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MASTER DEGREE IN PHYSICS

Master Thesis

**Development of systems and test of devices for the
ATLAS ITk detector moving from R&D to
construction**

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Introduction

The interaction of charged particles with matter is widely used in Physics research for particle tracking. The semiconductor detectors are some of the most common detectors used for this purpose. In these detectors, the passage of a ionizing particle determines a transfer of energy to the medium with the consequent production of an electrical signal that can be localized with high precision thanks to the possibility to make extremely small granular electrodes with microelectronics techniques. The need to develop high-precision tracking detectors began around the 1970s as a result of the development of the very first hadron colliders and the subsequent discovery of the charm quark that paved the way for the search for short-lived particles ($\sim$ ps). In collider experiments, a large number of particles are produced at the point of interaction, many of them are short-lived and can only travel for distances of the order of a few centimetres. It was, therefore, necessary to develop compact detectors, so that they could be placed as close as possible to the point of interaction, and with a resolution high enough to be able to discriminate a track despite the high density of particles produced. Among semiconductor detectors, silicon ones have become the most widely used, thanks to the low material cost and increasing industrial development in this material processing. In particular, modern techniques have allowed the fabrication of pixel detectors. They allow spatial a 3D spatial resolutions of the order of $10\text{ }\mu\text{m}$. For these reasons, silicon pixel detectors have become a standard choice in tracking systems in high-energy physics experiments.

The biggest large-scale (order of $1\text{-}2\text{ m}^2$) use of the pixel detectors was made at CERN in the ATLAS and CMS experiments operating at the Large Hadron Collider (LHC). The analysis of the two experiments led in 2012 to the observation of a new particle: the Higgs boson, the last missing piece in the Standard Model particle puzzle. While the LHC is providing a huge amount of data, allowing the experiments to assess and measure a multitude of processes, an upgrade of the accelerator is planned. It will lead to a significant increase in luminosity. This will improve the sensitivity of the analyses already carried out and will widen the possibility of new discoveries. To cope with the new potential of the accelerator, the ATLAS detector will be updated: in particular, its tracking system will be completely replaced by a new all-silicon detector, ITk, to be installed during the Long Shutdown 3 (2026-2028). It will consist of a Pixel detector at small radius and a large area Strip detector surrounding it. The ITk detector was designed to perform similarly to the ATLAS current tracking system, but in a much more hostile environment: both the level

of radiation in the detector and the number of particles per square centimeter will increase by a factor of seven. In particular, the innermost layer of the Pixel detector will have to face non ionising fluence up to $2 \cdot 10^{16} n_{eq}/cm^2$ and a ionising dose of 10 MGy. Due to this harsher radiation constraint, innovative high radiation-hard 3D pixel detectors will be used for the innermost layer. 3D technologies has been installed for the first time in the HEP detectors in the IBL upgrade of the ATLAS pixel detector. The 3D area was just $375 cm^2$, but this use paved the way to make the 3D technology a serious candidate for the future LHC detectors upgrade. After several years of R&D, ATLAS has decided in 2020 to use the 3D technology as baseline for the innermost pixel layer using a cell size of $25 \times 100 \mu m^2$ in the barrel and $50 \times 50 \mu m^2$ in the forward region. While the decision was taken, the community got the recommendation to validate the effective radiation hardness of the devices, up to the ultimate fluence with the pre-production samples.

This Master Thesis work focuses on the development of systems and the test of devices for the ATLAS ITk project. To contextualize the motivations and the results of my work some introductory chapters are necessary. Chapter 1 aims to give a brief overview on the basic operation principles of the LHC. Moreover, the main upgrades foreseen for the high luminosity program (HL-LHC) and the motivations for this project will be illustrated. Chapter 2 presents the current state of the ATLAS detector and the main results obtained so far. Particular attention has been paid to the description of the current tracking system to allow a more accurate comparison with ITk. Chapter 3 introduces the design of the new tracker and its expected performance; in particular, the focus is placed on the pixel detector, as the work of thesis is mainly focused on that. Chapter 4 shows the main interaction mechanisms of charged particles with the matter and how these can be exploited for the construction of a silicon detector. In addition, the basic principles of these detectors are presented by referring to the different possible designs and their use. Chapter 5 presents the work that I have carried out on the ITk devices. Ten ITk pixel hybrid modules were delivered to the INFN Genova laboratory at the beginning of 2022. These devices are the first assemblies with pre-production 3D sensors and readout chips ever qualified after irradiation by the ITk Pixel community. With these sample the ultimate radiation hardness of the 3D must be demonstrated. A general introduction on the sensor and on the chip is presented. Then, the chapter aims to describe the work that I carried out, within the Genova ATLAS ITk group, to qualify these modules. After assembly, characterization has been carried out in the INFN ATLAS Genova laboratory, where I collaborated to the realization of a test setup for the modules. Particular attention was paid to the calibration of the pixel readout threshold that allows to discriminate a signal from background noise. Modules were also tested with an X-ray tube in order to verify the integrity of the connection between the sensor and the chip, and more in general the response of the module to a real particle interaction. Moreover, the sensor IV curve was measured. The results obtained are encouraging: all tested modules are working and only one module presented serious problems related to data taking rate and connection between chip and sensor. After the laboratory characterization, in Spring few modules have been tested at CERN, using protons and pions beams. After these tests beam campaigns, I took care of the data analysis

to measure the sensor efficiency. In particular, I showed that the average efficiency is $(98.87 \pm 0.06)\%$, in agreement with the expectations. After the Spring tests beam campaign, two modules have been irradiated at Bonn and two at the CERN IRRAD facility, where I did all the preparations for the installation of the modules in the setup. Irradiated modules have been tested again with the beam at CERN in Summer. I joined this second two-weeks test beam campaign and I personally analysed the data. With the results, I showed that these pre-production sensors reached an efficiency of $(98.5 \pm 0.1)\%$ when measured perpendicular to the beam and an efficiency of $(99.9 \pm 0.1)\%$ when measured with an angle of 15° respect to the beam. Therefore I proved that sensors meet the ITk requirement to have a mean efficiency higher than 96% (97%) in the perpendicular (tilted) configuration after irradiation. Moreover, during the test beam, I participated to the study of the pre-production chip performance and sensor IV curves together with the colleagues of the Genova ATLAS ITk group.

I have presented my work at several meetings of the ITk collaboration. Preliminary results have been recently shown at iWoRiD 2022 and the SIF 2022.

Chapter 1

The LHC towards HL-LHC

1.1 The Large Hadron Collider at CERN

The Large Hadron Collider (LHC) is a two-ring-superconducting-hadron accelerator and collider. It is located at the European Organization for Nuclear Research (CERN), on the border between Switzerland and France [1]. It is installed in the existing 26.7 km tunnel, about 100 m beneath the ground, that was built between 1984 and 1989 for the LEP (Large Electron-Positron) machine. Its construction started in the early 2000s and its operations on 10 September 2008. The LHC is one of the most challenging projects in high-energy physics of our century working in fundamental particle physics and the physics of hadronic matter at extreme temperature and density. The machine can accelerate two different types of particles: protons and heavy ions, allowing the study of various physical phenomena. Protons are accelerated into the LHC as bunches of $O(10^{11})$ particles. The main goals of the LHC are to allow physicists to test Standard Model (SM) predictions, with a focus on the Higgs boson, and to look for new physical phenomena Beyond the Standard Model (BSM). For these tasks, the two proton beams collide at four points of the LHC ring where the detectors of four different purposes experiments operate. The two general-purpose experiments are ATLAS (A Toroidal LHC ApparatuS) [2] and CMS (Compact Muon Solenoid) [3], their focus is on the Higgs boson and its properties. Their work led to the announcement of the discovery of this particle in the summer of 2012 [4, 5]. The LHCb (LHC beauty)[6] experiment focuses on the study of b-quark properties and the matter-antimatter asymmetry. ALICE (A Large Ion Collider Experiment) [7] aims to study ion-ion collisions by looking for the so-called *quark-gluon plasma*, an exotic state of matter of the early universe.

The accelerator lifetime switches between years of operation and years of maintenance and upgrades. The LHC started colliding protons in 2009. The energy was gradually increased up to a centre-of-mass energy of 8 TeV in 2012. These three years of operation from 2009 to 2012 are the so-called Run1. The LHC was then stopped to allow updates on the accelerator and the detectors, during the so-called Long Shutdown 1 (LS1). After the consolidation of the electrical splices between the superconducting magnets (and many other

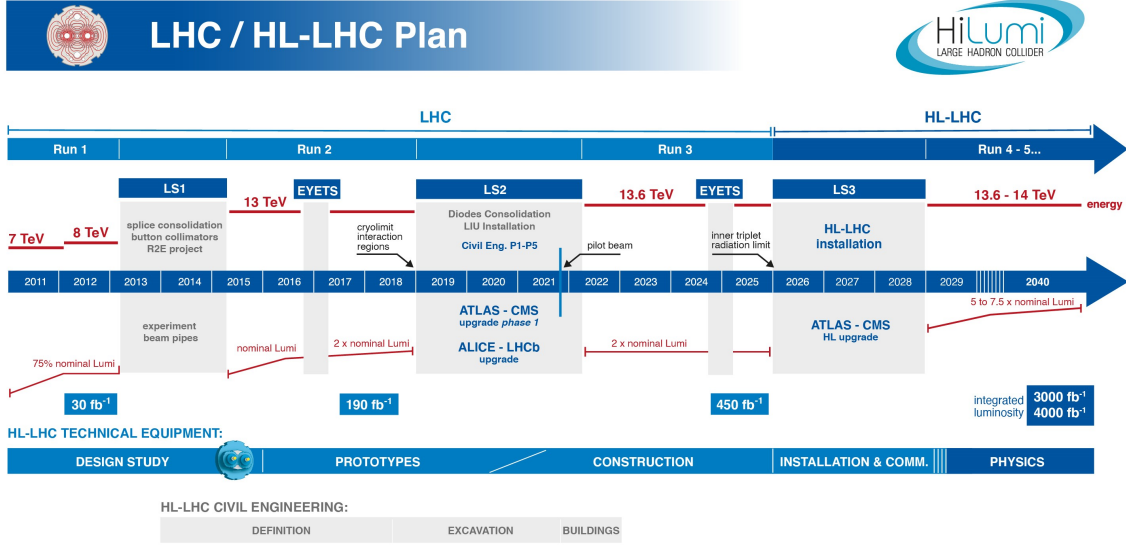


Figure 1.1: LHC and HL-LHC schedule. Nominal luminosity is $1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Image credit - CERN.

consolidation actions) in the LS1, the LHC operated in Run2 (2015-2018) at 13 TeV centre-of-mass energy and it has progressively increased the instantaneous luminosity attaining the nominal design value of $1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ on 2016. In 2018 the LHC reached a luminosity of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, pushing the potential of the accelerator to the limit. Summing data collected during Run1 and Run2, an integrated luminosity of 190 fb^{-1} was collected. Due to the pandemic, the Long Shutdown 2 lasted longer than expected: Run3 began in April 2022 with the LHC beam commissioning with 450 GeV protons. Stable beams with collisions at the record center of mass energy of 13.6 TeV started officially on 5th July. A gradual intensity increase will lead, again, to an instantaneous luminosity of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ during Run3. An integrated luminosity of 450 fb^{-1} is expected to be collected at the end of Run3. The new schedule plans the Long Shutdown 3 (LS3) to start in 2026 and to last for three years. After that, the High-Luminosity LHC (HL-LHC) project will start its operations. This upgrade of the LHC will lead to a significant increase in instantaneous luminosity. The plans for the operation of LHC are shown in figure 1.1.

1.1.1 Main elements of the LHC

The LHC tunnel, previously used by the LEP machine, is 26.7 km long and can be divided in eight straight sections and eight arcs. Four straight sections (each 280 m long) host the experimental caves. The main purpose of these sections is to house the magnetic elements ensuring beam crossing at the interaction point (IP) in the centre of the experiments. The

other four sections host accelerator's control services. Each straight stretch is equipped with an access point to the tunnel. The overall layout of the LHC is shown in figure 1.2.

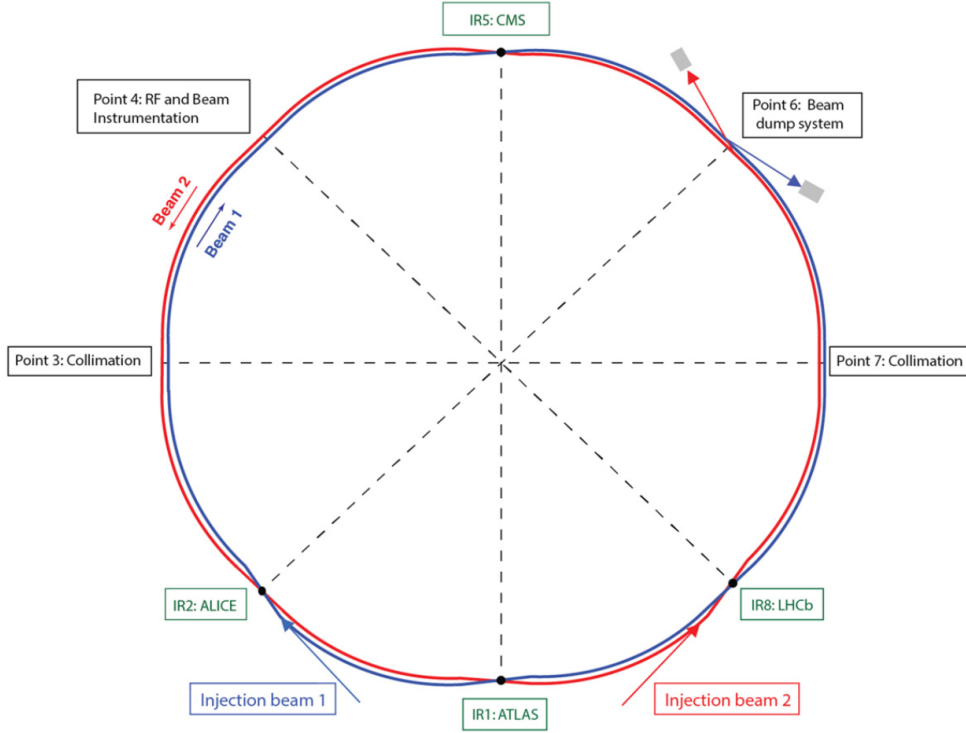


Figure 1.2: Overall layout of the LHC. The points of beam crossing are indicated as interaction regions (IR). The two counter-rotating beams (red and blue) travels separated in two different beam pipes and cross each other only at IR. Image credits - [11].

The main elements of the LHC are the magnets and the superconducting radio frequency cavities (RFs). RFs, operating at 4.5 K, provide the required acceleration for ramping up the beam energy to 6.8 TeV and for keeping the colliding proton beams tightly bunched. Each beam is equipped with eight cavities operating at 400 MHz. All the RFs systems are hosted in Point 4 [10].

Several types of magnets are used to keep beams stable in their orbits. The 1232 dipole magnets, 15 meters in length and 35 tons in weight, constitute the largest part of the LHC machine and cover 18.5 of the ring's 27.6 km [11]. The aim of these magnets is to bent particles' trajectory generating the centripetal force required to keep them circulating in the ring. Dipole magnets are designed to deliver the magnetic field on the two pipes at the same time. The cooling is provided by a cryogenic system cooled with 150 tons of superfluid helium at a temperature of 1.9 K. Quadrupole magnets play another important role: their magnetic field increases linearly in magnitude when moving out from the centre of the magnet which is close to zero. Off-axis particles in the beam could then be focused at the centre of the beam pipe or deflected away from the beam, depending on the direction of

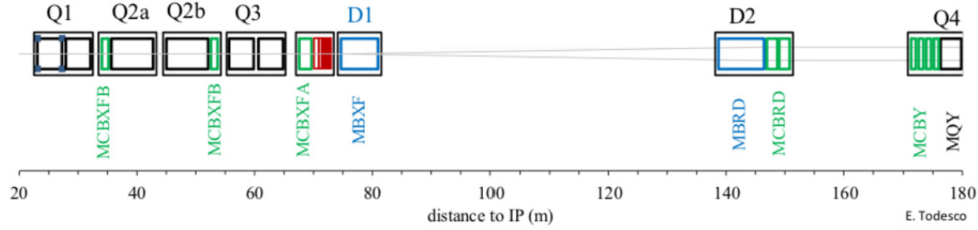


Figure 1.3: Schematic layout of the magnets immediately to the right of the ATLAS and CMS experiments in the HL-LHC. Q1, Q2a, Q2b, Q3 are the inner triplet quadrupole magnets. The beam axes are shown in grey. The D1 and D2 separation/recombination dipoles bring the two beams together as they pass through the inner triplet and the experiment. The corrector magnets are indicated in green. Image credits - [11].

the field that they encounter (hence on the polarity of the magnet). The beam stability is achieved using the so-called alternating-gradient focusing: quadrupole magnets are installed to focus in the horizontal plane and de-focus in the vertical one and vice versa. The beam size at a given IP is controlled by adjusting properly the focusing of quadrupole magnets installed in the regions close before and after the experiments. Additional magnets are placed on each side of the four experiments (figure 1.3). These high gradient quadrupole magnets are the so-called inner triplets and provide transverse beams size of the order of 16 microns at IP. These devices are the ones that most affect the luminosity at IP. Since inner triplets are the magnets closest to IP, they are the most exposed to radiation damage. Their conditions will be closely monitored during Run3 operation and mitigations will be deployed to allow collecting the planned integrated luminosity before LS3 starts. They will be replaced before the start of the High-Luminosity program.

The overall focusing properties are parameterized by the so-called beta function. This has a given value at each point around the ring. The value of the beta function at IP is referred to as β^* . The beta function then is one of the key elements that influence the collision rate and then the peak luminosity. Since the luminosity is inversely proportional to β^* , one of the main goals of HL-LHC is to reduce this factor. More details will be presented in section 1.2.2.

1.2 The High Luminosity LHC program

To extend the LHC discovery potential, a major upgrade is expected in the 2020s. This will increase its instantaneous luminosity (rate of collisions) by a factor more than five beyond the original design value and the integrated luminosity (total number of collisions) by a factor of ten. An integrated luminosity of $\sim 4000 \text{ fb}^{-1}$ is expected to be collected in 10 years. The project will lead to a maximum instantaneous luminosity of $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with an average of 200 proton-proton collisions per bunch-crossing. In addition, the number of protons per bunch will increase up to $2.2 \cdot 10^{11}$. The LHC is already a highly complex

and exquisitely optimised machine so this upgrade must be carefully conceived and requires new infrastructures (underground and on the surface) and over a decade to implement. The new configuration, known as High Luminosity LHC (HL-LHC), relies on several key innovations that push accelerator technology beyond its present limits. Among these are cutting-edge 11–12 T superconducting magnets, compact superconducting cavities for beam rotation with ultra-precise phase control, new technology and physical processes for beam collimation and 100-metre-long high-power superconducting links with negligible energy dissipation, all of which required several years of dedicated R&D effort on a global international level. The main equipment upgrades and layout modifications for HL-LHC will be carried out in the 600 m long insertion regions of LHC Point 1 (P1-ATLAS) and LHC Point 5 (P5-CMS). Other parts of the LHC need to be modified as well to deal with the upgraded performance yielding a total length of more than 1.2 km of modified machine and with 1 km of additional technical services and equipment required by the new components [1]. A comparison between HL-LHC and LHC during Run 3 performance is presented in table 1.1.

	LHC	HL-LHC
Beam energy [TeV]	6.8	7
Average n° of p-p collision ($\sim$)	30	200
Luminosity [$10^{34} cm^{-2} s^{-1}$]	2	5-7.5
Integrated luminosity after 10 year [fb^{-1}]	450	4000
Particles per bunch [10^{11}]	1.2-1.8	2.2

Table 1.1: HL-LHC and LHC Run 3 performance comparison

1.2.1 Physics goals of the upgrade

An important component of the HL-LHC programme is to carry out studies involving the recently discovered 125 GeV Higgs boson. One aspect is to perform precision measurements of the properties of this scalar particle in order to test the Standard Model pattern of couplings to elementary particles. In addition, many models of new physics are sensible to Higgs observables, so precise measurements will allow putting constraints on BSM physics, even if we could not have direct observation of new particles. The increase in statistics will also allow studying rare processes such as $H \rightarrow Z\gamma$ or those involving second-generation fermion couplings ($H \rightarrow \mu\mu$, $H \rightarrow cc$) which can open a novel window on the problem of flavour. Since the Higgs boson mass and the Higgs field (ϕ) vacuum expectation value are both known, the structure of the Higgs potential is fully predicted. We know that it involves two terms, proportional to ϕ^2 and ϕ^4 . The study of its expectation value will allow testing of Higgs self-coupling because it is related to the third derivative of the Higgs potential at its minimum. The study of Higgs self-coupling can be performed with the di-Higgs production,

which is sensitive to the (off-shell) $H^* \rightarrow HH$ process. It is a complicated analysis because of the low production cross section and the interference with other production modes, however, this can help in the field of BSM physics; for example, di-Higgs production can be greatly enhanced if the Higgs is a composite particle rather than an elementary particle [9].

One of the most studied processes at HL-LHC will be the scattering of two W bosons of the same charge since it features a smaller background from QCD production compared to other vector boson scattering processes. The WW scattering is guaranteed in the SM by the presence of the Higgs boson, hence the study of such a process is strongly connected to the understanding of the mechanism behind the spontaneous breaking of the electroweak symmetry [16]. The increased luminosity and the extended tracking coverage of the CMS and ATLAS detector will help to reject WW bosons background produced by QCD processes and focus on the search for WW bosons interested by scattering signature.

HL-LHC will also look, with greater sensitivity than LHC, for Beyond the Standard Model signatures. Supersymmetry (SUSY) remains one of the most attractive theories for physics beyond the SM, as it would explain the light mass of the Higgs boson and provide a candidate particle for Dark Matter. One of the processes with a low production cross-section, and therefore strongly dependent on high luminosity, is the direct production of the supersymmetric partners of the electroweak gauge boson. The Higgsino is the SUSY partner of the Higgs boson, its mass is expected to be close to the Higgs one. This particle mixes with SUSY partners of other bosons to make mass eigenstate, called neutralinos (χ^0) and charginos ($\chi^\pm$). SUSY theory foresees that only a few of these particles can be light (several hundred of GeV).

1.2.2 Luminosity at interaction point

The instantaneous luminosity, defined as the number of potential collisions per unit area per second, can be expressed for the LHC as:

$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi \beta^* \epsilon_n} R; \quad R = 1 / \sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}} \quad (1.1)$$

where γ is the relativistic gamma factor; n_b is the number of bunches per beam colliding at the IP; N is the bunch population; f_{rev} is the revolution frequency; β^* is the value of the beta function at the collision point; ϵ_n is the transverse normalized emittance; R is a luminosity geometrical reduction factor from the crossing angle; θ_c is the full crossing angle between colliding beam; and σ , σ_z are the transverse and longitudinal r.m.s. sizes of the beam [1]. The design of the HL-LHC targets the following key points:

- A significant lower β^* at the CMS and ATLAS IPs. This requires new wide aperture inner triplet magnets;
- An upgrade of the injection system that will increase the number of protons per bunch crossing, up to $2.2 \cdot 10^{11}$ p/b, while maintaining low beam size;

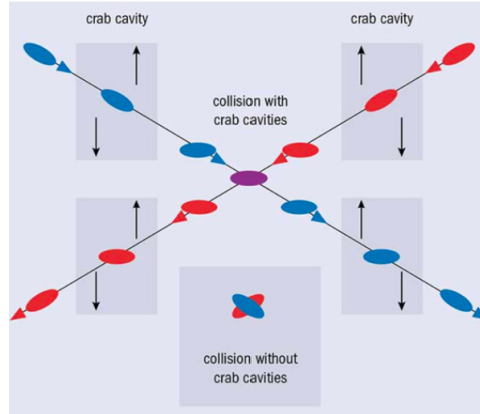


Figure 1.4: The counter-rotating beams of LHC are shown in red and blue. In the current LHC configuration, they collide with a crossing angle (bottom). In HL-LHC bunches will be tilted by the RF crab cavities causing a higher degree of overlap (purple) at IP increasing instantaneous luminosity. Image credits [11].

- The high bunch population will require a large crossing angle ($590 \mu\text{rad}$ instead of the current $300 \mu\text{rad}$) to avoid *long-range interaction* between protons of different bunches before the IP. The loss of luminosity due to the larger crossing angle will be balanced by using novel crab radio frequency cavities which are transversely deflecting RF devices that tilt the bunches during their passages along the crossing angle bump, so that they more effectively overlap at the IP [11]. A schematic drawing of crab cavities work is shown in figure 1.4. Crab cavities will be installed in Point 1 and 5 of the LHC tunnel to generate high brightness for the ATLAS and CMS detectors.

Together with the luminosity, at the HL-LHC the event pileup (PU) will rise substantially, becoming a major challenge for the experiments. At the final HL-LHC luminosity, the average number of interactions in a single crossing will be approximately 200. Most of the PU interactions are “soft” or “peripheral” collisions that do not contribute to the search for new physics at the 0.1-few TeV scale. A relatively small fraction of the collisions is considered “hard”, i.e. containing high transverse momentum particles that may come from high mass objects. Nevertheless, the presence of tracks and energy release from hundreds of extra collisions can degrade the performance of triggers and offline reconstruction of the hard scatter [9]. Since increasing luminosity will lead to an inevitable increase in PU events, this will require a significant improvement in the tracking and trigger systems of the ATLAS and CMS detectors. More information about the ATLAS detector upgrade will be presented in the following sections.

Chapter 2

The ATLAS Experiment

ATLAS is one of the two general-purpose experiments operating at LHC. The ATLAS collaboration includes about 6000 physicists, engineers, technicians and students from about 180 institutions in 42 countries and it is one of the largest collaborative efforts ever attempted in science.

2.1 Detector and upgrades overview

The ATLAS detector is forward-backward symmetric to the interaction point. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 tonnes. The magnet configuration comprises a thin superconducting solenoid surrounding the inner-detector cavity, and three large superconducting toroids (one barrel and two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters. This fundamental choice has driven the design of the detector [2]. The ATLAS detector is made up of several sub-detectors: the Inner Detector (ID), the electromagnetic calorimeter, the hadronic calorimeter and the Muon Spectrometer (MS), in addition, all these sub-detectors are supported by the Trigger and Data Acquisition system (TDAQ) and the Detector Control System (DCS). The ATLAS detector configuration at the beginning of Run3 (July 2022) is shown in figure 2.1.

To meet the growing potential of the LHC, the ATLAS detector needed (and will require in future) upgrades. Detailed information about the detector layout during Run1 can be found on reference [2]. The following paragraphs want to give a brief general overview of detector upgrades before they are extended in the following sections and chapters.

Phase 0 upgrades The first significant upgrades (Phase 0 upgrades) took place in 2013-2015 during LS1. Many sections of the detector were upgraded including a new ID cooling system, the replacement of the pixel internal services, new power supplies for the calorimeter and improved coverage of the MS between the barrel and endcap regions. However, the most significant improvement regarded the installation of a new barrel layer in the Pixel detector, the Insertable B-Layer (IBL). The IBL is an additional 4th pixel layer that has been built

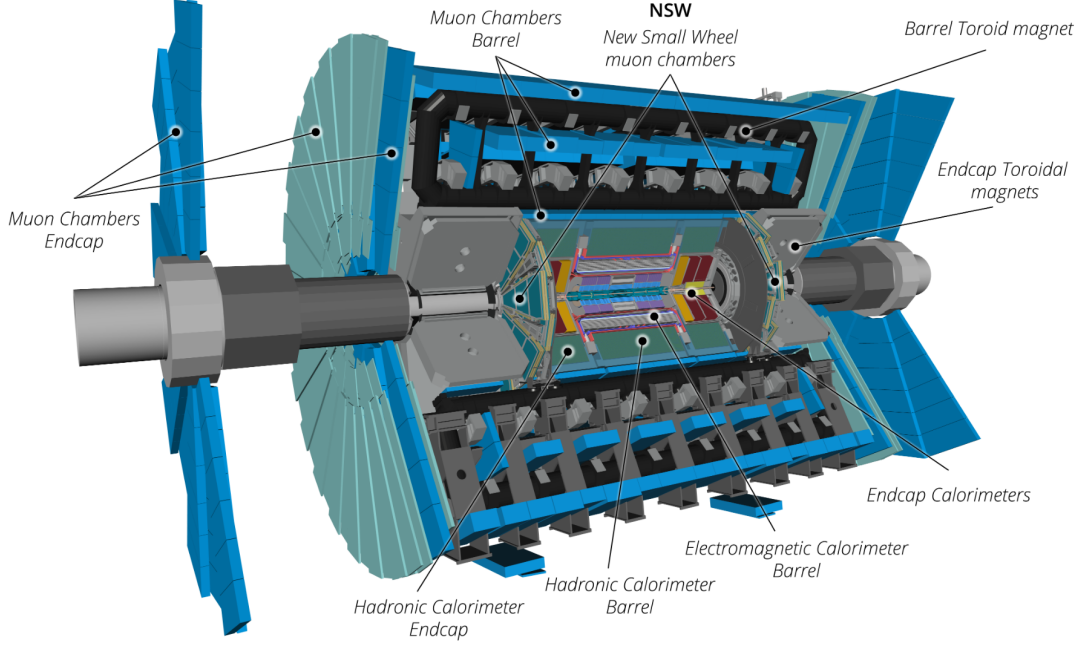


Figure 2.1: Overall layout and the main sub-detectors of the ATLAS for Run3. Image credits: ATLAS Collaboration.

around a new central beam pipe and then slipped inside the present Pixel detector in situ. The IBL (33 mm of radius) needed to fit between the innermost pixel layer (50.5 mm of radius) and the beam pipe. To make the installation possible a new beam pipe of radius 25 mm (4 mm smaller than the previous) has been used. Given its close position to the impact point, the IBL improved the detector vertex resolution, secondary vertex finding and b-tagging performance. Moreover, it will compensate for defects in the existing detector due to radiation damage [9]. The IBL consists of 14 staves arranged to form a cylinder, on each staff there are 20 modules: 12 with planar pixel sensors, 8 with 3D pixel sensors. The 3D sensors installed in IBL are the first-ever application in high energy physics of this technology, they will be described in depth in chapter 5.

Phase-I upgrades A second update campaign was held between 2019 and 2022 (Phase-I upgrade) during the LS2. During this period new sub-detectors, designed to be compatible with the HL-LHC program, were installed. The major improvements of the Phase-I upgrade are the New muon Small Wheels (NSW) installation and several updates for the trigger system. The NSW must ensure efficient tracking at high particle rate of up to $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and larger η coverage, with position resolution of $< 100 \mu\text{m}$. Also, the calorimetric trigger has been upgraded, in order to provide higher-granularity, higher-resolution and longitudinal

shower information from the calorimeter to the Level-1 trigger processors, this allows an improvement in electron, photon, τ -leptons and jets selection reducing background and improving fake objects rejection. To meet the new performance of the Level-1 trigger also the High-Level triggers have received important upgrades.

Phase-II upgrades The Phase-II upgrade will take place during the LS3 (2026-2028). The main update towards the high luminosity program regards the tracker and the muon and electron trigger system. The ATLAS tracking system will be completely replaced with a new all-silicon tracker, Inner Tracker (ITk): it will consist of a Pixel detector at a small radius and a large area Strip detector surrounding it. The ITk design was optimized to account for particle tracking performance, costs, engineering constraints, CPU time needed for reconstruction and other physics requirements. I will give more information about the ITk project in chapter 3. Moreover, the Phase-II upgrade foresees an upgrade of the hardware trigger from 100k to 1MHz, increasing the total trigger accept rate and minimising latency time.

2.2 ATLAS detector configuration for Run 3

This section wants to give a more extended description of the ATLAS detector configuration during Run 3. Over the ten years since the start of LHC the ATLAS detector has been performing far beyond expectations. Thanks to the hardware and software upgrades ATLAS performance improved year by year: ATLAS data taking efficiency (the fraction of the time ATLAS collects data while LHC delivers collisions in stable beam conditions) improved from 90% to 95% in the course of the eight years of data taking. Over the same period, the data quality efficiency (the fraction of collected data declared good for physics analyses) has increased from 88.8% to 97.5% [14]. Another important indicator of the detector status is the fraction of live channels: at the end of Run 2, ATLAS had about 99.5% of live channels in the calorimeters and over 95% in the tracking system. Analysis of live channels at the beginning of Run 3 is ongoing.

As highlighted before the detector consists of several sub-detectors that I will describe briefly in the following. More information can be found in reference [2], [15].

2.2.1 Inner Detector

The ATLAS Inner Detector (ID) has been designed to provide robust pattern recognition, excellent momentum resolution and both primary and secondary vertex measurements for charged tracks up to $\eta = 2.5$. It is immersed in the 2 T magnetic field delivered by the surrounding solenoid. The ID consists of a high-granularity Pixel detector in the region closest to the beam pipe and a Semi-Conductor Tracker (SCT) in the outer parts. These silicon detectors are complemented by the Transition Radiation Tracker (TRT), which enables radially extended track reconstruction up to $|\eta|=2$. In addition to the pixel detector,

the IBL detector was added as a fourth pixel layer (2014). A transverse section of the Inner Detector during Run 2 and Run 3 is shown in the figure 2.2.

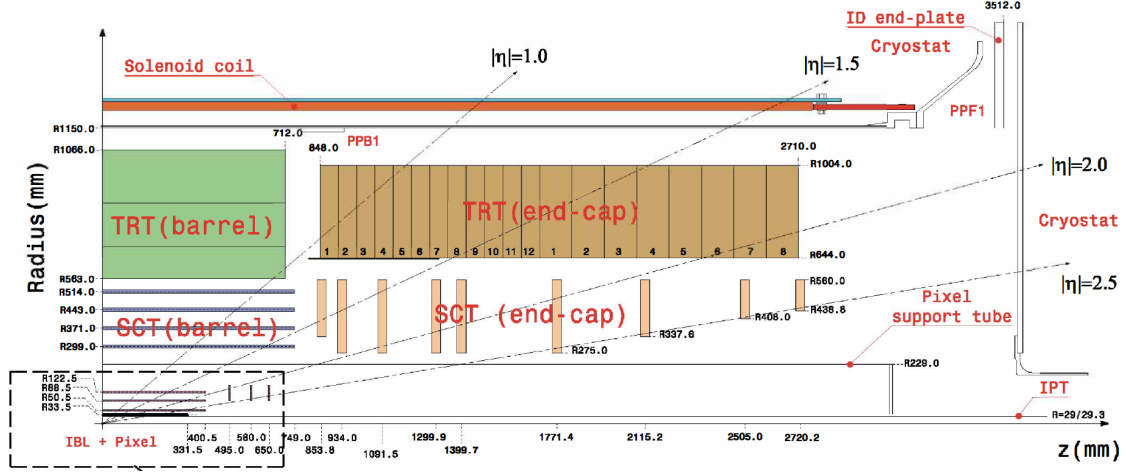


Figure 2.2: ATLAS ID layout, including the IBL detector. Image credits: ATLAS Collaboration

Insertable B-layer Since the performance of the ATLAS detector depends critically on the innermost layer of the pixel detector, a fourth additional layer of pixel was added to the ID in 2014: the IBL detector. Due to its reduced distance from the beam axis (33.5 mm), it led to the consolidation and improvement of the ID tracking performance in high luminosity scenarios. Its closeness to the beam and the high luminosity expected in Run 2 and Run 3 set new radiation hardness requirements for the IBL detector. The simulations foresee that the modules will be subjected to an overall fluence of $3.3 \cdot 10^{15} \text{ 1 MeV } n_{eq} \text{ cm}^{-2}$ (Non Ionizing Energy Loss, NIEL) for an integrated luminosity of 550 fb^{-1} at the end of Run 3.

The basic construction units of the IBL are hybrid pixel modules: the connection between the sensor and FE chip is achieved with bump-bonding and flip-chip technology. Planar modules are composed by a sensor tile connected to two read-out chips (dual modules) while the 3D modules are single devices, i.e. each sensor is joined to a single chip. Both kind of modules have the same pixel cell size of $250 \times 50 \text{ } \mu\text{m}^2$, except for the two central columns of the planar sensors that are extended to $450 \text{ } \mu\text{m}$, to cover the gap between the two adjacent read-out chips. The same chip was used for both modules: the FE-I4, designed in 130 nm CMOS technology. The 3D modules relies on 230 μm -thick 3D pixel sensor, while planar modules on 200 μm thick planar sensor. Since in the IBL it was not possible to superimpose the modules as in Pixel, in order to reduce the inactive area, an effective inactive edge width of 215 μm (175 μm) was designed for the planar (3D) sensors, instead of the 1100 μm of the Pixel detector ones. To fit in the reduced radial envelope and limit the material budget, the IBL modules are thinner than the pixels' ones, both sensors

and chip thicknesses being slightly reduced. The main characteristics of the IBL and the Pixel detector are compared in the table 2.1. In the IBL detector modules are loaded on 14 longitudinal support (staves) fixed between two thin carbon fibre tubular structures. Each stave hosts a single layer of 20 modules: 12 with planar sensors, in the central region of the stave, and 8 with 3D ones in the forward regions. Staves are tilted by 14° in order to save space and to ensure complete azimuthal coverage for high p_T tracks and for charge collection optimization. Cooling is achieved by means of a CO_2 two-phase system, where the coolant is circulated within titanium pipes embedded in the stave structure. Stave design and a transverse section of the IBL are shown in figure 2.3.

