

ATLAS ITk Silicon Strip Detector Performance Studies based on the System Test with Cosmic Muons at DESY

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Abstract

The ATLAS experiment is the world's largest collider-based particle physics experiment, located at the LHC in Geneva. An upgrade of the LHC will greatly increase the radiation environment and track density in the inner region of the detector. Therefore, an upgraded version of the innermost tracking detector, the ITk, is being developed. This thesis presents systems and experiments surrounding the ITk strip detector end cap.

As an ATLAS authorship qualification task, components of this detector, the bus tapes, were tested using a custom flying probe robot.

A System Test setup was constructed at DESY as a test bench for the end cap and its services. It allows the operation of the silicon strip modules in a realistic environment with cooling. A system for monitoring the safety and environmental variables of the setup was constructed. It was used to measure the tightness of the gas volume enclosing the System Test, showing that the petals are safe from condensation even in the event of a sudden stop of the external dry air supply. An additional setup for testing single petals, the petal coldbox, was developed. With the petal coldbox, the temperature-dependent on-module cooling performance was studied.

Both setups were used to study the noise of the detector modules. The repeatability of the noise measurements was studied, and the results were compared to an alternative DAQ system. A way of mitigating noise artefacts by treatment with ionised air was successfully tested with one of the petals. The noise environment before and after loading the modules onto the petal, as well as the difference between the noise environments in the coldbox and System Test, were studied. Finally, a successful measurement of the noise crosstalk between the petal's primary and secondary sides was performed.

Using an external trigger setup, a cosmic muon signal was measured with a petal inserted into the System Test by performing a latency scan. This muon signal was clearly visible as an extended plateau when performing a threshold scan with the same setup. This constitutes the first measurement of a real particle signal with a fully loaded petal.

During this thesis, simulation methods for the ITk strip end cap modules have been developed. In particular, a way to perform hit clustering in the native module coordinate system before transforming the cluster position and resolution into Cartesian coordinates is presented. The new simulation method was verified using a beam telescope made out of R0 modules, achieving the expected track reconstruction performance. Afterwards, a possible cosmic muon telescope setup in the System Test was investigated using Monte-Carlo simulations. The reconstruction of the cosmic muon flux from the simulated data was demonstrated, showing the feasibility of future cosmic muon tracking measurements with the System Test setup. The angular resolution of this setup was also determined and shown to be sufficient for measuring the flux. Finally, a method for determining the module efficiency exploiting the stereo module geometry is presented and demonstrated in a simulation scenario.

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Introduction

Long before humanity gained access to modern methods of experimental physics research, many schools of philosophy already understood matter to consist of small, indivisible parts. This concept, called “atomism”, was already advocated in the 5th century BC by the ancient Greek philosopher Leucippus and his student Democritus [1]. In the late 18th and early 19th centuries, the view that all chemical compounds consist of indivisible “atoms” had finally become established. At the beginning of the 20th century, Rutherford concluded from experimental data that the atom consists of a small, heavy, positively charged nucleus in its centre and a light, negatively charged shell [2]. In the early 20s, the atomic nuclei were revealed to consist of positively charged “protons” and neutral “neutrons”. However, even these particles soon turned out not to be indivisible. In the 1960s, the view prevailed that they consist of “quarks”, which are elementary particles [3, 4]. The existence of additional constituents, the “gluons”, was confirmed in 1979 by the TASSO (Two Arm Spectrometer SOlenoid) experiment at DESY (Deutsches Elektornen-Synchrotron) in Hamburg, Germany [5]. Today, the Standard Model of particle physics summarises our knowledge of the nature of matter and its interactions [6]. Even if, from today’s perspective, it represents the crown jewel of the atomistic worldview, some questions remain unanswered, such as the nature of dark matter, the mass of neutrinos or the unification of the different interactions.

In order to gain new insights into (beyond-) Standard Model physics, experiments are carried out at particle colliders. The largest of all accelerators currently used for high-energy physics is the LHC (Large Hadron Collider) at CERN (Organisation européenne pour la recherche nucléaire) in Geneva [7]. It brings protons to collision with a centre of mass energy of up to $\sqrt{s} = 14$ TeV at the 26.7 km long synchrotron. Detector experiments are located at the interaction points, measuring the products of these collisions and thus enabling comparisons with the predictions of the Standard Model. The largest experiment of this kind is called ATLAS (A Toroidal LHC ApparatuS) [8]. ATLAS consists of several layers, the innermost of which is responsible for measuring the tracks of charged particles originating from the interaction point. Due to a scheduled upgrade of the LHC, the accelerator will provide a significantly higher collision rate. Therefore, the current tracking detector of ATLAS will be replaced entirely. The sensitive area of this new tracking detector, called ITk (Inner Tracker), will be made entirely of silicon [9, 10]. It consists of an inner pixel detector and an outer strip detector. In turn, the strip detector comprises a “barrel” region, in which the silicon sensors extend parallel to the beam, and two “end cap” regions, in which the sensors are orthogonal to the beam axis.

The production of such a detector requires the participation of many institutes and industrial partners, which form a complex supply and production chain. Among many other production steps, DESY in Hamburg is responsible for integrating the detector parts into the global support structure of one of the end caps. DESY also carries out the ITk strip end cap System Test. In this, the modules, mounted on the local support structure (called “petal”), are operated in a realistic environment, and their correct functionality is examined in detector tests. Apart from testing i.e. their noise level and thermal performance, data collection with cosmic muons is planned to test the detector modules with an actual particle signal.

Following this brief introduction to the global context of the work, Chapter 2 introduces the Standard Model of particle physics, the LHC, and the ATLAS detector, including its upcoming upgrade with a focus on the ITk. Chapter 3 offers an overview of the fundamental principles of silicon tracking detectors. Chapter 4 describes the strip end cap of the ITk and the petals, as well as the relevant services.

The so-called “bus tapes”, which provide the conductive tracks for digital communication and power supply on the petals, are an example of the components subjected to several production steps at DESY in Hamburg. Chapter 5 describes the quality control tests conducted on the bus tapes as part of this thesis using a custom flying probe robot.

During the timeframe of this thesis, two experimental setups, the petal coldbox and the ITk strip end cap System Test, were developed. A new Interlock & Monitoring System (IMS) was developed for the latter. Chapter 6 gives an overview of these setups and presents measurement results of the atmosphere in the System Test coldbox and the cooling performance of the modules on the petal.

Chapter 7 presents the detector tests conducted with the modules. It investigates the repeatability of the results and compares them with results from an alternative data acquisition system. It also includes studies on the electrical noise environment in the experimental setups and the noise crosstalk between the modules on the petal.

Chapter 8 provides an overview of the physics of cosmic muons, which originate from extensive air showers. As part of this thesis, cosmic muon data was taken for the first time using a fully loaded petal using the System Test setup. These results are presented in Chapter 9.

Many studies with the System Test depend on the availability of fully loaded petals that can be inserted into it. A possible future setup of the System Test, which could be used as a cosmic muon telescope, consists of four petals. The performance of such a telescope was investigated using Monte Carlo simulations. The simulation methods developed for this purpose, their verification using a hypothetical beam telescope consisting solely of ITk strip end cap modules, and the results for the foreseen cosmic muon telescope setup are presented in Chapter 10. A potential method for determining module efficiency curves using cosmic muons is also introduced and investigated in a simulation.

Chapter 11 concludes the thesis with a summary of its results and an outlook on the near future of the System Test project. Experimental results are also summarised in a brief conclusion at the end of the respective chapter.

The ATLAS Experiment

An important building block in the experimental landscape of high-energy physics are collider-based detector experiments. These experiments allow for exploring the features of the theory framework, known as the Standard Model of particle physics, by measuring the properties of particles created during the collisions. The currently largest and highest-energy particle collider is the LHC at CERN in Geneva. It hosts the largest collider-based experiment ever built, the ATLAS detector. This chapter aims to give an overview of the Standard Model and the LHC, and explain the layout and need for the ongoing upgrade of the ATLAS detector.

2.1 The Standard Model of Particle Physics

To our current knowledge, all interactions of matter are mediated by four fundamental forces. The most prominent force on cosmic scales is gravity, which acts on all known matter. Its currently accepted description is Einstein's general theory of relativity, which describes gravity as the curvature of space-time by matter [11]. The three remaining forces, the strong and weak nuclear forces and the electromagnetic interaction, are described by quantum field theories and combined into the Standard Model of particle physics (see [6] for an overview of Standard Model physics).

2.1.1 Elementary Particles

The Standard Model distinguishes between two types of elementary particles: Fermions with half-integer spin and bosons with integer spin (see Figure 2.1). Fermions are divided into two classes, the quarks and leptons, each subdivided into three families with increasing mass. Among the quarks are the up and down, charm and strange, and the top and bottom quarks, each with the charge $+2/3$ and $-1/3$, as well as their corresponding antiquarks of opposite charge. Of the quarks, only the up and down quark are stable particles. Among the leptons are electrons, muons and tau leptons with a charge of -1 , and their corresponding antiparticles, with only the electron being a stable particle. In addition, each lepton is assigned a corresponding (anti-)neutrino that does not carry an electric charge. The first class of bosons are the vector bosons: photons, $W^\pm$ and Z^0 bosons, and gluons, which mediate the three fundamental forces. In addition, the scalar Higgs boson exists as a consequence of the Higgs mechanism.

Standard Model of Elementary Particles

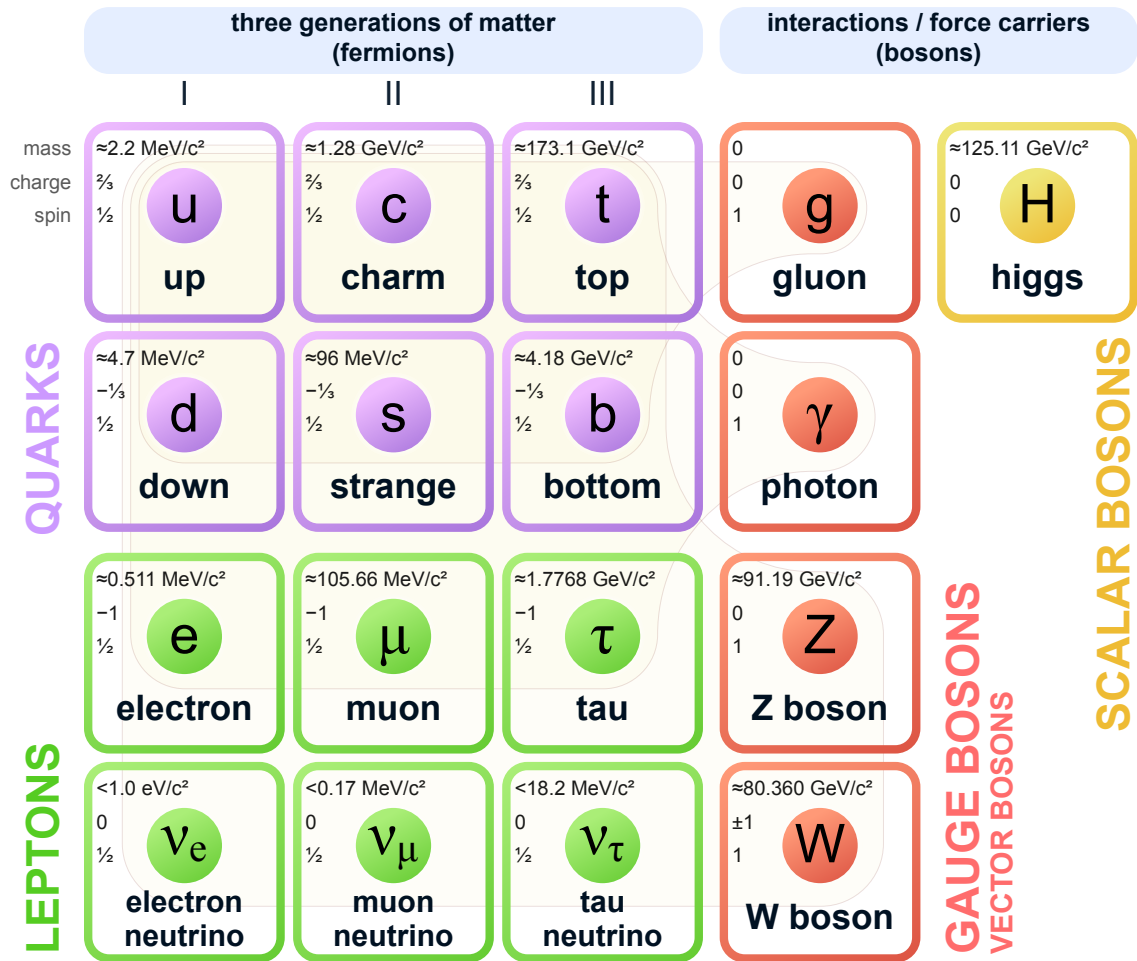


Figure 2.1: Fundamental particles of the Standard Model of particle physics with their masses, electric charges and spins [12].

2.1.2 Fundamental Interactions

The electromagnetic interaction is the force most present in our everyday lives and acts on all charged particles. It is mediated via the exchange of mass- and chargeless spin-1 bosons, the photons, and is e.g. responsible for forming atoms and chemical bonds. Paul Dirac paved the way for the theory of quantum electrodynamics in the 1920s by describing the spontaneous emission of radiation by atoms [13]. Through many further contributions (Julian Schwinger provided a comprehensive summary of the relevant publications in [14]), the theory was developed into one of the most successful and best-tested physics theories. “For their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles” [15], Tomonaga, Schwinger, and Feynman received the Nobel Prize in Physics in 1965.

In the 1930s, Enrico Fermi attempted to describe the beta decay of neutrons caused by the weak interaction assuming a direct interaction of four fermions (the neutron and the resulting proton, neutrino and electron) [13]. In the 1960s, Glashow [16], Salam [17] and Weinberg [18] finally succeeded in unifying the weak interaction with the electromagnetic interaction to form the theory of the electroweak interaction. “For their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current” [19], the three were awarded the 1979 Nobel Prize in Physics. In addition to the photon, the electroweak theory contains the $W^\pm$ bosons, which can change the flavour of a fermion by interacting with it (for example, a down quark is turned into an up quark in a β^- decay via a weak interaction carried by a W^- boson) and Z^0 bosons. The weak interaction is the only Standard Model mechanism for neutrinos to interact with other particles.

The strong interaction is only limited to the interaction of quarks and gluons. It is described by the theory of QCD (Quantum Chromodynamics), which has the gluon as its force-carrying boson, which carries a property called “colour charge”. Colour charges are never observed alone, as they always combined with other (anti-)colour charges to form a colour-neutral system. Unlike the other interactions, QCD exhibits “asymptotic freedom”; the interaction becomes stronger as the distance between the particles increases or the energy scale decreases. “For the discovery of asymptotic freedom in the theory of the strong interaction” [20] Gross, Politzer and Wilczek were awarded the 2004 Nobel Prize in Physics. Asymptotic freedom leads to quark confinement, which means quarks can never appear as free particles at “everyday” energy scales but are always found in bound states, called hadrons. Systems of two quarks are called mesons, and systems of three quarks (such as protons and neutrons) are called baryons. Quarks that drift apart at high energy cause a new quark-antiquark pair and, thus, new mesons to form. In high energy physics events, this manifests itself as quarks starting a cascade of hadronic particles in a thin cone called a hadronic “jet”.

So far, attempts have failed to unify the strong and weak interactions into a so-called GUT (Grand Unified Theory). There is also no generally accepted theory of quantum gravity. Unifying this with a hypothetical GUT can be seen as the holy grail of theoretical particle physics and is called the “theory of everything”.

