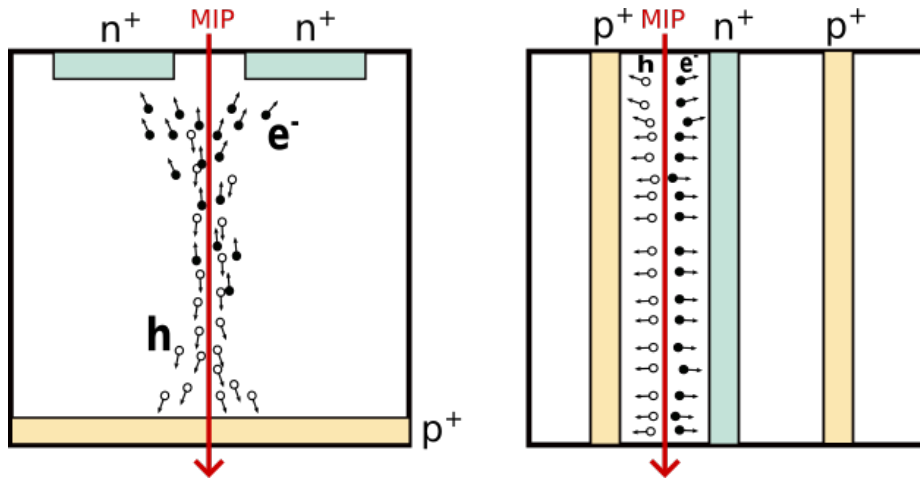


Figure 3.7: Schematic diagram of a planar (left) and a 3D (right) sensor, showing the charge carrier creation when a particle passes through, and the carriers movement before being collected on the electrodes [41].

Chapter 4

The ATLAS Inner Tracker for Phase II

4.1 ATLAS Phase II Upgrade

As already discussed in Sec. 1.4, the HL-LHC accelerator upgrades require major upgrades of the ATLAS detector in order to maintain the current performance capabilities under new challenging operating conditions. Thus the upgrade of the ATLAS detector is absolutely central to the exploitation of the rich physics potential provided by these large HL-LHC data sets.

In the HL-LHC environment, the primary detector challenges are to maintain excellent performance in vertex and track reconstruction, lepton identification, and heavy flavour tagging. These will be addressed through three fundamental detector upgrades: a complete replacement of the current tracking system; new radiation-hard readout electronics based on cutting-edge technologies for the tracking, calorimeter, and muon detector systems; and an upgraded Trigger and Data Acquisition (TDAQ) architecture to accommodate the increasing rates. These upgrades [42] are required to offset the effects of aging as well as the HL-LHC's rate and radiation environment, and are strategically designed to maximize the LHC's physics potential.

4.1.1 The Inner Tracker Upgrade

The ATLAS Inner Tracker plays an essential role in the reconstruction and identification of leptons, photons, hadronic decays and in the tagging of b-jets. The key role of the tracker in the ATLAS physics program becomes even more important in the HL-LHC era of high luminosity and high pile-up. The current tracker has been designed for ten years of operation at a peak luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with 23 pileup events per 25 ns bunch crossing and a Level-1 trigger rate of 100 kHz. It therefore cannot operate under the challenging HL-LHC conditions where the luminosity will be pushed up to $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$,

and it will be necessary to replace it. To face this dramatic increase of luminosity of the machine, a new all-silicon detector called Inner Tracker (ITk) with pixel and strip has been foreseen [43, 44] and is being constructed to be installed in the LS3.

The predictions for the particle fluences and ionizing doses for the ITk layout are based on an integrated luminosity of 4000 fb^{-1} and center-of-mass energy of 14 TeV for inelastic proton collisions. Fig. 4.1 shows the fluence distribution for the ITk Pixel Detector during HL-LHC operation [44]. The 1 MeV neutron equivalent fluences is presented in the plot and are normalized to a total of 4000 fb^{-1} .

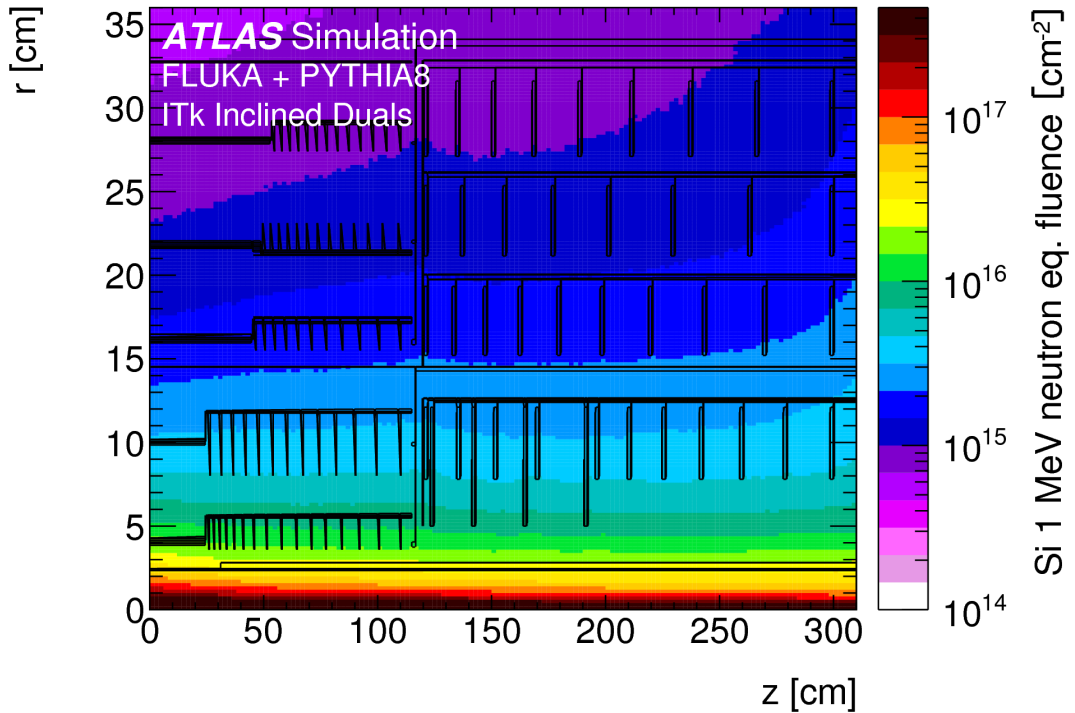


Figure 4.1: The fluence distributions for the Pixel Detector. In this plot, the fluence is set to 1 MeV neutron equivalent and it is normalised to 4000 fb^{-1} . Radiation background simulations have been performed for the ITk using the PYTHIA8 event generator and the FLUKA particle transport code. No safety factors are taken into account for this figure [44].

Being the main topic of this thesis work, the baseline design for the ITk will be discussed in great detail in this chapter.

4.1.2 The Calorimeter Upgrade

During the HL-LHC operation, the on-detector front-end electronics for the LAr and Tile calorimeters will be subjected to much higher radiation levels. Many ASICs in current front-

end electronics were not designed to withstand the radiation environment of the HL-LHC. The proposed front-end electronics upgrades will take advantage of technological progress to implement a robust architecture with the high radiation tolerance required to operate in the HL-LHC environment [45, 46].

The upgraded electronics will also be capable of handling very high data volumes, transmission rates up to the 140 Tbps expected at high luminosity, as well as a high digitization rate. The new front-end board, with a 16-bit dynamic range, will enable multiplexing, serialization, and high-speed optical link transmission in addition to providing analog to digital conversion at 40 MHz.

Due to space charge effects, the performance of the current forward calorimeter, which operates in the range of $3.2 < |\eta| < 4.9$, will significantly deteriorate. For HL-LHC operation, the forward calorimeter might therefore need to be replaced. The forward calorimeter, which is housed inside the endcap cryostat, could be completely replaced, or a new detector could be mounted in front of the current forward calorimeter.

4.1.3 The Muon Spectrometer Upgrade

The Phase-II upgrade completes the process that began with the New Small Wheel Phase-I upgrade project [27], which will replace the innermost endcap wheels, of adjusting the muon spectrometer to the LHC's continuously improving performance [47].

To cope the operational conditions at the HL-LHC, a significant upgrade to the ATLAS detector's muon spectrometer is planned for Phase II. The Resistive Plate Chambers (RPC), Thin Gap Chambers (TGC), and Monitored Drift Tube (MDT) chambers' trigger and readout electronics will be upgraded to work with a new trigger scheme that has higher trigger rates and longer latencies. Sharpening the momentum threshold will be achieved by incorporating MDT precision chambers into the hardware trigger. Additionally, the MDT front-end electronics will be changed. In order to improve the acceptability and durability of the trigger, new-generation RPC chambers will be installed in the inner barrel layer.

New small-diameter MDT chambers will be installed to replace some inner barrel layer MDTs chambers. To reduce the high trigger rate caused by random coincidences in the barrel-endcap transition region, new TGC triplet chambers will replace the existing TGC doublets. It is also intended to upgrade the power system significantly.

4.1.4 The Trigger and Data Acquisition Upgrade

The Phase II upgrade of the ATLAS trigger and data acquisition aims to preserve low transverse momentum thresholds for isolated electrons and muons, even as the luminosity increases. This objective is motivated by the need to maximize the acceptance of rare processes in physics. A new trigger architecture that can support rising trigger rates and data volumes up to a luminosity of $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is currently being developed.

The TDAQ Phase-II baseline architecture, based on a single-level hardware trigger with a maximum rate of 1MHz accept rate and a $10 \mu\text{s}$ latency, and it would function similarly

to the Phase I Level-1 trigger by accepting inputs from the calorimeter and muon systems. The Muon Drift Chambers data, Level-1 calorimeter data, and track segments matched to Level-1 muon and calorimeter features will all be available to the Level-1 trigger. As a result, the upgraded Level-1 trigger would deliver the required rejection using precise pattern recognition and topological triggers that match data detector systems.

To maintain the rejection by employing offline-type particle identification, the High-Level Trigger selection software must be upgraded the detector. To take advantage of the increased computing power made possible by technological improvements in computing, new selection software will be created. During data collection at peak luminosity during the HL-LHC operation, the event storage rate for offline analysis is expected to be between 5 and 10 kHz [48].

4.2 The ITk Layout

The ITk is an all-silicon detector consisting of a pixel subsystem [44] with a pseudorapidity coverage of $|\eta| < 4$ and a strip subsystem [43] covering up to $|\eta| < 2.7$. The pixel subsystem consists of five flat barrel layers and five layers of inclined or vertical rings providing coverage in the forward region. The baseline sensor technologies for the ITk Pixel system are 3D sensors for the innermost barrel and endcap layer (Layer 0) and thin planar sensors elsewhere (Layer 1 to Layer 4 in barrel and endcap). The 3D sensors used for the pixel subsystem will be discussed in more detail in Sec. 4.4. The strip subsystem comprises four strip module layers in the barrel region and six disks in the endcaps. This combination is designed to have at least 9 precision measurements per track for the full width of the expected beam spot size, which is assumed to be Gaussian shaped with a width of 50 mm, for any charged particle with $p_T > 1$ GeV traversing the detector in $|\eta| < 4.0$.

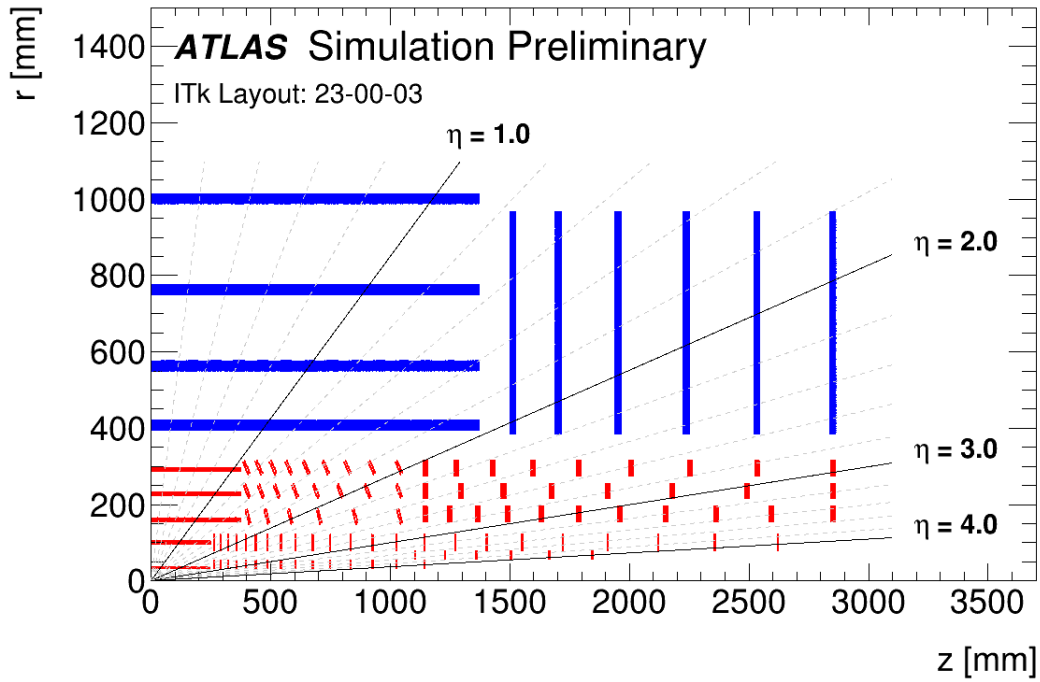


Figure 4.2: A schematic description of the ITk layout. Only one quadrant and only active detector elements are shown. The active elements of the strip detector are shown in blue, and those of the pixel detector are shown in red. The horizontal axis is along the beam line with zero being the nominal interaction point. The vertical axis is the radius measured from the interaction point [49].

After the TDR, the pixel innermost layers design has been finalized in order to further improve the ITk tracking performance [49]. The layer closer to the beamline has been

further brought closer reducing its radius from 39 mm to 34 mm, while the innermost point of the endcap rings has been moved inwards from 36 down to 33.2 mm. The reduction of the radius of the barrel section offered the opportunity to reduce the number of staves from 16 down to 12, while the number of endcap rings and their position in the innermost pixel layers have been re-optimized, all of that with a hit coverage equivalent to the previous layout. The new layout (the so-called 23-00-03) is presented in Fig. 4.2 (total ITk layout) and in Fig. 4.3 (only pixel sub-system).

Together with the last ITk layout, it was chosen to adopt 3D pixel sensors with a pitch of $25 \times 100 \mu\text{m}^2$ in the innermost layer (L0) of the ITk barrel sector whereas the pixel pitch will be $50 \times 50 \mu\text{m}^2$ in the endcap L0, with 3D sensors to optimise the tracking capability with an acceptable increase in the production complexity and cost. The 3D sensors were already used for the IBL upgrade, but the ITk 3D sensors feature now a significant evolution. They are produced in single-side technology, a simpler and more reliable process with both electrode types etched from the same side (more details in Sec. 4.4). The 3D sensor thickness is $150 \mu\text{m}$ for the L0. To continue with the comparison with IBL, the previous thickness was $230 \mu\text{m}$. This improvement allows the reduction of the cluster size and consequently of the data rate. The sensors are produced in a p-type wafer silicon-silicon bonded to a mechanical wafer. About $100 \mu\text{m}$ of mechanical wafer are kept after sensor back thinning to improve the mechanical structure.

Planar sensors will be in n-in-p technology, compared to the n-in-n used in the present ATLAS pixel system and in the IBL. The n-in-p is a simpler and cheaper (single-side) technology which has been successfully demonstrated in the last few years. The sensor thickness is $100 \mu\text{m}$ for the Layer 1 in the Inner System (L1) and $150 \mu\text{m}$ for the outer layers L2-L4 in the OB and OE, compared to the $200 \mu\text{m}$ thick sensors used in the planar part of the IBL. The pixel size will be $50 \times 50 \mu\text{m}^2$ for all the layers, compared to the $50 \times 250 \mu\text{m}^2$ of the IBL. The comparison between ITk and IBL is resumed in Tab. 4.1.

	Type	Active thickness [μm]	Pixel size [μm^2]	Technique	Layer
ITk	3D	150	50×50 / 25×100	Single-side	L0
	Planar	100	50×50	n^+ -in-p	L1
	Planar	150	50×50	n^+ -in-p	L2-L4
IBL	3D	230	50×250	Double-side	L0 Barrel
	Planar	200	50×250	n^+ -in-n	L0 Barrel

Table 4.1: IBL and ITk sensors comparison.

Regarding the modules, their construction proceeds in two steps. The first one is the hybridization, where the sensor tile is connected to one or four front-end chips through a flip-chip process, producing a bare module. The second step is the module assembly, where a flexible circuit (flex) is glued on the bare module and wire bonding is used to create

electrical connections with the front-end chips. After QC, the modules are loaded on the local supports and connected as a serial powered chain to the on-detector services. Planar and 3D sensors use different module designs. In the first instance, a single large sensor tile is flip-chipped to four front-end chips for the planar pixels (*quad module*), while in the second case three single-chip bare modules are connected to the same flex in a *triplet* (either linear- or ring-shape depending on the final location in the detector). Quad modules are the same everywhere: only the pigtails connecting the modules to the services differ depending on the module position in the detector across all planar layers of the detector. After assembly, a protective parylene layer is deposited on the planar modules' surface. The isolation provided by this layer will stop electrical discharge between the front-end and the sensor. It will be advantageous to give the wire bonds more mechanical stiffness in addition to preventing corrosion effects.

ITk layout is summarized in Tab. 4.2 and in Tab. 4.3.

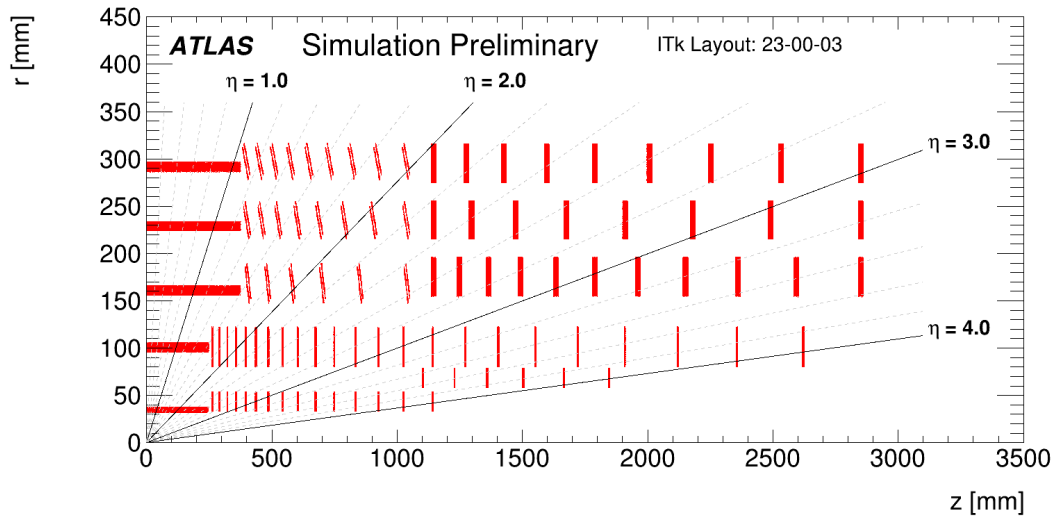


Figure 4.3: A zoomed-in view of the ITk pixel detector [49].

Barrel Layer	Radius [mm]	Rows of Sensors	Flat Barrel $ z $ [mm]	Flat Sensors per Row	Inclined Rings $ z $ [mm]	Inclined Rings	Module Type
0	34	12	0-245	24	-	-	triplets
1	99	20	0-245	12	-	-	quads
2	160	32	0-372	18	380-1035	2×6	quads
3	228	44	0-372	18	380-1035	2×8	quads
4	291	56	0-372	18	380-1035	2×9	quads

Table 4.2: Parameters for the ITk pixel flat barrel and inclined rings in the 23-00-03 layout. The number of sensors per row refers to a complete stave in the central, flat part of the barrel where sensors are placed parallel to the beam line. The number of inclined rings refers to both sides of the detector. Triplets consist of three connected read-out chips, each associated with a 2×2 cm² sensor, while “quad” modules are made of four connected read-out chips associated with a single 4×4 cm² sensor.

Ring Layer	Radius [mm]	$ z $ [mm]	Rings	Sensors per Ring	Module Type
0	33.20	263-1142	2×15	18	triplets
0.5	58.70	1103-1846	2×6	30	triplets
1	80.00	263-2621	2×23	20	quads
2	154.50	1145.5-2850	2×11	32	quads
3	214.55	1145.5-2850	2×8	44	quads
4	274.60	1145.5-2850	2×9	52	quads

Table 4.3: Parameters for the ITk pixel endcaps in the 23-00-03 layout. The radii refer to the innermost point of the sensors on a ring. The number of rings refers to both sides of the detector. Triplets consist of three connected read-out chips, each associated with a 2×2 cm² sensor, while “quad” modules are made of four connected read-out chips associated with a single 4×4 cm² sensor.

Fig. 4.4 shows the total number of expected pixel and strip measurements on track as a function of pseudorapidity, obtained using simulated single muons with $p_T = 1$ GeV. A minimum number of nine measurements is assured in the full detector acceptance, except for rare cases of tracks passing in the central gaps between pixel or strip barrel modules.

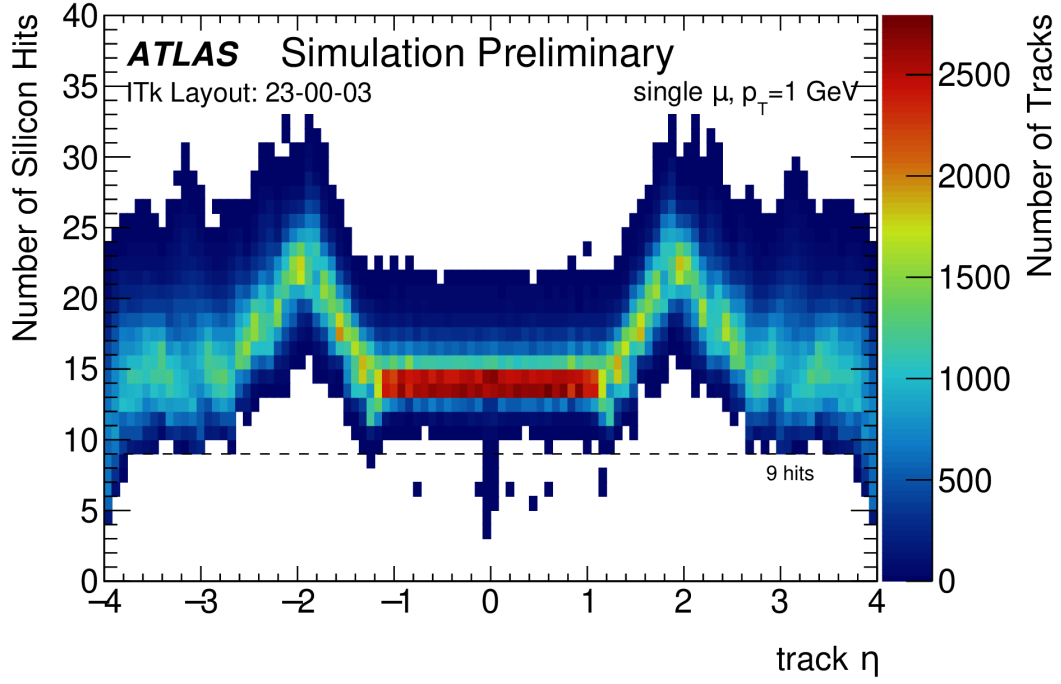


Figure 4.4: Number of strip plus pixel measurements on a track as a function of η . A sample of single muon events with $p_T = 1$ GeV is used. The muons are produced with a flat distribution between 0 to 2 mm in transverse distance to the beamline and at fixed values $z = -15$ cm, 0 cm, 15 cm, in equal amounts.

4.3 ITk Expected Performance

The reconstruction chain [50] starts with forming clusters of hits from the individual channels for the strip and pixel subdetectors. Each channel's ToT information is available for the pixel detector and is transformed into a representative charge measurement. Pixel and strip clusters are converted to 3D space-points. Building seeds, or combinations of three pixel or strip space-points, is where pattern recognition begins. Using precise knowledge of the material model and magnetic field, tracks are currently fitted using a global χ^2 -minimization technique. Tracks are ranked according to their hit content and track fit quality. When there is a conflict between two or more track candidates, the score difference is compared, and the track with the highest score is retained. The final tracks must satisfy the η -dependent requirements listed in Tab. 4.4.

Requirements	Pseudorapidity Interval		
	$ \eta < 2.0$	$2.0 < \eta < 2.6$	$2.6 < \eta < 4.0$
pixel + strip hits	≥ 9	≥ 8	≥ 7
pixel hits	≥ 1	≥ 1	≥ 1
holes	≤ 2	≤ 2	≤ 2
p_T [MeV]	> 900	> 400	> 400
$ d_0 $ [mm]	≤ 2.0	≤ 2.0	≤ 2.0
$ z_0 $	≤ 20.0	≤ 20.0	≤ 20.0

Table 4.4: Set of requirements applied during the track reconstruction in different pseudorapidity intervals. A hole is an intersection of the predicted particle's trajectory with an active sensor element from which no measurement is assigned to the track (inactive sensors are not taken into account). The hole counting doesn't consider layers before the first and after the last hit. z_0 and d_0 refer to the longitudinal and transverse impact parameters, respectively, and are defined with respect to the mean position of the beam spot.

4.3.1 Material Budget

The ITk system is significantly more complex than the current ATLAS tracker, with 60 times as many pixel channels and 10 times as many strip channels as the current system. The tracker's basic building block, the module, is made up of a sensor and readout electronics. In comparison to the current tracker, the ITk has about five times as many modules, and each module's surface is three times as large for the strip part and seven times as large for the pixel part, respectively. The amount of material has reduced in comparison to the current system, as shown in Fig. 4.5, despite an increase in surface and complexity.

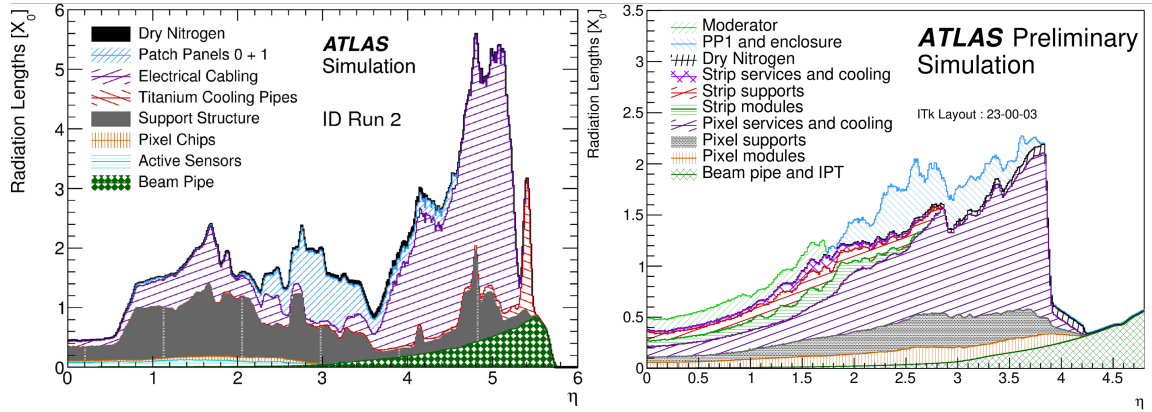


Figure 4.5: Comparison of material budget for the tracker in terms of X_0 between the present ID (a), and the current estimate for the ITk (b). Note that the vertical scale is not the same in the two plots. The ITk material distribution was updated in the first half of 2021 for the ITk Layout 23-00-03.

4.3.2 Efficiency and Number of Tracks with ITk

The data presented in Fig. 4.6 shows the effectiveness of the ITk detector for tracking 2, 10, and 100 GeV muons in the absence of pileup and it aligns well with results obtained using the Run 2 detector in the range of $|\eta| < 2.4$. It was noticed that there is a decrease of 0.5% in performance for 2 GeV muons in the barrel region, however, it is expected that with future adjustments to the tracking reconstruction configurations, especially by fine-tuning the material corrections, this decrease can be recovered.

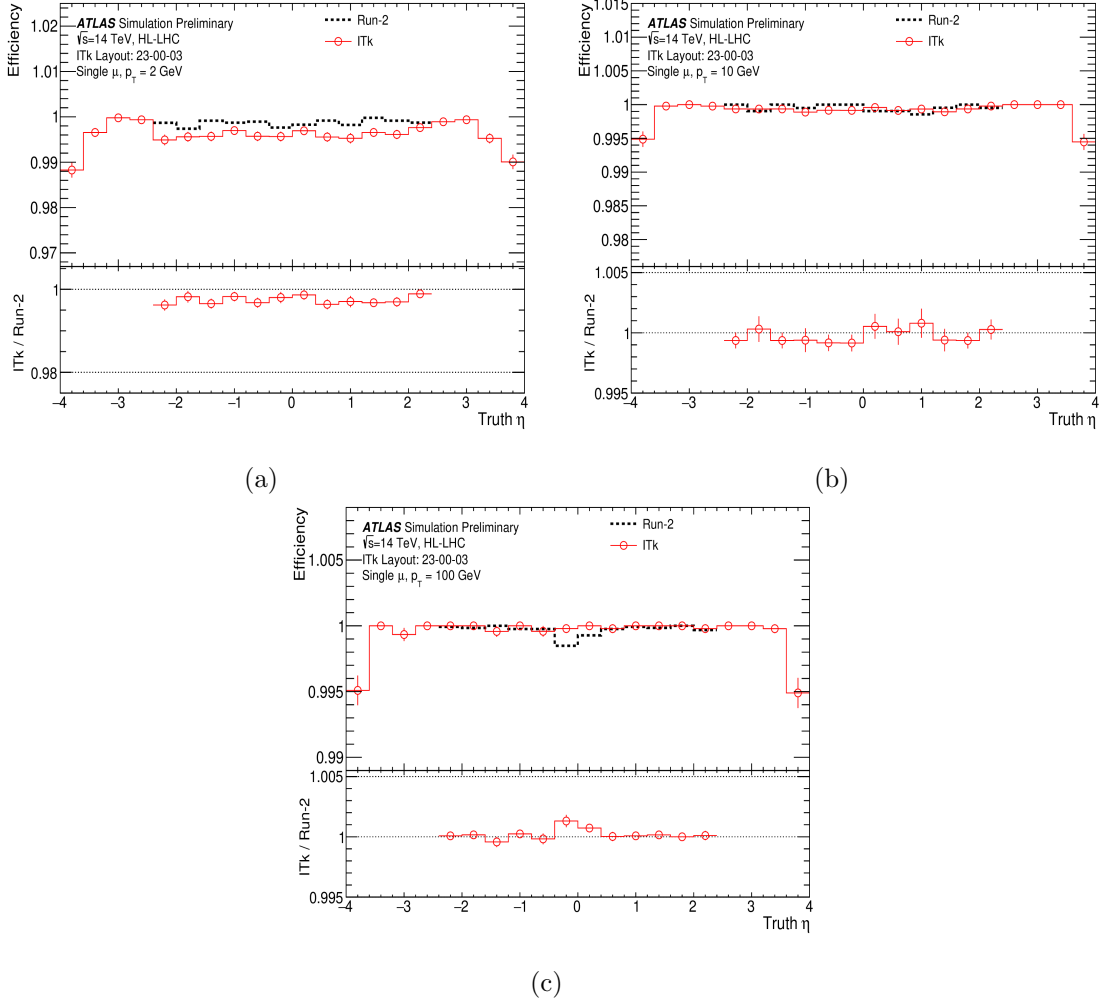


Figure 4.6: Tracking efficiency for single muons with $p_T = 2, 10$ and 100 GeV without pileup. The results are compared for muons between the Run 2 detector and the updated ITk layout.

The expected performance of the tracking system at an average number of interactions of $\langle \mu \rangle = 200$ is illustrated in Fig. 4.7. The figure showcases the efficiency of the system for $t\bar{t}$ events, specifically for particles with transverse momentum (p_T) greater than 1 GeV, originating from hard-scatter interactions as well as pileup interactions, all within the detector acceptance. This efficiency is compared to the efficiency obtained from the Run 2 detector when the average number of interactions is 38 . The performance of the tracking system in the central area of the ITk detector is comparable to that of the Run 2 detector, with a difference of 5% , and is similar to the performance in the forward area.

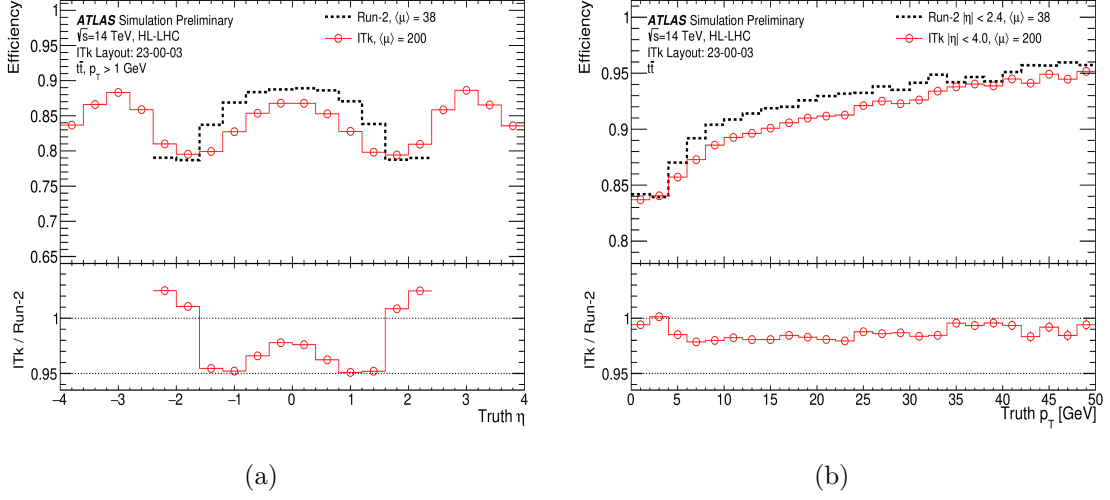


Figure 4.7: Tracking efficiency for $t\bar{t}$ events at $\langle\mu\rangle = 200$ with the updated ITk layout compared to the Run 2 detector at $\langle\mu\rangle = 38$.

The Fig. 4.8 depicts the number of tracks that have been successfully reconstructed with $p_T > 1$ GeV at an average number of interactions $\langle\mu\rangle = 200$. It can be observed that the graph is linear in its behavior with the ITk detector, indicating that the tracking efficiency remains robust over a wide range of pileup events and that the number of false tracks is minimal, estimated to be around 10^{-4} , despite the high average number of interactions. It's important to point out that in the preparation for the Run 3 data-taking the optimization of the tracking software already resulted in a significant decrease of the false rate compared to the Run 2 configuration.

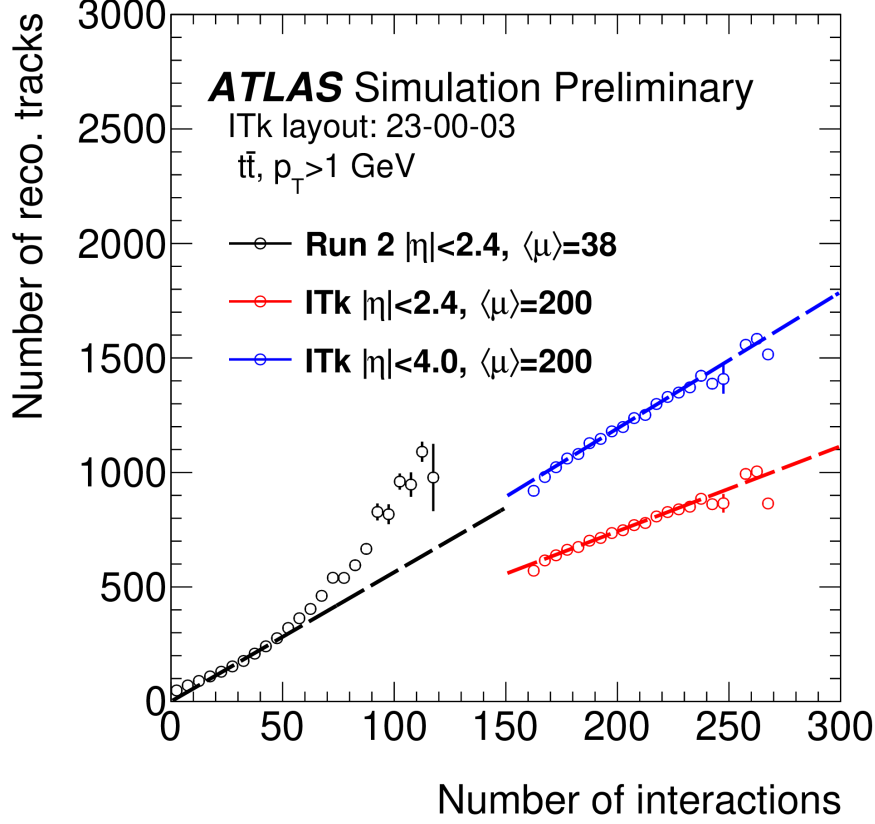
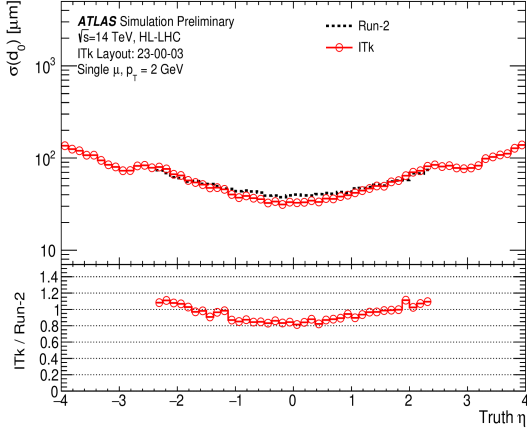


Figure 4.8: Number of reconstructed tracks per event with $p_T > 1$ GeV for $t\bar{t}$ events at $\langle \mu \rangle = 200$ with the updated ITk layout compared with the Run 2 detector at $\langle \mu \rangle = 38$. The dashed lines illustrate the results of linear fit performed over the limited range corresponding to 160 – 200 (0 – 40) interactions for ITk (the Run 2 detector) to illustrate the pileup dependence of this quantity. Note that the slopes of those linear fits are expected to differ between the different configurations presented.

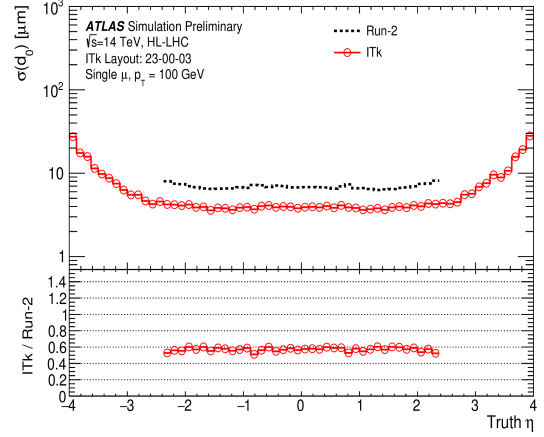
4.3.3 Track Parameter Resolution

Fig. 4.9 and Fig. 4.10 present the predicted precision of track parameter measurements for transverse (d_0) and longitudinal (z_0) impact parameters, as well as transverse momentum, for simulated muons with p_T of 2 and 100 GeV. These measurements are compared between the updated ITk layout and the Run 2 ATLAS detector. The similar radius of the innermost pixel layers in the ITk and Run 2 detector results in comparable d_0 resolution for 2 GeV muons, while the use of smaller pixel pitch in the ITk pixel detector (25×100 or $50 \times 50 \mu\text{m}^2$ against the pitch of $50 \times 250 \mu\text{m}^2$ for the IBL [21]) leads to a 2-fold improvement in z_0 resolution. For 100 GeV muons, which are less affected by material effects, the improvement in d_0 and z_0 resolutions are 2 and 4 times respectively. The transverse momentum resolution

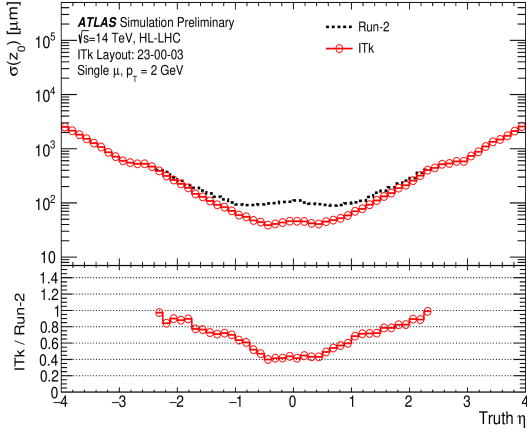
is only slightly impacted by the changes in the ITk layout and it is expected to perform better than the Run 2 resolution in the bending direction provided by the silicon strip sensors used in ITk, compared to the straw tubes used in the Run 2 ID.



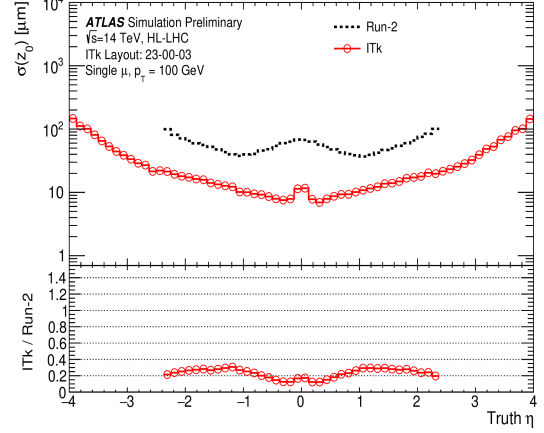
(a) Transverse impact parameter (d_0) resolution as a function of η for 2 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout.



(b) Transverse impact parameter (d_0) resolution as a function of η for 100 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout.

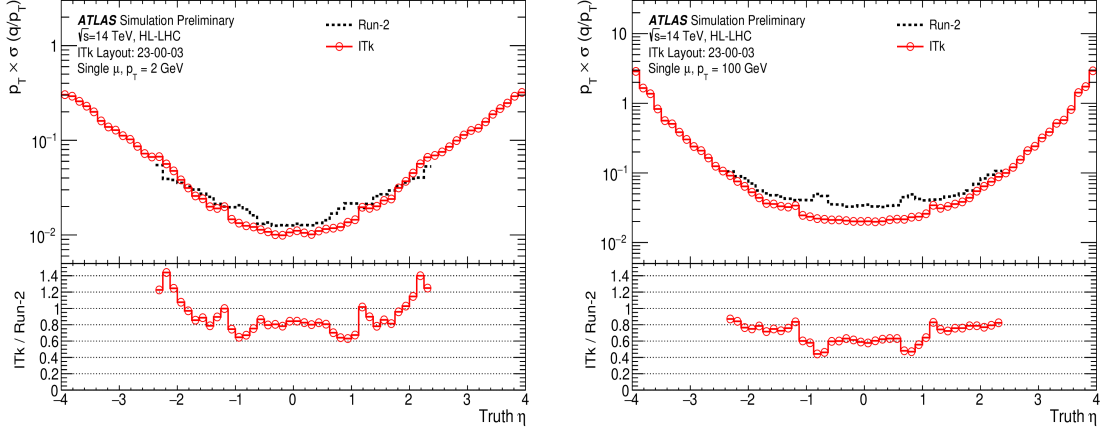


(c) Longitudinal impact parameter (z_0) resolution as a function of η for 2 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout.



(d) Longitudinal impact parameter (z_0) resolution as a function of η for 100 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout.

Figure 4.9: Expected track parameter resolutions for the transverse (d_0) and longitudinal (z_0) impact parameters for simulated muons with $p_T = 2$ and 100 GeV, compared for the updated ITk layout and the Run 2 ATLAS detector.



(a) Relative transverse momentum resolution as a function of η for 2 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout.

(b) Relative transverse momentum resolution as a function of η for 100 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout.

Figure 4.10: Expected track parameter resolutions for the transverse momentum for simulated muons with $p_T = 2$ and 100 GeV, compared for the updated ITk layout and the Run 2 ATLAS detector.

4.3.4 Jet Flavour Tagging

The identification of heavy flavor jets is carried out using low-level b-tagging algorithms that take advantage of the large impact parameters of tracks associated with b-hadron decay products for the IP3D algorithm, as well as properties of secondary vertices reconstructed from these tracks by the SV1 algorithm and the JetFitter algorithm [49]. The IP3D algorithm uses a log-likelihood ratio method, which is based on histogram templates of track impact parameter significances. These templates are constructed separately for different track categories that are defined based on the hit content and expected impact parameter resolutions. The performance of the SV1 and JetFitter algorithms is assessed through the utilization of a Boosted Decision Tree (BDT). This BDT incorporates various kinematic and topological vertex properties reconstructed by the SV1 and JetFitter algorithms to generate standalone discriminants. The outputs of all these low-level algorithms are combined using the MV2 multivariate algorithm, which uses another BDT [51]. The specific application and functioning of the algorithms for the ITk detector, as well as their performance results from previous design versions, have been discussed in greater detail in [49].

The performance of the new implementations is shown in Fig. 4.11 and is compared to the Run 2 performance using the same jet selections. The IP3D algorithm has improved performance, thanks to the better resolution of impact parameters expected with ITk and

the newly re-optimized track categorization. On the other hand, the SV1 and JetFitter performance is worse due to the higher rate of reconstructed secondary vertices (real and fake) in light jets, caused by the increased density of pileup tracks and the different amount of material in pixel layers near the interaction point. However, these algorithms still have some intrinsic discrimination that can be used for b-tagging. The best-performing algorithm is MV2, which has a 77 % b-jet efficiency working point and a light-jet rejection that is 20 % higher than what was achieved with the Run 2 detector, driven by the improved performance of IP3D. For all algorithms, the performance degrades with increasing $|\eta|$, which is expected based on the η -dependence of impact parameter resolutions. It's worth to mention that more powerful taggers such as DL1 [52] already exist for the current detector and will be studied for the upgraded ATLAS detector in the future.

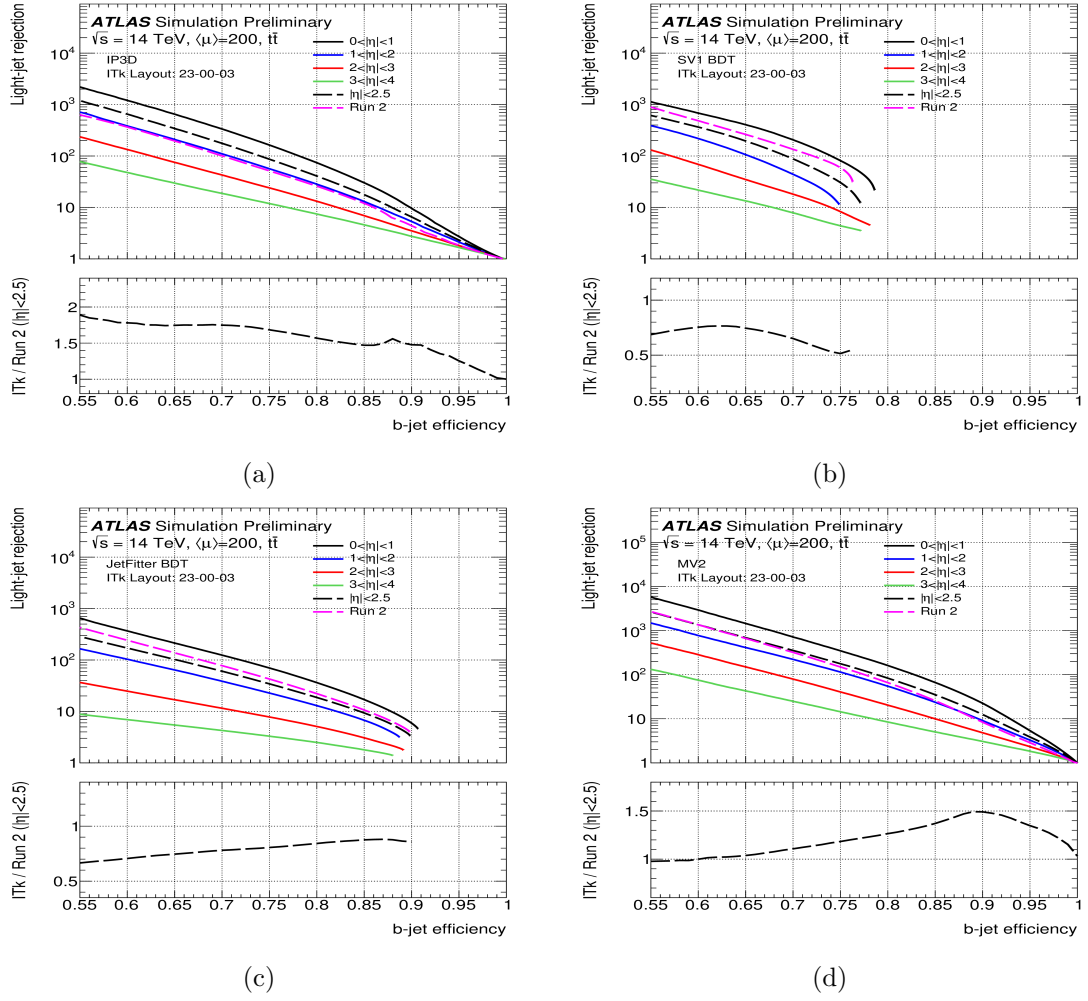


Figure 4.11: Light-jet rejection vs b-tagging efficiency for the IP3D (a), SV1 (b), JetFitter BDT (c) and MV2 (d) tagging algorithms for different η ranges, evaluated in $t\bar{t}$ events with 200 pileup events, obtained with the updated ITk layout.

4.4 ITk Pixel Modules

This section focuses on the main technical aspects concerning the 3D pixel modules for the ITk Upgrade.

4.4.1 3D Sensors

The sensors will be connected to the front-end chips of the ATLAS ITk pixel detector, which have a maximum capacitance of 100 fF per pixel. In the innermost layer, groups of three 3D modules will be connected to a single flex readout board, sharing the same bias voltage line. As previously mentioned, the innermost layer has strict requirements for performance after exposure to radiation. With the current plan, the fluence for the innermost pixel layer will exceed $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$. In these conditions, the hit efficiency must be at least 97 % before radiation exposure and 96 % after exposure at normal beam incidence, and 98 % and 97 % at a 14-15 degree incidence (the final orientation of the modules in the barrel of the ITk detector). The 3D sensors must have power dissipation performance better than $40 \text{ mW}/\text{cm}^2$ throughout the lifetime of the detector at a benchmark sensor temperature of -25° . The maximum operational bias voltage after irradiation should not exceed 250 V [53].

Specific productions of 3D sensor compatible with the first ITk prototype front-end chip (RD53A, presented in the next section) have been completed at CNM [54] (Spain, Barcelona), FBK [55] (Italy, Trento) and Sintef [56] (Norway, Trondheim).

Single-Side Approach

3D sensors are made by implanting electrodes vertically into bulk material using a method called Deep Reactive Ion Etching (DRIE) lithography. The p^+ and n^+ columns can be drilled from opposite sides of the silicon substrate (double-side approach) or just one side (single-side approach). However, the double-sided approach, which offers advantages in terms of process complexity and throughput, is not preferred for thin 3D pixels due to mechanical integrity and yield concerns. As a result, a single-side approach with a support wafer has been adopted by processing foundries. All columnar electrodes are etched from the front-side and at least partially filled with poly-Si. The junction (readout) columns stop at a safety distance of about $25 \mu\text{m}$ from the handle wafer, so as to avoid early breakdown, while the ohmic columns are etched deeper and penetrate the handle wafer. This allows the sensor bias to be applied from the back-side, which is beneficial for sensor assembly in a real detector system. To improve tracking performance, a portion of the handle wafer is removed as a post-processing step, leaving a thin section for back-side metal deposition for bias voltage. A schematic cross-section of this configuration is shown in Fig. 4.12. It should be noted that surface insulation layers, such as p-stop or p-spray, are not shown in the figure.

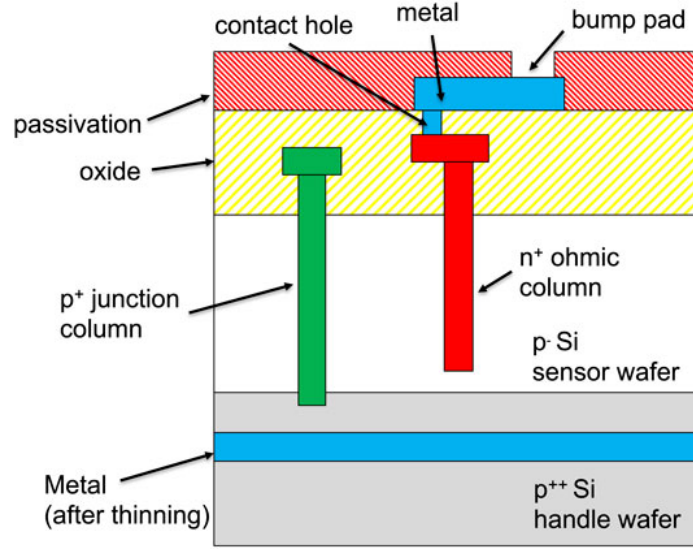


Figure 4.12: Schematic cross section of 3D pixels made from Si-on-Si bonded wafers. All the columns are etched from the top side. The handle wafer is thinned down to the desired thickness before depositing the metal on the backside. [53].

The Small Pixel Cells

On one hand, small pixel cells have small inter-electrode distance which improves the radiation hardness by reducing the drift length of charge carriers. On the other hand, high density of columnar electrodes can result in a loss of geometrical efficiency and an increase in sensor capacitance and noise. These issues can be addressed by using thin active layers. Assuming a constant aspect ratio (depth to diameter) attainable with Deep Reactive Ion Etching (DRIE) processing (typical values range from $\sim 20:1$ to $\sim 30:1$), a thinner substrates naturally lead to smaller capacitance and narrower electrode diameters (typical values range from ~ 5 to $\sim 8 \mu\text{m}$). It also contribute to decreasing the capacitance and improving the geometrical efficiency [57]. This is supported by the layout of the pixel cell, specific to the FBK technology, that is presented in Fig. 4.13 for three considered geometries in the R&D phase program. The three pixel cells differ in shape (50×50 or $25 \times 100 \mu\text{m}^2$) and number of the charge collector electrodes: one (1E) or two (2E). A key difference between the three cells is the different inter-electrodes distance of 35, 52, and $27 \mu\text{m}$ for 50×50 -1E, 25×100 -1E and -2E respectively (see Fig. 4.13), therefore significantly impacting the radiation hardness of the devices. The main constraint is the fixed size of the bump pads, which is relatively large compared to the pixel cell size, and the pad footprint is fixed due to the layout of the readout chip. This represents a critical problem in 25×100 -2E pixels, where the bump pads are very close to both the readout and the ohmic columns, making the layout very sensitive to lithography misalignment, making it difficult to obtain a good fabrication yield.