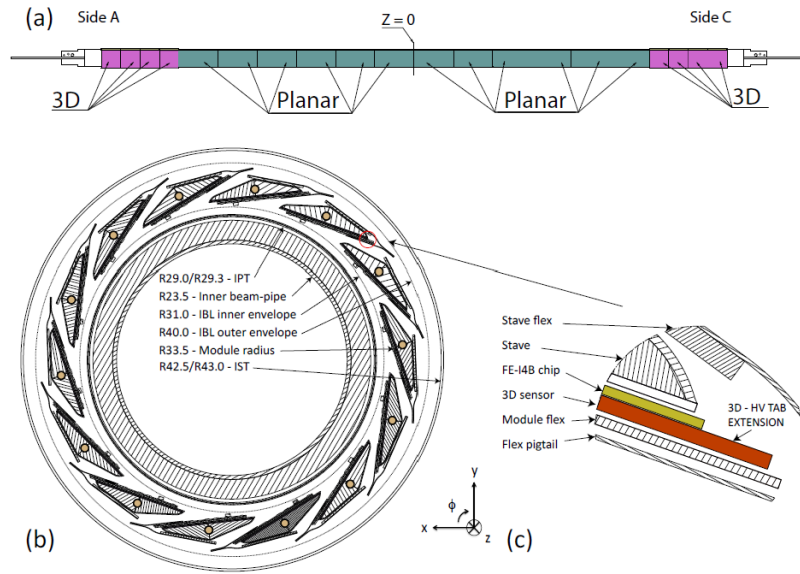


Figure 2.3: IBL layout: a) Longitudinal layout of planar and 3D modules. b) Transverse section of the IBL detector. c) Expanded view of the corner of the 3D module fixed to the stave. Image credits: ATLAS collaboration.

Pixel Detector The Pixel detector is designed to provide a very high-granularity, high-precision set of measurements close to the interaction point. The system provides three measurements over the full acceptance thanks to its three layers. Pixel Detector consists of three barrel layers (at a radius of about 5 cm, 9 cm and 12 cm) in its central parts; and of three disks, between radii of 9 and 15 cm, on each side. The overall layout is summarized in table 2.2. The entire pixel detector consists of 1744 hybrid modules (22.4 mm wide and 62.4 mm long), each covering an active area of $16.4 \times 60.8 \text{ mm}^2$, for a total of 1.7 m^2 with 80 million readout channels. The thickness of a layer of the pixel detector corresponds to 2.8% of a radiation length. Individual silicon modules are constructed to provide space point resolutions of $\sigma_{R\phi} = 12 \text{ } \mu\text{m}$ and $\sigma_z = 66 \text{ } \mu\text{m}$ in the barrel region and $\sigma_z = 77 \text{ } \mu\text{m}$ in the

disks. Sensor pixel cell size is $50 \times 400 \mu\text{m}$ (several pixels are $50 \times 600 \mu\text{m}$ to compensate for the gap between the FE chips). Barrel layers and end-caps disks of the pixel detector are sketched in figure 2.4.

Technical characteristics	Pixel Detector	IBL
Active surface (m^2)	1.73	0.15
Number of channels ($\times 10^6$)	80.36	12.04
Pixel size (μm^2)	50×400	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 2.1: Main features of the Pixel Detector and the IBL in comparison

	Radial extension (mm)	Lenght (mm)
Beam Pipe	$23.5 < r < 30$	$0 < z < 3512$
Pixel (IBL included)	$31 < r < 242$	$0 < z < 3092$
4 cylindrical layers (barrel)	$33.5 < r < 122.5$	$0 < z < 400.5$
2x3 disks (endcap)	$88.8 < r < 149.6$	$495 < z < 650$

Table 2.2: Pixel Detector and IBL overall layout. The z direction is along the beam axis. The radial distance from the beam axis is indicated as "r".

SCT The Semi-Conductor Tracker (SCT) is designed to provide four precision measurements per track in the intermediate range of the Inner Detector [15]. The SCT is based on silicon microstrip detectors. It consists of four barrel layers (radii of 300, 373, 447 and 520 mm) and nine wheels on each side of a slightly different radius in order to limit the coverage to $|\eta| < 2.5$. Each module consists of two strip detectors, one for each side. The two devices are glued together back-to-back at a 40 mrad angle, separated by a heat transport plate; the electronics is mounted above the detectors on a hybrid. The detector consists of 61 m^2 of silicon detectors, with 6.2 million readout channels. The spatial resolution is $\sigma_z = 580 \mu\text{m}$ and $\sigma_{R\phi} = 16 \mu\text{m}$. A section of the SCT is shown in figure 2.4.

TRT The Transition Radiation Tracker (TRT) is a gas detector based on the use of straw tubes. Electron identification capability is added by employing Xenon gas to detect

transition-radiation photons created in a radiator between the straws [15]. The TRT typically allows 36 points per track. This technology allows covering a very large area at a modest cost. Each straw is 4 mm in diameter and has a maximum length of 150 cm. The barrel contains about 50 thousand straws and covers a radial range from 56 to 107 cm. The end-caps consist of 18 wheels on each side for a total of 320 thousand straws. The total number of readout channels is 420 thousand. Each straw provides a spatial resolution of $170 \mu\text{m}$ per straw. Moreover, two independent thresholds are used to discriminate between transition-radiation signals and crossing particles (tracking hits pass the lower threshold and the transition-radiation the higher). A section of the TRT endcap is shown in figure 2.4.

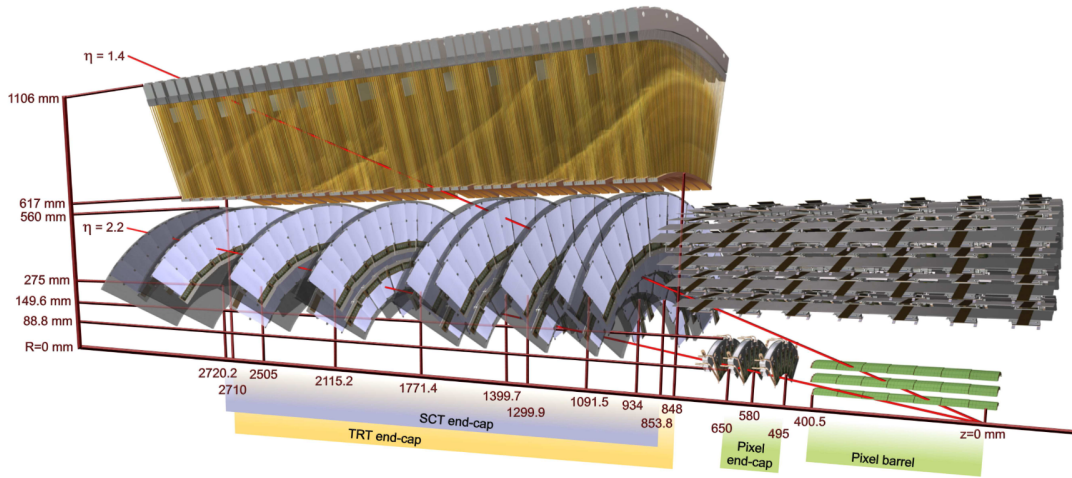


Figure 2.4: Layout of Pixel, SCT and TRT detectors. Image credits [2]

2.2.2 Calorimetry

The calorimeter system (figure 2.5) must provide good containment for an electromagnetic and hadronic shower, in order to measure particles' energy and position. It covers the pseudorapidity range $|\eta| < 4.9$. This system consists of two sub-detectors: the electromagnetic calorimeter and the hadronic calorimeter.

The electromagnetic calorimeter in the region $|\eta| < 3.2$ is provided by barrel and endcap high granularity lead/Liquid Argon (LAr) calorimeters. Hadron calorimetry is provided by the steel/scintillator-tile calorimeter, 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 optimised for electromagnetic and hadronic energy measurements respectively. The energy resolution of the two systems is listed in the table below (2.3).

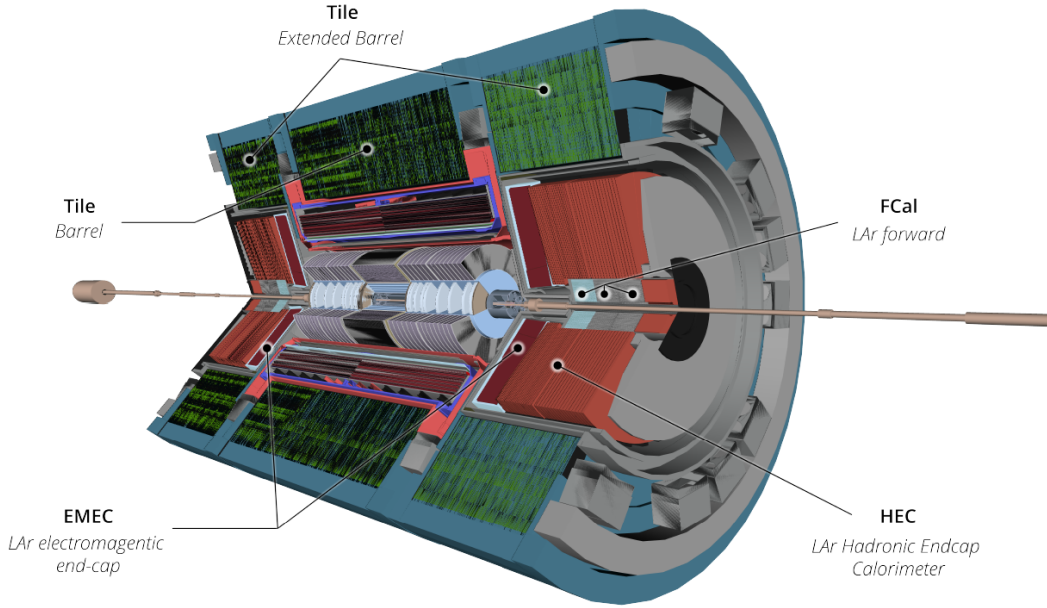


Figure 2.5: Cut-away view of the ATLAS calorimeter system. LAr is used as active medium for the electromagnetic calorimeters and all of the endcap and forward calorimeters; scintillating Tiles are used for the hadron calorimeter in the central region. Image credits: ATLAS collaboration

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

2.2.3 Muon Spectrometer

The muon spectrometer forms the outer part of the ATLAS detector, its radius R is in the range between $4.5 < R < 11$ m and its length is 46 m. It is designed to detect charged particles exiting the barrel and end-cap calorimeters and to measure their momentum in the pseudorapidity range $|\eta| < 2.7$ [2]. The overall layout of the muon system is shown in figure 2.6.

The muon spectrometer is designed to provide standalone measurements of the muon momentum with uncertainty in the transverse momentum varying from 3 % at 100 GeV to about 10 % at 1 TeV. Moreover, it provides a trigger signal for muons with a transverse momentum higher than few GeV.

The muon system comprises a barrel, consisting of three concentric, roughly cylindrical stations and two endcaps, each composed of three discs in planes perpendicular to the beam axis, referred to as inner, middle and outer “wheels”.

All three stations of the barrel region use multilayered Monitored Drift Chambers (MDT) devoted to precision position measurements. The inner and the middle stations also use Resistive Plate Chambers (RPC) for triggering and position measurements.

The middle and the outer wheels have MDT for precision tracking, the outer also has Thin Gap Chamber (TGC) for triggering and position measurements. The new inner wheel also referred to as New Small Wheel (NSW), are the main focus of the Phase-I upgrade. They provide tracking over a polar angle range of $1.3 < |\eta| < 2.7$ using two chamber technologies: small-strip TGC, optimized for Level-1 trigger, and MICRO MESH Gaseous Structure (Micromegas) detectors, optimized for particle tracking. NSWs will improve p_T resolution in the trigger and background rejection.

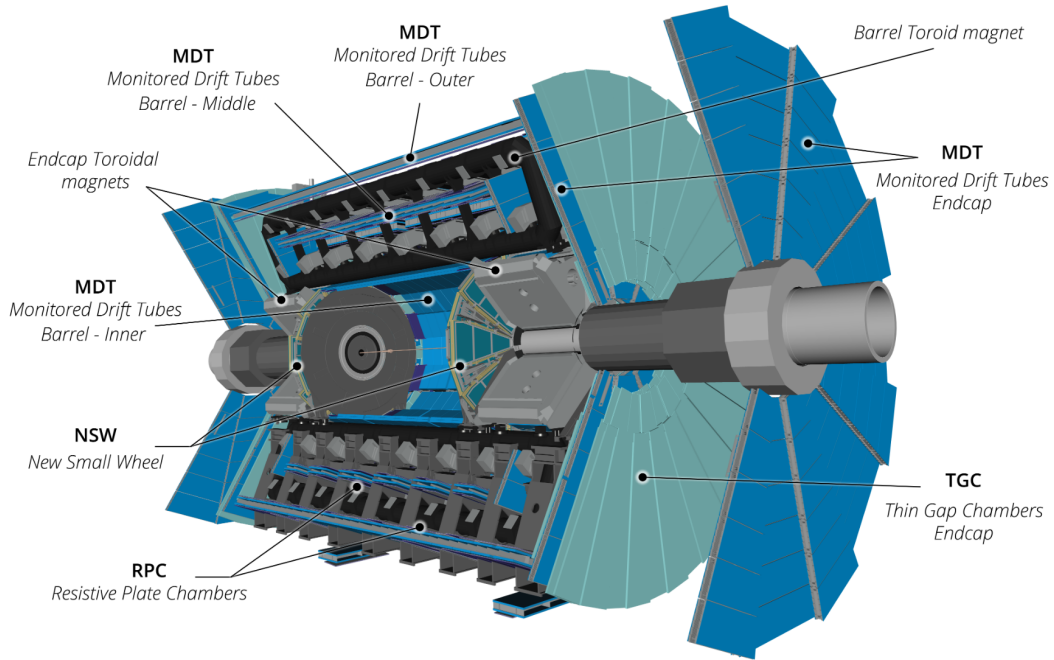


Figure 2.6: Cut-away view of the ATLAS Muon system. The main muon detector components upgraded for Run 3 (NSW) are visible. Image credits: ATLAS collaboration

2.2.4 Magnets

The ATLAS magnet system consists of one solenoid and three toroids. This system is 22 m in diameter and 26 in length, with a stored energy of 1.6 GJ. It provides the magnetic field over a volume of approximately 12000 m³ (define as the region which exceeds 50 mT) [2]. Figure 2.1 and 2.7 show the general layout of the system. The ATLAS magnet system consists of:

- **A solenoid**, aligned to the beam axis, provides a 2 T axial magnetic field in the inner detector. It is 5.3 m long, with an inner diameter of 2.44 m and an outer one of 2.63 m and it surrounds the inner system.
- **A barrel toroid and two end-cap toroids**, which produce a toroidal magnetic field of approximately 0.5 (1 T) for the muon detectors in the central (end-caps) region. The barrel toroid extends over a length of 25 m with an inner diameter of 9.4 m and an outer one of 20.1 m. The two end-caps, inserted at the two ends of the barrel, are 5 meters long, with inner and outer diameter of 1.6 m and 10.7 m respectively.

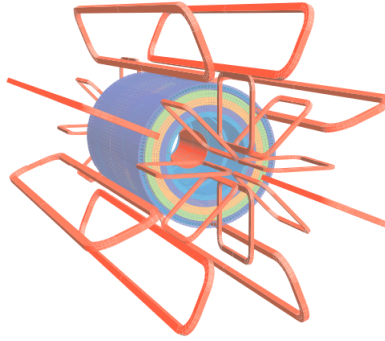


Figure 2.7: Geometry of magnet windings and tile calorimeter steel. The eight barrel toroid coils and the end-cap coils are shown in red. The solenoid winding lies inside the calorimeter volume. Image credits: [2]

2.2.5 Trigger and data acquisition

The Trigger and Data Acquisition (TDAQ) system is responsible for event selection and processing. The trigger system consists of a two-level event selection system: the Level-1 (L1) trigger system, which is hardware-based, and the High-Level-Trigger (HLT) which is software-based. The Data Acquisition (DAQ) system transport data from the detector to the offline processing. LHC has a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, leading to a maximum of 60 interactions per bunch crossing; this, multiplied by the bunch crossing rate (40 MHz) correspond to a data volume of $\sim 10^4$ Gbyte/sec. Since it is impossible and useless to

store all this data, the trigger system aims to reduce the event rate from 40 MHz to 1.5 kHz, which is then stored for offline analysis. TDAQ system is schematized in the figure 2.8.

The L1 trigger system relies on memories located on or near the detector to store information while the trigger decision is in progress. This selection should be as fast as possible, the design of the trigger system requires that L1 latency time is under $2.5 \mu\text{s}$. The trigger selection is tuned to reduce the event rate from 40 MHz to 100 kHz ($\sim 300 \text{ GB/s}$ of data), which is the maximum rate accepted by the detector readout system.

Level-1 Trigger system The Level-1 trigger uses information from the calorimeters and muon spectrometer to search for signatures from high- p_T muons, electrons, photons, jets and τ -leptons decaying into hadrons, as well as events with large missing transverse energy. The Region-of-Interest (RoI), a region of the detector with interesting signatures, includes information on the type of the event and on its features. The information of the RoI is then passed to the HLT for further analysis. The L1 trigger consists of:

- **Level-1 Calorimeter trigger system (L1-Calor).** The L1-Calor trigger identifies high- E_T objects such as electrons, photons, jets and τ -leptons, with isolation requirements. It also selects events with large missing transverse energy. The selection is based on the information from both the hadronic and electromagnetic calorimeters.
- **Level-1 Muon trigger system (L1-Muon).** The L1-Muon is based on inputs from the RPCs in the barrel region and the TGCs in the endcaps. It selects events containing high- p_T muons. Events selection is based on the coincidence of hits in the NSW and the TGC stations of the Outer Wheel for the endcap and on the coincidence of hits in the RPCs stations for the barrel. If required, it is possible to select events relying on the coincidence of hits on the muon system and the tile calorimeter.
- **Level-1 Topological trigger system (L1-Topo).** The L1-Topo trigger takes input containing kinematic information (e.g. E_T and η - ϕ coordinates) from the L1-Calor and L1-Muon systems and applies topological selections. This system is optimized for processes with unique topologies, such as B or J/ψ mesons decay to low- p_T leptons or vector-boson fusion production of a Higgs boson. These processes have large multi-jet backgrounds, and so the trigger system needs to be able to reject efficiently the background while maintaining low trigger thresholds.
- **Central Trigger Processor (CTP).** The final L1 trigger decision is made by the CTP. It receives inputs from the L1-Calor, L1-Muon and L1-Topo. It decides to reject or accept the event if this meets the selection requirements.

High-Level-Trigger (HLT) The HLT receives the events accepted from the L1 trigger. At this level, events are reconstructed at higher levels of detail than L1 providing a better energy and momentum resolution. The HLT reduces the event rate from 100 kHz to approximately 1.5 kHz ($\sim 4.5 \text{ GB/s}$ of data), which is then stored for offline analysis, with a

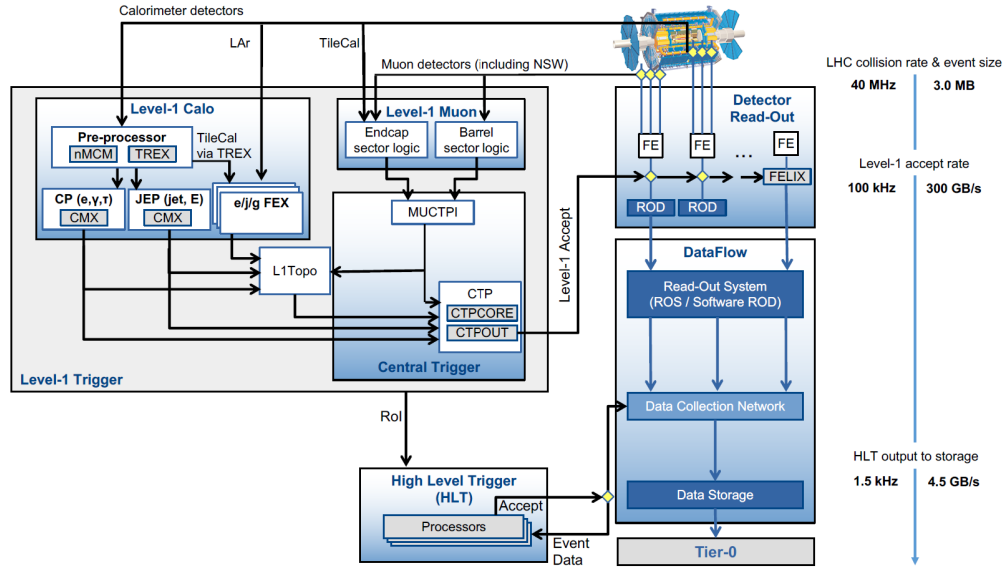


Figure 2.8: Schematic overview of the Trigger and DAQ system at the beginning of Run 3. Image credits: ATLAS collaboration

latency time of 400 ms for processing an event. The HLT selection criteria are optimized according to the type of search needed. The table 2.4 summarizes the input and output data flows for the two trigger levels.

	Input rate	Latency	Output rate	Data volume
LHC collisions	/	/	40 MHz	10^4 GB/s
Level-1 Trigger	40 MHz	$2.5 \mu s$	100 kHz	300 GB/s
High-Level-Trigger	100 kHz	400 ms	1.5 kHz	4.5 GB/s

Table 2.4: Input and output data flows of the trigger levels.

2.3 Key achievements

The main goals of the ATLAS experiment are studies on the electroweak standard model, focusing on the Higgs boson, the W/Z bosons and the top quark, looking for new physics phenomena BSM, flavour physics related to beauty and charm quarks and Quantum Chromodynamics tests. The major results achieved by the ATLAS collaboration analysing Run 1 and Run 2 data are the following:

Higgs physics After the announcement of the discovery of the Higgs boson by the ATLAS and CMS experiments in July 2012, more precise measurements have been performed using the Run 2 dataset, collected with a centre of mass energy of $\sqrt{s} = 13$ TeV. Figure 2.9 shows a summary of the Higgs boson mass measurements from the individual and combined analyses performed by ATLAS.

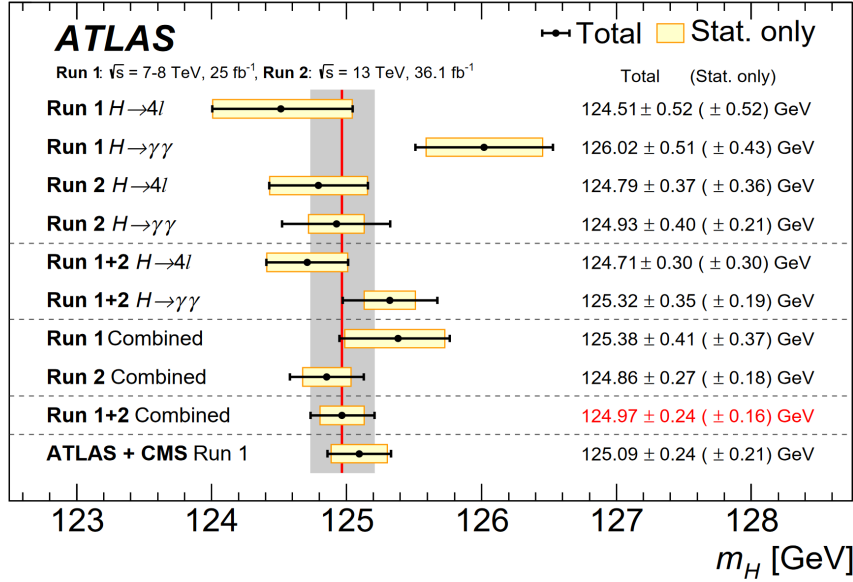


Figure 2.9: Summary of the Higgs boson mass measurements performed by ATLAS, compared with the combined Run 1 measurement by ATLAS and CMS. The (red) vertical line and corresponding (grey) shaded column indicate the central value and the total uncertainty of the combined ATLAS Run 1 + Run 2 measurement, respectively. Image credits [12].

To date, as shown in figure 2.9, the best estimate of the Higgs boson mass is:

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

This result is obtained by the analysis of the ATLAS and CMS combined Run 1 and Run 2 datasets. In addition, given the value of the Higgs boson mass, coupling properties of the Higgs boson to other SM particles, such as its production cross sections in p-p collisions and decay branching fractions, can be precisely computed within the SM. Regarding the production of the Higgs boson, the main processes are 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 couple of top anti-top quarks (t $\bar{t}$ H). Recent results on Higgs production cross section have been achieved using up to 139 fb⁻¹ of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector. The cross-section, normalized to its SM value, for each decay channel is shown in figure 2.10: the level of compatibility between the measurement and the SM prediction corresponds to a p-value

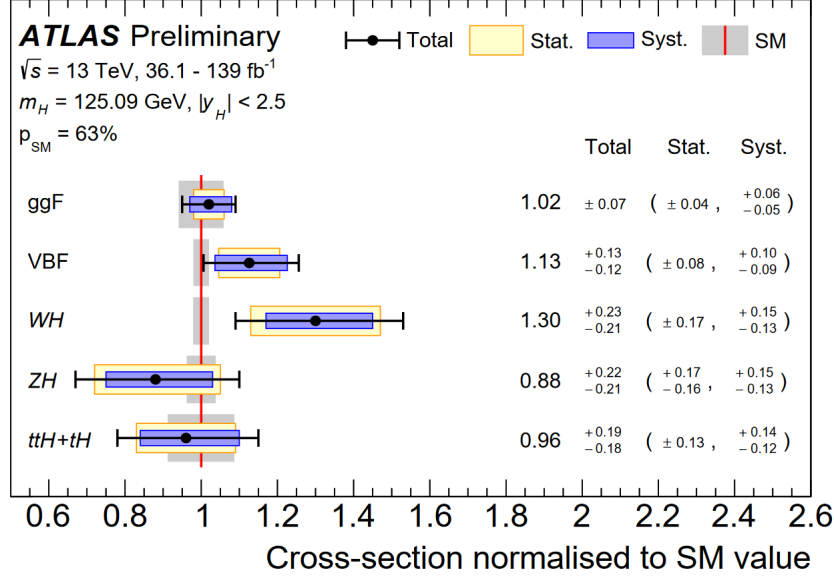


Figure 2.10: Cross sections for ggF, VBF, WH, ZH and $t\bar{t}H + tH$ production modes. The cross sections are normalised to their SM value, measured assuming SM values for decay branching fractions. Image credits [17].

$p_{SM} = 63\%$ [17]. Moreover, a description of both the production and decay mechanisms of the Higgs boson is obtained by considering the products $(\sigma \times B)_i f$ of the cross-section σ in production process i and branching fraction B to a final state f . The decay mode considered are $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, $H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$ and $H \rightarrow \mu\mu$. Production modes are the same as those listed above with WH and ZH processes joined together as they cannot be distinguished due to limited statistics. Measurements are in good agreement with SM predictions: the level of compatibility between them corresponds to a p-value $p_{SM} = 79\%$. Analysis results are reported in figure 2.11.

W/Z physics Measurements of electroweak vector-boson production at hadron colliders provide a benchmark for the understanding of quantum chromodynamic (QCD) and electroweak (EW) processes. In 2018, the W boson mass was measured by the ATLAS collaboration: the mass is obtained from template fits to the reconstructed distributions of the charged lepton transverse momentum and of the W boson transverse mass in the electron and muon decay channels, yielding: $m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.}) \text{ MeV}$ [18]. Since the W and Z cross-section predictions depend also on the Parton Distribution Functions (PDFs); they are thus sensitive to the underlying dynamics of strongly interacting particles. Therefore, measurements of W and Z bosons production offer a unique opportunity to test models of parton dynamics. Measurements were performed on the $W \rightarrow l\nu$ and $Z \rightarrow l^+l^-$ channels. Both absolute cross-sections and ratios were measured.

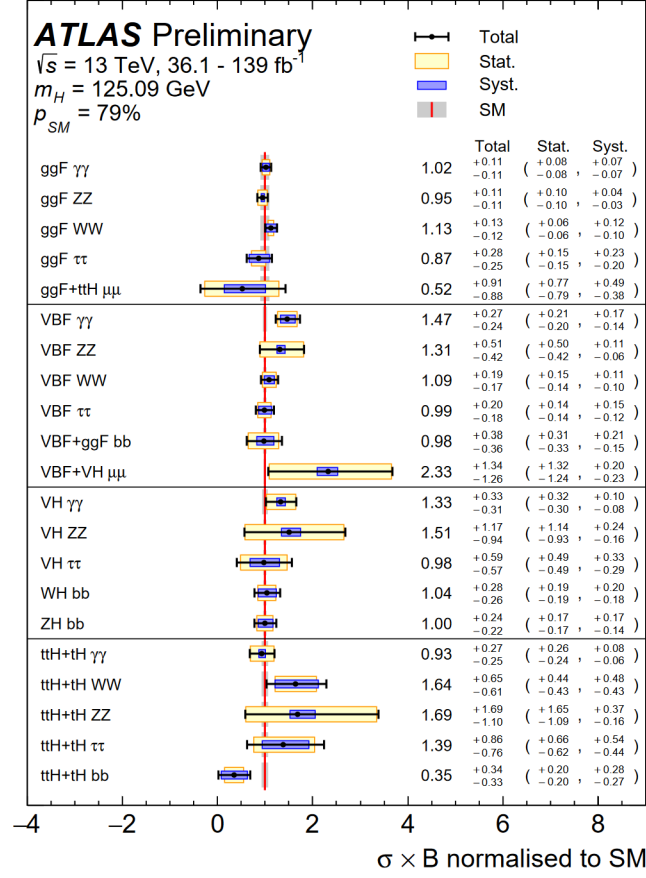


Figure 2.11: Cross sections times branching fraction for ggH, VH and $t\bar{t}H + tH$ production in each relevant decay channel, normalised to their SM predictions. Image credits [17].

The fiducial and total cross sections are found to agree with theoretical calculations based on NNLO QCD with NLO EW corrections [13].

Top quark The top quark is the heaviest of the known fundamental particles and therefore measurements of its properties are especially interesting as deviations from Standard Model predictions could be related to new physics phenomena. In ATLAS several measurements have been done. Precise measurements of the $t\bar{t}H$ coupling have been performed. The inclusive top pair production in p-p collisions is in good agreement with NNLO and NNLL prediction. Top quark mass is also measured, both directly from invariant mass and derived from the cross-section. Cross-section of $t\bar{t}$ has been measured at 5, 7, 8 and 13 TeV: results are consistent with the NLO QCD theoretical calculations and are shown in figure 2.12.

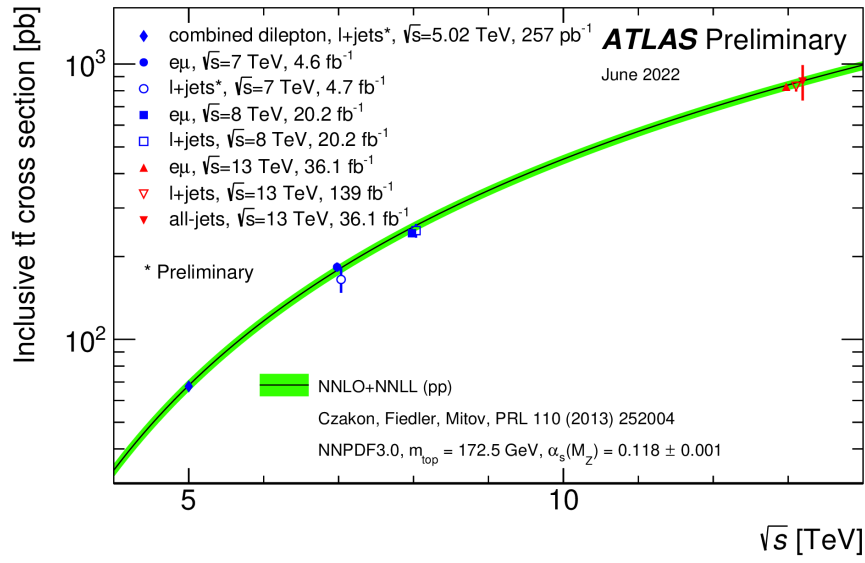


Figure 2.12: Summary of ATLAS measurements of the top-pair production cross-section as a function of the centre-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation. The theory band represents uncertainties due to renormalisation and factorisation scales, Parton density functions and the strong coupling. The measurements and the theory calculation are quoted at $m_t = 172.5$ GeV.

Chapter 3

The ATLAS inner tracker phase II upgrade

This chapter aims to provide an overview of the Phase-II ATLAS new tracker. Its layout, focusing on the pixel detector, and the expected performance will be presented.

3.1 ITk detector

For the High Luminosity upgrade of the Large Hadron Collider the current ATLAS Inner Detector will be replaced by an all-silicon Inner Tracker (ITk), installed during the Long Shut Down 3 (2026-2028), designed to face the challenging environment associated with the high number of collisions per bunch crossing. The new detector was designed to perform similar to the previous one, but in a much more hostile environment: both the level of radiation in the detector and the number of particles per square centimeter will increase by a factor of seven. To date the project has finished the prototyping phase and is about to enter into pre-production. The ITk will consist of a Pixel detector at small radius and a large area Strip detector surrounding it. The Strip detector has four barrel double-layers and six end-cap petal-design disks. The Strip detector, covering $|\eta| < 2.7$, is complemented by a 5-layer Pixel detector, composed of five barrel layers plus several endcap rings, extending the tracking coverage to $|\eta| = 4$. The ITk layout is shown in figure 3.1 and the numbers of modules/channels is summarized in table 3.1

The ITk system is much more complex with respect to the present ATLAS tracker, featuring 10 times the number of strip channels and 60 times the number of pixel channels with respect to the present system. The basic construction unit of the tracker is the module, composed of a sensor and readout electronics. The number of modules of the ITk is about five times larger with respect to the present tracker, and the surface of each module is 3 times and 7 times larger for the strip and the pixel parts, respectively. In spite of the increase in surface and complexity, the quantity of material has been reduced with respect to the present system, as shown in figure 3.2. The material reduction was obtained by using several advanced solutions. In the Pixel detector, thinner modules and inclined sections

have been implemented, together with a serial powering scheme and advanced materials for the local supports. A DC-DC powering and data transmission with optical links and lpGBT has been designed for the Strip detector. The tracking performance will benefit not only from the reduction in the quantity of material but also from the higher granularity, better hermeticity and the increased number of hits-on-track. Redundancy is very important not only to face some possible failures with time, but also to reduce the combinatorics in the reconstruction. The ITk will provide a minimum of 9 hits-on-track in the barrel, and 13 hits-on-track in the forward region, for particles with $p_T > 1$ GeV/c and $|z_{vtx}| < 15$ mm, as shown in figure 3.3.

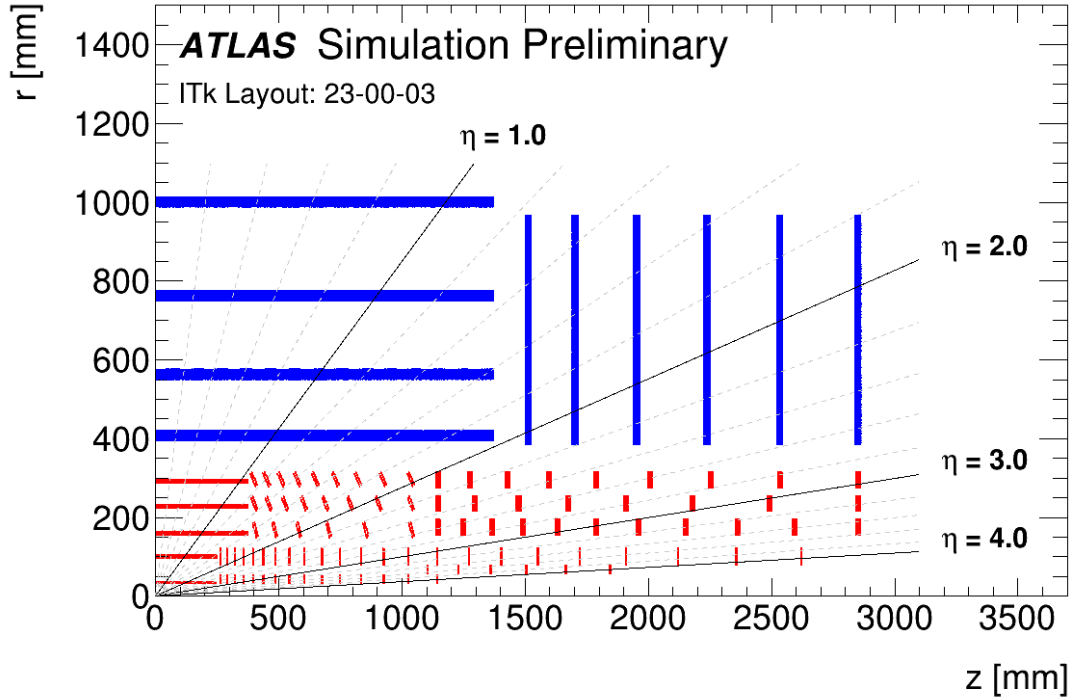


Figure 3.1: A schematic description of the ITk layout. The Strip detector is drawn in blue while the Pixel detector in red. Image credits [20]

ITk	Si [m ²]	Modules	Channels [M]	Barrel layers	Endcap disks
Strip	165	17888	60	4	6/side
Pixel	13	9164	5100	5	Several

Table 3.1: ITk surface, number of modules and channels.