2.1.3 Higgs Mechanism

In 1964, Higgs [21], Englert and Brout [22], as well as Guralknik, Hagen and Kibble [23], independently formulated a mechanism that describes how elementary particles acquire a mass through interaction with a scalar field (known today as the Higgs field). It is thanks to another work by Kibble that the

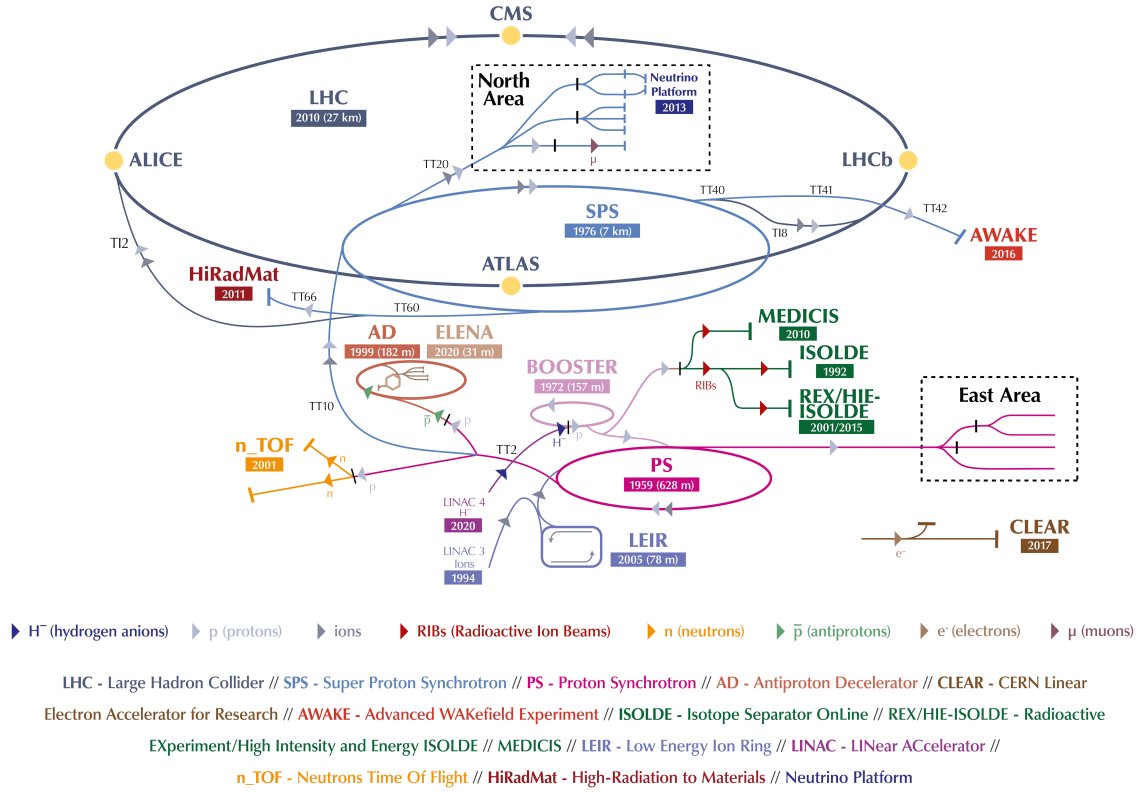


Figure 2.2: Schematic overview of the LHC, its pre-accelerator complex and the adjacent experiments [28].

mechanism could also be used for the non-Abelian electroweak theory [24]. The Higgs mechanism is an integral part of the Standard Model. It also predicts the existence of a Nambu-Goldstone boson, which is created by symmetry breaking. The existence of this Higgs boson was shown experimentally in 2012 by the ATLAS and CMS collaborations at the LHC in Geneva [25, 26]. “For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider” [27], Higgs and Englert were awarded the 2013 Nobel Prize in Physics.

2.2 The Large Hadron Collider

The LHC [7] is currently the largest particle accelerator in the world. The accelerator is located in the region of the Swiss-French border near Geneva and is operated by CERN. As a synchrotron in collider configuration, it accelerates protons in bunches of 10^{11} particles over a total distance of 26.7 km and collides them at a centre-of-mass energy of up to $\sqrt{s} = 14$ TeV with a bunch-crossing frequency of 1 per 25 ns at four interaction points. In addition, operation with heavy ions is possible. First, the linear accelerator Linac4 (Linear Accelerator 4) accelerates H^- ions to an energy of 160 MeV [29]. At the end of Linac4, the electrons are stripped from the ions, then the resulting protons are fed into the PSB (Proton Synchrotron Booster), where they are further accelerated to an energy of 2 GeV

[30, Chapter 3]. The particles then pass through the PS (Proton Synchrotron) [30, Chapter 4], where they are accelerated to an energy of 26 GeV, and the SPS (Super Proton Synchrotron) [30, Chapter 5], which they leave at 450 GeV to be injected into LHC in both directions.

A schematic overview of the LHC, its experiments and the CERN pre-accelerator complex can be found in Figure 2.2. The main LHC experiments ATLAS [8], CMS (Compact Muon Solenoid) [31], ALICE (A Large Ion Collider Experiment) [32] and LHCb (LHC beauty) [33] are located at its four interaction points. The ATLAS and CMS experiments are general-purpose detectors for collisions of high-energy hadrons. Both cover almost the entire solid angle of 4π and are capable of measuring a wide range of physical processes. The ATLAS detector, the upgrade of which is the focus of this thesis, is described in more detail in Section 2.3. LHCb specialises in b-physics, in particular the measurement of CP violation, while ALICE uses heavy ion collisions to study the properties of the quark-gluon plasma.

A particle collider is primarily characterised by its luminosity $\mathcal{L}$, which describes the number of particle interactions per unit area and time. Together with the cross-section σ of a process, this gives its interaction rate

$$\frac{dN}{dt} = \sigma \cdot \mathcal{L}. \quad (2.1)$$

In the case of two Gaussian-shaped colliding beams travelling nearly at the speed of light, the luminosity evaluates to

$$\mathcal{L} = \frac{N_1 N_2 f_{\text{rev}} N_b}{4\pi\sigma_x\sigma_y}, \quad (2.2)$$

where N_b is the number of particle bunches per beam, N_1 and N_2 are the number of particles per bunch for both beams, f_{rev} is the revolution frequency, and σ_x and σ_y are the widths of the Gaussian beam profiles in the respective axes [34, Chapter 4]. In case of beams crossing at an angle and not perfectly at the center, additional correction factors need to be applied, which are discussed in detail in [34, Chapter 6]. The LHC is designed for a luminosity on the order of $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, reaching a peak luminosity of $2.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in Run 2 [35, Table 1]. The integrated luminosity

$$\mathcal{L}_{\text{int}}(t) = \int_0^t \mathcal{L}(t') dt', \quad (2.3)$$

a measure of the total number of collisions accumulated over time, is usually given to describe the amount of physics data an experiment has accumulated in a specific experimental run (or over its lifetime). In practical applications, it is usually given in “inverse femtobarns”, where $1 \text{ fb}^{-1} = 1 \times 10^{43} \text{ m}^{-2}$.

2.2.1 HL-LHC Upgrade

The potential of a particle collider to produce a statistically significant sample of rare processes scales with its luminosity and its operational lifetime. To provide a better chance of recording such rare collisions, the luminosity of the LHC will be upgraded to 5.0×10^{34} to $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ during the third shutdown from 2026 to 2028 [36]. This is achieved, among other things, by introducing crab cavities for the ATLAS and CMS experiments. These change the angle at which the bunches meet in such a way that their overlap increases. The current schedule of the HL-LHC (High-Luminosity

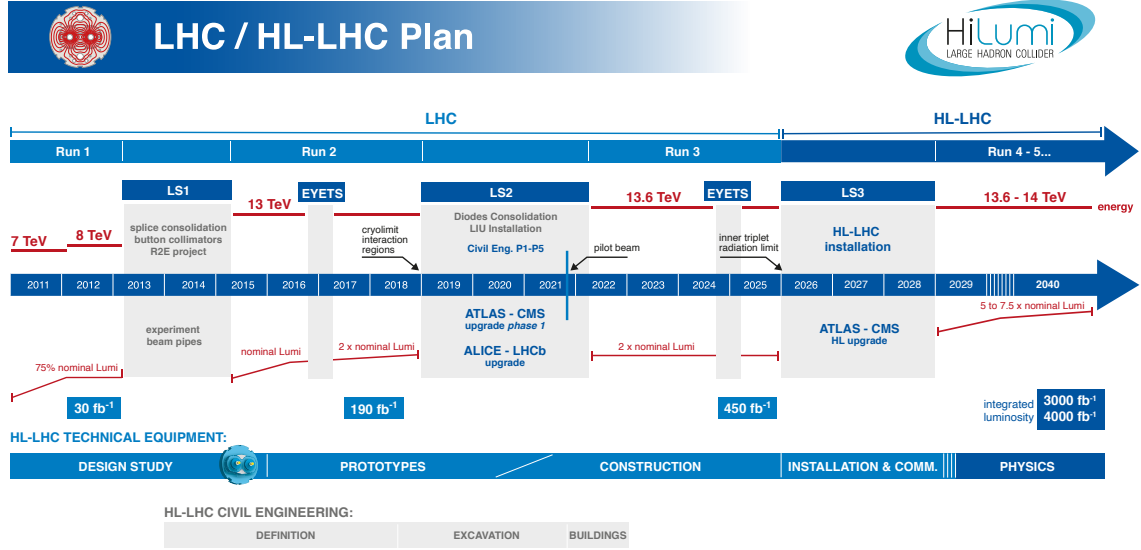


Figure 2.3: Schedule of the LHC operation, the upgrade efforts of the accelerators and experiments, and realised/planned luminosities (original schedule in [36, Figure 1.1], updated in [37]).

Large Hadron Collider) including its target luminosity are shown in Figure 2.3. All changes made to the beam optics are described in [36]. The HL-LHC upgrade will result in a higher number of simultaneous collisions (pile-up), which requires more precise tracking resolution to differentiate tracks originating from different initial vertices. Also, the higher track density results in a much higher radiation dose that the electronics needs to withstand over the detector’s lifetime, requiring a complete redesign of the inner tracking detectors of both the ATLAS and CMS experiments. In addition to the improved detectors, the main advantage of HL-LHC is that the increased luminosity will result in an integrated luminosity of at least 3 000 fb⁻¹ over the entire runtime (of which about 450 fb⁻¹ will be due to the runs before the upgrade). The physics potential contained in these events was comprehensively evaluated by an expert committee consisting of 5 working groups (“Standard Model”, “Higgs”, “Beyond the Standard Model (BSM)”, “Flavour”, and “QCD matter at high sensitivity”) [38].

A sample of the two previously unobserved decay modes of the Higgs boson ($H \rightarrow \mu^+ \mu^-$ and $H \rightarrow Z\gamma$) should become available. In addition, the parameters of the Higgs, such as the natural width of its mass or the self-coupling, can be measured much more precisely, providing important insights into electroweak symmetry breaking. The dataset will also enable the search for potential further Higgs bosons not included in the Standard Model up to a mass of 5 TeV.

Furthermore, the weak mixing angle will be measured more precisely. The world average includes measurements at the SLAC (Stanford Linear Collider) and LEP (Large Electron-Positron Collider), which differ by three standard deviations [39, Figure 11]. The HL-LHC results could provide a better understanding of whether these are systematic differences in the measurement results or new physics (such as a new neutral gauge boson [40]). The measurement uncertainties on the masses of the $W^\pm$ bosons and top quarks, as well as the parton distribution functions, will also be significantly improved

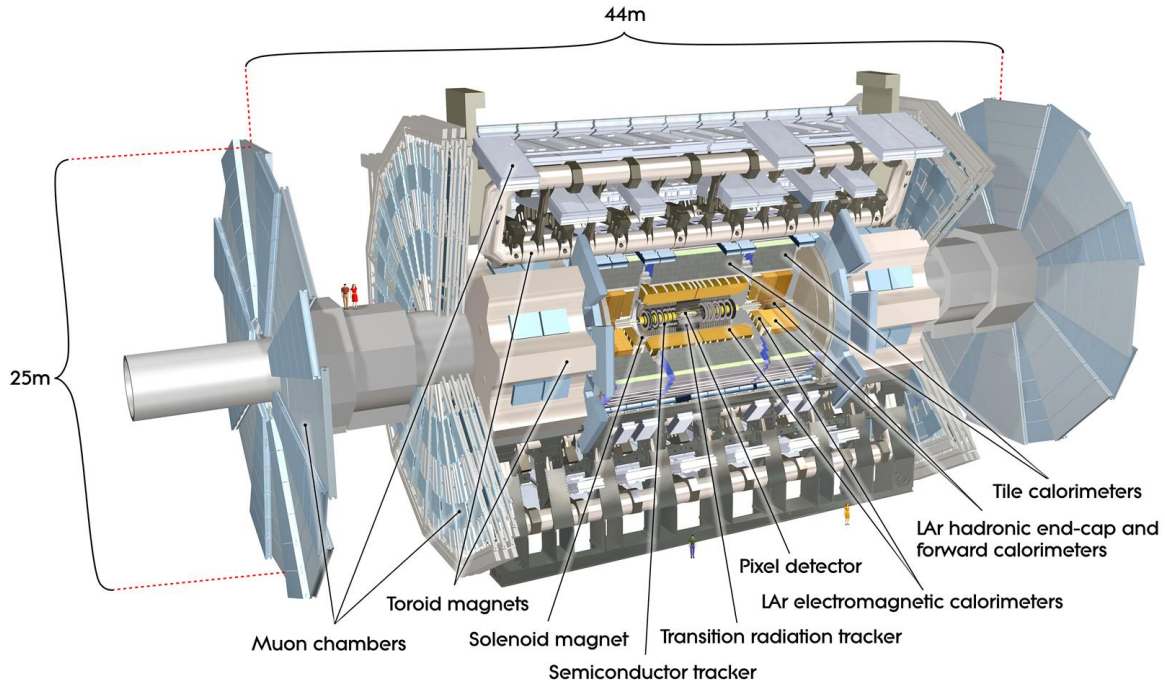


Figure 2.4: Overview of the ATLAS experiment and its subdetectors [41] before the HL-LHC upgrade.

by HL-LHC. The high statistics are also expected to lead to the discovery of several electroweak multiboson processes with a significance of $> 5\sigma$, as listed in [38, Table 1]. They also increase the physics reach for potential BSM processes containing, for example, potential supersymmetric particles or dark matter candidates.

2.3 The ATLAS Detector

The ATLAS detector is the largest experiment at the LHC with a length of 44 m, and a height and width of 25 m, weighing in at 7 000 t [8]. It is arranged in layers around the interaction point in a cylindrical shape in the direction of the beam and covers a solid angle of almost 4π . A schematic overview of the detector is given in Figure 2.4.

2.3.1 Coordinate System

ATLAS uses a right-handed coordinate system with its origin at the interaction point [8, Section 1.1]. Here, the unit vector of the x-axis points from the interaction point to the centre of the LHC, the y-axis points to the sky, and the z-axis is identical to the beam axis. The polar angle θ is the angle between the direction of a particle track and the beam axis, and the azimuth angle ϕ is measured in the xy-plane

from the x axis. Usually, instead of the polar angle, the pseudorapidity

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right) \quad (2.4)$$

is used. The component of the momentum of a particle projected into the xy-plane is called the transverse momentum p_T .

2.4 Inner Detector

The ATLAS ID (Inner Detector) [42, 43] is located in the innermost volume around the interaction point and is used to accurately measure the tracks in the 2 T magnetic field of the inner solenoid as well as the identification of particles. It consists of a pixel detector in the innermost volume, which records the tracks near the primary vertex, a strip detector called SCT (SemiConductor Tracker) around it and finally a TRT (Transition Radiation Tracker) in the outermost layer. The current layout of the ID is shown in Figure 2.5(a).