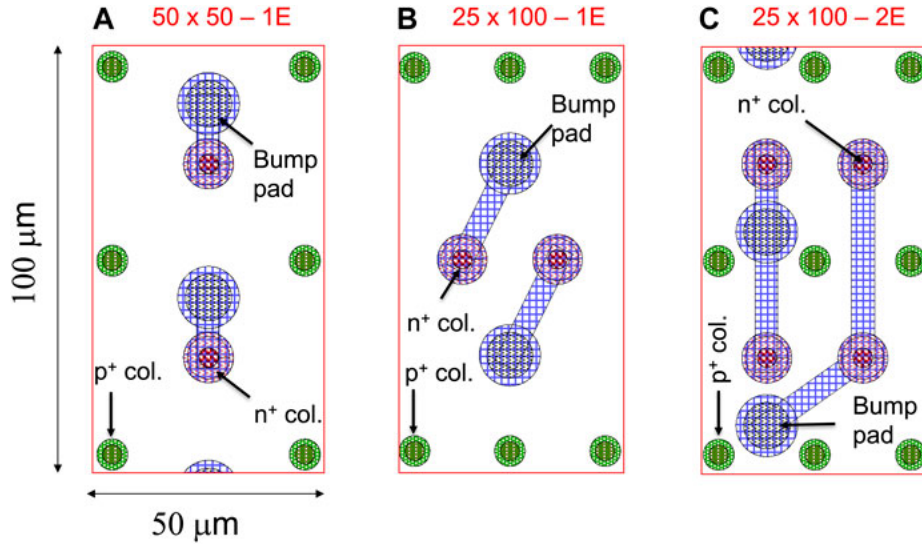


Figure 4.13: Layout of 3D sensors pixel cell: A) $50 \times 50 \mu\text{m}^2$ 1E. B) $25 \times 100 \mu\text{m}^2$ 1E. C) $25 \times 100 \mu\text{m}^2$ 2E. Only the FBK version is shown [53].

4.4.2 The Modules R&D: the RD53A Project

The RD53 Collaboration [58] was formed with the aim of developing the technology and design framework specifically for the pixel chips needed by the ATLAS and CMS detectors at the High Luminosity Large Hadron Collider. The collaboration comprises 18 member institutes. The primary deliverable of the RD53 Collaboration is the RD53A integrated circuit, which aims to validate the design environment and basic circuit blocks that will be reused in the production chips, thus minimizing most of the technical risk from the production design.

The RD53 collaboration have chosen the 65-nanometer feature size process mostly for its high logic density, not for radiation tolerance or smaller pixel size [59]. Logic density is essential for efficient operation in a very high hit rate environment with relatively long trigger latency as it determines how many hits can be stored per unit area during the latency period. Although radiation tolerance considerations exclude the use of the smallest size devices in the 65-nanometer technology, the logic density achieved is still about 3 times higher than in the 130-nanometer technology for similar radiation tolerance [44].

The RD53A chip (in Fig. 4.14) was designed to conform to prototype specifications that were previously established and approved by ATLAS and CMS. Due to budget constraints, the chip's physical size is smaller than what is desired for production, but it is still large enough to test the effects of larger chip designs and performances. The RD53A measures 20 mm in width and 12 mm in height, it has 76,800 pixels and 240 million transistors. It features three various analog front-end designs, Synchronous, Linear and Differential and two distinct pixel matrix read-out architecture implementations, allowing for in-depth performance evaluations. A discussion of the differences between the three FEs is beyond

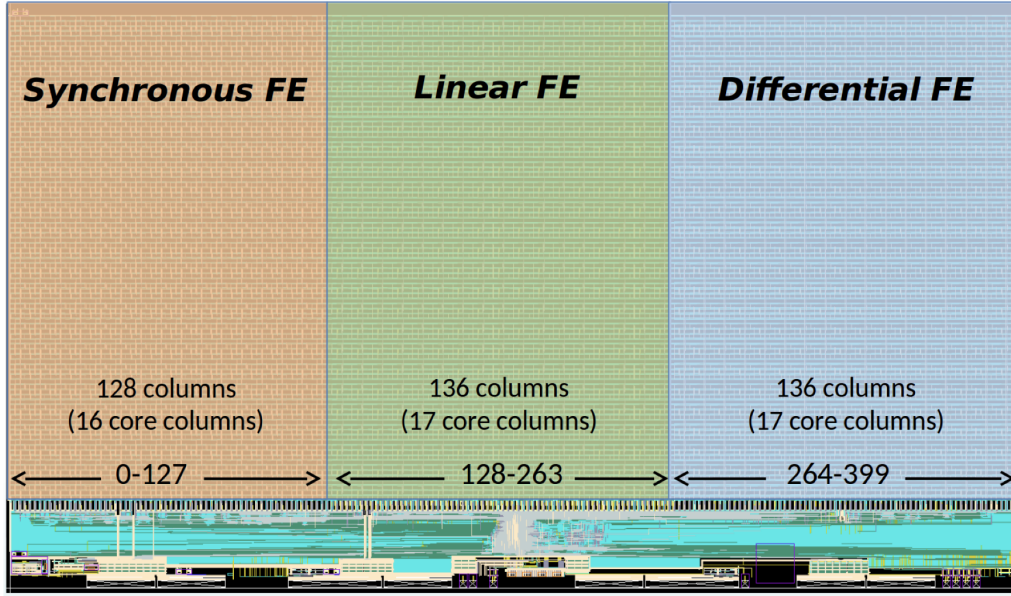


Figure 4.14: Photograph of the RD53A integrated circuit .

the scope of this thesis. A clear treatment can be found in [44]. Relevant, however, is the choice of Differential front-end design by the ATLAS collaboration, while the CMS collaboration chose to adopt Linear front-end for the construction of its chips.

The vendors FBK and SINTEF manufacture sensors on six-inch wafers, with 24 sensors per wafer, while CNM will produce them on four-inch wafers, with 9 sensors per wafer. The prototype results from all three vendors met the requirements, allowing for the move to the pre-production phase. As specified in the tender, FBK and SINTEF will produce the $50 \times 50 \mu\text{m}^2$ endcap sensors, while CNM will produce the $25 \times 100\text{-}1\text{E} \mu\text{m}^2$ barrel sensors. It's worth noting that for the ITk sensors, the edge termination is achieved using a $150 \mu\text{m}$ p-type column fences. FBK was the first vendor to deliver pre-production sensors in the summer of 2021. Results for both unirradiated and irradiated pre-production 3D sensors will be discussed in the following sections.

4.4.3 From R&D to Pre-Production: ITkPixV1.1

Compared to the Inner Detector and IBL ones, the read-out chips of the ITk modules will need to be much more radiation resilient. Due to the increased number of tracks, they will also need to be able to process more data. The main requirements of the ITk chips are the amplification and discrimination of signals in each pixel within 25 ns, handling and storage of hit data on chip until trigger signal arrives (ATLAS latency is $\sim 10 \mu\text{s}$) and sending out data with a rate up to $4 \times 1.28 \text{ Gbit/s}$.

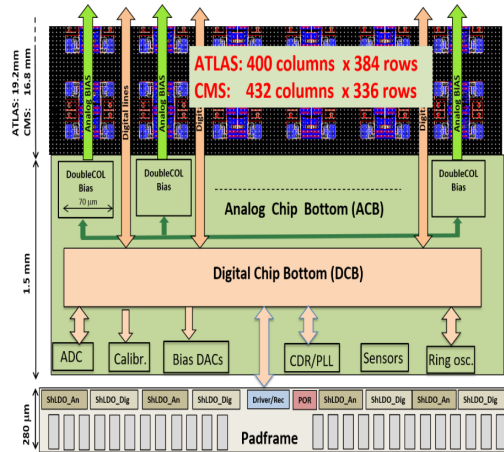
In order to characterize the sensors and develop multi-module systems, prototype modules with planar and 3D pixel sensors were constructed using the RD53A chip. For several

years, ATLAS and CMS worked together to test various devices. Following the success of the RD53A prototypes and their constructive criticism, RD53 continued to work on the final front ends for ATLAS and CMS. In order to maintain the development of the key building blocks as common as possible, a new common library has been created, known as RD53B, from which the ATLAS (ITkPixV1) and CMS derive in the final layout (CROC v1). The geometrical dimensions to accommodate different mechanical detector layouts and the analog read-out are the main differences between the two chips.

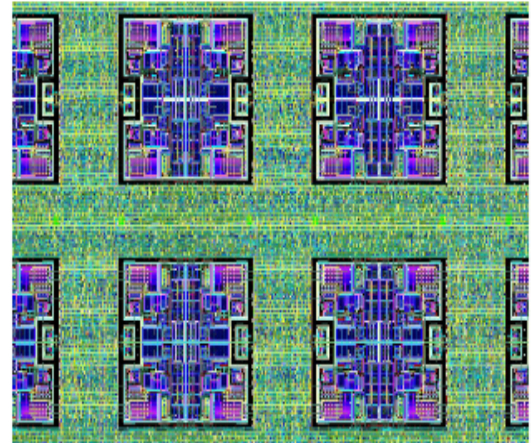
ITkPixV1.0, the ATLAS chip’s first version was submitted in March 2020. This very first version had a Time over Threshold (ToT) issue that resulted in a significant current increase and rendered it useless for data collection. In 2021, an updated version called ITkPixV1.1 was released. This version solved the ToT problem by simply disabling the ToT reading simply by modifying the most superficial layer of the silicon wafer during chip production. Only the binary readout of the hits is then feasible in this way. As a result, ITkPixV1.1 is still a prototype, and ITkPixV2, the chip’s final iteration, will be submitted at the end of 2022. Improvements to ITkPixV1 will be made, including the design fixture in the ToT.

General Characteristics

The ITkPixV1 chip measures approximately 2×2 cm and features a matrix of 384×400 pixels ($50 \times 50 \mu\text{m}^2$). The design and functional layout of the ITkPixV1 floorplan can be seen in Fig. 4.15a. The sensitive area of the chip, the pixel matrix, is located at the top and is organized as a matrix of 8×8 identical pixel “cores” that are repeated in 50 columns and 48 rows. The 64 core pixels are grouped in 16 identical “analog islands” with 4 pixels each and are embedded in a flat digital synthesized “sea” as depicted in Fig. 4.15b.



(a) Functional floorplan of the RD53B, the number of pixels columns and rows is shown both for the ATLAS ITkPixV1 and CMS CROC v1 chips.



(b) Layout view of analog island within the synthesized logic. Four complete islands can be seen in the center of the figure. One core contains 4 by 4 analog islands.

The peripheral circuitry, also known as the chip bottom, is located at the bottom of the chip and contains all the necessary systems and functionality for the chip, as well as the wire bonding pads. It includes all the global analog and digital circuits required for biasing, configuring, monitoring, and reading out the chip. The analog building blocks are grouped together in a block called Analog Chip Bottom (ACB), which is fully constructed and characterized in an analog environment. The ACB block is surrounded by a digital block called Digital Chip Bottom (DCB), which handles the input, output, and configuration of digital logic. The wire bonding pads are arranged in a single row along the edge of the chip, with a 1.7 mm separation from the first row of bumps, to ensure safe wire bonding after the sensor flip-chip.

Chip Powering The chip can be operated in either a passive or active mode. In passive mode, the chip's analog and digital circuits are powered directly by the supply voltage. In active mode, special regulators called Shunt-Low Drop Out (SLDO) are used to supply the voltages on the chip. These regulators are designed to maintain a constant voltage level during chip operation by diverting any excess current to ground. Additionally, the regulators can also be configured as pure Low Drop-Out linear voltage regulators for use in a traditional voltage-based supply scheme. The ITkPixV1 chip uses two different regulators, one for the analog components (SLDO-A) and one for the digital components (SLDO-D), which allows for both components to be powered by a single generator [60].

Pixel cell The electronics integrated into each pixel cell enable the amplification, differentiation of noise, digitalization, and temporary storage of hits. These functions are performed by the two main components of the chip: the analog and digital blocks. A diagram of the main components of a pixel cell is illustrated in Fig. 4.16. Further information on the two front-end electronics is provided in the following sections.

Pixel cell analog block The analog block of the chip processes the signal received from the sensor. It includes an operational amplifier (OA) with a feedback capacitor C_f that functions as a charge-sensitive amplifier, converting input charge into a voltage output. Once the OA reaches stability, the capacitor must be discharged to allow for the collection of the next signal. This is accomplished by a second circuit that supplies current to the feedback resistor, making the output signal duration proportional to the input charge. The current value of the discharge circuit can be adjusted to fine-tune the relationship between input charge and output signal duration. Additionally, a third circuit is integrated to compensate for any leakage current from the sensor that could potentially interfere with the OA's signal integration.

The analog block receives the signal from the sensor and amplifies it using a charge-sensitive operational amplifier (OA) with a feedback capacitor C_f . The output is then discharged to allow for the collection of the next signal. A second circuit is integrated to control the discharge and adjust the relationship between the input charge and the duration of the output signal. A third circuit is also integrated to compensate for high sensor leakage

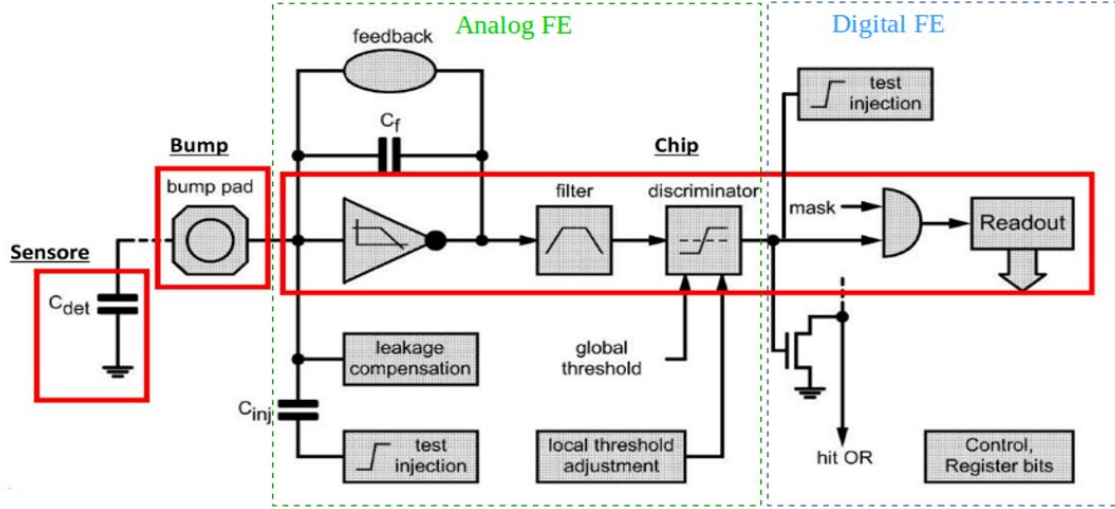


Figure 4.16: Analog and digital FE of a generic pixel cell components [38].

current. The output of the OA is then sent to a discriminator that separates the signal from background noise. If the signal exceeds the set threshold, it is digitized and sent to the digital block. The threshold can be adjusted globally (GDAC) or individually (TDAC) to balance between minimizing noise and maximizing detector efficiency cell by cell. The block also includes a charge injection circuit that simulates a particle interaction with the sensor, useful for testing and optimization without the need for a sensor or bump bond.

Pixel cell digital block The digital block processes the signal received from the analog block, but only if it surpasses the set threshold (sparse readout). In such cases, the digital block records the digitized signal and sends it out of the pixel cell. However, if the pixel is blocked (i.e. disabled), the signal will not be transmitted. Pixels can be disabled for various reasons, such as poor tuning of the threshold or excessive noise.

The digital block also records information about the column, row, the Time over Threshold (ToT) and the trigger. Additionally, like the analog block, it also has an injection circuit that simulates the signal of a particle interacting with the sensor by sending a digital input. This circuit is useful for testing the digital front-end.

The way in which a pixel is read depends on the type of experiment it is used in. In high rate experiments like ATLAS, a trigger signal is used to distinguish relevant hits from background noise. This trigger signal is sent to certain modules and enables the reading of specific hits based on a predetermined logic. In the ITkPixV1 chip, this external trigger is managed by the digital block, which then sends it to individual pixels. Additionally, for low rate experiments or testing purposes, the ITkPixV1 chip can also trigger the pixel matrix by using a circuit called Hit-OR. If a pixel records an event, it generates a Hit-OR signal and sends it to the digital block, which then acts as an external trigger for all pixels in the matrix.

Chapter 5

The ITk 3D Modules Qualification

5.1 Introduction

In this chapter, we will focus on the testing of the ITk 3D module, which has been performed both in Genova Laboratories and through beam test campaigns at DESY and at PS and SPS at CERN, after irradiating them up to $1.5 \times 10^{16} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ to study their behavior after exposing them to the very challenging environment of HL-LHC. The modules under test included both RD53A (R&D) modules and pre-production 3D modules, featuring sensors made by FBK and ITkPixV1.1 chips. The tests aim to evaluate modules performance in terms of their operability, efficiency, and noise levels.

The modules are mounted on what are called Single Chip Cards (SCC). These test cards are equipped with a large number of outputs for reading various parameters of both sensor and chip (voltage, current, temperature etc.). The results of the testbeam campaigns have shown that the ITk 3D modules have achieved excellent efficiency levels, meeting the design requirements for the HL-LHC environment.

Tab. 5.1 shows all the modules tested in the beam tests at DESY, PS, and SPS.

Module Name	Pixel Cell Dimension [μm^2]	Chip Version	Beam Test Facility	Irradiation Facility
W91-02	25×100	RD53A	DESY	/
W30-D11.3	25×100	RD53A	DESY	BU
W30-E3.3	50×50	RD53A	DESY	CYRIC
W30-E9.5	25×100	RD53A	DESY	CYRIC
SCC 2	50×50	ITkPixV1.1	PS	IRRAD
SCC 3	50×50	ITkPixV1.1	SPS	Bonn
SCC 4	50×50	ITkPixV1.1	PS and SPS	/
SCC 5	50×50	ITkPixV1.1	SPS	Bonn
SCC 6	50×50	ITkPixV1.1	/	/
SCC 8	50×50	ITkPixV1.1	/	IRRAD

Table 5.1: Devices list tested during DESY and CERN Beam Test campaigns.

5.2 Module Test Procedure

5.2.1 The Sensor IV Scan

To assess the performance of the sensors, each one is subjected to an IV curve measurement (refer to Sec: 3.3). The IV curve is obtained by incrementally increasing the V bias from 0 V to 80 V, in steps of 1 V. To carry out this measurement the high voltage power supply Keithley 2410C, which is integrated into the DCS, is used. The temperature of the module is monitored during the data collection process by utilizing the NTC situated near it. The IV curves are collected at room temperature, with the module being cooled solely by a fan positioned below the test board SCC. The results are presented in Fig 3.3. For each sensor, the breakdown voltage V_{bd} is determined. The V_{bd} is defined as the minimum voltage at which the leakage current rises by a factor of 2 over 5 V (refer to Eq. 5.1).

$$I_{leak}(V + 10V)/I_{leak}(V + 5V) > 2 \quad (5.1)$$

As V_{bd} exceeds 80 V for each of the sensors, the condition of $V_{bd} > V_{depl} + 20$ V (where V_{depl} is roughly 5 V for 3D sensors) is satisfied. Prior to this, IV curves were obtained for the sensors on a wafer in Trento, and the leakage current remained below 1 μ A for all of them. To compare the results of the two sets of measurements, the current is adjusted to the temperature of 20°C, which is achieved through the application of the following equation:

$$I_{leak}(T) = I_{leak}(T_R) \cdot \left(\frac{T}{T_R}\right)^2 \cdot e^{\left[\frac{E}{2k_B} \cdot \left(\frac{1}{T_R} - \frac{1}{T}\right)\right]} \quad (5.2)$$

The aforementioned equation is used to adjust the current to 20°C, where $T = 20^\circ\text{C}$, T_R represents the temperature at which the IV curve was obtained, E denotes the silicon energy gap, and k_B is the Boltzmann constant. The results from the wafer measurements are generally consistent with the leakage current detected in Genova on the SCC. The slight increase observed in Genova is not a major concern and could be attributed to the hybridization procedures such as wafer dicing and flip-chip bonding. Even after normalizing the leakage current to the sensor area (3.84 cm²), it remains insignificant compared to the sensor specification of 2.5 $\mu\text{A}/\text{cm}^2$. All sensors satisfy the leakage current requirement. The results of the SCC IV curves are illustrated in Fig. 5.16 and Fig. 5.26.

5.2.2 The Module Configuration

To achieve optimal chip operation, it is necessary to trim several parameters. The main current, I_{REF} , serves as a reference for generating all internal voltages of the chip, making precise trimming crucial. The desired value for I_{REF} is 4 μA . During the trimming process, voltage values to be checked can be adjusted by placing jumpers on SCC pins or modifying the chip configuration file parameters. Voltages can be monitored using specific SCC pins and a multimeter. The trimming procedure can be summarized as follows:

- Power on the chip in the LDO mode with a low voltage of approximately 1.6 V (for the RD53A an input voltage of 1.4 V was required).
- Configure the chip with parameters obtained from wafer measurements using a digital scan.
- Measure $V_{ref-ADC}$ using dedicated SCC pins.
- Adjust $V_{ref-ADC}$ by placing jumpers on the four I_{REF} pins on the SCC, aiming to get it as close to 0.845 V as possible.
- Adjust VDDD and VDDB values by modifying their respective parameters in the chip configuration file, targeting a value of 1.2 V for both voltages. VDDB should be measured against the analog ground reference (GND-A), whereas VDDD should be measured against the digital ground reference (GND-D). Values can be monitored using dedicated SCC pins and a multimeter.
- In the ITkPixV1.1 chips, to verify the calculated parameters, it can be measured V_{OFS} and V_{REF} against GND-A. To monitor V_{REF} , set the *MonitorI* parameter on the chip configuration file to 0 and use a jumper on the R-MUX pin. The monitoring pin for V_{REF} on the SCC is labeled as IMUX. The desired target value for V_{OFS} is 0.5 V, while for V_{REF} it is 20 mV.

5.2.3 The Chip Scans and Tuning

Several scans can be run on the chip, these allow verifying the correct functioning of the FE, tuning the thresholds, and collecting data. The scans and their purposes are listed in Tab. 5.2 and will be described in the following paragraphs.

Scan	Purpose
Analog	Charge injection to test the analog FE
Digital	Charge injection to test the digital FE
Threshold tuning	Allows tuning the pixel threshold
Threshold	Returns the pixel threshold
Noise occupancy	Allows masking noisy pixel
Self-trigger	Data taking
Time-over-Threshold	Test the uniformity in terms of ToT

Table 5.2: ITk module scans and their purpose.

Analog Scan The analog scan is employed to validate the proper functioning of the analog FE. During this process, N pulses (generally 100) are introduced to each pixel via the analog injection circuit inside the pixel cell. These pulses carry a charge that exceeds the maximum threshold of the pixel. Any pixel that records more or less than N hits is identified as faulty and gets masked. The results of the analog scan include two maps: one shows the hits detected by each pixel, while the other displays the masked pixels.

Digital Scan The process of digital scanning is used to verify the accurate functionality of the digital FE. In this method, the digital injection circuit inside each pixel cell delivers N digital signals (usually around 100) for testing. Any pixel that detects a number of hits greater or lesser than N is identified as faulty and gets masked. The outcomes of the scanning procedure are represented as two maps: one shows the hits registered by each pixel, while the other displays the masked pixels.

Threshold Scan The threshold scan is used to verify the threshold of each pixel in the chip. For this process, N pulses (typically 50) are introduced to each pixel for a set of predefined charge values. The intensity of the pulse increases from 200 to 2000 electrons, in increments of 100 electrons. The number of hits recorded is saved for each charge value, and an S-curve is fitted (as shown in Fig. 5.1). The charge value that records 50% of the N pulses is referred to as the average pixel threshold. Another parameter measured is the noise, which is defined as the width of the S-curve between the charge values that correspond to 10% and 90% of the recorded pulses. The scan outputs include maps for the threshold and noise, their distributions for each pixel, and the pixel TDAC maps.

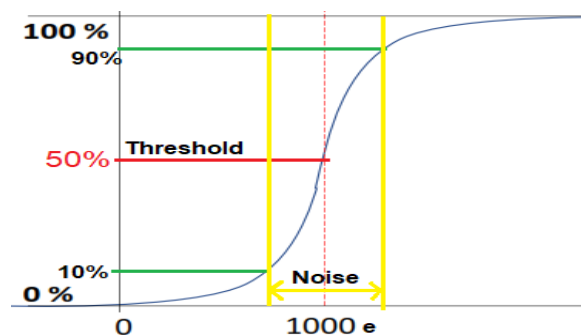


Figure 5.1: Threshold S-curve sketch.

Noise Occupancy The noise occupancy scan is performed to detect and mask pixels that exhibit high levels of noise. In this scan, a trigger with a fixed frequency is transmitted, and the number of hits for each pixel is recorded. It is recommended to run this scan without an external source to accurately detect the noisy pixels. The outputs of the scan include maps for noise occupancy and masked pixels. A pixel is classified as noisy when its noise

occupancy exceeds 10^{-6} , with noise occupancy defined as the ratio of the number of hits recorded to the number of received triggers, as shown below:

$$\text{Noise occupancy} = \frac{\text{Number of hits recorded}}{\text{Number of received triggers}} \quad (5.3)$$

Self-trigger Scan The self-trigger scan is used to accelerate data acquisition when an external source, such as a radioactive source or X-ray tube, is being used. This scan is based on the Hit-OR circuit of the pixel matrix. When a pixel detects a hit, a Hit-OR signal is produced by that pixel and transmitted to all other pixels in the matrix as a trigger signal. Essentially, whenever any pixel records a hit, the entire matrix is read. The scan outputs comprise of maps for pixel occupancy and their corresponding distributions.

Time over Threshold The ToT scan is allowed only on RD53A. In ITkPixV1.1, because of a bug, the ToT was hard-coded to a fixed value in the chip. This scan is used to verify the uniformity of pixel response in terms of ToT at a fixed value of the charge. This charge is injected 100 times into each pixel in the RD53A chip array, which performs the calculation of the ToT corresponding to each injection. At the end of the scan, each pixel is associated with a ToT value, corresponding to the average of the 100 measurements taken.

5.3 Module Testing at Genova Laboratories

5.3.1 Test Setup

The module testing setup inside the Genova laboratory (Fig. 5.2) consists of two PCs (“DCS PC” and “YARR PC”), low voltage and high voltage power supplies.

The DCS The main objective of the Detector Control System (DCS) is to oversee the surroundings, such as the temperature and humidity of the environment and module, and to automatize the control of both Low Voltage (LV) and High Voltage (HV) power supplies. To monitor the environmental temperature and humidity, a Sensirion SHT85 sensor is used, while an NTC placed on the SCC top close to the module is used to measure the temperature of the module. An Arduino-based system records the temperature and humidity and communicates with the DCS PC. To power the sensor, a Keithley 2410C supplies the required High Voltage (HV), and for the chip, an Agilent E3631A supplies the necessary Low Voltage. The power supplies are connected to the DCS PC through the General Purpose Interface Bus (GPIB) interface.

YARR A different PC is exclusively used for data acquisition purposes. This PC is furnished with a commercial Field Programmable Gate Array (FPGA) card known as Trenz Electronic TEF1002. The FPGA card is responsible for communicating with the modules through Display Port (DP) cables. The latest version of the Yet Another Rapid Readout

(YARR) software and firmware have been installed to enable smooth communication with the chip. Presently, YARR is the primary suite employed for ITk module testing, and the scans described in Sec. 5.2.3 are performed using this software.

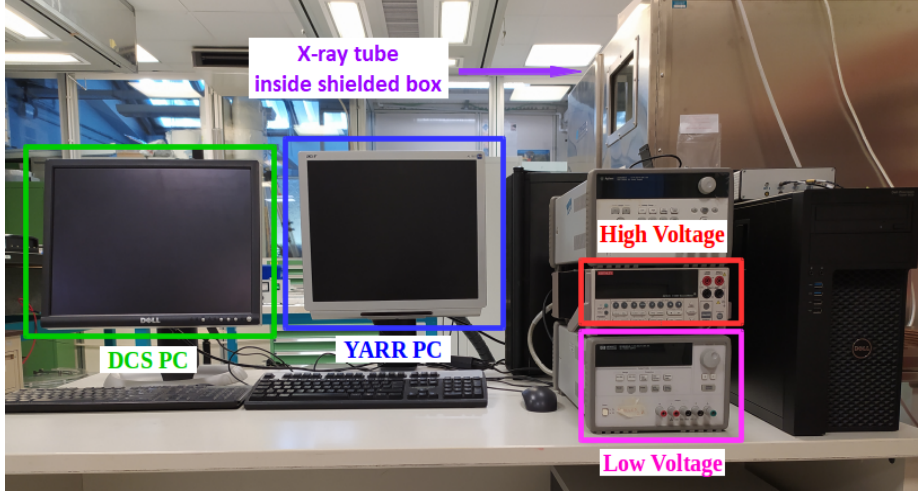


Figure 5.2: Genova laboratory module testing setup.

To make handling and cable connections easier, the modules were mounted on SCCs. The SCCs were prepared beforehand to hold the modules by milling the area where the module will rest on the PCB and gluing a thin aluminum plate onto the SCC with radiation-hard glue, Araldite 2011. The aluminum plate is advantageous as it results in lower material activation than the SCC material in case of irradiation, allowing for a shorter time for cool-down, and also facilitates thermal coupling of the module to the environment during testing after irradiation. Once the module is glued onto the aluminum plate with Araldite 2011, wire-bonding to the SCC is performed. A visual inspection of the wirebonds is carried out with a digital microscope, and any poorly fixed wirebonds are removed and replaced. The module is protected with a 3D-printed plastic cover after wirebond visual inspection. Details of the milling area, aluminum plate and wirebonds, for ITkPixV1.1 SCC 2 module after its assembly are shown in Fig. 5.3a, 5.3b, and 5.4, and 5.5, respectively.

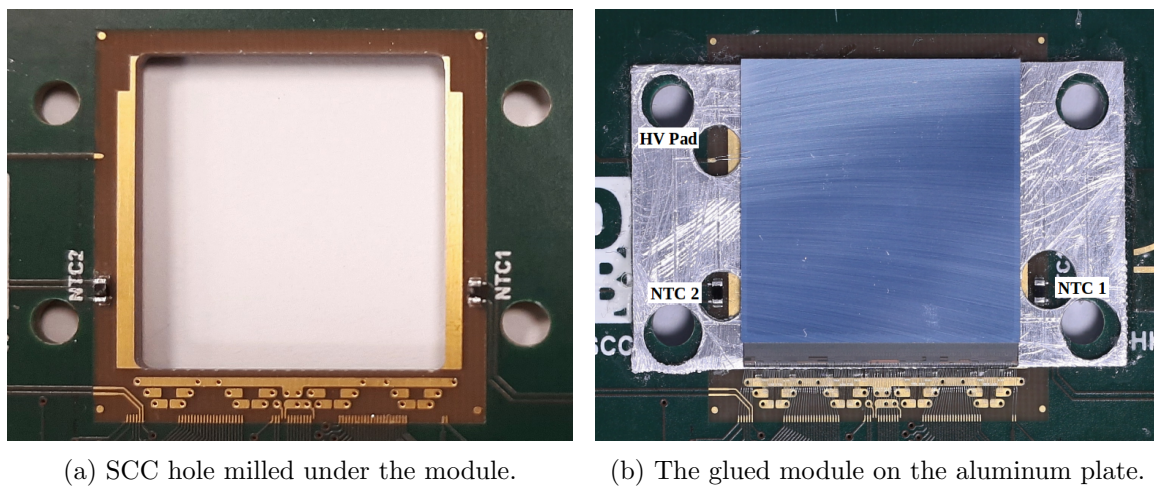


Figure 5.3: Details of the SCC before and after the aluminum plate glued to the module.

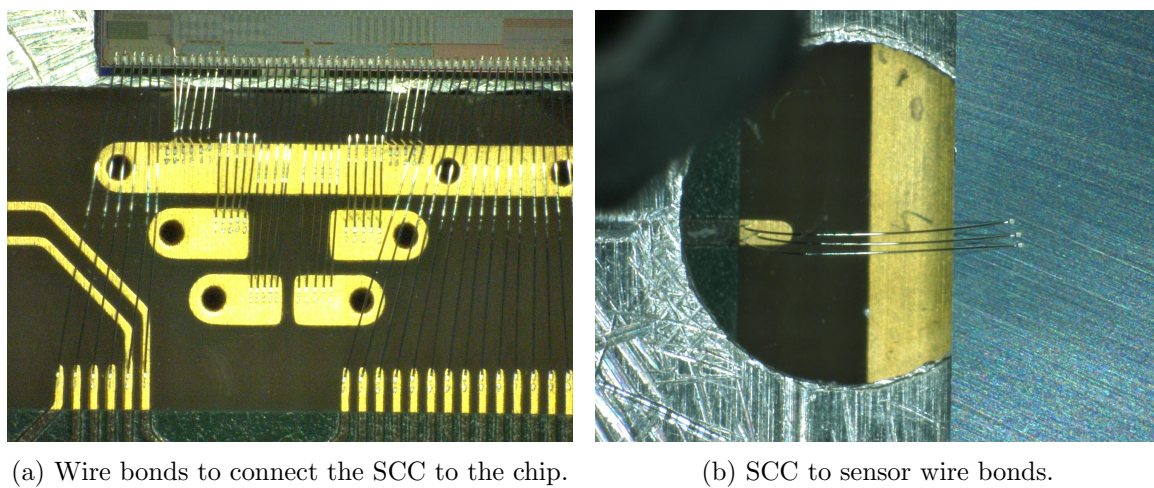


Figure 5.4: Details of the wirebonds from SCC to chip pads and the sensor back.

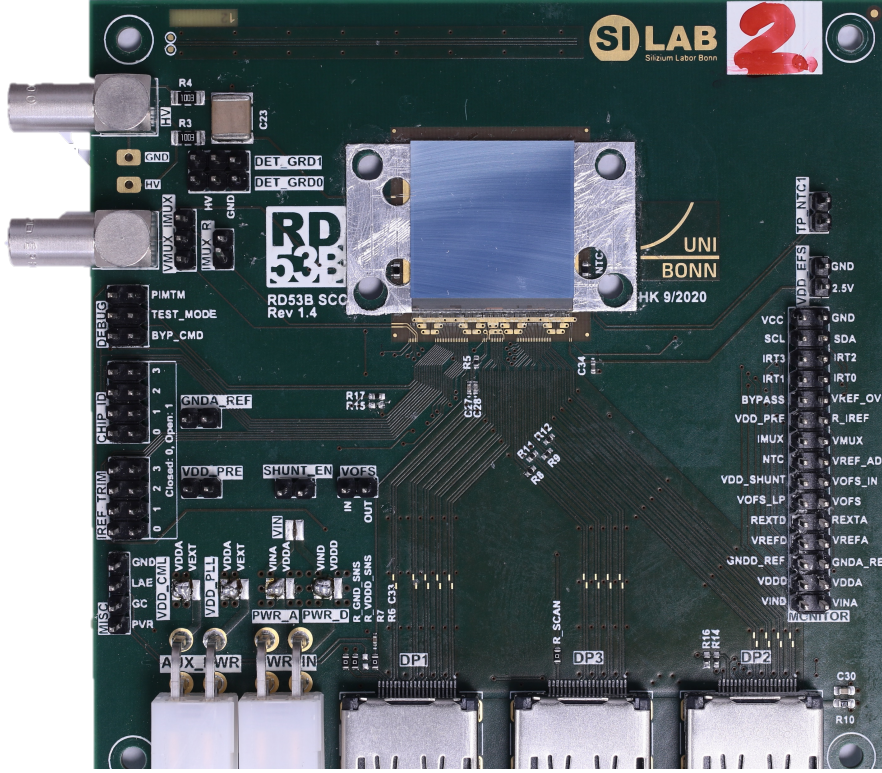


Figure 5.5: The second FBK+ITkPixV1.1 bare module mounted on an SCC.

Modules testing procedure is divided into several steps. The main goals are to verify the correct operation of the chip and the sensor and to check the goodness of bump-bonding connection between the two parts. The procedure starts with the sensor IV scan, after that the configuration parameter of the module have to be set for optimal operation and then one proceeds with a digital scan, an analog scan and end with a threshold tuning.

An example of this procedure is reported in the following section.

5.3.2 RD53A Results

Digital, Analog, Threshold Scan and Noise Distribution

The digital and the analog scans are done as explained in Sec. 5.2.3, 5.2.3. In Fig. 5.6a and Fig. 5.6b are shown a digital scan and an analog scan output plots.

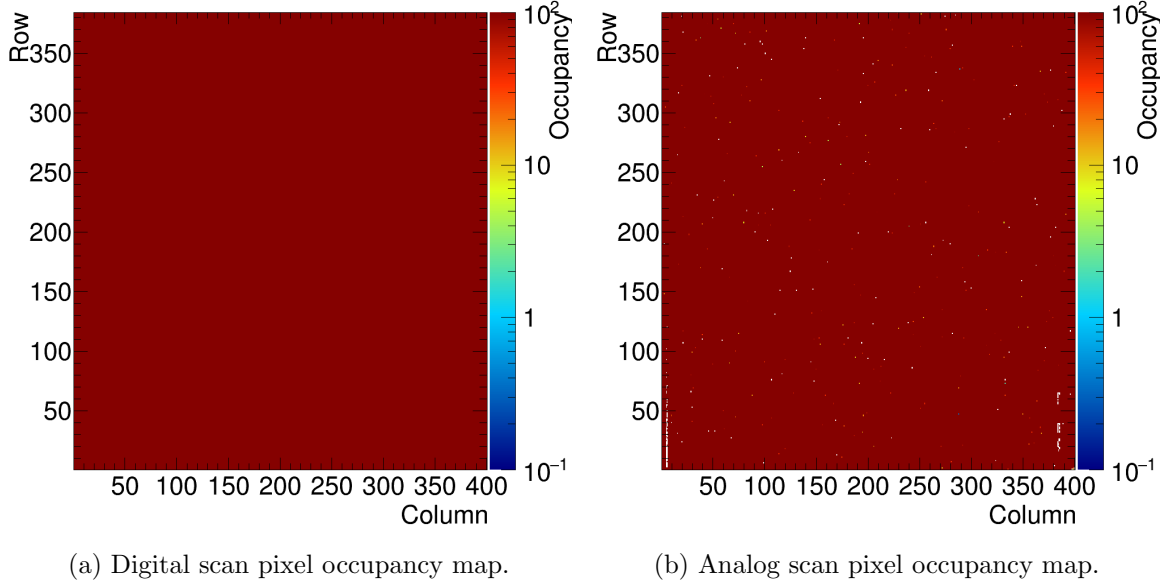


Figure 5.6: Example of module digital and analog scans.

As outlined in Sec. 4.4.3, the tuning process involves two stages: first, the global threshold is adjusted, followed by the fine-tuning of each pixel's Threshold DACs (TDACs). The desired threshold level is $1000 e^-$, and the tuning is performed with the sensor powered at 10 V. A threshold scan is conducted after the tuning process to verify the outcomes. For all SCCs, the tuning process was successful, with the threshold level being very close to the target of $1000 e^-$. As anticipated, the threshold noise is about $40 e^-$ for bare chips and $70 e^-$ for modules. In Fig. 5.7 and Fig. 5.8 the threshold and noise distributions of the RD53A modules are shown (they will be tested at DESY in 2021 after irradiation, as it is reported in next section). The mean value and standard deviation of the threshold and noise distributions are determined by fitting with a Gaussian function.

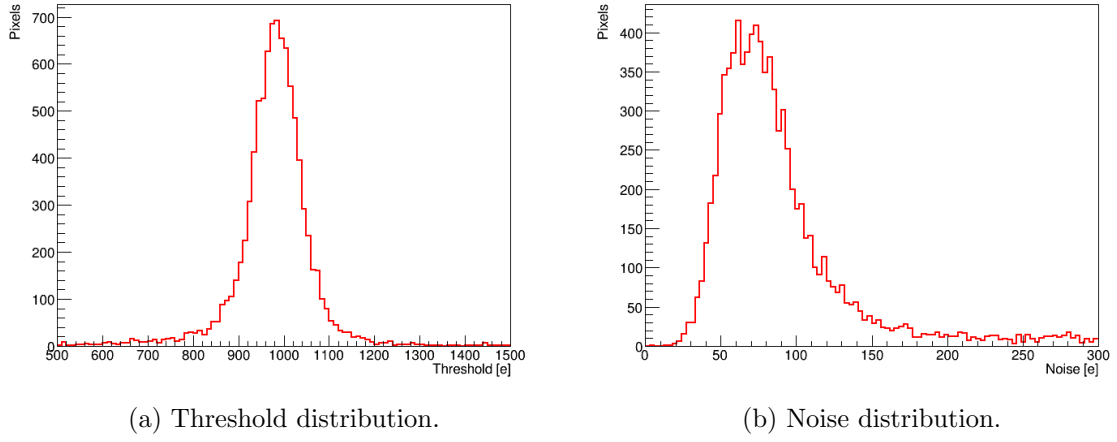


Figure 5.7: E3.3-50×50 μm^2 module threshold and noise distributions.

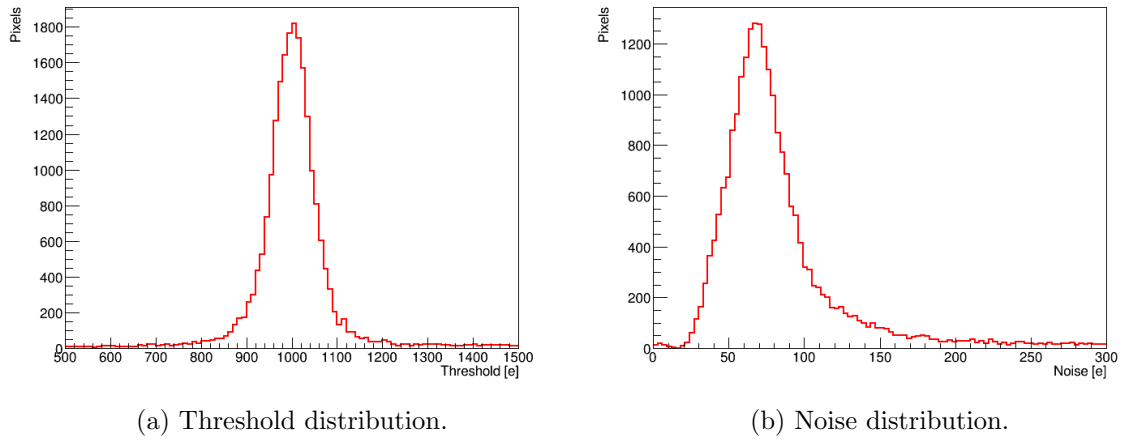


Figure 5.8: E9.5-25×100 μm^2 module threshold and noise distributions.

Time over Threshold distribution

This scan is used to verify the uniformity of pixel response in terms of ToT at a fixed value of the charge. This charge is injected 100 times into each pixel in the RD53A chip array, which performs the calculation of the ToT corresponding to each injection. At the end of the scan, each pixel is associated with a ToT value, corresponding to the average of the 100 measurements taken. Fig. 5.9 shows the results of this scan related to the injection of a charge equal to that used in the tuning procedure with a threshold value of 1000 e^- , and it is therefore expected that an average ToT of 8 bunch-crossing (bc) is associated with each pixel. It can be seen from the figure that the average values are close, within the dispersion

of the distributions, to the expected value for both the E9.5 and E3.3 chips.

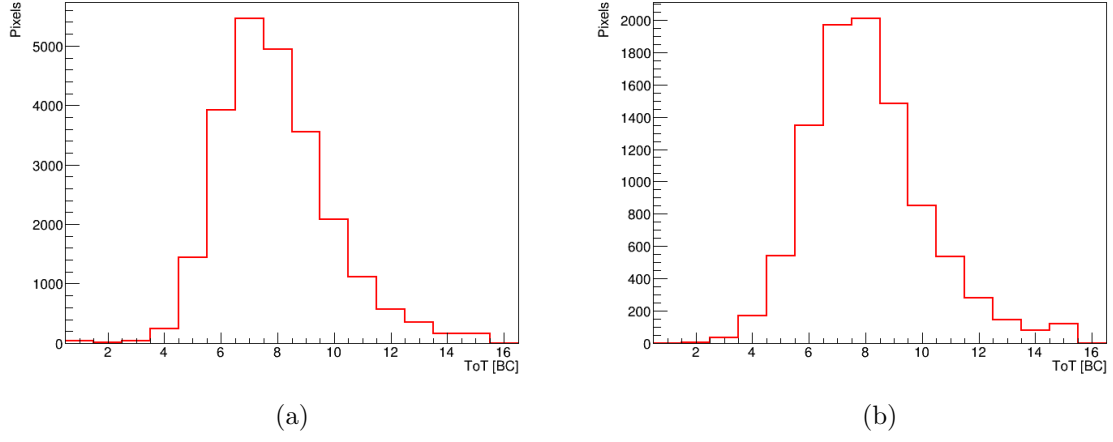


Figure 5.9: E9.5-25×100 μm^2 module and E3.3-50×50 μm^2 module ToT distributions. The plots show that the average ToT values are close to the expected value of 8 bc.

5.4 Beam Test at DESY and CERN Facilities

After a first evaluation in the lab, some of the devices were tested with particle beams, to measure their ultimate performance. The ITk module community made use of three beam test facilities from 2019 to 2022, the DESY (Deutsches Elektronen-Synchrotron) [61] facility at Hamburg-Bahrenfeld and the two SPS (super proton-synchrotron) [62] and PS (Proton Synchrotron) [63] facilities at CERN in Geneva.

The Detectors Under Test (DUT) presented in this chapter are modules composed of an FBK 3D pixel sensor, with an RD53A [59] front-end chip (those tested at DESY and PS) and with ITkPixV1.1 [60] front-end chip (those tested at PS and SPS in the latest test beam campaigns).

Furthermore, the results shown belong to campaigns of data taking on non-irradiated modules and on modules irradiated with different radiation fluences. The irradiation process will be discussed in more detail in Sec. 5.4.2. Both at DESY and at CERN a EUDAQ-type telescope was used. The data acquisition system is YARR and EUDAQ based. The telescope will be covered in detail in the next section.

5.4.1 Test Setup

EUDET beam telescope The EUDET Telescope is a beam telescope featuring high resolution, comprising two arms and three measuring planes per arm (Fig.5.10). The measuring planes are equipped with MIMOSA26 sensors. The MIMOSA26 sensor is based on the MIMOSA22 architecture, which is a Monolithic Active Pixel Sensor (MAPS) with fast binary readout. Additionally, it incorporates the SUZE01 prototype circuit that enables integrated zero suppression. The chip size measures 13.7×21.5 mm, and the sensor matrix consists of 576×1152 pixels with a pitch of $18.4 \mu\text{m}$, occupying an active area of $2.1 \times 1.06 \text{ cm}^2$. Depending on the beam energy, the amount of material between telescope planes, and subsequent multiple scattering, the MIMOSA26 achieves a minimum pointing resolution of $2 \mu\text{m}$.

Currently, the EUDET Telescope is operational at the CERN-SPS facility for 120 GeV/c pions beam experiments and the CERN-PS facility for 12 GeV/c protons. It has also been utilized at the DESY II facility, which operates a 6 GeV electron beam.

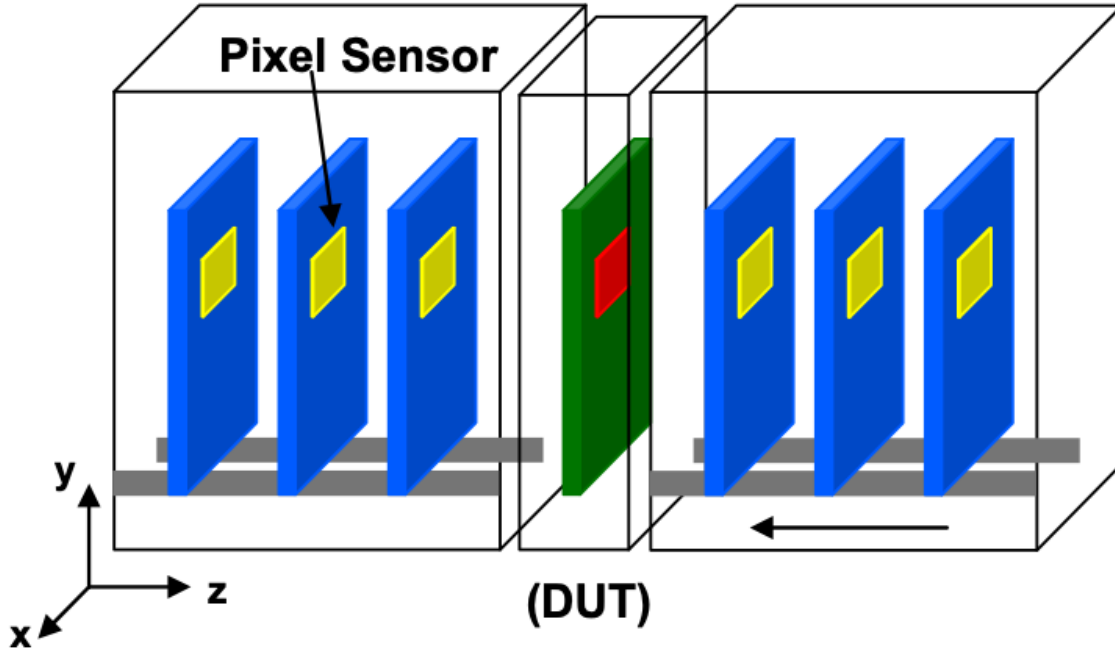


Figure 5.10: A sketch of the EUDET Telescope layout. The two arms with three planes each are shown in the figure. The DUT(s) is placed in the middle of the telescope, between the two arms [64].

At the beginning and at the end of the telescope arms two pairs of scintillators in cross configuration are placed. The coincidences of four scintillators, positioned to cover the MIMOSA26 sensor area, are used to generate the trigger signal for the readout. Their signal is sent to a Trigger Logic Unit (TLU), more specifically explained in the paragraph below, that distributes their AND logic output signal to all the planes of the telescope and to the DUTs.

The telescope is positioned on one of the big XY-tables. The planes are counted from 0 to 5 downstream. The X, Y, and Z directions are those shown in the sketch in Fig. 5.10. In the current mechanical setup, the planes of the telescope are easily adjustable as it is the distance between the two arms. Furthermore, it is possible to rotate the whole telescope in order to adjust it to the beam axis. This corresponds to a rotation around the Y-axis. A Huber cooling device is used for the pixel telescope. The cooling device uses water as a cooling liquid. A typical operating temperature is 14°C.

The DUTs are placed inside a custom-designed cooling box that is supplied by a commercial chiller, allowing it to reach a minimum temperature of -80°C, which is needed to operate with the irradiated modules. Unirradiated modules are tested at 20°C, while irradiated modules are tested at -34°C. The same solution could not be used at DESY due to the lower particle energy and the large mass of the chiller-based box which would lead to a significant amount of multiple scattering. In this facility, a lightweight Styrofoam box is

used instead. Here cooling for operations with irradiated modules is provided by dry ice which allows them to reach temperatures as low as the chiller-based box, but without the flexibility of precise temperature control.

Due to the MIMOSA26 sensors' long integration time —roughly 300 μ s compared to the DUTs' 25 ns— an additional reference plane is used to supply timing data for track selection. During the beam test campaigns reported in this thesis, a few hybrid modules were used as reference planes: an FE-I4 chip with a planar sensor, an RD53A chip with a planar sensor, or an ITkPixv1.1 chip with a 3D sensor.

Trigger Logic Unit A custom Trigger Logic Unit (TLU) manages triggers. The TLU is based on a ZestSC1 card from Orange Tree Technology Ltd. The card incorporates a USB 2.0 interface and a Spartan-3 FPGA from Xilinx. The TLU generates triggers that distribute it to the telescope and any DUT after receiving signals from scintillators in front of and behind the telescope. The trigger signal can be generated by arbitrarily combining the four scintillator inputs (AND, OR, VETO), and there is also an internal trigger generator for testing and pedestal runs. A variety of internal scalers enable running conditions to be monitored. A timestamp is stored in an internal buffer that can be read out over USB by a PC for each trigger that is generated, and a trigger counter is also incremented for each trigger. To ensure proper trigger synchronization, the DUTs have the option of reading out the trigger number via the DUT interface. The TLU is capable of controlling up to six devices, including the telescope and the DUT. DUTs can communicate using either LVDS over RJ45 connectors or NIM or TTL over LEMO connectors. They can choose from a variety of handshake modes as well. In the most basic mode, the DUT can only receive a trigger pulse without any handshake. For a slight enhancement in robustness, the DUT has the option to reply to each trigger with a busy signal. It will then remove the busy signal once it is prepared to receive another trigger. To ensure that triggers are not dropped and to address the issue of trigger desynchronization, the TLU expects a response from the DUT. This differs from the trigger-busy mode, as it is the DUT toggles a clock line while it is busy. In response, the TLU transmits the trigger number over the trigger line, bit by bit. This approach enables recovery from any potential trigger desynchronization offline. [65].

Data Acquisition Software and YARR Producer The Data Acquisition software, EUDAQ, is a custom framework designed to be lightweight, modular, and portable. A central Run Control displays a graphic interface to the user allowing them to control the other processes. The Data Collector receives data from the Producers, merging the separate streams into one and writing it into a file. The Producers communicate with the different pieces of hardware and generate data. The TLU Producer manages the TLU and transmits the timestamps to the Data Collector. Meanwhile, the YARR Producer, as described in the YARR Producer paper [66], oversees the readout boards and transmits the data from the telescope. In addition, a Log Collector collects log messages from all other processes into a central location. The online monitor reads the data file from the disk, generating histograms so that the user may monitor the quality of the data.

Corryvreckan Data Analysis Framework To assess the qualification of a device, two crucial pieces of information are necessary. Firstly, the accurate reconstruction of the beam particle trajectory, which involves aligning all telescope planes and DUTs. Secondly, establishing a correlation between the data obtained from the DUT and the particle that interacts with it. The CLICdp Collaboration has developed Corryvreckan, a versatile C++ analysis framework, specifically designed for analyzing test beam data. This program adopts a modular approach, enabling users to combine various modules, each serving a specific function, according to the requirements. The Corryvreckan manual [67] provides further details.

The analysis program operates by executing a sequence of diverse modules that facilitate data analysis and deliver results regarding the resolution and efficiency of the DUTs. Before aligning the telescope planes and DUTs, the data from both the telescope and DUTs are loaded into Corryvreckan. Additionally, noisy pixels are masked on each device. Subsequently, the efficiency of the DUTs is assessed and evaluated.

The Corryvreckan framework is loaded before to start the data analysis, which is organized into events. For each trigger signal from the scintillator, an event is produced. Each telescope plane's and the DUTs' hits data is loaded for each event. The noisy pixels are then tucked away by a mask that is made specifically for each device. Then clusters are rebuilt for each plane. Only using the cluster information, a preliminary alignment of the telescope plane and the DUT is performed. A subset of tracks used only for telescope alignment is selected following this initial pre-alignment. In each step of the alignment process for these tracks, the acceptance criteria for a track become more strict.

The telescope residuals are calculated at each alignment step. They can be used to check the alignment because they are defined as the distance between the cluster's position on the plane and the position of the track as projected onto the telescope. When telescope residuals are centered at zero and comparable to MIMOSA26 resolution ($\sim 5 \mu\text{m}$), telescope alignment comes to an end. Following the telescope alignment, a new subset of tracks is chosen for the DUTs alignment. Such tracks were rebuilt using the most recent telescope configuration. The alignment process concludes when the residuals of the DUT are centered around zero and approximately match the resolution of the device ($14 \mu\text{m}$ for our sensors). The program is able to evaluate the DUTs' efficiency once the telescope plane and the DUTs are aligned. The efficiency is calculated as the fraction of tracks intersecting a DUT active area for which a cluster has been found that meets a *spatial cut* of $100 \mu\text{m}$ (in both X and Y direction) and a *time cut* of 600 ns. It should be mentioned that masked pixels are not considered in the analysis and that the pixels next to masked pixels are also excluded.