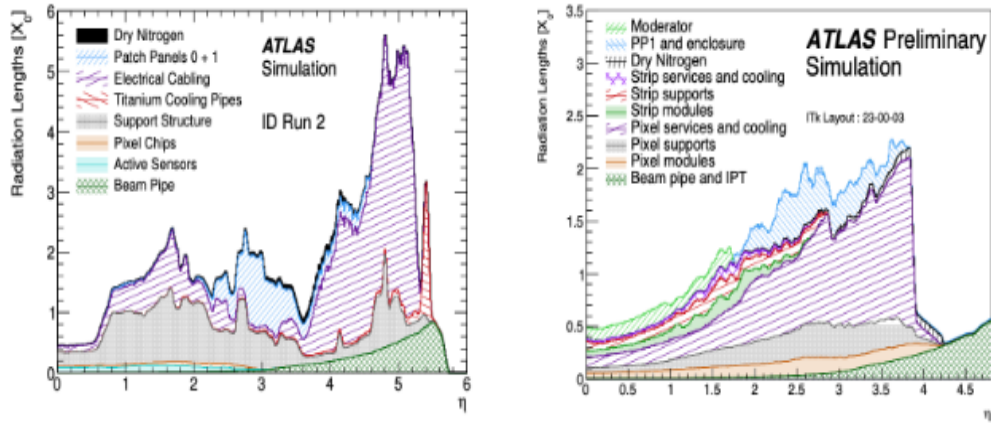


Figure 3.2: Comparison of material budget for the tracker in terms of X_0 between the present ID [left,[8]] and the current estimate for the ITk [right,[20]]. Note that the vertical scale is not the same in the two plots.

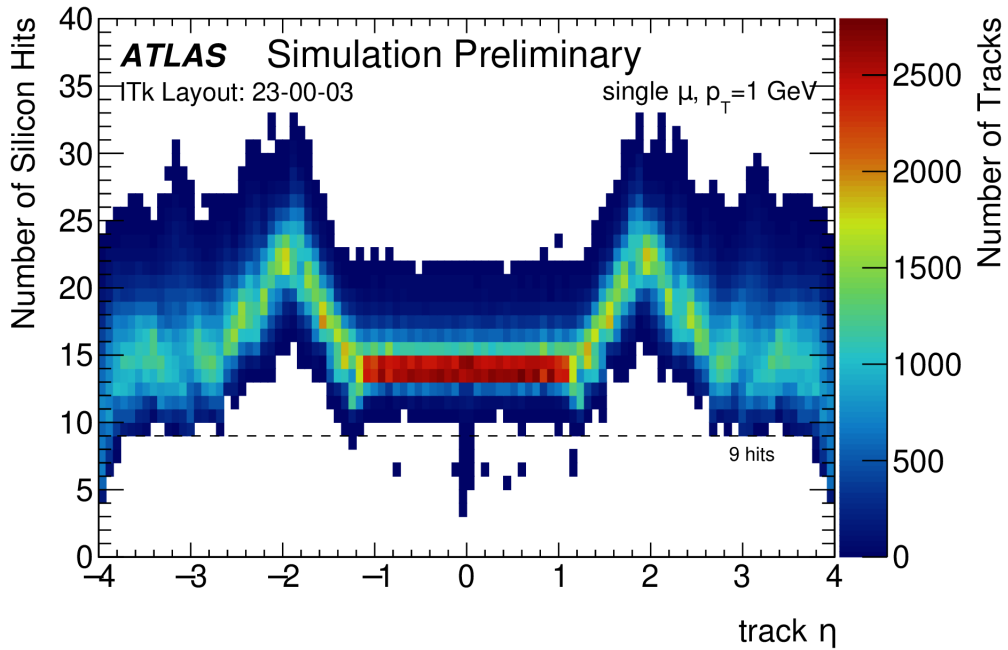


Figure 3.3: Expected distribution of hits-on-track as a function of η for particles with $p_T > 1$ GeV/c and $|z_{vtx}| < 15$ mm. Image credits [20].

3.2 ITk Pixel detector

The Pixel detector will consist of five barrel layers and a number of rings, resulting in about 13 m^2 of instrumented area. Each pixel layer comprises hybrid detector modules that will be read out by novel ASICs, implemented in 65 nm CMOS technology, with a bandwidth of up to 5 Gbit/s. Data will be transmitted on electrical cables up to the optical components on the detector periphery, and then optically to the off-detector readout system. To save material in the servicing cables, serial powering is employed for the supply voltage of the readout ASICs.

ITk Pixel layout The system is organised in three mechanically independent parts. An Inner System (IS) includes the first two innermost pixel layers and is designed to be replaced at around half the lifetime of the detector (2000 fb^{-1} , including safety factors); an Outer System (OS) includes an Outer Barrel (OB) with the three outermost pixel layers of flat staves and inclined sections, and two Outer Endcaps (EC), built by three pairs of concentric half-shells per side hosting half-rings populated with modules. The Outer System will not be replaced and is designed to survive until the end of the HL-LHC program (4000 fb^{-1} , including safety factors). The ITk pixel layout is shown in figure 3.4.

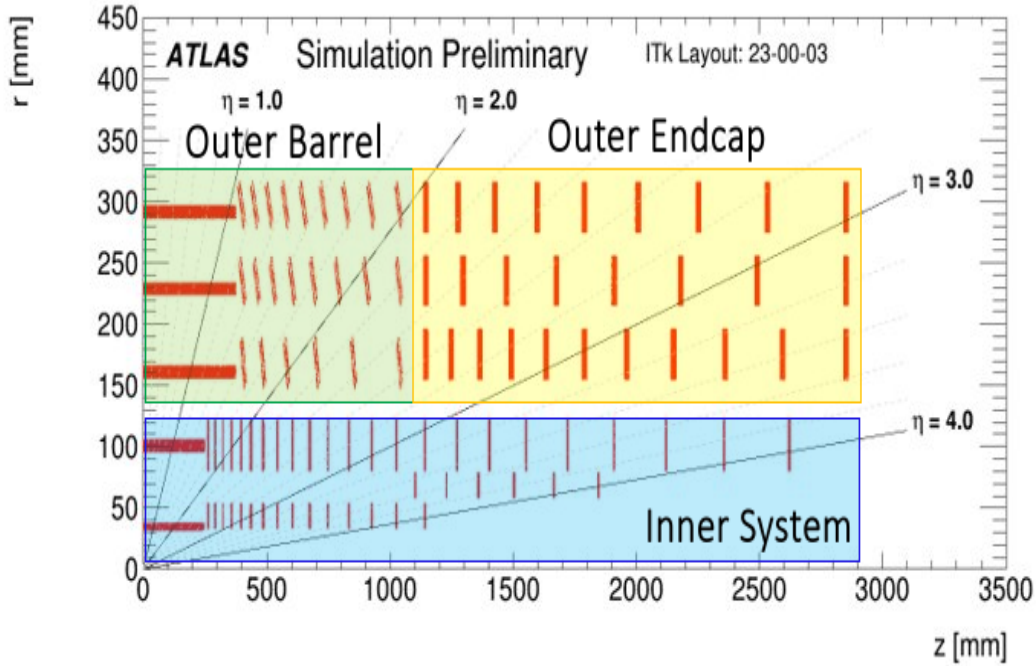


Figure 3.4: A schematic description of the ITk pixel layout. Image credits [20]

Pixel sensors Two different technologies have been chosen for the ITk pixel sensors: 3D sensors, which will populate the innermost layer (Layer 0 - L0), and planar sensors, which will be used in all others layers.

The 3D sensors were already used for the IBL upgrade, but 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 about the 3D sensors will be presented in section 5.1.1). The thickness of the active substrate is reduced to 150 μm , compared to the 230 μm of the IBL, allowing for a 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 μm of mechanical wafer are kept after sensor back thinning to improve the mechanical structure. The pixel cells are $25 \times 100 \mu\text{m}^2$ in the barrel part and $50 \times 50 \mu\text{m}^2$ in the forward parts to optimise the tracking capability with an acceptable increase in the production complexity and cost. The radiation hardness of the 3D sensors has been tested with irradiation campaigns and test beam characterization up to a fluence of more than $1 \cdot 10^{16} \text{n}_{eq}/\text{cm}^2$, showing a cluster efficiency larger than the ITk specification of 97% with a low operational bias voltage (80 to 140 V) and a low power dissipation ($< 10 \text{ mW}/\text{cm}^2$ at the operational temperature of -25°C).

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 μm for the Layer 1 in the Inner System (L1) and 150 μm for the outer layers L2-L4 in the OB and OE, compared to the 200 μm 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 performance of planar sensors have been demonstrated to match the ITk specifications of reaching a hit efficiency of 97% at the end-of-life bias voltage of 600 V (400 V) for the 150 μm (100 μm) sensors after irradiation to $5 \cdot 10^{15} \text{n}_{eq}/\text{cm}^2$.

A comparison between IBL and ITk sensors is summarized in table 3.2.

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

Table 3.2: Comparison between IBL and ITk sensors

Pixel modules Module 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, giving a bare module. The second step is the module assembly, where a flexible

circuit (flex) is glued to the bare module and connection to the front-end chips is established through wire bonding. The flex is then used to connect the module to the on-detector services. Groups of different modules are then organised from the electrical point of view in a Serial Powering (SP) chain. Detailed information about the ITk read-out chips will be presented in section 5.1.2.

The module design is different for 3D and for planar sensors. In the first case, 3 single-chip bare modules are connected to the same flex in a *triplet* (linear or ring-shaped depending on the final location in the detector); for the planar pixels, a single large sensor tile is flip-chipped to four front-end chips (*quad module*). All the planar layers feature a single common design for the modules, just the pigtails connecting the modules to the services depend on the module position in the detector. After the assembly, on the planar modules, a protective parylene layer is deposited on the surface. This layer will provide isolation, preventing electrical discharge between the sensor and the front-end. It will also be useful to provide additional mechanical stiffness to the wire bonds and will prevent corrosion effects.

Pixel local support Different designs of Local Supports are used for the different Pixel subsystems. The Inner System is based on Inner Staves and Coupled Rings in the barrel, while in the forward regions two additional flavours of ring design are used. The staves and the rings are hosting the linear triplets or the ring triplets in Layer-0 and the thin planar quads of Layer-1. The local supports for the Outer Barrel are organised with linear longerons and inclined half rings. One peculiarity of the Outer Barrel is that the modules are not directly glued to the local supports, but they are installed on high thermal conductive graphite cells, which are in turn installed on the local supports. This will allow reworkability of modules. In the Outer Endcaps the local supports are organised in double-sided half rings hosting the modules.

Pixel data transmission Data from the pixel modules are flowing at 1.28 Gbps on electrical twinax cables from the module flex to the optoboards located outside the detector, at a distance of up to 6 m. Here data are converted to optical signals and transmitted to the data acquisition system. A test bench has been built to demonstrate the data transmission chain, based on some prototype components, or more advanced parts whenever they were available. Results obtained with this setup are very good (Bit Error Rate $< 0.2 \cdot 10^{-12}$, to be compared with a specification of 10^{-12}). In general, several large-scale demonstrators are used to assess system-level functionalities. These setups allow to study thermo-mechanical performance of local supports loaded with modules, comparing experimental data to simulation to test the electrical behaviour of Serial Powering chains, the data flow model in general and, last but not least, the loading and integration procedures which will be used for the final tracker.

3.3 ITk expected performance

This section provides a short overview of the most important expected tracking performance.

Tracking efficiency The tracking efficiency obtained with the ITk layout is presented in figure 3.5 for 100 GeV muons without pileup and is very compatible with the one obtained with the Run 2 detector for $|\eta| < 2.4$. This result shows that the tracker is "airtight".

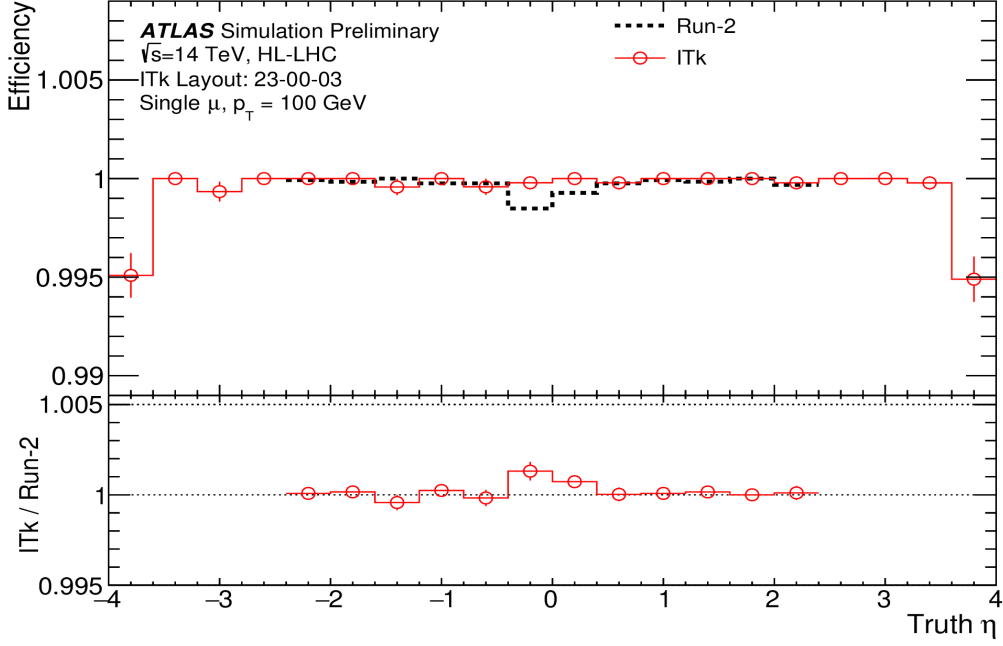


Figure 3.5: Tracking efficiency for single muons with $p_T=100$ GeV without pileup. The results are compared for muons between the Run 2 detector and the current ITk layout. Image credits [20]

Tracking fake rate Figure 3.6 shows the number of reconstructed tracks with $p_T > 1$ GeV/c at a pileup $< \mu > = 200$ for $t\bar{t}$ events. As displayed, this quantity exhibits a very linear behavior in the ITk detector, illustrating at the same time the robustness of the tracking efficiency over a large pileup range and the negligible tracking fake rate, estimated around 10^{-4} , in spite of the $< \mu > = 200$ environment. It should be noted that the optimization of the tracking software in preparation of the Run 3 data-taking has already significantly reduced the fake rate with respect to what is presented here as the Run 2 configuration.

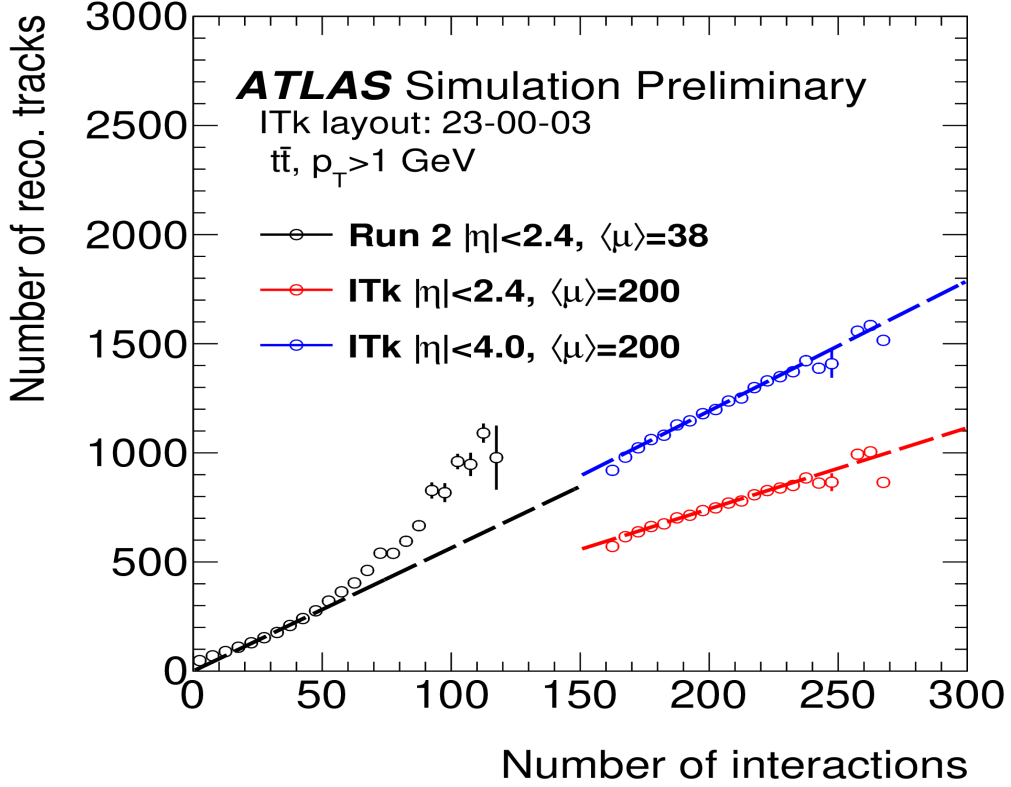


Figure 3.6: Number of reconstructed tracks per event with $p_T > 1$ GeV for $t\bar{t}$ events at $\langle \mu \rangle = 200$ with the updated ITk layout compared with the Run 2 detector at $\langle \mu \rangle = 38$. The dashed lines illustrate the results of the linear fit performed over the limited 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. Image credits [20]

Track parameter resolution Figures 3.7a and 3.7b present the ITk expected track parameter resolutions for the transverse (d_0) and longitudinal (z_0) impact parameters and the transverse momentum for simulated muons with $p_T = 100$ GeV, compared to the Run 2 ATLAS tracker performance. Thanks to the smaller pixel pitch used in the ITk Pixel detector, the d_0 and z_0 are respectively improved by a factor 2 and 4. The transverse momentum resolution (figure 3.7c) is expected to outperform the Run 2 resolution thanks to the improvements in the bending direction associated with the silicon strip sensors used in ITk, compared to the straw tubes used in the Run 2 ID [20].

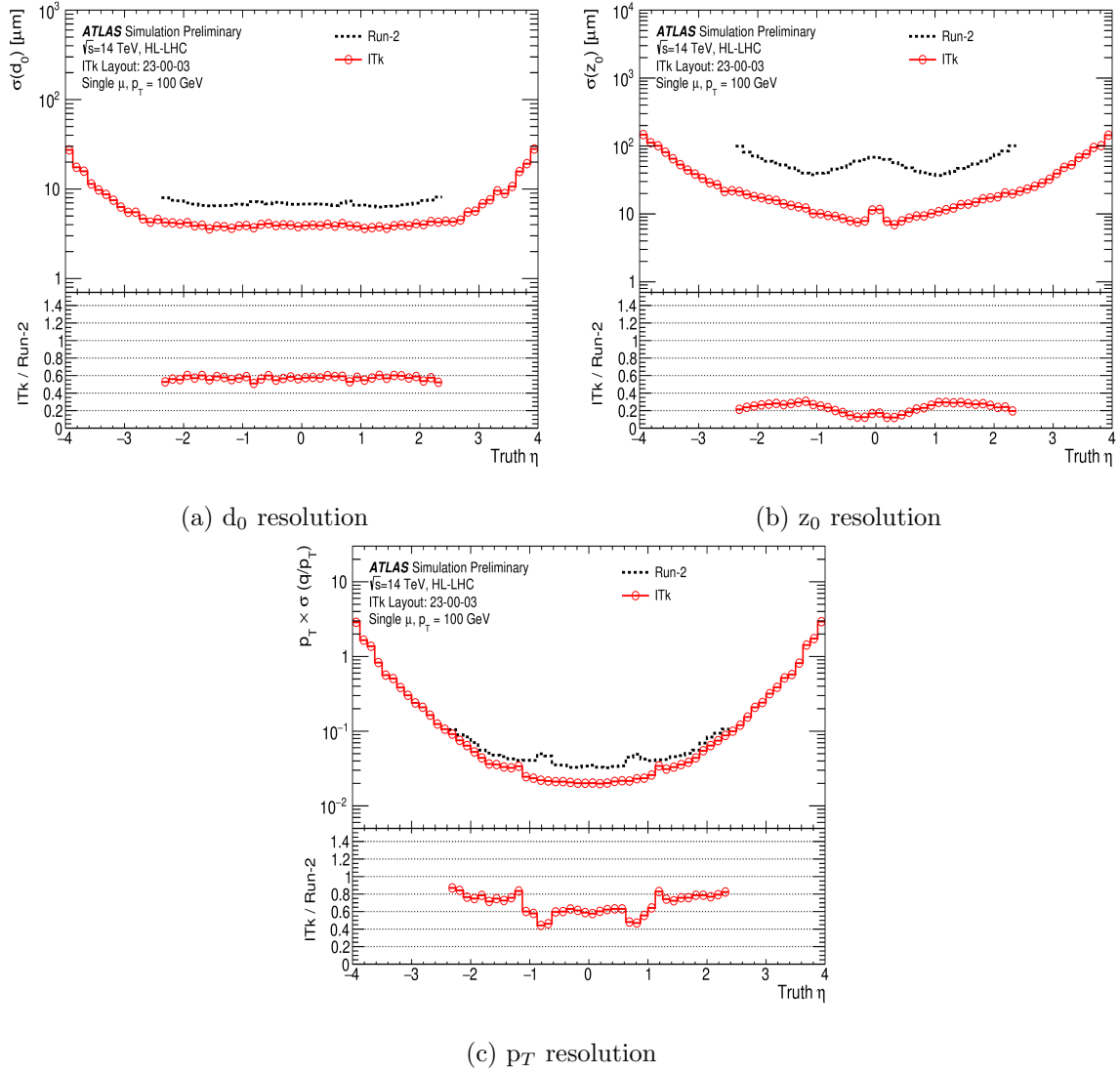


Figure 3.7: Transverse impact parameter (d_0) (a), longitudinal impact parameter (z_0) (b) and transverse momentum (p_T) (c) resolution as a function of η for 100 GeV muons without pileup, compared between the Run 2 detector and the updated ITk layout. Image credits [20].

Chapter 4

Silicon detectors

This chapter aims to give a brief overview of the operation and the design of silicon detectors in high-energy physics.

Semiconductor detectors allow for reconstructing the trajectory of charged particles, their use for this purpose became relevant from the 1970s. Silicon is cheaper than other semiconductors and can be found in great abundance. Therefore it has become the most used material for building large area tracking systems. In a silicon detector the signal is formed by collecting electron-hole pairs produced along the path of the charged particle through the active part of the detector. Silicon detectors have many advantages over gas detectors, which are also used for particle tracking. In particular, silicon detectors are faster ($\sim$ ns, to collect the signal) thanks to the smaller distance between the electrodes and to the larger speed of moving carriers. They also have a lower ionization energy and a much larger density, these features facilitate the collection of the signal. Moreover, high detector segmentation is possible and this allows much lower spatial resolutions ($\sim$ 1-10 μ m). However, there are also some disadvantages compared to gas detectors. Covering a large area with a gas detector is cheaper and gas mixture can be easily replaced to maintain high performance, while silicon crystals are increasingly damaged by radiation: in this case, the whole silicon detector should be replaced. Finally, a silicon detector may require cooling to be operated at low temperatures.

4.1 Interaction of particle with matter

An introduction about charged particle interaction with matter is needed before talking about the operation of silicon detectors. The most relevant interaction mechanisms of a charged particle with matter for the construction of a silicon tracking detector are: the loss of energy by ionization and the multiple scattering. Most of the information in the following paragraphs is taken from the reference [21, 22, 23].

Energy loss of charged particles The basic principle of all tracking devices is to detect the free charge resulting from the ionization of a medium due to a passing charged particle.

Ionization is due to the interaction between the charged particle and the electrons of the medium. The mean energy loss per unit length of a charged particle due to ionization is well described by the Bethe-Bloch formula:

$$-\left\langle \frac{dE}{dx} \right\rangle = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A\beta^2} \left[\frac{1}{2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta(\gamma)}{2} \right] \quad (4.1)$$

where:

- $\frac{dE}{dx}$ 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} is the maximum kinetic energy which can be imparted to a free electron in a single collision,
- $\delta(\gamma)$ is the density correction effect.

In the Bethe-Bloch formula, the $1/\beta^2$ term is dominant for low energies. The mean energy loss by ionization shows a minimum at $\beta\gamma \sim 3$, as shown in figure 4.1. A particle with an energy loss corresponding to the minimum of the Bethe-Bloch formula is called Minimum Ionizing Particle (MIP). A MIP penetrating into the detector is responsible for a uniform ionization along its path. Note that the Bethe-Bloch formula predicts the average value of the energy deposition distribution per unit length, but it can not describe the the behaviour of a single particle because of the stochastic nature of energy loss. 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.

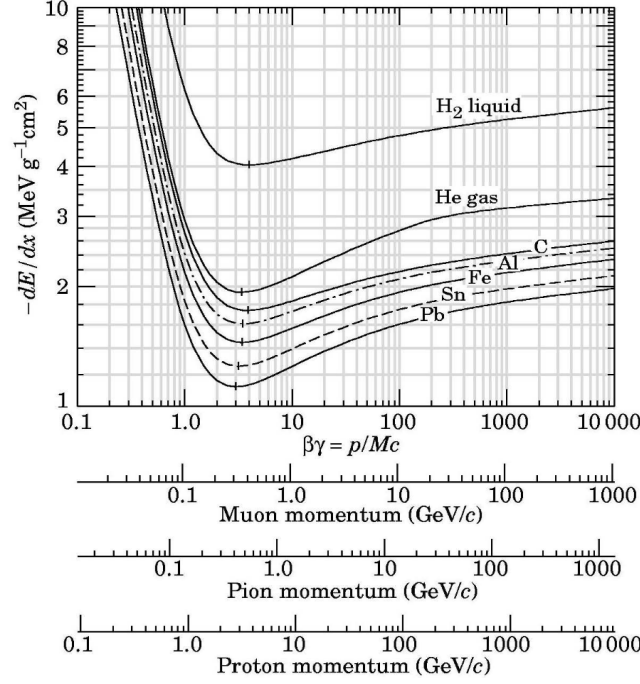


Figure 4.1: Bethe-Bloch energy loss for different particles in different materials as a function of their energy.

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 which are needed to promote an electron 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 .

Multiple scattering In addition to elastic collision with the atomic electrons, charged particles passing through matter also suffer repeated elastic collisions with nuclei, although with a much smaller probability. The scattering angle, after many interactions, roughly follows a Gaussian distribution with an RMS value of:

$$\theta_{RMS} = \frac{13.6 \text{ MeV}}{\beta p c} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right) \right] \quad (4.2)$$

where θ is the angle expressed in rad, p is the momentum of the particle in MeV, β is the velocity of particle expressed in natural units, z is the charge number of the considered particle and x/X_0 is the thickness of the absorption medium in units of radiation length. The radiation length of the silicon is 9.36 cm. In order to maximize the resolution in a tracking detector it is important to minimize the x/X_0 i.e. to build a detector as light as possible.

Photon interaction with matter Photons interact with matter mainly via three different processes:

- Photoelectric effect,
- Compton scattering,
- Pair production.

In the photoelectric effect and pair production, the photons are completely absorbed, while in Compton scattering their trajectory is deflected by the interaction with the electron.

A monochromatic photon beam penetrating through a material is not only changed in energy but it is also attenuated according to the law:

$$I(x) = I_0 \exp(-x/\mu) \quad (4.3)$$

where I_0 is the beam intensity before interacting, $I(x)$ is the beam intensity after traversing a thickness x through the material and μ is the attenuation length. The attenuation length is a material property, it can be expressed in function of the cross-section σ of the different interactions:

$$\mu = \mu_{photo} + \mu_{Compton} + \mu_{pair} = \frac{\rho}{uA} (\sigma_{photo} + \sigma_{Compton} + \sigma_{pair}) \quad (4.4)$$

where ρ is the material density, A is the atomic mass of the traversed material and u is the atomic mass unit.

Silicon is sensible to electromagnetic radiation from visible light up to the X-ray range.

4.2 pn-junction

Silicon is a crystalline material whose outer shell atomic levels have an energy band structure, two bands are present: a valence band, where bonded electrons are located, and a conduction band, with free electrons. The two bands are separated by an energy gap without energy levels. The energy gap is determined by the lattice spacing between the atoms and it changes with temperature and pressure.

In the lowest energy state, all the electrons in the valence band participate in covalent bonding between the lattice atoms. However, thermal action can excite an electron into the conduction band leaving a hole in its original position, so the next neighbouring electron in the valence band can jump and fill the hole: in that way the hole acts as a positive charge carries in the valence band. Free electrons act instead as the negative carries in the conduction band. Part of the electron-hole pairs generated by thermal energy recombine, at the equilibrium concentrations are the same. The concentration n_i of electron-hole pair is well described by the formula:

$$n_i = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2k_B T}\right) = AT^{3/2} \exp\left(\frac{-E_g}{2k_B T}\right) \quad (4.5)$$

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 build a performant silicon detector the number of intrinsic carries should be compared with the number of electron-hole generates by the passage of a charged particle. Let's suppose to have a MIP crossing a thickness $d = 300 \mu$ of silicon with an area $A = 1 \text{ cm}^2$ at 300 K. Silicon mean ionization energy is $I_0 = 3.6 \text{ eV}$ and the mean energy loss of a MIP is $dE/dx \sim 3.87 \text{ MeV/cm}$. So we will have:

$$\begin{aligned} \text{Signal charge} &= \frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6 \text{ eV/cm} \cdot 0.03 \text{ cm}}{3.62 \text{ eV}} \simeq 3.2 \cdot 10^4 \text{ } e^- h^+ \text{ pairs} \\ \text{Intrinsic charge} &= n_i \cdot d \cdot A = 1.45 \cdot 10^{10} \text{ cm}^{-3} \cdot 0.03 \text{ cm} \cdot 1 \text{ cm}^2 \simeq 4.35 \cdot 10^8 \text{ } e^- h^+ \text{ pairs} \end{aligned} \quad (4.6)$$

In that way the number of thermally generated electron-hole pairs is 4 orders of magnitude larger than the signal. The best way to reduce the intrinsic carrier charge is forming a reverse biased pn-junction possibly cooled.

Reverse biased pn-junction The silicon generally shows a low intrinsic conductivity that must be artificially increased to be used in a device. To modify its conductivity, usually, elements from III Group (i.e. Boron; also called *acceptors*) or V Group (i.e. Phosphorus, Arsenic; also called *donors*), having respectively one valence electron less (p-type) or more (n-type), are used. To build a pn-junction a p-type and n-type silicon are combined as shown in figure 4.2.

In the region of transition between n-type and p-type doped silicon, the majority of charge

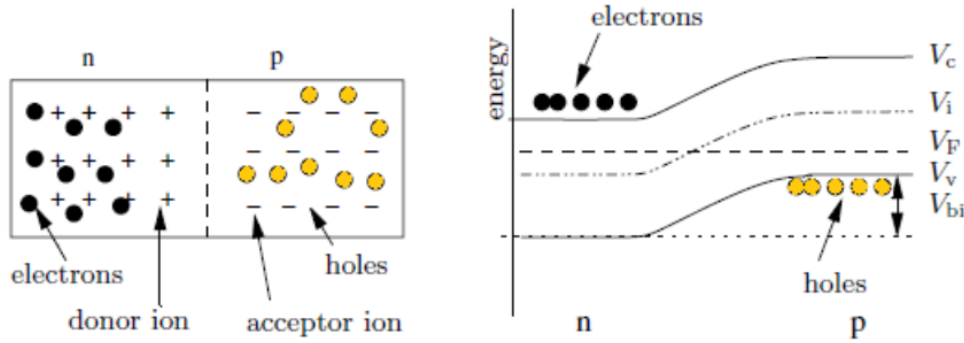


Figure 4.2: Sketch of p-type and n-type silicon in a pn-junction (left). Band diagram of a pn-junction (right). Image credits - [21].

carriers will diffuse from one side into the other, where they will recombine. That produces

a region, close to the interface, depleted from free charge carries [21]. In that region, also called the depletion region, donors and acceptors ions are left without their balancing charges: this induces the formation of an electric potential, the so-called built-in-Voltage V_{bi} , characterized as follows:

$$V_{bi} = \frac{k_B T}{e} \ln \left(\frac{N_A N_D}{n_i^2} \right) \quad (4.7)$$

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

If a negative potential, usually called V_{bias} , is applied to the p-side, the pn-junction is reverse biased, a current starts to flow in the reverse biased pn-junction: the so called leakage current. Thanks to the reverse bias the majority carriers from either side will be further remove and this will extend the depletion region. The width W of that region and the electric field can be evaluated using a one-dimensional Poisson equation, the result is a function of V_{bias} , V_{bi} and N_D , N_A :

$$W = x_p + x_n = \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_{bias} + V_{bi})} \quad (4.8)$$

where x_p and x_n are the extension of the depletion region on the n and p sides, respectively. A silicon detector is generally built with pn-junction realized by a low-doped material ($N_A \sim 10^{12} \text{ cm}^{-3}$) in which highly doped ($N_D > 10^{18} \text{ cm}^{-3}$) electrodes are implanted. Assuming a p-type bulk material, it is possible to neglect the term $1/N_D$ in equation 4.8. Moreover, since V_{bi} is in the order of 0.5 V, very small compared to typical operation V_{bias} , in the order of 10-100 V, the equation 4.8 can be further simplified:

$$W \simeq \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e N_A} V_{bias}} \quad (4.9)$$

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

$$E_{max} = \frac{2V_{bias}}{W} \quad (4.10)$$

The voltage bias value at which the electric field at the junction will reach critical values (i.e. E_{max}) is the so called breakdown voltage (V_{bd}). For V_{bias} values exceeding this limit, the so-called avalanche effect starts: 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. This avalanche effect will lead to a large increase in the leakage current of the device. The leakage current is therefore the results of the volume generated current, the surface generated one and the avalanche breakdown contribution, as shown in figure 4.3. The plot of the leakage current in function of the voltage bias is known as IV curve.

Using pn-junctions as a detector The reversely biased pn-junction is the basic element of silicon sensors. As an example, a pixel sensor can be seen as a reversely biased pn-diode.

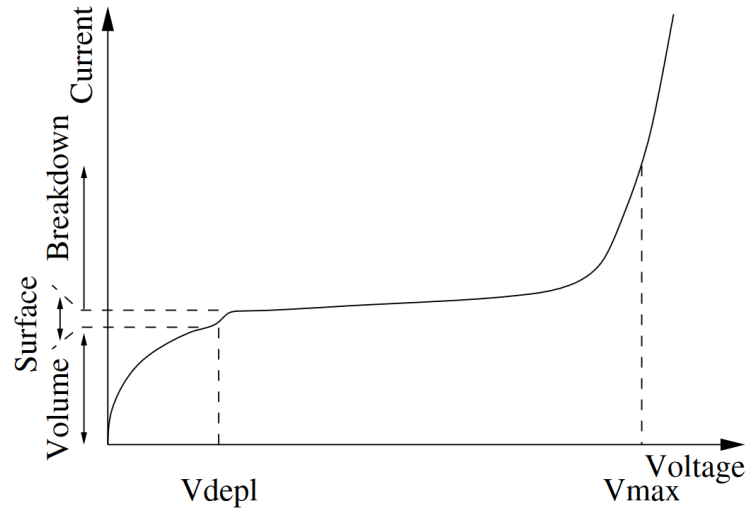


Figure 4.3: Typical shape of a silicon sensor IV curve with indication of the origin of different current contributions. Image credits [21].

It exploits the absence of intrinsic carriers in the depletion zone to have a good signal-to-noise ratio at the passage of a particle. Figure 4.4 shows the basic configuration used for operating a junction diode as a radiation detector. In order to be able to collect the charges produced by radiation, electrodes must be fitted onto the two sides of the junction. To prevent the formation of a rectifying junction with a depletion zone extending into silicon, a heavily doped layer of n-type and p-type material is used between silicon and the metal leads. To collect the charge signal from the detector, a pre-amplifier of the charge-sensitive type is generally used. Because of the low level of the signal, this pre-amplifier must have low-noise characteristics. Signal processing after the pre-amplifier also requires pulse shaping in order to obtain the best signal-to-noise characteristics [22].

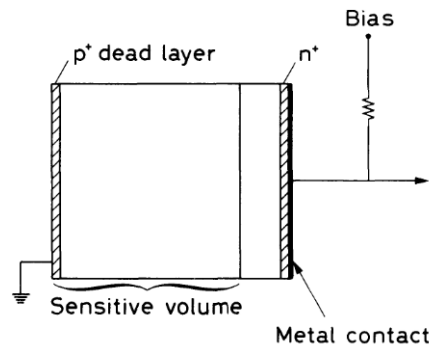


Figure 4.4: Basic layout of a junction diode detector. Image credits [22]

Radiation-induced effects on silicon Tracking devices are mostly used in the innermost regions of collider experiments. The high density of particles, in combination with the high repetition rates, exposes the detectors to high levels of radiation that impair the properties of silicon crystals by degrading their performance. Radiation-induced effects (radiation damage) are usually divided into bulk and surface defects. The former is caused by the displacement of crystal atoms while the latter includes all effects in the covering dielectrics and the interface region [21]. The main effects of radiation damage are:

- Increase of the leakage current,
- Change of the space charge in the depleted region (such as the type inversion) and subsequent increase of the full depletion voltage,
- Charge trapping, which makes it more difficult to collect the signal.