2.4.1 Pixel Detector

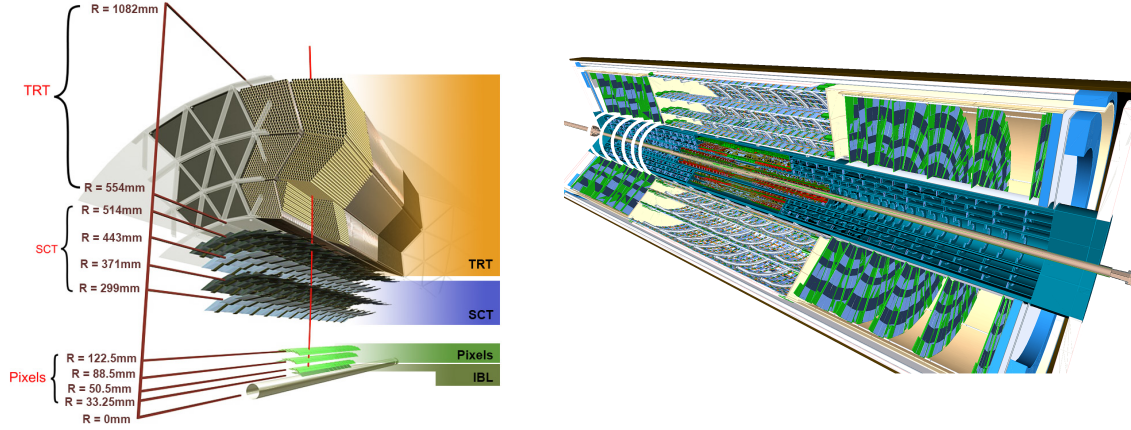
In order to obtain a high-resolution and unambiguous measurement of the tracks at the interaction point, the pixel detector with an acceptance region of $|\eta| < 2.5$ is located directly outside the beampipe [43, Chapter 10]. This consists of three layers of pixel modules in the barrel section and an additional “B-layer” very close to the interaction point, which was added during LS2 [44]. The ID pixel detector features 200 million binary readout channels of $50 \mu\text{m} \times 300 \mu\text{m}$ pixels, arranged in approximately 2500 modules. Currently, the IBL (Insertable B-Layer) constitutes the innermost layer of the detector. In addition to the conventional planar hybrid pixel sensors, it features $25 \mu\text{m} \times 250 \mu\text{m}$ 3D pixels with electrodes etched deep into the silicon bulk for improved performance in the high-radiation environment [45].

2.4.2 Strip Detector

Outside of the pixel detector, the strip detector is located. The current SCT measures tracks with $|\eta| < 2.5$ with a total of 6.2 million channels on an area of 61.1 m^2 of silicon [43, Chapter 11]. The detector is divided into two regions: In the “barrel” section, long support structures called “staves” are arranged along the beam direction to form a cylinder, while in the “end caps”, modules are arranged on support structures radially around the beam axis to better facilitate the measurement of tracks with higher pseudorapidity.

2.4.3 Transition Radiation Tracker

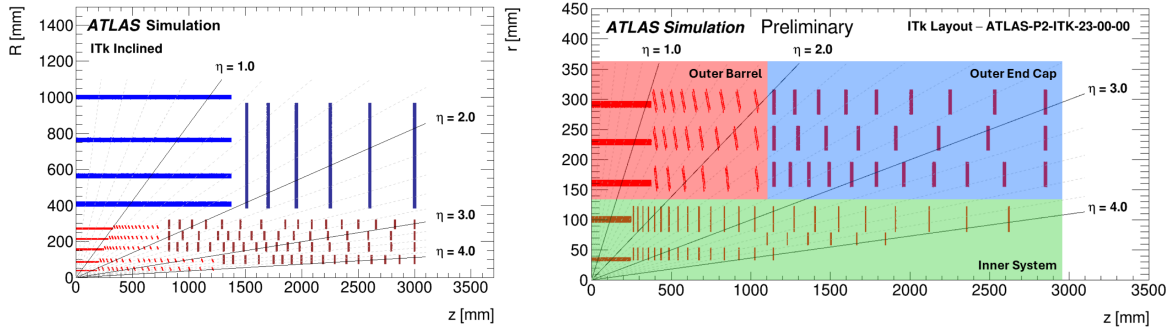
The outermost layer of the ATLAS ID is the TRT [43, Chapter 12]. It consists of 319 488 axially and 52 544 radially arranged 4 mm thick Kapton straws. A $31 \mu\text{m}$ thin gold-plated wire runs through the centre of these straws, and a high voltage is applied between this wire and the cathodes incorporated in the Kapton. Using a Xe-based gas mixture, the X-ray photons produced by transition radiation [46] allow electrons to be identified in addition to tracking [47]. After the installation of the upgraded tracking detectors, ATLAS will no longer feature a TRT.



(a) Layout of the ID with the IBL [48, Figure 1].

(b) Rendered image of the full ITk detector [10, Figure 3.6].

Figure 2.5: Layout of the ID and image of the full ITk.



(a) A quadrant of the layout of the active detector modules of the ATLAS ITk [10, Figure 3.5].

(b) Updated layout of the ITk pixel detector with its three subdetectors highlighted (adapted from [49]).

Figure 2.6: Layout of the ITk detector with a closeup of the pixel system.

2.5 Inner Tracker

In order to adapt to the denser collision environment of HL-LHC, the ID will be completely replaced by an improved all silicon tracker called ATLAS ITk (Inner Tracker). The construction of the ITk is a large detector production effort that is shared by a large number of institutes and private companies all over the world. DESY is involved in the production of one of the end caps as well as many key components for the new strip detector, which is presented in detail in Chapter 4. A picture of the full ITk is shown in Figure 2.5(b), its layout is shown in Figure 2.6(a).

2.5.1 Pixel Detector

The ITk pixel detector is going to be made up of three subdetectors. Their layout was specified in the initial technical design report [9] and updated in 2020 by the ATLAS collaboration [49]. The current layout is shown in Figure 2.6(b). The inner system is going to be located closest to the beam pipe and

will consist of two layers. Closest to the interaction point, hybrid 3D silicon sensors are used with pixel sizes of $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ in the end cap and $25\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ in the barrel regions. In the next layer, $100\text{ }\mu\text{m}$ thick planar hybrid silicon sensors with $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ pixels are employed. This part of the detector will cover tracks with $|\eta| < 4.0$ and will be replaced around 2000 fb^{-1} . Three additional layers make up the outer barrel and end cap regions of the ITk pixel detector, all of which will consist of $150\text{ }\mu\text{m}$ thick planar hybrid silicon sensors with $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ pixels. Overall, the pixel detector will feature five billion readout channels with an active silicon area of 13 m^2 . An overview of the current specifications and status of the pixel upgrade project is given in [50].

2.5.2 Strip Detector

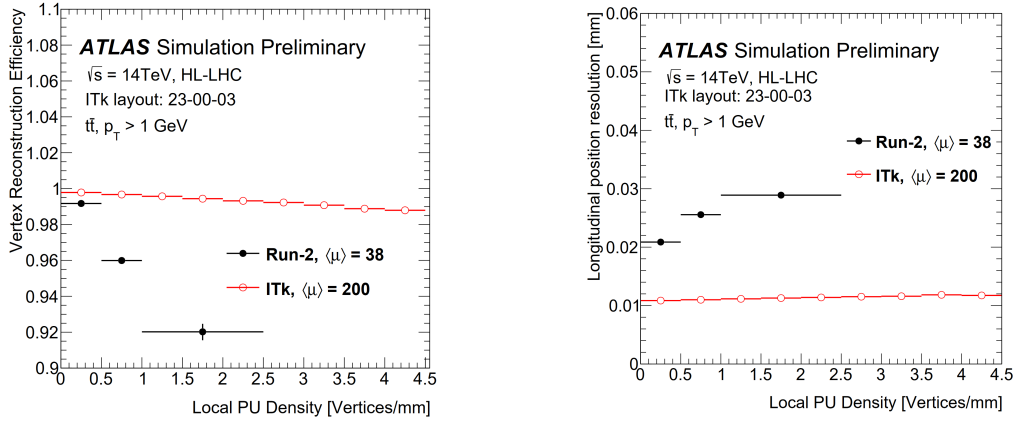
Outside of the pixel detector, the ITk strip detector will be located [10]. It will consist of a barrel and two end cap regions with a maximum acceptance of $|\eta| < 2.7$. In the barrel, strip modules are organised on local support structures called staves with two types of modules in four layers. For the inner two layers, hybrid silicon modules with short $2410\text{ }\mu\text{m} \times 75.5\text{ }\mu\text{m}$ strip are placed double sided with a stereo angle of $\varphi_s = 52\text{ mrad}$ at tilt angles of 11.5° for Layer 0 and 11° for Layer 1. The two outermost layers are built with the long $4820\text{ }\mu\text{m} \times 75.5\text{ }\mu\text{m}$ strip module flavour and are tilted at 10° [10, Table 3.1]. Both end caps feature six layers of modules arranged double sided on trapezoidal local support structures called “petals”, which are discussed in Chapter 4. Six module types, whose geometry is discussed in more detail in Section 10.1, are used at different radii in the end caps. In total, the ITk strip detector will have 59.87 million binary readout channels on 17 888 modules with a total active silicon area of 165.25 m^2 [10, Table 5.1].

2.5.3 Expected Performance

The expected performance of the ITk detector was extensively compared with the performance of the ID using Monte-Carlo simulations [51]. Here, the comparison of the performance of both detectors in a typical analysis scenario will be presented briefly: To test the ITk performance in the much denser collision environment of HL-LHC, the vertex reconstruction efficiency was compared for $t\bar{t}$ events with $p_T > 1\text{ GeV}$ for 38 pile-up events in the ID and 200 in the ITk, with the ITk surpassing the ID's performance for all vertex densities (see Figure 2.7(a)). The longitudinal position resolution is improved by the ITk by at least a factor of two over the ID (see Figure 2.7(b)). A comparison of four jet flavour tagging algorithms in the same scenario showed that two tested algorithms performed better with the ITk data. At the same time, the performance of the other algorithms under study decreased [51, Section 5.2]. Although this shows that a better flavour tagging performance is possible with the ITk, not all existing algorithms react insensitively to the higher number of reconstructed vertices.

2.6 Calorimeters

The ATLAS calorimeter system shown in Figure 2.8(a) is designed to absorb particles and thereby determine their energy. It is divided into an inner EM (electromagnetic) calorimeter for measuring EM showers, while the outer hadronic calorimeter is optimised for measuring hadronic showers. Both are designed as sampling calorimeters, i.e. the active detector components alternate with passive material that only serves to absorb particles. The EM calorimeter uses only LAr (Liquid Argon) as the active medium [52], which covers an acceptance range of $|\eta| < 3.2$, using a combination of lead and



(a) Vertex reconstruction efficiency vs. local pile-up density (b) Local position resolution vs. local pile-up density [51, Figure 16].

Figure 2.7: Vertex reconstruction efficiency and local resolution simulated from $t\bar{t}$ events for the ID and ITk.

stainless steel as a passive absorber. Using iron absorbers, the hadronic calorimeter is also equipped with LAr technology in the $1.4 \leq |\eta| \leq 4.8$ region, while an iron-scintillator tile calorimeter is used in the $|\eta| < 1.4$ region [53]. Within the scope of HL-LHC, the calorimeters must also be adapted to the changed conditions, such as a denser collision environment, modified TDAQ (Trigger and Data Acquisition) and higher radiation exposure. These modifications are described in [54, 55].

2.7 Muon Spectrometer

Of all the particle types that can be measured directly by the ATLAS detector, muons penetrate the furthest to the outside due to their relatively high mass and the fact they only interact electromagnetically with the detector material (see Section 3.1 for a discussion of energy loss of charged particles in matter). This is why the muon chambers, of which there are several types, are located in the outermost layer of ATLAS [56]. The trajectories of the tracks in the magnetic field are measured by MDTs (Monitored Drift Tubes) and CSCs (Cathode Strip Chambers). RPCs (Resistive Plate Chambers) and TGCs (Thin Gap Chambers) are installed in addition for fast trigger information and measurement of the muon coordinate orthogonal to the direction measured in the tracking chambers. Their layout is shown in Figure 2.8(b). Over the course of the ATLAS HL-LHC upgrade campaign, the number of trigger layers will be increased. Refer to [57] for an overview of all planned changes to the muon system.

2.8 Magnets

Four separate superconducting magnets are built into ATLAS [59]. In the centre is a solenoid surrounding the ID with a magnetic field of $\approx 2\text{ T}$. Outside the calorimeters are the barrel and two end cap toroids. The end cap magnets are located at both ends of the experiment, while the barrel toroid surrounds the experiment along the beam axis with the interaction point in its centre. Both types of toroidal magnets achieve a field of $\approx 3.5\text{ T}$.

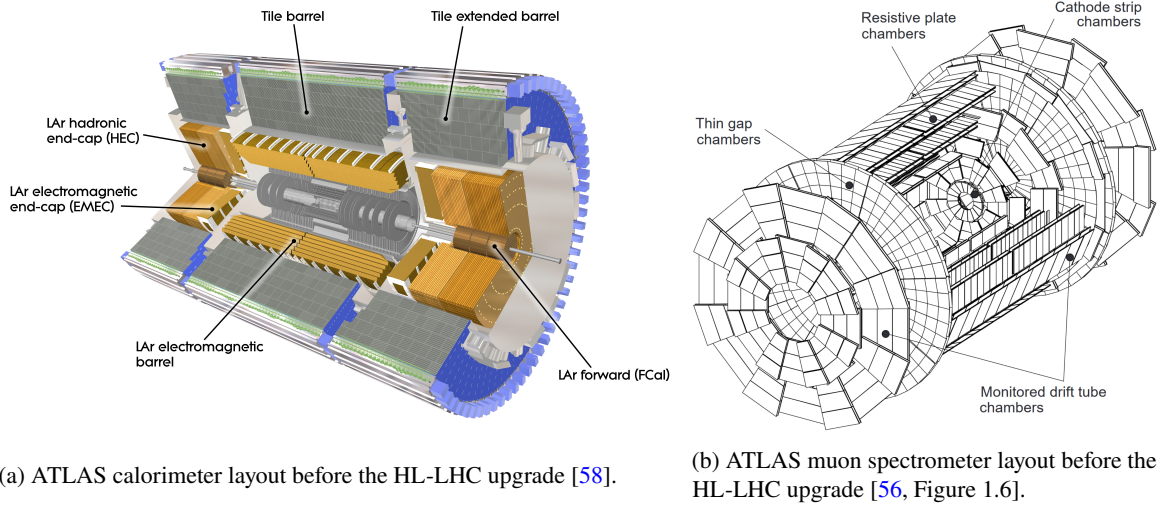


Figure 2.8: Current ATLAS calorimeter and muon systems.

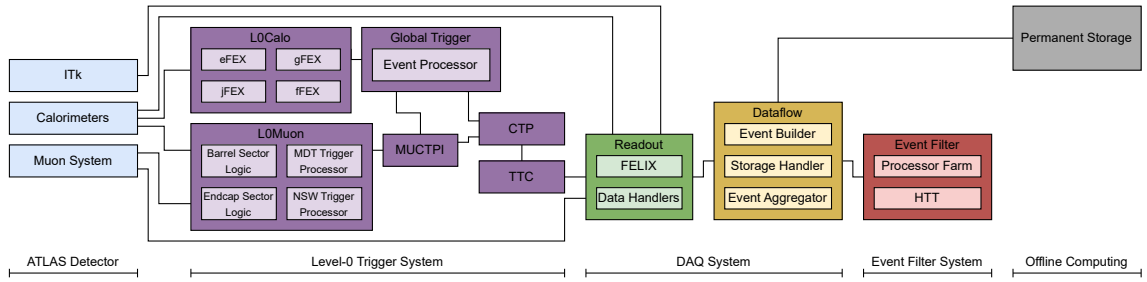


Figure 2.9: Overview of the new ATLAS Level-0 trigger, DAQ and Event Filter systems [60, Figure 1.3].

2.9 Trigger and Data Acquisition

The ATLAS TDAQ (Trigger and Data Acquisition) system will be completely revised as part of the HL-LHC upgrades [60]. The new system will consist of three main components: the hardware-based Level-0 trigger, the DAQ (Data Acquisition) system and the EF (Event Filter). In the detector, the former decides which events are to be read out by the DAQ system, which is initiated via the TTC (Trigger, Timing, and Control) system in the event of a positive decision. Part of the DAQ is the FELIX (Front-End Link eXchange) readout system, which is directly connected to the FE (Front-End) electronics in the ITk via fibre optic cables. In addition to the readout, the dataflow system is part of the DAQ, whose tasks are the assembly, collection and temporary storage of events. Finally, the EF is responsible for massive parallel execution of a series of complex event selection algorithms to make the best use of the available data rate in accordance with the ATLAS physics goals. An overview of all TDAQ components after the upgrade is provided in Figure 2.9.

Silicon Particle Detectors

The ever-improving precision of experiments in high-energy physics is owed in large part to the ongoing development and improvement of particle detectors. In the last decades, the use of semiconductor tracking detectors has gained acceptance due to their good temporal and spatial resolution. The principle of measuring ionising particles at p-n junctions has been known since the 1940s [61] and will be explained in this chapter. With the development of silicon microstrip detectors in the early 1980s [62], semiconductor detectors are used to measure additional spatial information, which also allows the measurement of charged particle tracks.