A ROOT file with several 1D and 2D histograms is created. It is used to check the results in terms of mean efficiency and to look into potential sources of inefficiencies. Additionally, it is possible to limit the analysis to a particular area of the device, or "Region Of Interest" (ROI). The local efficiency of a pixel cell can also be measured. The spatial coordinates of the clusters and the tracks intercepts could be interpreted in terms of local coordinates inside a pixel, because the program is aware of the location of each pixel cell, thanks to the geometry file.

5.4.2 Modules Irradiation

As mentioned above, the innermost layer imposes strict requirements in terms of performance after irradiation. With the replacement strategy, the fluence for the innermost pixel layer will exceed 1×10^{16} n_{eq}/cm². In these conditions, the hit efficiency is required to be larger than 97 % (96 %) before (after) irradiation at normal beam incidence and larger than 98 % (97 %) at 14-15° incidence (the final orientation of the modules in the ITk detector). During the whole lifetime of the detector, the power dissipation performance of the 3D sensors should be better than 40 mW/cm² at the benchmark sensor temperature of -25°C. The maximum operational bias voltage after irradiation should not exceed 250 V. For this reason, it is essential to test the modules in efficiency both pre- and post-irradiation.

Charged hadrons, with pions being the dominant particle type, constitute over 80% of the expected particle spectrum in the ITk pixel detector. Neutral hadrons, electrons, positrons, muons, and photons provide modest further contributions. Currently, none of the radiation facilities in use can provide a pion beam with enough flux to deliver the necessary high doses promptly. However, several facilities provide proton beams with energy ranging from tens of MeV to GeV, allowing researchers to examine the radiation hardness of sensors in terms of damage caused by Total Ionizing Dose (TID) and Non-Ionizing Energy Loss (NIEL) effects.

Three different facilities, the Medical Physics cyclotron of the University of Birmingham in the UK with proton beams of approximately 27 MeV, the Cyclotron Radio Isotope Center (CYRIC) of the Tohoku University in Japan with 70 MeV protons, and the Cyclotron of the Karlsruher Institut für Technologie (KIT) in Germany, have all been used to irradiate the RD53A module. In each of these facilities, the modules are maintained at temperatures below 0°C during the irradiation process, and the beam is moved over the sensor surface to ensure a consistent dose.

Facilities that offer higher energy beams have been preferred when available since they have reduced TID and chip damage due to the larger protons' energy. A 23 GeV proton beam from the PS accelerator at the IRRAD facility at CERN is used to irradiate RD53A modules. The facility's high-energy particle provides the simultaneous irradiation of many modules and directly reaches the target fluence of 1×10^{16} n_{eq}/cm². In contrast to the other facilities, IRRAD does not regulate the temperature of the modules during irradiation, and because of the heat produced by the high particle flux, significant annealing is expected.

Furthermore, neutron irradiations have been performed in the TRIGA Mark II research reactor of the Slovenian Jozef Stefan Institute (JSI) in Ljubljana. Since the TID due to gamma emission is really low —about 0.1 Mrad per 10^{14} n_{eq}/cm²— the neutron reactor only allows the analysis of NIEL damage. Even while such irradiation does not meet ITk's expectations, it has the advantage of causing the chip only minimal radiation damage, enabling its performance to be disentangled from the sensors. Unfortunately, the interaction with neutrons activates the tantalum contained in the RD53A chip, leading to several drawbacks like extended cooling times, high radiation transport costs, and difficult handling.

For this reason, only a few RD53A modules have been irradiated at JSI, while this facility has been mostly used for diodes.

For proton irradiation, the dose received and the corresponding equivalent neutron fluence is measured from the activation of an aluminum foil placed in front of the sensors during irradiation. In the case of neutron irradiation, it is instead extrapolated from the predicted neutron flux and the immersion time in the reactor. In both cases, a systematic uncertainty of 10%-15% is associated with the fluence values.

RD53A Modules Irradiation Among the RD53A modules listed in Tab. 5.1, three modules were irradiated before being tested at beam test in DESY during winter 2019 and 2020. These three modules all came from wafer 30 of batch 3 and were the D11.3, the E3.3, and the E9.5. The one from wafer 91 of batch 2, module W91-02 was tested at the DESY facility without irradiation.

Module D11.3 (25×100 -1E) was irradiated at the Medical Physics cyclotron of the University of Birmingham (BU) in the UK with 27 MeV protons up to 5×10^{15} n_{eq}/cm^2 fluency; The modules E3.3 (50×50) and E9.5 (25×100 -1E) were irradiated at Cyclotron Radio Isotope Center (CYRIC) of the Tohoku University in Japan using 70 MeV protons up to 10×10^{15} n_{eq}/cm^2 fluence. These modules with their irradiation fluences are listed in Tab. 5.3. The error on fluencies given to the modules was 10 %, with a mean dose of about 0.7 Grad.

Foundry	Sensor	Pixel Cell Dimension [μm^2]	Irradiation Facility	n_{eq} fluence [n_{eq}/cm^2]		Dose [Grad]
				Mean	Error	Mean
FBK	W30-D11.3	25×100	BU	0.5×10^{16}	10%	0.665
FBK	W30-E3.3	50×50	CYRIC	1.0×10^{16}	10%	0.7
FBK	W30-E9.5	25×100	CYRIC	1.0×10^{16}	10%	0.7

Table 5.3: Summary of equivalent neutron fluence received from R&D modules with FBK sensor tested at DESY facility.

Modules with ITkPixV1.1 Irradiated at Bonn In Bonn, SCC 3 and 5 were exposed to a proton beam with a 15 MeV energy up to a fluence of 1.0×10^{16} n_{eq}/cm^2 . A beam that was perpendicular to the SCCs was used to irradiate the modules. The entire surface of the module has been irradiated by scanning it with a very focused beam because the beam width is insufficient to cover the entire surface of the module. This means that throughout the irradiation procedure, the beam is periodically moved to cover the entire surface of the module. A segmented aluminum foil has adhered to the module's back in order to measure the proton fluence on the surface. Following irradiation, the sheet can be analyzed spectroscopically to extrapolate the fluence received.

A conversion factor is used to translate protons into 1 MeV neutrons with a equivalent. As a result, SCC 3 had a mean fluence of 1.01×10^{16} n_{eq}/cm² and SCC 5 had a mean fluence of 1.00×10^{16} n_{eq}/cm². A total of 1.13 Grad of ionizing radiation has been applied to both SCCs. Over the surface of the module, the received fluence is remarkably uniform, with variations of the order of 1%. Due to the systematic uncertainty in the conversion factor, the error on the proton fluence is in the order of 5%, whereas the error on the equivalent neutron fluence is in the order of 15%. A summary of the fluences is provided in Tab. 5.4, and the results of the fluence analysis performed in Bonn are displayed in Fig. 5.11.

SCC N°	Proton fluence [p ⁺ /cm ²]		n _{eq} fluence [n _{eq} /cm ²]		Dose [Grad]
	Mean	Error	Mean	Error	Mean
SCC 3	2.45×10^{15}	5%	1.01×10^{16}	15%	1.13
SCC 5	2.45×10^{15}	5%	1.00×10^{16}	15%	1.13

Table 5.4: Summary of the proton and equivalent neutron fluence received in Bonn by SCC 3 and 5.

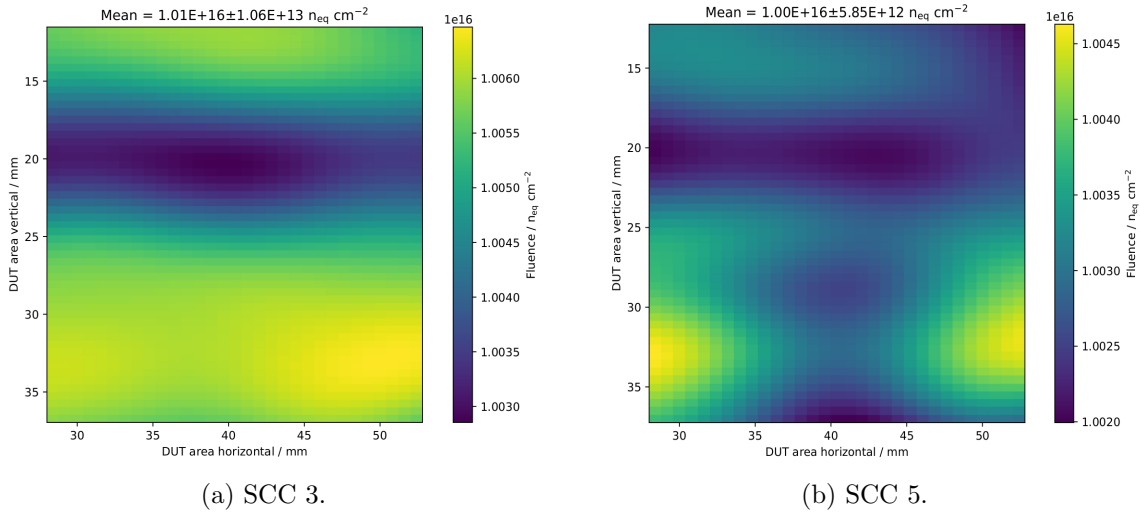


Figure 5.11: Proton fluence map of SCC 3 and 5 after the irradiation in Bonn. Note that the Z-axis scales are slightly different. For both SCCs the fluence variation over the module surface is about 1%.

Modules with ITkPixV1.1 Irradiated at IRRAD At the CERN IRRAD facility, SCC 2 and 8 were exposed to a proton beam with a 23 GeV target fluence of 1.7×10^{16} n_{eq}/cm². Since the beam's Full-Width Half Maximum (FWHM) is only 12x12 mm², it was also impossible to cover the entire surface of the module with a beam that was orthogonal to the

SCCs. Because scanning the module is not possible at IRRAD it was decided to tilt the modules by 30° with respect to the beam and place them on custom 3D printed supports (Fig. 5.12a). A segmented aluminum foil was attached to the back of the module during the SCC installation at IRRAD with Kapton tape to measure the fluence (Fig. 5.12b). A spectroscopic examination of the sheet after irradiation enables the reconstruction of the map of the received fluence. Given the scaling factor of $\sim 60\%$, an average proton fluence of the order of $\sim 2.9 \times 10^{16} \text{ p}^+/\text{cm}^2$ was observed. This is equivalent to $1.7 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$.

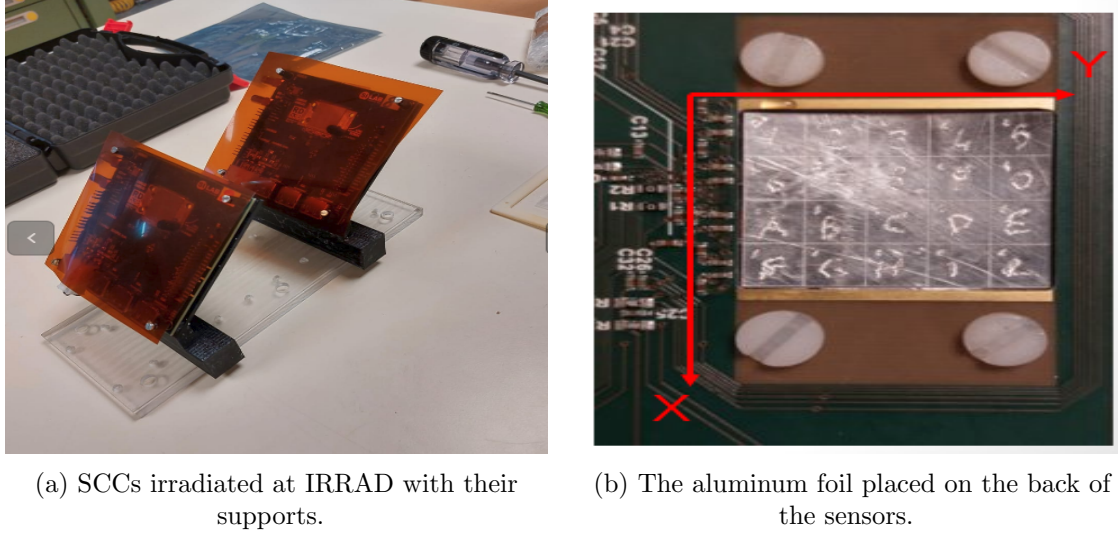


Figure 5.12: (a) Shows the SCCs placed on the holders with an angle of about 30° . The aluminum foil placed on the back of the module in (b).

The beam, however, was uncentered on the module due to a problem with the IRRAD focusing quadrupole. Fig. 5.13a displays the fluence map of SCC2 that was reconstructed using the aluminum spectroscopy analysis. Given that the lower edge of the module has experienced a higher fluence, it is obvious that the beam was uncentered in the Y direction. The fluence on the surface of the module is not evenly distributed; the map shows both areas with extremely high fluence ($8 \times 10^{16} \text{ p}^+/\text{cm}^2$) and areas with lower fluence ($1 \times 10^{16} \text{ p}^+/\text{cm}^2$). It was possible to extrapolate the location of the beam center by a Gaussian fit of the two distributions by projecting the map along the X and Y direction (indicated in Fig. 5.13b). Tab. 5.5 for the two SCCs shows the detachment between the center of the module and the center of the beam as well as the spread of the beam.

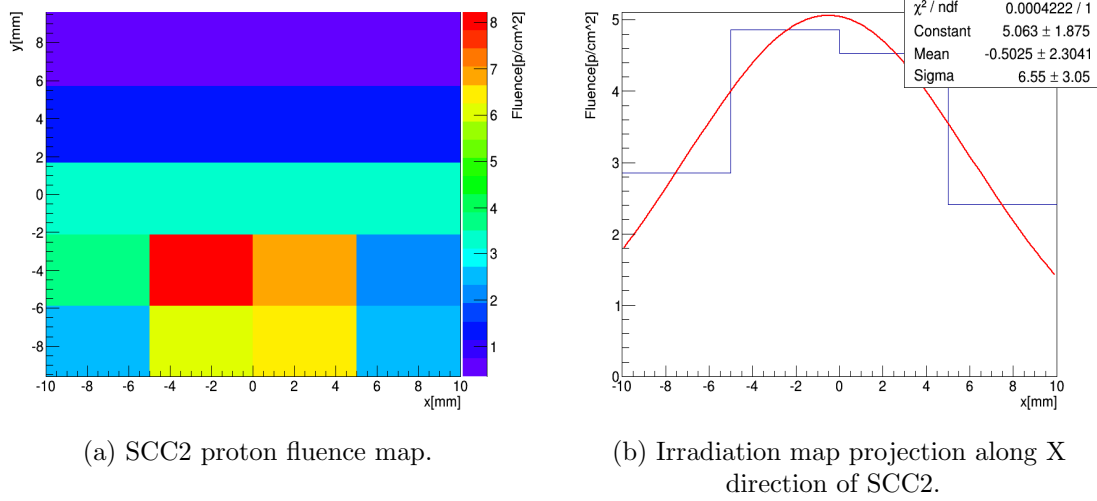


Figure 5.13: SCC 2 proton fluence map (a) and its average X projection (b). With these plots, the uncentered beam is clearly visible.

It was possible to understand that protons primarily passed through the bottom of the chip and on the wire-bonding pads by extrapolating the position and size of the beam integrated over the lengthy period of almost two months. The readout chips may no longer respond for the following reason: the chips themselves may have been damaged by the excessive TID. This fact, along with the excessively high protons fluence density, up to almost three times larger than requested, may explain why. Furthermore, the mechanical contact of the wire bonds between the card and the chip may have been negatively affected by ripples visible on the SCC's pads. In order to understand the contamination with halogens have accelerated the card damages at this high fluence, an analysis of the card material is currently being conducted.

Before irradiating new modules, it will be necessary to gain a better understanding of the irradiation conditions.

SCC N°	X position	X spread	Y position	Y spread	Mean fluence
	[mm]	[mm]	[mm]	[mm]	[10^{16} p ⁺ /cm ²]
SCC 2	-0.5	6.6	-5.2	5.3	3.0
SCC 8	-1.2	6.5	-7.6	6.0	2.7

Table 5.5: Summary of the distance between the extrapolated center of the IRRAD beam and the center of the module for both SCCs.

5.4.3 RD53A Modules Tested at DESY

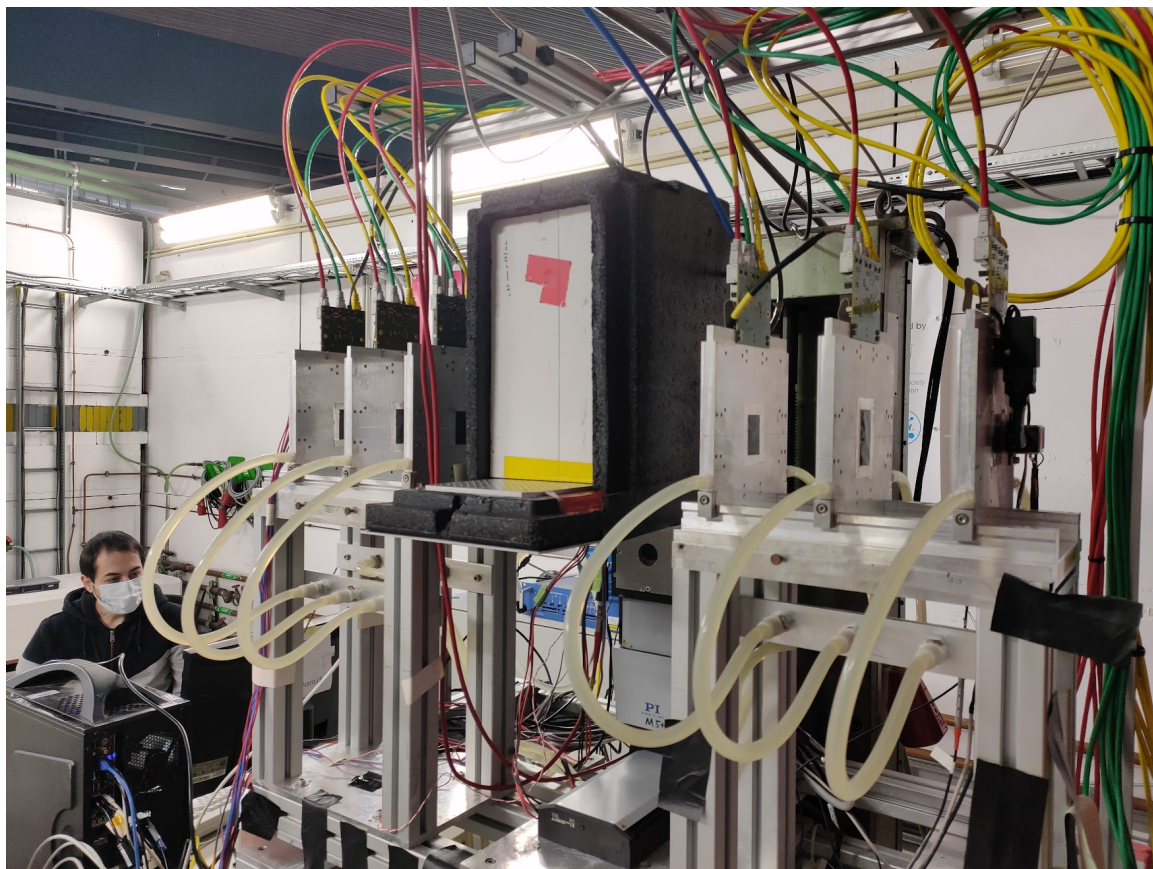


Figure 5.14: The EUDET Telescope at the DESY facility is shown in this figure. The box in the middle is a cold box where on a metal plate up to 3 modules can be fixed. The low temperature is reached with dry ice placed inside the box, in a compartment separated from the modules by a plate.

The electron/positron synchrotron DESY II is mainly an injector for DORIS and PETRA [68]. The average radius of the DESY II ring is 46.601 m (so the circumference is 292.8 m). It accelerates and decelerates in sinusoidal mode with a frequency of 12.5 Hz ($= 1/80$ ms).

A bremsstrahlung beam is generated by a carbon fiber in the circulating beam of the electron/positron synchrotron DESY II, as it is visible in the sketch in Fig. 5.15. The produced photons are converted to electron/positron pairs via a metal plate target (converter). Then the beam is spread out into a horizontal fan using a dipole magnet. Like a slice, the final beam is cut out of this fan with a collimator. The underlying physics is simple. The bremsstrahlung spectrum has a $1/E$ dependence. The energy distribution of the electron/positron pair production is nearly flat, the geometry is fixed by the beam pipe.

The beam momentum after the collimator can be selected by adjusting the dipole magnet current. However, the actual scenario is slightly more complex due to the time-varying energy of the synchrotron. This means that the bremsstrahlung edge of the photon spectrum changes over time with the accelerator cycles. It is important to note that the beam particles can only be generated when the energy of the accelerator (divided by the speed of light, c) exceeds the chosen momentum [61].

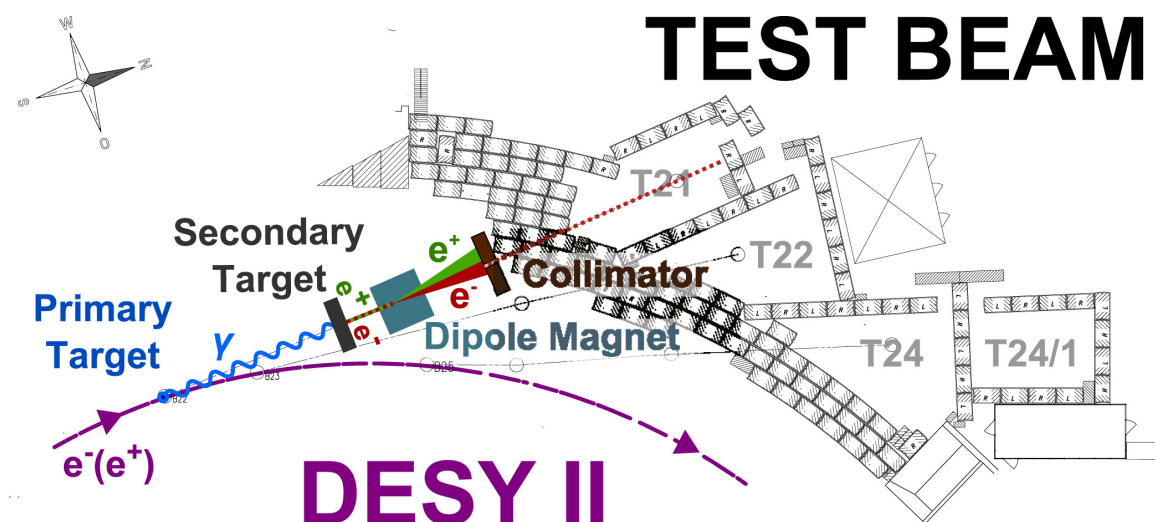


Figure 5.15: Schematic layout of test beam zones on the various DESY beamlines.

Electrical Properties

The leakage current is a basic property of silicon detectors that indicates their electrical quality. This has been measured as a function of the bias voltage for 3D diodes and 3D sensors bump-bonded to RD53A chips before and after irradiation. The 3D modules are kept at constant temperature and relative humidity of less than 50 % within a climate chamber. Before irradiation, the measurements are carried out at 20°C, while after irradiation the sensors are cooled down to -25°C. Diodes are measured in the same conditions either on a probe station with a temperature-controlled chuck or on dedicated Printed Circuit Boards (PCBs) inside a climate chamber. Systematic uncertainties for the measurements of the leakage current are dominated by the variation of the temperature which is measured with a precision better than 1°C corresponding to an uncertainty on the measured leakage current of less than 10 %.

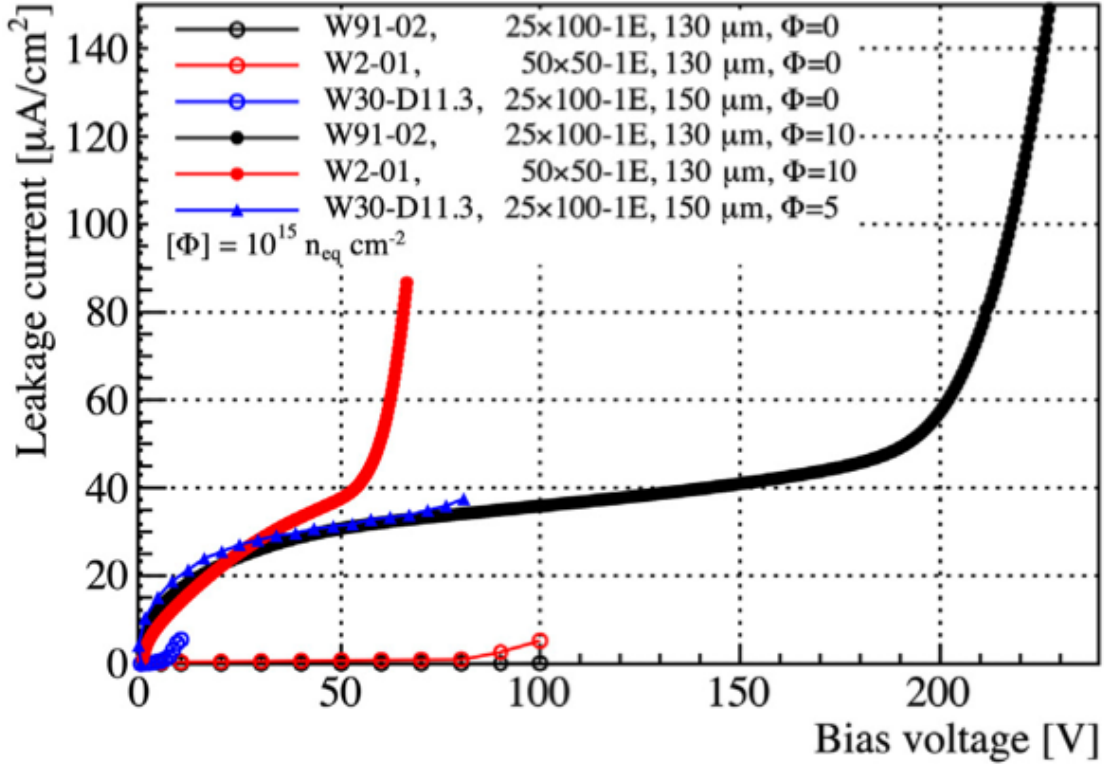


Figure 5.16: FBK sensors IV curves tested at DESY.

The leakage current as a function of the bias voltage for FBK RD53A sensors with different pixel geometries is compared in the plots in 5.16. The properties before irradiation are mostly consistent with the measurements at the wafer level with the exception of a few sensors which show a degradation of the I-V curves both in terms of leakage current level and breakdown voltage. After irradiation, the leakage current increases with the fluence and the breakdown is usually shifted towards larger voltages. Most RD53A sensors measured after irradiation show a breakdown larger than 120 V, while for one sensor the steep increase of the leakage current is observed between 50 and 100 V. Conversely, the other sensors show very similar electrical behaviors after irradiation despite their different I-V curves observed before irradiation.

The Beam Test Measurements and the Modules Hit Efficiency

The hit efficiency is defined as the fraction of events in which a particle passing through the active part of the DUT causes at least a recorded hit. Hence, it is highly influenced by the number of electron-hole pairs generated (proportional to the active thickness) and the chip threshold settings. The minimum hit efficiency target for ITk is 97 % throughout the

whole lifetime since lower values would cause problems for track pattern recognition [44]. Experimentally, the efficiency is determined in beam tests by extrapolating the reference track position to the DUT and searching for a hit cluster in the surroundings within a matching distance of up to two times the DUT pixel size. To disentangle the performance of the sensor from one of the RD53A chips and from the hybridization process, noisy as well as disconnected channels are excluded from the efficiency calculation. Results of hit efficiency measured as a function of the bias voltage is shown in Fig. 5.17 and 5.18 for RD53A chip modules with sensors produced by FBK, respectively.

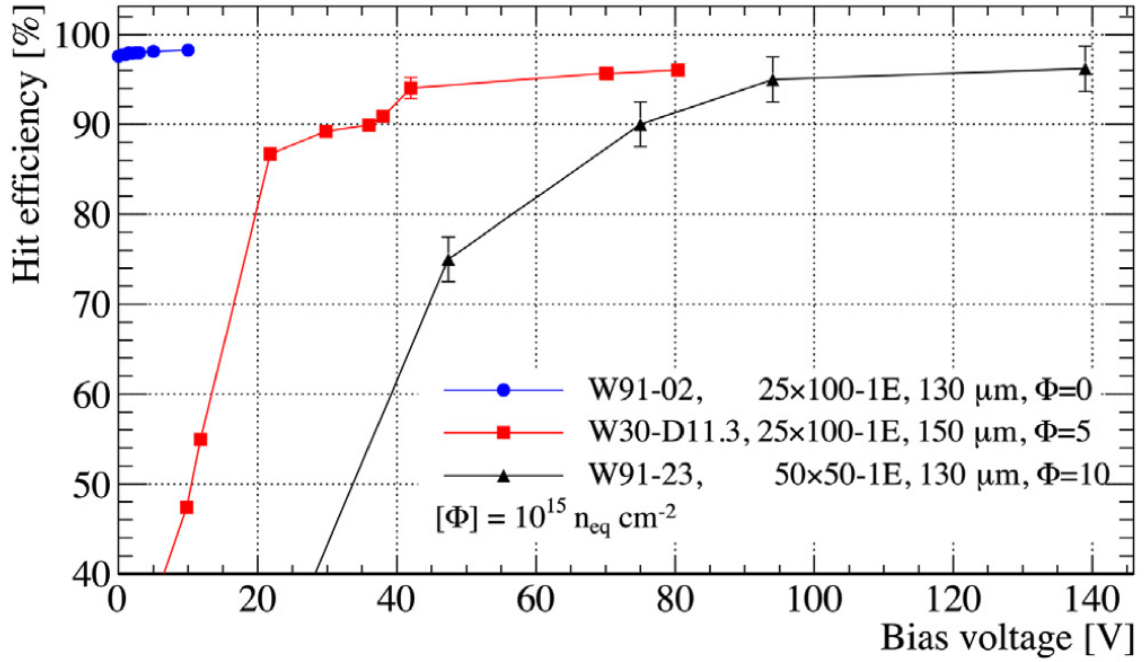


Figure 5.17: Hit efficiency as a function of the bias voltage for RD53A modules with FBK 3D sensors from the second batch, the W91-02 and the W91-23 (which is the one tested at SPS at CERN) before and after irradiation, and the third batch (W30-D11.3) after irradiation. The modules were tuned to a mean threshold of 1 ke^- . The modules were tested at DESY in 2019.

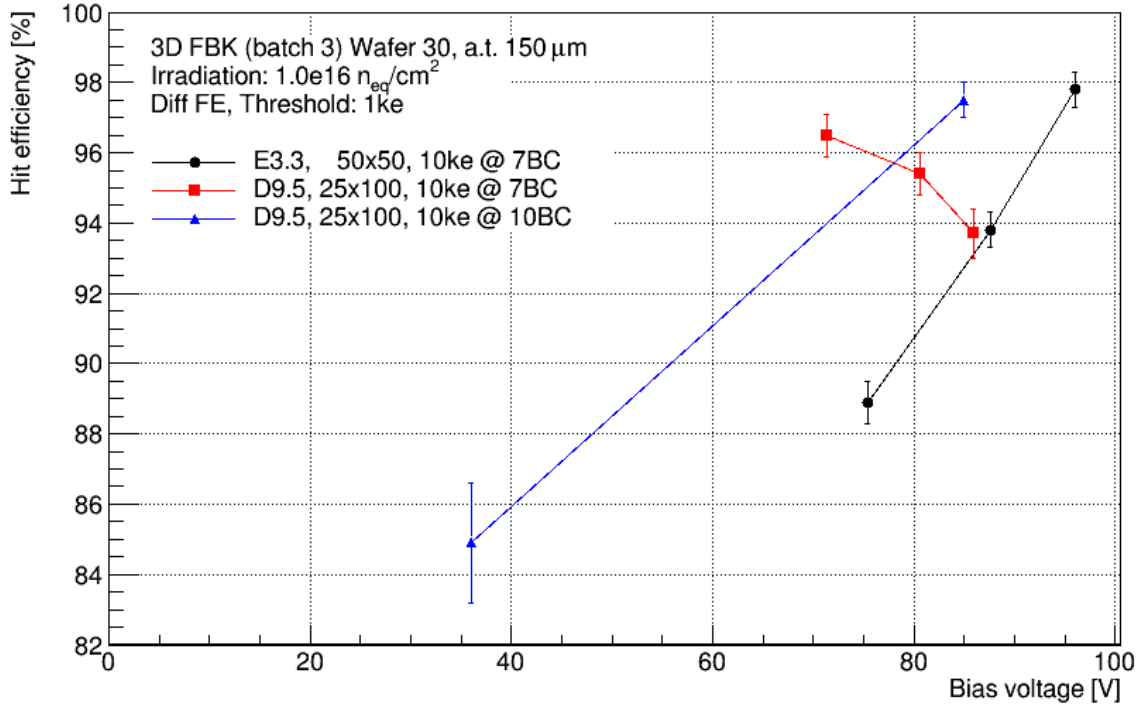


Figure 5.18: Hit efficiency as a function of the bias voltage for RD53A modules with FBK 3D sensors from the third batch (W30-E3.3 and W30-E9.5) after irradiation. The modules were tuned to a mean threshold of 1 ke^- . The modules were tested at DESY in 2020.

Before Irradiation Before irradiation sensors with $25 \times 100 \mu\text{m}^2$ pixel cell geometry show a hit efficiency over 97 % for perpendicularly incident tracks even with a bias of 0 V. Differences of less than 1 % efficiency have been observed for threshold tunings between 1.0 and 1.5 ke^- and for sensors produced by different foundries on substrate thicknesses from 100 to $150 \mu\text{m}$. Inefficiencies mainly correspond to particles crossing the fully passing p-type columns which are inactive as can be appreciated by looking at the local efficiency distribution over the pixel cells as shown in Fig. 5.19.

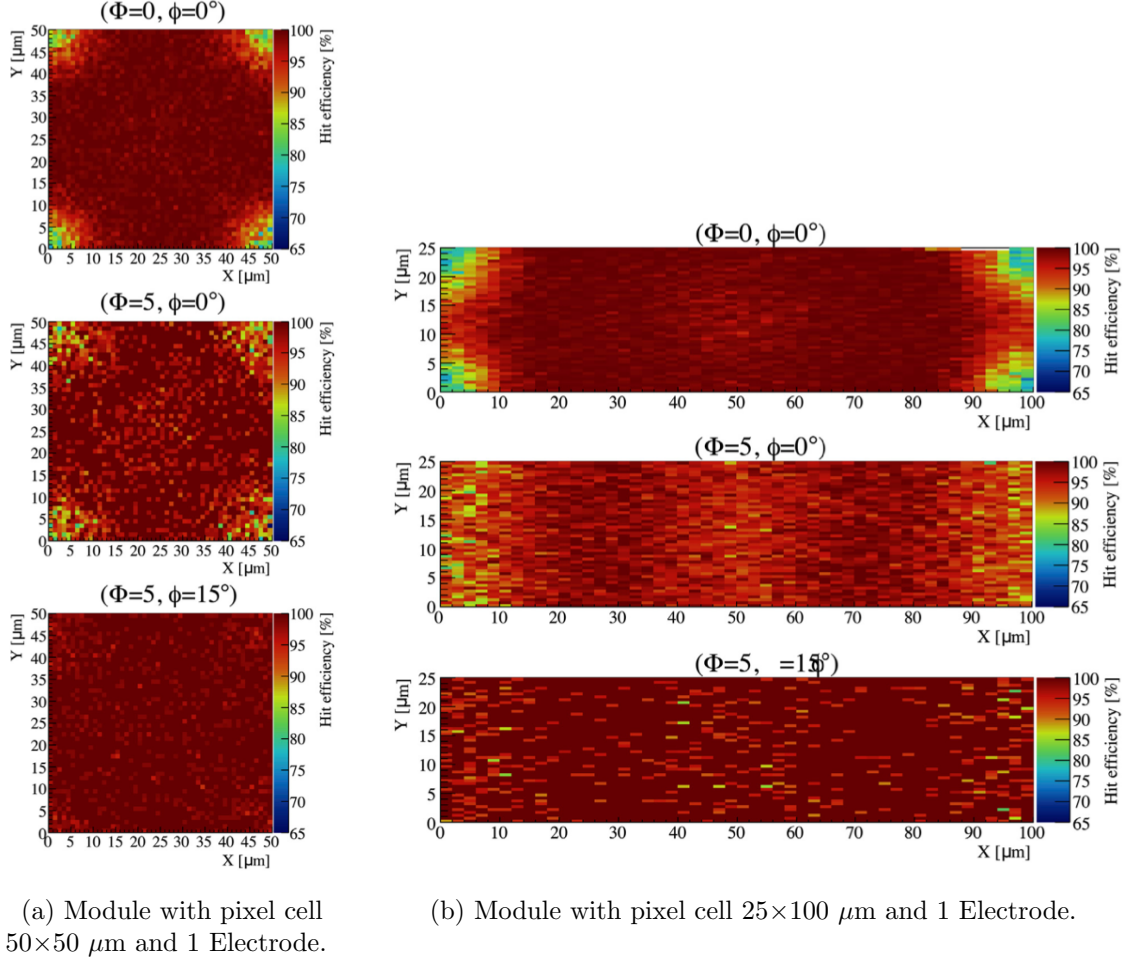


Figure 5.19: Hit efficiency over the surface of one pixel cell with 50×50—1E (a) and 25×100—1E (b) geometries. From top to bottom, the maps show modules measured before irradiation at perpendicular beam incidence ($\Phi=0, \phi=0^\circ$), after irradiation to $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ at perpendicular beam incidence ($\Phi=5, \phi=0^\circ$) and at 15° beam incidence angle ($\Phi=5, \phi=15^\circ$). The hit efficiency maps of the pixel cells are obtained displaying the reconstructed track impact point expressed in local pixel coordinates and projecting the data for all identical structures onto the same image [53]

After Irradiation Results of RD53A modules with 50×50-1E sensors from FBK production site have demonstrated the possibility of reaching a hit efficiency larger than 96 % for perpendicularly incident tracks after irradiation to $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ with about 40 V and after irradiation to $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ in the voltage range of 80–150 V with thresholds around 1 ke⁻ or lower.

The RD53A module with 25×100-1E sensor from FBK has been instead operated with

a threshold of 1 ke^- and after irradiation, to a fluence of $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ reaches the 96 % hit efficiency at 80 V.

Moreover, the RD53A modules with 50×50 -1E sensor, always from FBK, has been operated with a threshold of 1000 e^- after irradiation to a fluence of $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ reaching an efficiency over 97 % at 96 V of bias voltage, as shown in Fig. 5.18 with the module W30-E3.3. In Fig. 5.17 is shown the efficiency of the module W91-23. This one was tested by the collaboration at SPS at CERN before this thesis work started, but this module reaches an efficiency of 96 % at 140 V of bias voltage.

After irradiation to $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ the 25×100 -1E design has been measured with FBK sensor both at perpendicular track incidence and by tilting the device by 15° around the long pixel side. In the first case a hit efficiency over 98 % is obtained with a bias voltage of 140 V or larger (see the Fig. 5.17) with the module W30-D11.3, and an efficiency around 98 % is obtained with 90 V (see Fig. 5.18) with module W30-E3.3. In both cases, the devices have been tuned to a threshold of 1 ke^- . In this case, the efficiency distribution over the pixel cell is uniform since the particles are not passing all the way through the p-columns, as you can see in Fig. 5.19b.

In Fig. 5.18 is also shown the unexpected behavior of the W30-D9.5 module. This module shows a decreasing efficiency as the bias voltage increases. This behavior was solved by increasing the ToT of the module during data taking. The analysis of this phenomenon is postponed in the Appendix (Sec. A.6).

Module Name	Pixel Cell Dimension [μm^2]	Chip Version	Irradiation Facility	Fluence [$\text{n}_{\text{eq}}/\text{cm}^2$]		Beam Facility	Bias [V]	Efficiency [%]
				Mean $\times 10^{16}$	Error [%]			
W91-02	25x100	RD53A	-	-	-	DESY	0	97.1
W30-D11.3	25x100	RD53A	BU	0.5	10	DESY	80	97.0
W30-E3.3	50x50	RD53A	CYRIC	1.0	10	DESY	96	97.8
W30-E9.5	25x100	RD53A	CYRIC	1.0	10	DESY	85	97.5

Table 5.6: In this table a summary of the RD53A module tested at DESY with the measured mean efficiency is reported.

The hit efficiency results of the different modules and productions can be considered to be consistent within the tuning uncertainties ($\approx 200 \text{ e}^-$), taking into account the different active thicknesses of the prototypes we can conclude that they meet the requirements for the innermost pixel layer of the ATLAS ITk.

A summary of the efficiency of the RD53A module tested at DESY is presented in Tab. 5.6.

5.4.4 ITkPixV1.1 Modules Tested at CERN

After the Long Shutdown II lasted more than 3 years, LHC resumed regular operation in April 2022. Long Shutdown 2 was scheduled to last only two years, but LHC suffered some delays due to the ongoing COVID-19 pandemic. Nevertheless, CERN teams were able to make a number of upgrades and improvements to the particle accelerator to support next-generation science during the scheduled shutdown.

Along with LHC, all pre-accelerators, including the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS), two beam test facilities, have also been broken down.

The beam test campaign at PS began in April 2022 and then moved to SPS at beginning of May.

The modules tested at PS are shown in the Tab. 5.10. Only non-irradiated modules were tested at this facility, the results of which will be discussed in a later section.

After the PS beam test, at the SPS facility the modules shown in Tab. 5.10 were tested again. Four modules were subjected to irradiation before the SPS beam test campaigns: two at the CERN IRRAD facility to a target fluence of 1.5×10^{16} n_{eq}/cm² and two at the Bonn irradiation facility to a target fluence of 1×10^{16} n_{eq}/cm².

The Corryvreckan framework [67] was used for the data analysis.

5.4.4.1 Unirradiated Modules

Two test beam campaigns have been run in Spring 2022 to analyze how the unirradiated modules perform on the beam. The setup was moved to the SPS for the second test beam campaign after the first campaign was done at the PS test beam. A proton beam of 12 GeV was used at the PS facility, while a pion beam of about 120 GeV is available at the SPS. SCC 4 was tested in both facilities, whereas SCC 2 was only tested at the PS.

As already discussed and described in Sec. 5.4.1, the setup used for the two test beam campaigns is based on the MIMOSA26 telescope. For the PS and SPS test beams the setup is basically the same but with measly variations in the position of the telescope planes. Additionally, while at the PS, as a timing reference plane, a module with an FE-I4 chip and a planar sensor was added to the telescope, at the SPS, two batches of data were collected: one used as the timing reference plane the FE-I4 module, the second one using an RD53A chip and a planar sensor.

The DUTs efficiency was measured for both of them, to assess possible systematic differences. The devices used in the different batches and their positions are listed in Tab. 5.7. The setup is also equipped with an Arduino-based system to read the temperature from the NTC present on the SCCs. The chiller was set to have a temperature on the SCCs NTC of 15°C.

Facility	Batch N°	MIM 1	MIM 2	MIM 3	SCC2	SCC4	RD53A	MIM 4	MIM 5	MIM 6	FE-I4
PS	1	0	153	305	416	467	/	729	895	1032	921
SPS	1	0	150	304	/	509	/	780	932	1085	112
SPS	2	0	150	304	/	509	575	780	932	1085	112

Table 5.7: Devices and their position in mm along the beam direction for the different batches of data collected. The telescope planes are identified with “MIM”.

Data were collected at the PS facility biasing the DUT sensor with a bias voltage of 1, 2, 4, 6, and 10 V to measure the efficiency as a function of the voltage bias. Data were only collected with a bias voltage of 0 and 10 V during the SPS. Data were collected in both facilities with the SCCs perpendicular to the beam. Data collection is structured as a series of *runs*, each of which records a certain number of events triggered by the logic of the scintillator. The number of events per run is typically kept not large to prevent wasting a considerable data sample in the case of an error occurring. As a result, a large number of runs are collected for each bias voltage set point to have enough data to analyze.

Data Analysis

The Corryvreckan framework has been used to analyze the data. The reconstruction and data analysis are carried out following the procedure reported in Sec. 5.4.1. The SCC2 and SCC4 are the DUTs in this data-taking.

Data Loading and Pixel Masking At PS and SPS beam tests, the data collection was loaded in Corryvreckan: in this way, it is possible to visualize the hit map for each device. An example of this map is shown in Fig. 5.20a for the data taken at the SPS with SCC 4. Noisy pixels and dead pixels were correctly masked. A dedicated mask was created for each batch of data. An example of the pixel mask is presented in Fig. 5.20b.

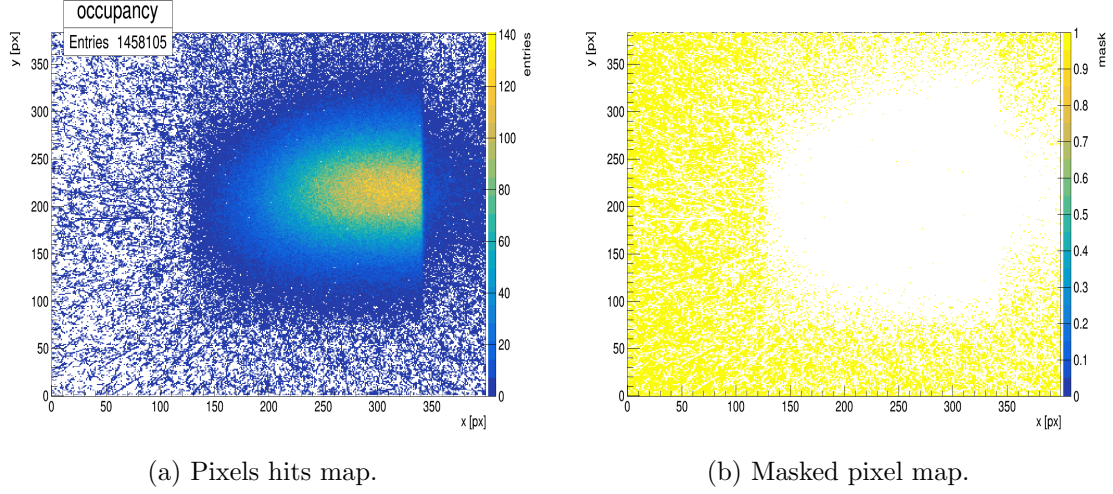


Figure 5.20: Hit (a) and masked (b) pixel maps from events collected at the SPS by SCC4. Due to the fact that scintillators are placed like a cross used as a trigger for data collection, the DUT area involved is squared shaped.

Offline Telescope and DUTs Alignment For the telescope alignment, the selection of a reference plane is needed. For our purpose, the fourth plane of the telescope was chosen. The choice of another plane would have been completely transparent for the alignment quality.

At the end of the alignment procedure, the distribution of the tracks χ^2 , and the plane's spatial residuals are recorded.

As shown in Fig. 5.21, the distribution of the tracks χ^2 after the alignment is mainly between 0 and 10 (Fig. 5.21b), while before the alignment it is much larger — as you can see in Fig. 5.21a. This means that the tracks fit managed to converge and the alignment was successful. Fig. 5.21 are done using the data taken at the SPS. For the PS telescope alignment, we get very similar results.

After alignment, the residual distributions of MIMOSA26 planes at the PS and the SPS were obtained. These distributions have been fitted with a Gaussian function to get the RMS which is, as expected, of the order of $4 \mu\text{m}$ in both directions. This is related to the pixel resolution of the telescope devices (as reported in Sec. 5.4.1).

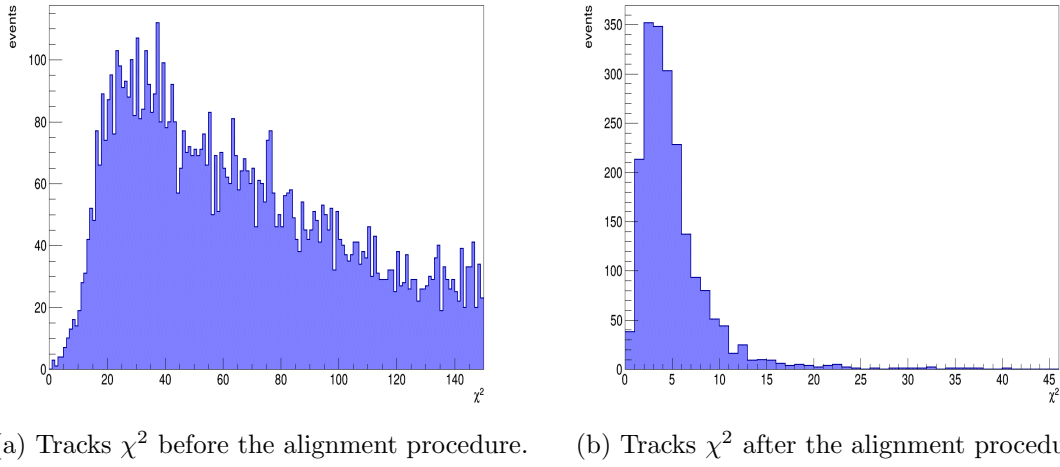


Figure 5.21: Comparison between tracks χ^2 before (a) and after (b) alignment, for SPS data.

The alignments of the DUT are slightly different between the PS and SPS test beam. The center of both residual distributions is zero, but the PS residuals are in the range of 21.5-24 μm , larger than the SPS ones, which are of the order of 13 μm . The lower particle beam energy, which increases multiple scattering primarily because of the cooling box's aluminum walls, may be the cause of the worse spatial resolution at the PS. When using a higher energy beam at the SPS, this phenomenon is minimal. Fig. 5.22 compares the PS and SPS residual distributions for SCC4 in the X direction. Tab. 5.8 lists the X and Y residuals from the DUTs alignment.

Although the residuals at the PS are higher than expected, it did not affect the efficiency analysis because the spatial cut for associating a cluster to the track projection on the DUT is 100 μm .

DUT	PS		SPS	
	Residual X [μm]	Residual Y [μm]	Residual X [μm]	Residual Y [μm]
SCC 2	21.5	23.9	/	/
SCC 4	21.6	24.0	12.9	12.8

Table 5.8: X and Y residuals (RMS) of DUTs after the alignment for both the PS and SPS setup.

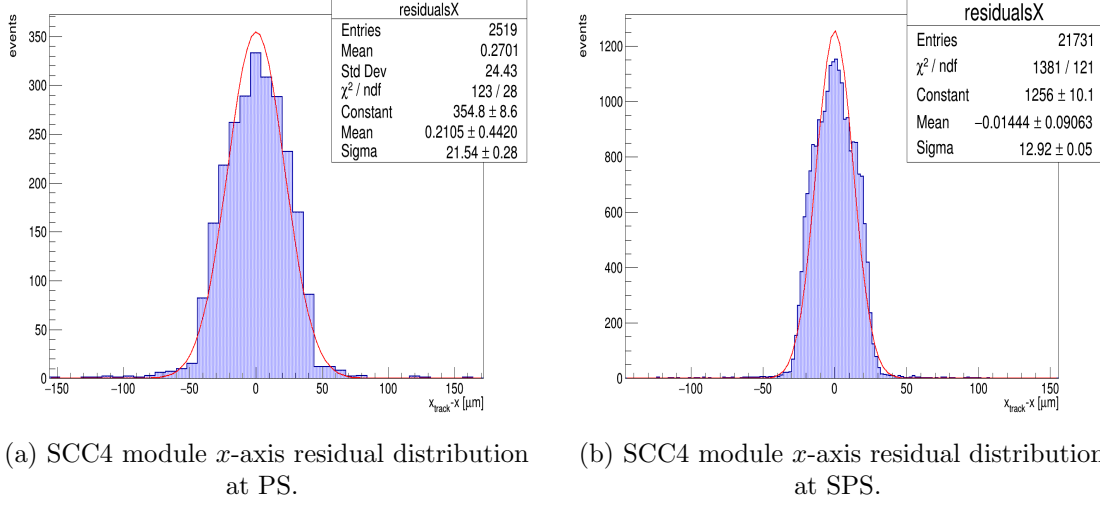


Figure 5.22: Residuals in the X direction of SCC 4 for both the PS and SPS setup. The residual RMS at the SPS is about 14 μm , while at the PS it is higher. The mean is centered in zero, as expected.

The alignment residuals of the DUT have been used to calculate the sensor resolution. The pixel spatial resolution for binary read-out is correlated with the pixel pitch. Only binary read-out is possible because the ToT reading function was disabled for the ITkPixV1.1 chip. As a result, the expected resolution for the $50 \times 50 \mu\text{m}^2$ 3D sensor is approximately 14 μm ($=50/\sqrt{(12)}$), in both the X and Y directions. We obtained a resolution of approximately 13 μm from the residuals analysis, which was slightly better than expected but compatible within errors.

Mean Efficiency In this paragraph, we are going to present the results of the unirradiated modules' mean efficiency and the pixel cell local efficiency.

A reference plane with a reasonable time resolution was used to improve the timing alignment between the DUT cluster and the track. Due to a problem with the DAQ system at the PS, where we tested two devices, it was not possible to use the FE-I4 module as the timing reference plane. As a result, when analyzing the SCC2's efficiency, the SCC4 was used as the reference, and vice versa.

The only DUT at the SPS was SCC4, and its efficiency was measured in comparison to both the FE-I4 module and the RD53A module. Because the DAQ's synchronization issues were solved, at SPS it was possible to use the FE-I4 module as a reference. The differences between the efficiency values for SCC4 obtained at SPS using the FE-I4 and those obtained using the RD53A are only of the order of 0.02 %. Data were collected between 0 and 10 V and the efficiency was calculated as a function of the bias voltage of the sensor. For each bias voltage point, some runs were collected; for each, the mean efficiency was evaluated and saved in a distribution. With a Gaussian fit the mean value and the standard deviation

of the distribution are extracted, which are used to represent the mean efficiency and its uncertainty for that bias point. Fig. 5.25 provides an example of the efficiency distribution using data collected at the SPS with a 10 V bias.

The SPS's observed mean efficiency is slightly higher than the PS's. The synchronization between telescope planes and DUTs has been optimized after moving the setup from the PS to the SPS, which undoubtedly helped to improve the efficiency analysis. Additionally, as was already mentioned, the multiple scattering at the PS is more accentuated due to the cooling box's walls, which could slightly affect the measurement. The PS and SPS results obtained at a 10 V bias, however, are compatible with errors.

Mean efficiency results are shown in Fig. 5.23. The results at SPS are consistent with expectations, demonstrating that the efficiency is already $(98.6 \pm 0.1)\%$ at 0 V and increases to $(98.87 \pm 0.06)\%$ at 10 V. Due to the widening of the depletion zone in the sensor, an increasing efficiency trend was seen as the voltage is increased. Therefore, the sensor satisfies the requirement of having an efficiency greater than 98 % before irradiation.