4.3 Design of silicon detectors

By using a simple silicon diode with only two electrodes, it is possible to detect the passage of a particle, but not its position. To have this additional information, two different solutions, concerning the design of the sensors, can be taken. The two different designs are sketched in figure 4.5 and consist of a strip geometry and a pixel geometry.

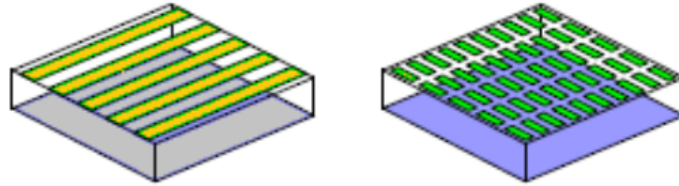


Figure 4.5: Strip (left) and pixel (right) sensor geometry. Image credits [23]

Strip geometry A strip detector is a pattern of strip-like shaped implants acting as charge-collecting electrodes. Placed on a low-doped fully depleted silicon wafer these implants form a one-dimensional array of diodes. By connecting each strip to a charge amplifier, a 1D position-sensitive detector is built. It is possible to build a 2D position-sensitive detector by placing a second array of strip-like implants on the backside of the silicon wafer, as shown in figure 4.6. Since double side strip detectors can record X and Y coordinates they are subject to the so-called ghost problem: in case of n hits, n pair of coordinates will be generated related to n^2 hits, but $n^2 - n$ of which are fake. A simple way to overcome this problem is to use a small stereo angle between opposite side strips instead of 90° . The time resolution of strip detectors is of the order of 10 ns, but if there are multiple events within

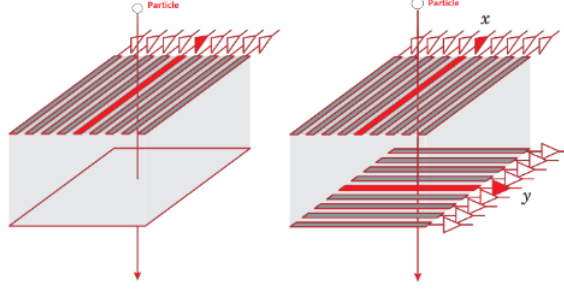


Figure 4.6: Single side (left) and double side (right) segmentation strip. Image credits [23].

one readout period, the position is not assigned without ambiguity. So, for regions with large hit occupancy, such as close to the interaction point, strips are not the best solution and a pixels detector must be used.

Pixel geometry Pixel detectors are an array of reverse biased pn-junction with electrodes segmented in both directions: this geometry allows reconstructing the X and Y coordinates of a crossing particle without ambiguity. Each pixel cell must be equipped with the Front-End (FE) electronics which are responsible for signal read-out. The electronics could be integrated directly into the same pixel cell of the sensor, in this case we have the so-called monolithic pixel detector. Alternatively, the electronics can be produced in separate wafers, then the sensor pixel has to be connected to the read-out chip cell with small solder bumps, obtaining the hybrid pixel detector. 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 case of binary read-out, the pixel spatial resolution can be simply related to the pixel pitch as:

$$\sigma_{pixel} = \frac{pitch}{\sqrt{12}} \quad (4.11)$$

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

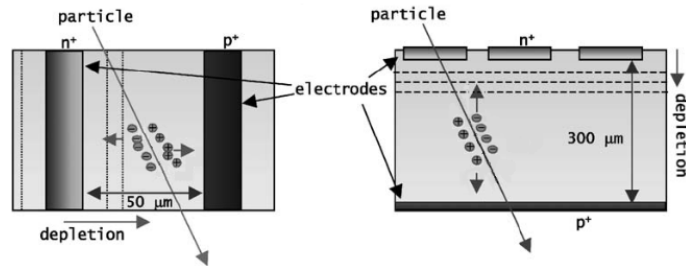


Figure 4.7: Comparison between a 3D and a planar sensor. Image credits [23].

Two main families of pixel sensors are used for high-energy physics experiments, figure 4.7: planar sensors and 3D sensors. The planar sensors generally 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. While in 3D sensors, the electrodes are implanted vertically by drilling columns 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 implies 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.

Chapter 5

ITk Pixel modules Qualification

This chapter focuses on the qualification done, both in Genova laboratory and with tests with beam, on several ITk pixel modules. These are hybrid pixel modules equipped with the ITkPixV1.1 chip and the very first 3D pre-production sensors made by FBK (Fondazione Bruno Kessler). Results of the chip and the sensor performance will be shown for both unirradiated and irradiated samples.

These devices are the first assemblies with pre-production sensors and readout chips ever qualified after irradiation by the ITk Pixel community. Results of these measurements demonstrate the excellent radiation hardness of this new generation of 3D pixel sensors that will enable the project to proceed with the production for the ITk tracker.

5.1 ITk 3D pixel sensors

Sensors shall be interconnected to the ATLAS ITk pixel front-end chips which impose a maximum capacitance per pixel of 100 fF. In the innermost layer, the 3D modules are attached in groups of three to a single flex readout board (triplet) sharing the same bias voltage line connecting them in series [24]. As mentioned above, the innermost layer imposes strict requirements in terms of performance after irradiation. With the current replacement strategy, the fluence for the innermost pixel layer will exceed $1 \cdot 10^{16} n_{eq}/cm^2$. 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 barrel of the ITk detector). During the whole lifetime of the detector, the power dissipation performance of the 3D sensors shall 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.

Single-side approach For the fabrication of 3D sensors, the electrodes are implanted vertically by drilling columns inside the bulk material using Deep Reactive Ion Etching (DRIE) lithography processes. The p^+ and n^+ columns may be drilled starting from the two opposite sides of the silicon substrate (double-side approach) or starting only from one

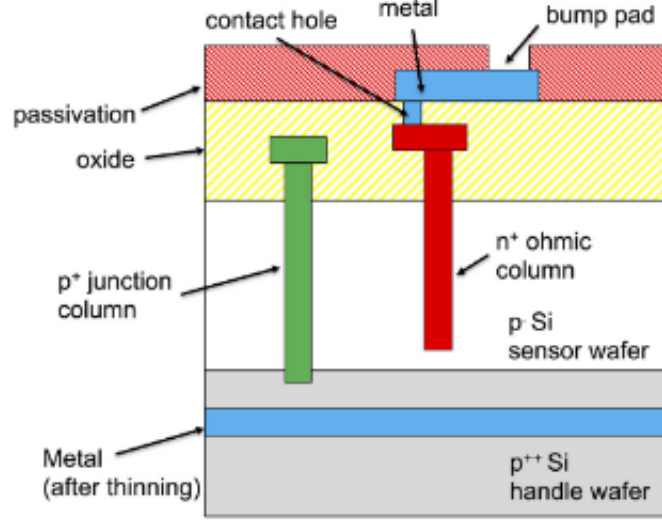


Figure 5.1: Transverse section of 3D pixel sensor made from Si-on-Si bonded wafer. All the columns are etched from the same side. The handle wafer is thinned down to the desired thickness before depositing a thin metal layer on the backside. Image credits [24]

(single-side approach). Double-sided technologies, which proved to offer several advantages in terms of process complexity and throughput for the IBL production, are not favored for the fabrication of thin 3D pixels, due to mechanical integrity considerations and larger yield for such a large 3D detector. As a result, a single-side approach with a support wafer has finally been adopted by all the processing foundries. All columnar electrodes are etched from the front-side and are (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, whereas the ohmic (bias) columns are etched deeper and penetrate into the handle wafer. By doing so, the sensor bias can be applied from the back-side, which is definitely an advantage for the assembly of the sensors in a real detector system. In order to reduce the material in this critical layer for the tracking performance, the handle wafer is partially removed as a post-processing step. A thin portion of it could be left to allow a back-side metal to be deposited for the application of the bias voltage. A schematic cross section of a device in this latter configuration is shown in figure 5.1. Note that surface insulation layers (p-stop or p-spray) are not shown.

Pixel cells On one hand, small pixel cells involve small inter-electrode distances, which inherently improves the radiation hardness, since they reduce the drift length of charge carriers. On the other hand, a high density of columnar electrodes could also result in a loss of geometrical efficiency, since the electrodes themselves are not efficient, as well as in an increase of the sensor capacitance (and noise). However, both these problems are attenuated by the use of thin active layers. The electrode capacitance scales with its depth

to a large extent, so thinner substrates naturally lead to smaller capacitance. Moreover, assuming a constant aspect ratio (depth to diameter) attainable with DRIE processing (typical values range from $\sim 20:1$ to $\sim 30:1$), thinner substrates allow for narrower electrode diameters (typical values range from ~ 5 to $\sim 8 \mu\text{m}$), that also contribute to decrease the capacitance and improve the geometrical efficiency [25]. The layout of the pixel cell, specific to the FBK technology, is presented in figure 5.2 for three considered geometries in the R&D phase program. The three pixel cells differs 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, therefore significantly impacting the radiation hardness of the devices (figure 5.3). It can be seen that the main constraint is due to the fixed size ($\sim 20 \mu\text{m}$ diameter at the metal level) of the bump pads, which is relatively large with respect to the pixel cells size. In addition, it should be noted that also the pad foot print is fixed due to the layout of the readout chip ($50 \times 50 \mu\text{m}^2$). While this is not an issue with the 25×100 -1E and 50×50 -1E pixels, it represents a critical problem in 25×100 -2E pixels, where the bump pads are very close to both the readout and the ohmic columns. This makes the layout very sensitive to lithography misalignment of just a few micrometers, that are typically achieved with mask aligners, making it difficult to obtain a good fabrication yield.

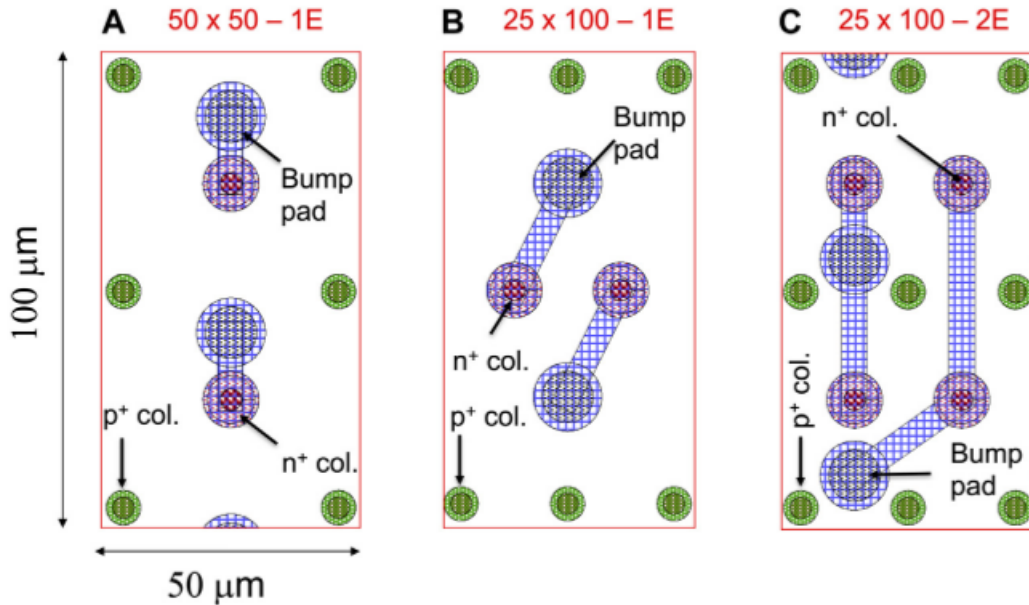


Figure 5.2: Layout of 3D sensors pixel cell: A) $50 \times 50 \mu\text{m}^2$ 1E. B) $25 \times 100 \mu\text{m}^2$ 1E. $25 \times 100 \mu\text{m}^2$ 2E. Image credits [24]

Vendors Prototyping of 3D pixel sensors, compatible with RD53A chips, have been carried out at CNM (Spain-Barcelona), FBK (Italy-Trento) and SINTEF (Norway-Trondheim).

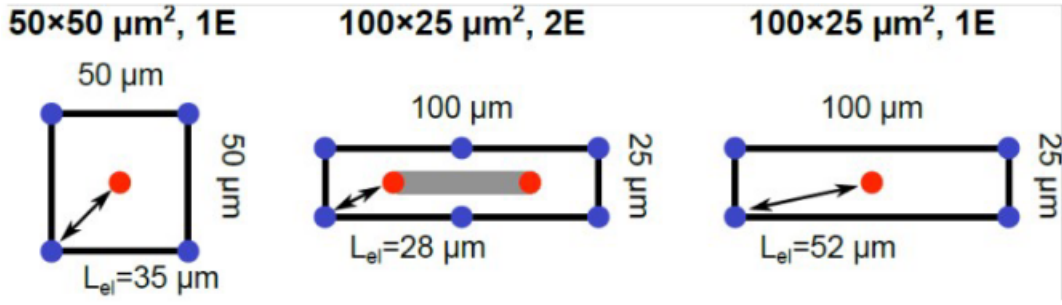


Figure 5.3: Different inter-electrodes distance of 35, 52, and 27 μm for 50x50-1E, 25x100-1E and -2E respectively

FBK and SINTEF will produce the sensors on six inch wafers (24 sensors per wafer), while CNM on four inch ones (9 sensors per wafer). The prototype results for the three vendors met the requirements and it was thus possible to move to the pre-production phase. In the tender, it was agreed that FBK and SINTEF will produce the 50x50 μm^2 endcap sensors, while CNM will produce the 25x100-1E μm^2 barrel sensors. Note that for the ITk sensors the edge termination is obtained with a 150 μm p-type column fences (figure 5.4). FBK has been the first vendor to deliver pre-production sensors in Summer 2021. Results on unirradiated and irradiated pre-production 3D sensor will be presented in the following sections.

5.1.1 FBK from prototypes towards pre-production

FBK started to develop 3D sensor technologies on four-inch wafers in 2004, in collaboration with Istituto Nazionale di Fisica Nucleare (INFN). For a few years the focus was on the ATLAS IBL 3D pixel production. After its completion in 2013, FBK updated its clean room to allow production on six-inch wafers (improving the sensor throughput) and the focus was moved towards the prototyping for the ITk project.

Prototyping FBK first prototypes for ITk were produced using mask aligner lithography. A mask aligner is a precision machine tool used in the semiconductor manufacturing process to transfer a pattern onto a wafer or substrate; the size of these patterns could be in the micro or nano scale. The patterns (i.e electrodes for the 3D sensors) are created using a shadow transfer method, where the pattern to be printed (photomask) is placed between a light source and the substrate to be patterned (wafer). The substrate is first coated with a photosensitive material, that reacts to the light projected from the shadow image. The resultant pattern is then developed using specific chemicals. The prototyping wafer, realized with mask aligner lithography, included different geometries: 50x50-1E, 25x100-1E and 25x100-2E. Fabrication yield for the 1E designs was about 60%, although with large non-uniformities from wafer to wafer. While, for the 2E design, fabrication yield fall to less than 20%. This low yield motivated the use of stepper lithography in the following

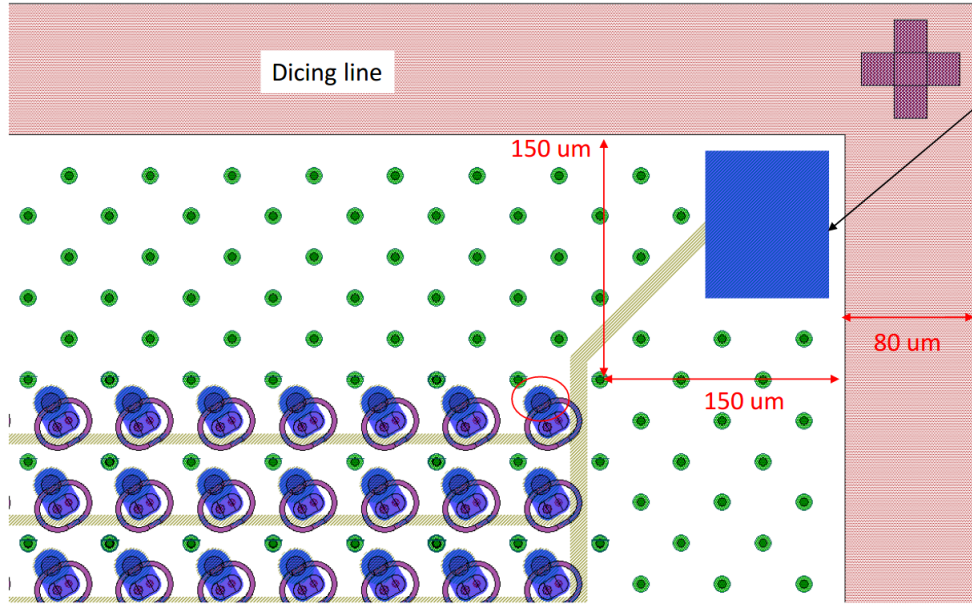


Figure 5.4: Layout details of slim edges for the FBK sensor. The p-type column are drawn in green. Figure shows that additional $150\ \mu\text{m}$ of p-type column fences are present at the edge of the sensor.

production batches in order to improve the pattern definition and layer alignment, which are essential for such a dense layout. Despite the choice to accommodate many design variants, which caused the stepper to be operated in a non-optimal way, the percentage of 1E designs sensors meeting the specifications was still about 60% with this technique, as with mask aligner. On the contrary, for the 2E design sensors, the percentage doubled, reaching almost 40%. Thanks to these results, it was decided to use the stepper for pre-production (and then in production) of the ITk sensors. Moreover, despite FBK has showed that it would be able also to produce the 2E critical design, it was decided that only the 1E design will be used in ITk. Although the 2E design should have been intrinsically more radiation hard thanks to the smaller electrodes inter distance, the 1E choice is justified by the fact that neither CNM nor SINTEF, both using mask aligner technology, have been able to achieve sufficiently high production rates for the 2E design. Using the 1E design allows to have a back-up solution in case one of the three vendors encounters unexpected problems during the production phase, that could make critical the development of the project. To demonstrate the ultimate radiation hardness for the 1E pre-production sensors is therefore a key milestone for the ITk project.

Pre-production FBK has delivered 7 pre-production wafer to CERN in the Summer 2021. Each wafer hosted 24 sensors and several test structures. Twenty sensor tiles were bump bonded at the IZM (Fraunhofer Institute for Reliability and Microintegration) and

distributed to testing sites (Genova, Berkeley, Bonn).

5.1.2 ITkPixV1 Front End Electronics

The read-out chips of the ITk modules will have to be much more radiation hard than the Inner Detector and IBL ones. They will also need to be able to process a larger amount of data, due to the increased number of tracks. 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 $4 \times 1.28 \text{ Gbit/s}$.

As both ATLAS and CMS pixel detectors have similar requirements, a R&D CERN Collaboration, RD53 [29], was founded in 2013 to develop the technology and deliver the read-out ASICs to the two experiments for their upgrades at the HL-LHC era. A half-size prototype, the RD53A chip, has been realized to prove the feasibility of building a large front end with the characteristics required using the technology of 65 nm CMOS. The use of this technology represents a significant improvement to the ones used for the Inner Detector (250 nm CMOS) and IBL (130 nm CMOS). The 65 nm CMOS technique is characterized by a decrease in the size of the transistors used: this allows the integration of front-end electronics in smaller pixel cells, without degrading its performance. This constraint was set by the increased granularity of the sensors.

The RD53A chip was used to build prototype modules with planar and 3D pixel sensors: this allowed to characterize sensors and develop multi-module systems. Devices were tested by both ATLAS and CMS collaboration for several years. After the positive results and feedback by the RD53A prototypes, RD53 moved on to develop the final front ends for ATLAS and CMS. A new common *library* has therefore been prepared, so-called RD53B, to keep the development on the key building blocks as common as possible, from which derive in the final layout the ATLAS (ITkPixV1) and CMS (CROC v1). The main differences of the two chips are geometrical dimensions to accomodate different mechanical detector layout and the analog read-out. The first version of the ATLAS chip, ITkPixV1.0, was submitted in March 2020. This very first version presented a problem with Time over Threshold (ToT), which caused a significant increase in current and made it impossible to use for data taking. An updated version, ITkPixV1.1, was presented in 2021: the issue with the ToT has been overcome with simple changes in the more external wafer layers by disabling its reading. In that way, only the binary readout of the hits is possible. While ITkPixV1.1 is therefore still a prototype, the final version of the chip, the ITkPixV2, will be submitted at the end of 2022. It will include improvements with respect to ITkPixV1, including the design fixture in the ToT.

The results presented in the following section have been obtained using the ITkPixV1.1 chip.

5.1.2.1 General characteristics

ITkPixV1 size is about $2 \times 2 \text{ cm}^2$ and consists of a matrix of 384×400 pixels ($50 \times 50 \text{ } \mu\text{m}^2$) and a chip bottom. The layout and a functional view of the ITkPixV1 floorplan are shown in figure 5.5.

The sensitive area of the chip, the pixel matrix, is placed at the top of the chip and is

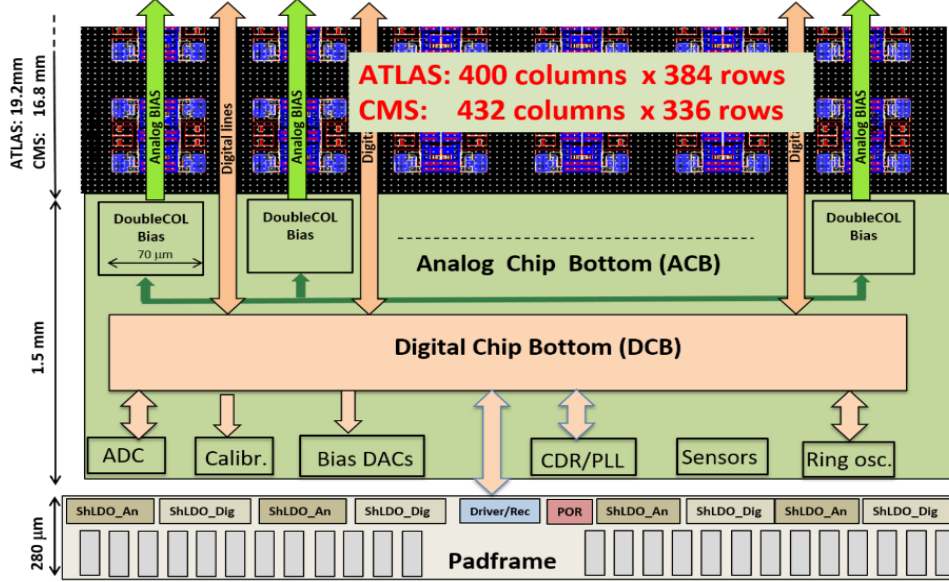


Figure 5.5: Functional floorplan of the RD53B, the number of pixels columns and rows is shown both for the ATLAS ITkPixV1 and CMS CROC v1 chips. Image credits [31]

arranged as a matrix of identical 8 by 8 pixel *cores* stepped and repeated in 50 columns and 48 rows. The 64 core pixels are organized in 16 identical *analog islands* with 4 pixels each, which are embedded in a flat digital synthesized "sea", as shown in figure 5.6.

The peripheral circuitry, also defined chip bottom, is placed at the bottom of the chip and contains all the system functionality and the wire bonding pads. It includes all global analog and digital circuitry needed to bias, configure, monitor and read out the chip. The analog building blocks are grouped in a macro-block called Analog Chip Bottom (ACB), which is fully assembled and characterized in an analog environment. The ACB block is surrounded by a synthesized block, called Digital Chip Bottom (DCB), which implements the input, output and configuration of digital logic. The wire bonding pads are organized as a single row at the chip edge, separated by 1.7 mm from the first row of bumps, in order to allow for safe wire bonding after the sensor flip-chip.

Chip powering The chip may be powered in a passive mode or an active one. In the former, the chip analog and digital circuits are powered directly by the supply. In the second, the voltages on the chip are supplied by special regulators, the so-called *Shunt* -

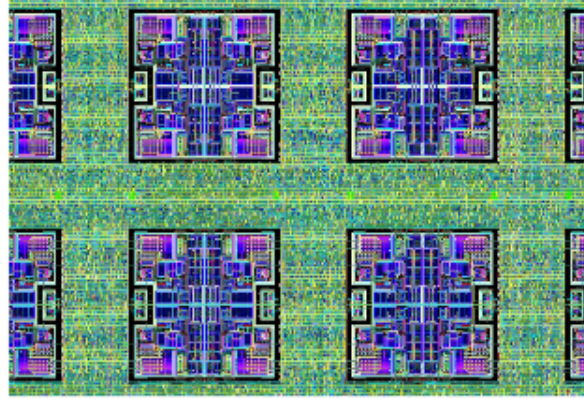


Figure 5.6: Layout view of analog island within the synthesized logic. Four complete islands can be seen in the center of the figure. One core contains 4 by 4 analog islands. Image credits [31]

Low Drop Out regulator (SLDO). The chips are designed to be used in serial powering: these regulators are devices that are used to maintain a constant voltage level during chip powering by deviating any excess current to the ground. Moreover, the regulators can be configured as a pure Low Drop-Out linear voltage regulator for usage in a conventional voltage based supply scheme (LDO). ITkPixV1 relies on two different regulators, one for the analog components (SLDO-A) and a second for the digital ones (SLDO-D): this allows to supply the two components with a single generator [31].

Pixel cell The front-end electronics integrated into each pixel cell allows for signal amplification, discrimination from noise, digitalization and temporary memory saving. These tasks are carried out by the two different components of the chip: the analog and the digital block. A sketch of the main components of a pixel cell is shown in figure 5.7. More details on the two front-end electronics are presented in the following.

Pixel cell analog block The analog block receives the signal from the sensor. The input signal is received by an operational amplifier (OA) with a feedback capacitor C_f . This circuit is a charge-sensitive amplifier, i.e. it could integrate the current flowing in the inverting terminal of the OA and generate a voltage with an amplitude proportional to the input charge. The OA output is stable when all the input charge is collected. It is then needed to discharge the capacitor to allow for the collection of the following signal. To achieve this scope, a second circuit, that supplies a current to the feedback resistor, is integrated. In this way, the output signal duration is proportional to the input charge. It is possible to adjust the value of the current of the discharge circuit and so to tune the relation between the input charge and the duration of the output signal. A third circuit is integrated into the analog block: the leakage current compensation. This is needed if

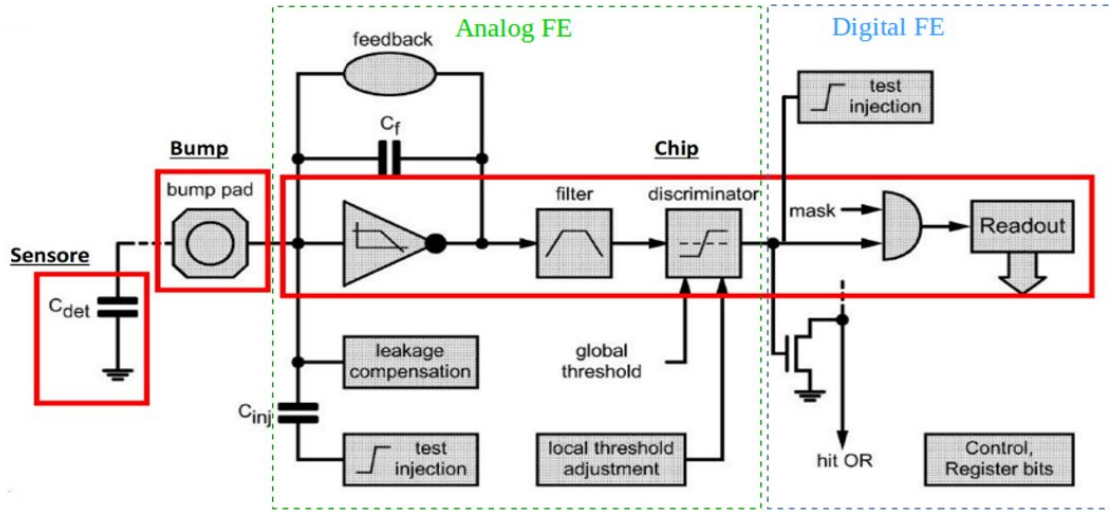


Figure 5.7: Generic pixel cell components: both analog and digital FE are shown. Image credits [21]

the leakage current of the sensor is too high: it could deviate part of this current before it reaches the OA, avoiding that it is integrated together with the signal.

The output of the OA is then sent to a discriminator that allows the discrimination of the signal from the background noise. If the signal overcomes the defined threshold, it is digitized and sent to the digital block. Threshold setting could be performed in two steps, acting on global parameters (GDAC), i.e. on all the pixels of the matrix, and local parameters (TDAC), i.e. acting on individual pixels. A high threshold is preferable to minimise noise. However, with a low threshold, multiple-hits clusters may be better reconstructed. When irradiation progressively reduces the generated charge and thus maximize the detector efficiency, it is preferable to keep the threshold rather low. Then the threshold set must balance these two needs.

The block is also equipped with an injection circuit which simulates the signal of a particle interacting with the sensor. The circuit is particularly useful for chip testing and optimization because it allows testing chip performance regardless of the sensor and the bump bond.

Pixel cell digital block The digital block receives a signal from the analog one if the signal is over the threshold. In that case, the digital block could record the digitized signal and transmit it out of the pixel cell. In case the pixel is masked (i.e. disabled) the signal is not transmitted. Pixels could be disabled for several reasons, the two most common issues are: bad tuning, i.e. the threshold is not properly set, or *noisy*, pixel sending signals even in the absence of an external source.

The information of a hit digitized records information on the column, row, the ToT and on the trigger. Also the digital block is equipped with an injection circuit which simulates

the signal of a particle interacting with the sensor by sending a digital input. The circuit is particularly useful for digital FE testing.

The reading of a pixel is enabled by the reception of a trigger signal; the trigger generation mode varies depending on the application for which a chip is designed. In experiments in which the frequency of the signals is very high, like the ATLAS experiment, it is necessary to identify the hits of real interest among all those received (i.e. those associated with events where the trigger logic of the experiment has recognized the probable production of an interesting event); only these will then be processed by the data acquisition system and saved to disk. In ITk, this is performed by using a trigger signal, external to the front-end. The trigger signal is sent to a group of modules and enables the reading of a certain subset of hits based on a certain logic. In the ITkPixV1 chip, the external trigger is managed by the DCB that re-routes it to individual pixels. Alternatively, for low particle rate and testing purpose, the ITkPixV1 chip could trigger the pixel matrix by using the *Hit-OR* circuit: if a pixel recorded an event, a Hit-OR signal is generated by the pixel and sent to the DCB, which re-routes it to all the pixels in the matrix, acting as an external trigger.

5.1.2.2 Chip scans and tuning

Several scans can be run on the chip, these allow to verify the correct functioning of the FE, tuning the thresholds and collecting data. The scans and their purposes are listed in table 5.1 and will be described in the following.

Scan	Purpose
Digital	Test the digital FE
Analog	Test the analog FE
Threshold tuning	Tune the pixel threshold
Threshold	Check pixel threshold
Noise occupancy	Mask noisy pixel
Self-trigger	Data taking

Table 5.1: Available ITkPixV1.1 scans and their purpose.

Digital scan The digital scan is used to test the correct operation of the digital FE: for each pixel, N digital signals (typically 100) are delivered through the digital injection circuit inside the pixel cell. All pixels that record more or less than N hits are masked, as they do not work properly. Scan outputs are a map of the hits recorded by each pixel and a map of the masked pixels.

Analog scan The analog scan is used to test the correct operation of the analog FE: for each pixel N pulses (typically 100) are injected, with a charge much greater than the maximum threshold of the pixel, through the analog injection circuit inside the pixel cell. All pixels that record more or less than N hits are masked, as they do not work properly. Scan outputs are a map of the hits recorded by each pixel and a map of the masked pixels.

Threshold scan The threshold scan is used to check the threshold of each pixel of the chip. For each pixel, N pulses (typically 50) are injected per each of the defined charge values: typically, the intensity of the pulse is increased from 200 to 2000 electrons, with a step of 100 electrons. For each charge value, the number of recorded hits is saved and the so-called S-curve is fit (figure 5.8). The charge that records 50% of the N pulses is defined as the mean pixel threshold. A second parameter that is measured is the noise, defined as the width of the S-curve between the charge values corresponding to 10% and 90% of the pulses recorded. Scan outputs are the threshold and noise maps, their distributions for each pixel, and pixel TDAC maps.

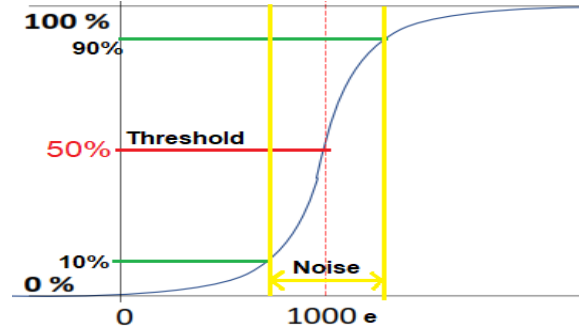


Figure 5.8: Threshold S-curve sketch.

Noise occupancy scan The noise scan is used to identify and mask noisy pixels. To do so, a fixed frequency trigger is sent and the number of hits for each pixel is recorded. This scan should be run without an external source in order to correctly spot noisy pixels. Scan outputs are the maps of noise occupancy and of the masked pixels. A pixel is defined as noisy when its noise occupancy is higher than 10^{-6} , having defined the noise occupancy as:

$$\text{Noise occupancy} = \frac{\text{Number of hits recorded}}{\text{Number of received triggers}} \quad (5.1)$$

Self-trigger scan Self-trigger scan is used to speed up data taking with an external source (radioactive source or X-ray tube). It relies on the Hit-OR circuit of the pixel matrix. When a pixel records a hit, an Hit-OR signal is generated by this pixel and sent to all the others pixels of the matrix as a trigger signal. So basically, whenever any pixel records a hit, the whole matrix is read. Scan outputs are pixels occupancy map and distribution.

5.2 Module testing in Genova laboratory

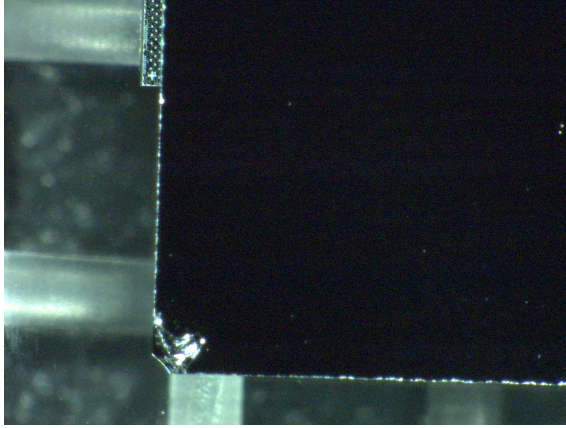
This section aims to describe the modules assembly, their configuration and test. All the procedures and results described were obtained in the Genova laboratory. Two bare ITkPixV1.1 chips (without sensor) and ten modules with FBK 3D pre-production sensor bump bonded to ITkPixV1.1 chip were delivered to Genova. Flip-chip and bump bonding procedures have been done at IZM. These ten modules are the very first 3D sensor pre-production modules ever tested in the ITk project. Chips or modules were mounted on dedicated Printed Circuit Boards (PCBs) designed by the RD53 collaboration, that host a single module/chip: they are called Single Chip Cards (SCCs). Initially, the two bare chips were assembled on SCCs and tested in order to finalize the hardware and software testing setup. Initial tests have been carried on these SCCs: in this way, the risks to eventually damage the modules for an incorrect setup configuration were minimized. In order to qualify the sensor pre-production, six out of the ten received 3D sensor modules were assembled on SCCs and devoted to special tests of quality assurance. Before mounting the modules or chips on the SCCs, a visual inspection with a microscope was executed. After that, the module was glued and wire bonded to the SCC. The SCCs have been numbered from 1 to 8 in order to easily identify the modules. The four remaining bare modules were sent to Milan, where they will be used for ITk module assembly. Chip and sensor ID, eventually together with the number of the SCC used for the assembly, are listed in table 5.2.

Type	Chip ID	Sensor ID	N° SCC	Bump Bond
Bare chip	0x141-7B	/	1	/
Bare chip	0x141-8B	/	7	/
Bare module	0x131-C9	W12-G	2	IZM
Bare module	0x131-A8	W12-M	3	IZM
Bare module	0x131-B8	W12-N	4	IZM
Bare module	0x131-CB	W12-J	5	IZM
Bare module	0x131-B5	W12-L	6	IZM
Bare module	0x131-3B	W14-K	8	IZM
Bare module	0x131-59	W14-H	/	IZM
Bare module	0x131-5D	W14-M	/	IZM
Bare module	0x131-3A	W14-O	/	IZM
Bare module	0x131-48	W14-Q	/	IZM

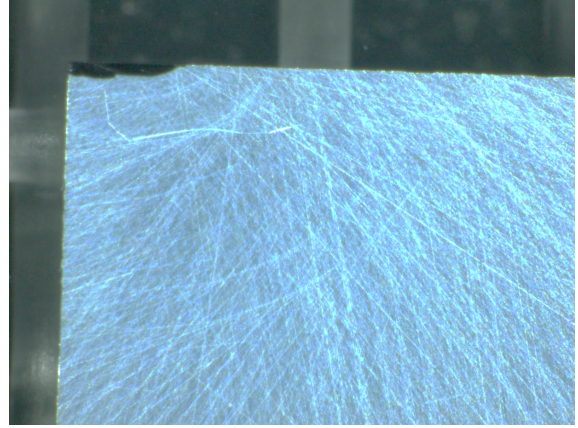
Table 5.2: Chip and sensor ID of the devices received in Genova. Eight of them were loaded on Single Chip Cards (SCCs), number of the card is reported.