3.1 Interaction of Charged Particles with Matter

When a charged particle passes through matter, it transfers energy to the material through excitation or ionisation. The amount of energy lost per unit length depends on the type and momentum of the particle (from now on referred to as “projectile”) and the material (from now on referred to as “target”). A very comprehensive overview of the subject is provided in [63, Chapter 34].

For heavy projectiles ($m_{\text{projectile}} \gg m_e$), such as protons and muons, the Bethe-Bloch equation approximates the energy loss over a broad momentum range [64, 65]. An example of a μ^+ projectile on a copper target is shown in Figure 3.1(a). Almost independent of the target material, the minimum energy deposition is found at $3.0 < \beta\gamma < 3.5$ for heavier elements (see Figure 3.1(b)). Above about $\beta\gamma > 1000$, radiative losses start to dominate. For silicon, the minimum is at $\gamma = 3.58$ with

$$\left\langle \frac{dE}{dx} \right\rangle_{\text{Si}}^{\text{MIP}} = 1.66 \text{ MeVcm}^2/\text{g},$$

so in a $d = 300 \mu\text{m}$ thick silicon detector, at least a charge of

$$Q_{\text{MIP}} = \left\langle \frac{dE}{dx} \right\rangle_{\text{Si}}^{\text{MIP}} \cdot d \cdot \rho_{\text{Si}} / \omega = 31\,690 \text{ electrons} \quad (3.1)$$

is generated inside the sensor volume, where $\rho_{\text{Si}} = 2.323 \text{ g/cm}^3$ is the density of silicon [66], and $\omega = 3.65 \text{ eV}$ is the energy required to generate an electron-hole pair [67].

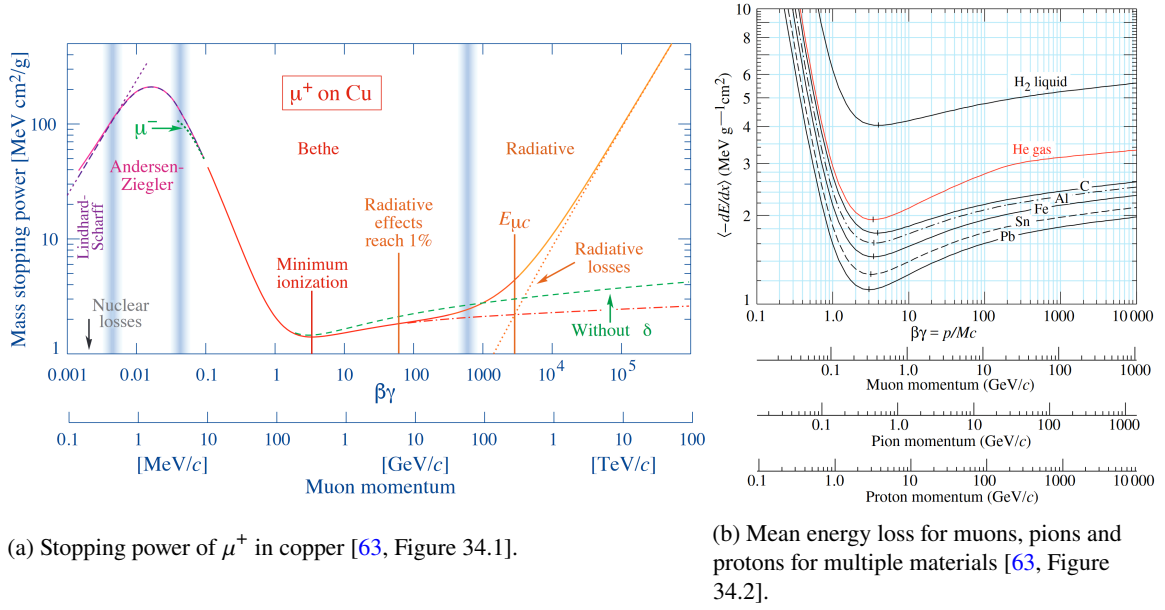


Figure 3.1: Mean energy loss in copper and multiple other materials. The point of minimum ionisation is only weakly dependent on the material.

The Bethe-Bloch formula is not valid for electrons and positrons. For these particles, ionisation losses dominate at low energy. Additionally, the projectiles interact with the electrons in the target via Møller [68] (in the case of e^-) or Bhabha [69] (in the case of e^+) scattering, and positrons also annihilate with the electrons in the target. At high energies, losses due to Bremsstrahlung dominate. A detailed treatment of the topic can be found in [63, Section 34.4].

In practical applications, the use of Monte Carlo methods has become widespread in order to obtain predictions about the interaction of particles with matter. In detector physics, for example, the Geant4 toolkit [70–72] is frequently used, which makes use of various models for different energy ranges and applications.

3.2 p–n Junction

A p–n transition occurs when a (n-doped) semiconductor with an excess of free negative charge carriers is brought into contact with a (p-doped) semiconductor with an excess of free positive charge carriers¹. In the process, the free charge carriers diffuse through the contact surface, free electrons and holes recombine. A “depletion zone” is created, which is charge-neutral to the outside. Its thickness is limited by the electric potential difference U_D resulting from the outer charged zones generating an opposing drift current [73, Section 8.3].

¹ In the context of semiconductors, a “hole” is the absence of a electron in the valence band, which can move as a quasiparticle and thus represents a free positive charge.

If a voltage U_{HV} is applied to the p-n junction as shown in Figure 3.2, the depletion zone increases to a width of

$$w(U_{HV}) \approx \sqrt{\frac{2 \cdot \epsilon_0 \cdot \epsilon_r}{e} \frac{1}{N_D} (U_D - U_{HV})}, \quad (3.2)$$

where ϵ_0 is the permittivity of vacuum, ϵ_r the relative permittivity of the semiconductor, e the elementary charge, N_D the density of electron donating doping impurities, and U_D the diffusion voltage of the p-n junction [73, Equation (8.35)]. This temperature-dependent diffusion voltage is given by

$$U_D = \frac{k_B \cdot T}{e} \cdot \ln \frac{N_A \cdot N_D}{n_i^2}, \quad (3.3)$$

where k_B is the Boltzmann constant, T the temperature, N_A the density of acceptor impurities, and n_i the intrinsic charge carrier density of the semiconductor [73, Equation (8.41)]. At room temperature, the diffusion voltage of silicon is $U_D \approx 0.7$ V.

When passing through the material of the detector, a particle causes an ionisation of the material by the mechanisms previously presented. In the case of a semiconductor, this causes the formation of free electron-hole pairs. These free charge carriers drift through the electric field to the cathode and anode of the sensor. During their movement, they generate a signal in the electrodes through influence. The total drift time is only a few nanoseconds for the common construction size of today's spatially resolving detectors [73, Section 8.4].

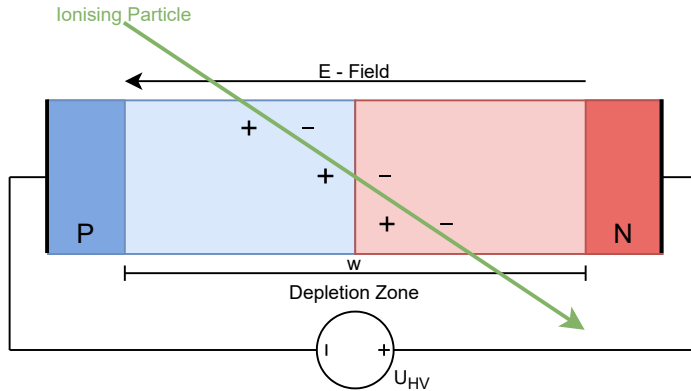


Figure 3.2: Schematic overview of an ionising particle passing through the depletion zone of a semiconductor detector. The particle generates electron-hole pairs that move towards the electrodes due to the applied external voltage.

3.3 Spatially Resolving Semiconductor Detectors

Apart from just detecting the presence of ionising radiation, p-n transitions can be used to determine the location of passing particles using a suitable geometry. A rough distinction is made between two categories of detectors; strip and pixel detectors.

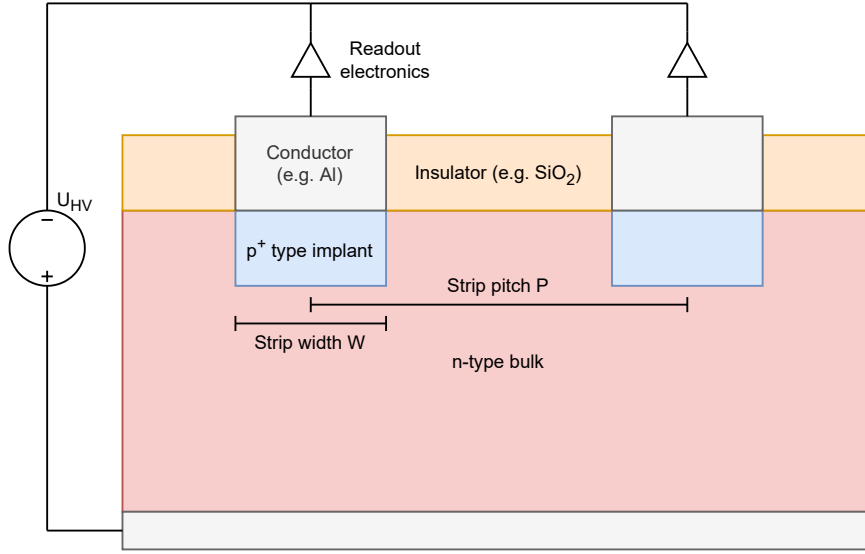


Figure 3.3: Schematic cross section of a strip detector. p-doped strips are implanted into an n-doped bulk and enable a one-dimensional position measurement of the hits.

3.3.1 Strip Detectors

p-doped strips are inserted into an n-doped bulk (see Figure 3.3). If a voltage U_{HV} is applied between the two materials, the transitions described in Section 3.2 occur between the strips and the bulk. The resulting electric field transports the positive free charge carriers created by an ionising particle to the next strip implant, where the readout electronics registers the hits. When only binary hit information is collected by the readout circuitry, the subdivision of the detector medium results in a spatial resolution of

$$\sigma_x^2 = \frac{1}{p} \int_{-\frac{p}{2}}^{\frac{p}{2}} x^2 dx = \frac{p^2}{12} \quad (3.4)$$

transverse to the strips, where p is the pitch of the strips [73, Equation (8.75)]. Two-dimensional spatial detection can be achieved by combining two strip sensors into a stereo module. For this purpose, two strip detectors, rotated by a stereo angle α with respect to each other, are mounted at a short distance behind one another. Thus, each ionising particle crossing the detector passes at least one strip of each of the two sensors. The strip overlay results in an parallelogram-shaped area where the reconstructed hit is located (see Figure 3.4(a)). In the case of a single strip, a uniform distribution is assumed for the calculation of the resolution (Equation (3.4)) of the strip detector. Since the area on which a hit was registered is trapezoidal in the case of stereo modules, the underlying distribution is triangular. The resolution in the $R\phi$ - plane (see Section 2.3.1) of stereo modules in the ATLAS coordinate system evaluates to

$$\sigma_{\perp} = \frac{\sigma_x}{\sqrt{2} \cos \frac{\alpha}{2}} \approx \frac{\sigma_x}{\sqrt{2}} \text{ (for small } \alpha \text{)}, \quad (3.5)$$

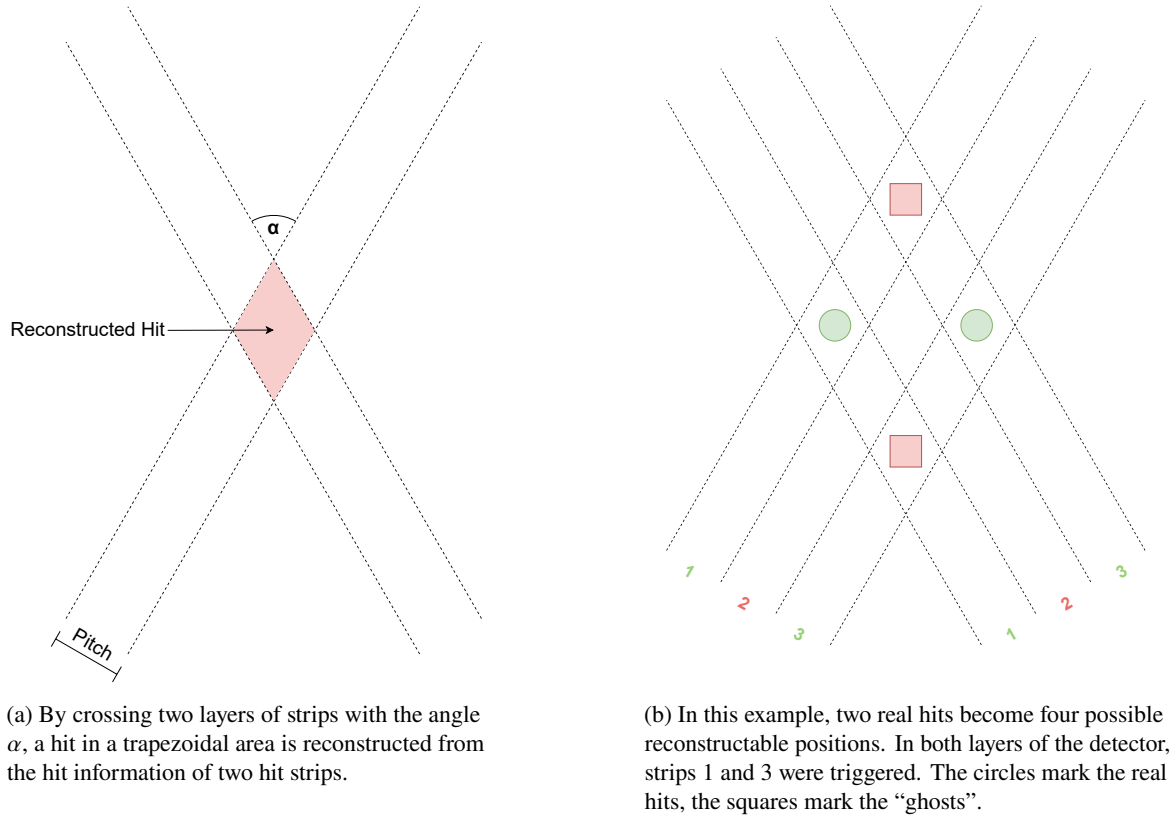


Figure 3.4: Schematic representation of the cross overlay of two strip sensors. The left image shows how the superposition of two strips allows the reconstruction of two-dimensional information, the right image illustrates the problem of ghost hits when several hits have been registered on the sensor.

in z it is

$$\sigma_{\parallel} = \frac{\sigma_x}{\sqrt{2} \sin \frac{\alpha}{2}} = \sigma_{\perp} \cot \frac{\alpha}{2} \approx \frac{\sqrt{2} \sigma_x}{\alpha} \text{ (for small } \alpha \text{)}, \quad (3.6)$$

where σ_x is the resolution of a single strip as in Equation (3.4) [74, Section 9]. If hits have been registered at several points of the detector, the assignment of the hits to an overlay area is no longer unambiguous. If no strip is hit more than once, a total of n^2 positions are possible with n registered hits. $n^2 - n$ of these are so-called ghost hits, which do not correspond to an actual hit position (see Figure 3.4(b)). To reconstruct the correct position, additional information is necessary, which can for example come from an additional pixel detector.

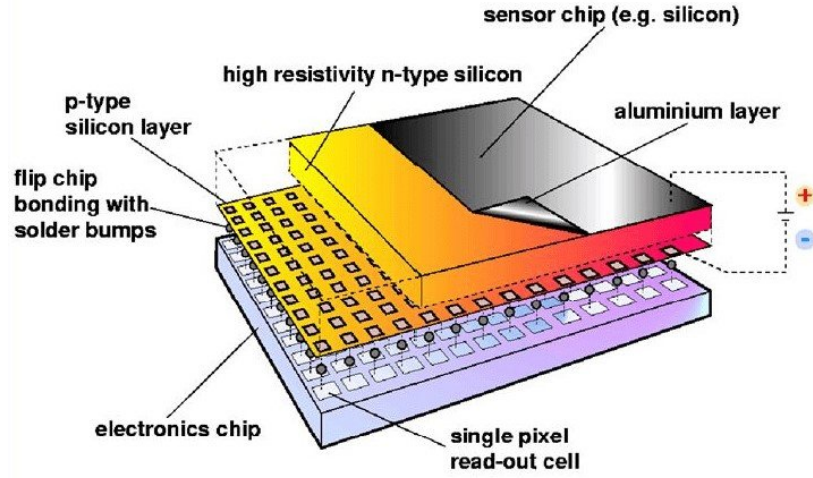


Figure 3.5: Pixel hybridisation via bump bonding [75].