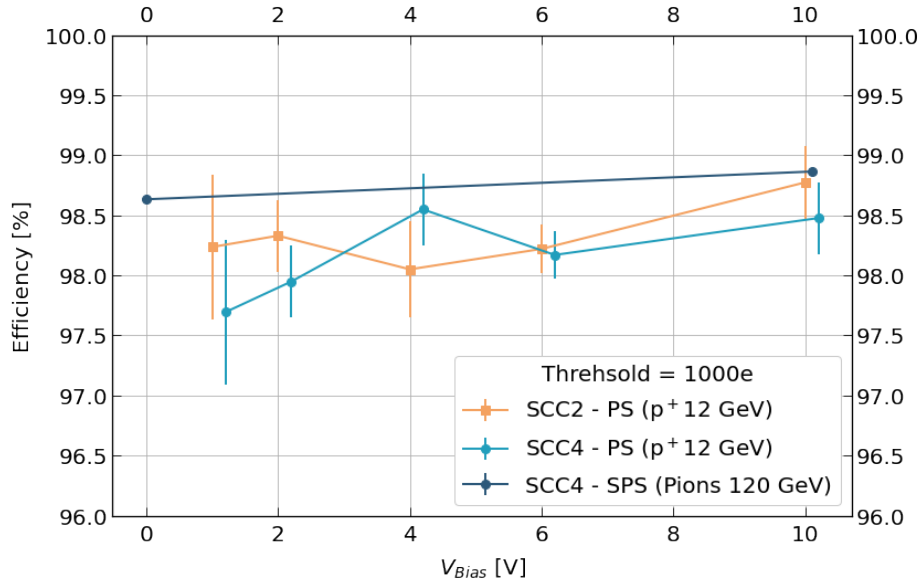


Figure 5.23: SCC4 and SCC2 mean efficiency as a function of the sensor bias voltage. The error on the efficiency is evaluated as the standard deviation of the efficiency distribution obtained in each run. PS data points are reported with slightly different bias values to facilitate the reading of the graph.

Systematic effects dominate in the errors in the efficiency values obtained with the PS data. The DUTs lost systematically the timing correlation with the telescope planes after a few events during data collection due to a trigger system problem. Additionally, it was observed that the alignment of the DUTs at the PS was not stable, which caused a gradual increase in the DUT residues during the analysis and might have negatively impacted the

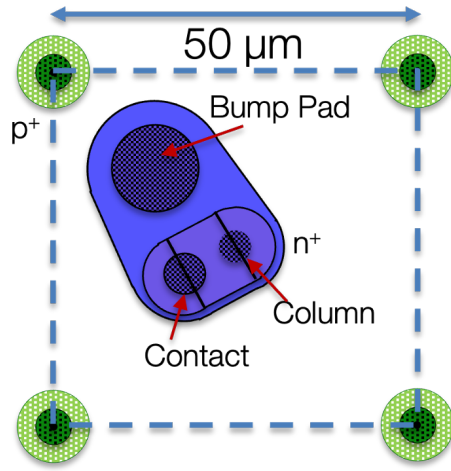
efficiency measurement. These factors make the efficiency values obtained at PS for each run much more unstable, falling between 95% and 99%, which increases the mean efficiency error.

You can find all the mean efficiencies with their uncertainties in Tab. 5.9 for both DUTs SCC2 and SCC4 and for both PS and SPS beam test facilities.

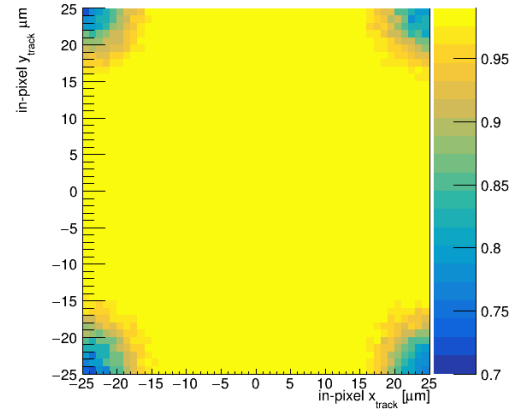
		SCC 2		SCC 4	
Where	V bias [V]	Efficiency %	uncertainty %	Efficiency %	uncertainty %
PS	1	98.2	0.6	97.7	0.5
PS	2	98.3	0.6	97.9	0.5
PS	4	98.1	0.3	98.6	0.3
PS	6	98.2	0.2	98.2	0.2
PS	10	98.8	0.3	98.5	0.3
SPS	0	/	/	98.6	0.1
SPS	10	/	/	98.87	0.06

Table 5.9: Summary of the efficiency measurements on unirradiated SCCs.

Pixel Cell Efficiency The spatial coordinates of the clusters and the tracks intercepts could be interpreted in terms of the single pixel cell, as discussed in Sec. 5.4.1, making it possible to study the local efficiency of the pixel cell for pixel detectors. We anticipate that the efficiency will be slightly lower in the corners of the sensor, where the p^+ columns are implanted, due to the geometry of the 3D sensor pixel cell, which is illustrated in Fig. 5.24a. The pixel efficiency map that was generated using SPS data collected with a bias voltage of 0 V is shown in Fig. 5.24b. As expected, the efficiency in this region is lower, around 75 %, whereas inside the pixel cell, it is close to 95 %.



(a) 3D sensor pixel cell.



(b) Pixel local efficiency map.

Figure 5.24: 3D sensor pixel cell and the local efficiency map (SPS data, 0 V bias): as expected, at the corner, where the p^+ columns are implanted, the efficiency is lower. No other structures are visible.

Even though the pixel cell contains additional structures (such as the n^+ column, the bump bond support pad, and the contact column between the n^+ column and the bump pad), these do not affect the efficiency, which is uniform in the center of the pixel. With the 10V data set, a corresponding map has been created. Fig. 5.25 displays the projection of the first row of the two local efficiency maps, which corresponds to a $1 \mu\text{m}$ wide line along $50 \mu\text{m}$ in the X direction. For both 0 and 10 V bias, the efficiency is greater than 98 % after $10 \mu\text{m}$ from the edge of the pixel cell.

Due to the $4 \mu\text{m}$ radius of the p^+ column's impact on the electric field's edge effects, signal collection in this area is less efficient. Additionally, there have been no noticeable changes in the lower efficiency zone's extension between 0 and 10 V. The efficiency in the column region is, however, a little lower at 0 V than it is at 10 V.

Inefficiency zones caused by p^+ columns are not visible in the pixel efficiency map of the PS data due to the alignment problems discussed above, but the mean efficiency of the pixel cell is consistent with the efficiency measured with SPS data.

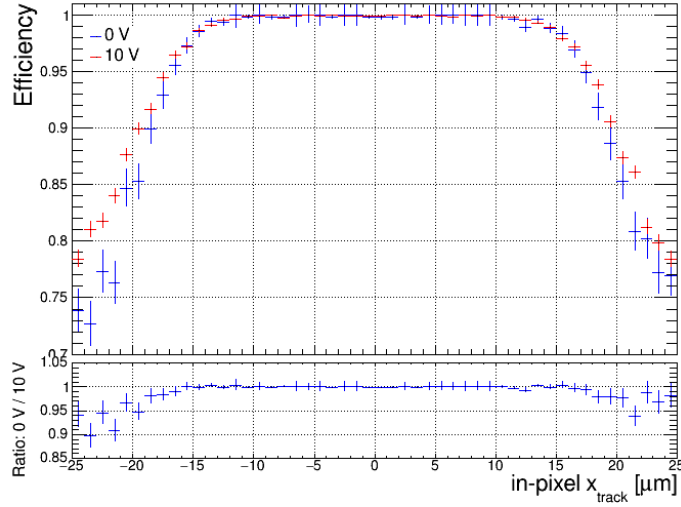


Figure 5.25: Pixel local efficiency map projection along X direction at the SPS for 0 V and 10 V bias.

5.4.4.2 Irradiated Modules

A test beam campaign was conducted in the summer of 2022 to analyze the irradiated modules' performance on the beam. With a pion beam of approximately 120 GeV energy, the campaign was conducted at the CERN SPS beam facility. During this test beam campaign, the SCCs irradiated in Bonn (SCC 3 and 5) and at IRRAD (SCC 2 and 8) have both been put to the test. No testbeam data was collected because an issue on SCC 2 and 8's wire bond pads made it impossible to communicate with them. However, the sensor IV curves were measured, results are presented hereafter. Instead, the two SCCs irradiated in Bonn operated without any critical problems.

Beam Test Setup The setup used for the two test beam campaigns is based on the MIMOSA26 telescope described in Sec. 5.4.1 and it is exactly the same one used during the Spring SPS test beam campaign. In this case, the unirradiated SCC 4 was used as the timing reference plane.

Electrical Properties Data was collected with SCC 3 and 5 during the campaign with a bias starting from 10 V up to 160 V with steps of 10 or 20 V in order to measure the efficiency of the sensors as a function of the bias voltage. A total of two sets of data were collected: one set had all of the SCCs parallel to the pion beam axis, and the other had them tilted by 15° with respect to the XY plane, as shown in figure SCCs tilted-overview. The leakage currents of the modules under examination are shown in Fig. 5.26. The values are clearly greater than those measured in the pre-irradiation modules. For reasons of simplicity, the plots of the IV scans measured before irradiation are in the Appendix, Sec. A.2.

The IV scans in Fig. 5.26 are rescaled to -25°C temperature to allow the comparison of these curves also with those obtained from the RD53A modules tested at DESY, shown in Fig. A.6 in Appendix.

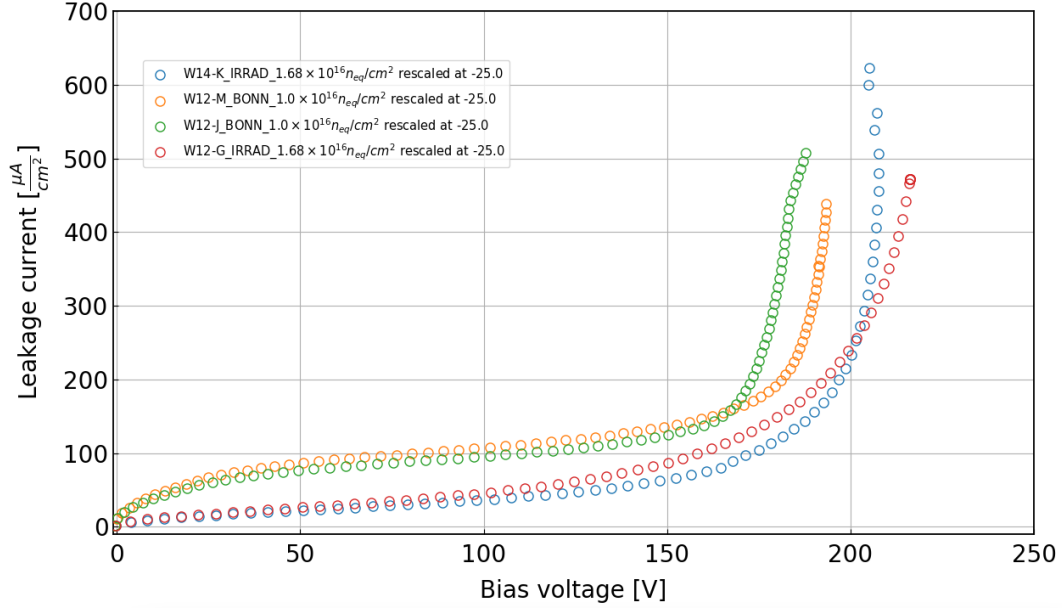


Figure 5.26: Leakage current in function of bias voltage of SCC3, SCC5, SCC2 and SCC8 modules after irradiation. The IV scans in the figure are rescaled to -25°C temperature to allow comparison of the curves with those obtained from the RD53A modules tested at DESY (DESY plots are reported in A.6).

The irradiated devices must be cooled down to maintain the leakage current below a safe limit and prevent thermal runaway (current increases with temperature, and power increases with current, thus increasing the temperature up to an unmanageable level). To increase heat exchange and further improve the cooling of the module, a thin copper tape was used to join the aluminum frame of the module to the back of the module (the copper tape is visible in Fig. 5.27).



Figure 5.27: Copper tape was added on the back of the modules to increase the thermal coupling between the sensor and the cooling box.

The module could be tested at a stable temperature of about -34°C because of the chiller and the copper tape. Since the working conditions reproduced by the efficiency measurement with the tilted DUTs are more analogous to those that will exist in the ITk detector, it is especially interesting.

The comprehensive list of modules tested during beam tests can be found in Tab. 5.10, which includes information about the beam test facility where the modules were tested and the corresponding radiation facility.

SCC N°	Module Name	First TB	Irradiation	Second TB	SCC Status
SCC 2	W12-G	PS	IRRAD	/	Irradiation issues not working
SCC 3	W12-M	/	Bonn	SPS	Fully functional
SCC 4	W12-N	PS	/	SPS	Fully functional
SCC 5	W12-J	/	Bonn	SPS	Fully functional
SCC 8	W14-K	/	IRRAD	/	Irradiation issues not working

Table 5.10: Devices irradiated and beam tested at CERN.

First, scans were run in both digital and analog modes at a temperature of -16°C. The modules' digital scan results were successful because SCC 3 and 5 both recorded 100% of functional pixels. In addition, the proportion of masked pixels was around 0.1%. A small number of the central area's pixels in SCC 5 were noted to have stopped functioning, but their amount was insignificant. When the temperature reached -34°C, data collection could begin.

At this temperature, SCC 5 was also successfully operated, but SCC 3 had a problem: It stopped sending data to the acquisition system. Numerous investigations were needed. Finally, the issue has been found: a few pixels in the bottom right corner prevented the chip from exchanging data with them. These pixels were already problematic even before to the irradiation and it's possible that the irradiation and the low temperature have caused further degradation in their performance. The most likely explanation is that these pixels were jamming the data stream by sending random signals.

By masking the two core columns on which these not functioning pixels are located, the problem has been conservatively fixed. The SCC 3 chip was once again operated successfully after using this solution. For SCC 3 and 5, the number of masked pixels was around 0.1 %. The additional masked pixels brought on by SCC 3's two masked core columns increase the overall masked pixel fraction to 4 %. Fig. 5.28 displays the maps of the masked pixels following digital and analog scan.

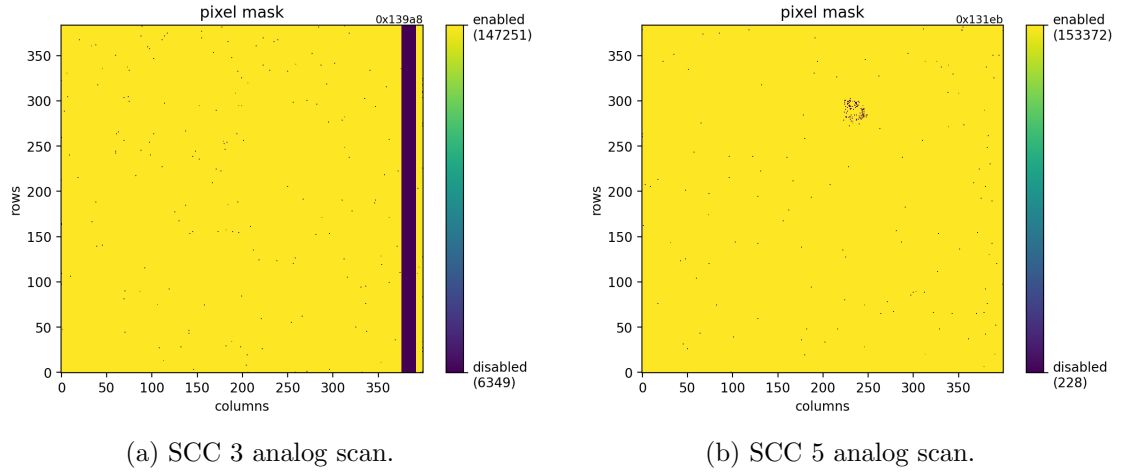


Figure 5.28: Masked pixel map for SCC 3 (s) and 5 (b) after irradiation. The fraction of masked pixel is about 4 % for SCC 3 (due to the 2 masked core columns) and about 0.1 % for SCC 5.

Threshold Behavior The threshold tuning was performed with the SCCs at a temperature of -34°C and with the sensor biased at 100 V. Moreover, due to the high leakage current (of the order of $50 \mu\text{A}/\text{cm}^2$), the leakage current compensation circuit of the chip was enabled. The target threshold was set to $1000 e^-$, and the tuning procedure worked smoothly. Results are shown in Tab. 5.11: as expected the threshold is close to $1000 e^-$ and the noise to $70e$. Both the threshold and the noise are uniform over the entire surface of the chip. An example of the threshold map and distribution is shown for SCC 5 in Fig. 5.29. Threshold tuning results are compatible with the ones obtained before the irradiation, within the uncertainty.

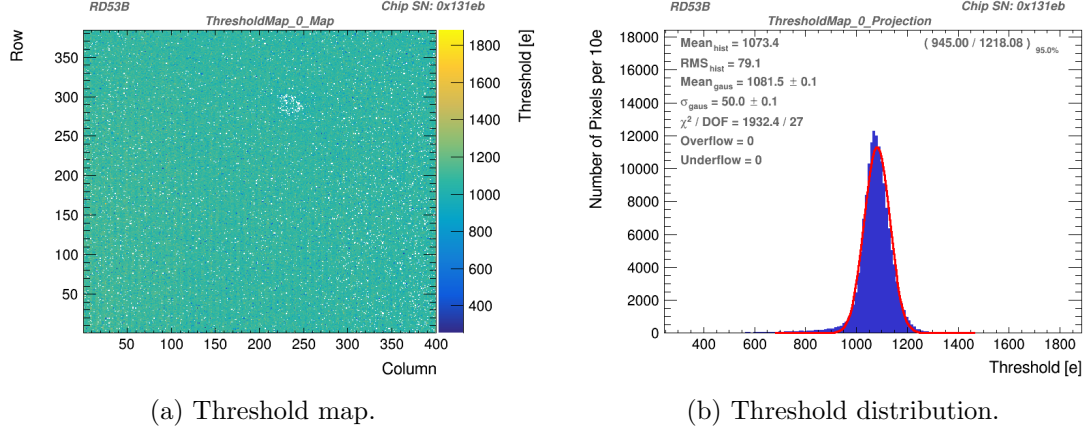


Figure 5.29: Threshold map and distribution for SCC5 after irradiation. As expected the threshold map is uniform and the mean of the distribution is about 1000 e^- .

The sensor was biased at 100 V for the threshold tuning, which was done in this configuration for all data collection. Because the tuning process takes a long time, it was decided to do it only once, to use most of the time available to collect data with beam. However, a threshold scan was conducted at various bias voltage values to verify the accuracy of the tuning. This allowed for the evaluation of threshold and noise variations as a function of bias voltage. The results are displayed in Fig. 5.30a. For both SCCs, the noise is stable at 75 e^- .

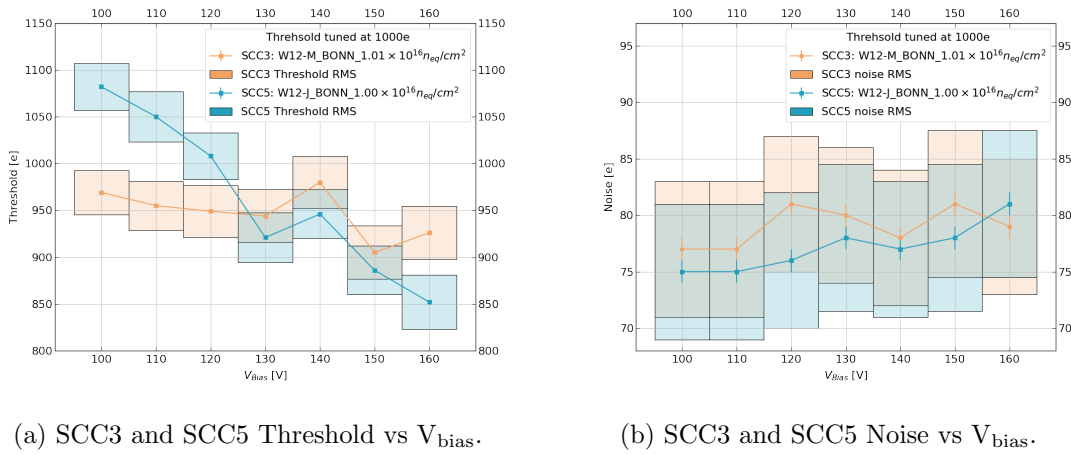


Figure 5.30: Threshold (noise) as a function of bias voltage after irradiation. The error bar reported is the mean error of the threshold (noise) distribution, while the colored columns are the standard deviation of the threshold (noise) distribution.

Particularly for SCC 5, the threshold appears to be decreasing with rising voltage. The

origin of this behavior is still unknown. Even though the leakage current compensation was turned on during the threshold scans, which should reduce the effect of the leakage current on the electronics, it is possible that this was causing the increased leakage current. Despite the unexpected behavior, this is not a significant issue since the ITk detector will be tuned at the precise bias voltage chosen for data collection. On the other hand, the threshold and noise dispersion remains stable while the bias is changed, showing that it was unnecessary to retune during test beam.

SCC N ^o	T [°C]	Irradiation n_{eq}/cm^2	Threshold mean [e^-]	$\sigma_{Threshold}$ [e^-]	Noise mean [e^-]	σ_{Noise} [e^-]	Masked pixel after tuning
SCC 3	25	Before	979	31	67	9	0.2%
SCC 3	-39	1.0×10^{16}	969	47	77	12	0.1% + 4%
SCC 5	25	Before	969	31	73	10	0%
SCC 5	-39	1.0×10^{16}	1082	50	75	12	0.1%

Table 5.11: Threshold tuning results of irradiated ITkPixV1.1 modules. Note that the number of masked pixels in SCC 3 is dominated by the 2 disabled columns. Threshold and noise standard deviation is indicated with σ .

As shown in the Tab. 5.11, less than one percent of the pixels were disabled by both SCC3 and SCC5 modules before data taking. A portion of the pixels is muted by the digital and analog scans, while after threshold tuning, those pixels that are noisy are further disabled. This is evaluated by a noise scan, whereby the modules are operated as they would be during a data taking but triggered at a fixed frequency. The occupancy distribution of individual pixels (the number of times the pixel has “turned on” divided by the number of triggers) is then plotted. You can see the distribution from Fig. 5.31a.

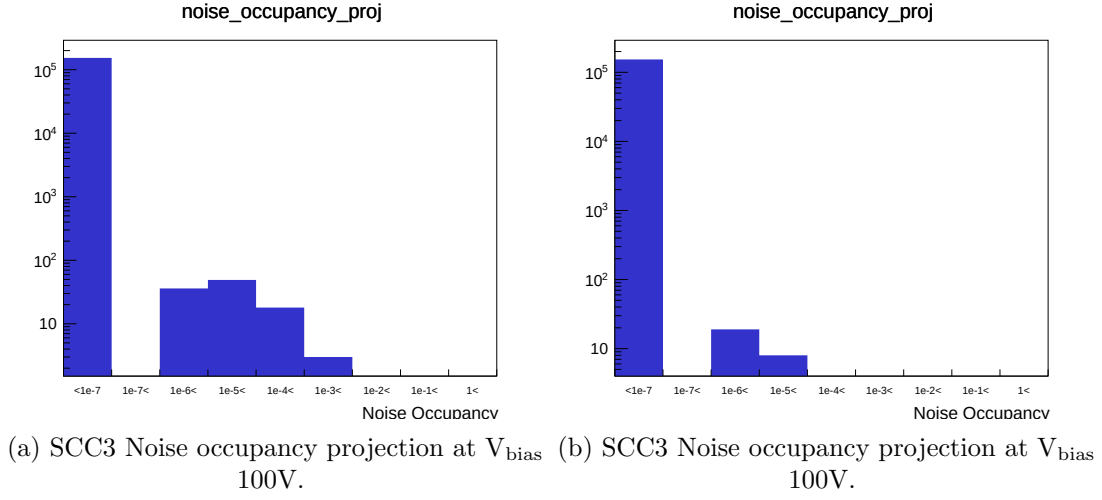


Figure 5.31: SCC3 pixel noise occupancy projection. Pixels are cut away if their noise occupancy results to be greater than 10^{-6} .

Currently, any pixels with an occupancy higher than 10^{-6} (a typical value for pixel modules, though not fixed) are deactivated. The chart in Fig. 5.31b illustrates that by conducting a second noise scan, the count of pixels classified as “noisy” and consequently having an occupancy above 10^{-6} reduces.

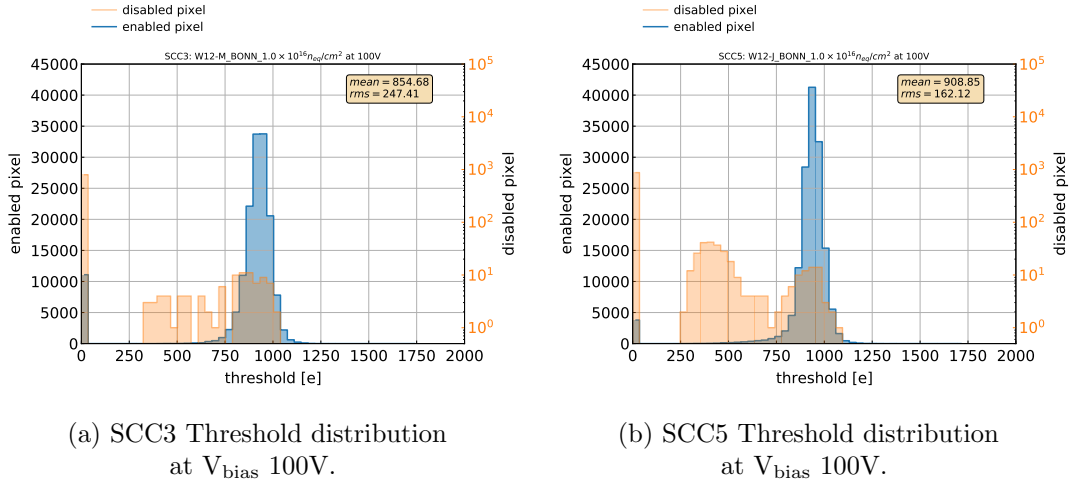


Figure 5.32: Threshold distribution of enabled (blue) and disabled (orange) pixels of SCC3 (a) and SCC5 (b) modules. The orange distribution is reported with a logarithmic scale on y -axis.

From a study of the threshold distribution of individual pixels (see Fig. 5.32), it can be

seen that most of the disabled pixels turn out to be tuned incorrectly in the threshold. In fact, from the Fig. 5.32 (the module voltage during this noise scan is 100 V), pixels kept in the data taking and which are in fact well distributed in threshold are shown in blue, while pixels removed from the data taking are shown in orange. Note how some pixels were not tuned at all (threshold value equal to $0e^-$) and this is due to the fact that those pixels were disabled during digital and noise scans.

The same study was done for the pixel noise and it can be seen from Fig. 5.33 (the voltage of both modules during this noise scan is 100V) how most of the disabled pixels in the SCC3 card turns out to have a noise distribution that tends to be greater than the non-disabled pixels, while as for the SCC5 card, the noise distribution of the disabled pixels is more uniform.

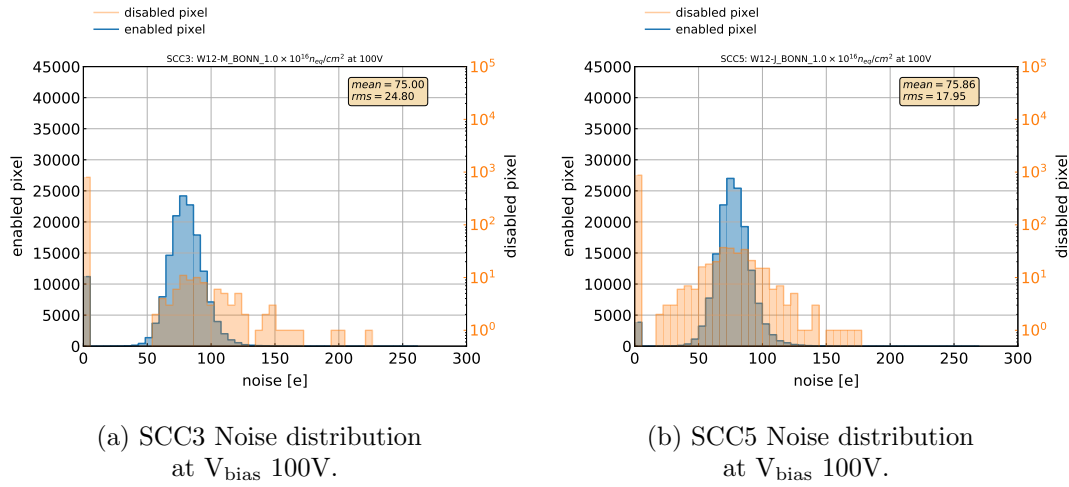


Figure 5.33: Pixel noise distribution of enabled (blue) and disabled (orange) pixels of SCC3 (a) and SCC5 (b) modules. The orange distribution is reported with a logarithmic scale on y -axis.

This can also be seen from Fig. 5.34, in which it is clear that as a function of bias voltage, the SCC5 card becomes noisier and the disabled pixels increase as a function of voltage. In contrast, the SCC3 card is less noisy and its trend of disabled pixels as a function of voltage is increasing but with a softer trend.

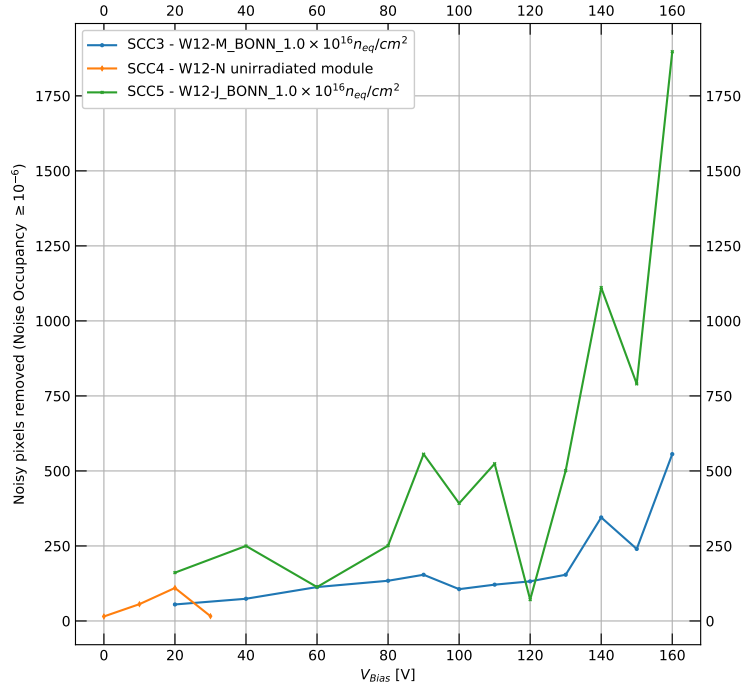


Figure 5.34: SCC3, SCC5, and SCC4 noisy pixel removed in the function of bias voltage. The pixel removed are the ones with Noise Occupancy over 10^{-6} after YARR Noise Scan.

For the sake of comprehensiveness, Fig. 5.34 presents the relationship between bias voltage and the number of disabled pixels in the SCC4 module. However, since the module is unirradiated, the count of disabled pixels remains consistently low. It should be noted that the statistical significance is limited due to the inability to operate the module at a bias voltage exceeding 10 V, given its unirradiated state

Sensor Results

Results for the sensor's mean efficiency, the pixel's local efficiency map, and the sensor IV curve following irradiation are presented in this section. The efficiency is extrapolated in the same way as explained in Sec. 5.4.1, using the same criteria that were applied to the analysis of the data collection using unirradiated SCCs. While the IV curve was measured for all four irradiated SCCs, the efficiency was only measured for SCCs 3 and 5.

As explained in Sec. 5.4.4.1, if the sensor is placed perpendicular to the beam, the particle will cross the p^+ columns perpendicularly for their entire length, while, if the sensor is slightly tilted, the particle will pass through the column only partially: in this way, it will release part of the signal in the central area of the pixel, which is active. Therefore, since

the efficiency is recovered in the corners, the resulting local pixel efficiency is higher in the case of the sensor tilted with respect to the beam.

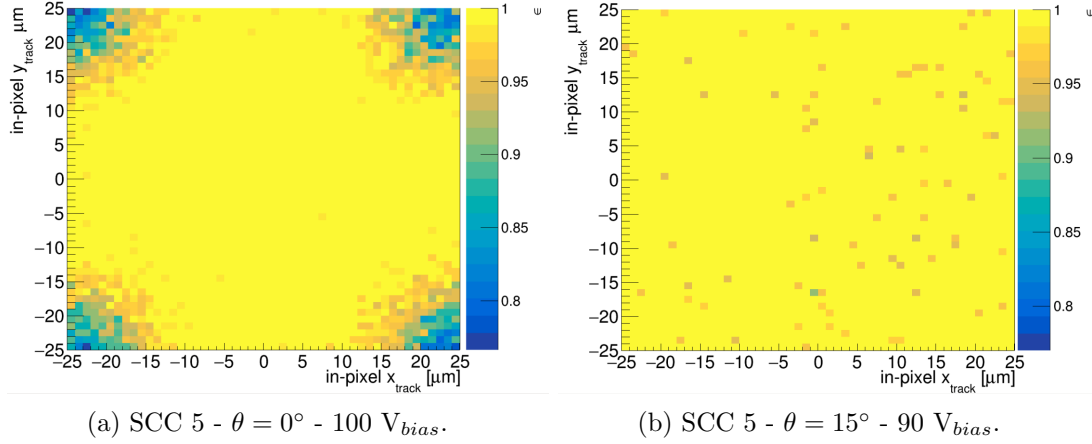


Figure 5.35: Pixel local efficiency map after irradiation for SCC 5 perpendicular ($\theta = 0^\circ$) and tilted ($\theta = 15^\circ$) with respect to the beam. Note that it is reasonable to compare the two maps, despite the different biases, since the sensor is fully depleted for bias higher than 90 V.

In both configurations—perpendicular to the beam and tilted—the pixel local efficiency map has been reconstructed. There are lower efficiency areas with a radius of about 10 μm from the corners of the efficiency map for the SCCs perpendicular to the beam, similar to the results for the SCCs before irradiation (Fig. 5.35a). Instead, in the configuration with the SCCs tilted, as shown in Fig. 5.35b, these lower efficiency areas are no longer distinguishable in the local efficiency map. Similar to what was done for the unirradiated modules, a reference plane with a reasonable time resolution—in this case, SCC 4—was used to improve the timing match between the DUT cluster and the track. Data was collected at various bias voltages and the efficiency was calculated as a function of the sensor bias voltage. The efficiency error could not be calculated as it was for the unirradiated samples because only a small number of runs were collected for each bias voltage. The run efficiency distributions could be constructed after a few bias voltage points which were collected with more statistics. In this case, an efficiency difference of the order of 0.1 % was noted. In light of this, it was decided to use this value as a slightly conservative uncertainty for all efficiency values discovered, while remaining consistent with the uncertainties seen for the high statistics runs of the unirradiated test beam campaign. Fig. 5.36 displays mean efficiency as a function of bias voltage. The efficiency exhibits a rising trend as voltage rises, as expected. The efficiency of SCCs perpendicular to the beam is approximately 97.5% at 40 V, meaning that the sensor is already nearly depleted. The efficiency decreases with increasing bias voltages, peaking (98.5 ± 0.1)% at 100V. The efficiency obtained with the SCCs tilted is slightly greater than the efficiency obtained with the SCCs perpendicular to

the beam, as might be expected. This may be supported by observing Fig. 5.35b with the local efficiency map, which makes it clear that the column inefficiency is recovered. At 90 V, the tilted configuration's saturation value is approximately $(99.9 \pm 0.1)\%$. All the efficiency results obtained with measures on modules SCC 3 and SCC 5 with tilted and not titled configuration are reported in Tab. 5.12

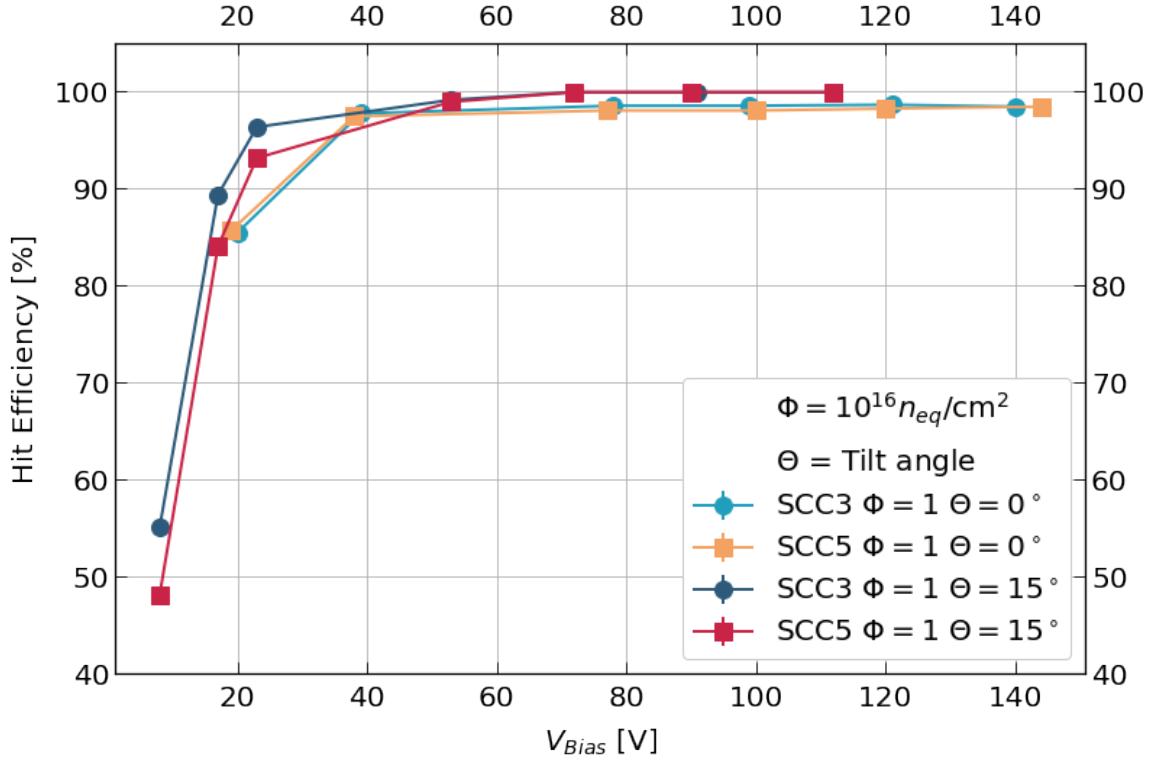


Figure 5.36: SCC3 and SCC5 mean efficiency after irradiation to a fluence $\Phi = 1 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$. The efficiency is measured both with the SCCs perpendicular ($\Theta = 0^\circ$) to the beamline and titled ($\Theta = 15^\circ$).

These results can be compared to those obtained for the prototype modules equipped with the FBK 3D sensor ($50 \times 50 \mu\text{m}^2$) and the RD53A chip exposed to the same fluence (Fig. 5.17 and Fig. 5.18).

The performance of the sensor actually determines the majority of the efficiency measurement, and the prototype sensors were essentially identical to the pre-production ones with the exception of the active region thickness ($130 \mu\text{m}$ for the prototypes vs. $150 \mu\text{m}$ for the tested SCCs). The chips in both instances were set to a threshold of $1000 e^-$. Results should therefore be consistent.

The prototype module results show that the efficiency saturation takes place at higher

	SCC 3			SCC 5		
θ	V bias [V]	Efficiency %	uncertainty %	V bias [V]	Efficiency %	uncertainty %
0°	140	98.4	0.1	144	98.4	0.1
0°	121	98.6	0.1	120	98.2	0.1
0°	99	98.5	0.1	100	98.0	0.1
0°	78	98.5	0.1	77	98.0	0.1
0°	39	97.7	0.1	38	97.4	0.1
0°	20	85.4	0.1	19	85.6	0.1
15°	112	99.9	0.1	112	99.9	0.1
15°	91	99.9	0.1	90	99.9	0.1
15°	72	99.9	0.1	72	99.9	0.1
15°	53	99.1	0.1	53	98.9	0.1
15°	23	96.3	0.1	23	93.1	0.1
15°	17	89.3	0.1	17	84.0	0.1
15°	8	55	0.1	8	48	0.1

Table 5.12: Summary of the mean efficiency measured on the irradiated SCCs.

bias voltages: at a bias voltage of about 90 V, the efficiency reaches 97 %, whereas, at 40 V, it is only about 60 %. It is still unclear why the results from this thesis differ from those from other studies. Although the fluence was the same, the irradiation campaigns were very different because prototypes were exposed to a 23 GeV proton beam at the IRRAD facility. Due to the small beam size (Gaussian with a standard deviation of about 12 mm) and the impossibility of scanning the sensor surface, the irradiation was not uniform, (according to what already said in 5.4.2). Due to these factors, the mean fluence has an uncertainty of 10 %.

On the other hand, despite being uniform (only 1 % variation over the entire surface of the sensor, Sec. 5.4.2), the fluence received by SCC 3 and 5 had an uncertainty of about 15 %.

Therefore, the fact that the sensors were actually exposed to a different fluence could account for the difference between the results obtained on SCCs and those on the prototype modules. To confirm the behavior seen and described in this thesis, a few more devices will be exposed to radiation.

It has been decided to proceed with a second irradiation of SCC 3 and 5 to achieve a total fluence of $1.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$, which is very close to the target specification value, to further evaluate the sensor performance.

The SCCs will then undergo additional testing at the SPS test beam. The new measurements may add some more information to the irradiation performance.

Chapter 6

The ITk Outer Endcap Local Support

In the tracker, the detector modules are supported by light Local Supports (LS), which provide mechanical support and cooling. The ITk detector is divided into three main parts, the Inner System (IS), the Outer Barrel (OB), and the Outer Endcap (OEC), and local supports are mechanically different in each part. My work thesis has focused on the OEC supports, as one endcap will be built by the Italian community (the other one by the UK community). This chapter describes my activity in this area and it is divided into five sections:

- The first two Sec. 6.1 and 6.2 give an overview of the design of the OECs, to introduce the necessary elements and to put the design of the LSs in context, including a brief description of LS manufacturing and assembly processes.
- The third Sec. 6.3 covers the OEC LS carbon foam density studies.
- The fourth Sec. 6.4 describes the procedures and results of the metrology and thermal property measurements done on the LS that was produced during the R&D phase in Genova.
- The fifth Sec. 6.5 outlines the activities carried out on the ITk Production Database regarding the Local Support components of the OE.
- The last Sec. 6.6 is focused on the misalignment studies of the ITk OE region.

6.1 The Outer Endcap Overview

The ITk Pixel OECs occupy the volume between the Inner Support Tube (IST) and the Pixel Support Tube (PST) at either end of the detector, as outlined in green in Fig. 6.1. The space they occupy is defined by $1114 \text{ mm} < |z| < 3018 \text{ mm}$ in length and $145 \text{ mm} < r < 327 \text{ mm}$

in radius. One endcap will be manufactured and assembled in Italy and the other one in UK.

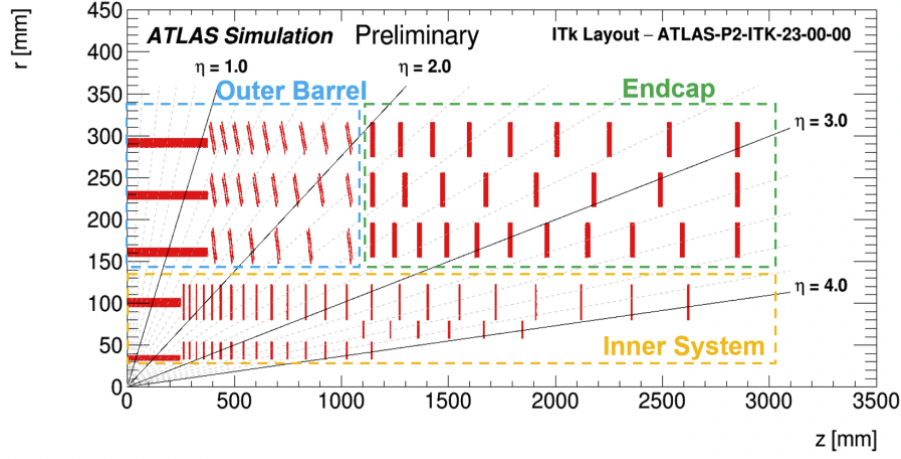


Figure 6.1: Schematic ATLAS ITk Pixel Detector layout in (r,z) plane, highlighting the regions corresponding to the IS (orange), OB (blue), and OEC (green). Only one quadrant and only active detector elements are shown.

Each ITk Pixel OEC consists of three layers (Layers 2, 3, and 4) of Half-Ring-shaped LS structures installed into half-cylindrical global support structures together with all associated cooling and electrical services, as shown in Fig. 6.2. The half cylindrical layers are assembled into full coaxial-cylindrical layers during the endcap integration process.

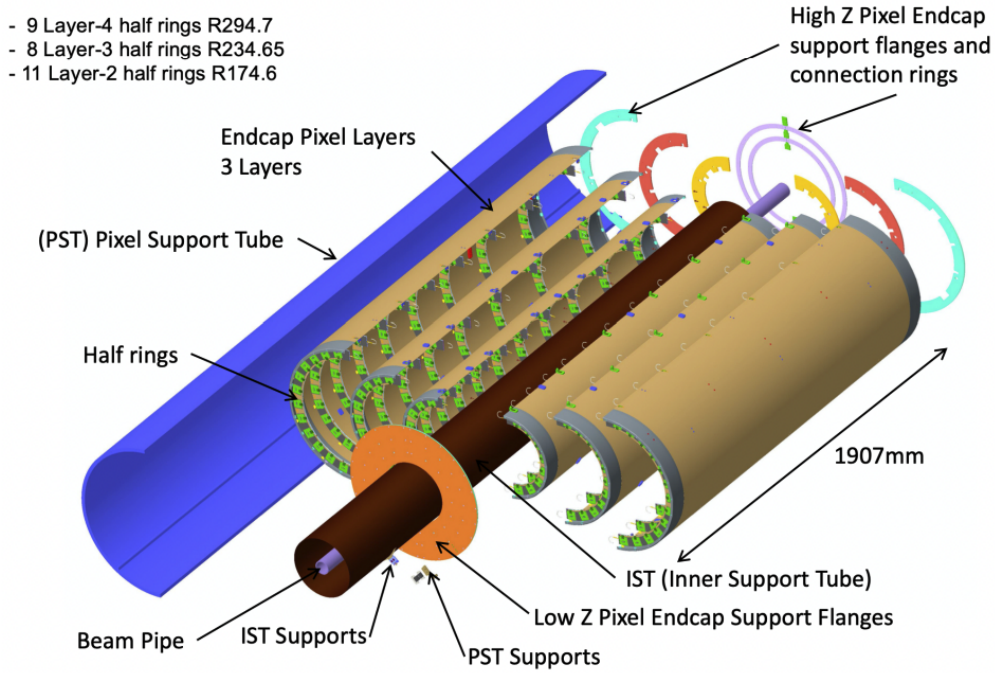


Figure 6.2: CAD representation (exploded view) of one ITk Pixel OEC. The Type-1 services have been omitted for clarity.

The basic local-support structure for the OECs is a “Half-Ring” (HR) (see Fig. 6.4), which supports two serial-powering chains of modules, one chain on each face of the HR. Tab. 6.1 shows the number of rings and modules in one OEC.

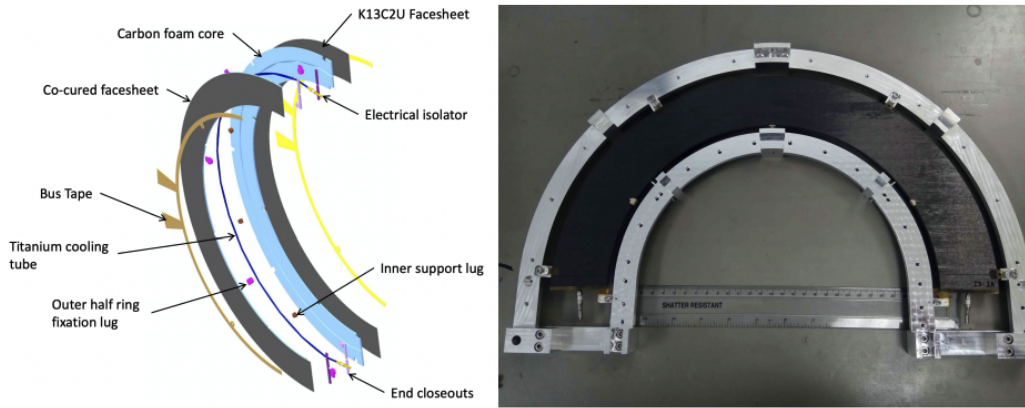


Figure 6.3: Left: an exploded view of an OEC HR, showing all mechanical components. Right: a prototype HR in its handling frame.

The HRs that support and provide cooling to the modules are also designed to support the Type-0 power electronics, which include one “bus tape” and one “power pigtail” per module. In particular, the HRs will house the so-called quad modules (described in Sec. 4.2).

The HRs, bus tapes, and power pigtails are designed to be as modular, portable, and self-contained as possible. While the three sizes of HRs and bus tapes are identical in design except for scale, the power pigtails are the same throughout the endcaps. The two sides of each HR are identical to each other, allowing for insertion into their half-layer in either orientation.

Data, clock, and command signals follow a separate path from power and monitoring, connecting through “data PP0s” multiple modules to bundles of twin-axial cables, “Type-1 data”, that run along the inner surface of the half-cylinders. The “Type-1 services”, which consist of cooling pipes, power cables, and data Twinax cables, connect the HRs to the first ITk Patch Panel (“PP1”). These services will be installed on the inner surfaces of the supporting half-cylinders before loaded HRs are inserted and will occupy the space between the outer rims of the HRs and the inner surface of the half-cylinder.

6.2 ITk Outer Endcap Local Support

6.2.1 Local Support Structures

The OECs LS structure consists of a titanium tube embedded in thermally-conductive carbon foam. An exploded view of a typical OEC HRs is shown in Fig. 6.3 and comprises two three-ply carbon-fiber facesheets co-cured with a carbon foam core, and a titanium cooling tube embedded inside the sandwich.

The titanium pipe is intended for the use of evaporative CO₂ coolant. In the final system, the HR will be operated near -30°C to prevent thermal runaway of the sensor after irradiation and the cooling system must remove 13.45 W per module (nominal). E.g., for a middle HR that supports 22 modules the total power dissipation is 296 W [44].

The cooling tube employed in the OECs design incorporates a ceramic electrical insulator, referred to as an electrical break (EB), at each end. This configuration, depicted in Fig. 6.3, ensures electrical isolation of the HR from the remaining components of the detector. The system Ti-Pipe with the Electrical Break is called Evaporator. The electrical path is grounded separately. The support also includes several small embedded components, including outer fixation lugs and inner support lugs for handling and support, as well as end closeouts to stabilize the tube-ends. These components are made of ULTEMTM, which is an amorphous thermoplastic material known as unreinforced polyetherimide [69].

6.2.2 Local Support Manufacturing and Assembly

In this section, the HR LS manufacturing and the assembly procedure are discussed.

The Evaporator The titanium pipe, which as already explained composes the core of the LS evaporation system, is cut to the proper length and bent to fit the shape of the HR. Then, the electrical breaks (EB) are fixed to the ends of the tube. During the procedures, a certain number of check tests are performed on the evaporator, like a go/no-go template check to evaluate the proper shape, a leak check (for both pipe and EB), and mechanical tests of the EB.

The Carbon Foam The material used as the HRs core is the “Lockheed Martin K9” carbon foam. From a raw carbon block measuring $12 \times 12 \times 1$ cubic inches, thin trapezoid-shaped slices are machined. The trapezoids manufacturing procedure foresees that only one face of the trapezoid is smoothed, leaving the other face “raw” instead, on which the Serial Number of the trapezoid is written and which therefore must remain visible throughout the HR production process. Furthermore, once the HR has been assembled, the outer faces (which correspond to the unpolished faces of the trapezoids) are definitively smoothed to obtain the desired thickness of the local support.

The machining procedure and the subsequently alignment to shape the HR is shown in Fig. 6.5.

A completed HR is made up of two layers of co-cured foam and carbon fiber pre-preg, with each layer, referred to as a “half-sandwich.” The foam layer in each half-sandwich is 2.35 mm thick, while each carbon-fiber facesheet is 0.15 mm thick. However, the slices are initially thicker to allow for machining down to a smooth, flat, and uniformly thin state. After machining, the HR has a thickness of 5 mm.

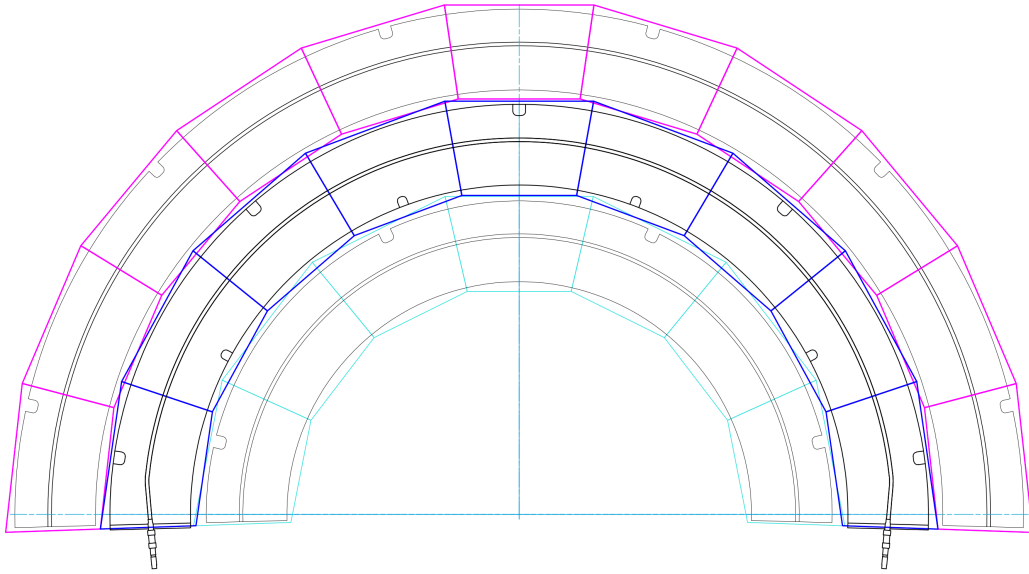
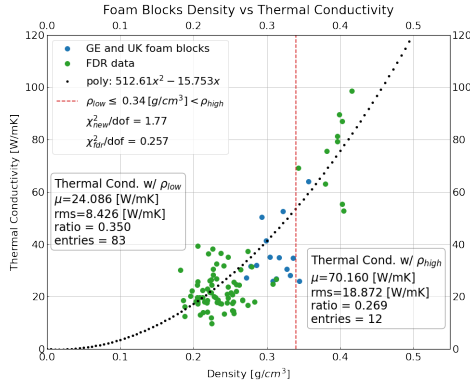
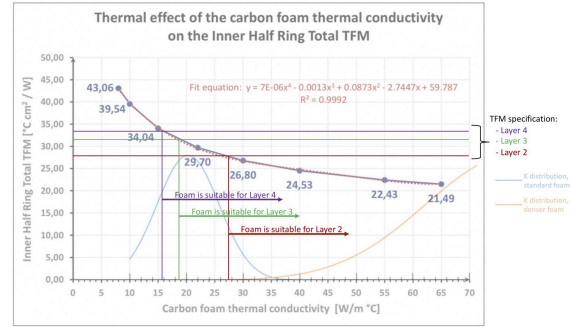


Figure 6.5: Foam trapezoid outlines in each of the three OEC HR sizes.