5.2.1 Bare modules visual inspection

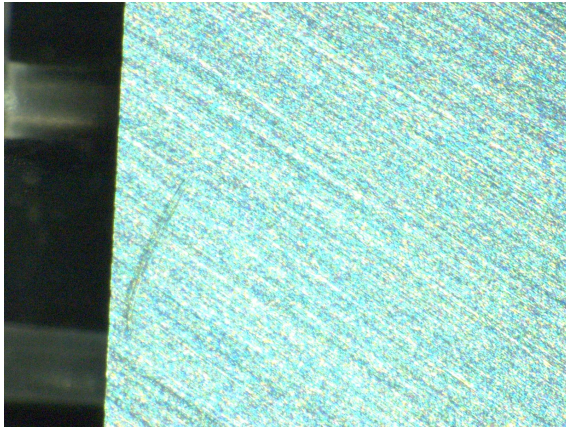
Bare modules and chips have been received in standard gel packs. Visual inspection of both top and bottom surfaces was done using a digital microscope. The edges and corners of the modules have been checked in detail, as they may be damaged during the wafer dicing procedure or handling. The inspection spotted few damaged corners on the chip (figures 5.9a) and on the sensor (figure 5.9b). Moreover, some scratches on the sensor surface have been noticed (figures 5.9c). In addition, some sensors edges shown an irregular profile with the signs of the saw used for wafer dicing (figure 5.9d). Although these defects should not be present, it seems that they have not affected the behaviour of the modules, as will be illustrated in the following sections.



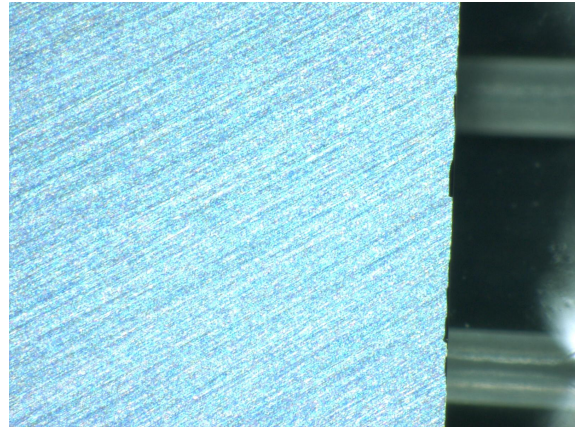
(a) Damaged corner, chip 0x131-C9



(b) Damaged corner, sensor W14-O



(c) Surface scratches, sensor W12-M



(d) Irregular edges, sensor W14-Q

Figure 5.9: Example of defects found during visual inspection on chips and sensors.

5.2.2 Test setup

The module testing setup inside the Genova laboratory (figure 5.10) consists of two PCs ("DCS PC" and "YARR PC"), low voltage and high voltage power supplies and an X-ray tube placed inside a shielded box.

DCS The Detector Control System (DCS) aims to monitor the environment (environmental temperature and humidity, temperature of the module) and to automatize the control of Low Voltage (LV) and High Voltage (HV) power supplies. The environmental temperature and humidity are read by a Sensirion SHT85 sensor. The temperature on the module is read through an NTC placed on the SCC top, very close to the module. Temperatures and humidity are recorded by an Arduino-based system which communicates with the DCS PC. The HV, needed to power the sensor, is supplied by a Keithley 2410C, while the Low Voltage, needed to power the chip, is supplied with an Agilent E3631A. Power supplies are connected to DCS PC through the General Purpose Interface Bus (GPIB) interface.

YARR Another PC is dedicated to data acquisition. It is equipped with a commercial Field Programmable Gate Array (FPGA) card, Trenz Electronic TEF1002, that communicates with the modules through Display Port (DP) cables. The last version of the Yet Another Rapid Readout (YARR) software and firmware are installed, to communicate with the chip. Currently, YARR is the main used suite for ITk module testing. The scans, listed in section 5.1.2.2, are executed with this PC.

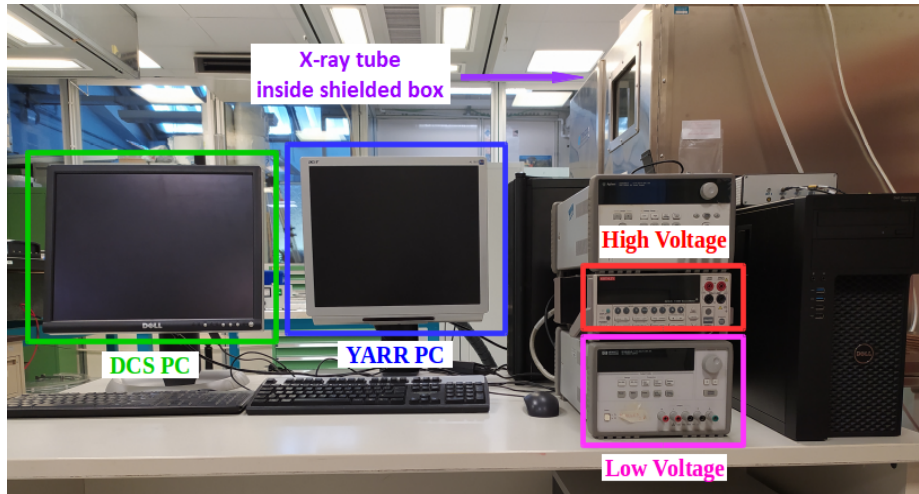


Figure 5.10: Module testing setup inside Genova laboratory.

X-ray tube The X-ray tube (Amptek Mini-X2) [26] is hosted inside a shielded box, to avoid any radiation in the laboratory environment (figures 5.11 and 5.10). The Mini-X is used at its maximum power of 4 mW. It is possible to set the operation voltage, which

changes the X-rays energy, and the current, which adjusts the X-rays flux. For our purpose, the voltage was set to 50 kV and the current to $80 \mu\text{A}$. The emission X-rays energy spectrum is between 0 eV and 50 keV. The X-ray tube is located about 12 cm above the module, with the tip of the X-ray tube centered to the pixel matrix center.

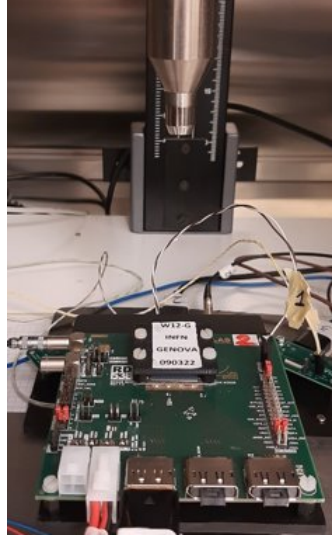


Figure 5.11: Mini-X2 X-ray tube inside the shielded box. The module to be tested is placed under the tip of the X-ray tube.

5.2.3 Modules assembly and testing

The modules were mounted on SCCs to facilitate handling and to easily connect input and output cables. Before the assembly, the SCCs were prepared to host the modules. Firstly, the area of the PCB under which the module will rest is milled, in order to remove material (mainly copper). On top of the hole, a thin (0.5 mm) aluminum plate is glued onto the SCC with the radiation hard epoxy Araldite 2011. In case the SCC is irradiated, the aluminum plate will result in lower material activation than the SCC material: this will imply a shorter time for cool-down. Moreover, the Al plate will ease the thermal coupling of the module to the environment when tested cold after irradiation. Finally, the module is glued on the aluminum plate with Araldite 2011. After glue curing (24 hours) the module is wire-bonded to the SCC. The module assembly is complete and testing can start. The first check is the visual inspection of the wirebonds with a digital microscope: wirebonds that looks not properly fixed are removed and replaced. A view of SCC 2 after the module assembly is shown in figure 5.12, whereas details of the milled area and of the aluminum plate are in figures 5.13a and 5.13b. Figure 5.14 shows two detailed pictures of the wirebonds. After wirebonds visual inspection, the module is protected with a 3D-printed plastic cover.

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 steps are the following:

- Sensor IV scan
- Module parameter configuration for optimal operation
- Digital and analog scan
- Threshold tuning
- X-ray scan

These steps will be explored in the next sections.

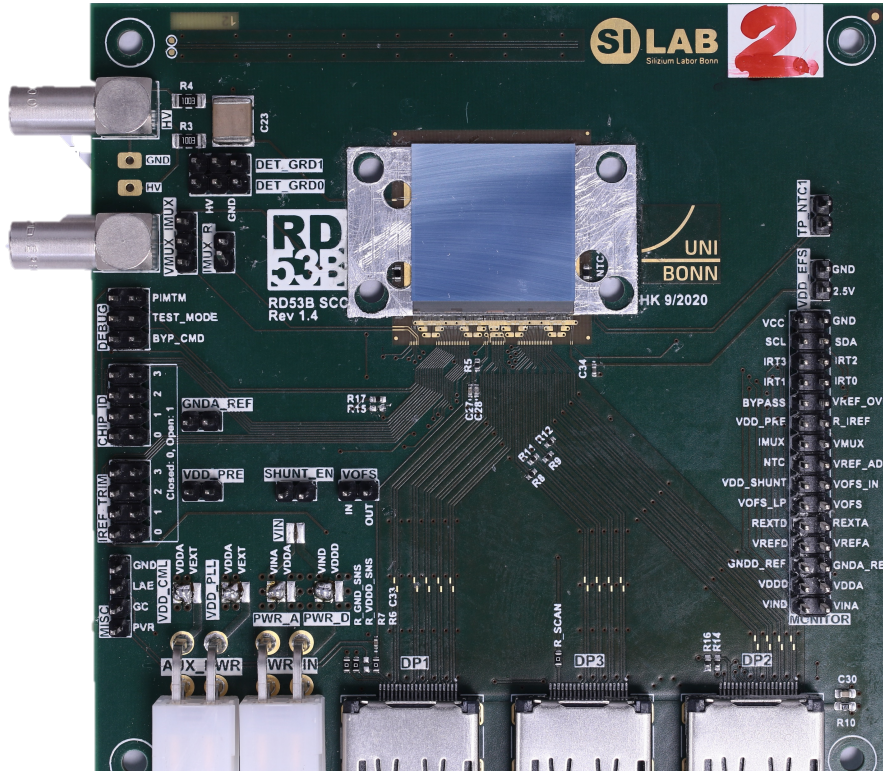
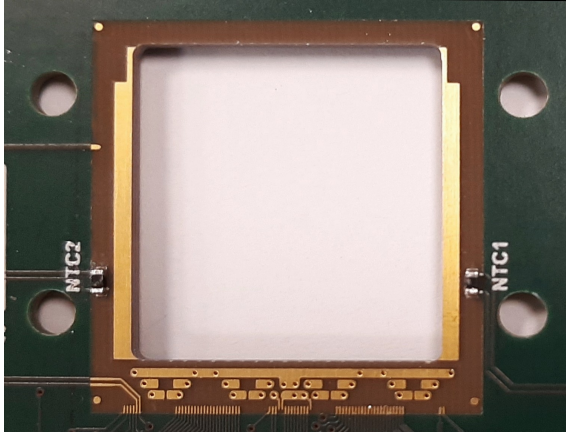
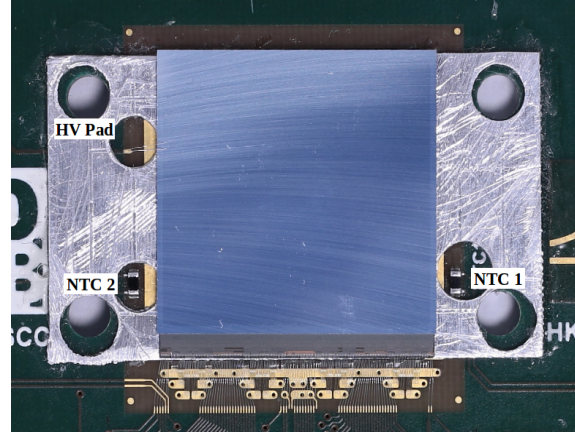


Figure 5.12: Module mounted on SCC 2.

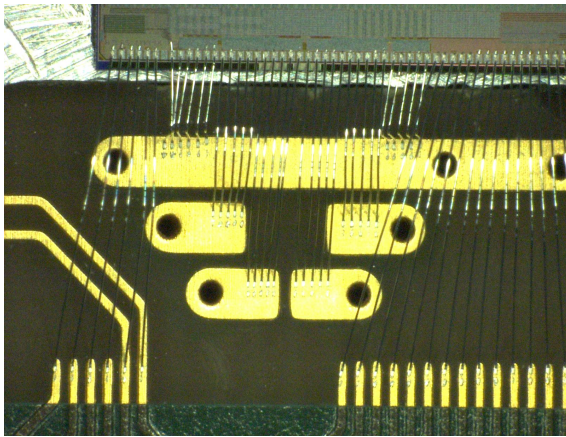


(a) Hole milled on the SCC under the module

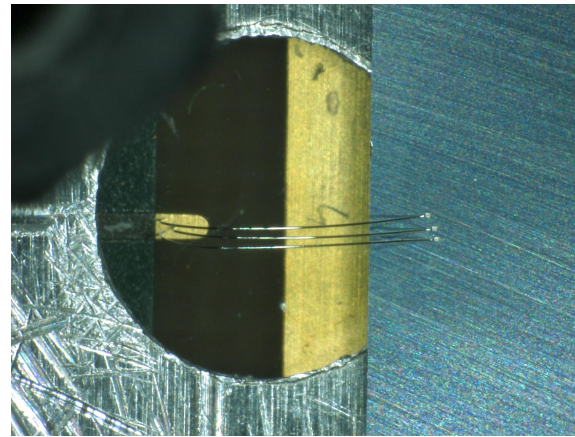


(b) Module glued on aluminum plate

Figure 5.13: SCC details before and after gluing the aluminum plate and the module.



(a) SCC to chip wire bonds



(b) SCC to sensor wire bonds

Figure 5.14: Overview of wirebonds from SCC to chip pads and sensor back.

5.2.3.1 Sensor IV scan

To evaluate the sensor performance the IV curve (section 4.2) is measured for each of them. The curve is made by increasing the V bias from 0 V up to 80 V, with steps of 1 V. The measurement is performed with the Keithley 2410C, integrated into the DCS. During the data taking, the temperature was monitored using the NTC placed close to the module. The IV curves are taken at room temperature, cooling the module only with a fan placed below the SCC. Results are shown in figure 5.15. For each sensor, the breakdown voltage V_{bd} (defined as the minimum voltage at which the leakage current increases by a factor of 2 over 5 V, equation 5.2) is evaluated.

$$I_{leak}(V + 10V)/I_{leak}(V + 5V) > 2 \quad (5.2)$$

Since V_{bd} is greater than 80 V for all the sensors, the requirement of $V_{bd} > V_{depl} + 20$ V (V_{depl} is about 5 V for 3D sensors) is respected. IV curves were previously measured with sensors on wafer in Trento. Leakage current was below 1 μ A for all of them. To compare the two sets of measurements the current is scaled to the temperature of 20°C, using the following equation:

$$I_{leak}(T) = I_{leak}(T_R) \cdot \left(\frac{T}{T_R}\right)^2 \cdot \exp\left[\frac{E}{2k_B} \cdot \left(\frac{1}{T_R} - \frac{1}{T}\right)\right] \quad (5.3)$$

where $T = 20^\circ\text{C}$, T_R is the temperature at which the IV curve was taken, E is the silicon energy gap and k_B is the Boltzman constant. Wafer results are roughly compatible with the leakage current measured in Genova on SCC. The slight increase observed in Genova is not worrisome, it may be due to the hybridization steps (wafer dicing, flip-chip). The leakage current, normalized to the sensor area (3.84 cm^2), is still negligible with respect to the sensor specification of 2.5 $\mu\text{A}/\text{cm}^2$. All the sensors respect the requirement on the leakage current. Results of wafer and SCC IV curves are shown in figure 5.16 for SCC 3. Breakdown voltage and leakage current values at 25 V scaled to 20°C are summarized in table 5.3.

SCC N°	V_{bd} [V]	$I_{leak}(25V)$ [$\mu\text{A}/\text{cm}^2$]
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 5.3: Summary of breakdown voltage (V_{bd}) and leakage current at 25 V (I_{leak}) scaled to the temperature of 20°C.

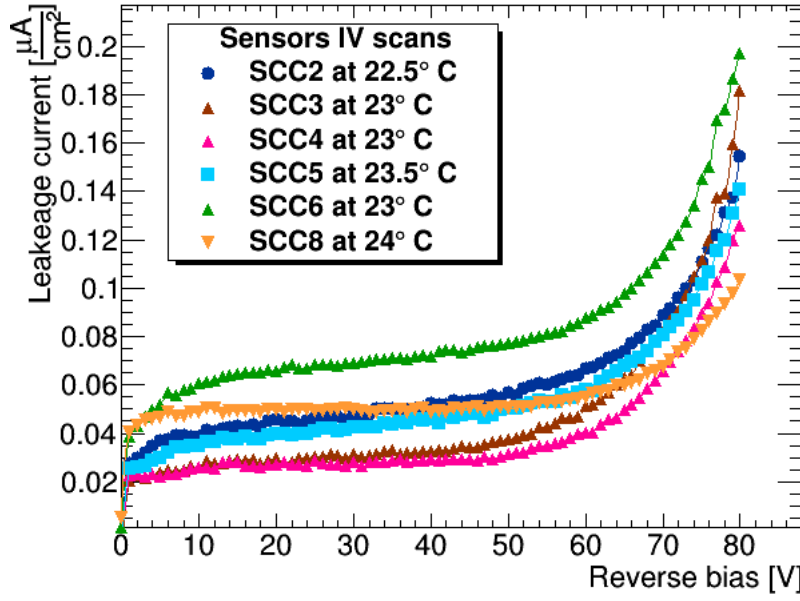


Figure 5.15: Sensors IV measured on SCCs in Genova.

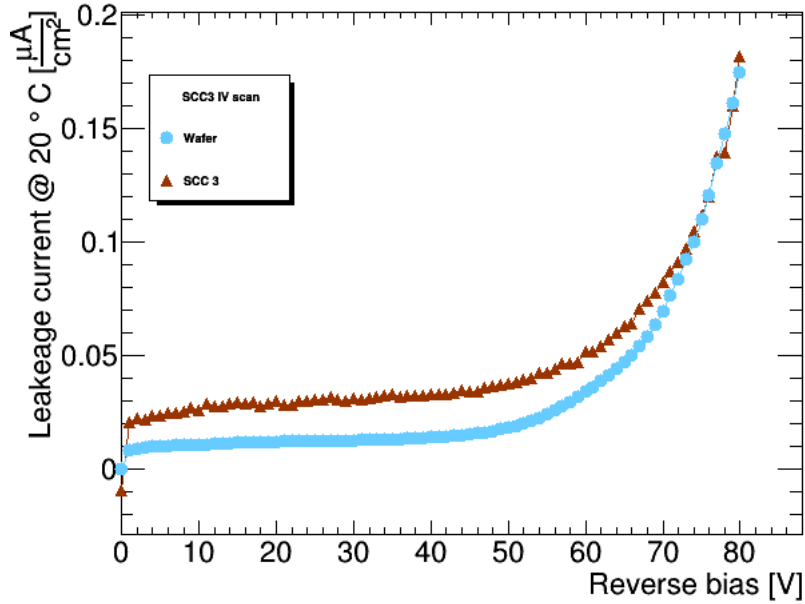


Figure 5.16: Sensors IV measured on SCCs in Genova and on wafer level at Trento.

5.2.3.2 Module configuration

For the optimal operation of the chip, the trimming of several parameters is needed. The main current, I_{REF} , is the reference for the generation of all the internal voltages of the chip, so careful trimming is required. The target value for I_{REF} is $4 \mu\text{A}$. During the trimming procedure, the voltage values to be checked could be adjusted by placing jumpers on SCC pins or by changing chip configuration file parameters. The voltages could be monitored with a multimeter using devoted pins on the SCC. The used trimming procedure can be summarized as follow:

- Power the chip in the LDO mode with low voltage of about 1.6 V.
- Configure the chip, with the parameters measured at the wafer level, by executing a digital scan.
- Measure $V_{ref-ADC}$ on the devoted SCC pins.
- Adjust $V_{ref-ADC}$ to get it as close as possible to 0.845 V by placing jumpers on the four I_{REF} pins on the SCC.
- Adjust VDDD and VDDA values by changing the respective parameters in the chip configuration file. The target value for both voltages is 1.2 V. VDDA should be measured against the analog ground reference (GND-A), while VDDD against the digital ground reference (GND-D). Values are monitored with a multimeter using devoted SCC pins.
- Crosscheck the derived parameters: V_{OFS} and V_{REF} . Both voltages should be monitored versus GND-A. To monitor V_{REF} , a jumper on the R-MUX pin is needed and the parameter *MonitorI* on the chip configuration file should be changed from 63 to 0. V_{REF} monitor pin on SCC is labelled as IMUX. The target value for V-OFS is 0.5 V while for V_{REF} it is 20 mV.

Since V_{REF} is applied to a resistance of $5 \text{ k}\Omega$, it is possible to obtain the value of I_{REF} by simply doing the ratio: $V_{REF}/5 \text{ k}\Omega$. No anomaly has been found in the voltage values after trimming. Values of the voltages mentioned above are listed in table 5.4.

5.2.3.3 Digital and Analog scans

To prove the correct operation of both the digital and analog front-end parts of the ITkPixV1.1 chip, digital and analog scans were performed on each module.

Digital scan The digital scan is done as explained in section 5.1.2.2. Modules responded positively to the digital scan: all pixels recorded 100 hits over 100 pulses injected, no pixels were masked. Only SCC 3 shows tiny defects with 0.16% of masked pixel. For example, SCC 5 hit map and masked pixel map are shown in figure 5.17.

	$V_{ref-ADC}[V]$	VDDD [V]	VDDA [V]	V-OFS [V]	V_{REF} [mV]
Target	0.845	1.2	1.2	0.5	20
SCC 1	0.841	1.203	1.198	0.532	20.0
SCC 2	0.843	1.193	1.203	0.534	20.7
SCC 3	0.843	1.195	1.197	0.596	20.4
SCC 4	0.844	1.198	1.206	0.543	21.0
SCC 5	0.849	1.194	1.205	0.539	20.2
SCC 6	0.843	1.201	1.199	0.538	20.3
SCC 7	0.841	1.203	1.211	0.510	19.3
SCC 8	0.810	1.209	1.197	0.591	19.6

Table 5.4: Summary of chip voltages after trimming. Target values are shown in the second row.

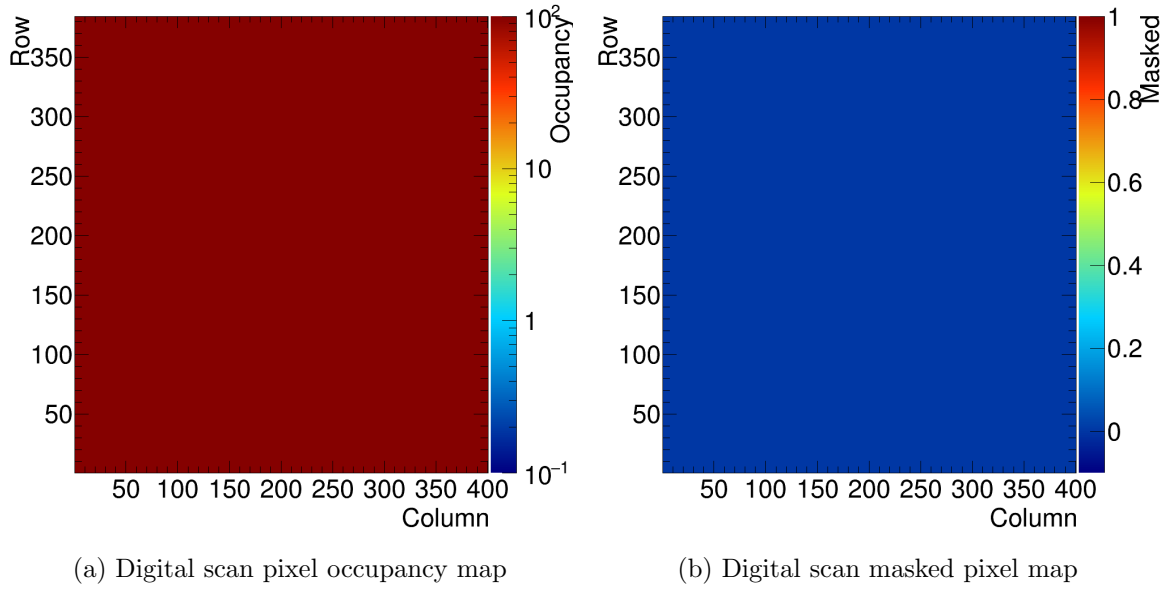


Figure 5.17: Example of digital scan results - SCC 5 -

Analog scan The analog scan is done as explained in section 5.1.2.2. Results showed that almost all the pixels recorded 100 hits over 100 pulses in each module. Exceptionally, on SCC 3, few pixels (0.82%) were found not to work properly, recording less than 100 hits. These pixels were masked before threshold tuning and data taking. Although these pixels did not represent a significant problem, as their number is negligible (0.01%), it is

important to report them as they may spot some potential problem in the hybridization or the handling of the devices. More detail about that will be presented in section 5.3.5. SCC 3 hits and masked pixel map are shown in figure 5.18.

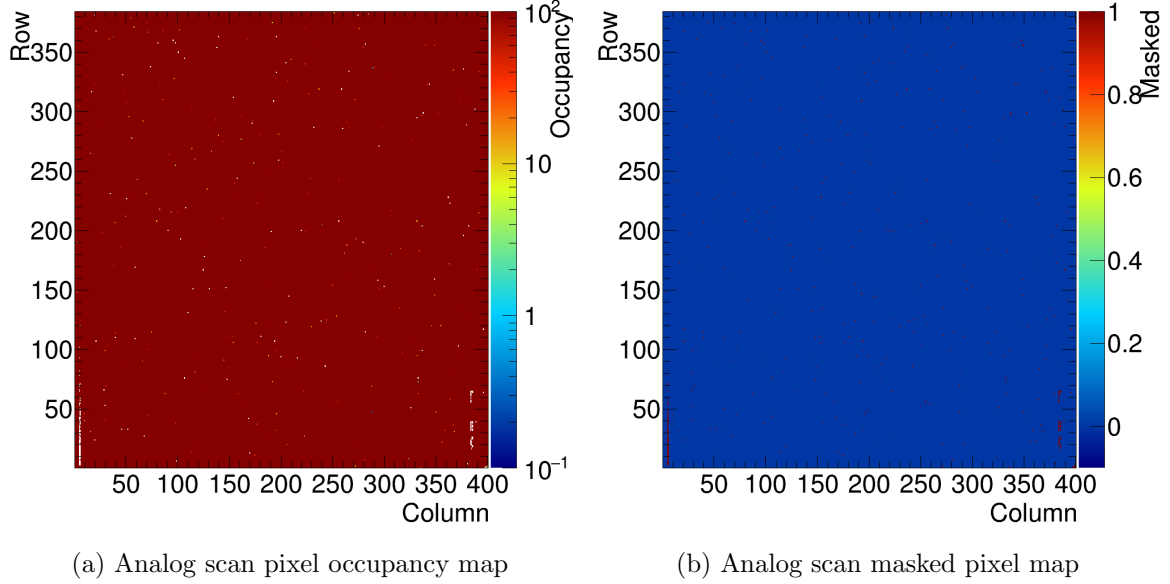


Figure 5.18: Example of analog scan results - SCC 3 -

Results of digital and analog scans are listed in table 5.5, the fraction of working pixels for each scan, such as the ones not masked, is reported.

SCC N°	Digital scan	Analog scan
SCC 1	100%	100%
SCC 2	100%	100%
SCC 3	99.84%	99.18%
SCC 4	100%	100%
SCC 5	100%	100%
SCC 6	100%	100%
SCC 7	100%	100%
SCC 8	100%	100%

Table 5.5: The fraction of working pixels is shown for both digital and analog scans. Pixels that did not work were masked.

5.2.3.4 Threshold tuning and noise analysis

As explained in section 5.1.2.1, the tuning procedure consists of two steps: the tuning of the global threshold and then a finer tuning of each pixel Threshold DACs (TDACs). The target threshold is set to 1000 e . Tuning is done with the sensor powered at 10 V. A threshold scan is done at the end of the tuning to check the results. For all SCCs the tuning procedure was successful: the threshold is very close to 1000 e and the threshold noise is about 40 e for bare chips and 70 e for modules, as expected. Only a few pixels of SCC 3 failed the tuning procedure. Examples of threshold and noise maps and distributions are shown in figures 5.19 and 5.20. The two distributions are fitted with a Gaussian function to get the mean value and the standard deviation.

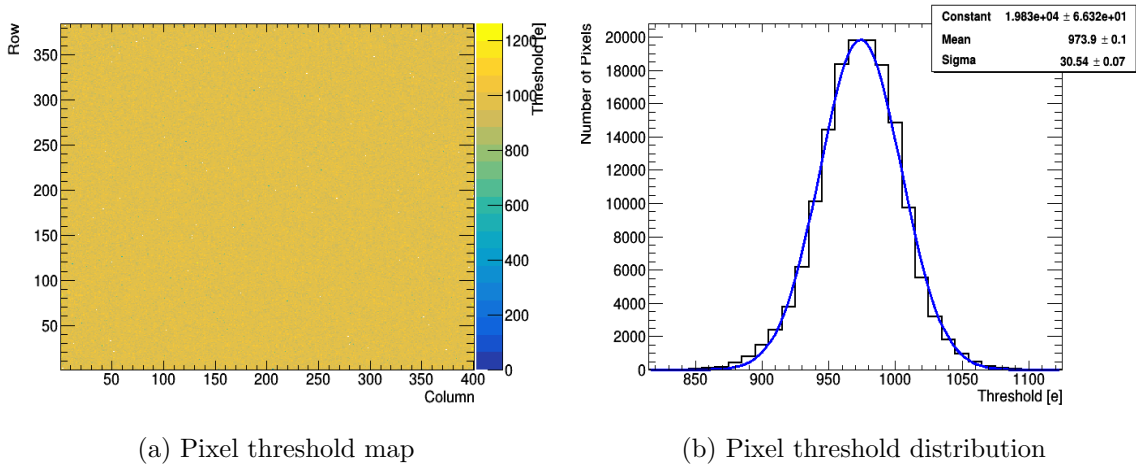


Figure 5.19: Example of threshold scan results - SCC 4 -

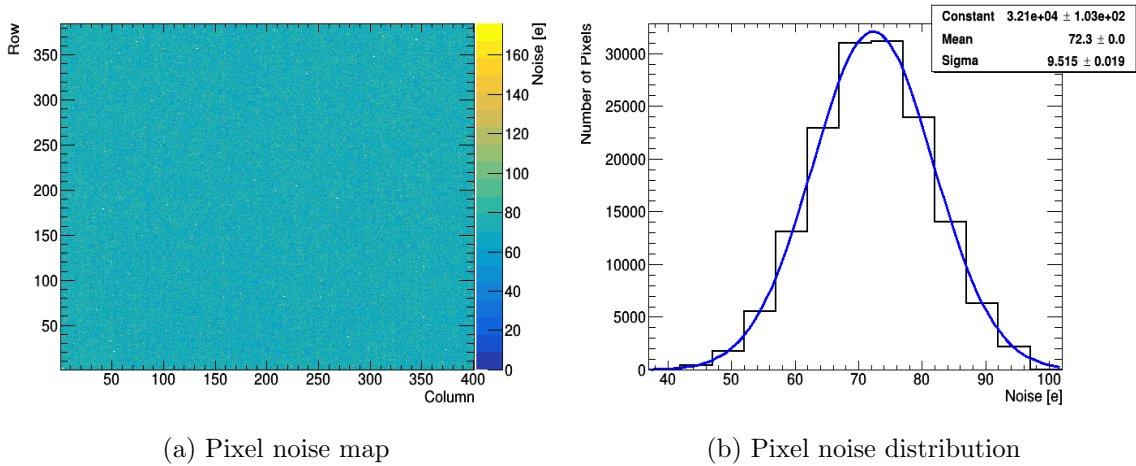


Figure 5.20: Example of threshold scan results - SCC 4 -

The results obtained are summarized in table 5.6 in terms of threshold and noise mean value and Standard Deviation (StD) for scans with 10 V bias applied to the sensor. Values are obtained by fitting threshold and noise distribution with a Gaussian function as in figures 5.19 and 5.20.

SCC N°	Mean Threshold [e]	Threshold StD [e]	Mean Noise [e]	Noise StD [e]	Comments
SCC 1	969	31	39	7	
SCC 7	961	29	41	7	
SCC 2	975	29	73	10	
SCC 3	974	31	67	9	Few untuned pixels
SCC 4	974	31	73	10	
SCC 5	973	30	71	10	Few disconnected bumps
SCC 6	973	29	70	10	Large area of disconnected bumps
SCC 8	962	31	75	10	

Table 5.6: Summary of threshold and noise mean and Standard Deviation (StD) after tuning with 10 V bias on the sensor. SCCs with bare chip (SCC 1 and 7) are reported in the first rows.

Noise versus HV The noise dependence on sensor bias voltage was measured for SCC 2 and SCC 4. Results are reported in figure 5.21. As expected, the noise decreases by increasing bias voltage. Moreover, it reaches a plateau at about 6 V: this means that the sensor is completely depleted at this bias voltage, as predicted by design.

The threshold scan allows a rough determination of the disconnected bumps: mean threshold noise is about 80 e at 0 V bias and about 70 e at 10 V bias. Comparing the threshold noise map and distribution of scans with and without applying bias voltage to the sensor, disconnections can be spotted. If there is no difference in pixel noise between the two scans, the pixel bump could be not properly connected. For this purpose, a second threshold scan, at the end of the tuning, is done without bias to the sensor (0 V). To identify candidate disconnected pixels, a map is made with the difference between the noise measured with 0 V bias and that measured at 10 V bias. Pixels with disconnected bumps will have a noise difference of about 0 e in the map. With this procedure, several pixels with disconnected bumps were spotted on SCC 5 and 6. The module X-ray scan confirmed this hypothesis, as will be explained in the following section.

Issues on SCC 5 Noise analysis with and without applying bias to the sensor spotted an area of fully or partially disconnected bumps on SCC 5. Results has been confirmed by the X-ray scan. These pixels are shown in figure 5.22a. These are barely visible (too few pixels to be noticed by eye) when comparing the two noise distributions executed with

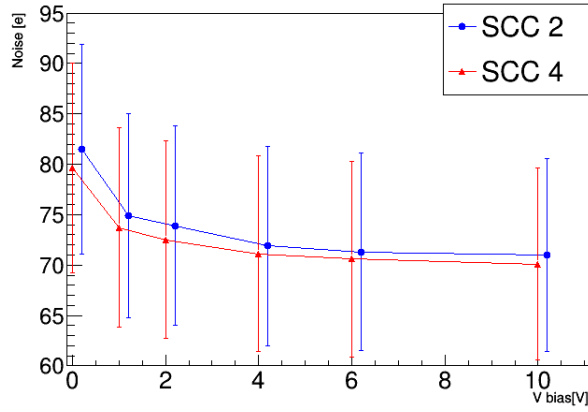


Figure 5.21: Threshold noise versus bias voltage. Noise decreases, reaching a plateau at about 6 V. The standard deviation of the threshold noise distribution is reported as the error, points were collected at 0, 2, 4, 6, and 10 V bias. The points of SCC 2 are reported with a slightly higher bias value to facilitate the reading of the graph.

sensor bias of 10 and 0 V. Although the reason of these disconnected bumps is still not completely clear, it is suspected to have been caused by a vacuum pump suction cup that picks up the module after bump-bonding. Indeed the semi-circular shape of the region in question is similar to the shape of the suction cup.

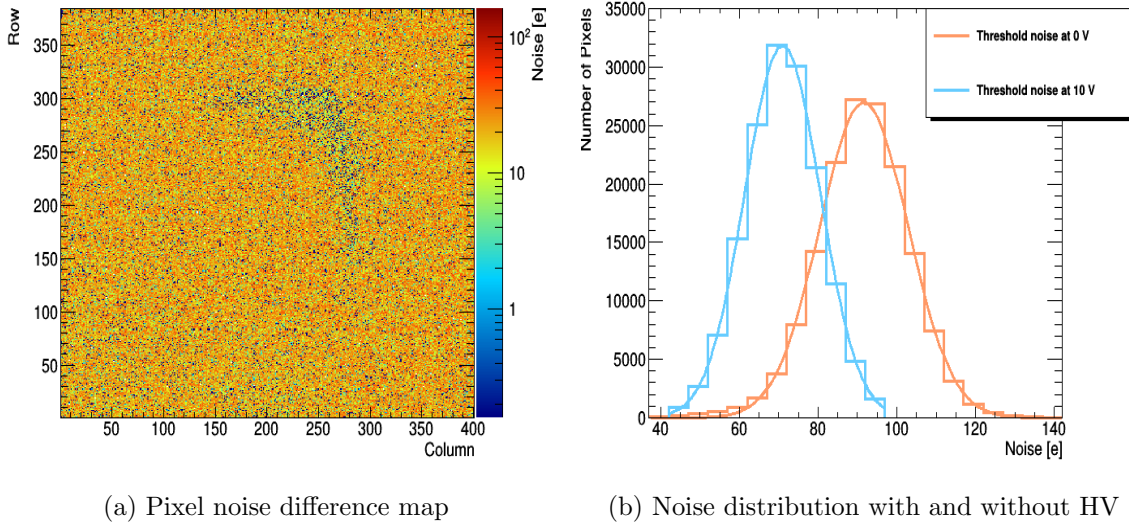


Figure 5.22: The difference between the pixel noise map taken with (10 V) and without bias (0 V) with SCC 5 is presented on the right. Pixels with disconnected bump have a value around 0 e.