3.3.2 Pixel Detectors

Instead of dividing the active silicon area into elongated strips that provide one-dimensional location information, it can also be divided into small rectangles called pixels. By reading out the individual pixels, the passage of a particle is unambiguously assigned to a two-dimensional position on the chip. Analogous to Equation (3.4), the binary resolutions of a pixel detector are

$$\sigma_x = \frac{p_x}{\sqrt{12}} \quad \text{and} \quad \sigma_y = \frac{p_y}{\sqrt{12}}, \quad (3.7)$$

where p_x and p_y are the pixel pitches in the respective dimension. Since the pixel detector requires its own readout electronics for each readable position, the number of channels at the same resolution is significantly higher than with a strip detector (n^2 vs. $2n$). This additional expense compared to the strip detector is justified above all when the measurement of particle tracks is not possible with a strip detector due to the high density of tracks and unambiguous position information is needed. In modern particle physics experiments such as ATLAS or CMS, there is therefore usually a pixel detector in the immediate vicinity of the collision point, the task of which is to measure the tracks in the vicinity of the primary vertex. In contrast to strip detectors, the electrical connection between the front-end electronics and the active sensor surface cannot be established using wire bonding in hybrid pixel detectors due to the high channel density. Instead, the front-end chip is applied to the surface of the silicon sensor using small solder balls in a process known as bump bonding (see Figure 3.5).

3.4 Readout and Noise

The charge generated by an ionising particle passing through the semiconductor generates a current signal at the electrode. This signal is processed by the connected readout electronics. For this purpose, the current signal is first converted into a voltage by a charge sensitive amplifier, which then has to remain stable long enough to be read out, while not overlapping with pulses from following events (“pile up”). A filter electronics, called “pulse shaper”, is therefore connected downstream of the amplifier, after which the digitisation takes place via the ADC (Analog-to-Digital Converter). In the case of a binary readout, the ADC consists of a comparator that compares the input voltage with a threshold voltage U_T . This adjustable voltage regulates the sensitivity of the sensor; it must be adjusted in such a way that neither false hits stemming from electrical noise start compromising the data, nor are too many real hits disregarded.

In the case of spatially resolving semiconductor detectors, each individual strip or pixel is equipped with such a readout chain. Here it is also necessary to be able to adjust the threshold of each individual channel in such a way that differences in the analog signal response between the channels are compensated. This is achieved by charging an internal capacitor with a fixed calibration charge, which a circuit located on the readout chip injects on command. This signal is then passed through the readout chain, simulating a hit and allowing to calibrate the front end electronic’s reaction to a charge signal from the detector. A variation of the threshold with a fixed charge is called a “threshold scan”. If no charge is injected, the procedure is referred to as a “noise occupancy scan”.

The noise of a detector arises from electrical fluctuations both in the detector volume itself and in the readout electronics. First of all, any electric current is superimposed by a thermal motion of the charge carriers, which generates random isotropic fluctuations of the current. This Johnson-Nyquist noise [76, 77] of the current I through a resistor R amounts to

$$d \langle I^2 \rangle_{\text{thermal}} = \frac{1}{R} 4k_B T df. \quad (3.8)$$

When charge carriers have to cross a potential barrier, as is the case with a p-n junction, additional statistical fluctuations occur, which are referred to as shot noise [78]. Shot noise is described by

$$d \langle I^2 \rangle_{\text{shot}} = 2eI_0 df, \quad (3.9)$$

where I_0 denotes the average current through the potential barrier. Lastly, there is frequency-dependent noise behaviour called $1/f$ noise, which was first observed by Johnson. A theoretical description that comprehensively describes the behaviour has not been found to date. It manifests as

$$d \langle I^2 \rangle_{1/f} = K_\alpha \cdot \frac{1}{f^\alpha} df \quad (\alpha \in [0.5, 2]), \quad (3.10)$$

where K_α is a constant dependent on the process [73, Equation (17.82)]. An additional source of noise is electromagnetic interference by other electronic circuits in the detector, such as the power supplies. The noise of a silicon detector is often given as a ENC (Equivalent Noise Charge) in number of e^- , which is the noise at the amplifier output divided by its charge gain.

3.5 Effects of Ionising Radiation

Ionising radiation damages the lattice structure of silicon by forming impurities [79]. For example, collisions with the lattice atoms can create vacancies, atoms can be deposited in positions outside of the normal lattice positions or foreign atoms (e.g. remnants of heavy ion projectiles) can be introduced. These imperfections can increase leakage currents or shift switching thresholds of transistors, which affects the functionality of the electronics. Because this kind of damage to the silicon volume and detector electronics accumulates with the amount of radiation received, they are categorised as TID (Total Ionising Dose) effects. This damage can be at least partially repaired by annealing the semiconductor at high temperatures. But also short-term disturbances of the function of the electronics can be caused by radiation. For example, the ionisation trace of a traversing particle can cause a transistor to switch, which can result in settings being changed, false hits being generated in the detector, or temporarily stored data becoming compromised. These effects are called SEUs (Single Event Upsets). For this reason, particle detectors often use data encodings that allow the recovery of the original data despite single bit errors. Furthermore, critical digital electronics are usually designed with TMR (Triple Modular Redundancy). In this technique, logic circuits are tripled, and the results of the calculations are compared. A majority voter then decides the outcome. In this way, the probability of SEUs influencing the electronics is drastically reduced at the cost of increased silicon area and power consumption of the circuits.

3.6 Track Reconstruction

Tracking detectors are used in high-energy physics experiments in combination with a magnetic field forcing the charged particles created in the collisions onto a spiral path. In the case of the ATLAS detector, the tracking detector is located inside a solenoid whose field lines run parallel to the beam axis. The curvature of the path is therefore created in a plane orthogonal to the beam axis, with the gyroradius

$$r_g = \frac{p_T}{|q|B}, \quad (3.11)$$

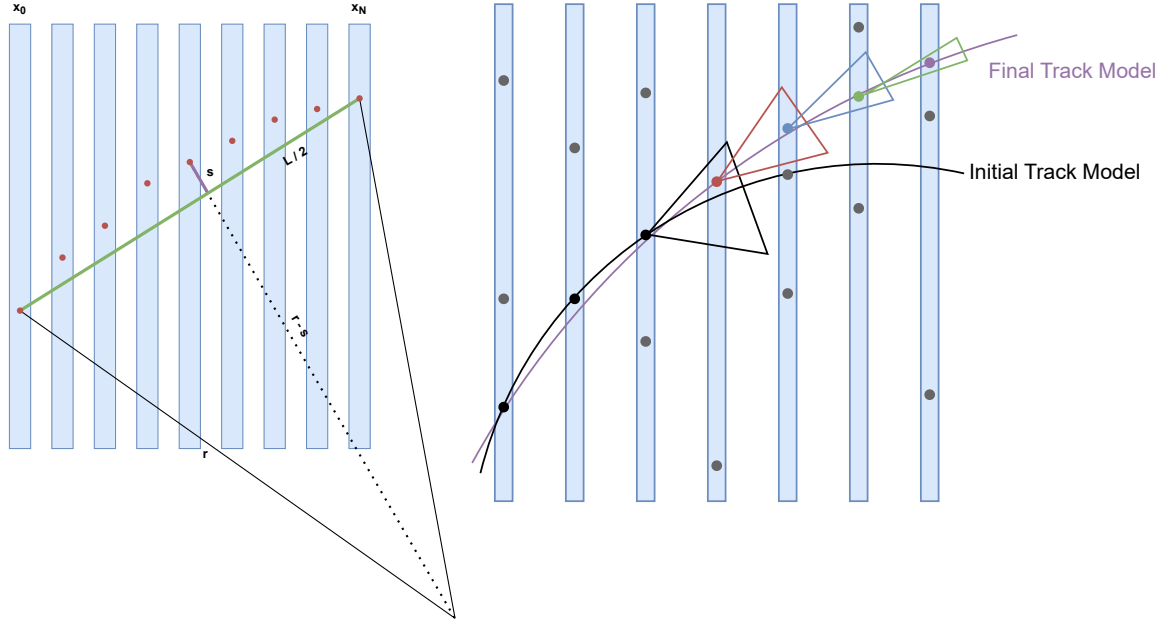
where p_T is the “transverse momentum” of the charged particle (the component orthogonal to the beam axis, see Section 2.3.1), q is the electric charge of the particle and B the magnetic flux density.

To obtain the sign of the charge and the momentum from the curvature, hits in the detector that belong to the same track must first be identified. A classic method for determining the momentum from these hits is to measure the sagitta s (see Figure 3.6(a)). For a track of length L measured by N equidistant detector elements with spatial resolution σ_X , the momentum resolution evaluates to

$$\left(\frac{\sigma_{p_T}}{p_T} \right)_{\text{Meas.}} = \frac{p_T \cdot \sigma_X}{|q|BL^2} \sqrt{C_N} \text{ with } C_N = \frac{720(N-1)^3}{(N-2)(N+1)(N+2)} \stackrel{N \geq 10}{\approx} \frac{720}{N+4} \quad (3.12)$$

[73, Equations (9.47) - (9.49)] (also known as the Gluckstern formula based on [80]). Multiple scattering on the active and passive detector material makes an additional contribution to the uncertainty of the momentum measurement. With $[p_T] = \text{GeV}/c$, $[L] = \text{m}$ and $[B] = \text{T}$, it evaluates to

$$\left(\frac{\sigma_{p_T}}{p_T} \right)_{\text{Scatt.}} = \frac{0.054}{LB\beta} \sqrt{\frac{x}{X_0}}, \quad (3.13)$$



(a) Method of measuring the sagitta s from the maximum deviation of a curved track from a straight track defined by its start and end point. (b) Example of a Kalman filter for track fitting. Three points are chosen to build an initial model which is iteratively refined.

Figure 3.6: Visualisations of the sagitta s and Kalman filter methods used in track reconstruction.

where x is the total length of the track, X_0 the average radiation length in the detector and $\beta = v/c$ is the particle velocity [73, Equation (9.56)]. The total uncertainty of the measurement

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{\text{Total}}^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)_{\text{Meas.}}^2 + \left(\frac{\sigma_{p_T}}{p_T}\right)_{\text{Scatt.}}^2 \quad (3.14)$$

therefore has a part that is proportional to p_T and a constant part (since $\beta \approx 1$ in high energy physics). While the first part of the uncertainty is dominated by the design and the number of sensors, the second part is dependent on the material of the detector, motivating the use of modern, lightweight materials such as carbon fibre in the construction of tracking detectors for improving of the overall performance of the experiment.

A more modern approach than selecting a set of hits and applying the sagitta s method is given by the Kalman filter approach (based on [81]), which performs the selection and fitting of the track in one algorithm. It utilizes a track model (i.e. a three-dimensional spiral) that is fitted to a set of points. The predictions of the fit are propagated into the next layer of the detector, choosing new points and refining the fit (see Figure 3.6(b)). Since only points that are compatible with the hits already in the track are added, this approach greatly reduces the number of combinations of points that need to be checked before the best-fit track to the hit data is found, greatly reducing computation time in a high pile-up environment like HL-LHC.

ITk Strips End Cap

The ITk strip detector (see Section 2.5) consists of three main parts: a barrel section with modules arranged parallel to the beam axis, with the interaction point in its centre, enclosed by an end cap section on each side with modules orthogonal to the beam. One of the end caps will be assembled at DESY in the cleanroom of the DAF (Detector Assembly Facility). Each end cap consists of a carbon fibre global support structure holding six discs of 32 so-called “petals”. Each petal provides electrical and cooling services for six module types mounted on both sides. The structure of the end cap, the petals and their modules, and the services required for their operation are described in detail in this chapter.

4.1 Modules

There are six module types for the end cap section of the ITk strip detector, which differ in their geometry, the number of readout channels and the number of silicon sensors used. For an overview of the different sensor shapes, see Figure 4.1. Modules R0 - R2 each consist of one silicon sensor, while modules R3-R5 are split modules with two silicon sensors each. The modules are arranged on both sides of the petals, in increasing order in the R coordinate (see Section 4.2).

The modules’ sensors are designed as n^+ in p silicon strips, which have a “radial strip” geometry (see Section 10.1) in which all strips of a row measured from the beam axis start and end at the same radii. Via their integrated stereo angle of 20 mrad, the strips overlap on the primary and secondary sides of the petal and allow a two-dimensional reconstruction of hits (see Section 3.3.1).

The main readout electronics of the modules are the ABCStars (ATLAS Binary Chips), which provide binary readout for 256 channels [82]. They reside on the hybrids, which are PCB (Printed Circuit Board)s providing the necessary power and data lines for the ABCStars [83]. The hybrids also feature the HCCStars (Hybrid Controller Chips), which bundle the 160 Mbit s^{-1} data streams of up to 11 ABCStars into a single electrical link [84]. All of the readout chips are powered via radiation hard DC-DC converters residing on the power boards, converting the external LV (Low Voltage) of 11 V into the 1.5 V consumed by the ABCStars and HCCStars [85]. These PCBs also feature the AMAC (Autonomous Monitor and Control) chips [86], which combine various DCS (Detector Control System) tasks. They provide measurements of i.a. the input and output voltages of the DC-DC converters, the temperature values of several thermistors on the power boards and the connected hybrids, and the bias currents of the silicon sensors, via a built-in ADC. They are also responsible for switching the LV for

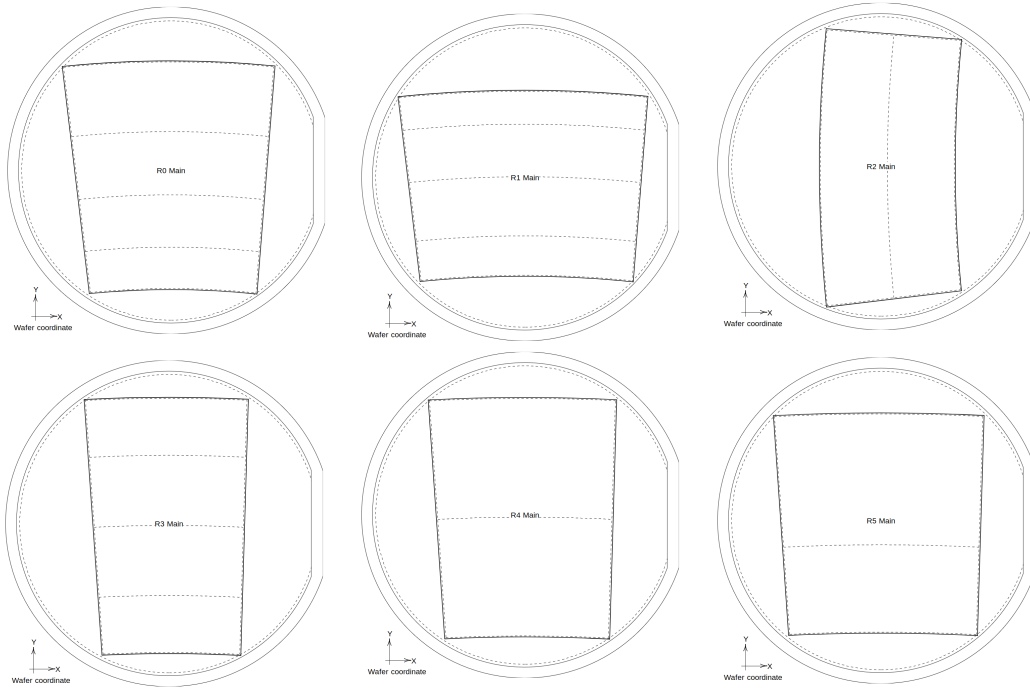


Figure 4.1: Shape of the silicon sensors for modules R0 - R5 (upper left to lower right) and their position on the 6 inch silicon wafers during manufacturing [87, Figures 4 - 9].

the readout chips and the HV (High Voltage) for biasing the silicon sensors. The modules' hybrids and power boards are glued directly onto the sensors [10, Figure 7.3]. The number of hybrids and the chips installed on them depends on the module type, which are listed in Table 4.1. Individual silicon strips are connected to the inputs of the ABCStars with thin aluminum wire bonds. Connections between the power board and hybrids and to the local support structure are also established by wire bonding. The electrical connection of the high voltage to the silicon bulk is achieved using an HV TAB (HV Tape Automated Bond). An overview of the assembly of all these module components is given in Figure 4.2.