The double-densified carbon foam was selected to enhance the support thermal conductivity. As shown in Fig. 6.6a, the thermal conductivity of the foam is slightly correlated with its density. As explained in the caption, but the plot indicates that using a foam produced through double densification, with an average density of 0.22 g/cc, increases the thermal conductivity by approximately three times compared to a foam produced through a single densification cycle.



(a) Carbon foam density vs thermal conductivity



(b) TFM vs thermal conductivity.

Figure 6.6: (a) Plot of Lockheed Martin K9 130ppi carbon foam thermal conductivity vs foam density from data collected in 2015-2019. The green dot lower cluster corresponds to the standard foam, which has undergone only one densification cycle, while the green dot upper cluster corresponds to twice-densified foam. The blue dots correspond to the last twice-densified foam batches machined at Genova and UK. (b) FEA prediction of the variation in the Thermal Figure of Merit as a function of the carbon foam thermal conductivity.

It is necessary to ensure sufficient cooling to the modules under extreme heat load conditions when qualifying the local support design from a thermal perspective. The worst-case thermal resistance along the path between the cooling pipe and the module is quantified by the Thermal Figure of Merit (TFM) of a local support structure.

The TFM is defined as:

$$[H]TFM = (T_{module} - T_{C0_2}) / (Power / Area) \quad (6.1)$$

The foam's thermal conductivity for the OEC HR determines the TFM, as shown in Fig. 6.6b. Finite Element Analysis (FEA) is used to predict the TFM and for three HR layers (L2, L3, and L4), a TFM of about 28, 31 and 34°Ccm²/W is respectively expected that correspond to a thermal conductivity of about 16, 19, and 27 W/m °C. However, excessive radiation length (X_0) negatively affects tracking performance. The OECs occupy the pseudorapidity range of approximately $2.0 < \eta < 3.6$; the total amount of material in the ITk in this region is estimated to be 1.3% X_0 per layer. A track going through this region will pass through as many as six OEC rings, so the increase in material budget due to the denser foam is approximately 0.18% X_0 per HR, corresponding to a very small absolute increase and therefore acceptable.

The Half-Sandwich The half-sandwich (shown in the bottom picture in Fig. 6.7) is composed by a different number of carbon foam trapezoids (shown in the higher picture in

Fig. 6.7), depending on the layer assigned to the half-sandwich to be produced. To construct the structure, three layers of pre-preg are layered in the 0/90/0 orientation. The trapezoid segments are then positioned on top, with the smooth side facing downwards and accurately aligned with the cut-out ring shapes. The assembly is then covered with a pre-made silicone frame, vacuum-sealed in a bag, and placed in the autoclave for curing. Once cured, the structure is thoroughly inspected for any defects before machining it down to a final thickness of 2.50 mm using a 16 mm end mill. During machining, the outside profile, pockets for outer fixation lugs and inner support inserts, and the half-diameter groove for the pipe are created.



Figure 6.7: Top: machined foam trapezoid. Bottom: a co-cured prototype “half-sandwich” before further machining.

The Half-Ring The HR assembly is a complex procedure, summarized in the following steps. The process involves cutting carbon veils to shape and placing them on a polymer gluing surface, cleaning various parts with isopropanol, and ensuring the assembly plate was clean and coated with PTFE. The next steps include connecting the plate to a vacuum pump, dry-fitting lugs in place, fixing pipe guides, preparing and mixing Hysol adhesives, wetting out the carbon veils with Hysol, and inserting closeout bottom halves, outer fixation

lugs, and inner support lugs. The final steps include adding the other half-sandwich to create the HR sandwich structure, inserting the ring end wedge, placing the assembly plate onto the vacuum table, and leaving the HR to cure for 48 hours under vacuum. Once cured, the ring is carefully removed from the assembly plate.

A fully assembled bare HR is shown in Fig. 6.3.

Once the bare HR is produced, a copper-on-Kapton bus tapes were cured into the middle of the HR layup and carry traces for serial power, High-Voltage, and one NTC thermistor per module. Then the HR is mounted in an aluminum handling frame, as is shown in Fig. 6.3-Right. Because of the serial-powering architecture, the backplane of each module has to be isolated from the electrically conductive carbon fiber surface. A thermal conductive and electrical isolating adhesive is ensured by placing with an automatic glue dispenser about 100 μm thick, square shaped layer below the center position of each quad module chip. The mounting procedure is done automatically by a custom pick-and-place machine which picks up the module, places it across the HR, and with a camera the right alignment of the module is checked. After the modules are mounted on the HR, the module pigtails are connected to the bus tapes.

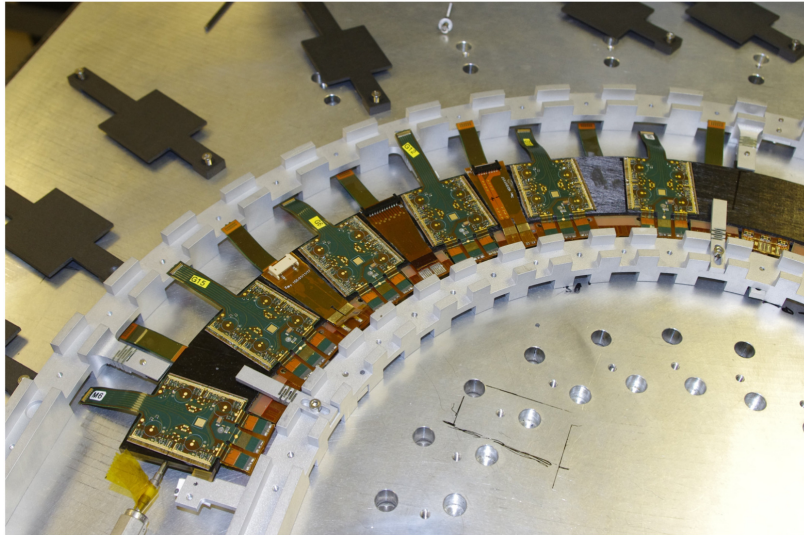


Figure 6.8: The first RAL loaded HR (Ring-0) after loading the modules.

The entire procedure was performed by the Rutherford Appleton Laboratory (RAL) and Oxford team (UK) and by the Genova and Lecce teams (Italy) [70]. In Fig. 6.8 the first HR loaded at RAL is shown (also called Ring-0).

6.3 Foam Density Studies

As already said in Sec. 6.1, ITk Outer Endcap Local Supports, the so-called HRs, are mainly made of carbon foam.

Carbon foam was selected as the low-density core material for LSs (Local Supports) to fulfill various structural and performance-related goals. Its machinability is notably advantageous, allowing for ease of shaping and modification. Additionally, the use of carbon foam helps to maintain a low total mass for the supports, including a reduced radiation length. Furthermore, the thermal performance of carbon foam composites used in HRs proves to be excellent, as illustrated in Fig. 6.6b. This makes carbon foam an ideal choice as a support material for pixel modules operating in the demanding environment of the HL-LHC.

The carbon foam used for the ITk LSs is produced by two companies, the Lockheed Martin Corporation [71] and the Entegris [72]. Actually, during the R&D phase, the collaboration purchased the carbon foam from Allcomp Inc., which was lately acquired by the Lockheed Martin Corporation. This acquisition caused an interruption in production, and the collaboration decided to look for a backup vendor, Entegris, which produces a material that is similar in the main features to the baseline foam.

Lockheed Martin produces carbon foam with varying densities and thermal conductivities (see Fig. 6.6b). Lockheed Martin’s “K9” foam is distinguished from other carbon foams on the market by its much greater 3D isotropy. The foam is made by infiltrating highly oriented carbon throughout the cellular structure of low-density vitreous carbon foam by chemical vapor deposition, rather than grown bottom upwards as other competing foams. This feature is vital to the performance of the ITk pixel LS structures as the isotropic foam smooths the temperature profile across an electronic heat source (such as a silicon module) as well as conducts the heat in the direction normal to the cooling pipe. The K9 foam also machines very well, again due in part to its 3D mechanical isotropy.

Standard K9 foam is produced by one “densification cycle” of adding carbon to the base foam and processing at high temperatures. The base foam block has size $12 \times 12 \times 1$ cubic inches; a 1-cubic-inch cube is removed from one corner of each block to measure the density and thermal conductivity of the block. This measurement is destructive and it has been used in past productions as a representation of the average block properties. This single densification cycle produces foam with an average density of 0.22 g/cm^3 and an average thermal conductivity of about 20 W/mK , although there is a wide spread in both quantities - see the lower cluster of data points in Fig. 6.6b. It should be noted that most of the data points that appear in Fig. 6.6b are taken from different foam blocks (i.e. one measurement per block). It is not known if the variation within a particular block is similar to that from block to block; studies are currently underway at the vendor to investigate this aspect and prepare an updated acceptance procedure that does not rely uniquely on the corner measurement.

The foam’s thermal conductivity can be enhanced by additional densification cycles; the results of a 2nd cycle appear as the higher cluster of data points and also in the blue colored data in Fig. 6.6b; the thermal conductivity of this “twice-baked” foam is consistently greater

than 50 W/mK, and the density is around 0.3 g/cm³. The ITk pixel detector requires twice-baked foam to ensure that thermal-performance specifications are met for all LSs produced. This kind of foam has been chosen to be used for the production of the pre-production LSs.

6.3.1 Carbon Foam Machining

To produce the carbon foam trapezoids, the ATLAS Genova group has developed a procedure that consists in cutting the raw foam block into three 100 mm-wide strips with a band saw and a dedicated tool. The top and the bottom surfaces of these strips are smoothed with a drum sander; each strip is cut into four or five 1-inch thick rectangles using the same band saw and tool; each of these rectangles are cut into four or five thinner slices then refined with a dedicated tool; in the end, the thin slices are cut into trapezoids of the desired dimension with an aluminum trapezoid shaped cutter.

Just before the last step, the thin rectangular slices are measured in weight and dimension to derive their density.

The ATLAS UK group adopts a different method to cut the trapezoids from the blocks: first, the raw carbon foam block is cut with a band saw into 14 or 15 smaller blocks, approximately 100×59 mm. Each of these small blocks can produce four trapezoids, yielding 56-60 trapezoids per Lockheed Martin block. The trapezoids are then milled from the small blocks according to the following procedure: the small block is held in a fixture clamped to a milling machine. The top 1 mm is skimmed off to leave a smooth flat surface, then the trapezoid shape is milled to a depth of approx 5 mm. The trapezoid resulting from the procedure is marked with a serial number on one side (the mark will be removed in a later stage of HR production). The top is sawn off along the milled step to give a 4.0±0.5 mm thick trapezoid. This will be milled down to the required thinness (2.5±0.1 mm for co-cured foam and facesheet) in a later stage of HR production. The table is then raised 6mm and the process is repeated three more times.

6.3.2 Lockheed Martin Density Analysis

The purpose of the following analysis is to evaluate the density dispersion within the foam blocks. In fact, the concern that prompted us to proceed with the following analysis was to obtain trapezoids with widely varying densities due to possible density anisotropy within the foam block. For this purpose, the origin of the individual thin rectangles within the block was plotted using a local coordinate system of the foam block. These coordinates system is shown in Fig. 6.9 with the ID with which each trapezoid is labeled so as to maintain a history of the position of the trapezoid within the foam block.

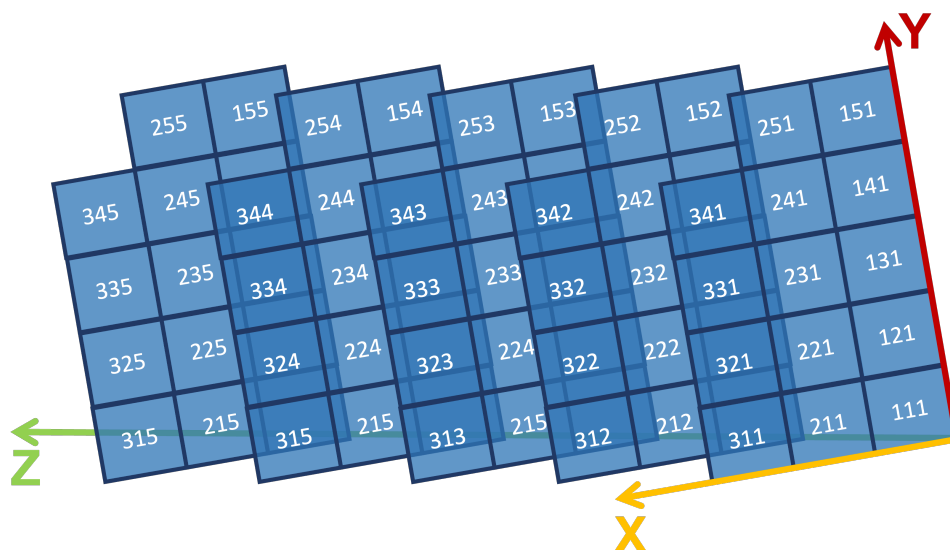


Figure 6.9: Foam blocks coordinates system used to identify the position of the trapezoids (and rectangles) into the blocks.

The carbon foam blocks used for the density analysis are listed in Tab. 6.2. All the carbon foam blocks under exam are made by Lockheed Martin with a double densification cycle. As shown in Fig. 6.9, all the blocks are missing a corner, rectangular in shape. This is because Lockheed Martin cut this edge and use it to measure density and thermal conductivity. This type of measurement is totally destructive, so the vendor uses a small part of the block to make it.

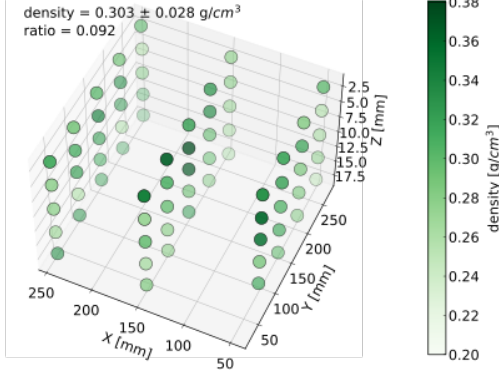
Lot N°	SN	Nominal Density (g/cm ³)	Nominal K (Watt/mK)	Institute	Type
6	13	0.304	35.17	Genova	Pre-Prod
7	4	-	-	Genova	Prototype
13	32	0.272	27.18	Genova	Pre-Prod
14	7	0.278	31.56	Genova	Pre-Prod
12	10	-	-	UK	Prototype
12	11	-	-	UK	Prototype
13	29	0.299	41.40	UK	Pre-Prod
13	43	0.317	34.95	UK	Pre-Prod

Table 6.2: List of the carbon foam blocks machined to create trapezoids. The Lot Number and the Serial Number (SN) are the block's identification numbers. The nominal density and the nominal Thermal Conductivity (K) are provided by the vendor (they were provided only for the pre-production blocks), the Institute is the one where the carbon foam blocks were cut and the trapezoids were produced. Finally, the Type column shows whether the block is a prototype or a pre-production one.

Starting from the foam trapezoids geometrical dimensions, a three-dimensional map of the density distribution within the blocks has been made and discretized on single trapezoids (rectangles actually, but for simplicity of exposition they will be called trapezoids, as they were already machined into their final shape).

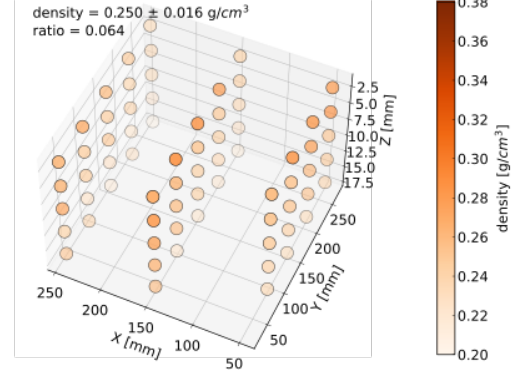
The blocks analyzed are the pre-production blocks and the R&D blocks, softer in density, for a total of four. The density distributions along the three dimensions are shown in Fig. 6.10.

Foam block LOT06_SN13_GE density 3D distribution



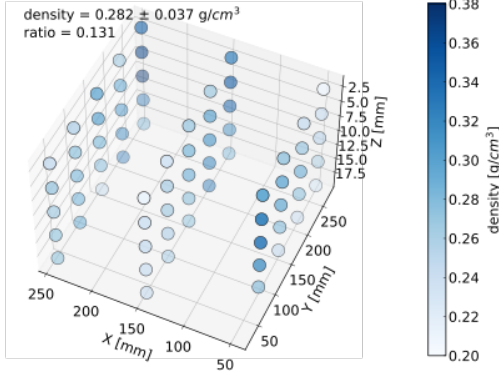
(a) Higher density foam block machined in Genova.

Foam block LOT13_SN32_GE density 3D distribution



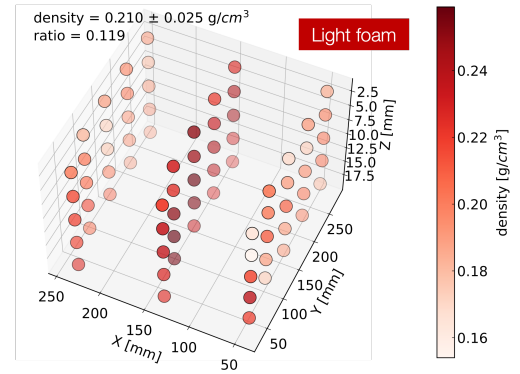
(b) Higher density foam block machined in Genova.

Foam block LOT14_SN07_GE density 3D distribution



(c) Higher density foam block machined in Genova.

Foam block LOT07_SN04_GE density 3D distribution



(d) Lower density foam block machined in Genova.

Figure 6.10: Genova machined foam blocks density distribution. The blocks are reconstructed by the trapezoids ID which contains the information on the three coordinates of the trapezoid within the block.

The analysis was performed also on UK R&D blocks, with lower density, and pre-production blocks with higher density, for a total of four. For these blocks, the density distribution in three dimensions is shown in Fig. 6.11

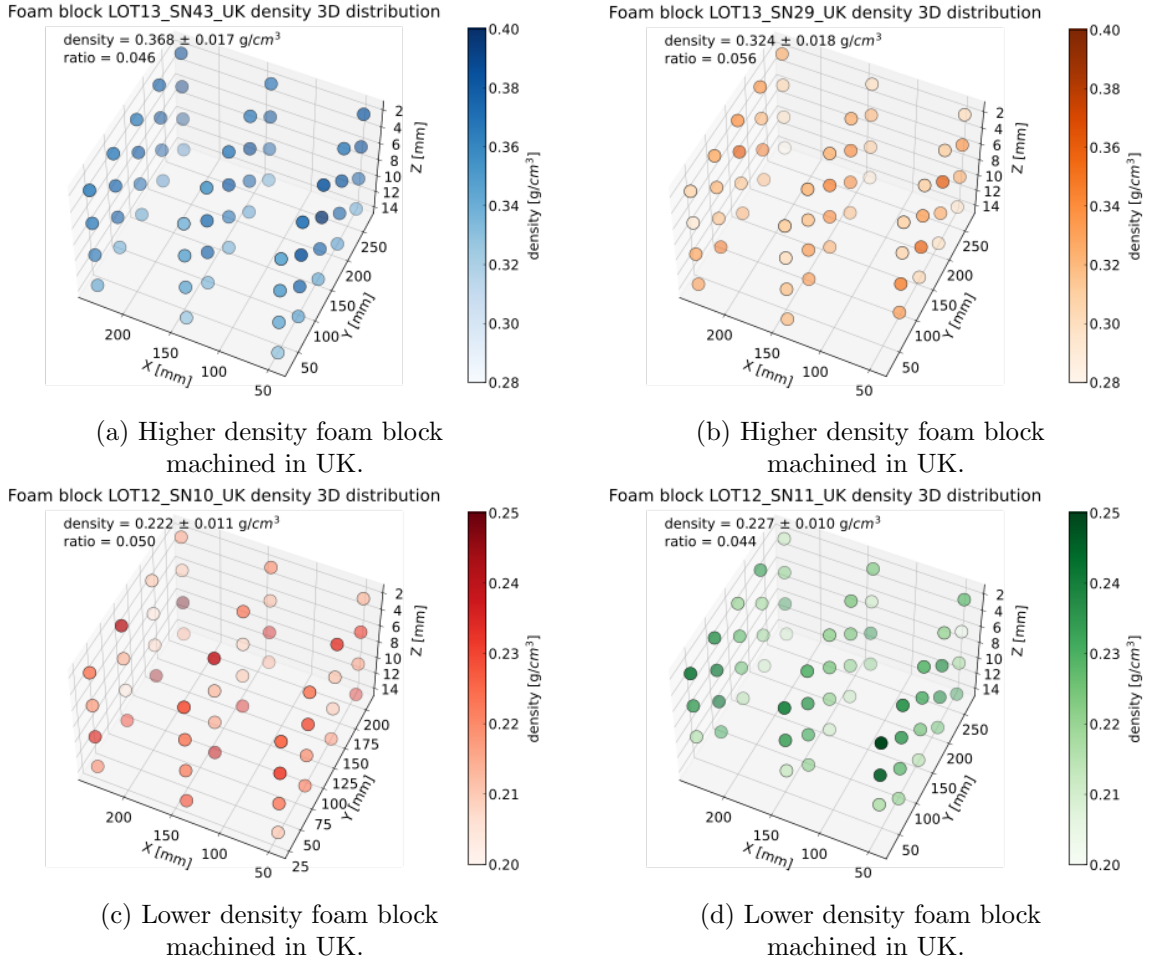


Figure 6.11: UK machined foam blocks density distribution. The blocks are reconstructed by the trapezoids ID which contains the information on the three coordinates of the trapezoid within the block.

From Fig. 6.10 and 6.11 there are no clear spikes of density within the blocks. Moreover, the density distributions have a maximum RMS value of 13% between the Genova blocks and RMS values less than 6% between the blocks machined in UK.

To confirm the absence of spikes in density distribution within the blocks, the density distribution was studied along each axis. The results are shown in Fig. 6.12 and 6.13. In these plots, each point on the graphs represents the average value of the density calculated on the density value of trapezoids that are on the plane with fixed axis coordinates (e.g. fixed a value on x -axis, the mean density value of the trapezoids which correspond to the chosen x -axis value). The RMS of each curve has been estimated. Again, no clear trend has been founded in density values along the axis, and in general, we have an RMS for each curve that is much smaller than the density dispersion within the entire block.

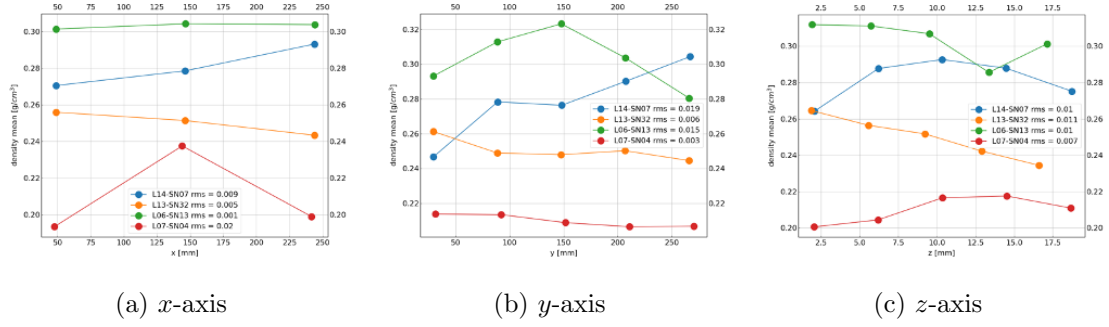


Figure 6.12: Density distribution along the three axis. Each colored curve corresponds to a different block. Each point on the graph represents the average value of the density, averaged over all trapezoids on the same coordinate on the axis under consideration. The foam blocks were machined in Genova. For each curve is estimated the RMS (in g/cm^3).

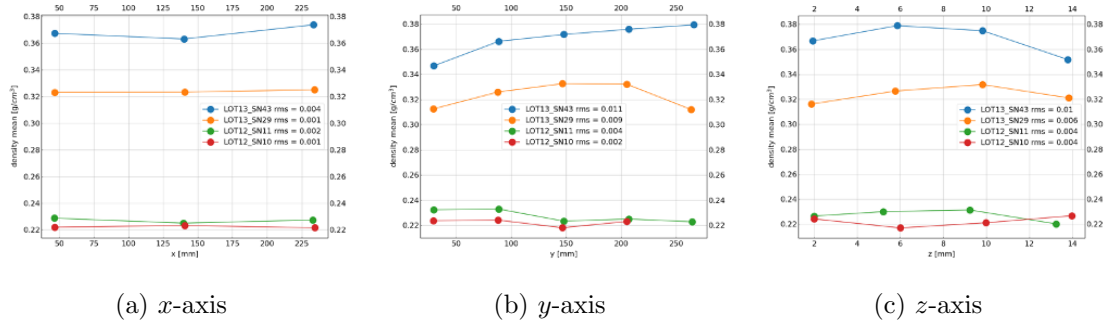
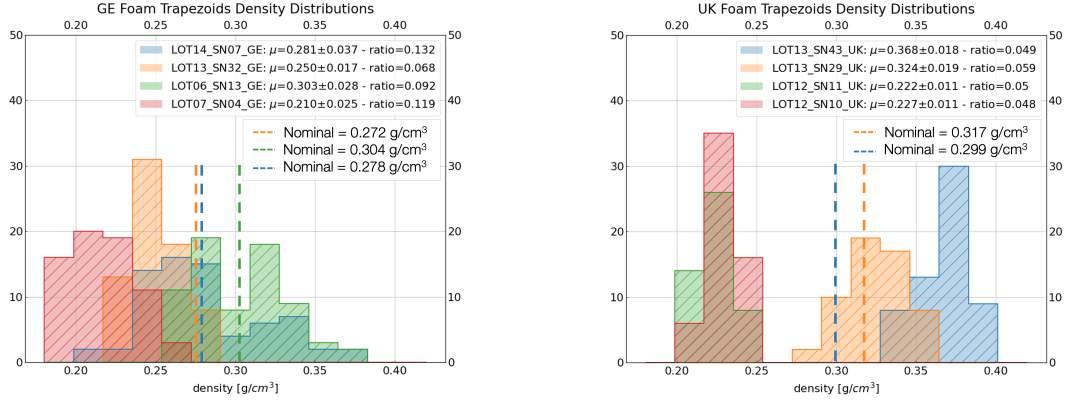


Figure 6.13: Density distribution along the three axis. Each colored curve corresponds to a different block. Each point on the graph represents the average value of the density, averaged over all trapezoids on the same coordinate on the axis under consideration. The foam blocks were machined in UK. For each curve is estimated the RMS (in g/cm^3).



(a) Genova foam trapezoids density distribution. (b) UK foam trapezoids density distribution.

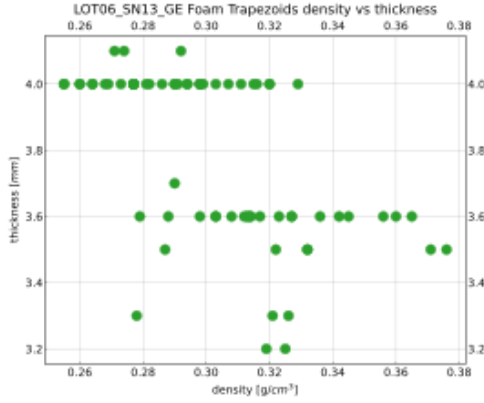
Figure 6.14: Trapezoids density distributions of foam blocks processed in (a) Genova (b) UK. In the plots are reported the nominal density values (from Lockheed Martin) of the higher density foam blocks and the mean density (evaluated as g/cm^3) of each block.

Lot N°	SN	Measured Density (g/cm^3)	Nominal Density (g/cm^3)	Institute	Type
6	13	0.303 ± 0.028	0.304	Genova	Pre-Prod
7	4	0.210 ± 0.025	-	Genova	Prototype
13	32	0.250 ± 0.017	0.272	Genova	Pre-Prod
14	7	0.281 ± 0.037	0.278	Genova	Pre-Prod
12	10	0.227 ± 0.011	-	UK	Prototype
12	11	0.222 ± 0.011	-	UK	Prototype
13	29	0.368 ± 0.018	0.299	UK	Pre-Prod
13	43	0.324 ± 0.019	0.317	UK	Pre-Prod

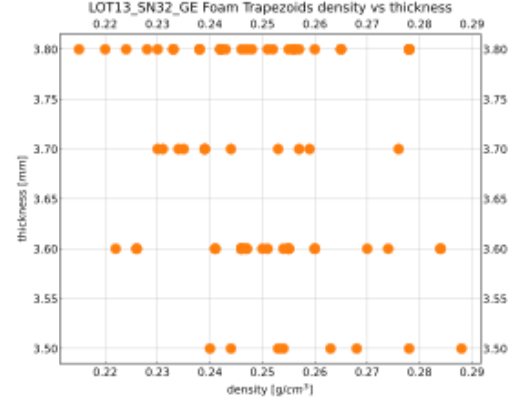
Table 6.3: The list of the mean density results with the nominal density values are reported in this table. The Lot Number and the Serial Number (SN) are the block's identification numbers. The nominal density is the one provided by the vendor (it was provided only for the pre-production blocks), and the Institute is the one where the carbon foam blocks were cut and the trapezoids were produced. Finally, the Type column shows whether the block is a prototype or a pre-production one.

In Fig. 6.14 the density distribution of the trapezoids cut in Genova (6.14a) and in UK (6.14b) are shown, while in Tab. 6.3 the mean density values obtained with the analysis are reported with the nominal values provided by the vendor (when they were provided). In these plots are also reported the nominal density values issued by the vendor (only for the higher density foam blocks). Two main evidences emerge from these plots: The foam density measurement performed by the Genova group seems to be less accurate (generally more dispersed) than the density measurement performed by the UK group. The plots show the percentage errors of the mean of the distributions, and it can be seen that the density distributions measured by the blocks machined in Genova show a percentage error on the mean ranging between 7% and 13%, while the density distributions measured in the UK are around a percentage error of 5-6%. Instead, there appears to be good agreement between the Genova density measurement with the density nominal values reported by the vendor, while the UK measurement appears to discord more (e.g. over 3 sigma for block LOT13-SN43).

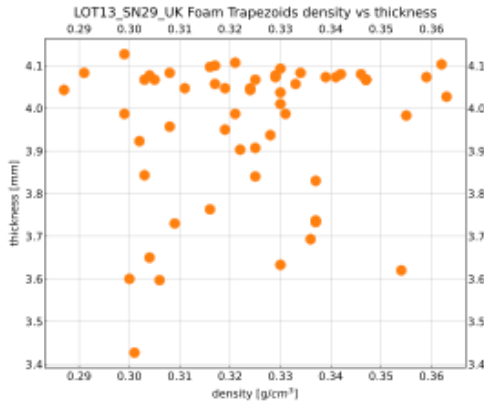
The difference between the density dispersion produced at Genova and those produced in the UK can be attributed to a different block processing procedure in the production of trapezoids. In fact, although in both laboratories the trapezoids are produced using a band saw, the trapezoid thickness measurement in UK is done using a caliper, while at the Genova laboratories, a coordinate measuring machine (CNM) equipped with a touching probe is used. The different thickness measurement is well shown in Fig. 6.15, where the results of Genova and UK measurements are shown in function of the density.



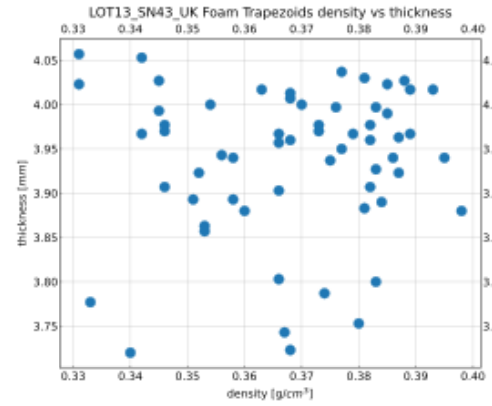
(a) Higher density foam block machined in Genova.



(b) Higher density foam block machined in Genova.



(c) Higher density foam block machined in UK.



(d) Higher density foam block machined in UK.

Figure 6.15: The four plots show the density dependency from the thickness measurement.

In the end, a plot of density vs thermal conductivity is reported in Fig. 6.16. In this plot, each point corresponds to a Lockheed Martin foam block, even those not yet processed in the Genova or UK laboratories. This plot shows the dependency of thermal conductivity on density. This dependency does not appear to be particularly strong and in fact, it can be seen that the dispersion of the thermal conductivity is much greater than that of the density (with a factor of 3). We can therefore conclude that the density dispersion intrinsically present within the foam blocks supplied by Lockheed Martin does not appear to be significant to preserve the position of the trapezoids and therefore of the local ITk supports. For this reason, the collaboration decided that density measurements of individual trapezoids would no longer be made during production, instead they would be measured once on the whole block. This will greatly speed up production workflow.

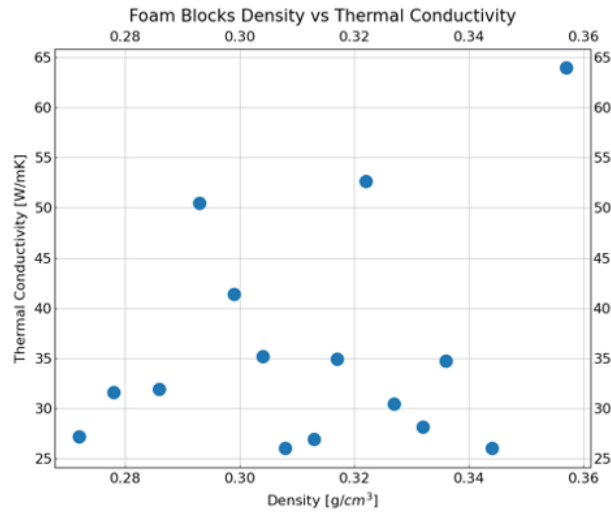


Figure 6.16: Foam blocks thermal conductivity in function of density. Each point corresponds to a single Lockheed Martin foam block. Not all the foam blocks provided by the vendor are machined, but the vendor provides the collaboration with the thermal conductivity and density value measured before shipping.

6.3.3 Entegris Density Analysis

Entegris' carbon foam, called PocoFoam, is machined in Genova Laboratories in order to test its density distribution. The block under examination is $1.6 \times 12.1 \times 12.1$ cubic inches per 3.45 lbs and has a nominal density value of 0.408 g/cc. The vendor doesn't provide the thermal conductivity of this particular block, but the company assures that its carbon foam has a thermal conductivity of 45 W/mK. The machining process was the same as that used for the Lockheed Martin blocks, but as shown in Fig. 6.17 not the whole block was machined, but just a certain number of sub-blocks "representative" of the whole block were chosen. In addition, three blocks, 231, 341, and 121 will be used for thermal conductivity evaluation.



Figure 6.17: The PocoFoam ATK3722 carbon foam block partially machined at Genova Lab. Circled in pink are the sub-blocks that were machined to produce the trapezoids of which weight and dimensions were measured to enable the block density distribution study.

Fig. 6.18 shows the density distribution of the foam trapezoids, having arranged them in their position within the block. As it can be seen, the block was not completely reconstructed, this is because after being machined and divided into 12 sub-blocks, only 6 were chosen to be machined and divided into trapezoids. The figure, in addition to showing us

an average density of $\mu = 0.384 \pm 0.028 \text{ g/cm}^3$, also shows a clear trend in the density distribution within the block, although the RMS shows how the dispersion remains below 8%. Indeed in Fig. 6.19, which shows the density distribution of the trapezoids, it can be seen that this distribution is pigeonholed around its mean value and there are no evidences of a density trend within the block.

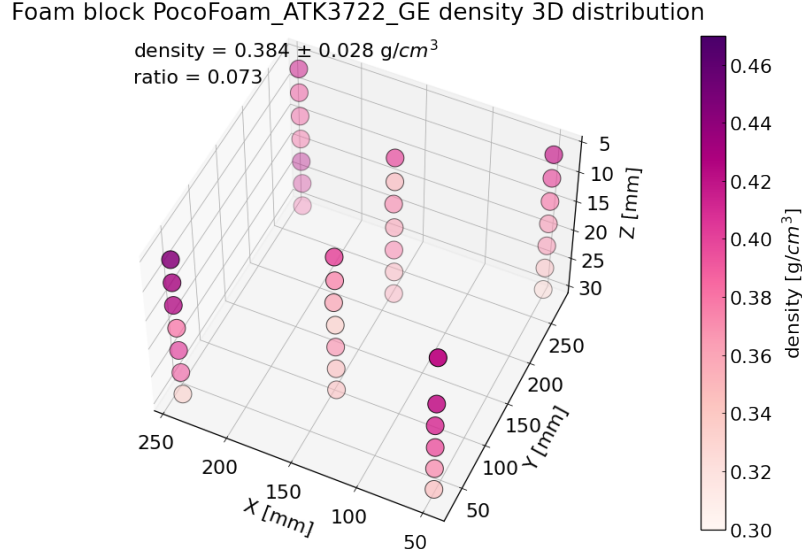


Figure 6.18: PocoFoam ATK3722 carbon foam block density distribution. The block is reconstructed by the trapezoids ID which contains the information of the three coordinates of the trapezoid within the block.

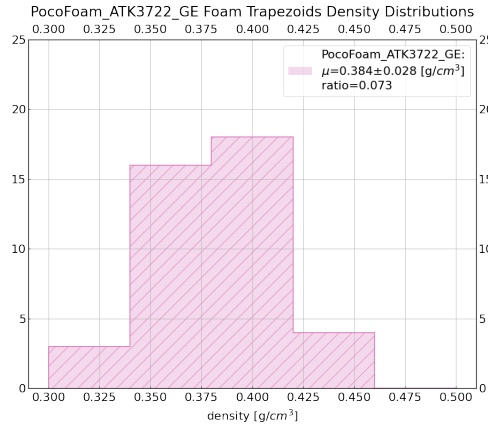


Figure 6.19: Trapezoid density distributions of the PocoFoam ATK3722 carbon foam block.

Finally, to conclude the study, the density distributions of trapezoids along the three axes are shown in Fig. 6.20. The distributions shown in these plots were calculated in the same way as for the study carried out on the Lockheed Martin blocks, that is, by averaging the density and taking into account only the trapezoids positioned at a certain fixed coordinate. From the three plots, no clear trend in density along the three axes has been observed. The density trend, along all three axes, consistently falls within the range of error bands.

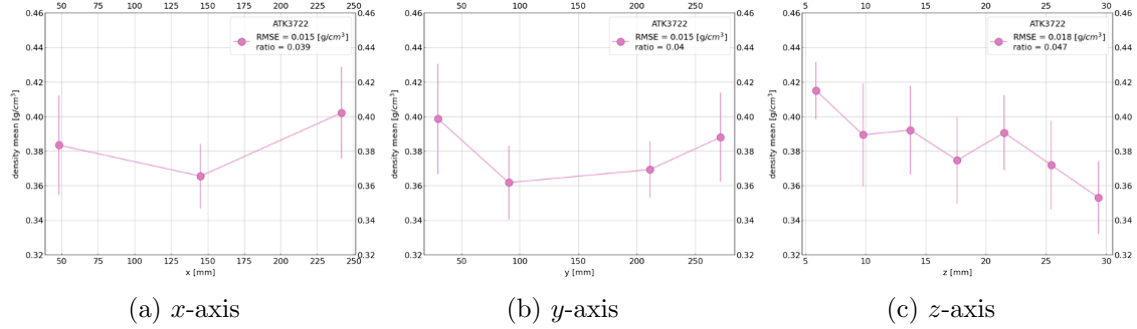


Figure 6.20: PocoFoam ATK3722 density distribution along the three axis. Each point on the graph represents the average value of the density, averaged over all trapezoids on the same coordinate on the axis under consideration. The foam block was machined in Genova.

Based on our findings, there is no evidence of a specific trend in the dispersion of density within the foam block. However, the analysis of dispersion, measured in terms of RMS, consistently indicates a value 8% lower than the mean. This suggests that the PocoFoam from Entegris is suitable for constructing the LSs of the ITk endcap.

6.4 Local Support Metrology and Thermal Properties

The temperature range to which the supports of a detector are exposed is a crucial factor in determining its mechanical performance. Since various components may have different coefficients of thermal expansion, changes in temperature can cause uneven deformations and generate stress in the structure. This, in turn, can lead to time-dependent stability issues as the modules carried by the supports move from their original aligned positions, potentially impacting the detector's tracking performance. Inside the detector, the minimum coolant temperature is set to be -35°C , while the expected module interlock temperature is $+40^{\circ}\text{C}$. For these reasons, the OEC LSs must meet stringent thermal and mechanical requirements once assembled. To ensure that the LS meets all the quality standards required by the collaboration, a series of Quality Assurance (QA) and Quality Control (QC) tests are designed to be operated on the supports themselves. The former, QA tests, to be carried out before the production (and pre-production) phase of the objects, also include the possibility of partial (or total) destruction of the object under test.

In this section are reported the procedures and the results of two tests performed on the bare HRs in Genova laboratories: a QA test on thermal expansion metrology on a Layer-2 HR, and a QC test to measure thermal performances of the HRs with a thermocamera.

The QA test on thermal expansion metrology, along with several other tests, allowed the construction procedure of the bare HRs to pass the Final Design Report (FDR) and thus be able to enter the pre-production phase.

6.4.1 Thermal Expansion Metrology Measurements

The reason for measuring the OEC HR thermal deformation is twofold:

1. It's essential to verify the compliance with the LS specs, in order to prescribe a maximum displacement of the support as a function of the temperature variation.
2. The Finite Element Analysis (FEA) model (reported briefly hereafter), developed to study HR behaviors when loads (including temperature variation) are applied, must be validated experimentally. To perform this measurement, it was decided to study the HR corner displacement as a function of temperature, keeping the other corner fixed, as it is visible in Fig. 6.21. In fact, for the design of the FEA model, it is necessary to have at least one constraint on the simulated object. In this way, the experimental results can be compared with the results obtained by the simulation.

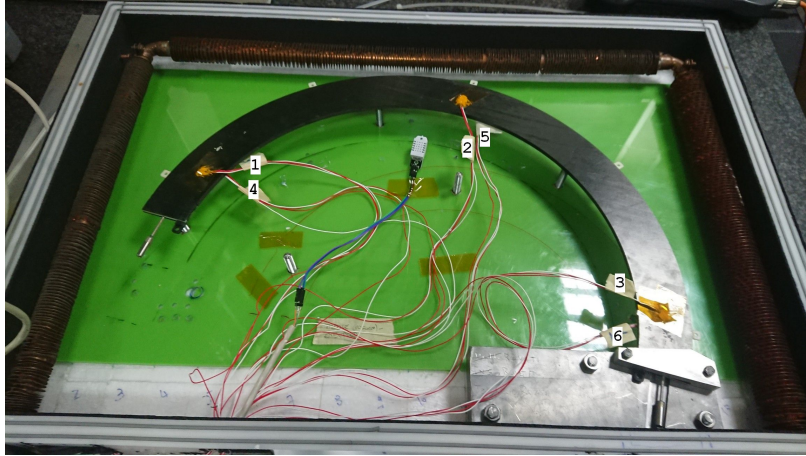


Figure 6.21: Experimental setup to measure the thermal deformation of the OEC HR. The numbers label the six temperature sensors used to measure the temperature on the surface of the HR. Another temperature sensor is placed in the middle of the box to measure the environmental temperature.

The Experimental Procedure

A contactless measuring system is needed so that the HR could be free to move without friction. To measure without contact, an optical system has been chosen. An environmental box to house the HR has been made, with a transparent cover to allow optical measurements. A heavy lead constraint was placed into the box, to immobilize one corner of the HR, leaving the rest of the LS free to move. Inside the box, with a dissipator connected to a chiller, the temperature of the HR is changed to induce thermal deformation. The chiller operates in the range 5-80°C.

The temperature and the humidity are measured with seven sensors: six sensors are attached to the HR surface; one was placed in the middle of the box. Three sensors out of six were placed on the top skin of the HR, and three on the bottom one. The observed temperature variation on the HR was about 30°C, while the chiller temperature varied between 5 to 80°C. The variation across the surface of the HR is within 1°C, while the influence of the laboratory ambient temperature results in a $\pm 1^\circ\text{C}$ variation between the different runs. For this reason, the error in the temperature has been estimated to be $\pm 2^\circ\text{C}$.

On the skin of the HR, there are no precise markers. It was decided to drill four holes 0.5 mm diameter, to use as measurement points called R1, R2, R6, and R7:

- R1 is in the opposite side of the constraint on the outer rim of the HR
- R2 is on the outer rim, in the middle of the HR
- R6 is on the outer rim, near the constraint
- R7 is on the inner rim, near the constraint

R1 and R2 were placed on the HR to analyze the absolute movement of the local support. Additionally, two holes, R6 and R7, were added to monitor the residual movements of the constrained side, the first located on the outer rim, while the second is positioned on the inner rim. Furthermore, the measurements of the hole positions for the four outer fixation lugs (L1, L2, L3, and L4) were included. These holes are numbered starting from the free corner to the constraint, with L1 being the closest and L4 being the farthest from the constraint

Two measurement machines have been used: a Hexagon Coordinate Measuring Machine (CMM) DEA Mistral, with which X and Y positions were measured, equipped with a Chromatic Confocal Optical Pen (STIL) to measure the Z coordinate. This setup is shown in Fig. 6.22 with the STIL equipped to the CNM.

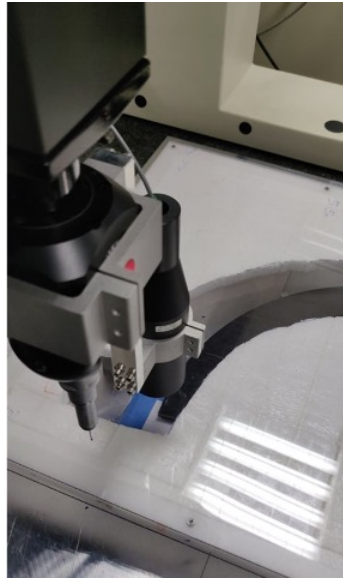


Figure 6.22: The optical pen STIL, equipped to the CNM, during a measurement in Genova laboratories.

Some measurements have also been collected using a Physik Instrumente (PI) Gantry Stage, equipped with a confocal camera. The first method has proved slow but with an excellent Z resolution thanks to the use of the STIL. The Gantry has the advantage that the picture of the hole regions can be taken in a very short time, but with the disadvantage that the Z measurement is done by varying the focus on the camera, which gives a resolution of 10-15 μm to compare with 1 μm for the STIL. With this setup, the measurement of the displacement presents a few problems: the constraint is still not ideal. It moves with the temperature changes and its movement induces a systematic shift in the position of the HR. In order to overcome this problem, it was decided to focus on the determination of distances between points, for example between R1 and R6 or L1 and L4, rather than on

the displacement of a single point.

Due to the transparent box cover, the thermal isolation of the box does not allow a temperature variation greater than 25-30°C, with a range from 17°C to 44°C. The actual range depends on the ambient temperature, so each measurement is associated with the corresponding measured DT. The measures are collected starting from the laboratory temperature (22°C), then increasing the temperature (32°C and 44°C) and finally dropping it to its minimum value (17°) and repeating this procedure several times in order to augment the statistic.

The Data Analysis

Two different algorithms are used to analyze the data, to have a cross-check of analysis quality. Once data is collected, the first algorithm requires a manual zoom around the hole, and then it finds the coordinates of the contour of the hole as the last non-zero Z value before dripping into the hole (the optical instrument in fact has a sampling depth of a few centimeters, so anything beyond this depth of field is picked up by the instrument as a zero e.g. the internal part of the holes). Using these coordinates a circular fit is performed to find the centre and the radius of the hole. In Fig. 6.23 the data collected with the STIL around the fixation lugs region is shown. The color scale represents the elevation on the z-axis. The Fig. 6.24 shows the schematic procedure with which the hole centre is found with this algorithm.

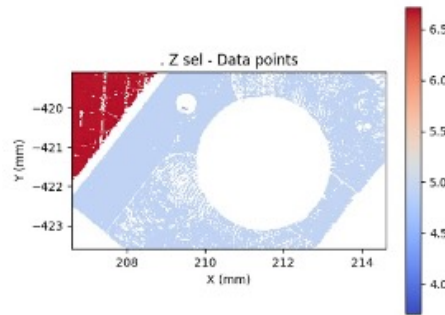


Figure 6.23: A fixation lug image collected using the STIL. The color scale represents the elevation on the z-axis.

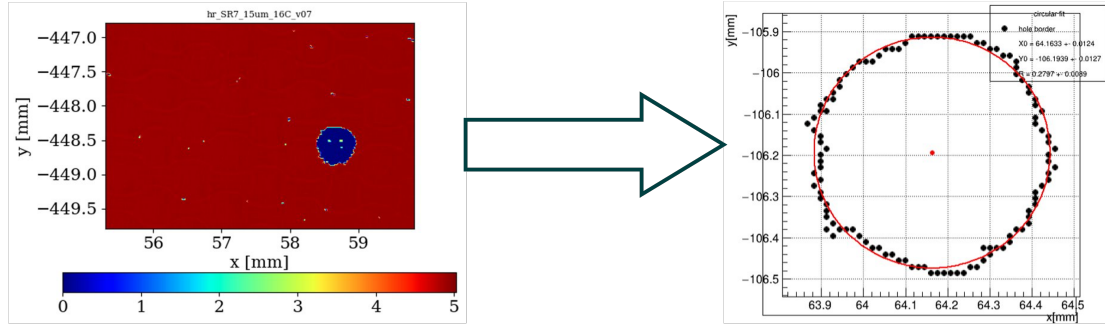


Figure 6.24: The hole centre finder algorithm. Starting from the data collected by the STIL, the hole is manually focused, then the hole contour is found and the centre of the hole is evaluated with a circular fit on the coordinates of the contour.

The other algorithm uses the OpenCV python library. The function `HoughCircles()` is a powerful tool for the circle detection within the images. In this way the hole contour was extracted and again, the pixels of the contour were fitted by a circle as shown in Fig. 6.25.

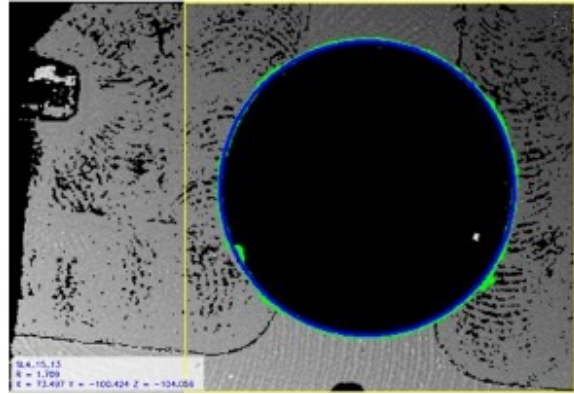


Figure 6.25: The hole perimeter and its centre are found using the OpenCV python library.

Despite several attempts to improve the constraint, the plot of the x , y , and z position of the individual points still show drifts and inhomogeneous variations with the temperature. This effect is clearly visible in Fig. 6.26 where the displacements of the single reference points under measurement are reported in function of time. In these plots, the run number is the data-taking ID.

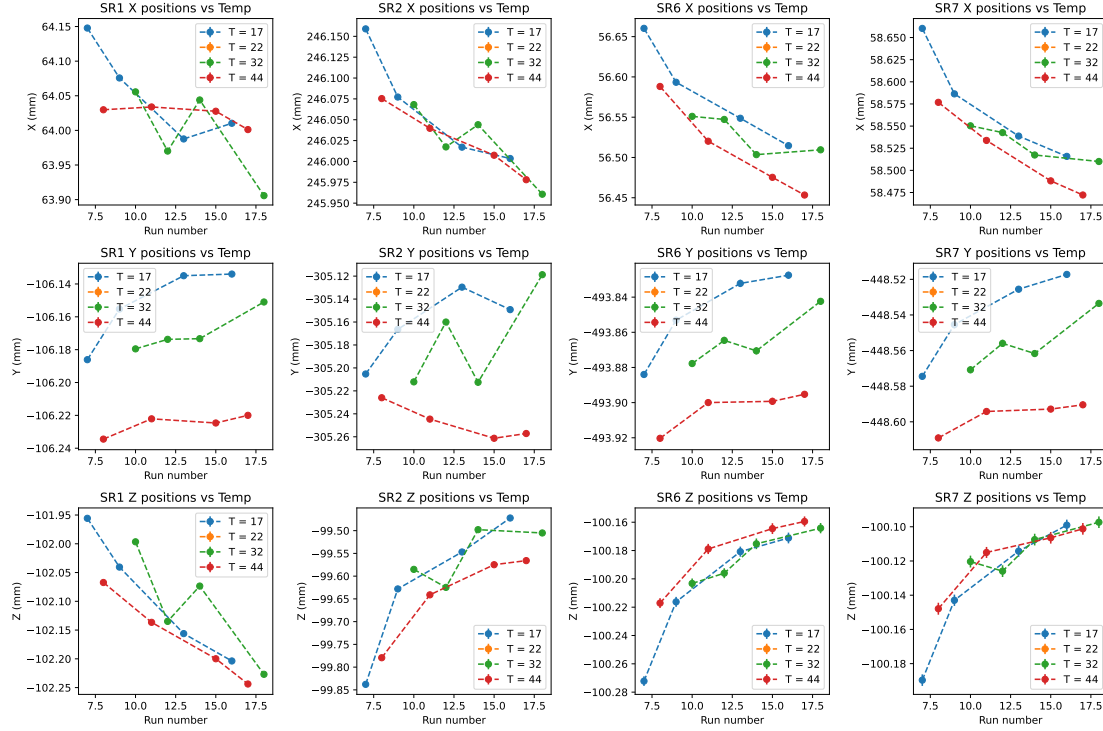
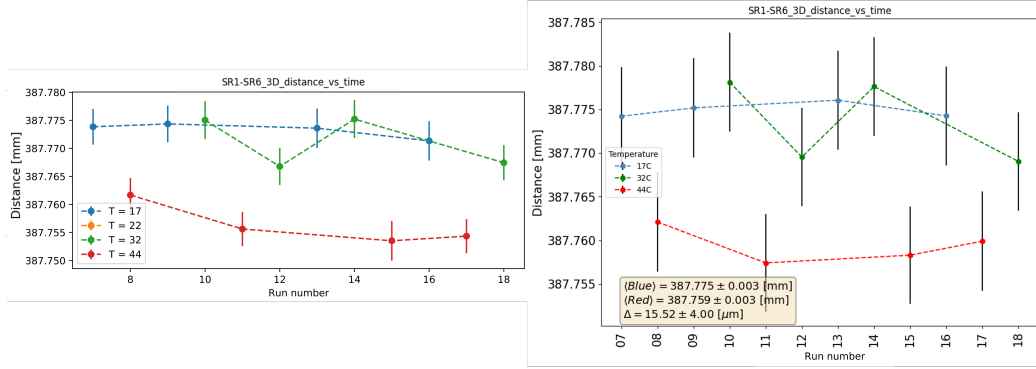


Figure 6.26: The displacement of the single reference point under measurements vs time (the run number is the data-taking ID). In these plots a sort of hysteresis of the LSs is visible, while the temperature cycles are repeated.