Issues on SCC 6 The same noise analysis with and without applying bias to the sensor spotted a large area of fully or partially disconnected bumps on SCC 6. Results has been confirmed by the module X-ray scan. These pixels are shown in figure 5.23a: they are visible in the map of the threshold noise difference between 10 V and 0 V as pixels that have a value around 0 e . They are also visible in the threshold noise distribution in the range between 60 and 80 e as pixels that do not follow the Gaussian distribution at 0 V (blue curve). The cause of the disconnection of these bumps is not clear yet, it could be due to a defect in the process of bump bonding, as the affected area is quite large and in a corner with fairly defined edges.

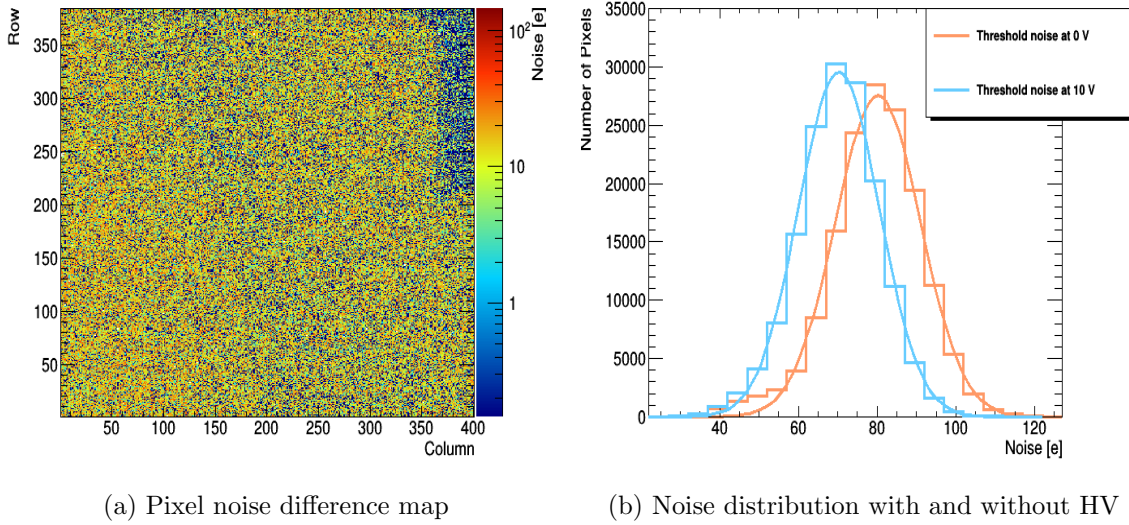


Figure 5.23: The difference between the pixel noise map taken with (10 V) and without bias (0 V) with SCC 5 is presented on the left. Pixels with disconnected bump have a value around 0 e . These are also visible in the two noise distributions on the right.

5.2.3.5 Modules X-ray scans

Before executing the X-ray scan in self-trigger mode, it is important to mask the noisy pixel. These are masked by performing two noise occupancy scans with a trigger frequency of 40 kHz (each one 60 seconds long). Then the X-ray tube is switched on and a self-trigger scan is performed. The duration of this scan is, again, 60 seconds. An example of the SCC 2 X-ray occupancy map is shown in figure 5.24a: on this map the 3D printed filament pattern is slightly visible, together with the paper label *INFN GENOVA* placed above the cover left. These scans allow to identify noisy pixels and to check bumps disconnection. The fraction of noisy pixels is found to be less than 0.1%. Self-trigger scans spotted the same areas of disconnected pixels on SCC 5 and 6, as discussed in section 5.2.3.4. A further issue was found with SCC 6: this module recorded a lower rate of hits. This problem may be caused by some damaged pixels in the disconnected bump area that adversely affect

data transmission. The average number of hits per pixel per second collected during the X-ray scan and the number of masked pixels are reported for each module in the table 5.7. Note that the average number of hits per pixel is obtained by fitting the X-ray occupancy distribution with a Gaussian function (figure 5.24b).

SCC N°	Masked pixels	Hits/(pixel/s)	Comments
SCC 2	0.001%	112	
SCC 3	0.07%	113	
SCC 4	0.001%	111	
SCC 5	0.049%	113	A few disconnected bumps - About 1000 pixel with lower efficiency
SCC 6	0.08%	< 30	Few hits/(pixel·s) and a large area of disconnected bumps
SCC 8	0.03%	117	

Table 5.7: Number of masked pixel after two noise scans (each one 60 seconds long). Mean number of hits per pixel per second collected by a self-trigger scan.

Edges pixel The X-ray occupancy map (figure 5.24a) showed that the edges pixel recorded more hits than all the other ones on the module. If we look at the occupancy distribution, two different peaks are visible (figure 5.24b). These are fitted with a Gaussian function: central pixels recorded about 6700 hits/pixel while edges pixel about 10000 hits/pixel in 60 seconds. So the edges pixels, both horizontal and vertical, recorded about 30% more hits than the central ones. This is explained by the fact that the electric field that collects the charge in the edges pixels extends partly also in the additional ohmic columns placed at the edges of the sensor, as explained in section 5.1.1. Moreover, also from the projections on the X and Y axes of the occupancy map (figure 5.25) it is evident that the edge pixels recorded more hits than the central ones. Calculating the ratio between the total number of hits collected from an edge column and those from a central one we get 1.49 ± 0.06 . While the ratio between the total number of hits collected from an edge rows and those from a central one gives $1.52 \sim 0.05$. As expected, the two results are compatible since for both columns and rows the edge termination is obtained with $150 \mu\text{m}$ p-type column fences.

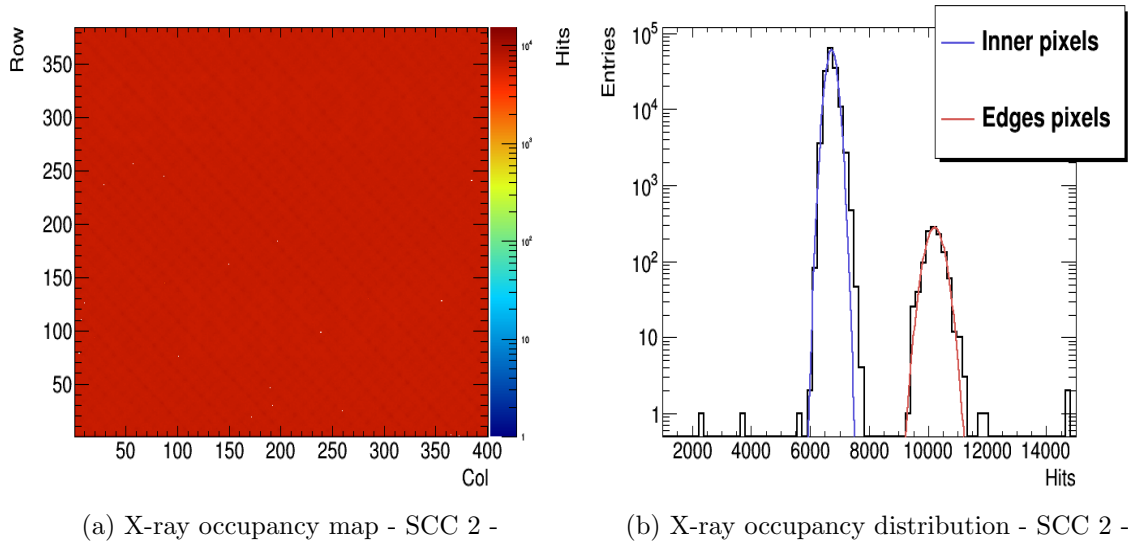
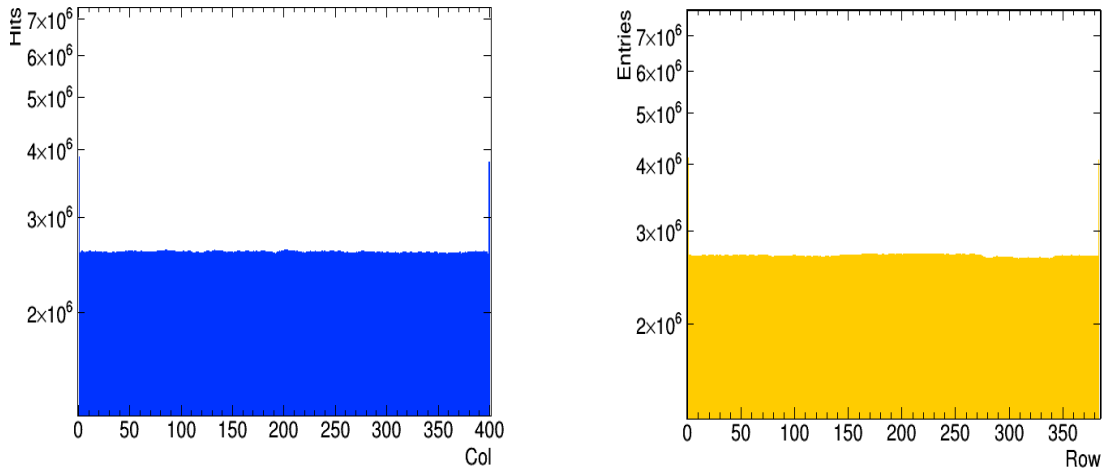


Figure 5.24: The X-ray occupancy map is shown on the left. Figure on the right shows the X-ray occupancy distribution. Edges pixels recorded about 30% more hits than the central ones and are fitted with the red Gaussian function. The blue function fits the central pixels.



(a) X-ray occupancy map X projection - SCC 2 - (b) X-ray occupancy map Y projection - SCC 2 -

Figure 5.25: SCC 2 X-ray occupancy map X and Y projections. In both cases, it is clear that edge pixels recorded more hits.

Issue on SCC 5 The X-ray scans spotted several pixels (~ 1000) with lower occupancy (below 6000 hits/pixel) in the central area of the module on SCC 5: results are shown in figure 5.26. This area is compatible with the one already identified by analyzing the noise

from threshold scan. Since these pixels record hits, even if at a lower rate than the others, their bumps could be only partially disconnected.

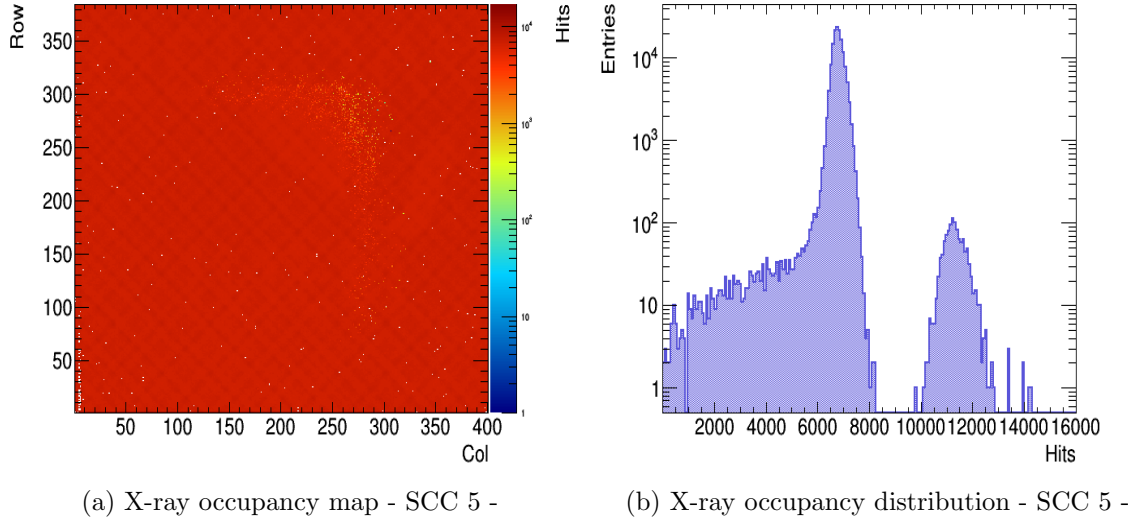


Figure 5.26: The X-ray occupancy distribution is shown on the left. About 1000 pixels with lower efficiency (hits < 6000) are slightly visible, these are the pixels in the central area of the module, as shown on the left. The occupancy distribution on the right shows pixels with a higher number hits: these are the edges one.

Issue on SCC 6 The X-ray scans spotted a large area of fully or partially disconnected bumps on the top right corner of the module on SCC 6, which is shown in figure 5.27a. This area is compatible with the one already identified by analyzing the noise. Another issue was found: SCC 6 pixels recorded less than 30 hits per pixel per second, i.e. $\sim 25\%$ of the expected rate, much less than the pixels of the other SCCs, which collected about 110 hits per pixel per second. This could be related to few very noisy pixels in the damaged region not correctly masked by the standard procedure. We have observed also at the test beam, see section 5.3.5.2, that in this case the full chip data-taking can be affected. Also in this case the X-ray occupancy distribution (figure 5.27b) shows several pixels which collected more hits (about 400) than the others, these are the edge pixels.

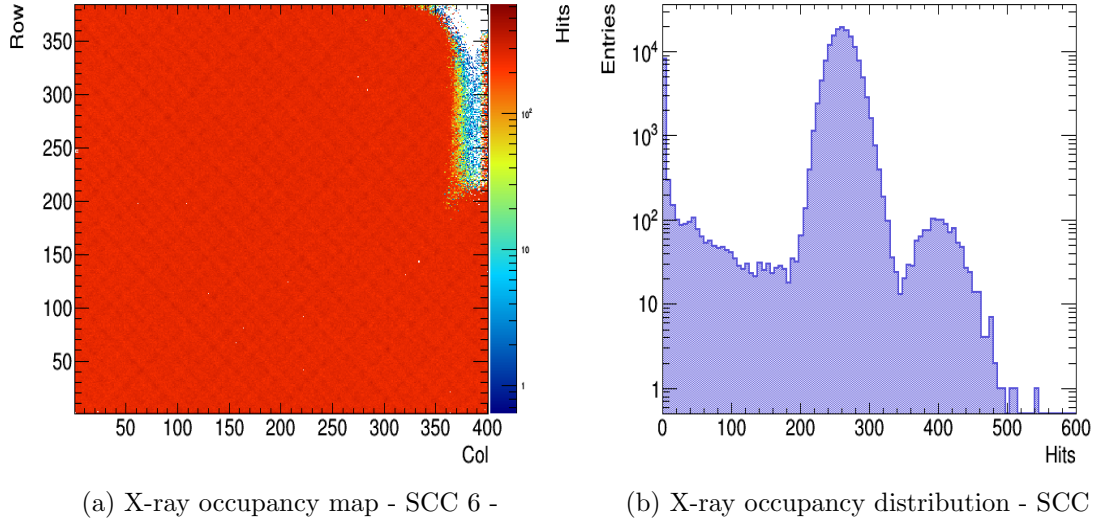


Figure 5.27: The X-ray occupancy map is shown on the left. A large area of disconnected bumps is visible in the top right angle of the map. On the right, pixels with a higher number of hits (about 400) are the edge ones, while pixels with the number of hits < 200 are the ones with totally or partially disconnected bumps.

5.3 Test beam at CERN and irradiation

Few of the modules presented in the previous section have been tested in Spring 2022 at CERN Proton Synchrotron (PS) and Super Proton Synchrotron (SPS) test beam facilities. After these test beam campaigns, four modules were irradiated: two at the CERN IRRAD facility to a target fluence of $1.5 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$ and two at the Bonn irradiation facility to a target fluence of $1 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$. After irradiation, the modules have been tested during the Summer at the CERN SPS test beam. This was the first time the irradiated ITkPixV1 chip and the FBK pre-production 3D sensors were tested on the beam. Results on sensor and chip performance will be presented in the following. For the data analysis, the Corryvreckan framework [30] was used. Table 5.8 presents a summary of the irradiations and beam tests done with the SCC cards assembled in Genova.

5.3.1 Test beams setup

Pixel modules have been measured before and after irradiation at the PS, using 12 GeV protons, and at the SPS, using 120 GeV pions, at CERN. In both cases, a EUDAQ-type telescope was used. The data acquisition system is YARR and EUDAQ based. The telescope has been used to reconstruct beam particle trajectories and to determine the impact point on the studied devices. The telescope has two arms, each one consisting of three planes made of MIMOSA26 [32]: They are $18.4 \times 18.4 \mu\text{m}$ pixel monolithic sensors with an active

SCC N°	Spring TB	Irradiation	Summer TB	SCC Status
SCC 2	PS	IRRAD	/	Irradiation issues - not working
SCC 3	/	Bonn	SPS	Fully functional
SCC 4	PS / SPS	/	/	Fully functional
SCC 5	/	Bonn	SPS	Fully functional
SCC 6	/	/	/	Bump bonds issue
SCC 8	/	IRRAD	/	Irradiation issues - not working

Table 5.8: Devices irradiated and tested at the CERN test beams.

area of $2 \times 1 \text{ cm}^2$ that can provide a minimum pointing resolution of $2 \text{ } \mu\text{m}$, depending on the beam energy, the amount of material between telescope planes and the consequent multiple scattering. The coincidences of two scintillators placed at the two ends of the telescope, covering the MIMOSA26 sensor area, are used to generate the trigger signal for the readout. Their signal is sent to a Trigger Logic Unit (TLU) that distributes their AND to all the planes of the telescope and to the Devices Under Test (DUTs). The DUTs are placed inside

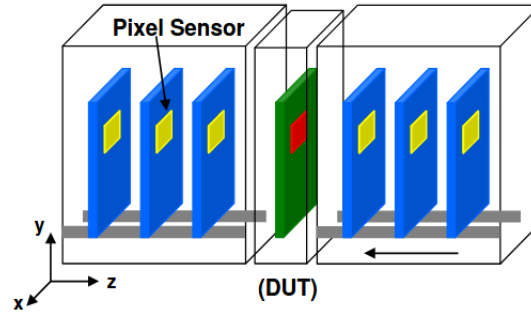


Figure 5.28: Sketch of MIMOSA26 telescope layout. Image credits [32]

a cooling box served by a commercial chiller, this allows reaching a temperature of -80°C inside the box to study irradiated modules. Irradiated modules are tested at -34°C while unirradiated are tested at 20°C . Due to the large integration time of the MIMOSA26 sensors (about $300 \text{ } \mu\text{s}$) with respect to the DUTs (of the order of 25 ns), an additional reference plane should be used to provide timing information for track selection. Several different reference planes are available: a hybrid module with a FE-I4 chip and a planar sensor, a hybrid module with an RD53A chip and a planar sensor or one of our unirradiated SCCs with ITkPixv1.1 chip and 3D sensor. A sketch of the MIMOSA26 planes of the telescope is shown in figure 5.28 and a picture of the setup in figure 5.29.

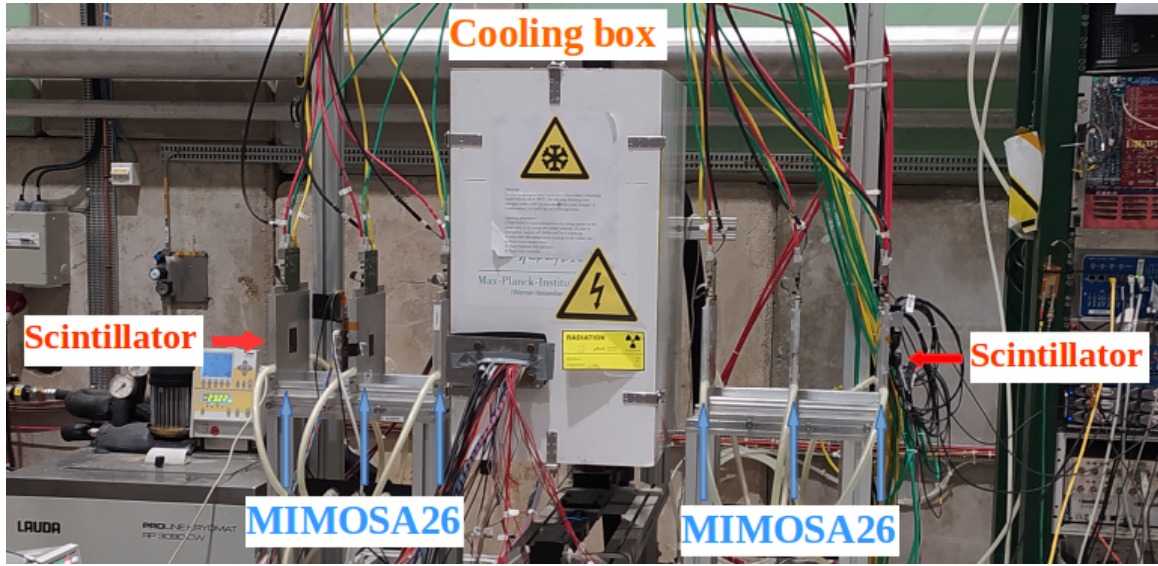


Figure 5.29: Picture of test beam setup at SPS, CERN.

5.3.2 Corryvreckan data analysis framework

To qualify a device, there are two essential information: first of all the beam particle trajectory must be correctly reconstructed, including aligning all the telescope planes and the DUTs. Secondly, the correlation between this particle impinging on the DUT and the DUT data must be found. Corryvreckan [30], a flexible C++ analysis framework, has been developed by the CLICdp Collaboration to analyze test beam data. The program is based on a modular concept: several modules, each with a specific function, can be combined according to the needs of the user.

The program works with a temporary storing information framework infrastructure: the Clipboard. In the Clipboard, during the event processing, collections of elements (i.e. tracks, clusters, etc.) are saved and can be accessed by each module via their data type. The clipboard consists of three parts:

- **The Event:** the central element for storing the data while being processed. This includes the time frame within which all data are located as well as trigger numbers associated with these data.
- **Temporary Data Storage:** data only available during the processing of each individual event. It is automatically cleared at the end of the event processing. The temporary storage acts as the main data structure to communicate information between different modules. It can hold multiple collections of Corryvreckan objects such as pixel hits, clusters or tracks.

- **Persistent storage:** data that are not cleared at the end of each event processing. They can be used to store information used in multiple events.

The program is based on two file types: special geometry files, where the spatial (X, Y, Z, rotation) and material information related to the setup is saved (these files are modified during the analysis to optimize the alignment of the telescope and DUT planes), and root files, where the results obtained by each module are instead saved.

The Corryvreckan framework provides a set of global parameters that control the behaviour of the program. The main parameters are:

- **detectors file:** set the geometry file to be used by a specific module. It is the only global parameter required, as the framework will fail to start if not specified.
- **detectors file update:** set the geometry file to be modified at the end of the analysis. If no file is specified, geometry is not updated.
- **histogram file:** set the root file where the results of the analysis are saved.
- **number of events:** determines the total number of events of the framework to be processed. It could be used to reduce the duration of the analysis to quickly check the data quality.
- **number of tracks:** determines the total number of tracks of the framework to be processed. It could be used for the same purpose as the previous parameter.

Coordinate system The coordinate system used by the program is based on a system of right-handed Cartesian axes XYZ. The Z axis is aligned with the beam and points in the same direction. The telescope and DUT planes could lie on the XY plane or could be tilted.

5.3.2.1 Corryvreckan modules

To analyze the data and provide the results on the resolution and efficiency of the DUTs, the program is based on the execution of a sequence of several modules. Firstly, the telescope and DUT data are loaded on Corryvreckan and the noisy pixels are masked on each device, then the telescope planes are aligned, followed by the DUTs. Finally, the efficiency of DUTs is measured. Modules to be run are listed, in order of use, in the following.

1. EventLoaderEudaq This module allows data recorded by EUDAQ and stored in the EUDAQ-native raw format to be read in Corryvreckan. This is needed since the DAQ system of PS and SPS test beam is based on EUDAQ, as will be explained in the following sections. The geometry file of the setup is needed as an input, only the telescope planes and DUTs specified in this file will be loaded.

2. Mask Creator This module reads objects for each device from the clipboard, and masks pixels considered noisy. Pixels are masked following the *frequency method*: pixels which a hit rate larger than *frequency cut* times the mean global hit rate are masked. *Frequency cut* should be set by the user. This module also allows masking "dead" pixels (i.e. the ones which did not record any hit because they are dead or out of the beam) by setting the parameter *masking dead pixel* true. A root file with the information of masked pixels is produced at the end of the analysis.

3. Clustering Spatial This module reconstruct clusters from the input data of each detector specified in the geometry file. The cluster is built with an iterative process, starting from a pixel that has recorded a hit. The eight pixels that surround it are checked: if one of them has recorded a hit, it is added to the cluster, and so on. If the hit information is binary (as for the ITkPixV1.1 chip, with ToT disabled) the arithmetic mean of the cluster pixels is calculated to find its center.

4. Pre-alignment This module performs a translational telescope and DUTs plane pre-alignment. The rotational alignment is not changed. A reference plane should be specified in the geometry file. Correlations with the reference plane in X and Y are calculated for each detector. The required translational shifts in X and Y are calculated as the mean of the 1D correlation histogram along the axis for each detector. This module only uses the hit information to build the correlation plots. The hits correlated with the reference are the ones that have a maximum time difference of *time cut rel* times the *time resolution* of the detector. Both parameters could be set by the user. At the end of the module analysis, the geometry file is updated with the shift evaluated by this module.

5. Correlation This module collects pixels and clusters objects from the clipboard and creates correlation and timing plots with respect to the reference detector. This module is used to check if the correction to the geometry file done by the pre-alignment module works, and so if the pre-alignments of the detectors are fine.

6. Tracking 4D This module performs a basic tracking reconstruction: clusters from the first plane in Z are related to clusters close in time and space on the other detector planes using straight-line tracks. After the association, tracks are saved in the clipboard and a root file with the telescope planes residuals is created. The DUTs are excluded from this operation, they will be analysed by the following modules. Module parameters are:

- *time cut rel*: factor by which the *time resolution* of each detector plane will be multiplied. This value is used as the maximum time difference allowed between clusters and tracks for cluster association to the track.
- *spatial cut abs*: specifies a set of absolute values (X and Y) which defines an ellipse for the maximum spatial distance between cluster and track for cluster association to the track.

- *min hits on track*: minimum number of associated clusters needed to create a track.

7. Alignment Track Chi2 This module performs translational and rotational telescope plane alignment. The alignment is performed with respect to the reference plane set in the geometry file. This module uses tracks on the clipboard to align telescope planes. For each telescope detector, except the reference plane, this method moves the detector, refits all the tracks and minimises the χ^2 of these new tracks. The method automatically iterates through all devices contributing to the track. Modules parameters are:

- *iterations*: number of times the chosen alignment method is to be iterated.
- *max track chi2ndof*: maximum track χ^2/ndof value allowed for the track to be used in the alignment.

At the end of the module analysis, a root file with the final alignment of the telescope is created. Note that for a better alignment, the modules *Tracking 4D* and *Alignment Track Chi2* should be run several times, gradually decreasing the parameters *spatial cut rel* and *max track chi2ndof* in order to facilitate the convergence of the fit, and so the minimization of the tracks χ^2 .

8. DUT Association This module is used to establish an association between clusters on the DUT plane and a reference track. Modules parameters are:

- *spatial cut abs*: specifies a set of absolute values (X and Y) which defines an ellipse for the maximum spatial distance in the XY plane allowed between the center of the cluster and the intercept of the tracks for cluster association to the track.
- *time cut rel*: number of standard deviations the *time resolution* of the detector plane will be multiplied by. This value is then used as the maximum time difference allowed between a DUT cluster and the track, for the association.

Note that for the timing association, a reference plane should be indicated by setting a parameter in the geometry file. DUT clusters association is performed for each cluster. A root file is created with the spatial distribution of the associated clusters and the not-associated ones.

9. Alignment DUT Residuals This module performs translational and rotational DUT alignment. The alignment is performed with respect to the reference plane set in the geometry file. The module uses tracks previously reconstructed for the alignment. It moves the DUTs and minimises the unbiased residuals calculated between the track intercept with the plane and the center of the cluster on the DUTs. The parameter *iterations* allows setting the number of times the chosen alignment method is to be iterated. At the end, a root file with the DUTs residuals distributions is created. Note that for a better alignment, modules *DUT Association* and *Alignment DUT Residuals* should be run several times gradually decreasing the parameter *spatial cut abs* in order to facilitate the minimization of the residuals.

11. Analysis Efficiency This module measures the efficiency of the DUT by comparing its cluster positions with the interpolated track position at the DUT. Note that in the analysis masked pixels are not taken in account, in addition also the pixels neighbouring to a masked one are discarded. Modules main parameters are:

- *spatial cut abs*: specifies a set of absolute values (X and Y) which defines an ellipse for the maximum spatial distance in the XY plane allowed between the center of the cluster and the intercept of the tracks for the efficiency measurement.
- *time cut rel*: number of standard deviations the *time resolution* of the detector plane will be multiplied by. This value is then used as the maximum time difference allowed between a DUT cluster and the track, for the efficiency measurement.
- *time cut abs*: maximum time difference allowed between a DUT cluster and the track, for the efficiency measurement.

5.3.2.2 Data analysis with Corryvreckan

The data analysis starts by loading on the Corryvreckan framework: data are organized in events. An event is created for each trigger signal from the scintillator. For each event the hits information are loaded for each telescope plane and the DUTs. Then, a mask is created for each device, in order to mask noisy pixels. Clusters are then reconstructed for each plane. A first pre-alignment of the telescope plane and of the DUT is made only using the clusters information. After this very first pre-alignment a subset of tracks used only for telescope alignment is selected. With these tracks the alignment proceeds in several steps, in which the acceptance parameters of a track are increasingly stringent. At each alignment step, telescope residuals are calculated. They are defined as the difference between the position of the projection of the track on the telescope plane and the position of the cluster on the plane, and allow to check the alignment. Telescope alignment stops when telescope residuals are comparable to MIMOSA26 resolution ($\sim 5 \mu\text{m}$) and are centered around zero. After the telescope alignment, a new subset of tracks, reconstructed with the last telescope configuration, is selected for the DUTs alignment. The DUTs are aligned in steps in the same way of the telescope plane. Again the alignment stops when the DUTs residuals are of the order of the device resolution ($14 \mu\text{m}$ for our sensors) and centered in zero. With both the telescope plane and the DUTs aligned, the program is ready to analyze the efficiency of the DUTs. The efficiency is calculated as the ratio of the number of tracks for which a cluster, that meets a *spatial cut* of $100 \mu\text{m}$ (in both X and Y direction) and a *time cut* of 600 ns, has been found and the number of total tracks. Note that in the analysis masked pixels are not taken in account, in addition also the pixels neighbouring to a masked one are discarded. Table A.1 of the appendix A lists the modules, with their parameters, used for our test beam reconstruction and analysis.

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 investigate where inefficiencies might come from. Moreover, it is also possible to restrict the analysis to a specific region of the device, the so-called

Region Of Interest (ROI).

For pixel detectors, it is also possible to measure the local efficiency a pixel cell. Since the program knows the position of each pixel cell, thanks to the geometry file, the spatial coordinates of the clusters and the tracks intercepts could be interpreted in terms of local coordinates inside a pixel size.

5.3.3 Spring 2022 test beam with unirradiated modules

During Spring 2022, two test beam campaigns have been performed to study the performance of the unirradiated modules on the beam. The first campaign took place at the PS test beam, then the setup was moved to the SPS, where the second test beam campaign was done. At the PS facility, a proton beam of 12 GeV was used, while at the SPS a pion beam of about 120 GeV is available. SCC 2 was tested only at the PS, while SCC 4 in both facilities.

Beam test setup The setup used for the two test beam campaigns is based on the MIMOSA26 telescope described in section 5.3.1. This setup is basically the same both for the PS and SPS test beams, apart from tiny variations in the position of the telescope planes. At the PS, a module with a FE-I4 chip and a planar sensor was added to the telescope as a timing reference plane. At the SPS, instead two batches of data were collected using as the timing reference plane either the FE-I4 module or an RD53A chip and a planar sensor. DUTs efficiency was measured for both of them, in order to assess possible systematic differences. The devices used in the different batches and their positions are listed in the table 5.9. 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 5.9: 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 taking In order to measure the efficiency of the sensors as a function of the voltage bias, at the PS facility data were collected supplying the DUT sensor with a bias of 1, 2, 4, 6 and 10 V. During the SPS data taking, data were taken only with a bias of 0 and 10 V. In both facilities data were collected with the SCCs perpendicular to the beam. Data taking is organized as a sequence of *runs*, each of them recording a predefined number of events triggered by the scintillators logic. The number of events per run is usually not too large, to avoid wasting a large data sample in case something goes wrong. As a results many runs

are collected for each bias voltage set point, in order to have a sufficient amount of events to analyze.

5.3.3.1 Data analysis

As explained in section 5.3.2, the data has been analyzed using the Corryvreckan framework. The reconstruction and the analysis of the data are performed as explained in section 5.3.2.2. In this data-taking the DUTs are the SCC 2 and the SCC 4. In the following the results on alignment and tracks reconstruction will be presented, then the efficiency measurements will be reported.

Data loading and masking The data collected at test beam were 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 figure 5.30a for the data taken at the SPS with SCC 4. Noisy pixels and dead pixel were correctly masked. For each batch of data, a dedicated mask was created. An example is presented in figure 5.30b.

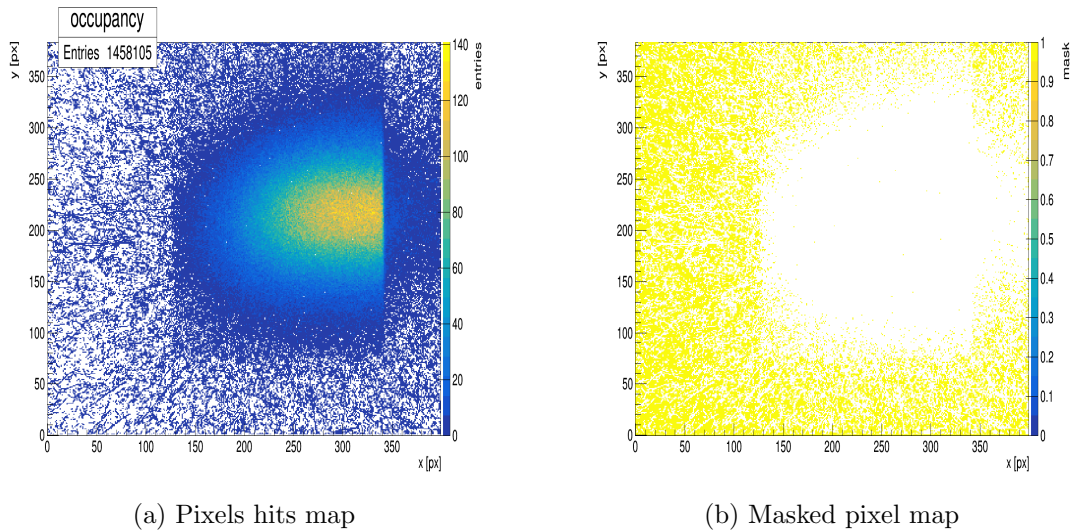
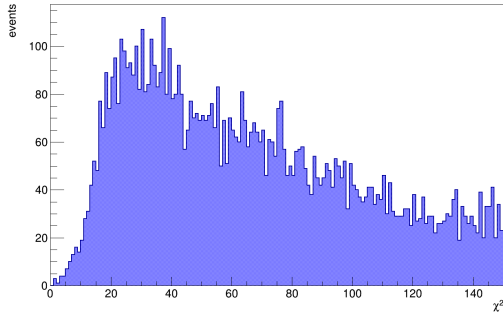
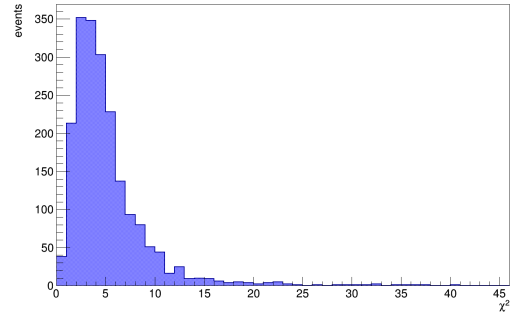


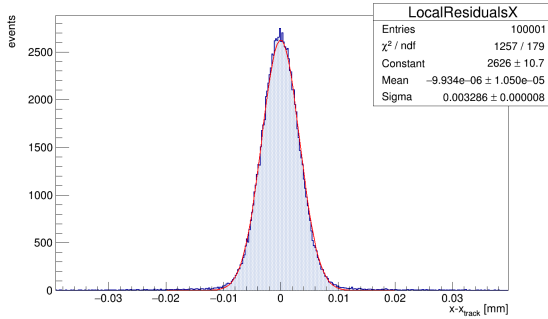
Figure 5.30: Hit and masked pixel maps from events collected at the SPS by SCC4. The square shape of the hits map is due to the shape of the scintillators used to trigger the event.

Offline alignment of the telescope 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. The alignment procedure has been explained in section 5.3.2.2.