4.1.1 Front-End Electronics

The ABCStars are connected to the sensor implants via AC coupling. A two-stage shaping amplifier is located behind a preamplifier for each channel, which supplies the discriminator with a signal of 85 mV per fC of charge deposited in the detector with a peaking time of 21 ns [82, Section 11.2.3]. The operating point of the second stage of the shaper can be adjusted using a trimming voltage (see Section 7.1.1). After the shaping amplifier, a discriminator compares the signal with a threshold voltage BVT and forwards a digital output signal to the buffer. For a schematic overview of the analog front-end, see Figure 4.3. The data of the discriminators and the BCID (Bunch Crossing ID) (see Section 4.6.3) of the last 512 events (corresponding to a buffer length of 12.8 μ s) are temporarily stored here. An edge detection circuit can register hits either by the mere presence of a signal or by a positive edge (change of the discriminator output from 0 to 1) [82, Section 11.7.3]. When an external trigger signal is received, the event is transferred from the buffer of the readout circuit, which is a fixed

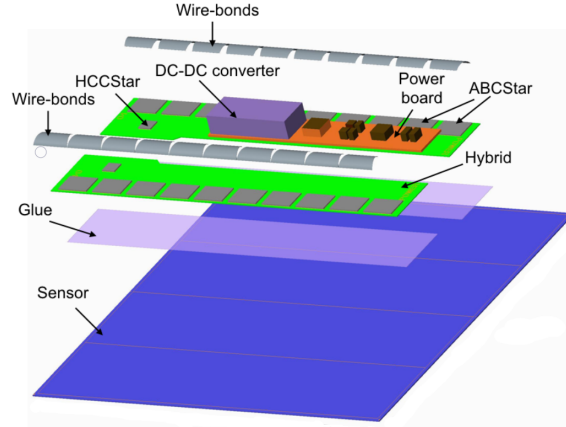


Figure 4.2: Overview of the assembly of the ITk strip modules [10, Figure 5.3].

Table 4.1: Numbers of hybrids and front-end chips for all module flavours [10, Figure 6.29].

Module	Hybrid #	HCCStars	ABCStars per HCCStar
R0	0	1	8
	1	1	9
R1	0	1	10
	1	1	11
R2	0	2	6
R3	0	2	7
	1	0	7
	2	2	7
	3	0	7
R4	0	2	8
	1	0	8
R5	0	2	9
	1	0	9

number of events in the past (the so-called trigger latency) [82, Section 11.8.1]. A significant reduction in the data volume is achieved by using a cluster finder circuit to summarise clusters of a maximum of 4 consecutive strips in 12-bit frames instead of sending the complete 256-bit hitmap of the chip for each event [82, Section 11.9]. The downstream readout block handles the serial transmission of the cluster data to the upstream HCCStar at 160 Mbit s^{-1} , and the coordination of external and periodic register read/write requests. For a detailed description of the data flow inside the ABCStars, refer to [82, Section 11.10]. One HCCStar combines the data from up to 11 connected ABCStars into a single 640 Mbit s^{-1} data stream and simultaneously forwards clock, configuration and trigger data from outside to the front-end chips [84]. The “Star” designation indicates that all ABCStars are connected directly (star-shaped) to the HCCStar. In an earlier iteration of the chip design, two closed loops with ABCStars connected in series were foreseen [88]. A 60 fF capacitor is assigned to each channel for calibration purposes. The calibration pulse, which is variable in its delay and amplitude, can be applied to these capacitors to simulate a charge deposited in the detector to test the front-end’s reaction to different injected charges. For details on this calibration circuit, see [82, Section 11.2.5]

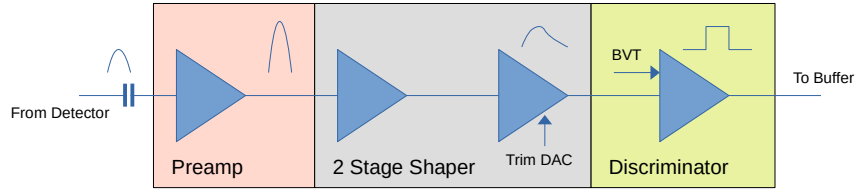


Figure 4.3: Simplified overview of the front-end signal amplification circuit. A more detailed description is found in [82, Section 11.2.3] and [89].

and [89, Figure 7]; for a description of the detector tests performed with it, see Section 7.1.

4.1.2 Operating Window

The threshold for all modules must be set to reject noise to prevent fake tracks from polluting the dataset. On the other hand, the detection efficiency decreases with an increasing threshold. As a compromise between these concerns, the modules' threshold will be set within an operating window where the hit efficiency is above 99% while, at the same time, the noise occupancy remains below 1×10^{-3} Hits/Strip/Event over the entire lifetime of the detector [10, Section 2.3.2]. While the lowest possible threshold in this window can be determined by performing a noise occupancy scan (see Section 7.1), the efficiency-based upper limit must be determined for both new and irradiated modules in high-energy particle test beam campaigns [90, 91].

4.2 Petals

Petals are near trapezoidal structures combining two layers of modules, local support, cooling and electrical services. The main components of the petal are shown in Figure 4.4.

4.2.1 Petal Core

The local support of the petal, called the petal core [10, Section 9.2.1][92, 93], is a lightweight carbon fibre composite structure with integrated cooling and electrical power, data and DCS lines. The bus tapes, thin flexible Kapton PCBs, are cured to a carbon fibre prepreg and attached to both sides of the core. Inside the cores, a titanium cooling loop is placed through which liquid CO_2 flows as a coolant. A thermally conductive foam surrounds this pipe. The spaces not directly adjacent to the cooling loop are filled with a carbon fibre honeycomb. On the outside, the core is sealed by injection moulded closeouts. On the low- R side, the closeout has a single locator, while the high- R side features two locators. The petal is kinematically fixed in the end cap at these three holding points, i.e. the petal is kept free of tension and movement even if the global support structure moves to a limited extent (e.g. due to thermal expansion). Modules are mounted on the surface of the petal core by thermally conductive adhesive.

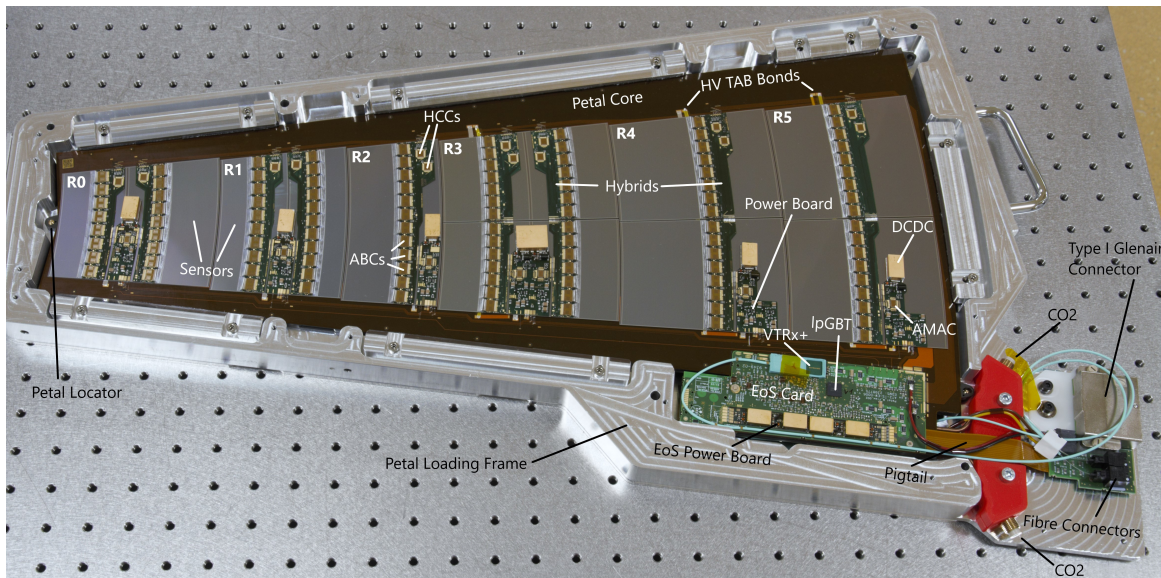


Figure 4.4: The ITk strips end cap petal shown from the front side with component labels.

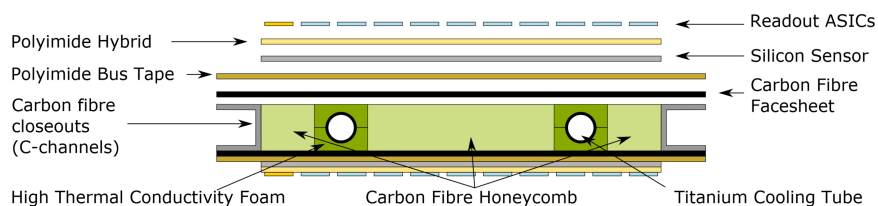


Figure 4.5: Overview of the internal structure of the petal cores [10, Figure 9.1].

4.2.2 Bus Tapes

The bus tape [10, Section 9.3.1][94, 95, 96] is a composite film consisting of three layers of polyimide (trade name Kapton), between which two layers of copper¹ are sandwiched (see Figure 4.6). Conductive traces within the copper layers can be contacted through holes (pads) in the Kapton films. The bus tape contains differential lines for TTC, detector, and DCS data and lines for supplying LV and HV to the modules. For a more detailed description, see [97, Appendix A]. There are two flavours of tapes, front and back, intended for the opposing sides of the petal core. A distinction is made between the three production stages: the tapes reach DESY in the bare state and are still very flexible. They are then co-cured with a carbon fibre prepreg in the next stage to achieve the necessary rigidity. Finally, an external company combines a front and a back tape with the other components to form a petal core. At each of the three stages of production (bare, co-cured and on core, see Figure 4.7), the tapes are electrically tested using a bus tape testing robot (see Chapter 5). To allow for a machine vision system to locate the pads on the tape, small circular features, called fiducials, are integrated into the layers of the tapes.

¹ Note that the additional shielding layer shown in [10, Figure 9.6] is not present in the production design of the end cap bus tapes.

Top Cover Layer	25 μ
Adhesive	25 μ
Top Copper	17.5 μ
Base Polyimide	50 μ
Bottom Copper	17.5 μ
Adhesive	25 μ
Bottom Cover Layer	25 μ

Figure 4.6: Lay-up of the ITk strips end cap bus tapes (adapted from [10, Figure 9.6], previously published in [97]).

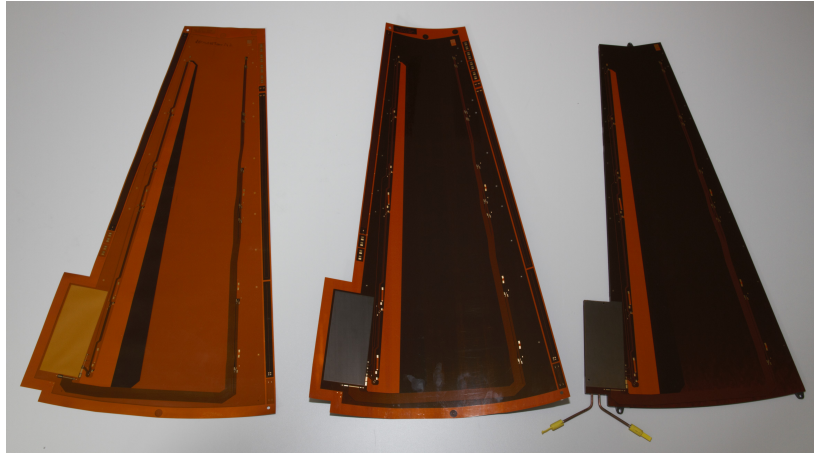


Figure 4.7: The three production states “bare”, “co-cured” and “on core” of the end cap front bus tapes (from left to right).

4.2.3 End-of-Substructure Card

The EoS (End of Substructure) card is glued to both sides of the petal core on the high- R end of the petal. A lpGBT (low power GigaBit Transmitter) [98] attached to it is connected to the 14 HCCStars on the petal side via e-links [99]. These each send detector data at 640 Mbit s^{-1} , summarised by the lpGBT into a single $10.24 \text{ Gbit s}^{-1}$ uplink with 8.96 Gbit s^{-1} user data with the addition of error correction data and headers [10, section 12.1]. Conversely, the lpGBT receives a TTC data stream of 2.56 Gbit s^{-1} in the downlink (of which 1.28 Gbit s^{-1} is user data), split into four segments and sent to the HCCStars. The configuration data of the modules is also sent via the downlink to the ABCStars via the HCCStars. Both the uplink and the downlink of the lpGBT are connected to an optical transceiver module called VTRx+ (Versatile Transceiver) [100]. This module converts the uplink into an optical signal and receives the downlink data. The EoS card has its own DC-DC converter, providing power to the EoS card’s components as well as to the module AMAC chips. There is also a NTC (Negative Temperature Coefficient resistor), which the interlock system uses to monitor temperature thresholds (see Section 4.4.1). All electrical and optical connections are routed via a flexible PCB to a connector board attached to the outside of the global support structure (this section is called “pigtail”, see Figure 4.11(d)).

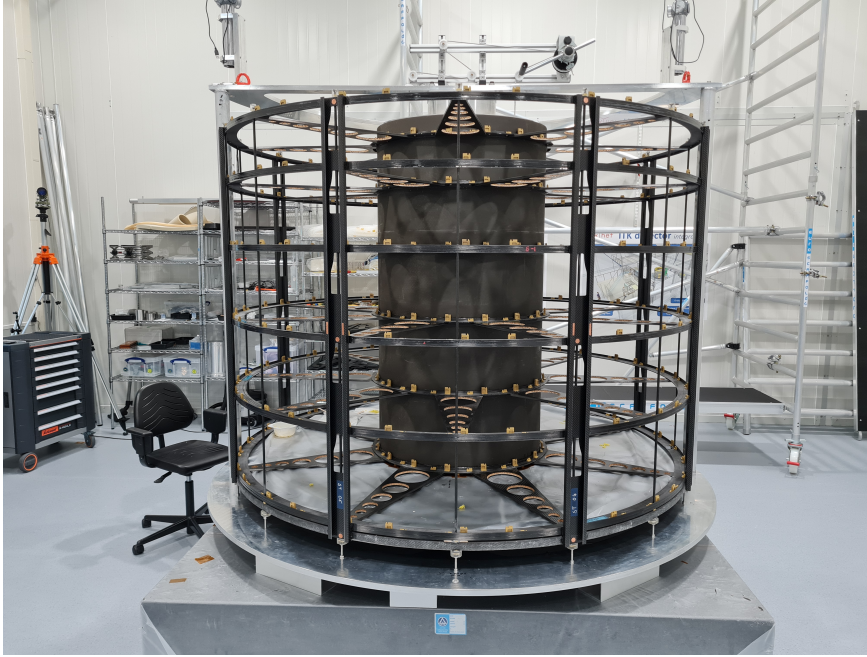


Figure 4.8: Global mechanical support of the end cap during its construction in a cleanroom at NIKHEF (Nationaal Instituut voor Kernfysica en Hoge-EnergieFysica) [102].

4.3 Global Mechanical Support Structure

Once assembled and tested, the petals are integrated into the global end cap support structure shown in Figure 4.8 [10, Section 10.4][101]. One end cap has six discs, the distances between which get larger with the increasing z coordinate. The discs are designed as a carbon fibre wheel with locking points on the inner and outer rings. The petal locators are inserted into the locking points and then fixed in place kinematically using a clamping mechanism. Thirty-two petals are loaded into each disc, sixteen of which are raised in relation to the other petals (front layer petals). The discs are attached to a carbon fibre inner cylinder, where the pixel detector will be located in the finished ITk detector. On the outside, the discs are stabilised by stiffening carbon fibre rods and the service trays, which guide all cables, optical fibres and cooling lines along the z direction until the outer edge of the end cap. In addition, a stiffener disc is attached parallel to disc 5 (the disc furthest away from the interaction point). The end cap is radially enclosed by the outer cylinder, into which it is inserted via a rail system after petal integration. The outer cylinder also acts as the outer radial boundary of the volume of the ITk detector. In z , the end cap is sealed by the structural bulkhead. The outer cylinder and the bulkhead are electrically conductive, resulting in a closed Faraday cage for the ITk.