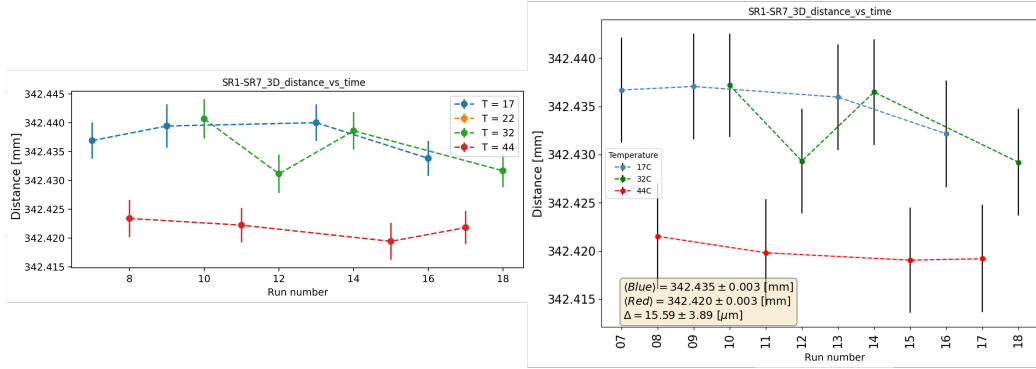
This effect is due to thermal deformations of the constraint itself and associated hysteresis. To mitigate this effect it has been decided to calculate the spatial distance between pairs of points.

The Results

The algorithms have been mutually validated by comparing their results. In Fig. 6.27 the distances between R1 and R6 and between R1 and R7 are plotted as a function of the run number. For each run, the data were collected at a given temperature. The temperature goes from 17°C to 44°C several times. The data were collected using the PI Gantry instead of CMM with the STIL optical pen; the results are compatible.



(a) R1-R6 spatial distance vs time at the different temperatures. On the left the data collected via PI Gantry, on the right the data collected using the CMM equipped with the STIL.



(b) R1-R7 spatial distance vs time at the different temperatures. On the left the data collected via PI Gantry, on the right the data collected using the CMM equipped with the STIL.

Figure 6.27

Thermo-mechanical Finite Element Studies

The inner HR (the Layer-2) is modeled via an ANSYS Finite State Model (FEM) in order to evaluate the mechanical performance compared to the specifications. These FEA studies have been carried out by the Milano ATLAS Group. The key characteristics of the FEA model under consideration include a mesh consisting of 3.8 million nodes, solid elements modeled using quadratic order, and the inclusion of a structural glue layer in the model [73]. A constraint in a corner of the HR was applied to the model so that the simulation results could be compared with those of the environmental chamber experiment. Fig. 6.28 illustrates an example of the HR modeled using FEA, where the constrained region is highlighted in blue.

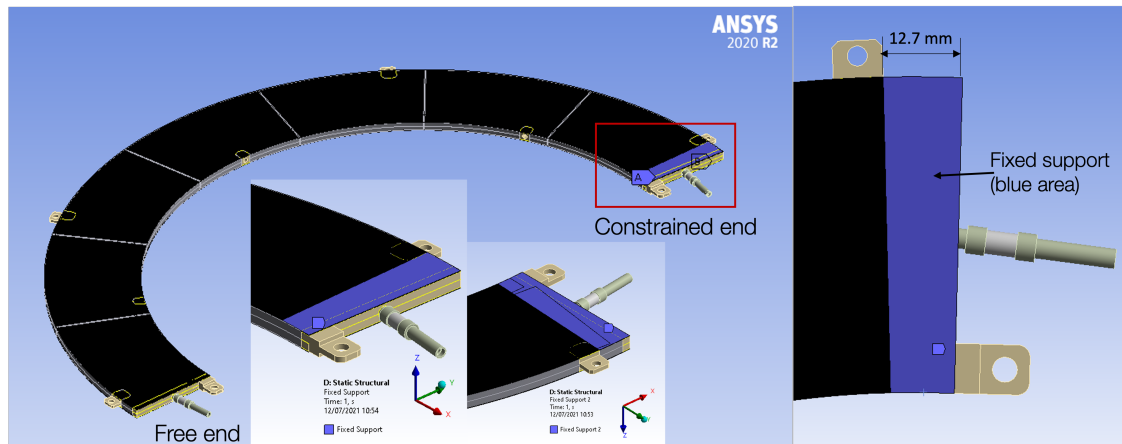


Figure 6.28: The Finite Elements Model of the L2 HR is shown. The blue area corresponds to the LS constraint.

The FEA Validation

The results from the thermal-deformation measurements on a Layer-2 HR have been compared to FEA predictions using the model described above. Tab. 6.4 reports the results obtained by the FEA simulation and the experiment. As we can see from these results, the shifts measured are compatible in direction with the shifts predicted by the FEA simulation. Considering the large measurement errors, the comparison between predicted and measured thermal expansion coefficients is acceptable. Both the simulation and the experiment show that the absolute variation is smaller than $2 \mu\text{m}$ per degree, which means that the linear thermal expansion coefficient of the bare HR can be assumed within $2 \text{ ppm}/^\circ\text{C}$. The analysis suggests that deformation determined by the FEA and by the experiment are compatible with the LS specs, which require a displacement smaller than $3 \mu\text{m}$ per centigrade degree in the circumferential direction as a more stringent requirement.

Spatial Distance	FEA Simulation Results		Experimental Results	
	ΔL [μm]	$\Delta L/\Delta T$ [$\mu\text{m}/^\circ\text{C}$]	ΔL [μm]	$\Delta L/\Delta T$ [$\mu\text{m}/^\circ\text{C}$]
R1 to R6	40.7	1.5	15.5 ± 4.0	0.63 ± 0.15
R1 to R7	39.4	1.5	15.6 ± 3.9	0.59 ± 0.15
R1 to R2	-4.7	-0.17	-5.0 ± 4.0	-0.18 ± 0.15
R6 to R7	0.8	0.03	0.4 ± 3.9	0.00 ± 0.14
L1 to L4	21.1	0.78	5.4 ± 2.5	0.18 ± 0.94
L2 to L3	-10.2	-0.38	-20.1 ± 2.6	-0.75 ± 0.11

Table 6.4: FEA and experiments results in comparison.

6.4.2 Thermal Conductivity Measurements

This study introduces a qualification technique that utilizes thermal image analysis of thermo-active support structures. The technique's capability to detect structural defects has been evaluated through sensitivity studies on dedicated test structures and ATLAS-ITk pixel OEC support structures. Results show that this technique is a suitable candidate for quality control in the final LS production for the ITk pixel OECs.

The defects that can be revealed are:

- Defects due to the presence of a gap between two trapezoids;
- Defects due to incorrect placement of glue around the pipe (different thickness/glue is not present);
- Presence of a gap between the pipe and foam;
- Large air bubbles in the foam;
- Defects present on the pre-preg (also on the outer face and therefore visible by eyes);
- Presence of obstructions in the pipe;
- Misalignment of the pipe due to the difficulty of keeping the pipe well aligned when gluing the two half-sandwiches together.

The method was developed by ATLAS group in Manchester. The proposed measurement is carried out through the use of a thermal imaging camera to capture the heat diffusion process inside a HR. For this purpose, the following experimental setup was developed at the Genova laboratories:

- An open cabinet covered entirely by insulating material for both light and heat radiation.
- A chiller for pumping hot water at 55 °C.
- An infrared thermal camera FLIR SC620. The sensor is 640x480 pixels with a maximum frame rate of 30 Hz (shown in Fig. 6.29).
- The HR under test.
- A computer from which to use the ResearchIR Max 4.40 software [74], proprietary software for capturing video with the thermal camera and allowing conversion of such video to csv files.
- The analysis software developed by ATLAS group in Manchester to analyze the data collected with the thermal camera [75, 76].



Figure 6.29: Infrared Thermal Camera FLIR SC620. The camera has a sensor of 640x480 pixels, and a maximum frame rate of 30Hz [77].

The thermal camera has a depth of field of a few centimeters. For this reason inside the cabinet, the thermal camera is fixed at the top about 1 meter away from the HR to be filmed. Since an outer HR cannot be imaged in its entirety at this distance, a system to move the camera in the horizontal plane was made. In this way it was possible to shoot both the left and right ends of the HR, albeit separately. Special fittings allowed us to pump hot water from the chiller into the pipe of the HR. Each video has a duration of 10 seconds. The decision regarding the duration of time was influenced by two primary factors. Firstly, it was observed that within approximately 10 seconds, the portion of the HR captured by the thermal camera achieves thermal equilibrium;

When converting the video to CSV format, the resulting file size amounts to approximately 1 GB, which is quite substantial. Given that four measurements need to be collected for each HR (two videos for each face of the LS), the space occupied by the output of these measurements should not be overlooked, as it accumulates significantly.

The process of analyzing thermal images can be divided into three main steps:

- shape recognition,
- starting time determination,
- temperature profiles extraction.

While steps 1 and 2 are generic and can be adapted to different configurations, step 3 is specific to the design of the analyzed HR.

Once the video has been converted to csv using ResearchIR Max software, you can start analysis using the analysis software developed by the Manchester group. The frames used in the analysis span the entire heating process, with some frames selected before the start of the heating process, to aid with timing measurements, and most frames selected within a few seconds after the start of the process, when the cooling effect is most visible.

Python 3 and scikit-image are used to process the frames. The first step in the analysis is shape recognition, which is used to distinguish the region of interest (RoI) from the background in the raw data. A Canny filter [76] is applied to the temperature map, performing a Gaussian filter to reduce noise and then applying hysteresis thresholding to identify the RoI edges. The output of the filter is a binary map of the edges, and the shape of the prototype is determined using the RANdom SAMple Consensus method (RANSAC).

Different models can be combined to reproduce the geometry of the object being analyzed. For example, in this analysis, the HR consists of two circles for the inner and outer rims and lines for the straight edges. The RANSAC algorithm is applied multiple times to the data points until all edges of the HR are found. The determined shape is time-independent and can be used as a filter for all frames in the cooling process. In Fig. 6.30 the output of the HR edge recognition step is reported.

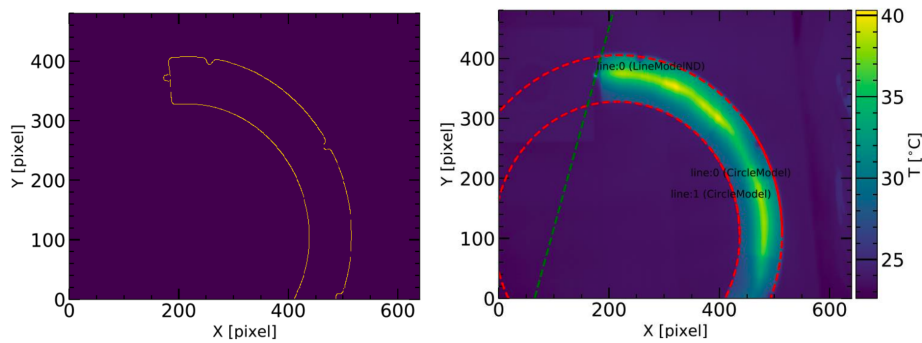


Figure 6.30: HR edge recognition output.

For the points before the cooling starts, the starting frame is the first measured frame and the automatic fit includes points afterwards. For the rising edge, the frame with the highest first derivative of the temperature standard deviation is chosen as the starting point. The automatic fit is applied forwards and backwards to include frames later and earlier with respect to this frame until the best range is found. Fig. 6.31a shows the fit to determine t_0 for a single cooling process.

At a specific time $t = t_0 + 1.5$ s, temperature profiles are extracted perpendicular to the cooling pipe from the bi-dimensional T distributions, using the circle model parameters obtained from the RANSAC algorithm [76]. To achieve this, the Cartesian coordinates of points within the RoI are converted to polar coordinates using the center of the circle formed by the inner rim as the origin. The temperature profiles are obtained within the polar angle range of the circle, divided into 300 segments, and their radial starting and ending points are determined by their intersections with the inner and outer circles. Temperature values along the profile are then interpolated from the raw data, while points outside the HR shape are not considered. The procedure is illustrated in Fig. 6.31b, where the arrows represent the radial directions.

Typically, the temperature distribution along the profiles during the cooling process is expected to follow a Gaussian pattern. However, as the cooling pipe in the HRs is bent, the cooling process in the regions to the left and right of the pipe is expected to be different. Hence, the width of the Gaussian in the fit is not constrained to be the same in both directions. An example of the fitting procedure is shown in Fig. 6.31c.

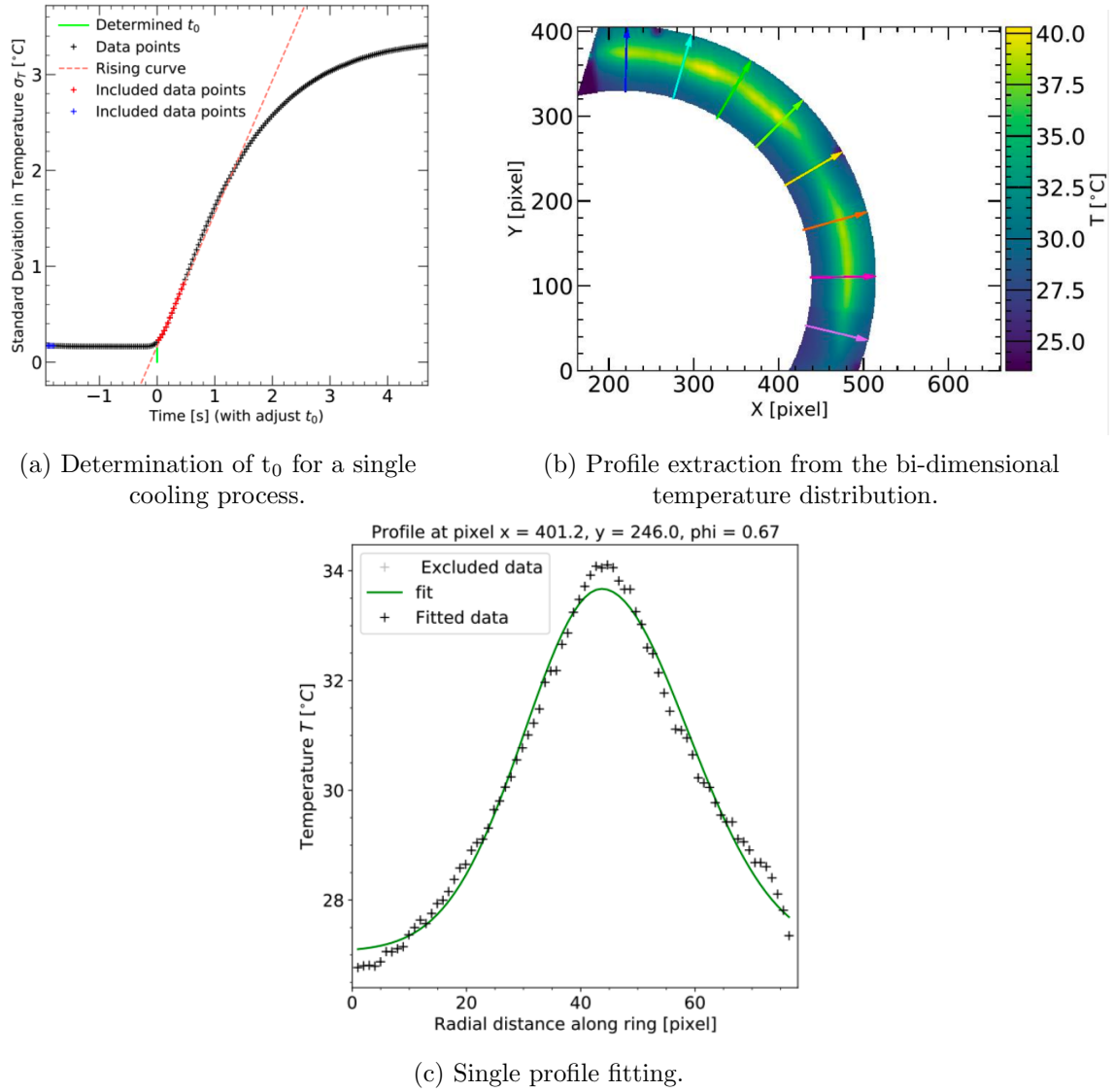


Figure 6.31: (a) Temperature standard deviation of a thermal frame as a function of the recording time in the QC measurement. The distribution is used to determine the starting time of the cooling process and to synchronize and compare different QC measurements. (b) Temperature profiles perpendicular to the cooling pipe, are defined by the arrows. (c) Fitting of a single profile (green solid line), over a sketch of the transverse section of the HR.

Measurements on HRs at Genova Laboratories

Following the procedure laid out in the previous section, two data-taking campaigns were carried out on two different HR prototypes for testing called L2.0IT and L2.1IT, both inner HRs constructed in Italy in 2020. The difference between these two HRs lies in the fact that for L2.0IT the co-curing was conducted by Plyform, while for the second one, it was conducted by Loson.

The HRs under examination are shown in Fig. 6.32: on the right, the HR_L2.0IT and on the left the HR_L2.1IT, with the detail of its damage. The damage in question was caused in the laboratory. Still, as the subsequent analysis will show, it is a superficial damage that did not affect the integrity of the pipe in the slightest. As mentioned earlier, it should be noted that these two HRs are not pre-production models.



Figure 6.32: On the left the HR_L2.0IT, on the right the HR_L2.1IT. Below the HR on the right a detail of the damaged part is shown.

During the HR_L2.0IT test, a strange behaviour in heat propagation was noticed in a particular sector of the HR. In fact, as can be clearly seen from Fig. 6.33, in the presence of fixation lags, the thermal contact between the pipe and the trapezoids that compose the HR is lost. The temperature profile of the object was derived from the analysis and is presented in Fig. 6.34. The figure clearly demonstrates a noticeable discontinuity in the heat distribution across the surface of the HR. This is probably due to the production method of this particular HR and also to the use of excessively thick lugs, causing the detachment of the two half-sandwiches.

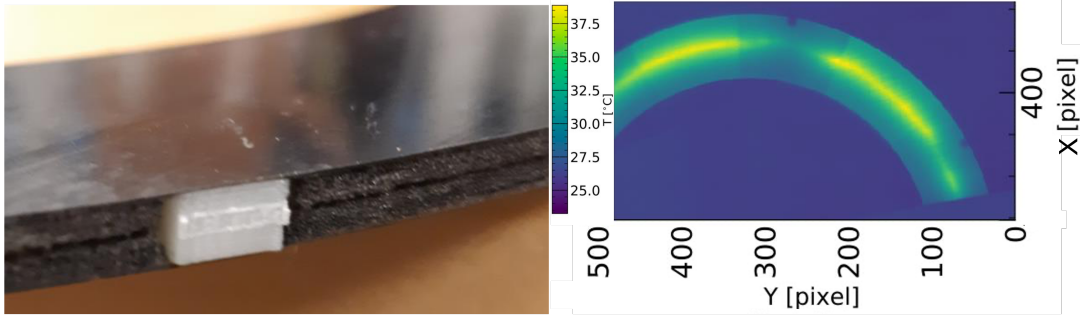


Figure 6.33: (right) The HR profile in the sector where the heat is not well propagated. The half-sandwiches separation due to the thickness of the fixation lugs is clearly visible. (left) The figure of the HR taken by the thermal camera.

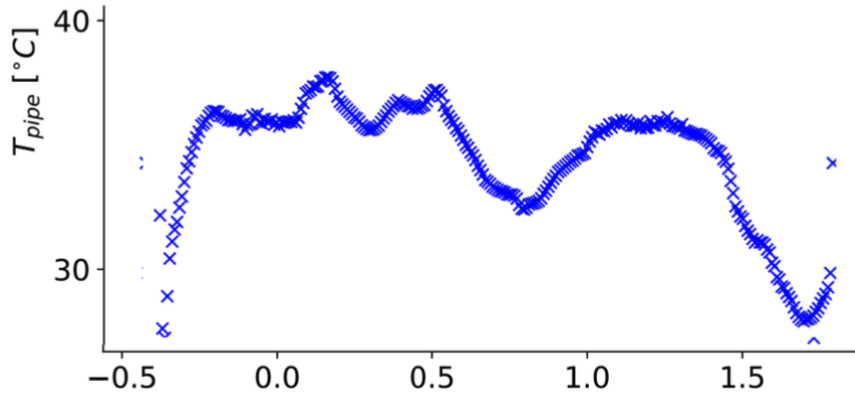


Figure 6.34: On the x -axis the position of the pipe temperature is given in angular coordinates. Temperature shape along the pipe direction. From this picture, the inhomogeneous distribution of the heat is clearly visible for the HR_L2.0IT.

The study of HR_L2.1IT was carried out in the same way. The total shape of the HR is shown in Fig. 6.35 (broken down into two separate figures). In this case, no clear discontinuity in heat propagation is observed preliminarily, but the damage present on the surface of the HR can be appreciated from the thermal image. The temperature profile of the HR was obtained at the end of the analysis, and as we can see from Fig. 6.36, in this case, the profile is reasonably constant throughout the angle swept by the pipe. In fact, the drop in the plot on the left corresponds to a variation of a few degrees from the average value.

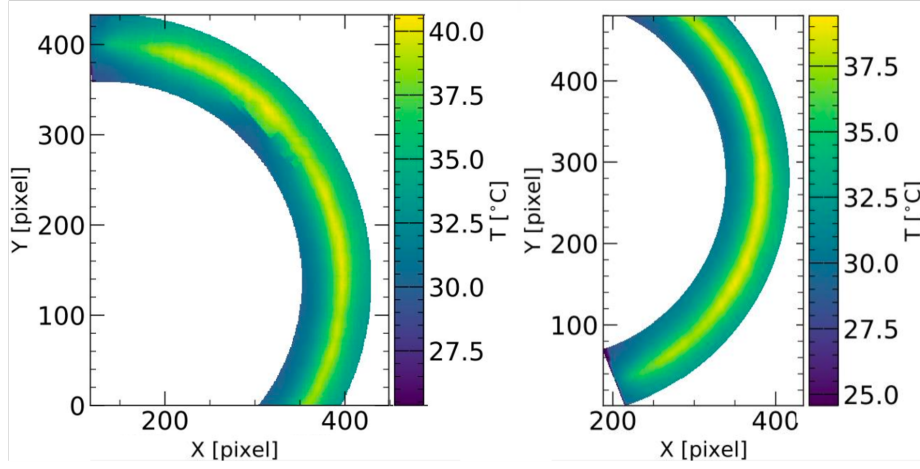


Figure 6.35: The shape of the HR_L2.1IT. The two figures represent the right and left sides of the same HR face.

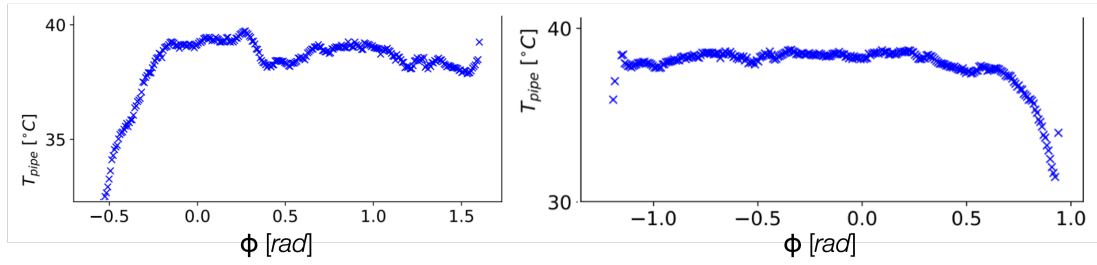


Figure 6.36: On the x -axis the position of the pipe temperature is given in angular coordinates. Temperature shape along the pipe direction on both faces of the HR. In this case, the heat distribution is reasonably constant throughout the pipe direction.

These initial measurements have allowed the collaboration to adopt this procedure as a quality control (QC) test for HRs post-construction. Subsequently, significant improvements have been made to the setup in Genova. The insulated cabinet has been replaced with a custom box that houses the HR, and the pipe is now securely attached to the chiller using fixed attachments. One of the main concerns with the previous setup was the absence of permanently anchored attachments to the cabinet, which posed a risk of causing stress and potential damage to the pipe. Furthermore, a cooling system has been implemented within the box, facilitating a faster cooling/heating phase for the HR after the liquid is circulated inside.

6.5 ITk Production Database

ITk Production Database (ITkPDB) [78] is an information system for registering all components used in the CERN Inner Tracker of the ATLAS experiment. The Inner Tracker (ITk) consists of approximately 500k components and its construction will take several years. The Inner Tracker will run for about 10 years and data should be available for a period of 20 years.

Due to this huge amount of components, the ATLAS ITk collaboration has decided to set up a Production Database that will allow each construction and testing site to keep track of every component, elementary or assembled, and the results of the test on such components. My work on the ITk Production Database was focused on the implementation of the ITk Pixel OEC LS.

The first FDR (Final Design Review) was held in 2020, focused on the back-end, while a second FDR assessing the readiness of the user interfaces has been held in October 2022.

6.5.1 Outer Endcap Local Support Structure

Starting from the OEC LS Assembly Breakdown Structure (ABS) [79], a tree structure was created.

As it's shown in Fig. 6.37, every HRs is composed of a Bare HR, the naked carbon structure, on which the Type-0 Tape are assembled, a Low Voltage and High Voltage End of Stave Cards (LV/HV EoS), a Power and Data Pigtail and in the end a certain number of Quad Modules glued with their Adhesive.

Also two Reusable objects a Handling Frame and Transport box are included. It was chosen to link both of them to the HR Assembly level to simplify the disassembling process when the HR will be moved from the Handling Frame into the Shell for the final installation into the endcap Shell.

Similarly, the tree structure representing the Bare HR Assembly that was produced is presented in Fig. 6.38.

In both assembly structures, some components are independent from the layer, while others are layer-dependent or orientation-dependent (orientation means that the object will be installed in right or left shell). For this reason in tree structures of Fig. 6.37 and Fig. 6.38, the wording *L2* has been written before the component names, likewise, the *Right-handed* wording, to specify which components are layer/orientation dependent and which are not. It is important to specify that the orientation of the HR Assembly comes from the gluing of the Type-0 Tape on the HR surface. Certainly, prior to the addition of the Type-0 Tape, the Bare HR exhibits complete symmetry and can be configured with either a right or left flavor.

Similarly, it is important to specify how these components are not dependent from the OEC side (*A-side* or *C-side*) because on both sides they are identical but mirrored.

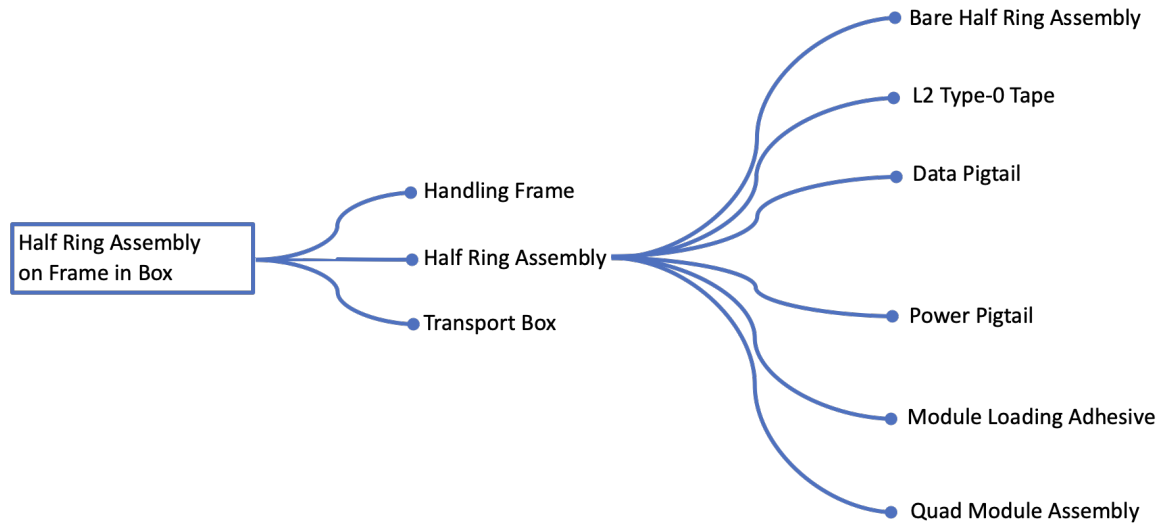


Figure 6.37: Loaded HR tree structure.

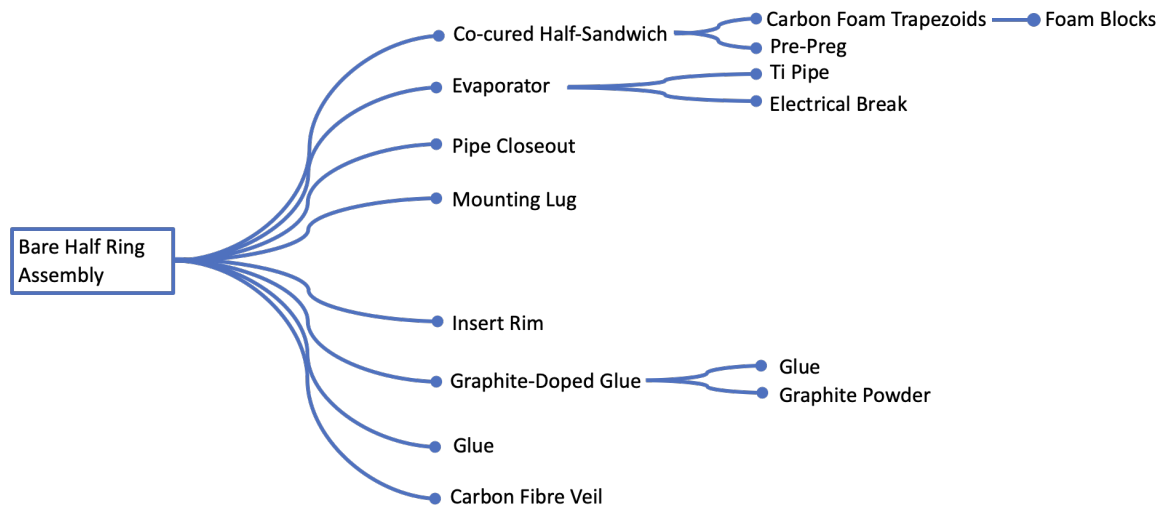


Figure 6.38: Bare HR tree structure.

6.5.2 ITk Production Database Components

As just said in the introduction of this section, the work on Production Database started with the instantiation of the whole OEC LS components inside the Database.

The total list of components is the following:

1. Half Ring Assembly
 - 1.1. Bare Half Ring Assembly
 - 1.1.1. Co-cured Half Sandwich
 - 1.1.1.1. Carbon Foam Trapezoids
 - 1.1.1.1.1. Foam blocks
 - 1.1.1.2. Pre-Preg Foil
 - 1.1.2. Evaporator
 - 1.1.2.1. Titanium Pipe
 - 1.1.2.2. Electrical Break
 - 1.1.3. Pipe Closeout
 - 1.1.4. Mounting Lug
 - 1.1.5. Insert Rim
 - 1.1.6. Graphite-doped glue
 - 1.1.6.1. Glue
 - 1.1.6.2. Graphite powder
 - 1.1.7. Glue
 - 1.1.8. Carbon Fibre veil
 - 1.2. Type-0 Tape
 - 1.3. Power/Data Pigtails
 - 1.4. Module Loading Adhesive
 - 1.5. Quad Module Assembly
2. Handling Frame
3. Transport Box

To differentiate the components within the database, all of them were assigned names with the prefix “OEC”, indicating their association with the Outer Endcap rather than the Outer Barrel (OB) components. This naming convention ensures clear distinction and helps maintain organization and clarity within the database.

Component Types

Certain components within the system exhibit distinct “Component Types.” The database is organized in such a manner that it allows for the existence of a single component with a given name, while also accommodating various types of that particular component. As a result, we can instantiate different types of the same component for each instance, thus providing flexibility and versatility in the system. For instance:

- OEC Half Ring
 - HR Layer 2-Right Handed (HRL2R)
 - HR Layer 2-Left Handed (HRL2L)
 - HR Layer 3-Right Handed (HRL3R)
 - HR Layer 3-Left Handed (HRL3L)
 - HR Layer 4-Right Handed (HRL4R)
 - HR Layer 4-Left Handed (HRL4L)

And each type of OEC Half Ring Assembly has its own children connected:

- HRL x R (where x is the layer number)
 - L x Bare Half Ring
 - L x R Type-0 Tape
 - L x Pigtail
 - Quad Module
 - Module loading Adhesive

There are two different Pigtail types:

- OEC Pigtail
 - OEC Power Pigtail
 - OEC Data Pigtail

Component Categories

Inside the Production Database, the components are divided into *Categories*. For each component, a Component Category is needed.

Inside the Production Database, there are several different Components Categories to categorize the components: *Assembly*, *Item*, *Bulk*, *Material*, and *Reusable*.

Assembly

By definition, **Assembly** component is:

something that consists of several children components being combined together.

OEC Components that belong to Assembly Category are

- OEC HR
- OEC Bare HR
- OEC Half-Sandwich
- OEC Evaporator
- OEC Type-0 Tape

For example, Each Bare HR is composed of several different components, as we can see in the list in the Sec. 6.5. This dependency between the Assembly and their *children* allows recording which components have been used to compose the Assembly.

Item, Bulk, and Material

By definition **Item** components are:

individual items with no components assembled into it.

It was decided to use this kind of category to instantiate “elementary” components because they have to be tested individually. The following components belong to this category:

- OEC Electrical Break for Ti Pipe
- OEC Pigtail
- OEC Ti Pipe

Bulk components are:

components that arrive in batch and have no sub-type.

This kind of component is grouped in batches and for the assembly purpose, there is no need to identify every single component.

Inside the Production Database only the batch is stored with an identification code, the *Batch Number*.

The following components belong to the Bulk category:

- OEC Insert Rim Closeout
- OEC Mounting Lugs
- OEC Pipe Closeout

Material components are defined as follows:

a pile of material from which a number of objects can be made without knowing precisely how many.

In particular, the OEC components included inside the Production Database are the following:

- OEC Graphite Doped Glue
- OEC Graphite Powder
- OEC Carbon Fibre Veil
- OEC Carbon Foam Trapezoids
- OEC Glue
- OEC Loading Adhesive
- OEC Pre-preg
- OEC Foam Blocks

Reusable components are defined as:

objects which need to be traced during production but do not actually go into the detector.

These kind of components are used several times, for example, to ship HR from one institute and another, so it's important to register them inside the database to track their position. Only two components have been instantiated as Reusable: OEC Handling Frame and OEC Transport Box.

6.5.3 Stages and Test

For each component, several stages have been created. In the context of the ITkPDB, *Stage* means:

The stages collect information about the current state of an object.

In Tab. 6.5 are reported the complete stages list divided by component category.

	Assembly	Reusable	Item-Bulk-Material
Reception	Yes	Yes	Yes
Assembly	Yes	No	No
QC Test	Yes	Yes	Yes
Package	Yes	Yes	No
Shipping	Yes	Yes	No

Table 6.5: OEC LS component stages table.

Every component has a first stage called “Reception Stage”. During this stage, some components are tested through a visual test.

For the Assembly Components, the second stage is the “Assembly Stage”, in which the component is assembled.

The second stage for Reusable, Item, Bulk, and Material components is the “QC Test Stage”, in which the components are tested.

In the end, Assembly and Reusable are moved to the “Package and Shipping Stage” (the name of the stages is explanatory of the stage itself).

As it has been said, during Reception Stages and QC Test Stages components are tested. Several tests are already included inside the Production Database.

You can find the whole test list for each component in Tab. 6.6.

6.5.4 Serial Number, Batch Number, and Properties

To identify components placed into ITk Production Database, they are identified through a Serial Number or Batch Number.

The basic difference between a Serial Number and a Batch Number lies in the fact that Serial Numbers are self-generated by the Production Database (with the coding schema chosen by the community) while the Batch Number could be chosen case by case by the shifter maintaining the code uniqueness.

The ITk Production Database identifies with a Serial Number the Assembly, Item, and Reusable components, while the Material and Bulk components are identified by Batch Number.

A document on LS Serial Number is being written by the community [80]

Serial Number

The LS Serial Number is a unique identifier code automatically assigned by the system to each component.

The Serial Number has got this form: **20UPEXXN₁N₂N₃N₄N₅N₆N₇**.

The Serial Number composition is reported below:

- The Serial Number begins with the code **20U**, where **20** is the ATLAS Number, while **U** is the Upgrade Identifier.
- The code **PE** identifies the Pixel OEC components.
- **XX** is the Components Identifier. These two letters univocally recognize the components types (eg: for the component OEC Half-Sandwich the Components Identifier is **HS**).

Assembly	Item	Bulk	Material	Reusable
Half Ring Grounding Test	Electrical Break for HR Ti pipe Visual Inspection Impedence	Insert Rim Batch Check	Foam Block Dimension Weight Reception test	Transport Box
Bare Half Ring Jig Thermal Grounding Shielding Metrology Pressure	Pigtail	Carbon Fibre Veil	Graphite Powder	Handling Frame
Half-Sandwich Visual Inspection Gap Gap Dimension Picture	Ti pipe Jig Diameter Visual Inspection	Mounting Lugs Batch Check	Pre-preg Visual Inspection Density Tensile Properties	
Evaporator Jig Test Leak test Pressure			Carbon Foam Trapezoids Angle Thickness Flatness Visual Inspection	
			Pipe Closeout Jig Test	Glue Weight Viscosity
Type-0 Tape Impedance Functionality			Loading Adhesive	

Table 6.6: OEC LS Tests.

- **N₁** is the Layer Number. This number can assume the following values: 2, 3, 4 (the only three possible layers for the OEC LS Components), and 9, which means that this particular component is the same for every layer.
- **N₂** is the Production Type number. This number can assume the following values:
 - Pre-Production = 0;
 - Production = 1;
 - Prototype = 2;
 - All = 9;
- **N₃...N₇** count the Nth object.

Batch Number

Batch Number allows greater freedom of choice, so as to adapt the object numbering with contingency. For example, the Batch Number could be the vendor batch identifier.

At the moment this criteria was chosen by the OEC Foam Blocks and OEC Foam Trapezoids Batch Numbers. Using the Batch identifier with which the vendor named the Foam Blocks shipped to the laboratories in Genova, the Batch Numbers of these components have been decided:

- OEC Foam Blocks Batch Number is **SNXX-LotYY**, where **XX** and **YY** are the Foam Block vendor chosen serial number and lot number respectively.
- OEC Foam Trapezoids inherit the Batch Number from the Foam Block from which they are produced, plus a **ZZ** number ranging from 0 and 99: **SNXX-LotYY-ZZ**.

Properties

For each component within the ITkDB, certain properties have been defined. Properties are additional information that help the shifter to better store information about the component in the database.

During the development phase, the following properties for the components were chosen:

- Assembly, Item and Reusable components:
 - Shifter Name: the name of the person who is entering the component into the database
 - Layer Number: the number of layer for which the component is assembled. This information is stored in the Serial Number as Layer Number (**N₁**). It was used `codeTable` data type for this property.

- Production Type: this property stores the information about the type of production for which the component is being assembled. Production Type can only assume values 0, 1, 2, and 9 as mentioned in the section concerning Serial Numbers (Sec. 6.5.4). This information is stored in the Serial Number as Production Type Number (**N₂**). It was used `codeTable` data type for this property.
 - Part Number: it is an Alternative ID and is a “human readable” Serial Number. This property is useful for shifters to find objects in the database without having to use the Serial Number.
- Material and Bulk components:
 - Shifter Name: the name of the person who is entering the component into the database
 - Batch Number: this property is the Batch Number identifier explained in Sec.. 6.5.4. This property is an Alternative Identifier and is also Unique. Its data type is a `string`.
 - Part Number: it is an Alternative ID and is a “human readable” serial number. This property is useful for shifters to find objects in the database without having to use the Serial Number.

6.5.5 Bare HR Assembly inside Production Database

To test this work, the components already present in the Genova laboratory were inserted into the ITkPDB, and then an initial bare HR was assembled. It was started with OEC Foam Blocks SN20-Lot12 and OEC Foam Trapezoids L4 from which they are produced: SN20-Lot12-[01,...,25].

For these particular Foam Trapezoids, the density had been measured for each of them, rather than inheriting the one from the parent block, and it was included into the ITkPDB as a result of the Foam Trapezoid density tests. The OEC Pre-preg L4 was included in the ITkPDB, twice, and then assembled into two different OEC Half-Sandwich L4.

In Fig. 6.39 a picture of one of these OEC Half-Sandwich L4 produced by Genova is shown.

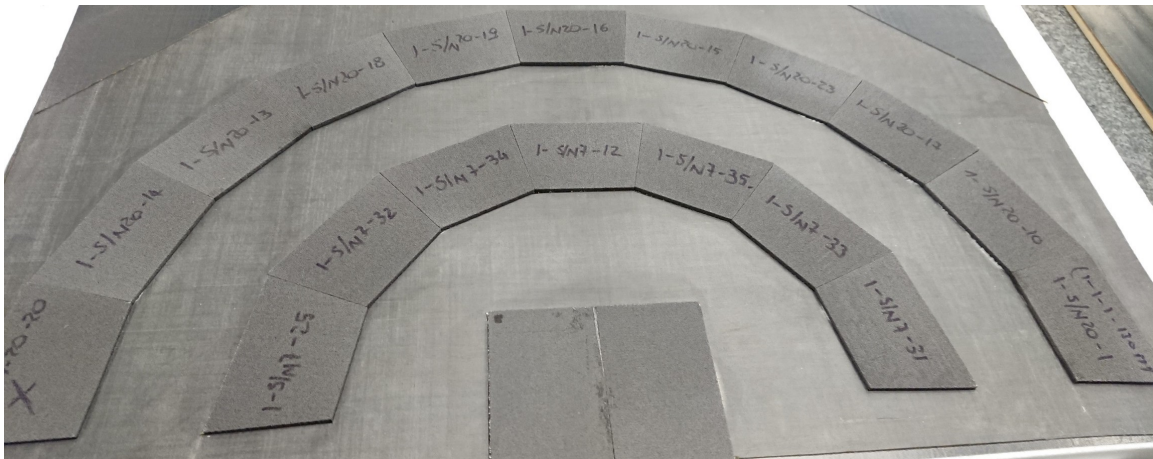


Figure 6.39: Half-Sandwich assembled.

To assemble a Half-Sandwich (HS) into the Production Database the link to the HS children is needed.

To preserve the information on individual Foam Trapezoid placement on the HS, each trapezoid was linked in the following order into the list of children of the HS:

- Look at the HS on the table with the concavity facing down (as it is shown in Fig. 6.39).
- Trapezoids, with visible name, were linked from left to right.

In the database the picture of the HS with a trapezoids visible name it was included.

To assembly a complete OEC Bare Half Ring L4, the remaining components that compose the Bare Half Ring (BHR) it was stored in the database.

Starting with the OEC Titanium Pipe L4 and two OEC Electrical Breaks for HR Ti Pipe, they have been assembled in an OEC Evaporator L4.

At last, the remaining components were added:

- OEC Glue for HR,
- OEC Doped Glue for HR, the assembly composed by the OEC Glue and the OEC Graphite Powder,
- OEC Inner Rim Closeout for HR L4 and OEC Outer Rim Closeout for HR L4,
- OEC Inner Rim Tapped Insert for HR,
- OEC Pipe Closeout for HR L4.

At this point, all these components were linked as children to the Bare Half Ring (BHR). With the only precaution, the HSs were added as children in numerical order, i.e. by first adding the HS with the lowest Serial Number. This HS will be the “face up” of the BHR.

In Fig. 6.40 the real BHR assembled by Genova is shown.

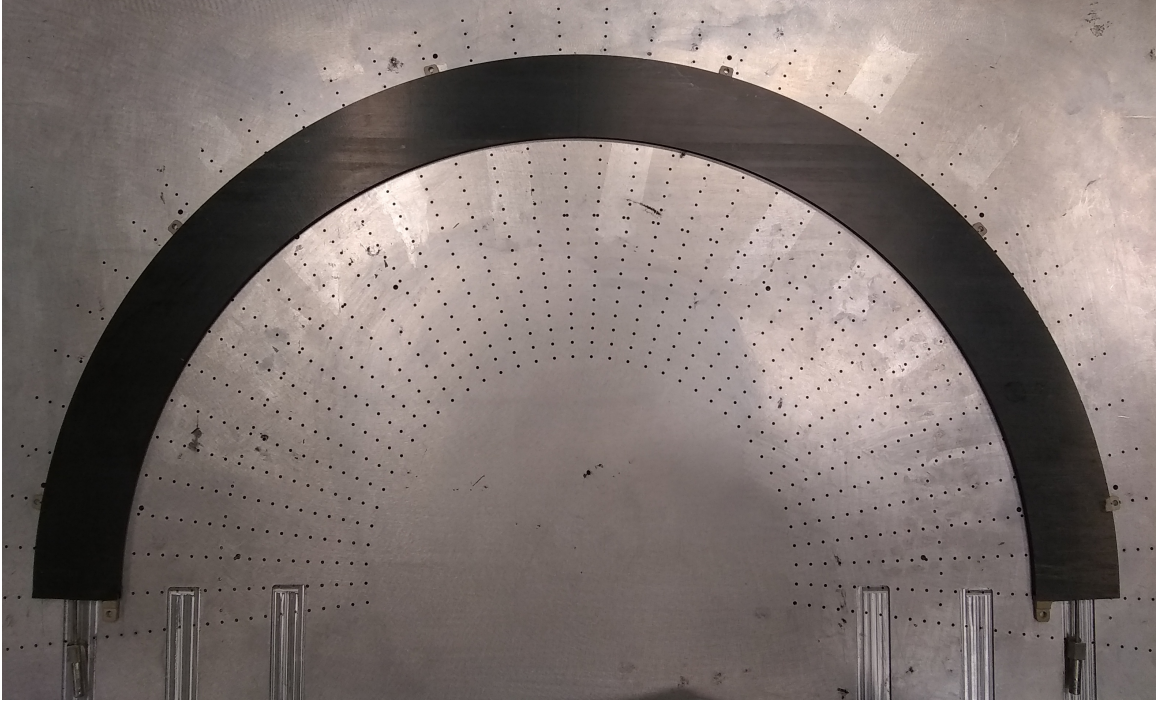


Figure 6.40: Bare HR assembled.

When assembling the OEC Bare Half Ring, which exhibits complete symmetry, it can be installed in any of the four Half-Shells that enclose ITk's OEC. However, the symmetry is broken once the Type-0 Tape is affixed to the Bare Half Ring, resulting in the HR being permanently designated as either "right" or "left". This process is depicted in Fig. 6.41.

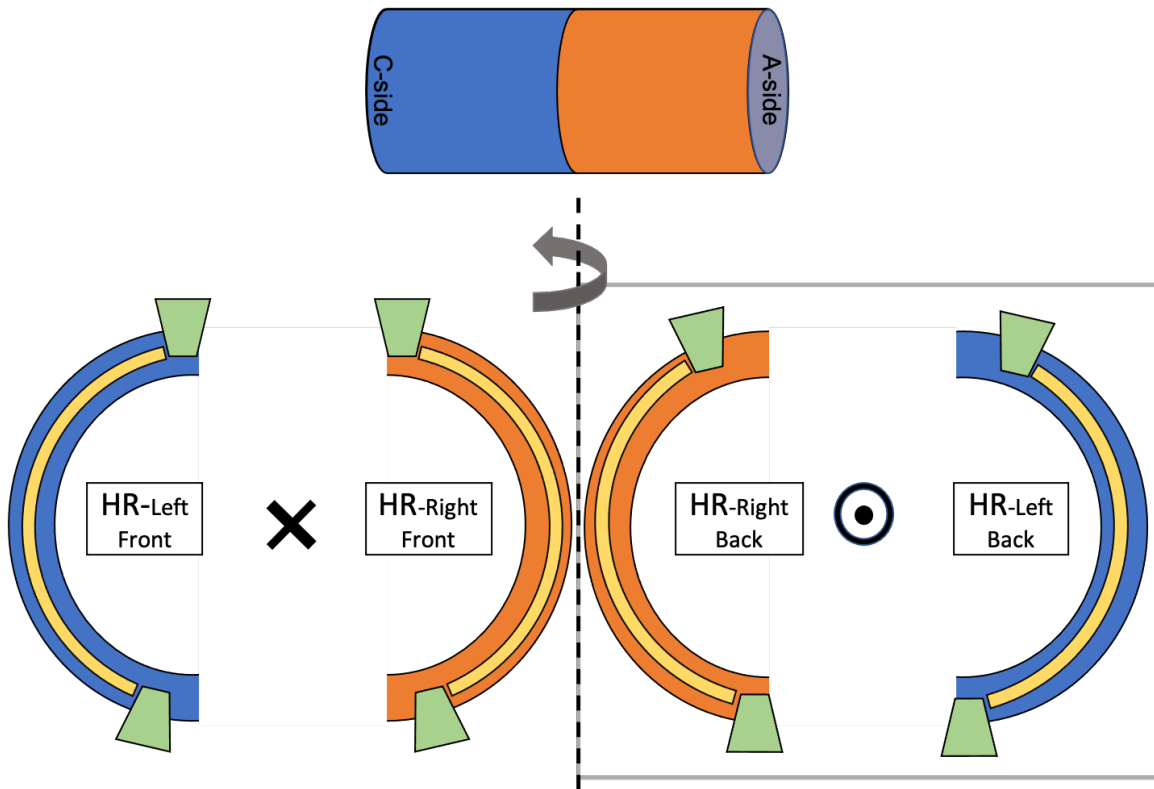


Figure 6.41: Schematic reproduction of an HR to which the Type-0 Tape has been added. The tape breaks the symmetry and makes the HR “left” or “right”.

To preserve the information chain on *which Foam Trapezoids is in which place* on each HR, it is, therefore, essential to keep track of which tape has been glued onto which Half-Sandwich.

6.6 The Impact of Misalignment on Tracking Performances

6.6.1 Introduction

Precisely reconstructing the trajectories of charged particles generated in proton-proton and heavy-ion collisions at the LHC and in future at the HL-LHC is a critical issue for many of the physics processes investigated by the ATLAS Collaboration. Accurate reconstruction of charged particles is necessary for almost every measurement performed by the ATLAS detector, ranging from Standard Model processes to the search for new phenomena. To achieve this task, ATLAS employs the Inner Detector (and ITk detector in the next future) tracking system to obtain precise position measurements of charged particles as they move through the detector. The energy deposits (hits) from charged particles recorded in individual detector elements are utilized to reconstruct their trajectories (tracks) and estimate the associated track parameters. The precision achieved for the track parameters is determined by various factors, including the intrinsic resolution of sensitive devices, the knowledge of the magnetic field, the material distribution inside and before the tracker, and the geometry of the detector elements. The goal of the detector alignment is to determine as precisely as possible the actual geometry of the active detector elements and to track any changes in the geometry over the time. Poor knowledge of the actual geometry of the active detector elements results in a deterioration of reconstructed track resolution. To limit the degradation of track parameter resolution for high-momentum tracks below 20 percent compared with a perfectly aligned detector, minimum accuracy criteria were established. Additionally, correlated geometrical distortions can result in systematic biases in the reconstructed track parameters. These biases can be introduced by actual detector deformations, to which the alignment procedure has little sensitivity, or by the procedure used to determine the alignment parameters. These correlated biases are referred to as “weak modes” of alignment. The objective of this study is to determine the bias in the reconstruction procedure by intentionally introducing misalignment in the region of the ITk detector’s endcap. Subsequently, the goal is to assess the extent to which this bias can be mitigated by offline realignment of the detector and identify the types of misalignments that are not-recoverable. The ultimate aim is to generate a document that can be shared with the detector construction and integration groups, providing them with an estimate of the maximum errors that can be rectified through software.

However, this work should still be considered very preliminary, because the realignment procedure was not performed.

6.6.2 Alignment Procedure

Track Fitting and the Global χ^2 Method

In this section, the formalism for in situ alignment of the ATLAS ID using reconstructed tracks is briefly introduced (but so far this formalism will be also valid with ITk). The concept of Global χ^2 alignment is introduced, together with a discussion on “weak modes”.

The approach used is rooted in the Newton-Raphson method and aims to determine

the trajectory parameters as well as a set of alignment parameters denoted by α . In this context, the alignment parameters are defined as the six degrees of freedom (DoF) of each alignable structure that provide a unique definition of its position and orientation in space. These correspond in three translations, T_x , T_y , and T_z , and three rotations, R_x , R_y , and R_z . The translations are relative to the origin of the reference frame of each alignable structure, and the rotations are performed around the Cartesian axes.

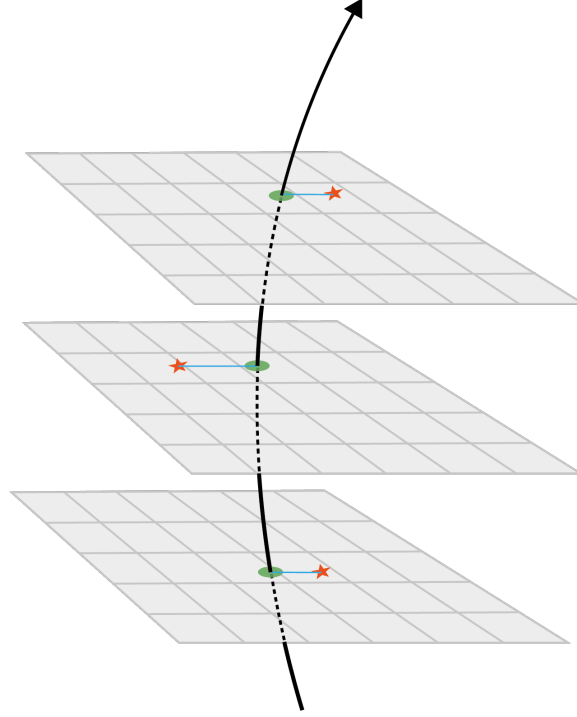


Figure 6.42: The figure illustrates how a charged particle passes through detector planes. The red stars indicate the measurement, m_i , made on the i^{th} layer. A black line represents the fitted track trajectory for a given set of track parameters, τ , and a green ellipse represents the position of the intersection of the fitted track with the surface on which the i^{th} measurement is made, denoted by $e_i(\tau)$. Finally, a blue line shows the residuals, r_i , which represent the difference between the measured value and the predicted value from the fitted track.

The Newton-Raphson method (for a more complete discussion, see [81]) is an iterative approach used to determine the best fit for a set of measurements of a track left by a charged particle in active detector elements. The fit quality is represented by a track χ^2 , calculated from the distances between the hits in the detector (i.e., track measurements) and the fitted track (residuals). A track trajectory in a magnetic field is parameterized by five parameters: $\tau = (d_0, z_0, \phi_0, \theta_0, q/p)$, where d_0 and z_0 are transverse and longitudinal impact parameters and ϕ_0 and θ_0 are azimuthal and polar angles of the track, respectively, defined at the point

of closest approach to the z-axis of the reference frame. The ratio of q/p is the inverse of the particle momentum (p) multiplied by its charge (q) (see [82] for more details).