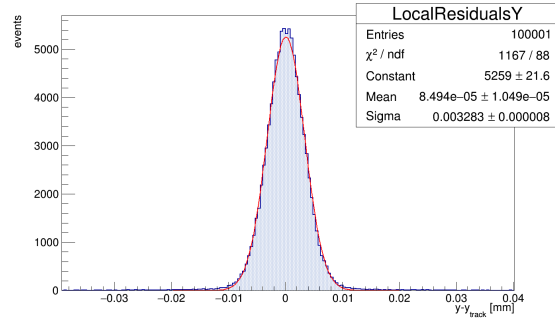
At the end of the alignment procedure, the distribution of the tracks χ^2 , and the planes spatial residuals are recorded. As shown in figure 5.31, the distribution of the tracks χ^2 after

(a) Tracks χ^2 before of the alignment(b) Tracks χ^2 at the end of the alignmentFigure 5.31: Comparison between tracks χ^2 before and after alignment, SPS data.

the alignment is mainly between 0 and 10, while before the alignment it is much larger. This means that the tracks fit managed to converge and the alignment was successful. Figure 5.31 is realized using the data taken at the SPS. For the PS telescope alignment, we get very similar results. As an example, the residuals distribution of the first MIMOSA26 plane at the SPS is shown in figure 5.32. The distribution has been fitted with a Gaussian function in order to get the RMS which is, as expected, in the order of $4 \mu\text{m}$ in both directions, since it is related to the pixel resolution of the telescope devices. The residuals are listed in table 5.10 for both the PS and SPS telescope alignment.



(a) Residuals in x direction



(b) Residuals in Y direction

Figure 5.32: X and Y residuals of the telescope plane 1 after the alignment with the SPS data. As expected, residuals RMS is in the order of $5 \mu\text{m}$, and the mean is centered in zero.

Plane	PS Telescope		SPS Telescope	
	Residual X [μm]	Residual Y [μm]	Residual X [μm]	Residual Y [μm]
1	2.7	2.8	3.3	3.3
2	3.8	4.1	3.2	3.2
3	4.6	4.8	5.3	5.3
4	7.1	7.1	5.2	5.2
5	4.2	4.3	3.7	3.7
6	3.2	3.2	4.4	4.3

Table 5.10: X and Y residuals (RMS) of telescope planes after the alignment for both PS and SPS setup.

DUTs alignment The PS and SPS results on the DUTs alignments are slightly different. Both residuals distributions are centered around zero, however, the PS residuals are in the order of $25 \mu\text{m}$ while the SPS ones are, in the order of $14 \mu\text{m}$. This effect in the alignment at the PS could be related to the lower particle beam energy which increases the multiple scattering, primarily due to the aluminum walls of the cooling box. While at the SPS, with a higher energy beam, this phenomenon is negligible. A comparison between the PS and SPS residual distributions in the X direction for SCC 4 is shown in figure 5.33. The X and Y residuals from DUTs alignment are listed in table 5.11. Although the residuals at the PS are higher than expected, this was not a concern for the efficiency analysis, as the spatial cut to associate a cluster to the projection on the DUT of the track is of $100 \mu\text{m}$, as it was explained in section 5.3.2.2.

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

Resolution The sensor resolution has been calculated from the DUTs alignment residuals. As explained in section 4.3, in case of binary read-out, the pixel spatial resolution is related to the pixel pitch. Since for the ITkPixV1.1 chip the ToT reading was disabled, only binary read-out is possible. Therefore the expected resolution for the 3D sensor $50 \times 50 \mu\text{m}^2$ is about $14 \mu\text{m}$ in both X and Y directions. From the residuals analysis we got a resolution of about $13 \mu\text{m}$, slightly better than expected, but compatible within errors.

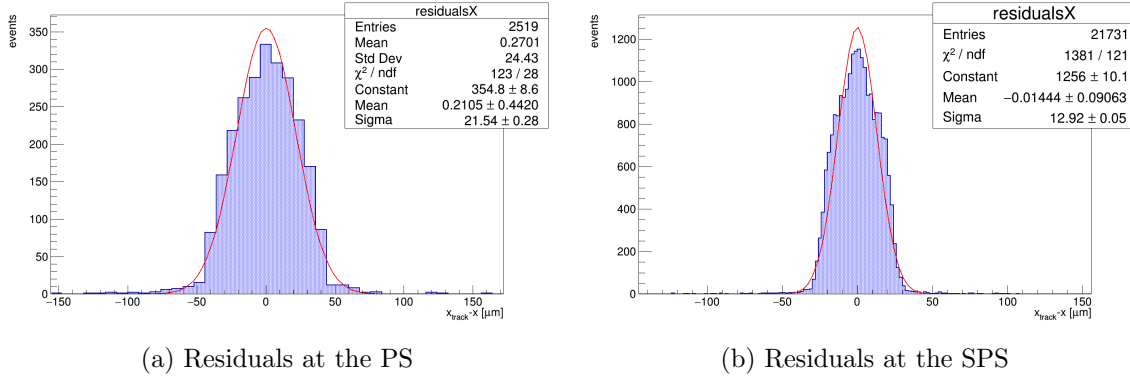


Figure 5.33: Residuals in the X direction of SCC 4 for both the PS and SPS setup. As expected, residuals RMS at the SPS is about 14 μm , while at the PS it is higher. The mean is centered in zero, as expected.

5.3.3.2 Results

This section presents the results on the average efficiency, the local efficiency of the pixel cell and the resolution of the FBK 3D sensors.

Mean efficiency As explained in section 5.3.2, the efficiency is calculated as the ratio of the number of tracks for which a cluster, that meets the above requirements, has been reconstructed and the total number of tracks. For a better timing match between the DUT cluster and the track, a reference plane with a reasonable time resolution was used. At the PS, where we tested two devices, due to an issue with the DAQ system, it was not possible to use the FE-I4 module as the timing reference plane. Therefore the SCC 4 was used as the reference for the SCC 2 efficiency analysis and vice-versa. At the SPS, the only DUT was SCC 4: its efficiency was measured with respect to both the FE-I4 module and the RD53A module. In this case, it was possible to use the FE-I4 module as a reference because the synchronization problems in the DAQ were fixed. The efficiency values for SCC 4 got at SPS using the FE-I4 and the ones got using the RD53A shows variations only of the order of 0.02%. The efficiency was measured as a function of the sensor bias voltage, collecting data between 0 and 10 V. Several runs were collected for each bias voltage point: for each one, the mean efficiency is evaluated and stored in a distribution. The mean value and the standard deviation of this distribution are then extracted by a Gaussian and are taken as the mean efficiency and its uncertainty for that bias point. An example of the efficiency distribution is shown in figure 5.34 for the data collected at the SPS at 10 V bias.

The mean efficiency observed at the SPS is slightly higher than the PS one. After moving the setup from the PS to the SPS, synchronization between telescope planes and DUTs has been optimized, this has certainly contributed to improving the efficiency analysis (more information about these synchronization issues are presented in appendix A). Moreover, as

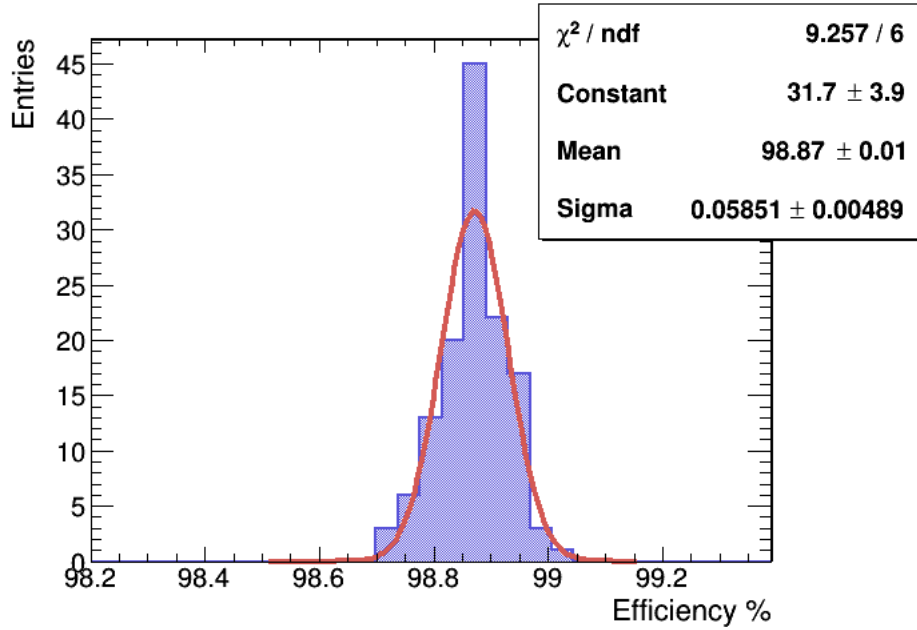


Figure 5.34: Distribution of the DUT efficiency computed for each individual run at the same bias voltage, in this case 10 V, at the SPS for SCC 4. The mean value and the RMS of this distribution are used to quote the mean efficiency and its error for a bias voltage setting.

mentioned above, the multiple scattering, due to the walls of the cooling box, at the PS is more accentuated and this could have slight negative effects on the measurement. However, the results got at 10 V bias at the PS and SPS are compatible within errors.

Mean efficiency results are shown in figure 5.35. SPS data provide a more robust estimate for the reasons that will be explained below. Results are as expected and shows that the efficiency is already $(98.6 \pm 0.1)\%$ with a bias voltage of 0 V, reaching $(98.87 \pm 0.06)\%$ with a bias of 10 V. As expected, an increasing efficiency trend was observed as voltage increased, due to the widening of the depletion zone in the sensor. The sensor has therefore met the requirement to have efficiency higher than 98% before irradiation.

The errors on the efficiency values got with the PS data are dominated by systematic effects. During data taking, due to an issue in the trigger system, the DUTs lost systematically the timing correlation with the telescope planes after few events, as shown in the Appendix A (plot A.1). Moreover, it was also noticed that the DUTs alignment at the PS was not stable: this led to a gradual increase in the residues of DUTs during the analysis which may have adversely affected the efficiency measurement. More information about this issue is presented in Appendix A (plot A.2). For these reasons, the efficiency values obtained at PS for each run are much more unstable, in a range between 95% and 99%, which leads to larger errors on the mean efficiency.

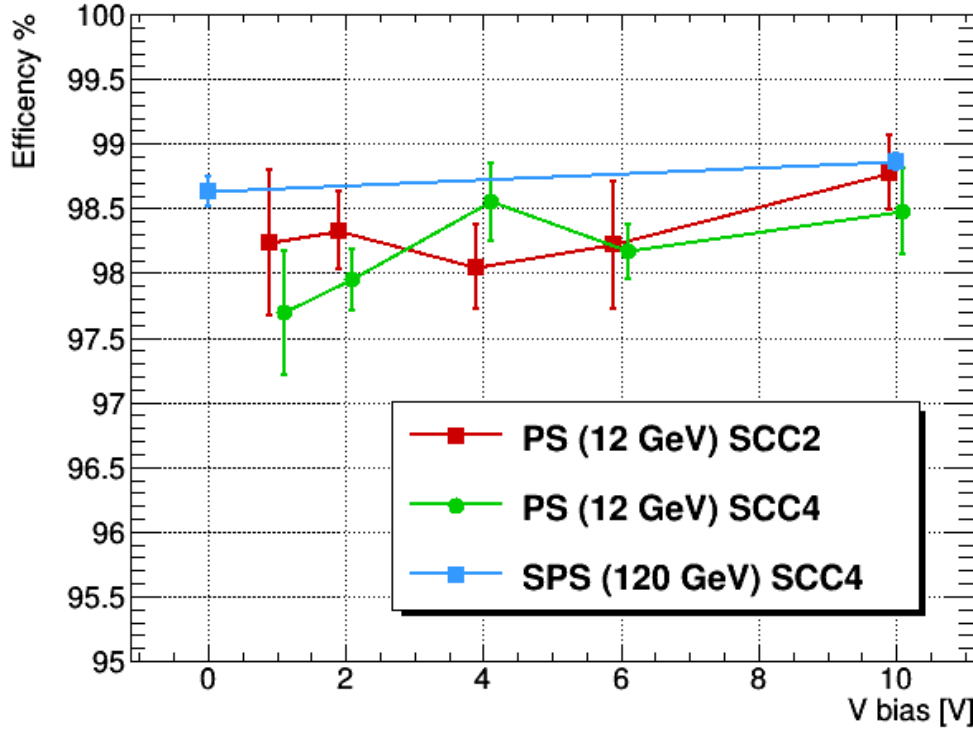


Figure 5.35: SCC 4 and 2 mean efficiency as a function of the sensor bias voltage. The error on the efficiency is evaluated as the standard deviation of the efficiency distribution obtained in each run. PS data points are reported with slightly different bias values to facilitate the reading of the graph.

Pixel cell efficiency For pixel detectors it is also possible to study the pixel cell local efficiency: the spatial coordinates of the clusters and the tracks intercepts could be interpreted in terms of the single pixel cell, as explained in section 5.3.2. Due to the geometry of the 3D sensor pixel cell, which is shown in figure 5.36a, we expect that in the corners of the sensor, where the p^+ columns are implanted, the efficiency is slightly lower. Figure 5.36b shows the pixel efficiency map reconstructed with the SPS data collected with a bias voltage of 0 V. As expected, in these regions the efficiency is lower, of the order of 75%, while in the inner region of the pixel cell it is close to 99%. Although there are other structures inside the pixel cell (i.e. n^+ column, bump bond support pad, contact column between n^+ column and bump pad) these do not affect the efficiency, that looks uniform in the central region of the pixel. A similar map has been constructed for the 10V data set. The projection of the first row of the two local efficiency maps (corresponding to a $1 \mu\text{m}$ wide line along $50 \mu\text{m}$ in the X direction) is shown in figure 5.37. The efficiency is higher than 98% after about $10 \mu\text{m}$ from the edge of the pixel cell for both 0 and 10 V bias. The electric field is affected

Where	V bias [V]	SCC 2		SCC 4	
		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 5.12: Summary of the efficiency measurements on unirradiated SCCs.

by the edge effects due to the $4\ \mu\text{m}$ radius p^+ column: in this region the collection of the signal is therefore less efficient. Moreover, no significant changes has been observed in the extension of the lower efficiency zone between 0 and 10 V. However, the efficiency in the column region at 0 V is slightly lower than at 10 V.

Due to the alignment issues explained above, inefficiency zones due to p^+ columns are not visible in the pixel efficiency map of the PS data, however the mean efficiency of the pixel cell is compatible with the one measured with SPS data.

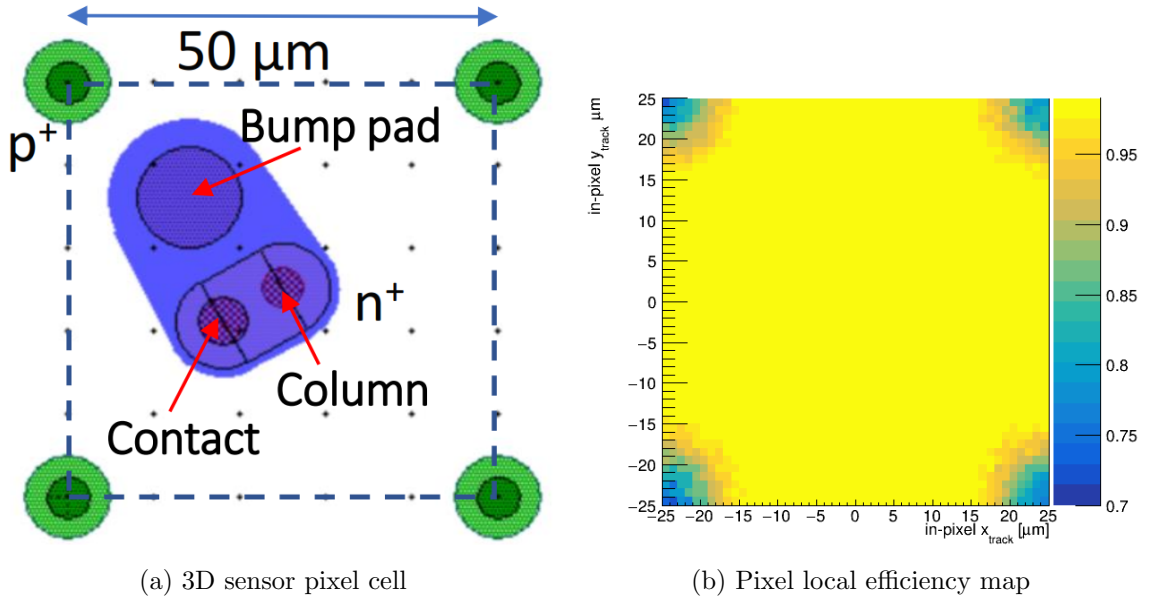


Figure 5.36: 3D sensor pixel cell and the local efficiency map (SPS data, 0 V bias): as expected, at the corner, where the p^+ columns are implanted, the efficiency is lower. No others structures are visible.

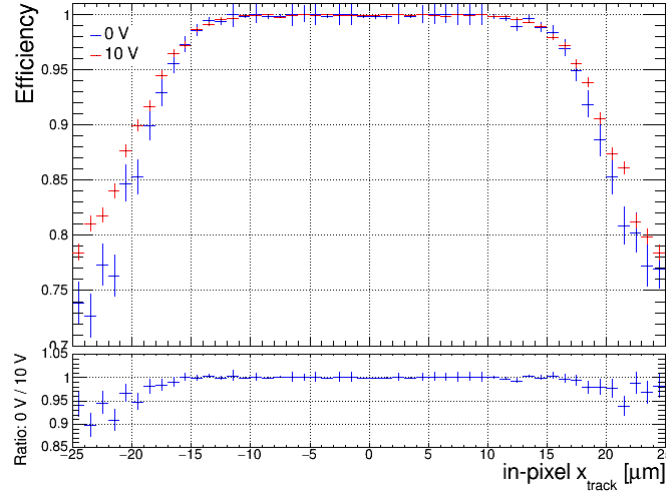


Figure 5.37: Pixel local efficiency map projection along X direction at the SPS for 0 V and 10 V bias.

5.3.4 Modules irradiation

As the key requirement of the 3D sensor is the performance after irradiation, four of these modules have been sent to irradiation: SCC 2 and 8 at the CERN IRRAD facility, while SCC 3 and 5 in Bonn. The summary of the irradiations is presented in table 5.8. The main goals of the irradiation are to have a uniform proton fluence over the entire surface of the module and to better simulate the irradiation conditions inside the ITk detector.

Irradiation in Bonn SCC 3 and 5 have been irradiated in Bonn with a 15 MeV proton beam up to a fluence of $1 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$. Modules have been irradiated with a beam perpendicular to the SCCs. Since the beam width is not sufficient to cover the entire surface of the module, the irradiation has been done scanning the entire surface of the module with a very focused beam: i.e. during the irradiation procedure, the beam is periodically moved to cover the entire surface of the module. In order to measure the proton fluence on the module surface, a segmented aluminum foil is placed on the back of the module. After irradiation, a spectroscopic analysis of the sheet allows the extrapolation of the fluence received. The conversion from protons to 1 MeV equivalent neutrons is done with a special conversion factor.

Results show a mean fluence of $1.01 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$ for SCC 3 and of $1.00 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$ for SCC 5. Both SCCs have received a ionising dose of about 1.13 Grad. The fluence received is very uniform over the surface of the module, with variations of the order of 1%. The error on the proton fluence is in the order of 5%, while the error on the equivalent neutron fluence is in the order of 15%, due to the systematic uncertainty on the conversion factor. The fluence analysis has been done in Bonn and the results are shown in figure 5.38, while

a summary of the fluences is presented in table 5.13.

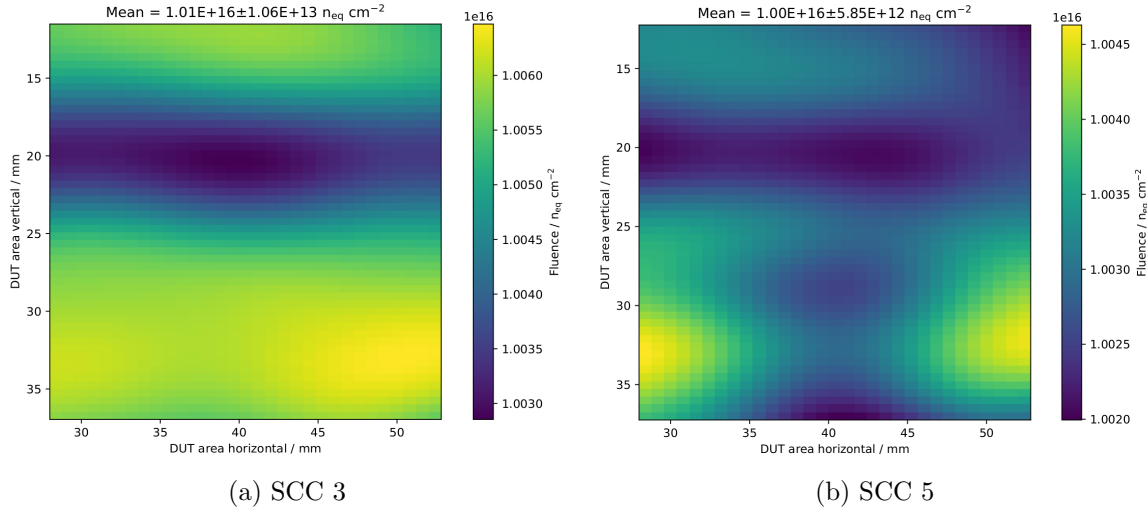


Figure 5.38: Proton fluence map of SCC 3 and 5 after the irradiation in Bonn. Note that the Z axis scales is slightly different. For both SCCs the fluence variation over the module surface is about 1%.

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

Table 5.13: Summary of the proton and equivalent neutron fluence received in Bonn by SCC 3 and 5.

Irradiation at IRRAD SCC 2 and 8 have been irradiated at the CERN IRRAD facility with a 23 GeV proton beam targeting a fluence of $1.7 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$. Since the Full Width Half Maximum (FWHM) of the beam is only $12 \times 12 \text{ mm}^2$, also in this case it was not possible to cover the entire surface of the module with a beam perpendicular to the SCCs. Since scanning the module is not possible at IRRAD, it was decided to tilt the modules by 30° with respect to the beam, placing them on special 3D printed supports (figure 5.39a). During the installation of the SCCs at IRRAD, a segmented aluminum foil was fixed with Kapton tape on the back of the module in order to measure the fluence (figure 5.39b). After irradiation, a spectroscopic analysis of the sheet allows for reconstructing the map of the received fluence. It was observed an average proton fluence of the order of $2.9 \cdot 10^{16} p^+/\text{cm}^2$, thus equivalent to $1.7 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$, given the scaling factor of $\sim 60\%$.

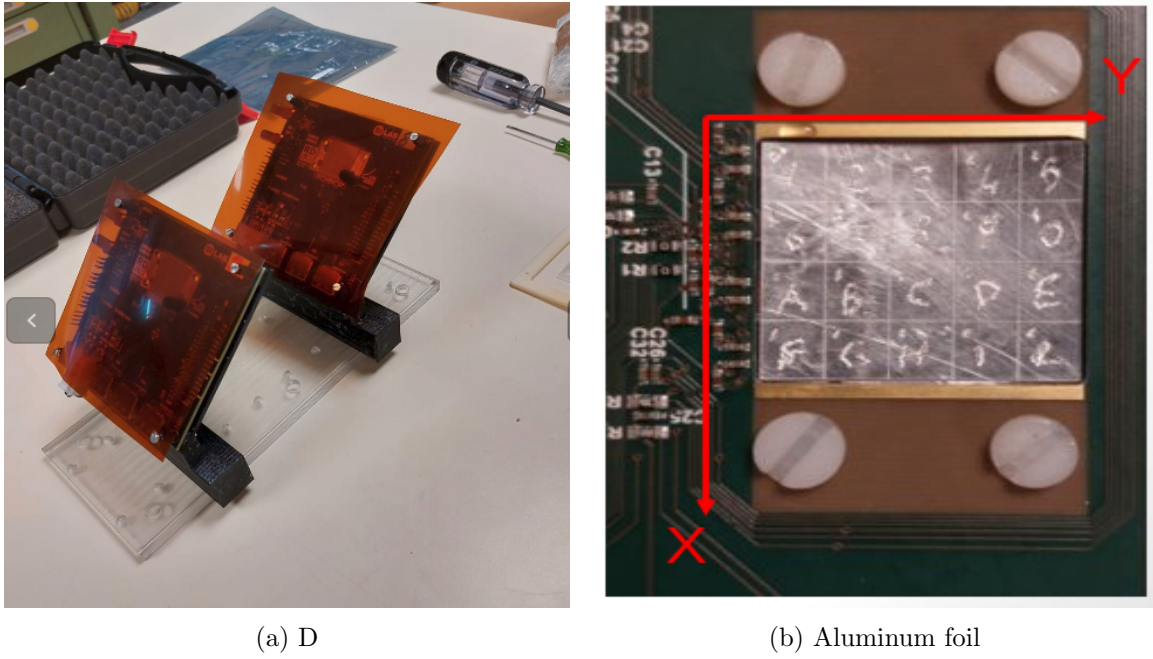


Figure 5.39: The SCCs placed on the holders with a angle of about 30° are shown in 5.39a. The aluminum foil placed on the back of the module in figure 5.39b.

However, due to an issue with the IRRAD focusing quadrupole, the beam was not aligned with the center of the module. The fluence map of SCC 2 reconstructed with the aluminum spectroscopy analysis is shown in figure 5.40a. It is clear that the beam was not centered in the Y direction, since the lower edge of the module has received a higher fluence. The fluence on the module surface is far from uniform; the map presents both regions with very high fluence ($8 \cdot 10^{16} \text{ p}^+/\text{cm}^2$) and with lower ($1 \cdot 10^{16} \text{ p}^+/\text{cm}^2$). By projecting the map along the X and Y direction (indicated in figure 5.39b) it was possible to extrapolate the position of the beam center by a Gaussian fit of the two distributions (figure 5.40b). The distance between the center of the module and the center of the beam, as well as the spread of the beam are presented in table 5.14 for the two SCCs.

SCC N°	X position	X spread	Y position	Y spread	Mean fluence
	[mm]	[mm]	[mm]	[mm]	[$10^{16} \text{ p}^+/\text{cm}^2$]
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 5.14: Summary of the distance between the extrapolated center of the IRRAD beam and the center of the module for both SCCs.

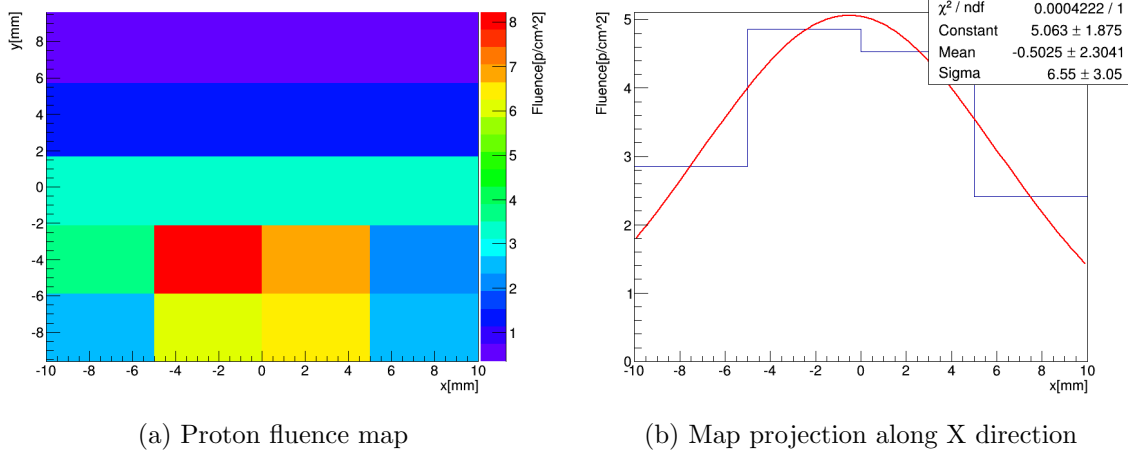


Figure 5.40: SCC 2 proton fluence map and its average X projection. It is clearly visible that the beam was not centered.

By extrapolating the position and size of the beam integrated over the long period of almost two months, it was possible to understand that protons passed mainly in the bottom of the chip and on the wirebonding pads. This fact, along with the too high protons fluence density, up to almost 3 times larger than requested, may explain why the readout chips do not respond any more: the chips themselves may have been damaged due to the too large TID. Moreover, the ripples visible on the SCC's pads may have deteriorated the mechanical contact of the wirebonds between the card and the chip. For the latter effect, analysis of the cards material is ongoing, in particular to understand the contamination with halogens that may have accelerated the card damages at this high fluence. A better understanding on the irradiation conditions will have to be achieved before the irradiation of new modules.

5.3.5 Summer 2022 test beam with irradiated modules

During Summer 2022, a test beam campaign has been done to study the performance of the irradiated modules on the beam. The campaign took place at the CERN SPS beam facility with a pion beam of about 120 GeV energy. Both the SCCs irradiated in Bonn (SCC 3 and 5) and at IRRAD (SCC 2 and 8) have been tested during this test beam campaign. Due to the wire bond pads issue with SCC 2 and 8, it was not possible to communicate with these devices: no testbeam data was taken. However the sensors IV curve were measured, results are presented in the following. Instead, the two SCCs irradiated in Bonn worked without significant problems.

Beam test setup The setup used for the two test beam campaigns is based on the MIMOSA26 telescope described in section 5.3.1 and it is exactly the same used during the Spring SPS test beam campaign. In this case, the unirradiated SCC 4 was used as the

timing reference plane.

Data taking During the campaign, in order to measure the efficiency of the sensors as a function of the bias voltage, data were collected with SCC 3 and 5 with a bias starting from 10 V up to 160 V with steps of 10 or 20 V. Two batches of data were collected: the former with all the SCCs perpendicular to the pion beam axis and a second batch with the SCCs tilted by 15° with respect to the XY plane, as shown in figure 5.41. Due to radiation damage, the leakage current of the sensor increases by some orders of magnitude with respect to the value observed before the irradiation. In order to keep the leakage current under a safe limit and to avoid the thermal run-away (current increases with temperature, power increases with current, thus increasing the temperature up to an unmanageable level) the irradiated devices must be cooled down. In addition, to improve the cooling of the module, a thin copper tape was applied connecting the back of the module up to its aluminum frame: this allowed to increase the heat exchange (the copper tape is slightly visible in figure 5.41). Thanks to the chiller and to the copper tape, it was possible to test the module at a stable temperature of about -34°C . The efficiency measurement with the tilted DUTs is particularly interesting as it reproduces working conditions more similar to those that will occur in the ITk detector.

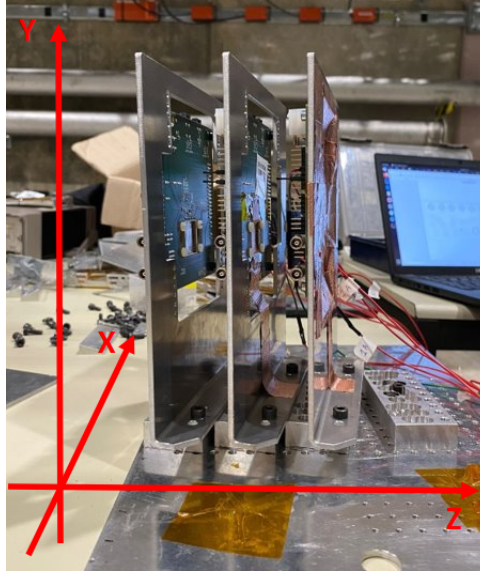


Figure 5.41: Overview of the SCCs in the tilted setup. The copper tape from the back of the module to the aluminum frame is slightly visible.

5.3.5.1 Offline alignment of the devices

The data, collected with SCC 3 and 5, has been analyzed using the Corryvreckan framework. The reconstruction of the data is done in exactly the same way explained in section 5.3.2

and 5.3.3.1. Results on the telescope and DUTs alignment are presented in the following. After the alignment, the efficiency was measured using the unirradiated SCC 4 as the timing reference plane. The following sections will present efficiency results and chip performance after irradiation.

Telescope alignment Results on the telescope alignments show residuals in the order of $4\ \mu\text{m}$, consistent with the measurements of the previous test beam and with the expectations. An issue occurred during data taking: after collecting several runs, the third MIMOSA26 plane of the telescope failed to collect hits in a large part of the active area: an example of its problematic hit map is presented in figure 5.42. However, since it was not possible to change this telescope plane, data was nevertheless recorded in this configuration. Afterwards, the tracks have been reconstructed using only five telescope planes: this has not influenced neither the alignment of the telescope and the DUTs nor the measurement of the efficiency, as it will be presented below. Data taken at about 100, 120 and 140 V bias have been analyzed with six telescope planes, while all the other data with only five telescope planes.

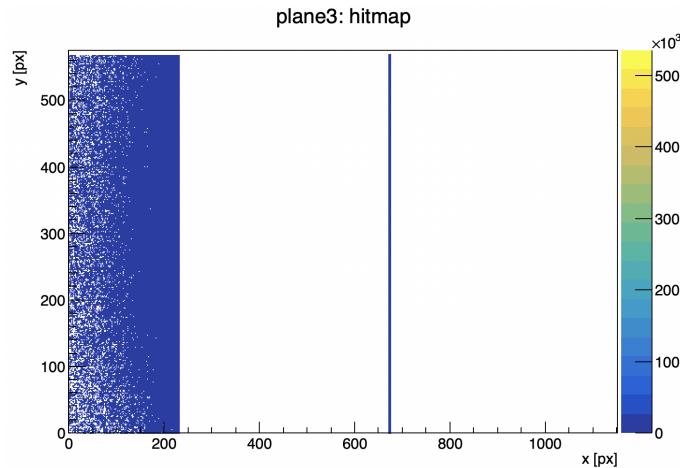


Figure 5.42: Telescope MIMOSA26 plane 3 issue: during data taking, at a certain point, this plane failed to collect data in a large part of the active area.

DUTs alignment SCC 3 and 5 were perpendicular to the beam. After the DUT alignment, residuals are, as expected, in the order of $14\ \mu\text{m}$, compatible with the ones obtained before the irradiation and compatible with the resolution of the sensor. However, an issue was found during the analysis of the data taken with the SCCs tilted with respect to the beam axis. At the end of the alignment procedure, the DUTs showed residuals in the X direction higher than expected (in the order of $25\ \mu\text{m}$), while the residuals in the Y direction were in the order of $14\ \mu\text{m}$. The reason for this difference is not related to the device resolution, but most probably due to a minimization problem occurring during the alignment

analysis. However, this slight misalignment does not influence the efficiency analysis, since, as explained before, the association of a cluster to a track is made with a spatial cut of $100\ \mu\text{m}$ in both X and Y direction. An example of X and Y residuals measured with the SCC 5 tilted is shown in figure 5.43.

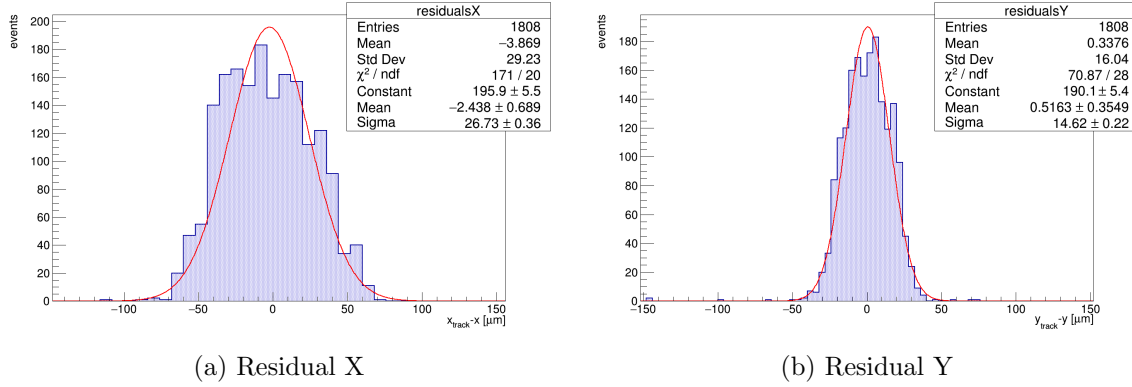


Figure 5.43: Residuals obtained with the SCC 5 tilted: RMS of the distribution in the X direction is about $10\ \mu\text{m}$ larger than the one in the Y direction.

5.3.5.2 Chip Results

This section presents the results of the ITkPixV1.1 chip performance after irradiation. Results presented concerns SCC 3 and 5. As explained in section 5.3.4, it was not possible to establish a communication with the chip of SCC 2 and 8 due to the large fluence received at IRRAD. Significant improvements in chip behaviour compared to RD53A have been observed. First we noticed that the chip configuration values (section 5.2.3.2) remained unchanged after irradiation. It was also noted that the chip is capable of being switched on and configured even at low temperatures, which was not possible with RD53A.