4.3.1 Petal Insertion

Fully loaded and tested petals are inserted into the global support structure during end cap integration. The modules attached to both sides of the petal, especially the sensors and wire bonds, are highly susceptible to mechanical damage and may, therefore, not collide with other components during this procedure under any circumstances. The petal insertion tool was developed at DESY to perform this



Figure 4.9: Petal insertion tool with a dummy petal attached to the insertion hand.

delicate procedure (see Figure 4.9). Petals are held in place with the insertion hand, a mechanical grabbing tool made mainly of thermoplastic and carbon fibre. The position of the insertion hand can be precisely controlled using the insertion tower. It allows for guided movements in the R , ϕ and z directions, as well as rotation around the R axis and tilting with respect to the disc plane. The insertion tower also rotates around the tower platform on a rail system to allow access to all possible positions in the end cap. In this way, the petal is navigated to the petal locators, which are then closed to hold it in place. After insertion, the insertion hand is removed, and a short “ping test” is performed to verify the electrical function of all petal components. Finally, the cooling loops of the petal are connected to the cooling manifold of the end cap using an orbital TIG (Tungsten Inert Gas) welding process.

4.4 Powering Scheme

Both sides of each petal require a LV supply of 11 V. In addition, the modules require a HV of up to -550 V for biasing the silicon sensor. Modules R0 and R2, as well as R4 and R5, are each supplied via the same HV line, while modules R1 and R3 each have an independent HV supply. The total of two LV and eight HV lines, as well as the petal NTCs, are connected to the type I Glenair connector via the pigtail of the EoS card (see Figure 4.11(d)). The type I cable connected to this leads to the PP1 (Patch Panel I) enclosed in the bulkhead via the service trays of the global support structure (see Figure 4.11(c)). There, the cables of two petals are combined into a type II Glenair connector. The connected type II cable leads to PP2 (Patch Panel II) outside the solenoid (see Figure 4.11(b)). PP2 contains DC-DC converters, which step down an LV supplied by the power supplies from 48 V to the 11 V required by the petals, as well as HV switches. From there, two type III cables per petal lead to PP3 (Patch Panel III) in the UX15 cavern area outside the detector. At last, type IV cables lead to the PSU (Power Supply Unit) in the US15 cavern. Type IV cables are going to be reused from the SCT, while new type I, II and III cables are going to be ordered for the ITk upgrade. A visualisation of this

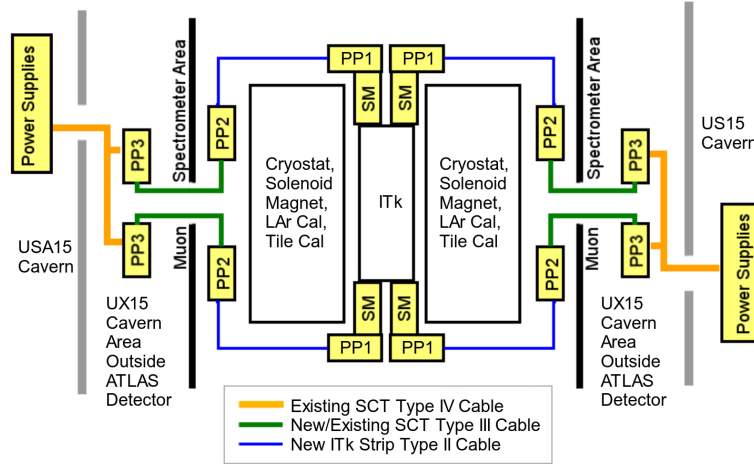


Figure 4.10: Powering scheme for the ITk strips end caps (taken from [10, Figure 17.2]). After the finalization of the ITk strips Technical Design report, a decision has been made to replace the existing SCT type III cables [103].

powering scheme is shown in Figure 4.10.

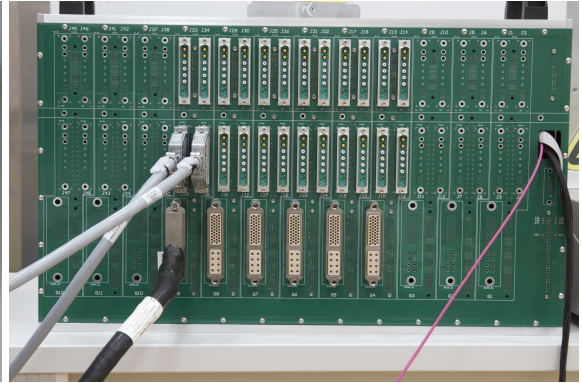
The PSUs have a modular design and consist of LV and HV modules (see Figure 4.11(a)). Each LV module provides eight channels with 48 V output voltage, and the HV modules 16 channels with up to -550 V. The PSU crate also has a control module that monitors and controls the channels via an OPC UA (Open Platform Communications Unified Architecture) server. Each channel also features an inhibit signal input that allows for emergency shut-off by the interlock system. A voltage of 3.3 V deactivates the channel inhibit of the PSU and allows operation. In contrast, a drop to 0 V leads to an emergency shutdown of the channel and prevents it from being switched on again until the normal operational state has been restored. HV channels are always switched at a rate of 10 V s^{-1} in order to prevent damage to the silicon sensors.

4.4.1 Interlock System

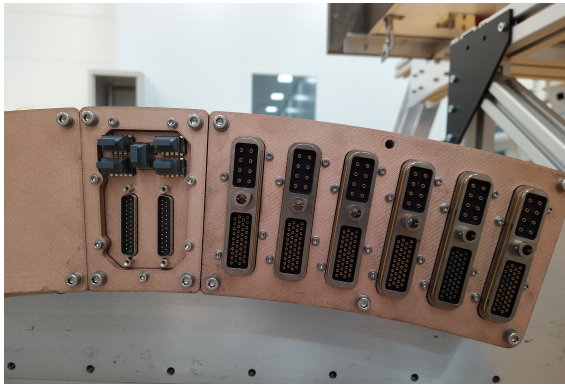
The ITk has its own interlock system, which consists of modular crates (see Figure 4.12). The LISSY (Local Interlock & Safety System) crates contain Eurocard PCBs that cover various functions of the interlock system and are connected to the interlock and monitoring FPGA (Field Programmable Gate Array)s via I^2C buses [104]. T2I (Temperature to Interlock) cards compare the temperature value of an external 10k NTC with a threshold voltage. They also allow the detection of a broken NTC cable and temperature reading via an ADC in the monitoring channel. These cards are connected to the NTCs on the petals' EoS cards. OUT cards forward decisions from the interlock FPGA to the power supplies as a 3.3 V signal. Per crate, a GSS (Global Safety System) card is used to connect to the MIC (Main Interlock Crate), which coordinates the exchange of interlock decisions between the LISSY crates and also transmits global interlock decisions from the DSS (Detector Safety System) and BIS (Beam Interface System) to them [105]. The interlock FPGA continuously queries the status of all T2I and GSS inputs. A corresponding interlock decision is made based on a logic function freely programmable by the user (see Section 6.2.3 for an application example) and forwarded to the OUT cards, which enable or disable the PSU channels accordingly. The monitoring FPGA monitors the



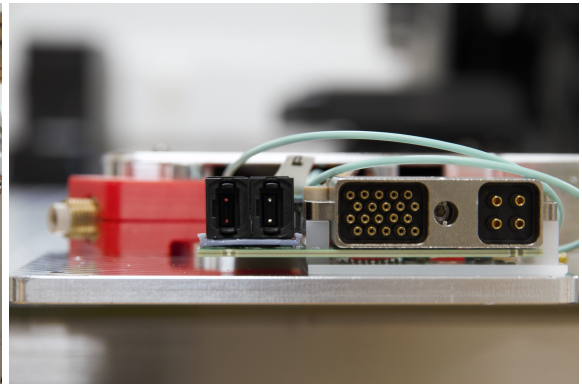
(a) ITk PSU with three HV and LV modules.



(b) Connector side of PP2 with one type II and two type III cables connected.



(c) View of the System Test PP1 before insertion in the bulkhead. The type II connectors are shown on the right, on the left are four fibre-optic connectors for detector data, two DCS connectors for environmental monitoring signals and a fibre-optic connector for humidity monitoring.



(d) View of the type I Glenair connector at the petal pigtail together with the petal fibre connectors.

Figure 4.11: Closeup pictures of the PSU, PP2, PP1 and the petal power connector.



Figure 4.12: Front side of the LISSY crate used in the ITk strips end cap System Test (see Section 6.2.3) without the monitoring FPGA installed.

status of all cards via dedicated monitoring circuits and a separate I²C bus. It then makes the status available to the control room via an OPC UA server. It also enables simulating interlock states, such as the temperature of a petal being too high, using test signals on the cards to verify the interlock FPGA's reaction.

4.4.2 Grounding and Shielding

To prevent external electromagnetic interference or coupling between signal sources in the detector from generating unnecessary noise and, thus, additional measurement uncertainties, the entire detector follows a strict grounding and shielding strategy [106]. The strategy relies on a Faraday cage surrounding the entire detector. All power supply channels are floating and are routed through a shielded cable into the detector. Their ground is connected to the electrically conductive petal core. The shield of the cables is connected to the Faraday cage of the ITk but is isolated from the earth connection of the PSUs. Instead, the earth connection of the entire system is established at a single point from the Faraday cage. During the integration procedure, this connection is equipped with a ground fault monitor to alarm the construction team of any unintended ground connections [107]. All petals in the strips end cap are electrically isolated from the global support structure via the petal locking points to prevent the formation of ground loops. The cooling loops also contain ceramic electrical breaks to prevent potential equalization via the cooling lines. The supply lines for the cooling agent have additional electrical breaks in their feed-through in the bulkhead. The local LV and HV ground on the petal is connected with the petal core for all modules.

4.5 Cooling

The ATLAS ITk detector has unique requirements for its cooling system. The silicon sensors operate below $-30\text{ }^{\circ}\text{C}$ and must have a homogeneous temperature over the entire detector area. At the same time, the coolant must be radiation-hard and have a long radiation length. In addition, it must not be electrically conductive to avoid ground loops inside the cooling manifolds. For this reason, an evaporative 2-phase cooling system based on fluorocarbon was already used in the ID [108]. These systems have the advantage over mono-phase systems of reaching lower temperatures. In addition, there is no significant temperature gradient across the cooled components as long as the coolant has not evaporated entirely. The ITk uses the newer 2PACL (Two-Phase Accumulator Controlled Loop) concept [109][10, Chapter 19] with CO₂ (also known as R744 refrigerant), which has already been successfully applied in the IBL of the current pixel detector [110]. In addition to its low costs, CO₂ as a refrigerant has environmental advantages. The global warming potential of the C3F8 refrigerant (also known as R218) previously used in ID is 8830 times higher than that of CO₂ over a span of 100 years [111].

The boiling point of liquid CO₂ depends on its pressure. In 2PACL systems, a large volume of CO₂ is stored in the so-called accumulator, which is connected to the cooling loop. The accumulator contains a gaseous volume of a cooling agent at the top, while liquid settles at the bottom. The pressure inside can be adjusted by heating or cooling the accumulator. Inside the cooling loop, the pressure equalises to the accumulator pressure, influencing the boiling point of the CO₂. In the cooling loop, the liquid refrigerant is circulated by a pump and evaporates in the detector, cooling it to the temperature set by the accumulator pressure. The boiling of the refrigerant is initiated using a capillary, a thin section of

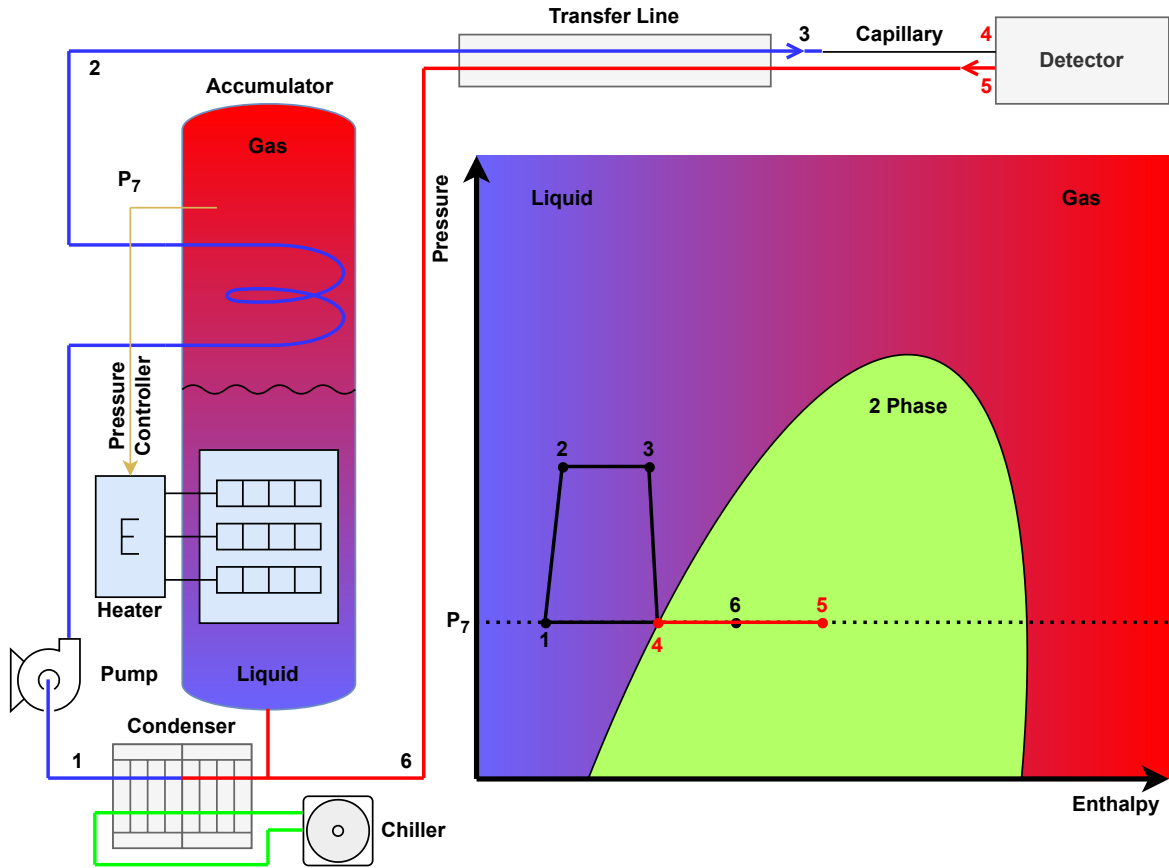


Figure 4.13: Schematic overview of the 2PACL system concept with CO₂ phase diagram (partially inspired by the illustrations in [113]).

tubing that forces a significant pressure drop. Sixteen petals in the same disc are connected into a cooling manifold with an expected total cooling power of 1 344 W [112]. The enthalpy of the now partially gaseous refrigerant is reduced again in a heat exchanger by an external condenser circuit, and the cycle repeats. Figure 4.13 provides an overview of the entire cooling cycle.

4.6 Readout

The detector is read out via an optical fibre. Currently, the ITSDAQ and FELIX + YARR readout systems are available for loaded petals.

4.6.1 ITSDAQ

ITSDAQ (ITk Strips DAQ) is an FPGA-based system used to read out modules or single loaded petals during detector production [114]. For petal readout, the ITSDAQ firmware is loaded onto a Digilent Genesys 2 FPGA board [115], to which an optical transceiver is connected (see Figure 4.14(a)). Detector tests (see Section 7.1) can then be carried out in the ITSDAQ software on a PC connected via



(a) Genesys 2 FPGA board with one optical transceiver installed on the right. The external trigger signal is received up to 24 petals. In the picture, a single 24-fibre cable (pink) and a ATLAS TTC fibre (purple) are installed, another 24-fibre port is available. Also, a LEMO input for the DAQ busy signal is present on the right.

Figure 4.14: Hardware of the ITSDAQ and FELIX DAQ systems.