The track χ^2 is computed from all measured track-hit residuals, $r_i = e_i(\boldsymbol{\tau}) - m_i$, where m_i is the position of the i^{th} measurement and e_i is the position of the intersection of the fitted track with the surface on which the i^{th} measurement is made. The determination of the intersection position (e_i) includes the measurement in question, which causes r_i to be a biased residual. The track χ^2 is defined, using vector notation, as

$$\chi^2 = \mathbf{r}^\top \Omega^{-1} \mathbf{r}, \quad (6.2)$$

where $\mathbf{r}$ is the vector of track residuals and Ω is the covariance matrix of the corresponding measurements. The parameters of a track's trajectory, $\boldsymbol{\tau}$, are those that minimize this χ^2 . The minimization is achieved using the first and second derivatives of the χ^2 with respect to $\boldsymbol{\tau}$. By defining the derivative $G = \partial \mathbf{r} / \partial \boldsymbol{\tau}$, the condition for the minimization of the χ^2 can be expressed as

$$\left(\frac{d\chi^2}{d\boldsymbol{\tau}} \right)^\top = 2G^\top \Omega^{-1} \mathbf{r} = 0. \quad (6.3)$$

To find the values of $\boldsymbol{\tau}$ that satisfy Eq. 6.3, an iterative procedure is used to evaluate the first and second derivatives of χ^2 with respect to the current iteration's track parameters, $\boldsymbol{\tau}_0$. If the derivative G was constant, the problem would be linear and the solution would be exact. However, the derivative G depends on the track parameters themselves, so the procedure is repeated until a convergence criterion is met.

To improve the track fit, additional parameters $\boldsymbol{\theta}$ are added to account for the effects of Multiple Coulomb Scattering (MCS) of the particle with the detector components. As a result, the residuals now depend on both $\boldsymbol{\tau}$ and $\boldsymbol{\theta}$, and the variance of the scattering angles, Θ . The scattering parameters derivatives of residuals are defined as $S \equiv \partial \mathbf{r} / \partial \boldsymbol{\theta}$. Therefore, χ^2 must be minimized for $\boldsymbol{\tau}$ and $\boldsymbol{\theta}$ simultaneously. The following simplified notation is used to describe the Global χ^2 method for alignment, including MCS:

$$\chi_{\text{Track}}^2 = \mathbf{r}^\top \Omega^{-1} \mathbf{r} + \boldsymbol{\theta}^\top \Theta^{-1} \boldsymbol{\theta}. \quad (6.4)$$

The Global χ^2 is a track-based alignment method which uses a χ^2 built from a large sample of reconstructed tracks and their associated hits in the detector elements being aligned. The alignment parameters are determined by minimising the Global χ^2 with respect to the alignment parameters:

$$\chi_{\text{Global}}^2 = \sum_i \chi_{\text{Tracks } i}^2 \quad (6.5)$$

where $\chi_{\text{Tracks } i}^2$ is the χ^2 of the i^{th} track as given by Eq. 6.4

The Inner Detector Alignment

The ATLAS Inner Detector (see Sec. 2.2.1 for more details) is comprised of numerous active detector components, each of which can be considered an alignable structure or a grouped

collection of modules, such as a subdetector. The alignment process is performed at different hierarchical levels based on the assembly structure of the ID. Beginning with the largest physical structures at *level 1*, the detector subsystems are aligned by separating them into endcaps and barrel regions to correct for collective movements. At *level 2*, individual barrel layers and endcap disks are treated as physical structures, while *level 3* corresponds to the alignment of a silicon module or TRT wire. The SCT modules are treated as a single element in the alignment procedure due to their high construction precision. The levels are addressed sequentially during the alignment procedure. For a complete discussion see [81].

In Run 2 and Run 3, the alignment levels were updated to accommodate the Insertable B-Layer (IBL). These changes are straightforward for levels 2 and 3, as the IBL represents merely an additional Pixel layer or additional silicon modules, respectively. Since the support structure of the IBL is mechanically independent from the previously installed Pixel subdetector, IBL movement is not expected to be correlated with collective Pixel movements. As a result, the IBL is treated as a separate physical structure at level 1.

The ITk detector will inherit the alignment procedure just discussed, clearly adapting it to its new layout (Sec. 4.2).

6.6.3 Misalignment Studies with ITk Layout

In this section the misalignment machinery for the ITk pixel detector into the Athena release 21.9 framework [30] will be discussed. The purpose of this work is to show that the misalignment procedure still works with the ITk pixel detector, using ATLAS-P2-ITK-22-02-00 geometry with a sample of single muons with p_T of 1 GeV and 10 GeV to evaluate the track parameter resolutions at different regimes.

The development and validation of ID alignment software for ITk involves extending the current alignment software to allow basic alignment studies of the ITk layout. Starting from the pixel misalignment, the aim is to provide a procedure that includes the strips sector. The purpose of this work is to obtain results that are useful in the detector construction phase. The main interest arising from this work is to understand how much a given misalignment value caused in the construction phase is recoverable in the software realignment phase.

Framework Tests

To test the misalignment procedure, a misalignment using a random Gaussian distribution (G) with $\sigma = 1, 3$, and $10 \mu\text{m}$ has been applied to the nominal pixel ITk geometry in the region. In Fig. 6.43 the difference between the misaligned position and the nominal position of the ITk modules are reported. The local shift transformation applied to the single pixel modules can be summarized in the following transformation matrix:

$$\begin{bmatrix} x_{\text{trasl}} & y_{\text{trasl}} & z_{\text{trasl}} \\ R_{xx} & R_{xy} & R_{xz} \\ R_{yx} & R_{yy} & R_{yz} \\ R_{zx} & R_{zy} & R_{zz} \end{bmatrix} \rightarrow \begin{bmatrix} G(0, \sigma) & G(0, \sigma) & G(0, \sigma) \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The applied shifts are therefore Gaussian distributed random translations, without applying any of rotation around the axes.

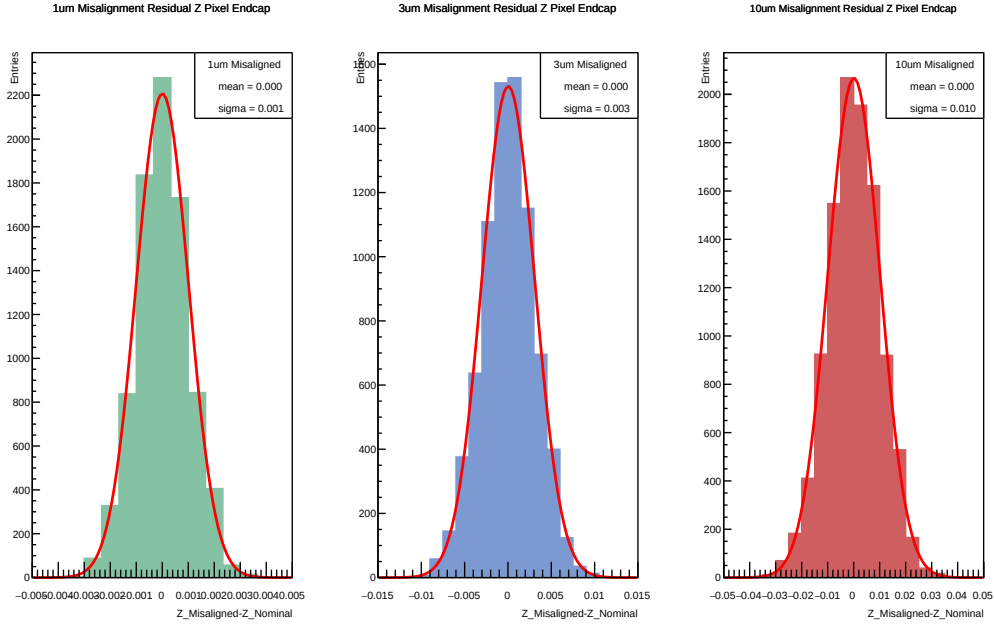


Figure 6.43: The figure shows the position of the ITk modules from whom their nominal positions have been subtracted. The misalignments applied were gaussian distributed random shifts with a $\sigma = 1, 3, 10 \mu\text{m}$.

Two samples with 50k simulated single muon track with $p_T = 1 \text{ GeV}$ and $p_T = 10 \text{ GeV}$ have been used to run reconstruction of the detector (not the re-alignment, just the reconstruction) with and without loading misalignment databases. Track parameter resolutions were plotted for different muon p_T to compare the resolution obtained from the three different misaligned geometries.

The first results of the local shift transformation show that all pixel modules were randomly misaligned in x , y , and z by a Gaussian distribution with $\sigma = 1, 3, 10 \mu\text{m}$. Fig. 6.44 and Fig. 6.45 show the effect of these three misalignment shift on the resolution of track impact parameters (d_0 and z_0) for both p_T values of the single moun samples.

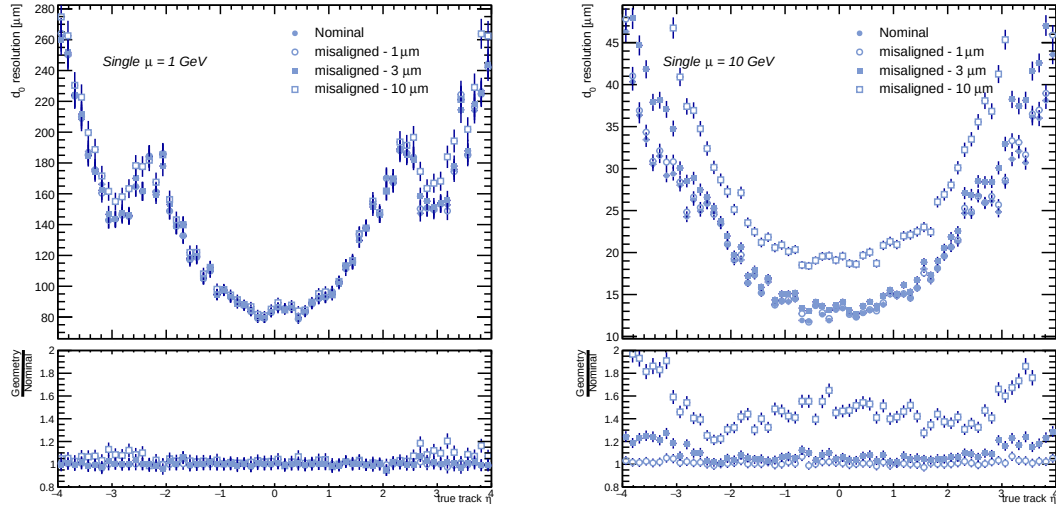


Figure 6.44: d_0 resolution as a function of η after the shifts have been applied individually to the ITk modules of the pixels. The detector was reconstructed using two types of data samples: (a) single muon with $p_T = 1$ GeV and (b) single muon with $p_T = 10$ GeV. Below each of the figures are the ratios of the resolution values of the impact parameter to its nominal value. For tracks at very low momentum, the additional misalignments are small with respect to the multiple scattering contribution, while at larger momentum a degradation of the performance is observed for the 10 μm smearing.

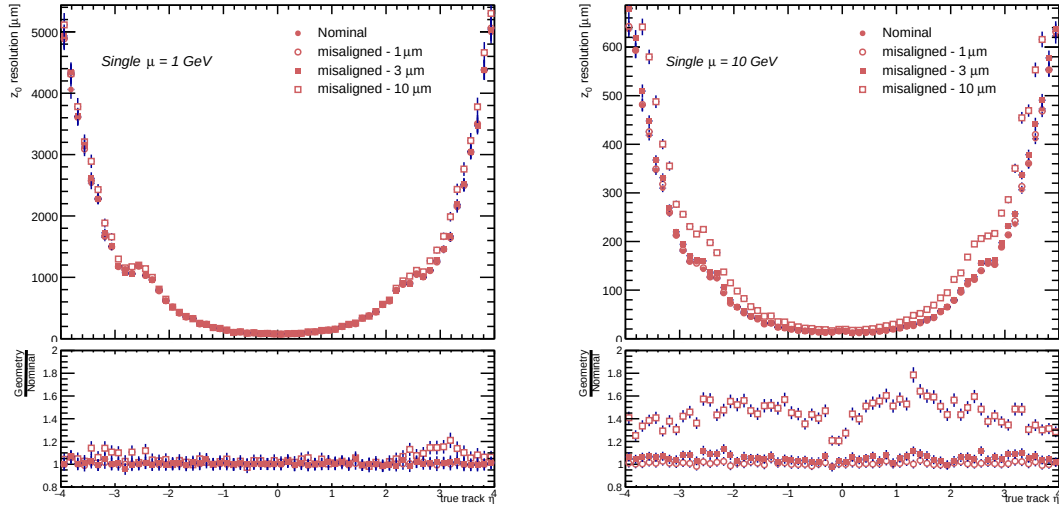


Figure 6.45: z_0 resolution as a function of η after the shifts have been applied individually to the ITk modules of the pixels. The detector was reconstructed using two types of data samples: (a) single muon with $p_T = 1$ GeV and (b) single muon with $p_T = 10$ GeV. Below each of the figures are the ratios of the resolution values of the impact parameter to its nominal value. For tracks at very low momentum, the additional misalignments are small with respect to the multiple scattering contribution, while at larger momentum a degradation of the performance is observed for the $10 \mu\text{m}$ smearing.

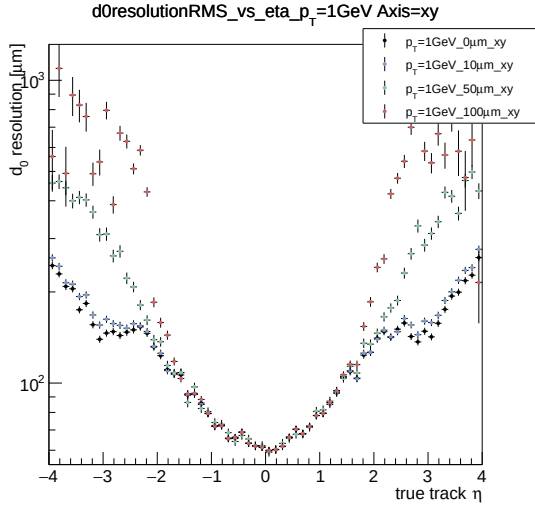
The plots in Fig. 6.44 and Fig. 6.45 show that the misalignment machinery for ITk Pixel System in Athena release 21.9 is functioning.

Misalignment Studies in the ITk Endcap

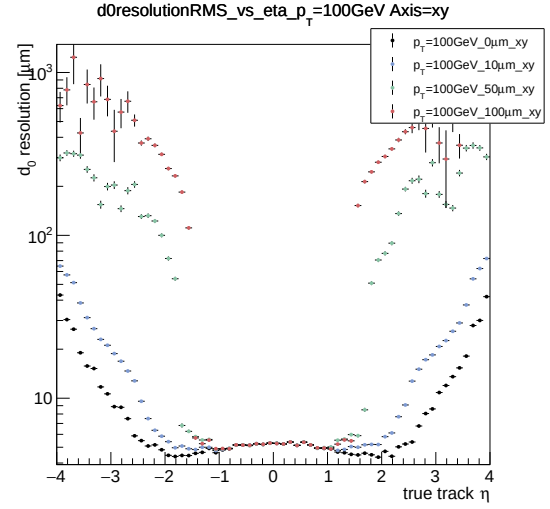
Having verified the functioning of the framework, we moved on to study the effects of a mismatch on ITk modules. As mentioned in the previous section, initially the Athena misalignment framework was tested but without touching the ITk strip subsystem since it was not enabled in the framework. So first the strips were included. Then the misalignment procedure was repeated, this time enabling both pixels and strips in the endcap area, leaving the barrel modules in their nominal position instead. As mentioned in the previous section, the final purpose of the study is to obtain useful information on module placement errors during detector assembly from the Italian and English communities involved in the construction of the ITk endcap. In addition, we also want to understand what possible deformations or misalignments are not recoverable during the software realignment of the detector. Therefore, by applying misalignments of 1, 10, 50, and $100 \mu\text{m}$ Gaussianly distributed both in the xy-plane and along the z-axis separately, the detector was reconstructed using two simulated muon samples at two p_T values that were representative of a good portion of the muon spectrum, $p_T = 1$ GeV and $p_T = 100$ GeV.

In Fig. 6.46 and 6.47 are reported the impact parameter resolution obtained with the reconstruction with the two different muon samples, having p_T of 1 and 100 GeV. The plots show the effect of the misalignment of the ITk modules on d_0 and z_0 parameter resolution and the effect on the reconstruction efficiency. Due to the track selection cuts, the higher the misalignment applied to the modules, the fewer hits per track founded by the reconstruction algorithm and the lower the number of tracks reconstructed. On the plots the drop of the efficiency occurs by the increase of the statistical error (the vertical error bar) of the points. The effect exhibits greater strength on the xy -plane, but it is also clearly visible along the z -axis for the z_0 parameter.

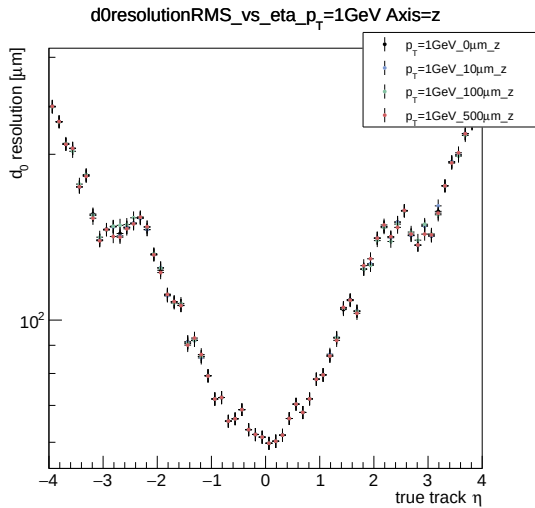
Fig. 6.48 shows the effect of the misalignments on the p_T resolution. The effect of the reconstruction efficiency is clearly visible in xy -plane (the transverse momentum is not affected by the position of the modules along the z -axis).



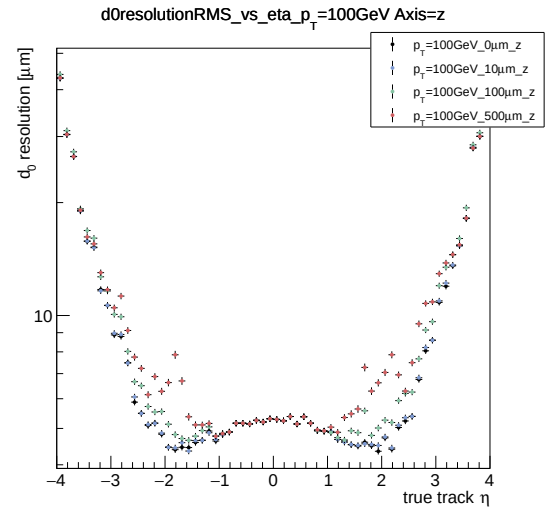
(a) d_0 resolution vs η with single muons tracks having $p_T=1$ GeV along the xy -plane.



(b) d_0 resolution vs η with single muons tracks having $p_T=100$ GeV along the xy -plane.

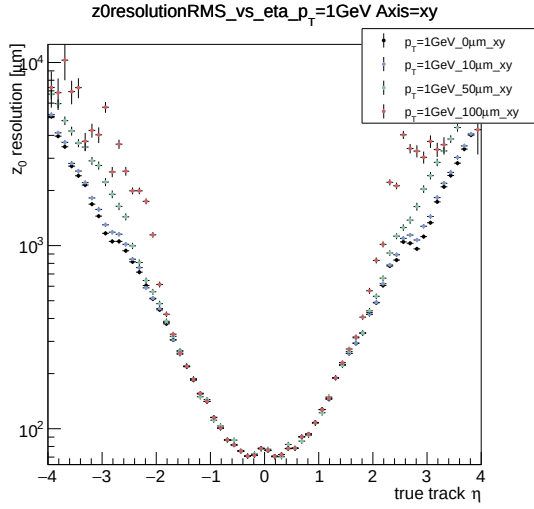


(c) d_0 resolution vs η with single muons tracks having $p_T=1$ GeV along the z -axis.

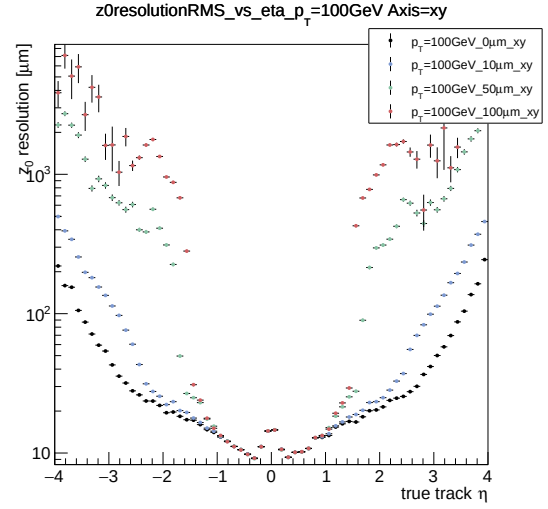


(d) d_0 resolution vs η with single muons tracks having $p_T=100$ GeV along the z -axis.

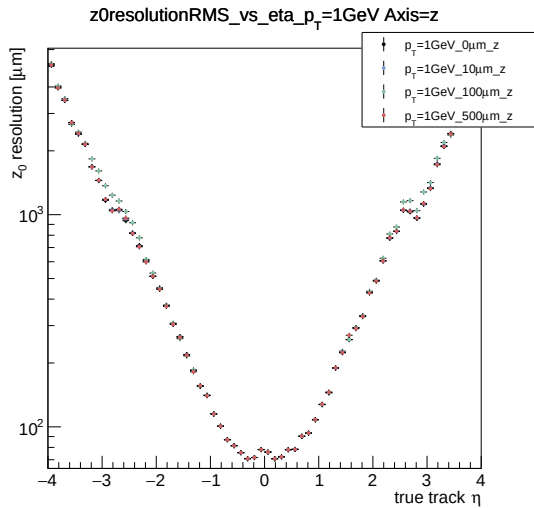
Figure 6.46: On top: d_0 resolution vs η with single muon tracks having $p_T=1$ GeV and $p_T=100$ GeV along xy -plane. The two plots show efficiency drop with higher misalignment values. This effect is due to the too tight track selection applied. On the bottom: d_0 resolution vs η with single muon tracks having $p_T=1$ GeV and $p_T=100$ GeV along z -axis. The effect of the misalignment is less visible along this axis because the impact parameter d_0 is not strongly dependent by the z position of the detector. The misalignment was applied in the endcap region only.



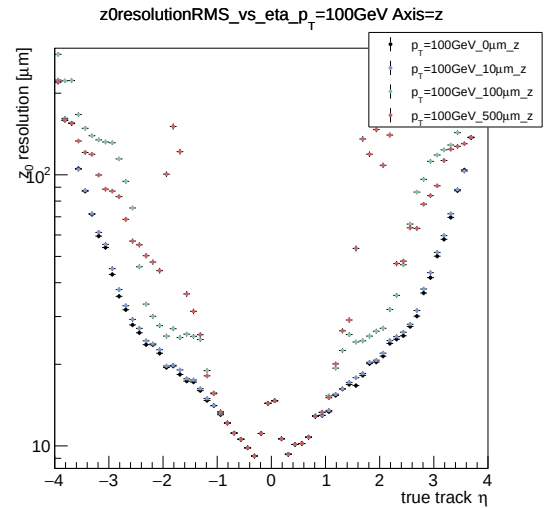
(a) z_0 resolution vs η with single muons tracks having $p_T=1$ GeV along the xy -plane.



(b) z_0 resolution vs η with single muons tracks having $p_T=100$ GeV along the xy -plane.



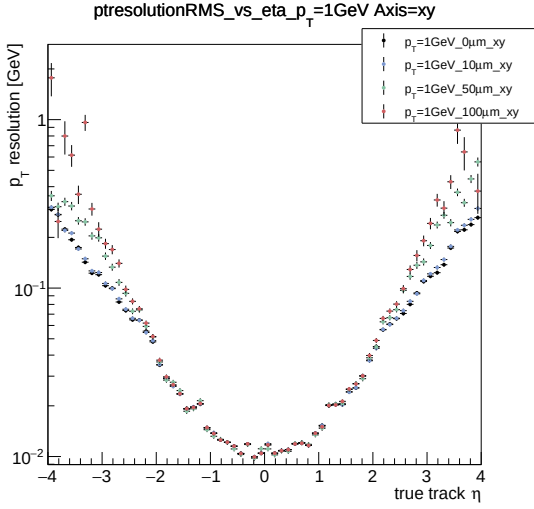
(c) z_0 resolution vs η with single muons tracks having $p_T=1$ GeV along the z -axis.



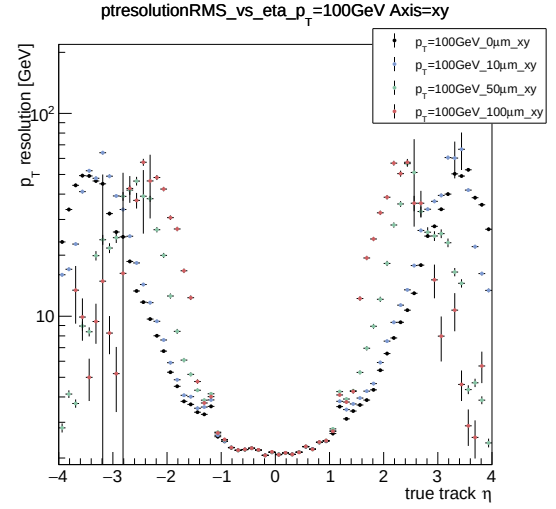
(d) z_0 resolution vs η with single muons tracks having $p_T=100$ GeV along the z -axis.

Figure 6.47: On top: z_0 resolution vs η with single muon tracks having $p_T=1$ GeV and $p_T=100$ GeV along xy -plane. The two plots show efficiency drop with higher misalignment values. This effect is due to the too tight track selection applied. On the bottom: z_0 resolution vs η with single muon tracks having $p_T=1$ GeV and $p_T=100$ GeV along z -axis. In this case, the effect of misalignment is better seen, especially at high p_T , than the effect on the parameter d_0 .

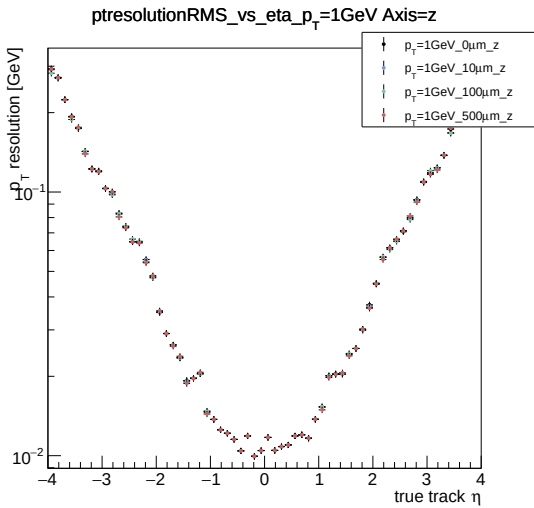
The misalignment was applied in the endcap region only.



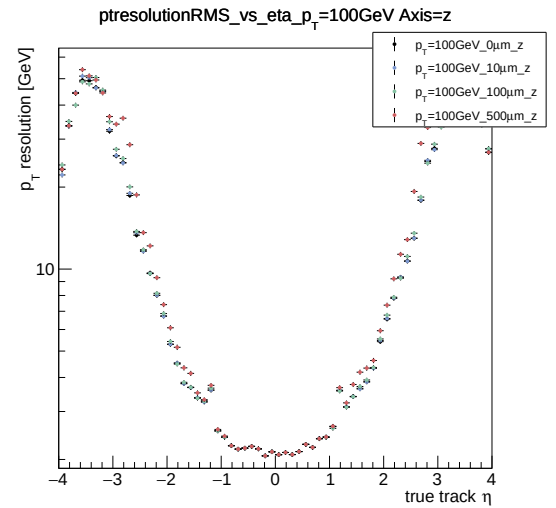
(a) p_T resolution vs η with single muons tracks having $p_T=1$ GeV along the xy -plane.



(b) p_T resolution vs η with single muons tracks having $p_T=100$ GeV along the xy -plane.



(c) p_T resolution vs η with single muons tracks having $p_T=1$ GeV along the z -axis.



(d) p_T resolution vs η with single muons tracks having $p_T=100$ GeV along the z -axis.

Figure 6.48: On top: p_T resolution with vs η with single muon tracks having $p_T=1$ GeV and $p_T=100$ GeV along xy -plane. The two plots show the efficiency drop with higher misalignment values. This effect is due to the too tight track selection applied. On the bottom: p_T resolution with vs η with single muon tracks having $p_T=1$ GeV and $p_T=100$ GeV along z -axis. The z -axis does not affect the estimation of the p_T resolution. Thus the effect of misalignment along z -axis, as expected, is negligible.

The misalignment was applied in the endcap region only.

Fig. 6.49 demonstrates a dramatic decline in reconstruction efficiency as the misalignment applied to the modules reaches a significant level.

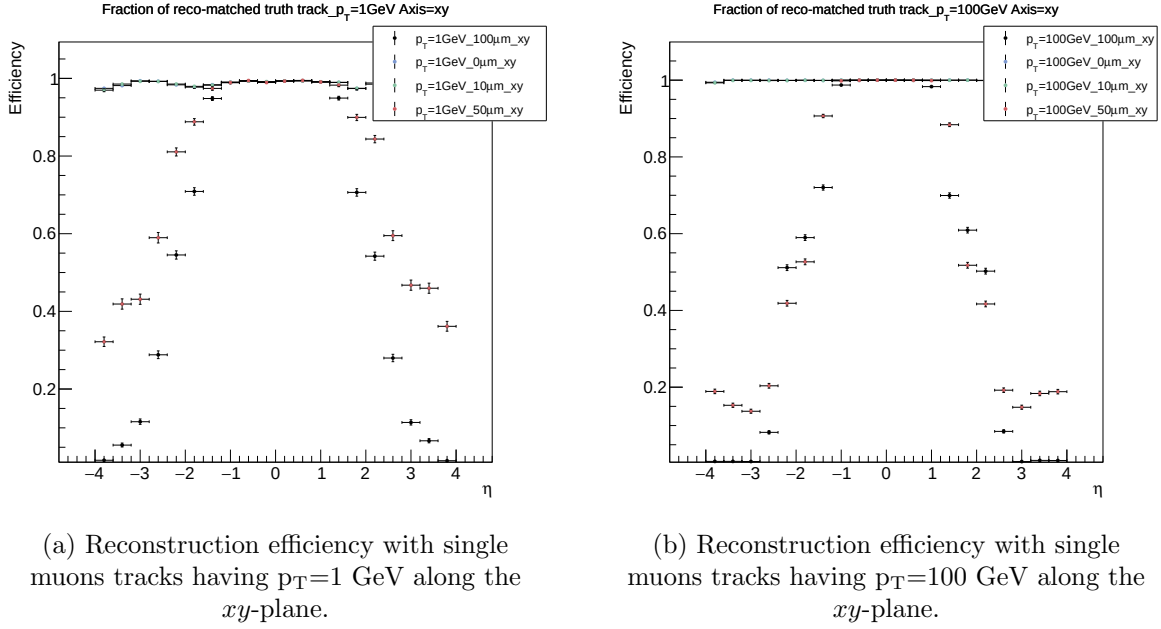


Figure 6.49: Track reconstruction efficiency vs eta with single muon tracks of 1 GeV and 100 GeV. The reconstruction efficiency drops dramatically as the misalignment value increases. This effect is due to the too tight track selection applied. The misalignment was applied in the endcap region only.

In order to obtain a better reconstruction efficiency, the cuts on the tracks must be released, e.g. decreasing the number of hits required for the reconstruction of the tracks. It will be the next step in this work before starting detector realignment tests, with which it will be possible to get the information about the software ability in terms of recovering of the modules misalignment after the detector construction and integration.

Conclusions

This thesis work has been done within the ITk project, the upgrade of the ATLAS tracking system, planned to be installed during the LHC Long Shutdown 3 (2026-2028) in order to deal with the upgrade of the LHC accelerator to the High Luminosity period. ITk is a full Silicon tracker, with a Pixel detector located at a small radius and a large area Strip detector surrounding it. Both detectors have a barrel central region and two end-caps, one on each side to cover the forward regions. Moreover, the Pixel detector is divided into an Outer System, permanent, and an Inner system, that will be replaced after about half of the total integrated luminosity. The Pixel detector, and in particular its innermost layers, will be subject to unprecedented radiation hardness requirements due to the HL-LHC operation parameters. To meet these requirements, ATLAS decided, based on preliminary results on prototypes, to use the innovative high radiation-hard 3D pixel detectors to cover an area of approximately 0.6 m^2 in the innermost layer. To optimize the tracking performance, the pixel cell size will be of $25 \times 100 \text{ } \mu\text{m}^2$ in the barrel and $50 \times 50 \text{ } \mu\text{m}^2$ in the forward region. The Pixel detector building blocks, the modules, are supported by local supports, which provide mechanical stability and cooling, via a pipe embedded in the system where high pressurized CO_2 is flowing. My thesis focuses on two main topics: the characterization of ITk Pixel End-Cap local supports in terms of their thermal and mechanical properties, and the characterization of ITk Pixel 3D modules, both the R&D ones called RD53A modules and the pre-production ones using ITkPixV1.1 chips.

On the local supports side, the Genova ATLAS group together with several Italian institutes (Milano, Lecce, and Frascati) is working on the Outer Endcap Half-Rings (HR) design and production and integration, and more in general, the INFN is involved in the construction of one entire Pixel ITk Outer Endcap, while the other one is under the responsibility of UK institutes.

Half-Rings are made primarily of carbon foam. This material was chosen to meet Thermal Figure of Merit demands from the community while maintaining a material density low enough to meet the constraints imposed by the material budget.

A campaign of measurements aimed at characterizing the density distribution of carbon foam, which, before becoming part of the local supports, is processed into trapezoids, starting from a block of about $1 \times 12 \times 12$ cubic inches, was then carried out. From these studies, it was possible to conclude that within the block there are no hot points where there is

a sharp discontinuity in the density distribution and indeed, the foam block production process returns a sufficiently homogeneous object in terms of density, with a maximum dispersion of 13 percent. This analysis was performed on samples from two different carbon foam vendors, and for both the results are encouraging. This study allowed the community to be confident enough to decide to abandon the measurement of the density of individual trapezoids during Half-Ring production, an extremely time-consuming measurement.

During the production of HRs prototypes, the thermo-mechanical properties of local supports were studied. These measurements served two different purposes: to validate the simulation valence of the HRs of a Finite Elements Model (FEM) and more generally to verify compliance with the specifications of the local supports in terms of their deformation when stressed by a temperature change. By placing the HR inside an environmental chamber, its temperature was varied in a range of about 20 degrees, and using a compound optical measuring system installed on a coordinate measuring machine, several reference points were measured on the surface of the HR, and then the coordinates of these points, respectively, were subtracted to obtain an estimate of the thermal expansion coefficient of the HR. The data obtained, once analyzed, were then compared with those simulated by FEM, and agreement was observed both in terms of direction and an absolute value of deformation. Both the simulation and experiment results show that the absolute variation is less than $2\text{ }\mu\text{m}$ per degree, which means that the coefficient of linear thermal expansion of the bare half-circle can be assumed to be within $2\text{ ppm}/^{\circ}\text{C}$, which is well below the value required by the specifications, i.e., $3\text{ }\mu\text{m}$ per degree.

In addition, to validate the thermal performance of the bare supports prior the loading of active components, a detection study of HR anomalies in heat propagation was carried out by placing liquid inside the pipe and recording the diffusion process through a thermal chamber. This test, developed by the British group, was reproduced at the Genoa laboratories and was shown to be able to reveal possible HR dysfunctions due, for example, to suboptimal thermal contact between the pipe and the carbon structure or possible obstructions to the passage of liquid inside the pipe. This preliminary study convinced the community of the goodness and reliability of the test, and subsequently, a more adequate setup was put in place to be able to conduct the test in a more controlled and repeatable manner during the supports production.

The thesis work also reports the progress achieved in the implementation of the components and tests concerning the Outer Endcap local support within the ITk Production Database. This work allows anyone who works in the field of construction, assembly, and testing of local supports to be able to save production data concerning local supports into a centralized database.

Furthermore, module misalignment studies were also done for the local supports of the ITk Outer Endcap. This study was conducted to obtain an estimate of the maximum recoverable misalignment via software and provide useful information to construction sites. To do this, a misalignment framework present in the ATLAS offline software, Athena was used. However, this study is still in the development stage.

Regarding the ITk 3D pixel module, this thesis work is focused on the characterization of four R&D 3D modules RD53A and six pre-production modules in a period that goes between 2019 and 2022. The RD53A modules, with a pixel pitch $50 \times 50 \mu\text{m}^2$ and $25 \times 100 \mu\text{m}^2$ produced by FBK, were qualified before and after being irradiated with a fluence of $0.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ in Birmingham University in UK and with a fluence of $1.0 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ in Tohoku University, in Japan. I participated in all the measurements conducted on these modules, especially during the testbeam campaigns conducted in the DESY testbeam facility. The test includes the IV curve measurements of the sensor and the readout chip tests such as threshold calibration. The tuning threshold at 1000e^- was successfully reached with also the noisy pixel mask and the Time Over Threshold (ToT) tuning to the value of 8 bunch crossing. At DESY testbeam campaigns before irradiation, the modules with both pixel cell geometries have shown a hit efficiency over 97% for perpendicularly incident tracks even with a bias voltage of 0 V. Inefficiencies of about 25% mainly correspond to particles crossing the fully passing p-type columns implanted into the sensor surface which are inactive. After irradiation, the modules with the sensor pitch $50 \times 50 \mu\text{m}^2$ have demonstrated the possibility of reaching a hit efficiency larger than 96% for perpendicularly incident tracks with 40 V of bias voltage and an irradiation fluence of $0.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$, and with 80-150 V of bias voltage after irradiation fluence of $1.0 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$. The modules with a pixel pitch $25 \times 100 \mu\text{m}^2$ were tested after irradiation fluence of $0.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and reached a hit efficiency of 96% at 80 V, whereas after irradiation of $1.0 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ was obtained a hit efficiency over the 98% for both module configurations, perpendicular and tilted by 15 degrees with respect to the beamline (which is a realistic geometry for the modules in the ITk detector) with a bias voltage of 90-140 V. Only one RD53A module $25 \times 100 \mu\text{m}^2$ had shown an unexpected behavior, with a decreasing efficiency trend in the function of the bias, but it was tested again after changing the ToT calibration and it was recovered.

The initial units with pre-production 3D sensors and readout chips ITkPixV1.1 to be approved after irradiation by the ITk Pixel community are the pre-production modules. The qualification procedure involved both the INFN laboratory in Genova and CERN, with particle beam testing occurring there. As part of the ATLAS ITk group, the modules were characterized in Genova. The 3D modules were mounted on a Single Chip Card (SCC) or PCB after passing a visual inspection to ensure the quality of the pre-production. The six SCCs were subjected to several measurements in Genova, including tests on the readout chip, such as threshold calibration, and IV curve measurements of the sensor's IV curve. After successfully threshold tuning to 1000e^- , data analysis was done to find pixels with disconnected bump bonds. At CERN beam facilities, the five good SCCs were further characterized both before and after irradiation. At CERN beam facilities, the five good SCCs were further characterized both before and after irradiation. Two unirradiated SCCs were tested in the spring, and data analysis was performed to determine the sensor efficiency, which was discovered to be almost 99%, in line with expectations. It was also determined that the local efficiency of the pixel cell is about 25% lower where p+ electrodes are implanted. Following the spring tests, two SCCs were exposed to radiation at the IRRAD

facility at CERN ($1.7 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$) and two at Bonn ($1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$). Unfortunately, the irradiation in the IRRAD samples was not uniform, causing some areas of the modules to receive a too high ionizing dose that damaged the read-out chip. The two SCCs were tested on the CERN beam in Summer in two configurations: perpendicular to the beam and tilted at 15° . In contrast, the irradiation in Bonn demonstrated uniform fluence across the sensor surface. I helped with data gathering and outcome analysis. The modules mean efficiency was found to be 99.9% when tilted of 15° and 98.5% when placed perpendicular to the beam. In light of this, it was shown that the sensors satisfy the ITk requirement of having a mean efficiency greater than 96 (97)% in the perpendicular (tilted) configuration after irradiation. The pre-production modules were more efficient than the prototype modules, and they did so at a lower bias voltage (roughly 40 V) (which required about 100 V). Given that the declared uncertainty on the radiation fluence exceeds 10% for both the prototypes and our samples, the discrepancy between these results may be the result of different radiation fluences. To further understand this, more study is required. Our samples will undergo additional radiation treatment to achieve a fluence of $1.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ before being tested once more on the beam with additional samples. These results might confirm our observations and provide additional information. In addition, I worked with colleagues from the Genova ATLAS ITk group to test chip performance and sensor IV curves. The chips that had been exposed to radiation performed as intended, and the results of the threshold calibration at 1000e^- agreed with those that had been obtained earlier. The sensor leakage current showed a slightly higher value after irradiation than that seen in prototype modules, but the annealing may account for the variations.

An interesting study was performed on the threshold distribution of the individual pixels. The study showed that most of the disabled pixels turn out to be tuned incorrectly in the threshold. From this study, it seems clear that the noisy pixel comes out from untuned (or badly tuned) pixels and they can be recovered and included in the data taking just by performing a fine-tuning of the module. This kind of fine-tuning is currently under investigation by the pixel community.

The results of my thesis work confirm the excellent performance of the FBK 3D pre-production sensors.

I have presented my works during several collaboration meetings. These results were also shown at the SIF Conference in 2020, in which I won a “special mention” and I have published my work in the physics journal *Il Nuovo Cimento* [83], again at the SIF Conference in 2021 and at IFAE conference in April 2023. My results on RD53A modules characterization were published in a paper in 2021 [53] and were presented at many conferences, including at IFAE 2023 [84] and with an invited talk at Corfu - Future Accelerators Workshop 2023 [85] and on a poster at LHCC 2022 [86].

Appendices

Appendix A

Appendix

A.1 The Beam Test Setup at CERN



Figure A.1: The EUDET Telescope at the SPS facility is shown. Inside the cold box in the middle of the telescope, there are 3 Single Chip Cards RD53B, where the first one is used as the reference frame, and a quad module. The SCCs are placed in 15 degrees tilted configuration. On top of the box, there is the cold system of the box.

The EUDET telescope utilized at CERN beam facilities is the same as the one employed in previous beam tests at DESY. However, there are notable differences in the setup. Firstly, the YARR computer has been completely replaced to address issues related to the previous YARR PC's underperforming hardware. Additionally, the cold box, which houses the modules under test, is not cooled with dry ice but instead utilizes a commercial chiller. This chiller enables a module surface temperature as low as approximately -34°C . Fig A.1 showcases an image of the SPS beam test setup.

The pixel modules have been tested before the irradiation and after irradiation respectively at PS and SPS. The composition of the beam and the energy of the particles that compose the beam delivered to the test lines are different. At PS the beam is composed of protons at 12 GeV, while at SPS the beam is mainly composed of Pions at 120 GeV. At SPS the secondary particle beam is produced by the interaction of the primary proton beam with a momentum of 400 GeV/c slowly extracted from SPS, on two thin beryllium plate primary targets, named T2 and T4, located ~ 15 m underground to optimize the radiation shielding. As you can see from the Fig. A.2, the proton beam that interacts with the T4 target serves the beamline H8 (and also the H6) where the ITk beam test campaign takes place.

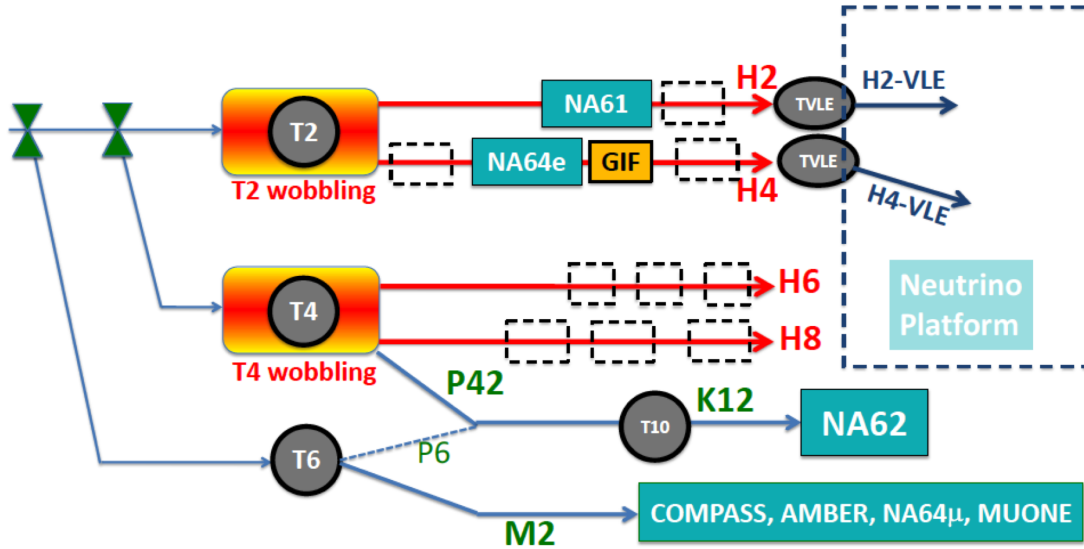


Figure A.2: Schematic layout of experiment and test beam zones on the various North Area beam lines (not to scale). [62]

A.2 Modules IV Scans Pre-irradiation

The results of the wafer and SCC IV curves are shown in Fig. A.4 for SCC 3. Breakdown voltage and leakage current values at 25 V scaled to 20°C are summarized in table A.1.

SCC N°	V_{bd} [V]	$I_{leak}(25V)$ [$\mu A/cm^2$]
SCC 2	> 80	0.04
SCC 3	> 80	0.02
SCC 4	> 80	0.02
SCC 5	> 80	0.03
SCC 6	> 80	0.05
SCC 8	> 80	0.04

Table A.1: Summary of breakdown voltage (V_{bd}) and leakage current at 25 V (I_{leak}) scaled to the temperature of 20°C.

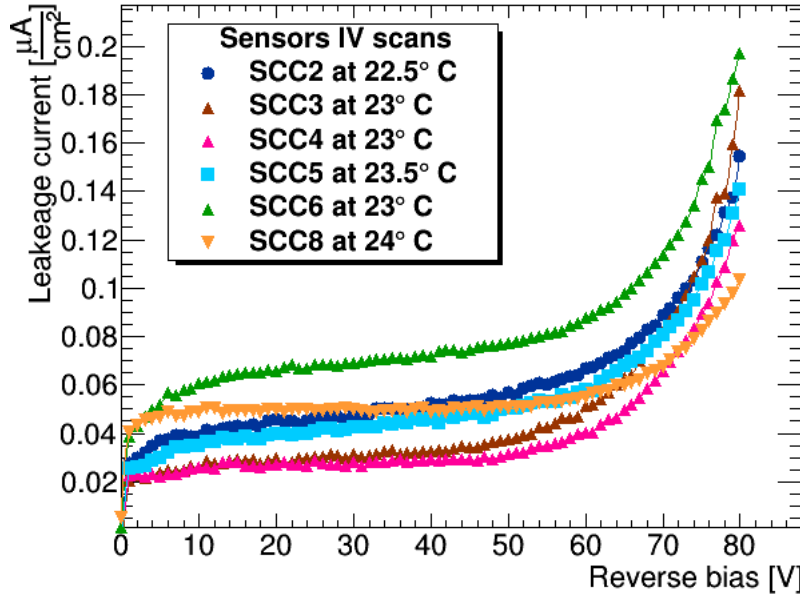


Figure A.3: Sensors IV measured on SCCs in Genova.

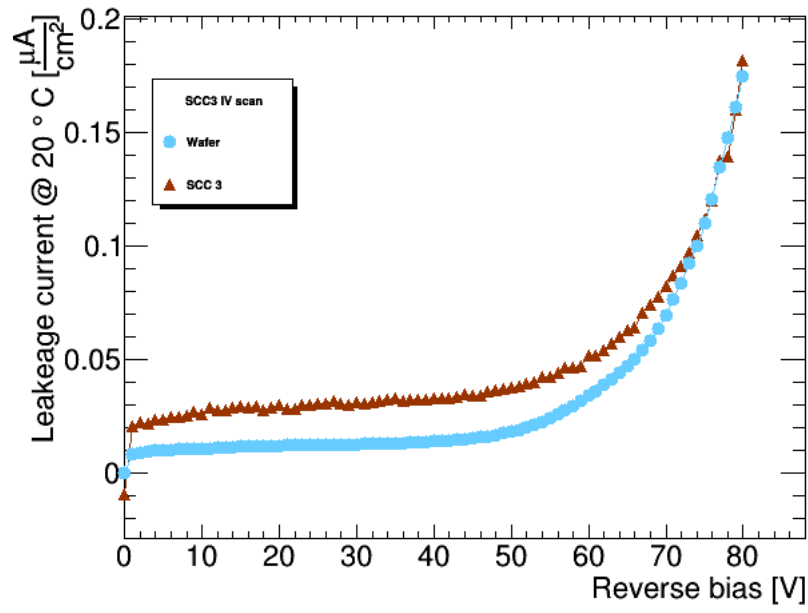
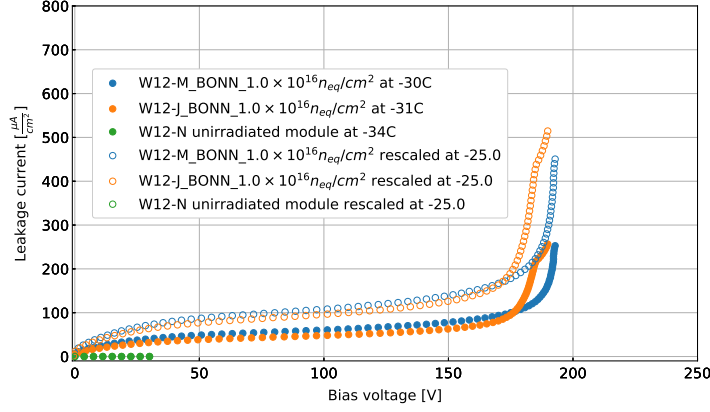


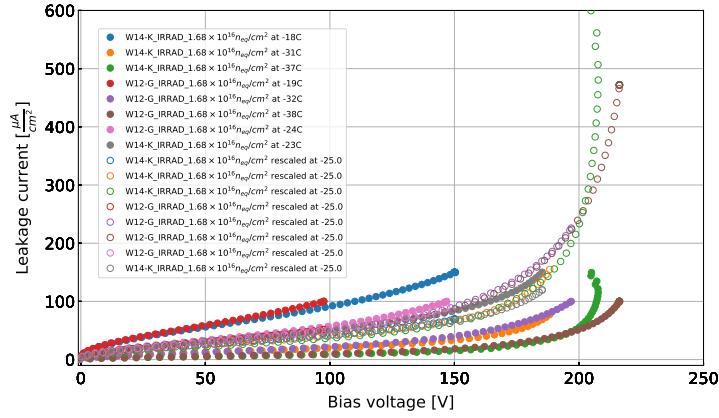
Figure A.4: Sensors IV measured on SCCs in Genova and on wafer level at Trento.

A.3 Modules IV Scans Post-irradiation

In Fig. A.5 the IV scans of the pre-production modules are shown after their irradiation to $1.0 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$. In the plots, the IV scans are presented with their leakage current value measured during testbeams and with the value rescaled by the temperature to -25° to make the IV scans comparable to each other, using the Eq. 5.2.



(a) IV scan SCC3, SCC4 and SCC5 modules after irradiation.

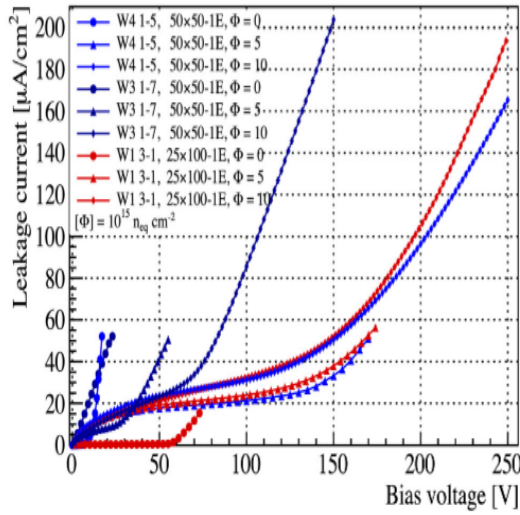


(b) IV scan SCC2 and SCC8 modules after irradiation.

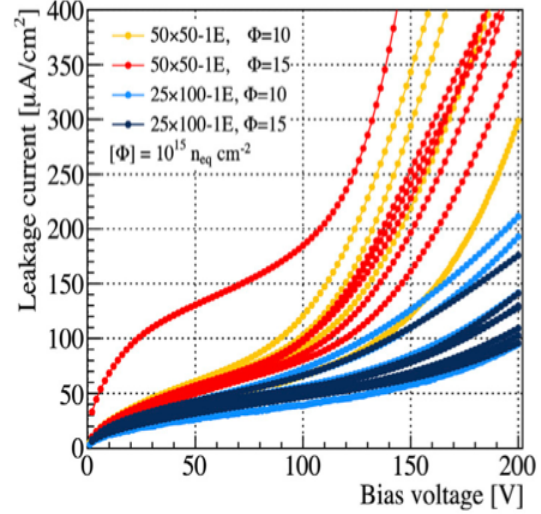
Figure A.5: Leakage current in the function of the bias voltage of SCC3, SCC4, and SCC5 modules (a), and SCC2 and SCC8 modules (b). The IV scans rescaled to -25°C temperature are shown, to allow comparison of the curves with those obtained from the RD53A modules tested at DESY A.6.

The pre-production modules' IV scan trends, compared with the IV scans of the RD53A modules irradiated with the same fluence, show a performance overly positive. The values

of the leakage current of the RD53A are shown in Fig A.6 together with the IV scans of the diodes produced by FBK and irradiated with different fluence values (from 0 to $1.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$). The IV scans shown in these plots are consistent with each other when we go to compare modules with sensors of equal size and equal irradiance.



(a) IV scan irradiated FBK prototypes.

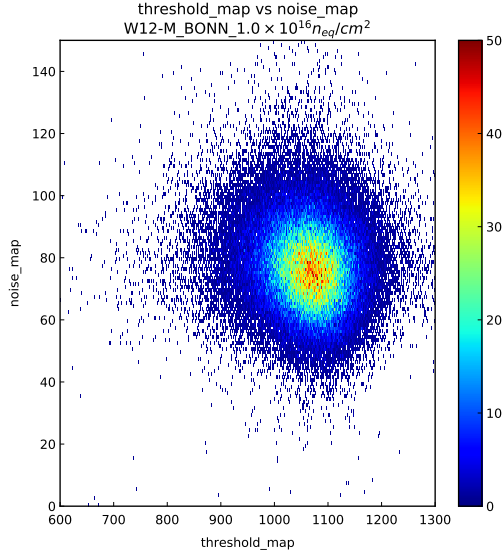


(b) IV scans diodes produced by FBK.