Analog and Digital scan results The digital and analog scans were firstly performed at a temperature of -16°C . The digital scan results on the modules were successful: both SCC 3 and 5 recorded 100% of working pixels. Also, the analog scan presented very good results for both SCCs: the number of masked pixels was about 0.1%. In SCC 5, it was noted that few pixels in the central area (which had the bump disconnected before irradiation, see section 5.2.3.5) stopped working, but their number was negligible. Then, the temperature was moved down to -34°C to start data taking. SCC 5 was successfully operated also at this temperature, while SCC 3 showed an issue: it stopped sending data to the acquisition system. Many investigations were required. Finally, the cause of the problem has been identified: several pixels in the bottom right corner prevented the exchange of data with the chip. These pixels were already problematic before the irradiation (see section 5.2.3.3) and maybe because of the irradiation and the low temperature their performance has degraded

more. The most probable explanation is that these pixels were sending random signals jamming the data stream. The issue was conservatively fixed by masking the two core columns on which these pixels lie. After applying this solution, the SCC 3 chip was operated successfully again. The amount of masked pixel was about 0.1% for both SCC 3 and 5. Additionally, the masked pixels due to the 2 masked core columns of SCC 3 bring the total fraction of masked pixels to 4%. The maps of the masked pixels after the digital and analog scan are shown in figure 5.44. The number of masked pixels for each SCC is reported in table 5.15.

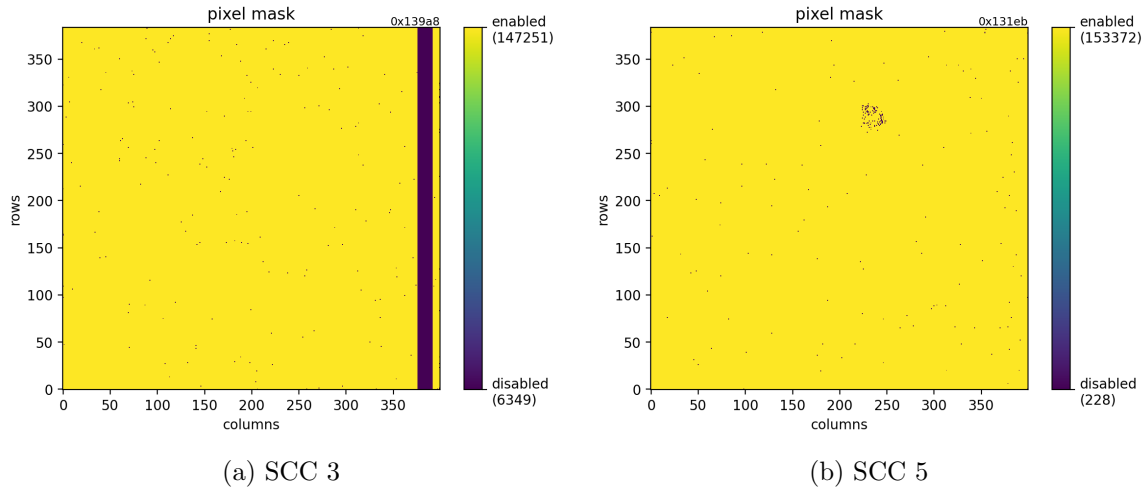


Figure 5.44: Masked pixel map for SCC 3 and 5 after irradiation. The fraction of masked pixel is about 4% for SCC 3 (due to the 2 masked core columns) and about 0.1% for SCC 5.

Threshold tuning results 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 (in 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 $1000 e$, the tuning procedure worked smoothly. Results are shown in table 5.15: as expected the threshold is close to $1000 e$ and the noise to $70 e$. 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 figure 5.45. Threshold tuning results are compatible with the ones obtained before the irradiation, within the uncertainty.

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

Table 5.15: 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 are indicated as StD.

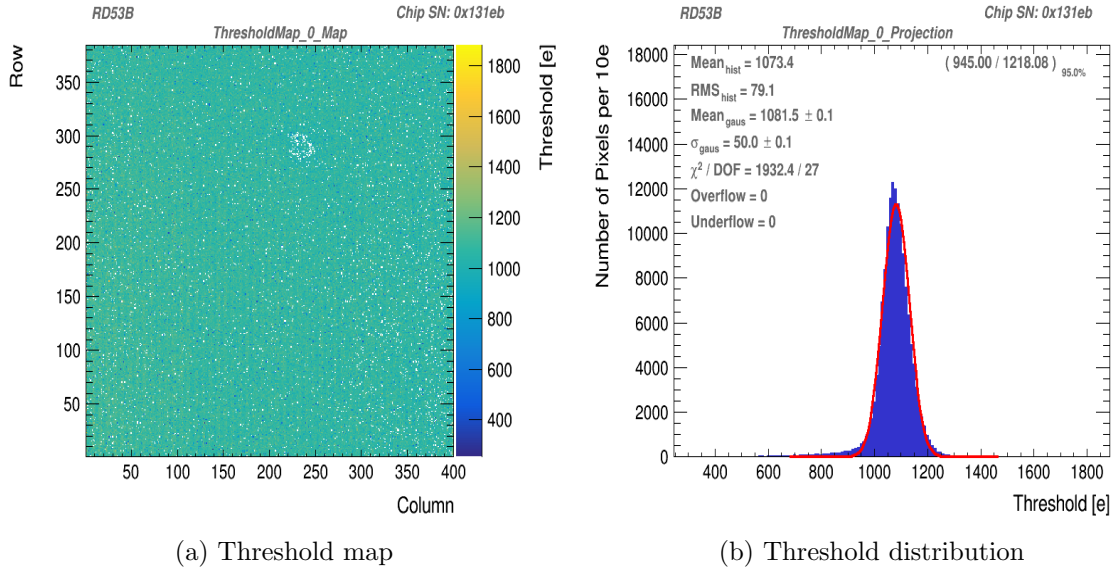
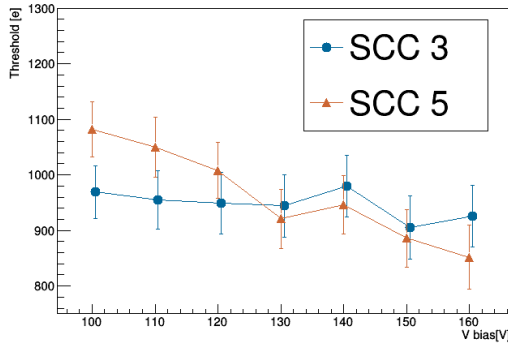


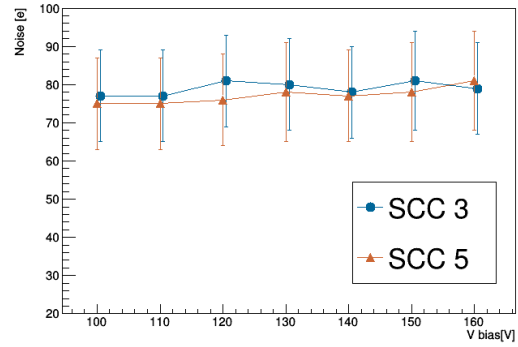
Figure 5.45: Threshold map and distribution for SCC 5 after irradiation. As expected the threshold map is uniform and the mean of the distribution is about 1000 e.

Threshold and noise versus bias The threshold tuning was performed with the sensor biased at 100 V: this tuning configuration was used for all the data taking. Since the tuning procedure is time consuming, it was decided to perform it only once, in order to exploit the available time to collect data on the beam. However, to confirm the validity of the tuning, a threshold scan was performed at several bias voltage values: this allowed to check threshold and noise variations as a function of the bias. Results are shown in figure 5.46, the error used for each point is the standard deviation of the threshold or noise distribution. The noise is stable around 75 e for both SCCs. The threshold seems to have a decreasing trend with increasing voltage, in particular for SCC 5. The reason of this behaviour is still

unknown. It could be related to the increased leakage current, even if the threshold scans were taken with the leakage current compensation enabled that should mitigate the impact of the leakage current on the electronics. Despite the unexpected behavior, this is not a significant problem as, in the ITk detector, the tuning will be performed at the exact bias voltage selected for data taking. On the other side, the threshold and noise dispersions stay $\sim$ stable while varying the bias, thus indicating that a re-tuning during the test beam data-taking was not needed.



(a) Threshold as a function of bias



(b) Noise as a function of bias

Figure 5.46: Threshold and noise as a function of bias voltage after irradiation. In both cases, the error reported is the standard deviation of the threshold or the noise distribution. Bias values are reported with a tiny offset to facilitate the reader.

5.3.5.3 Sensor Results

This section presents results on the mean efficiency of the sensor, the pixel local efficiency map and the sensor IV curve after irradiation. The efficiency is calculated as explained in section 5.3.2, the same parameters used for the analysis of the data collected with the unirradiated SCCs have been used. The efficiency was measured only for SCC 3 and 5, while the IV curve was measured for all the four irradiated SCCs.

Pixel cell efficiency The pixel local efficiency map has been reconstructed for both the configurations: with the SCC perpendicular to the beam and tilted. The efficiency map for the SCCs perpendicular to the beam are similar to those obtained for the SCCs before irradiation: there are lower efficiency areas with a radius of about $10 \mu\text{m}$ from the corners (figure 5.47a). In the configuration with the SCCs tilted, instead, these lower efficiency areas are no longer visible in the local efficiency map, as shown in figure 5.47b. As explained in section 5.3.3.2, 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 case of the sensor tilted with respect to the beam.

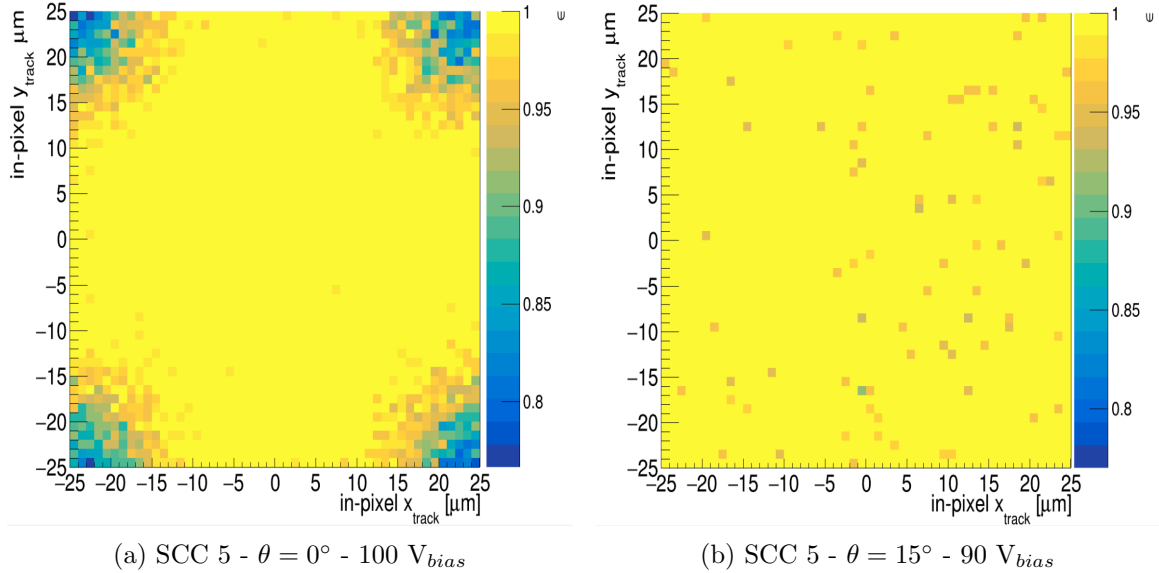


Figure 5.47: Pixel local efficiency map after irradiation for SCC 5 perpendicular ($\theta = 0^\circ$) and tilted ($\theta = 15^\circ$) with respect to the beam. Note that it is reasonable to compare the two maps, despite the different bias, since the sensor is fully depleted for bias higher than 90 V.

Mean efficiency As done for the unirradiated modules, in order to have a better timing match between the DUT cluster and the track, a reference plane with a reasonable time resolution was used, in this case SCC 4. The efficiency was measured as a function of the sensor bias voltage, collecting data at several bias voltages. Since only few runs were collected for each bias voltage, the error on the efficiency could not be calculated as done for the unirradiated samples. However, a couple of bias voltage points were collected with more statistics and it was possible to construct the runs efficiency distribution. In this case, a difference of the order of 0.1% in efficiency was observed. It was therefore decided to use this value as slightly conservative uncertainty for all the efficiency values found, but still consistent with the uncertainties observed for the high statistics runs of the unirradiated test beam campaign. Mean efficiency as a function of the bias voltage is shown in figure 5.48. As expected, the efficiency shows a growing trend as voltage increases. In case of SCCs perpendicular to the beam, the efficiency is about 97.5% at 40 V: the sensor is already almost completely depleted. For higher bias voltages the efficiency saturates, reaching $(98.5 \pm 0.1)\%$ at 100 V. The efficiency is very uniform all over the surface of the sensor (figure A.3 in appendix A). As expected, the efficiency obtained with the SCCs tilted is slightly higher than the one got with the SCCs perpendicular to the beam. This may be justified by looking at the pixel

local efficiency map in figure 5.47b, where it is evident that the column inefficiency is recovered. The saturation value reached in the tilted configuration is about $(99.9 \pm 0.1)\%$ at 90 V.

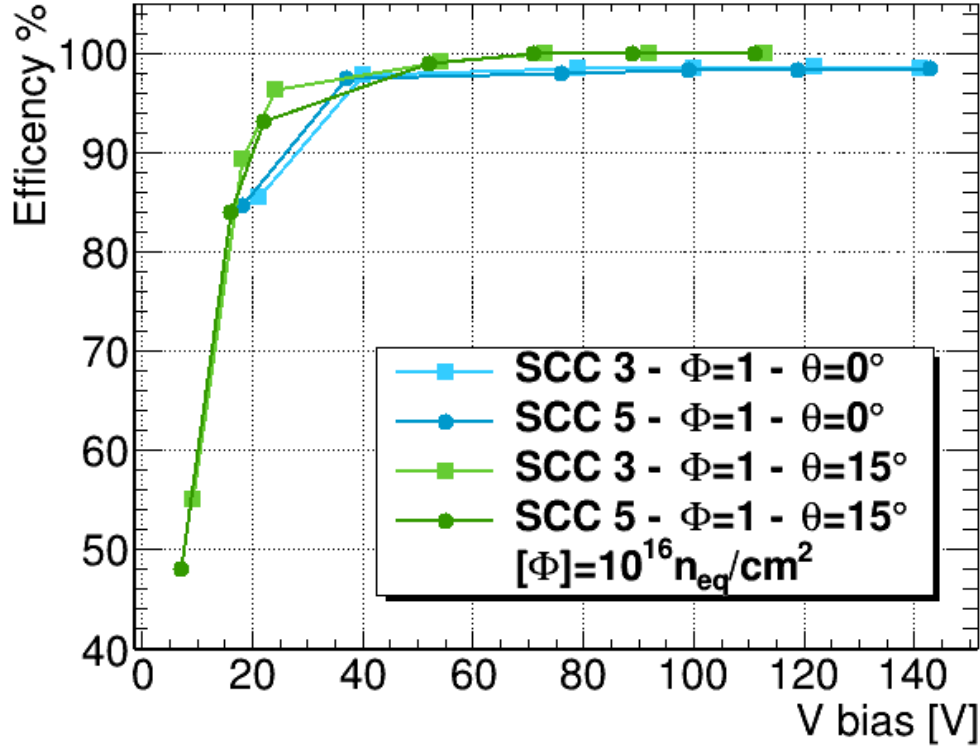


Figure 5.48: SCC 3 and 5 mean efficiency after irradiation to a fluence $\Phi = 1 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$. Efficiency is measured both with the SCCs perpendicular ($\theta = 0^\circ$) and tilted ($\theta = 15^\circ$) with respect to the beam.

These results may be compared with those obtained for the prototype modules with FBK 3D sensor ($50 \times 50 \mu\text{m}^2$) and RD53A chip irradiated to the same fluence [24] (figure A.4 in appendix A). In fact, the efficiency measurement is dominated by the sensor performance and the prototype sensors were very similar to the pre-productions ones, except for the active region thickness (130μ in the prototypes and $150 \mu\text{m}$ for the tested SCCs). In both cases, the chip was tuned to a threshold of 1000 e. Therefore, results should be compatible. Actually, the results on the prototype modules reach the efficiency saturation at higher bias voltage: 97% is reached at a bias voltage of about 90 V, while at 40 V the efficiency is only about 60%. The reasons of the difference with respect to the results presented in this thesis is still not clear. However, although the fluence is the same, the irradiation campaigns were very different since prototypes were irradiated at the IRRAD facility, with a 23 GeV proton beam. The irradiation was not uniform due to the limited size of the beam

	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 5.16: Summary of the mean efficiency measured on the irradiated SCCs.

(Gaussian with a standard deviation of about 12 mm), and due to impossibility of scanning over the sensor surface [24]. These conditions lead to an uncertainty of about 10% on the mean fluence. On the other hand, the uncertainty on the fluence received by SCC 3 and 5 was about 15%, although it was uniform (only 1% variation over the entire surface of the sensor, section 5.3.4). So the difference between the results obtained on SCCs and those on the prototype modules could be due to the fact that the sensors were actually irradiated to a different fluence. Few more devices will be irradiated to confirm the behaviour observed and described in this thesis.

In order to further evaluate the sensor performance, it has been decided to proceed to a second irradiation of SCC 3 and 5 to reach a total fluence of $1.5 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$, very close to the target specification value. After that, the SCCs will be tested again at SPS test beam. The new measurements may add some more information to the irradiation performance.

Sensor IV curve Sensor IV curves have been measured on all irradiated SCCs in a range of bias voltage between 0 V and 200 V. Measurements have been done at about -30°C on SCC 3 and 5. Several measurements in a temperature range between -18°C and -38°C were done for SCC 2 and 8. In both cases, in order to compare the results with prototype modules, curves have been scaled to the temperature of -25°C, using the equation 5.3.

Figure 5.49 shows the IV curves of SCC 3 and 5 obtained after the irradiation at Bonn: the leakage current is about $100 \mu\text{A}/\text{cm}^2$ at 100 V bias, scaled to -25°C: it is about four times larger than the currents of the prototypes (about $\mu\text{A}/\text{cm}^2$ at 100 V, figure A.5 in

appendix A). However, prototype modules were irradiated at a temperature of about 0°C , while during the irradiations at Bonn and IRRAD were at room temperature and the SCCs temperature was not constrained: therefore, significant annealing is expected due to the heat generated by the large particle flux. Moreover, devices have been kept for days/weeks at room temperature for the Bonn/IRRAD devices, respectively. The temperature history of the devices could explain the higher leakage current observed on SCC 3 and 5 with respect to devices irradiated at similar fluences.

Figure 5.49 shows the results obtained with the SCCs irradiated at IRRAD up to a fluence of $1.5 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$: the leakage current is about $50 \mu\text{A}/\text{cm}^2$ at 100 V bias, scaled at -25°C . During the prototyping phase, only diodes were irradiated at this fluence (figure A.6 of the appendix A). These currents are compatible with the ones obtained on the diodes, however diodes are dominated by edges effect due to the much smaller surface (about 2 mm^2), then the comparison is not optimal. Moreover, as explained in section 5.3.4, the irradiation at IRRAD was not uniform over the surface of the sensor, for this reason the result is not entirely comparable to devices which are irradiated uniformly.

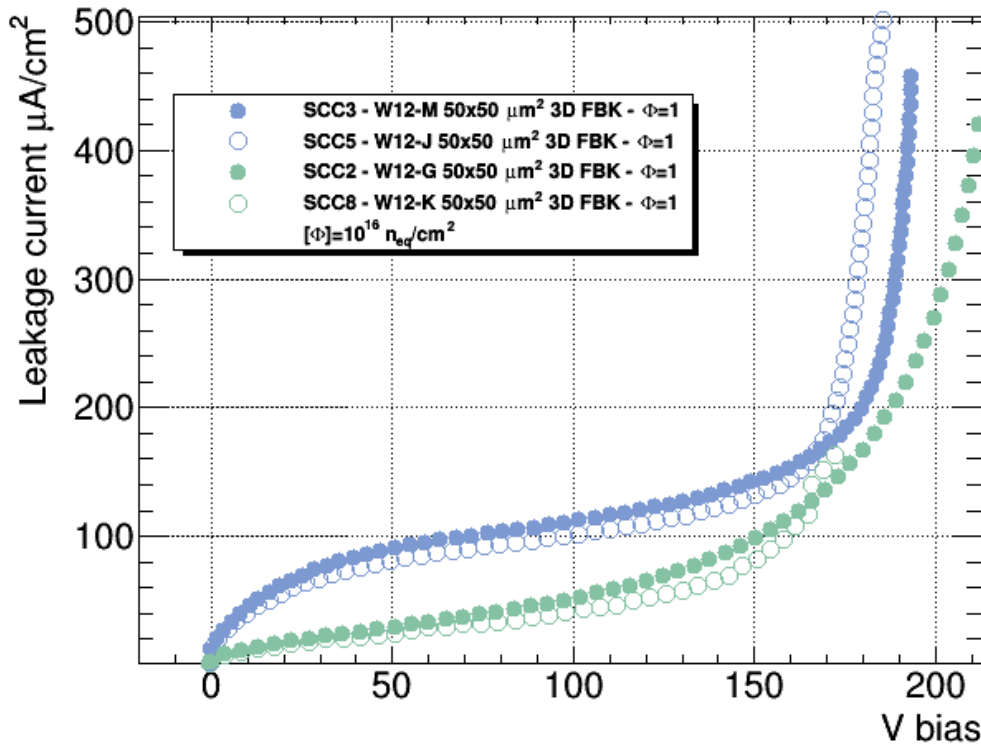


Figure 5.49: Sensor IV curves for the SCCs irradiated in Bonn and IRRAD. Both the measured curves and the scaled at 25°C are shown

Conclusions

The activities of this Thesis fit in the context of the ATLAS ITk project. ITk is the new tracking system that will be installed during the LHC Long Shutdown 3 (2026-2028), before the beginning of the High Luminosity LHC program. It will be an all-silicon tracker, and it will consist of a Pixel detector at small radius and a large area Strip detector surrounding it. The HL-LHC will set unprecedented radiation hardness requirements for the innermost layers of the Pixel detector. Due to this harsher radiation constraint, innovative high radiation-hard 3D pixel detectors will instrument an area of about 0.6 m^2 in the innermost layer. ATLAS has decided in 2020 to use the 3D technology 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. While the decision was taken on the basis of preliminary results on prototypes, the community got the recommendation to validate the effective radiation hardness of the devices, up to the ultimate fluence with the pre-production samples.

My thesis work focuses on the characterization of six 3D pre-production pixel modules. These devices are the first assemblies with pre-production 3D sensors and readout chips ever qualified after irradiation by the ITk Pixel community. The qualification work is carried out partly in the INFN laboratory in Genova and partly at CERN, where I had the possibility to test the devices on a particle beam. I started the characterization of the modules in Genova, working within the ATLAS ITk group. In order to qualify the pre-production, these 3D modules are devoted to special tests of quality assurance. After visual inspection, they were mounted on a PCB card, also known as Single Chip Card (SCC). In the Genova laboratory, I participated to all the measurement performed on the six SCCs, starting from the IV curves of the sensor, showing that the leakage current is compatible with measurements done at wafer level. I also took part in several readout chip tests. In particular, I took care of the threshold calibration. Tuning at the target threshold of 1000 e was successful. I also performed tests and analyzed the data to detect pixels with disconnected bump bond. Results of this analysis spotted several disconnected bumps on two out of six SCCs. We confirmed these results by taking data with X-ray source. The results spotted also some data taking issues on one of the two SCC with disconnected bumps: therefore it was decided to keep that SCC in Genova for further measurements. We now know, thanks to the experience gathered at the test beam, that this sort of behaviour may be generated by noisy or low quality bumped pixels, and specific tests will be run to investigate better the anomalous behaviour. The other five good SCCs have been further

characterized at CERN beam facilities before/after irradiation. Two unirradiated SCCs were tested in Spring at the CERN PS and SPS beam test facility. I personally took care of the data analysis to measure the sensor efficiency. In particular, I showed that the efficiency is $(98.87 \pm 0.06)\%$, in agreement with the expectations. Moreover, the analysis of the pixel cell local efficiency was carried out. The results I got show that the local efficiency is about 25% lower in the areas where p^+ electrodes are implanted. After the Spring tests beam campaign, two SCCs were irradiated at Bonn ($1 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$) and two at the CERN IRRAD facility ($1.7 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$), where I participated to the preparation and installation of the modules in the beamline. The irradiation in Bonn showed uniform fluence all over the sensor surface, while for the IRRAD samples the irradiation was not uniform: unfortunately, in this case, some areas of the modules received a very high ionizing dose, much higher than the amount that can be sustained by the chip. We were not able to communicate with the chip of these two SCCs, so they could not be tested again on the beam. Instead, the two SCCs irradiated in Bonn have been tested on the CERN beam in Summer. Data were taken in two configurations: with the modules perpendicular to the beam and tilted of 15° with respect to the beam axis. This second case is particularly interesting as it reproduces the realistic geometry of the modules in the ITk detector. I participated to the data taking and I analysed the data as they were recorded, thus providing an important immediate feedback to the team. The mean efficiency is $(98.5 \pm 0.1)\%$ when modules are placed perpendicular to the beam and $(99.9 \pm 0.1)\%$ when measured with an angle of 15° respect to the beam. Therefore I proved that sensors meet the ITk requirement to have a mean efficiency higher than 96% (97%) in the perpendicular (tilted) configuration after irradiation. Prototype modules irradiated and tested in similar conditions reached the target efficiency at a higher bias voltage (about 100 V) with respect to these pre-production modules (already saturated at about 40 V). The difference between these two results could be due to a different radiation fluence, as the declared uncertainty on the fluence is larger than 10% for both the prototypes and our samples. Further investigation is needed. Our samples will be further irradiated to reach a fluence of $1.5 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$, then tested again on the beam. Other samples will be irradiated as well. These results could add more information and eventually confirm our observations. The analysis of the pixel local efficiency map showed that the inefficiency in the region of the p^+ electrodes is recovered in the tilted configuration, as expected. Besides the efficiency analysis, during the test beam period I also participated to devoted tests to study the pre-production chip performance and sensor IV curves, together with colleagues of the Genova ATLAS ITk group. The irradiated chips were successfully operated and the results of the threshold tuning at 1000 e were compatible to results obtained before irradiation. The sensor leakage current after irradiation showed a slightly higher value with respect to the one observed on prototype modules, however annealing was not taken into account and could potentially explain the differences.

The results of my thesis work confirm the excellent performance of the FBK 3D pre-production sensors. I have presented my work at several meetings of the ITk collaboration. Preliminary results have been shown at the international conference iWoRiD 2022 in June. In September, I have personally presented the results at the Italian Physics Society congress

(SIF 2022). An abstract to the international workshop PIXEL 2022 conference has just been submitted. In the next months, these results will be discussed at the ITk pixel sensor Production Readiness Review, which will allow the ITk project to proceed with the sensor production. About 100 modules with ITkPixv1.1 chip and FBK 3D sensor from the pre-production wafers will be distributed to the sites involved in the triplet module assembly. The assembled modules will contribute to validate the modules assembly and multi-module testing setups in view of the ITk detector production.

Appendices

Appendix A

Additional plots

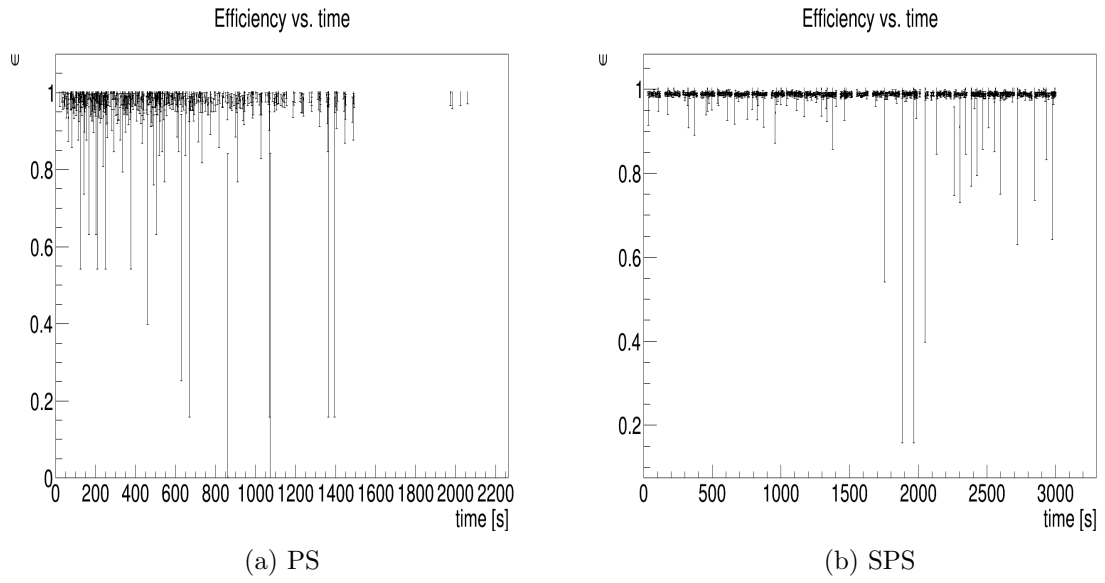


Figure A.1: Efficiency as a function of the data taking time: in PS data it is clearly visible the systematic loss of correlation, while in SPS data the efficiency is much more stable over the time. This effect has adversely influenced the mean efficiency measurement at PS.

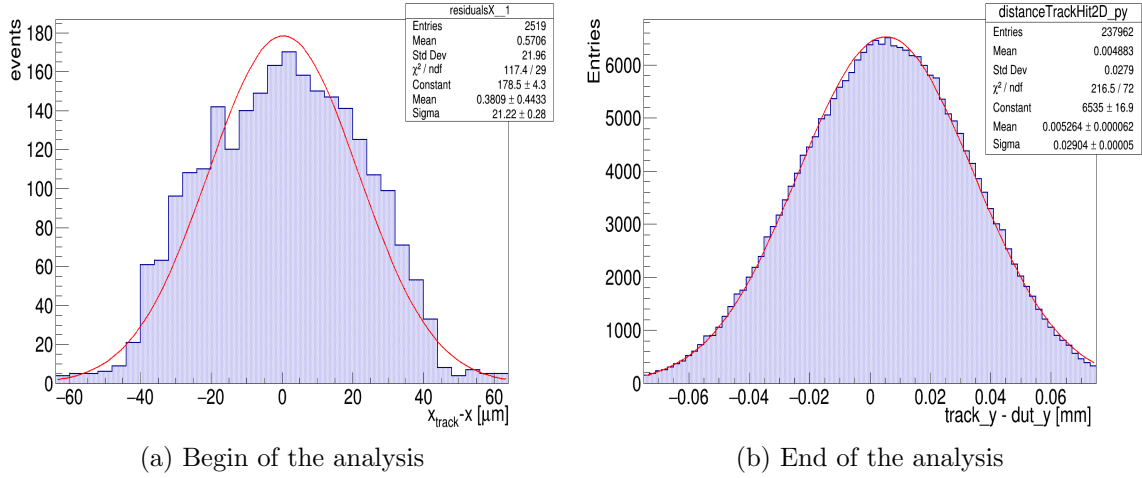


Figure A.2: Residuals of DUT (SCC 2) for several runs at the beginning of the analysis (just after the run used for to derive the alignment) and for several late runs. An increase of about 10 μm in the residual standard deviation is noted for late runs. This may have affected efficiency analysis, particularly for tracks that were not initially perfectly aligned.

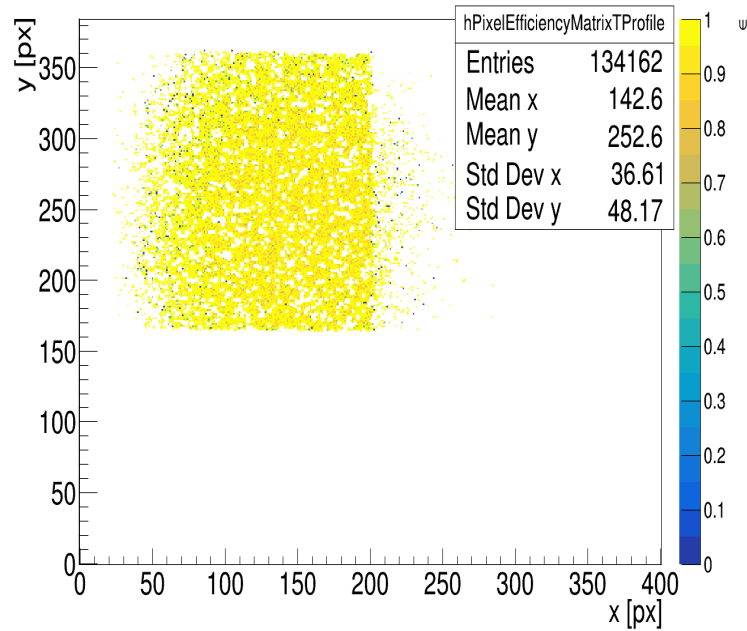


Figure A.3: Sensor efficiency overview. The surface of the sensor (SCC 3) show uniform efficiency after irradiation. Areas with no its are excluded from the analysis because they have not registered any hit.

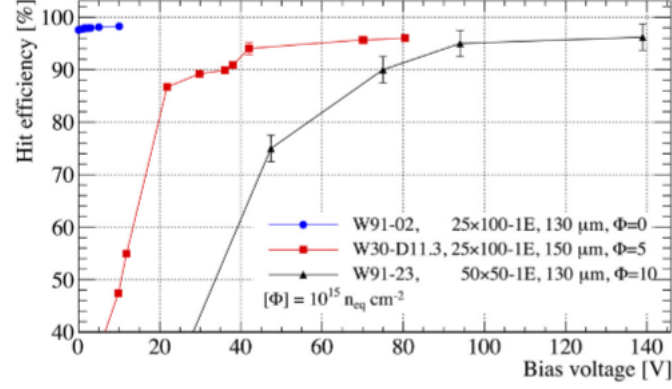


Figure A.4: Efficiency of prototype modules with RD53A chip and 3D FBK sensor. Sensors have been irradiated to a fluence Φ and tuned to a threshold of 1000 e. Image credits [24]

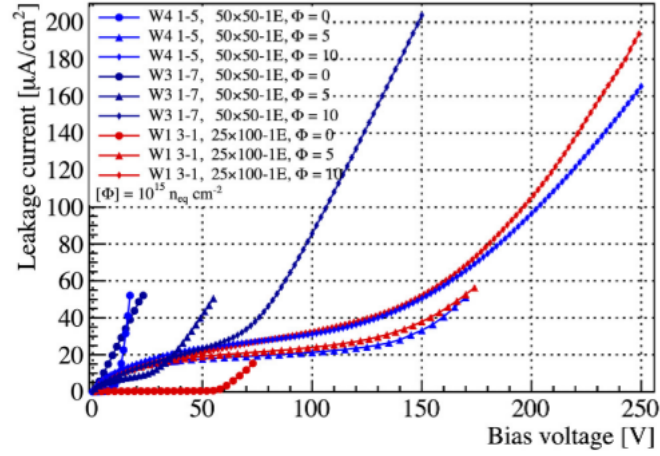


Figure A.5: Prototype modules IV curve. Sensors have been irradiated to a fluence Φ . Image credits [24]

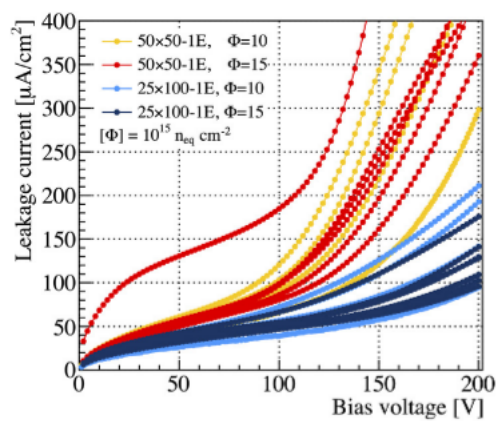


Figure A.6: FBK diode prototypes IV curve. Diodes have been irradiated to a fluence Φ . Note that in the small area diodes the edge effect is expected to have a significant contribution. Image credits [24]

Module	Frequency cut	number of events	spatial cut abs (X,Y) [μm]	time cut abs [ns]	max hits on track	mix track chi2ndof	Comments
Event Loader Eudaq	/	/	/	/	/	/	/
Mask creator	15	All	/	/	/	/	Masking
Clustering	/	10 k	/	/	/	/	/
Pre alignment	/	10 k	/	/	/	/	/
Module	Frequency cut	number of tracks	spatial cut abs (X,Y) [μm]	time cut abs [ns]	max hits on track	mix track chi2ndof	Comments
Tracking 4D	/	10 k	100, 100	600	N-1		Align telescope
Alignment Track Chi2	/	10 k	/	/	/	25	Align. telescope
Tracking 4D	/	10 k	50, 50	600	N-1	/	Align. telescope
Alignment Track Chi2	/	10k	/	/	/	10	Align. telescope
Tracking 4D	/	10k	30, 30	600	N-1	/	Align. telescope
Alignment Track Chi2	/	10k	/	/	/	5	Align. telescope
Tracking 4D	/	100k	50, 50	600	N		Tracks for DUT align.
DUT Association	/	100k	150, 150	600	N		Align DUT
Alignment DUT Residuals	/	/	/	/	/	/	/ Align DUT
DUT Association	/	100 k	50, 50	600	N		Align DUT
Alignment DUT Residuals	/	/	/	/	/	/	Align DUT
DUT Association	/	100k	20 ,20	600	N	/	Align DUT
Alignment DUT Residuals	/	/	/	/	/	/	Align DUT
Analysis Efficiency	/	All	100, 100	600	N	/	Efficiency analysis

Table A.1: The Corryvreckan modules and their parameters used for our analysis. Note that modules are listed in order of use. N is the number of telescope planes available.

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