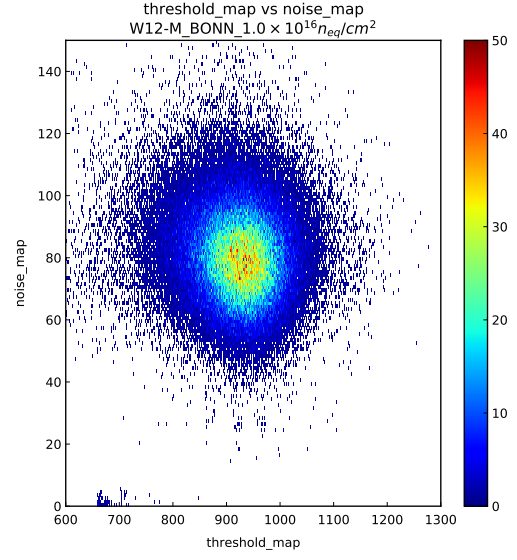
Figure A.6: (a) Prototype modules leakage current in function of bias voltage curve. Sensors have been irradiated to a fluence Φ . (b) Diodes IV scans produced by FBK and irradiated to a fluence Φ [53].

The comparison between the results obtained from the pre-production and the RD53A and FBK diodes results, suggests that the nominal fluence provided by Bonn is not the fluence to which the pre-production sensors were exposed, but rather, from the IV scans we suspect that the actual fluence is closer to a value of $0.5 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$.

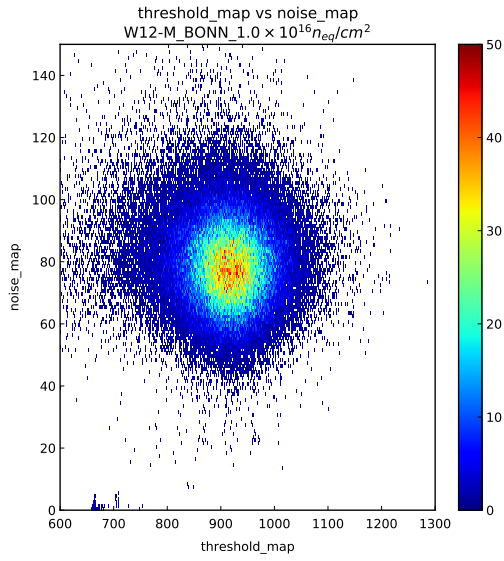
A.4 SCCs threshold vs noise scatter plots



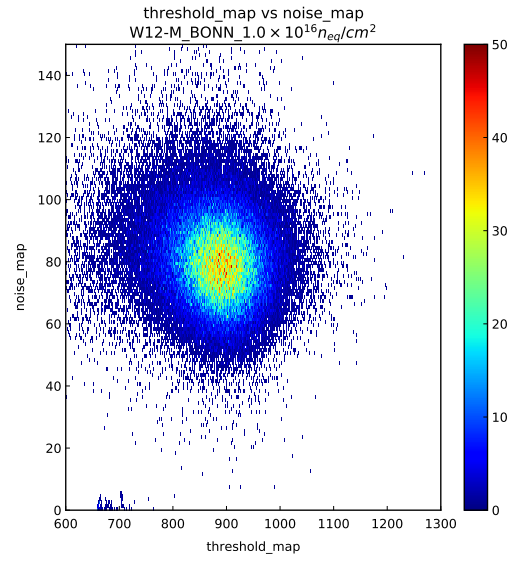
(a) SCC3 20V



(b) SCC3 100V

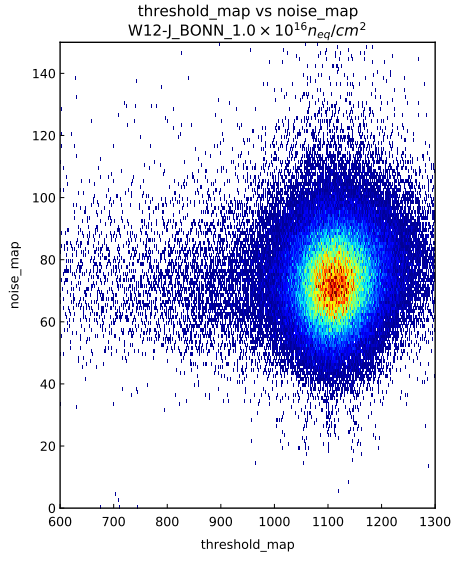


(c) SCC3 150V

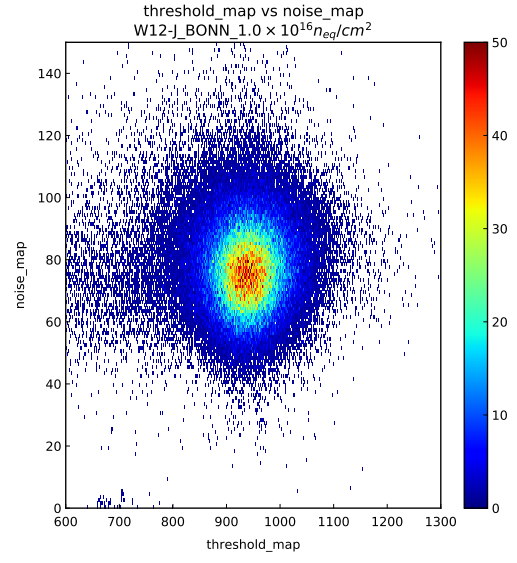


(d) SCC3 160V

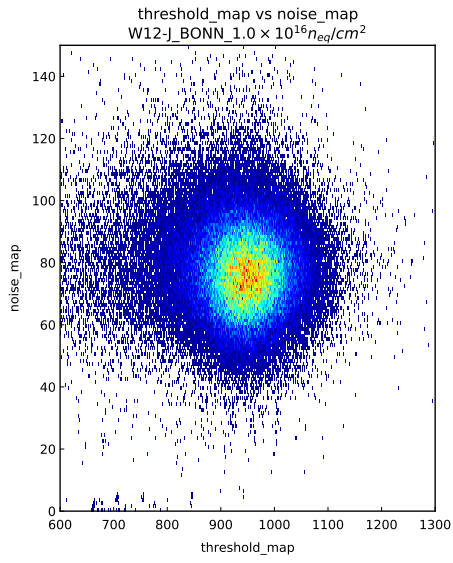
Figure A.7: The four plots show the SCC3 threshold vs noise scatter plots for different bias: 20, 100, 150 and 160 V.



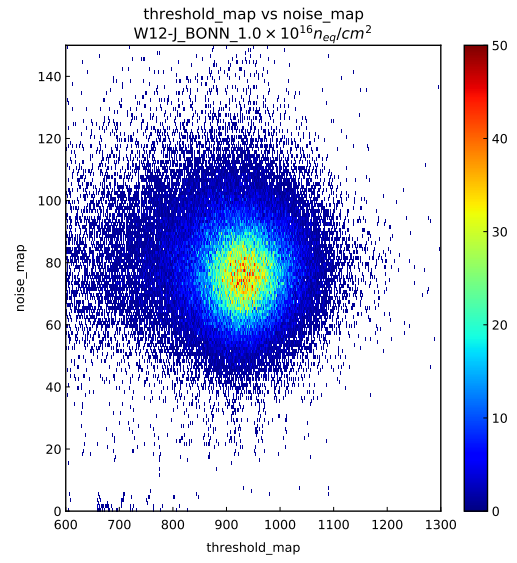
(a) SCC5 20V



(b) SCC5 100V



(c) SCC5 150V



(d) SCC5 160V

Figure A.8: The four plots show the SCC5 threshold vs the noise scatter plots for different bias: 20, 100, 150 and 160 V.

A.5 SCC3 and SCC5 threshold and noise distribution of the enabled and disabled pixel

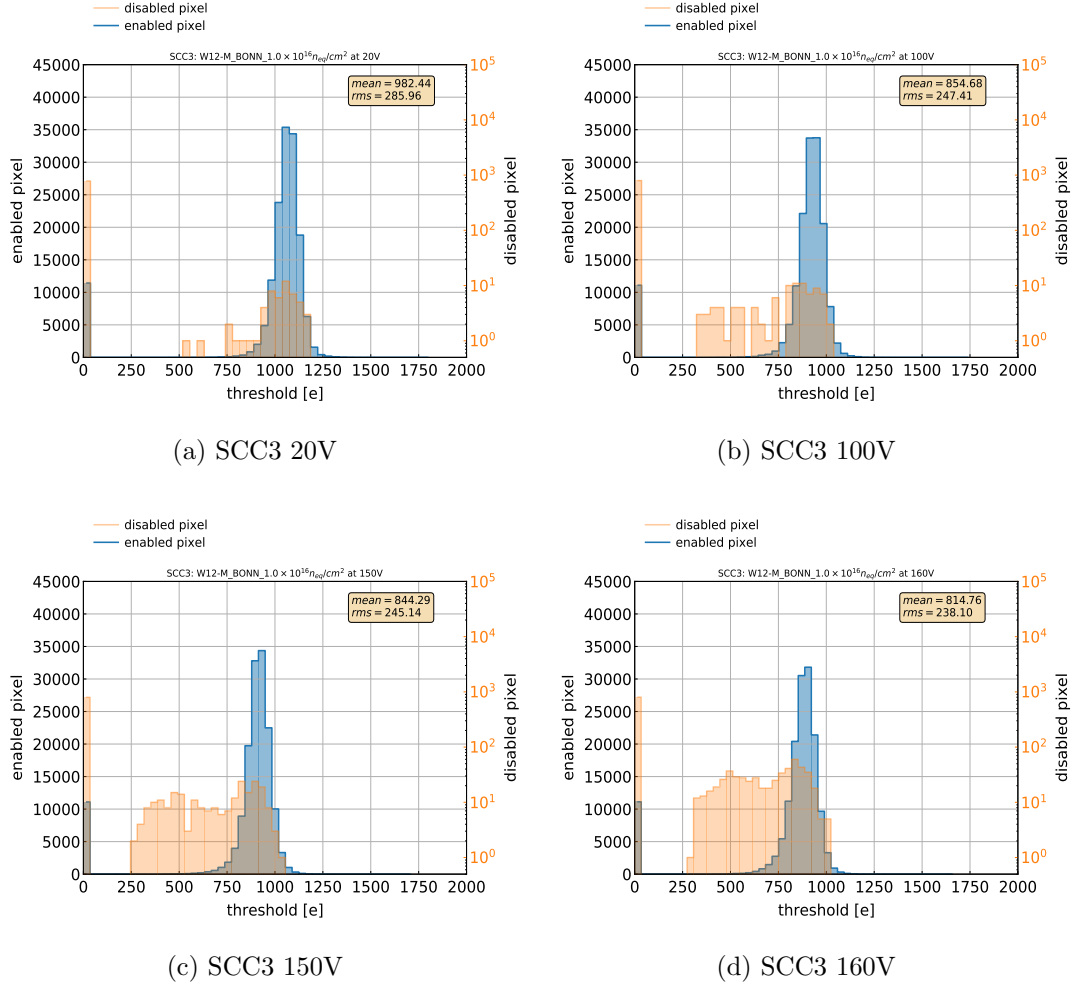


Figure A.9: The four plots show the SCC3 threshold distribution of the enabled (blue) and disabled (orange) pixels in the sensors matrix, for different bias: 20, 100, 150 and 160 V.

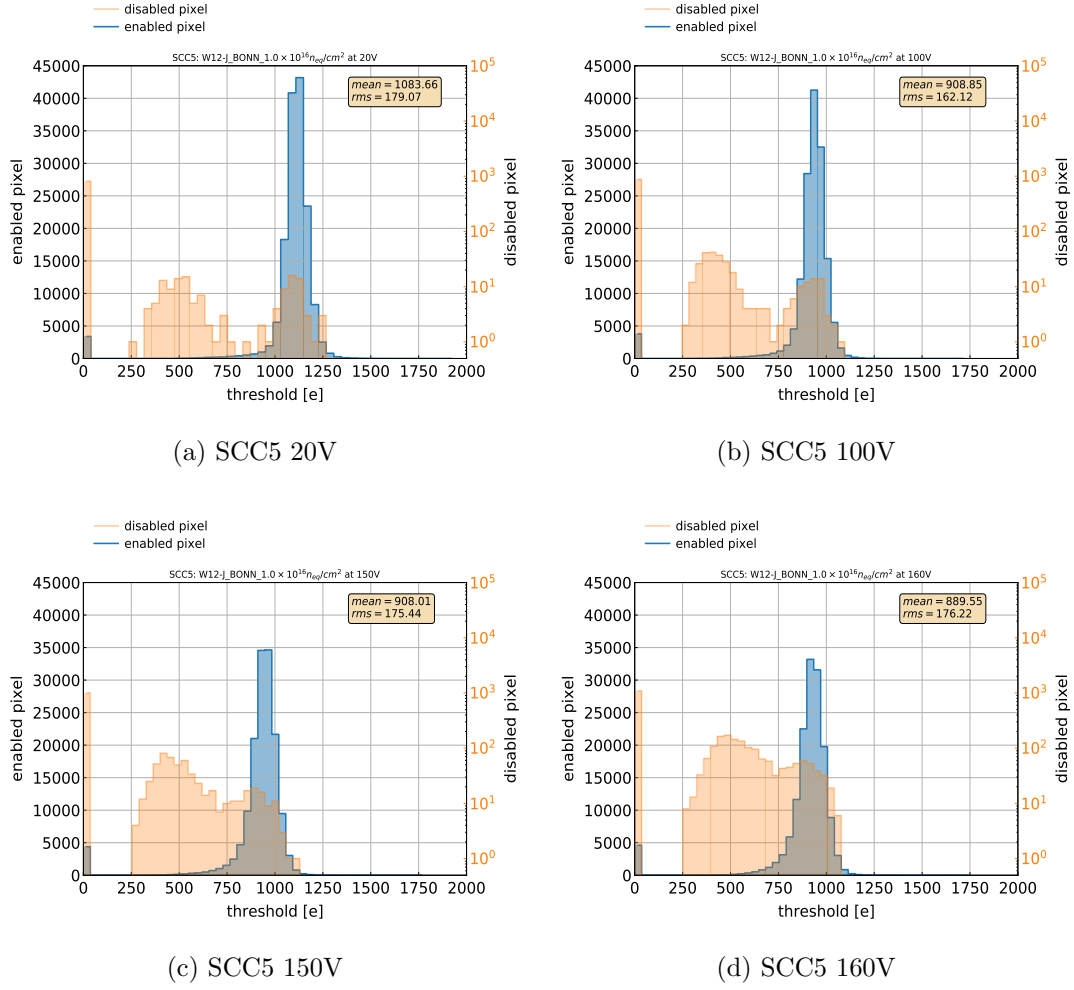


Figure A.10: The four plots show the SCC5 threshold distribution of the enabled (blue) and disabled (orange) pixels in the sensors matrix, for different bias: 20, 100, 150 and 160 V.

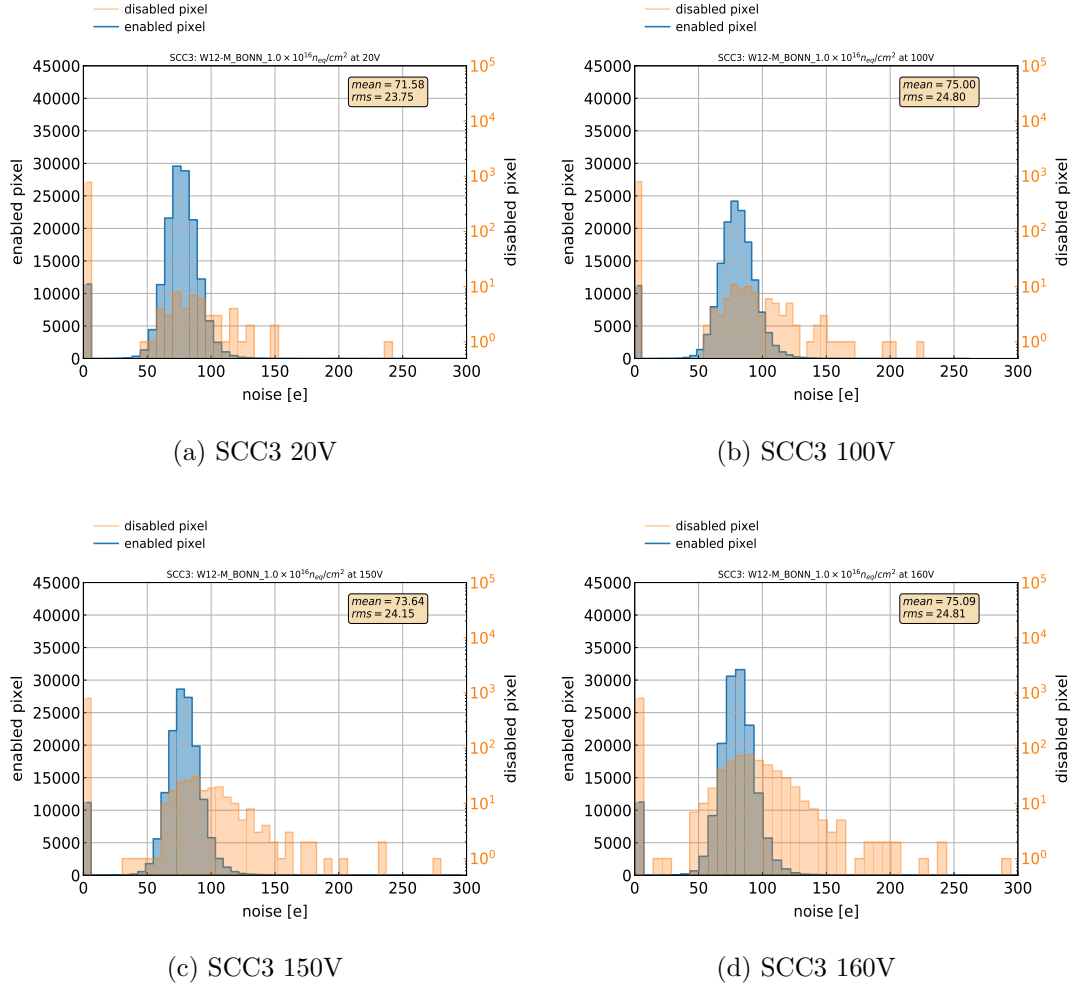


Figure A.11: The four plots show the SCC3 noise distribution of the enabled (blue) and disabled (orange) pixels in the sensors matrix, for different bias: 20, 100, 150 and 160 V.

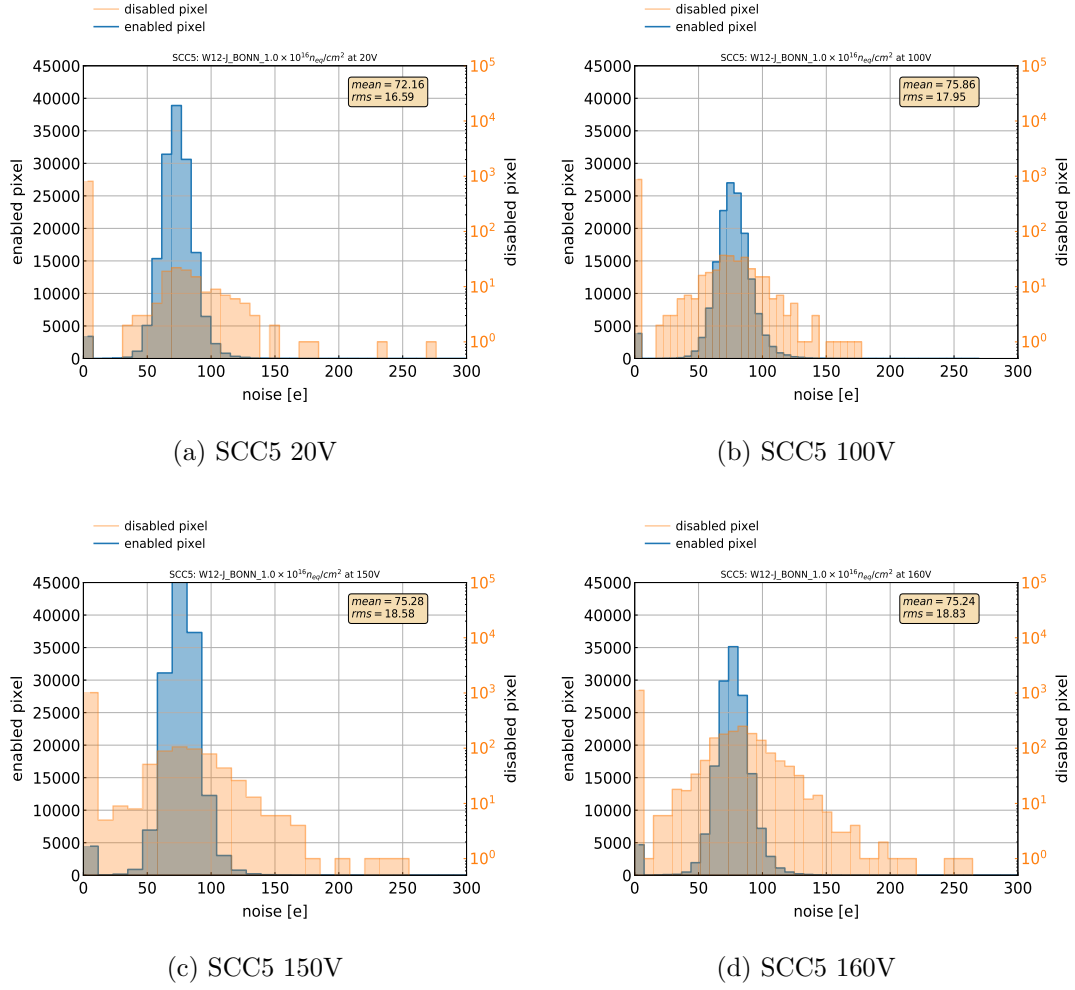


Figure A.12: The four plots show the SCC5 noise distribution of the enabled (blue) and disabled (orange) pixels in the sensors matrix, for different bias: 20, 100, 150 and 160 V.

A.6 W30-D9.5 RD53A module ToT with unexpected behavior

In Fig. 5.17, are reported the efficiency curves in function of the bias voltage of the 30th FBK wafer. All the modules were irradiate in CYRIC to 1.0×10^{16} n_{eq}/cm². The RD53A module named D9.5 have shown an unexpected behavior: it's efficiency decrease at higher bias voltages. To understand this phenomenon the charge collection of the module was investigated, comparing it with the charge collection of the module E3.3 which did not exhibit the strange behavior. The modules were tuned with the same threshold, 1000e⁻, and with the same ToT, 7 bunch-crossing (BC), which means to be able to collect a charge of 10ke⁻ in a window of 7 BC.

Injecting a charge of 3 to 10 ke⁻, the ToT vs charge was extrapolated.

As shown in Fig. A.13, for the E3.3 module, the cluster charge measured in ToT shifts toward higher ToT values as the voltage increases: the blue, red, and black curves correspond to the cluster charge collections with modules at different bias voltage. The opposite behavior can be seen for the D9.5 module: the curves shift toward lower ToT values as the voltage increases. By converting the ToT to electrons, as shown in Fig. A.14 the actual value of the cluster charge collected from the modules at different bias voltages was found.

In Tab. A.2 the bias voltage, the ToT cluster charge, and the efficiency for both modules are reported.

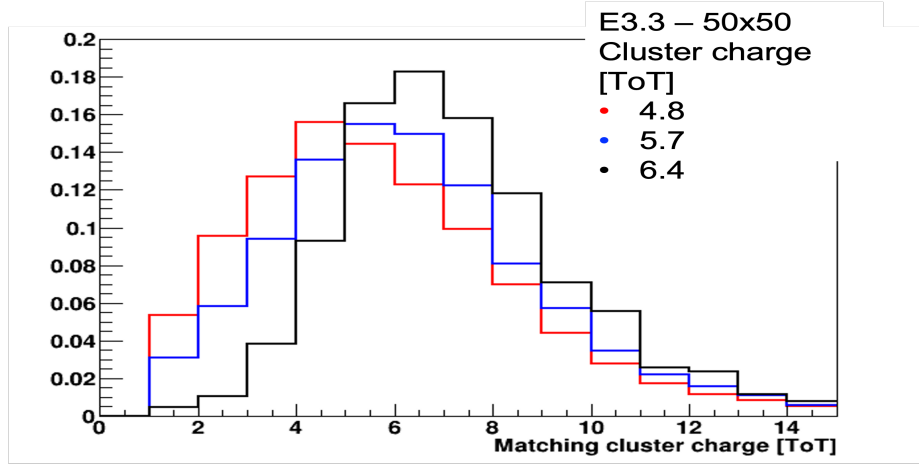
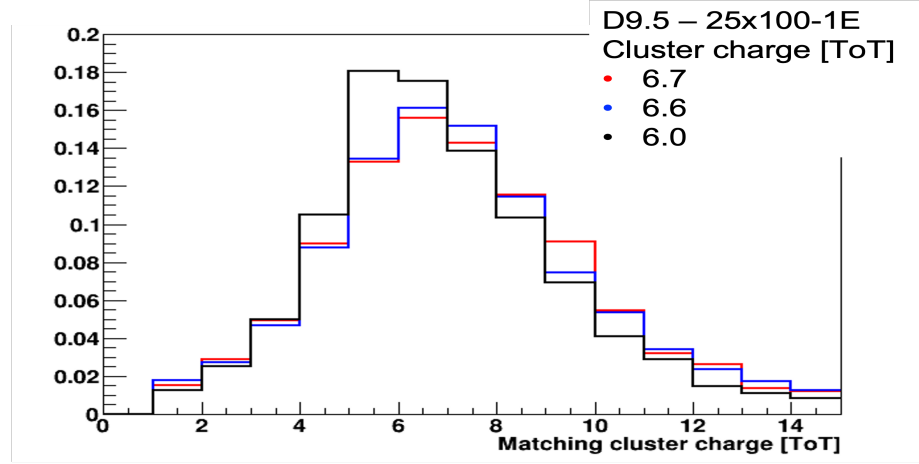
(a) Module W30.E3.3 - $50 \times 50 \mu\text{m}^2$.(b) Module W30.D9.5 - $25 \times 100 \mu\text{m}^2$.

Figure A.13: (a) The cluster charge ToT after injecting charge into the module E3.3; (b) the cluster charge ToT after injecting charge into the module D9.5. Three colors represent three different bias voltage, as reported in Tab. A.2.

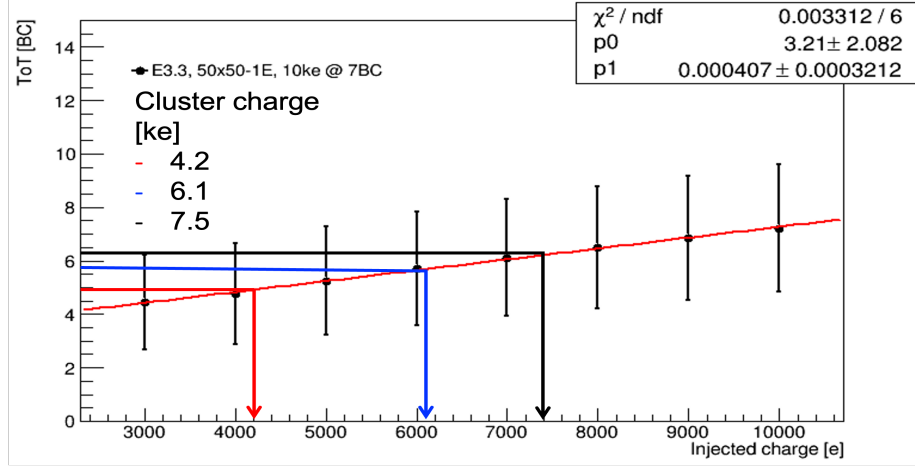
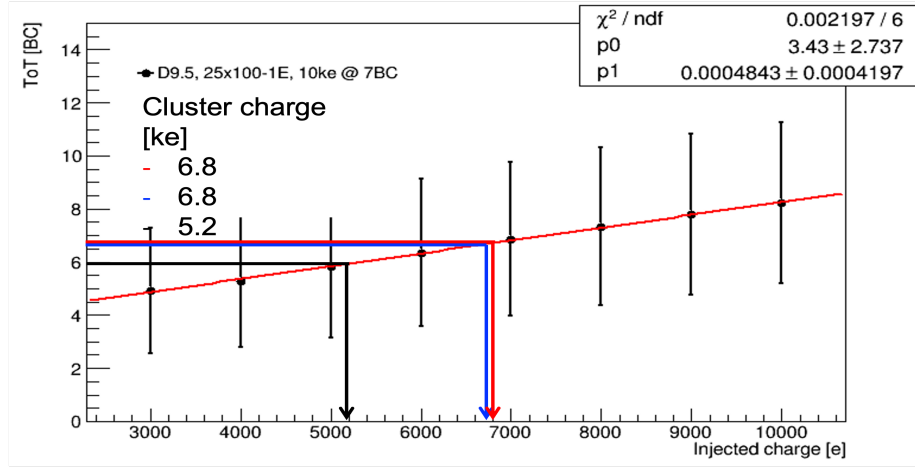
(a) Module W30.E3.3 - $50 \times 50 \mu\text{m}^2$.(b) Module W30.D9.5 - $25 \times 100 \mu\text{m}^2$.

Figure A.14: (a) The ToT conversion in ke^- for the module E3.3; (b) the ToT conversion in ke^- for the module D9.5. Three colors represent three different bias voltage, as reported in Tab. A.2.

Module	Bias [V]	Cluster Charge [ToT]	Cluster Charge [ke]	Efficiency [%]
E3.3	75.4	4.8	4.2	88.9
	87.6	5.7	6.1	93.8
	96.0	6.4	7.5	97.8
D9.5	71.4	6.7	6.8	96.5
	80.6	6.6	6.8	95.4
	86.0	6.0	5.2	93.7

Table A.2: Cluster charge (both in ToT and ke^-) of the modules E9.3 and D9.5 at different bias voltages (and therefore different efficiencies). The different colors (red, blue, and gray) stand for the three colors shown in Fig. A.13 and Fig. A.14.

Module	Bias [V]	Cluster Charge [ToT]	Cluster Charge [ke]	Efficiency [%]
D9.5	36.0	6.8	5.2	84.9
	85.0	8.8	8.6	97.5

Table A.3: Cluster charge (both in ToT and ke^-) of the modules D9.5 At different bias voltage (and therefore different efficiencies) after the ToT calibration for 10 BC time window.

From the data summarized in Tab. A.2, it can be easily understood that in the case of the D9.5 module, the unexpected behavior of decreasing efficiency as the bias voltage increases may refer to a decrease in cluster charge, always as the bias voltage increases.

The ToT module under investigation was then re-calibrated to 10 BC. At this point, the same analysis shown previously was conducted again, and as can be seen from the plots in Fig. A.15 with this new calibration and finally an expected trend of charge collection as the voltage increases and likewise also the efficiency was obtained. Tab. A.3 shows the values of voltage, cluster charge ToT, and module efficiency at the two working points tested.

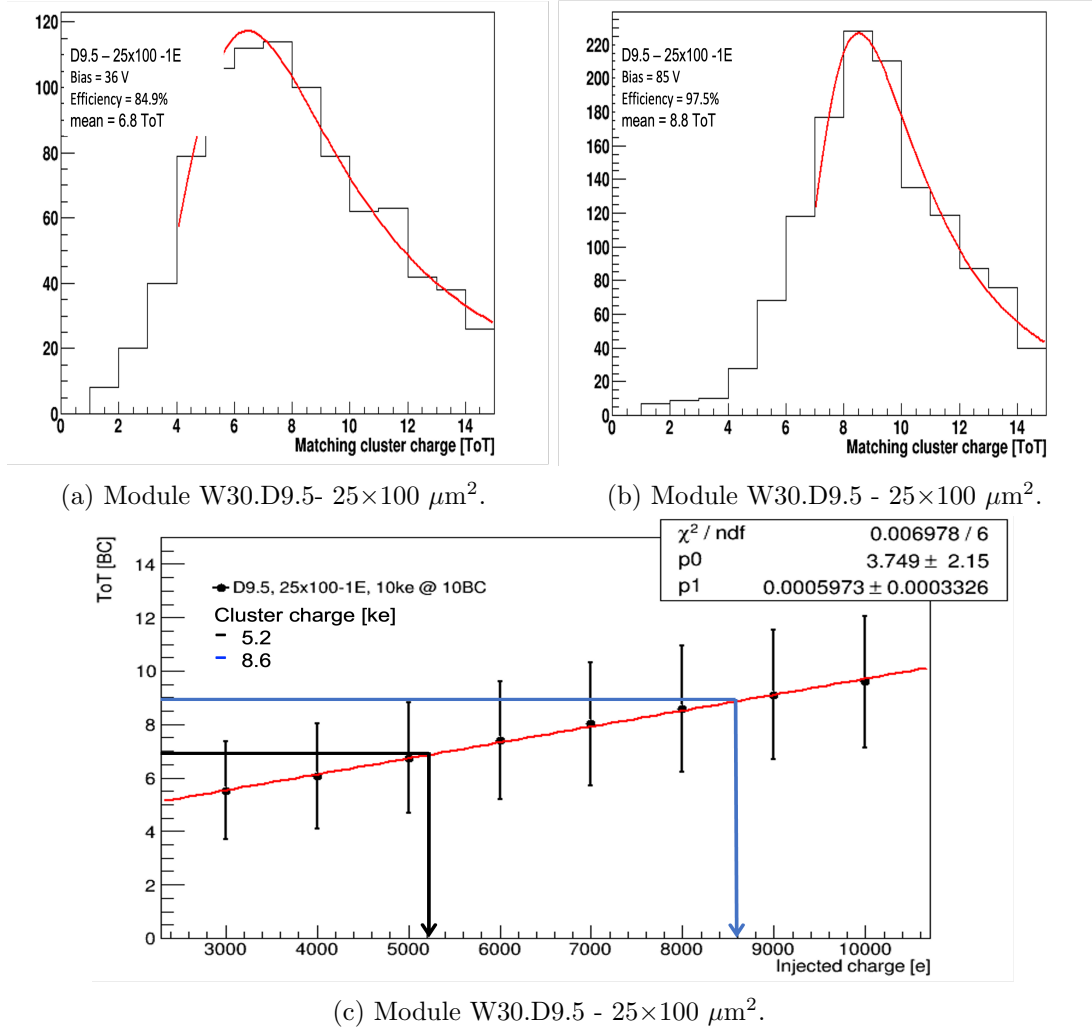


Figure A.15: The module under examination is W30.D9.5 - $25 \times 100 \mu\text{m}^2$. (a) The ToT cluster charge obtained injecting charge in the module with a bias voltage of 36 V that corresponds to an efficiency of 84.9 %; (b) The ToT cluster charge obtained injecting charge in the module with a bias voltage of 85 V that corresponds to an efficiency of 97.5%. (c) The ToT conversion in ke^- and the two working points tested are highlighted by the blue rows.

Bibliography

- [1] L. Evans et al., LHC Machine, *Journal of Instrumentation*, 3(08):S08001–S08001, aug 2008, doi:10.1088/1748-0221/3/08/s08001.
- [2] CERN, LEP design report, CERN, Geneva, 1984, copies shelved as reports in LEP, PS and SPS libraries.
- [3] The ALICE Collaboration, The ALICE experiment at the CERN LHC, *Journal of Instrumentation*, 3(08):S08002–S08002, aug 2008, doi:10.1088/1748-0221/3/08/s08002.
- [4] The ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, *Journal of Instrumentation*, 3(08):S08003–S08003, aug 2008, doi:10.1088/1748-0221/3/08/s08003.
- [5] The CMS Collaboration, The CMS experiment at the CERN LHC, *Journal of Instrumentation*, 3(08):S08004–S08004, aug 2008, doi:10.1088/1748-0221/3/08/s08004.
- [6] The LHCb Collaboration, The LHCb Detector at the LHC, *Journal of Instrumentation*, 3(08):S08005–S08005, aug 2008, doi:10.1088/1748-0221/3/08/s08005.
- [7] E. Mobs, The CERN accelerator complex in 2019. Complexe des accélérateurs du CERN en 2019, *CERN Internal Note*, Jul 2019, general Photo.
- [8] O. S. Brüning et al., LHC Design Report, CERN Yellow Reports: Monographs, CERN, Geneva, 2004, doi:10.5170/CERN-2004-003-V-1.
- [9] AC Team, Diagram of an LHC dipole magnet, Jun 1999, all figures including auxiliary figures are available at <https://cds.cern.ch/record/40524>.
- [10] L. Guiraud, Model of an LHC superconducting quadrupole magnet. Aimant quadripôle supraconducteur, Jan 2000, all figures including auxiliary figures are available at <https://cds.cern.ch/record/40918>.
- [11] D. Dominguez, LHC images gallery, July 2014, <https://home.cern/resources/image/accelerators/lhc-images-gallery>.

-
- [12] . M. . T. Hortala, Why the LHC magnets are blue – and other colourful accelerator questions answered, <https://home.cern/news/news/accelerators/why-lhc-magnets-are-blue-and-other-colourful-accelerator-questions-answered>.
- [13] LHC cycle, settings and efficiency UFOs, https://indico.cern.ch/event/1224987/contributions/5153318/attachments/2579893/4449512/TheLhcCycle-Chamonix2022_v2.pdf.
- [14] R. Bruce et al., Review of LHC Run 2 Machine Configurations, *9th LHC Operations Evian Workshop*, pages 187–197. 11 p, 2019.
- [15] The ATLAS Collaboration, Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s} = 13$ with the ATLAS Detector at the LHC, *Physical Review Letters*, 117(18), oct 2016, doi:10.1103/physrevlett.117.182002.
- [16] LHC/HL-LHC Plan, last update February 2022.
- [17] G. Apollinari et al., High luminosity large hadron collider HL-LHC, *arXiv preprint arXiv:1705.08830*, 2017.
- [18] G. A. et al., ATLAS pixel detector electronics and sensors, *Journal of Instrumentation*, 3(07):P07007, jul 2008, doi:10.1088/1748-0221/3/07/P07007.
- [19] The ATLAS collaboration, Operation and performance of the ATLAS semiconductor tracker, *Journal of Instrumentation*, 9(08):P08009, aug 2014, doi:10.1088/1748-0221/9/08/P08009.
- [20] The ATLAS TRT collaboration and E Abat et al., The ATLAS Transition Radiation Tracker (TRT) proportional drift tube: design and performance, *Journal of Instrumentation*, 3(02):P02013, feb 2008, doi:10.1088/1748-0221/3/02/P02013.
- [21] M. Capeans et al., ATLAS Insertable B-Layer Technical Design Report, Technical report, ATLAS-TDR-019, Sep 2010.
- [22] B. Abbott et al., Production and integration of the ATLAS Insertable B-Layer, *Journal of Instrumentation*, 13(05):T05008–T05008, may 2018, doi:10.1088/1748-0221/13/05/t05008.
- [23] S. Parker et al., 3D — A proposed new architecture for solid-state radiation detectors, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 395(3):328–343, 1997, ISSN 0168-9002, doi:[https://doi.org/10.1016/S0168-9002\(97\)00694-3](https://doi.org/10.1016/S0168-9002(97)00694-3), proceedings of the Third International Workshop on Semiconductor Pixel Detectors for Particles and X-rays.
- [24] Barbero, Marlon and Arutinov, David and Hemperek, Tomasz and Karagounis, Michael and Kruth, Andre and Vermes, Norbert and Beccherle, Roberto and Darbo, Giovanni and Dube, Slindile and Elledge, David and Garcia-Sciveres, Maurice and Gnani, Dario

- and Mekkaoui, Abderrezak and Fougeron, Denis and Menouni, Mohsine and Gromov, Vladimir and Kluit, R. and Schipper, Jan, FE-I4 ATLAS pixel chip design, *VERTEX*, 01 2009.
- [25] ATLAS Collaboration, ATLAS liquid-argon calorimeter: Technical Design Report, Technical design report. ATLAS, CERN, Geneva, 1996, doi:10.17181/CERN.FWRW.FOOQ.
 - [26] ATLAS Collaboration, ATLAS tile calorimeter: Technical Design Report, Technical design report. ATLAS, CERN, Geneva, 1996, doi:10.17181/CERN.JRBJ.7O28.
 - [27] A. Collaboration, New small wheel technical design report, *CERN, Meyrin, Switzerland, Tech. Rep*, 6, 2013.
 - [28] ATLAS Collaboration, ATLAS magnet system: Technical Design Report, 1, Technical design report. ATLAS, CERN, Geneva, 1997, doi:10.17181/CERN.9O5C.VDTM.
 - [29] H. Kate, The superconducting magnet system for the ATLAS detector at CERN, *Applied Superconductivity, IEEE Transactions on*, 9:841 – 846, 07 1999, doi:10.1109/77.783428.
 - [30] C. Leggett et al., AthenaMT: upgrading the ATLAS software framework for the many-core world with multi-threading, in *Journal of Physics: Conference Series*, volume 898, page 042009, IOP Publishing, 2017.
 - [31] The ATLAS Collaboration, Measurement of the Higgs boson mass in the $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ channels with $\sqrt{s}=13$ TeV pp collisions using the ATLAS detector, *Physics Letters B*, 784:345–366, 2018, ISSN 0370-2693, doi:https://doi.org/10.1016/j.physletb.2018.07.050.
 - [32] ATLAS Collaboration, Combined measurements of Higgs boson production and decay using up to 139 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment, Technical report, CERN, Geneva, 2021, all figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-053>.
 - [33] M. Aaboud et al., Measurement of the W -boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *Eur. Phys. J. C*, 78(2):110, 2018, doi:10.1140/epjc/s10052-017-5475-4, [Erratum: *Eur.Phys.J.C* 78, 898 (2018)].
 - [34] LHCb collaboration, Status of W boson mass measurements, , 2022.
 - [35] D. Caforio, Recent results and highlights from the ATLAS experiment, *AIP Conference Proceedings*, 1819(1):020001, 2017, doi:10.1063/1.4977117.

-
- [36] ATLAS Collaboration, Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset, 2022, doi:10.48550/ARXIV.2205.06013.
- [37] S. Seidel, Silicon strip and pixel detectors for particle physics experiments, *Physics Reports*, 828:1–34, 2019, ISSN 0370-1573, doi:<https://doi.org/10.1016/j.physrep.2019.09.003>, silicon strip and pixel detectors for particle physics experiments.
- [38] L. Rossi et al., Pixel Detectors: From Fundamentals to Applications, Particle Acceleration and Detection, Springer Berlin Heidelberg, 2006, ISBN 9783540283331.
- [39] Leo, William R, Techniques for nuclear and particle physics experiments: a how-to approach, Springer Science & Business Media, 2012.
- [40] A. Gaudiello, Studio di Rivelatori a Pixel di nuova generazione per il Sistema di Tracciamento di ATLAS., Ph.D. thesis, University of Genova, Italy, 2013, presented 13 Jun 2013.
- [41] J. Duarte-Campderros et al., Results on Proton-Irradiated 3D Pixel Sensors Interconnected to RD53A Readout ASIC, *Nucl. Instrum. Methods Phys. Res., A*, 944:162625, 2019, doi:10.1016/j.nima.2019.162625.
- [42] ATLAS Collaboration, Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment, Technical report, CERN, Geneva, 2012, draft version for comments.
- [43] ATLAS Collaboration, Technical Design Report for the ATLAS Inner Tracker Strip Detector, Technical report, CERN, Geneva, 2017.
- [44] ATLAS Collaboration, Technical Design Report for the ATLAS Inner Tracker Pixel Detector, Technical report, CERN, Geneva, 2017, doi:10.17181/CERN.FOZZ.ZP3Q.
- [45] ATLAS Collaboration, ATLAS Liquid Argon Calorimeter Phase-II Upgrade: Technical Design Report, Technical report, CERN, Geneva, 2017, doi:10.17181/CERN.6QIO.YGHO.
- [46] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS Tile Calorimeter, Technical report, CERN, Geneva, 2017.
- [47] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer, Technical report, CERN, Geneva, 2017.
- [48] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS TDAQ System, Technical report, CERN, Geneva, 2017, doi:10.17181/CERN.2LBB.4IAL.

-
- [49] ATLAS Collaboration, Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC, Technical report, CERN, Geneva, 2021, all figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024>.
- [50] ATLAS Collaboration, Expected Tracking Performance of the ATLAS Inner Tracker at the HL-LHC, Technical report, CERN, Geneva, 2019, all figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-014>.
- [51] ATLAS Collaboration, Optimisation and performance studies of the ATLAS b -tagging algorithms for the 2017-18 LHC run, Technical report, CERN, Geneva, 2017, all figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2017-013>.
- [52] G. Aad et al., ATLAS b -jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV, *The European Physical Journal C*, 79(11), nov 2019, doi:10.1140/epjc/s10052-019-7450-8.
- [53] S. Terzo et al., Novel 3D Pixel Sensors for the Upgrade of the ATLAS Inner Tracker, *Frontiers in Physics*, 9, 2021, ISSN 2296-424X, doi:10.3389/fphy.2021.624668.
- [54] CNM, Centro Nacional de Microelectrónica, <http://www.cnm.es/>.
- [55] FBK, Fondazione Bruno Kessler, <https://www.fbk.eu/>.
- [56] Sintef, Stiftelsen for industriell og teknisk forskning, <https://www.sintef.no/en/>.
- [57] C. DaVia et al., The geometrical dependence of radiation hardness in planar and 3D silicon detectors, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 603(3):319–324, 2009, ISSN 0168-9002, doi:<https://doi.org/10.1016/j.nima.2009.02.030>.
- [58] The RD53 Collaboration, <https://rd53.web.cern.ch/>.
- [59] M. Garcia-Sciveres, The RD53A Integrated Circuit, Technical report, CERN, Geneva, 2017.
- [60] RD53 Collaboration, The RD53B-ATLAS Pixel Readout Chip Manual, https://gitlab.cern.ch/rd53/RD53B_Manual/-/jobs/22820094/artifacts/file/RD53B_ATLAS_Main.pdf.

-
- [61] R. Diener et al., The DESY II test beam facility, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 922:265–286, 2019, ISSN 0168-9002, doi:<https://doi.org/10.1016/j.nima.2018.11.133>.
- [62] D. Banerjee et al., The North Experimental Area at the Cern Super Proton Synchrotron, Technical report, , 2021.
- [63] P. Burdelski et al., CERN Proton Synchrotron East Area Facility: Upgrades and renovation during Long Shutdown 2, volume 4/2021 of *CERN Yellow Reports: Monographs*, CERN, Geneva, 12 2021, ISBN 978-92-9083-608-7, 978-92-9083-609-4, doi:10.23731/CYRM-2021-004.
- [64] C. Hu-Guo et al., A ten thousand frames per second readout MAPS for the EUDET beam telescope, in Proceedings of the Topical Workshop on Electronics for Particle Physics, pp.47-51, CERN, 2009, doi:10.5170/CERN-2009-006.47.
- [65] J. Behr, Test beam measurements with the EUDET pixel telescope, *EUDET-Report-2010-01*, 2, 2010.
- [66] T. Heim et al., YarrEudaqProducer, <https://gitlab.cern.ch/YARR/YarrEudaqProducer>.
- [67] S. Spannagel et al., User Manual for the Corryvreckan Test Beam Data Reconstruction Framework, Version 1.0, Technical report, CERN, Geneva, 2019.
- [68] G. Hemmie, DESY II, a new injector for the DESY storage rings PETRA and DORIS II, *IEEE Trans. Nucl. Sci.; (United States)*, NS-30:4, 8 1983, doi:10.1109/TNS.1983.4332706.
- [69] ULTEM™ Resin Family of High Heat Solutions, <https://www.sabic.com/en/products/specialties/ultem-resin-family-of-high-heat-solutions>.
- [70] J. Matheson et al., Atlas itk pixel endcap demonstrator “ring-0” construction and testing, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 986:164753, 2021, ISSN 0168-9002, doi:<https://doi.org/10.1016/j.nima.2020.164753>.
- [71] Lockheed Martin Corporation: *We never forget who we’re working for*, <https://www.lockheedmartin.com/>.
- [72] Entegris Inc., <https://poco.entegris.com/en/home/products/premium-graphite/thermal-management-materials/pocofoam.html>.
- [73] ATLAS-PIXEL-ENDCAP_FEA-MATERIALS-DATABASE_v1.0, <https://edms.cern.ch/ui/#!/master/navigator/document?D:100877794:100877794:subDocs>.

-
- [74] ResearchIR MAX, <https://www.flir.it/products/flir-research-studio/?vertical=condition%20monitoring&segment=solutions>].
 - [75] Matteo D’uffizi et al., Ring-Tools, https://gitlab.cern.ch/nscharmb/ring_tools/-/tree/Cleaning.
 - [76] ATLAS Collaboration, Thermal characterisation of thermo-active support structures and its application in the ATLAS pixel outer endcap local supports, Technical report, CERN, Geneva, 2021.
 - [77] FLIR SC620, https://www.butterfly.com/PDF/FLIR/FLIR_catalog_general_IT.pdf.
 - [78] ITk production database web user interface, <https://uos9.plus4u.net/uu-dockitg01-main/78462435-41f76117152c4c6e947f498339998055/book/page?code=home>.
 - [79] ITk Outer Endcap Local Support Assembly Breakdown Structure (ABS), <https://edms.cern.ch/ui/#!/master/navigator/item?P:1494949617:100243432:subDocs>.
 - [80] ITk Outer Endcap Local Support Serial Number Internal Document, <https://cds.cern.ch/record/2746044>.
 - [81] ATLAS Collaboration, Alignment of the ATLAS Inner Detector in Run-2, *Eur. Phys. J. C*, 80(12):1194, 2020, doi:{10.1140/epjc/s10052-020-08700-6}.
 - [82] ATLAS Collaboration, Alignment of the ATLAS Inner Detector and its Performance in 2012, Technical report, CERN, Geneva, 2014, <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-047>.
 - [83] Vannoli, L, 3D pixel modules characterization with RD53A readout for ATLAS ITk Upgrade, *Nuovo Cimento C*, 44(2-3):82, 2021, doi:10.1393/ncc/i2021-21082-9.
 - [84] Leonardo Vannoli et al., Qualifica di moduli a pixel per ITk con chip di readout ITkPixV1 e i primi sensori 3D di pre-produzione di FBK, <https://agenda.infn.it/event/34702/contributions/194391/>.
 - [85] Leonardo Vannoli on behalf of ATLAS Collaboration, ATLAS ITk Pixel Detector Overview, <https://indico.cern.ch/event/1273702/contributions/5349557/>.
 - [86] Leonardo Vannoli, Characterization of pre-production 3D FBK sensors for the ATLAS ITk Pixel detector upgrade, <https://indico.cern.ch/event/1204801/>.

Acknowledgements

Non posso non iniziare questa sezione di ringraziamenti senza enunciare un fatto: se ad un certo momento della mia vita ho capito che fare un dottorato potesse essere una buona idea, questo lo devo alla Saletta ATLAS della Sapienza.

Partiamo quindi da qui. Ringrazio quei luoghi e i loro abitanti (che sono tanti e sarebbe difficile elencarli tutti senza rischiare di dimenticarne qualcuno) i quali mi hanno permesso di credere che alla fine, dopo una laurea magistrale in fisica, un Ph.D. mezzo ci stava.

Vorrei ringraziare Claudia, relatrice, mentore ed amica. Tanto mi ha insegnato e molto ancora avrebbe da insegnarmi. Ma oltre al lavoro, non dimenticherò le ottime cene insieme in un periodo che, per forza di cose, mi vedeva da solo in una città che non conoscevo (e che non potevo esplorare). Grazie di cuore.

Un ringraziamento profondo anche a Lucrezia R., Simo, Lucrezia B. ed Alessandro. Un gruppo che prima non c'era è nato grazie a voi, e mai avrei pensato di riuscire a ritrovare un po' di quell'ambiente che avevo lasciato andandomene da Roma e che mi aveva spinto a prendere la strada della ricerca. Condividere con voi svago e disperazione (elementi sempre presenti nella vita del dottorando) è stato ciò di cui avevo più bisogno durante questo ultimo anno.

Per rimanere su Genova, un ringraziamento molto sentito va a Martino, o Mago, o Merlino, che dir si voglia: la sua opera di inclusione sociale nella *societas* genovese è stata strenua e non vana. Compagno di ottime e mai banali discussioni, di certo uno dei miei riferimenti in quel di Zena.

Un ringraziamento speciale va a Togliattigrad: la creazione e la condivisione di uno spazio che mai è sembrato soltanto un appoggio temporaneo a Ginevra, è quanto di più bello mi sia capitato in questi 3 anni (e mezzo) di Ph.D. Grazie quindi a Rappy, Luigi e Cholo, il nucleo fondante, a Sebba e Luis che hanno vissuto quei luoghi con noi (e successivamente ne hanno raccolto le redini), ma anche a Noemi e Giulia che ivi hanno speso per un periodo più breve ma lasciando in quello spazio una impronta profonda.

Un ringraziamento particolare a Rappy, Cholo, Sebino e Luis, con i quali l'esperienza

di coabitazione è stata non solo facile ma direi naturale. E un ringraziamento anche per il supporto nei momenti di maggior difficoltà. Siete dei grandi amici.

Luigi: non si può dire che non ci conoscessimo prima di andare a vivere insieme a Togliattigrad, ma sicuramente non mi aspettavo fosse così intenso il legame che si è venuto a creare. Una amicizia che mi ha dato e mi sta dando tantissimo. Una parte di questo traguardo sicuramente lo dedico (e lo devo) a te.

Rimanendo in tema Ginevra, non posso non ringraziare Silvia, compagna di un anno di co-working a Ginevra e di ancor più serate. Un'amicizia nuova che sento fortissima, con una persona stupenda con cui ho scambiato tanto e scambierò ancora molto.

Fred, Kia, Mandy e Peppo. Buona parte della mia crescita personale la devo a voi e probabilmente non avrei intrapreso questa crociata del Ph.D. se non fosse stato per la vostra influenza (indiretta o diretta). Grazie di supportarmi e sopportarmi da quasi 20 anni.

Gli Sbandati (aka Noi della Fiaschetta, Brigata Castagnole, Fiasche team, etc.): se gli amici del liceo per certi versi non si scelgono, nel mio caso quelli dell'università me li sono scelti ancora meno. Mi avete cooptato all'inizio della triennale e non ho più avuto modo di liberarmi di voi. E per questo vi ringrazio moltissimo. Senza di voi la mia vita universitaria (ma anche fuori dall'università) sarebbe stata divertente meno della metà di un terzo di quanto non lo sia stata insieme a voi.

Alla mia famiglia voglio solo dire grazie di tutto! Il supporto che mi avete dato durante tutto questo lunghissimo percorso accademico è stato impagabile. Non posso che riconoscervi una fetta importante di questo traguardo, che non sarebbe proprio iniziato se non fosse stato per tutti voi. Grazie Titti, grazie Babbo, grazie Giuls!

Un ringraziamento speciale va a Titti. Mi hai dato molto più del supporto che avrei mai potuto immaginare di chiedere. Da ultimo l'aiuto, nella correzione delle bozze di questa tesi. Questa tesi è anche un po' tua. Grazie di cuore!

Noemi, senza di te, la tua pazienza, la tua forza, la tua determinazione e (forse soprattutto) il tuo gusto estetico, questo dottorato sarebbe andato diversamente. Ti sei sorbita tutto, dai successi, agli insuccessi, e soprattutto tutta la preparazione ai quei successi e a quegli insuccessi. Una parte consistente di questo lavoro è anche merito tuo e quindi se alla fine mi dovessero veramente proclamare dottore in fisica sappi che per me, dottoressa, lo sei un po' anche tu. Ti voglio bene piccola Enne, e questa tesi la dedico a te.