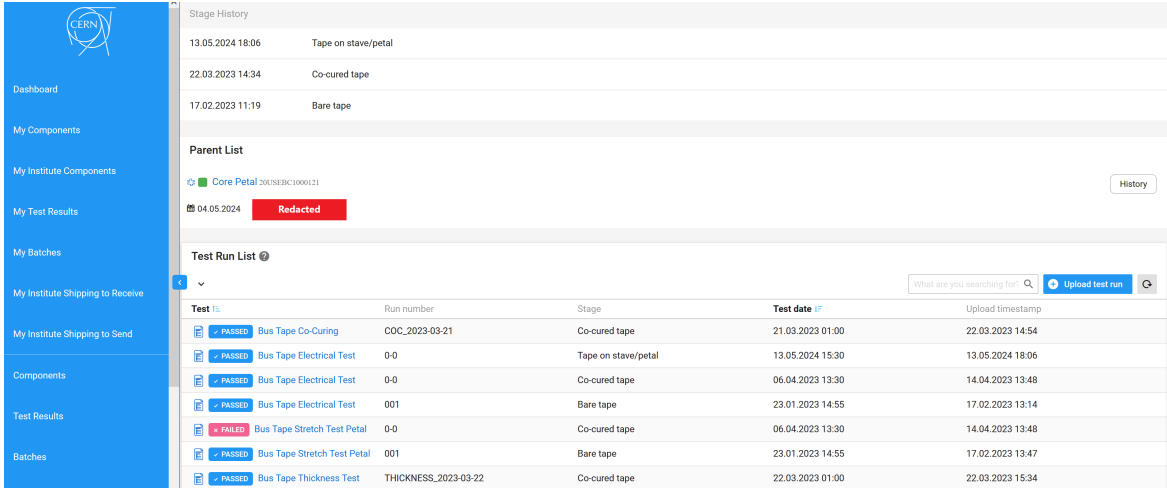
Ethernet, and the results are saved as ROOT, JSON, and PDF files. Using an HDMI cable, the FPGA board can receive external trigger signals from an AIDA-TLU (Trigger Logic Unit), which is mainly used for beam tests of individual modules [116]. The data from the module and other detectors (such as a beam telescope) are synchronised and saved using the EUDAQ system [117]. This feature was used during this thesis to take data with cosmic muons (see Chapter 9).

4.6.2 FELIX + YARR

The FELIX (Front-End Link eXchange) system is the readout currently used in the ATLAS detector [118]. It consists of servers on which the readout software runs. FLX-712 cards, which can process a maximum number of 48 bidirectional optical links, are inserted in these servers (see Figure 4.14(b)). In addition, the card is connected to the ATLAS TTC system and forwards the information received via the downlinks to the connected detector modules. In the detector, the data is received by the Software Readout Drivers (SW RODs) and processed further. The YARR (Yet Another Rapid Readout) software [119] was used for this thesis. YARR interacts with the FELIX software via a network connection, reads out data and enables the user to perform parameter scans. A comparison of the test results of a loaded petal between the ITSDAQ and FELIX + YARR setups can be found in Section 7.1.6.

4.6.3 TTC System

The TTC (Trigger, Timing, and Control) system is responsible for providing the individual detector components with a range of signals required for the readout [120]. Firstly, the 40.079 MHz BC (Bunch Crossing Clock) and the ORB (Beam Orbit) signal, which indicates a full rotation of the bunches in the LHC, provide information about the current BCID (Bunch Crossing ID). The L1A (Level-1 Trigger Accept) signal instructs to read out the current event. In addition, a trigger-type word for every L1A (TTYP), local auxiliary trigger signals (TTR) and additional TTC commands such as the BCR (Bunch Counter Reset) or ECR (Event Counter Reset) are transmitted. In the other direction, the



The screenshot displays the ITk production database interface. On the left is a blue sidebar with navigation links: Dashboard, My Components, My Institute Components, My Test Results, My Batches, My Institute Shipping to Receive, My Institute Shipping to Send, Components, Test Results, and Batches. The main content area is divided into three sections: Stage History, Parent List, and Test Run List.

Stage History

Date	Time	Stage
13.05.2024	18:06	Tape on stave/petal
22.03.2023	14:34	Co-cured tape
17.02.2023	11:19	Bare tape

Parent List

Core Petal 200/SEBAC10000121

04.05.2024 Redacted

Test Run List

Test ID	Run number	Stage	Test date	Upload timestamp
PASSED Bus Tape Co-Curing	COC_2023-03-21	Co-cured tape	21.03.2023 01:00	22.03.2023 14:54
PASSED Bus Tape Electrical Test	0-0	Tape on stave/petal	13.05.2024 15:30	13.05.2024 18:06
PASSED Bus Tape Electrical Test	0-0	Co-cured tape	06.04.2023 13:30	14.04.2023 13:48
PASSED Bus Tape Electrical Test	001	Bare tape	23.01.2023 14:55	17.02.2023 13:14
FAILED Bus Tape Stretch Test Petal	0-0	Co-cured tape	06.04.2023 13:30	14.04.2023 13:48
PASSED Bus Tape Stretch Test Petal	001	Bare tape	23.01.2023 14:55	17.02.2023 13:47
PASSED Bus Tape Thickness Test	THICKNESS_2023-03-22	Co-cured tape	22.03.2023 01:00	22.03.2023 15:34

Figure 4.15: Screenshot of a bus tape in the ITk production database after various production steps and tests.

readout of the individual detectors communicates with the BUSY signal that no further L1A signals may be accepted, for example, if the buffers of the DAQ system are full.

The TTC commands originate from the detector's CTP (Central Trigger Processor) and are forwarded by it to the individual detector parts [121]. For these, the ALTI (ATLAS Local Trigger Interface), which forwards the TTC signals to the readout hardware, replaces the four legacy TTC modules [122].

4.7 ITk Production Database

The ITk detector consists of a large number of individual parts that are subjected to component tests at various stages of production at different production sites. The ITk production database (see Figure 4.15) was developed to organise the large amount of data that accumulates and make it available to all production sites [123, 124]. Each component of the detector is registered there with a serial number. During the production steps, test results can be added to the components, several components can be combined into assemblies and component shipments can be created between the production sites. Project stakeholders can, therefore, trace the production status, location and compliance with the quality criteria for each component at any time. During the production of the end cap, DESY carries out production steps and component tests on a large number of detector components, in particular during module building and loading, production of the EoS cards, and during the testing of bus tapes and other components of the petal core. The DIDIS (DESY ITk Database Interaction Script) library was developed during this thesis to simplify interaction with the database and, in particular, to enable automated uploading of test results [125]. It provides simplified Python access to all database functions relevant to production and allows for batch processing of test results and component registrations.

Testing of Bus Tapes

To ensure a low electrical failure rate of the petals of the new ITk strip detector, the bus tapes (see Section 4.2.2) are tested in all three production stages (bare, co-cured and core) on a custom made BTR (Bus Tape Testing Robot). For testing the barrel tapes, one BTR is located in Oxford [126] and one in Yale, while the end cap tapes are tested in Ljubljana at JSI (Jožef Stefan Institute) [127] and at DESY in Hamburg [128]. During this thesis, changes were made to the DESY BTR setup as part of an ATLAS authorship qualification task described in [97].

5.1 DESY Bus Tape Testing Robot

The DESY BTR shown in Figure 5.1 consists of two independently movable stages, each equipped with a camera and a measuring tip connected to a DMM (Digital Multimeter) (see Figure 5.2(a)).

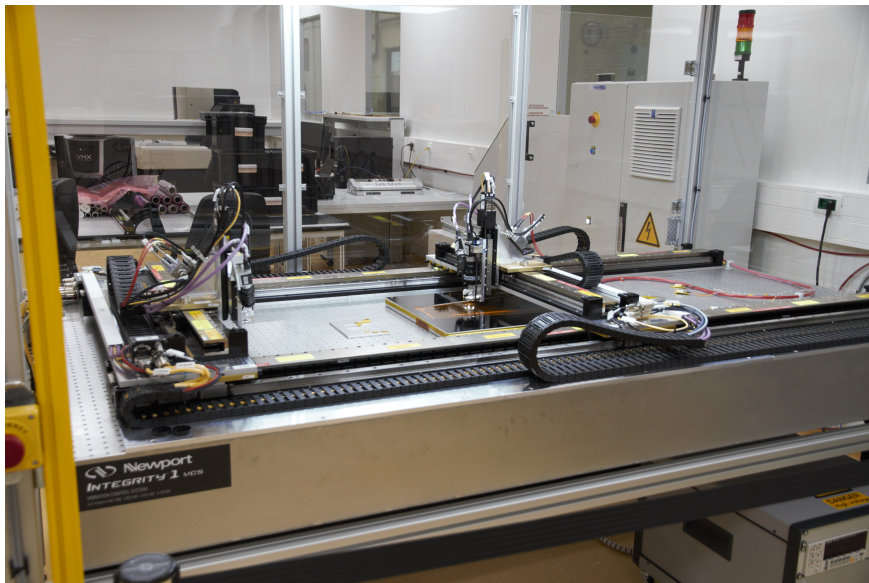
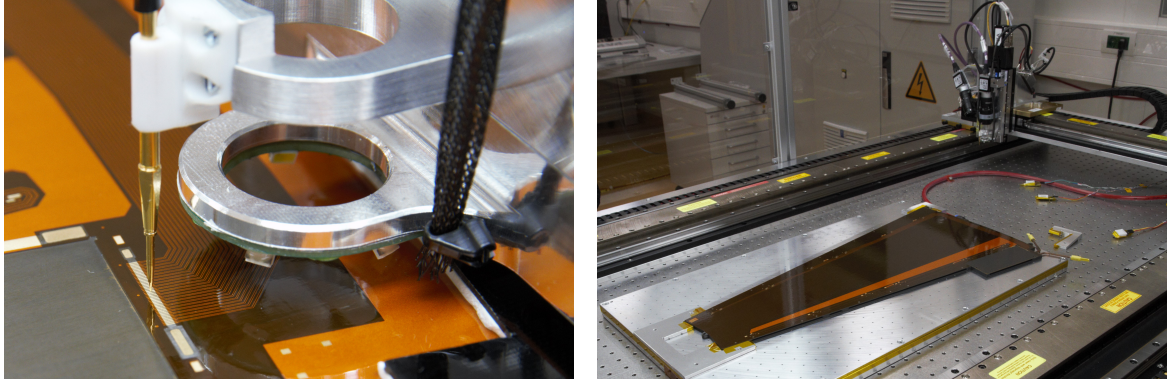


Figure 5.1: View of the DESY BTR with a co-cured bus tape placed on the vacuum chuck.



(a) Electrical probe touching on a differential pad at the EoS area of a co-cured bus tape. (b) Petal core mounted on the BTR vacuum chuck.

Figure 5.2: Pictures of a BTR stage probing an electrical pad on the bus tape and of a petal core before testing.

A vacuum chuck is mounted on the table of the robot, on which a bus tape can be fixed for measurements. For the BTR to make contact with the electrical pads on the bus tape, the position of the tape relative to the stages must first be measured. For this purpose, the expected positions of the fiducials are approached with both stages. The actual position is then measured with the help of a machine vision code via the cameras. From this position data, the tape's deformation compared to the design specifications can be calculated as part of the “stretch test”. The measurement variables

$$\frac{dx}{x} = \frac{(x_2^M - x_1^M) - (x_2^D - x_1^D)}{x_2^D - x_1^D} = \frac{x_2^M - x_1^M}{x_2^D - x_1^D} - 1 \quad \text{and} \quad \frac{dy}{y} = \frac{y_2^M - y_1^M}{y_2^D - y_1^D} - 1 \quad (5.1)$$

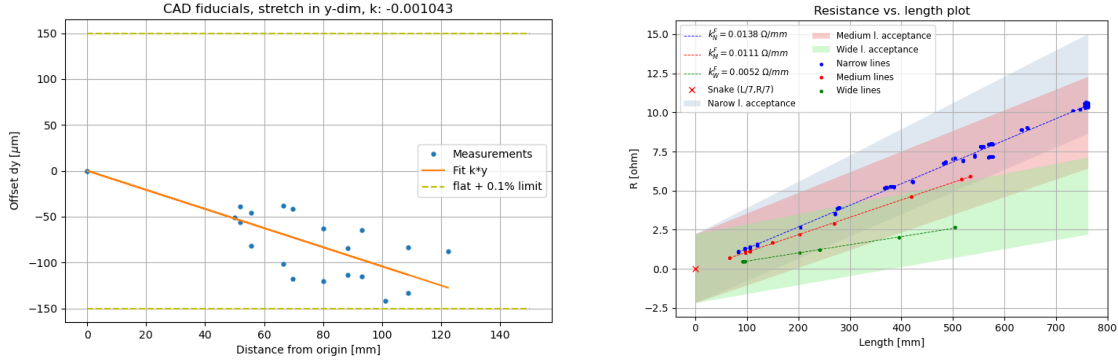
are recorded for all fiducials, where $x_{1,2}^D$ and $y_{1,2}^D$ are the coordinates of a pair of fiducials according to the design, and $x_{1,2}^M$ and $y_{1,2}^M$ are the corresponding coordinates measured by the BTR. The stretch test is passed if the maximum distance deviation between the origin¹ and any other fiducial is less than 300 μm in the x and 150 μm in the y direction. In addition, the average stretch of the tape in both dimensions is calculated. For this, the variables in Equation (5.1) are plotted against the distance of the fiducials in the respective dimension. Finally, a fit with a linear model is performed, whose slope provides the average stretch. An example of such a stretch result is shown in Figure 5.3(a). The average stretch in x and y , together with the information whether both stretch tests were passed, is stored as a test result for each production stage of the tape in the ATLAS ITk production database (see Section 4.7).

The electrical tests are now performed by contacting the corresponding pads on the tape. A distinction is made between three types of tests:

Resistance Measurements Both stages contact pads on the same electrical line with their probes. The DMM connected to the probes determines the electrical resistance. A single test is passed if the

¹ The origin fiducial is the one closest to the beam axis.

5.2 Test Results of Pre-Production B Bus Tapes



(a) Stretch test result for the y dimension with respect to the origin fiducial.

(b) Results of the electrical test arranged according to the type of line.

Figure 5.3: Test result plots for the bare tape 20USEBT1000031 (from the generated measurement report [129]).

measured resistance R_{Measured} of the line of length l meets the criterion

$$R_{\text{Measured}} \in [0.9 \cdot l \cdot r_{\text{Line}} - 2 \Omega, 1.1 \cdot l \cdot r_{\text{Line}} + 2 \Omega], \quad (5.2)$$

where $l \cdot r_{\text{Line}}$ is the expected nominal resistance for the measurement. Depending on the type of line, $r_{\text{Line}} = 15.5, 12.25$ and $6.1 \Omega \text{ m}^{-1}$ for narrow, medium and wide lines respectively. The whole tape passes the test only if the measured resistance of all lines is within the acceptance range (exemplified in Figure 5.3(b)).

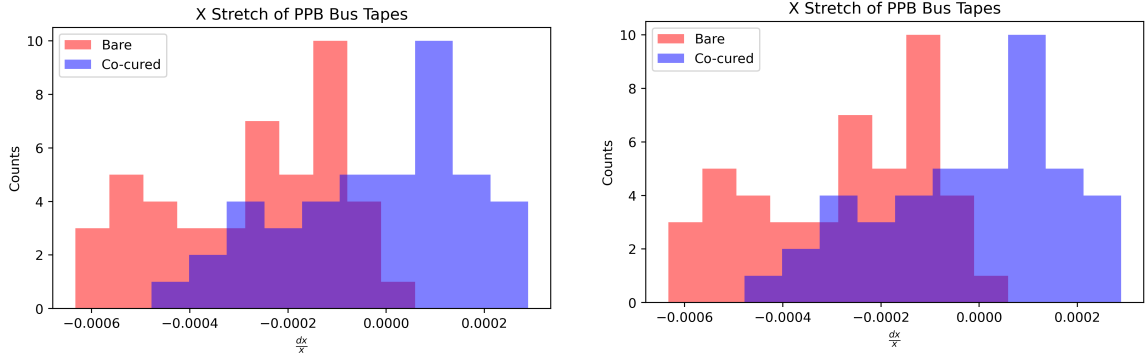
Electrical Shorts The bus tapes feature dense collections of differential lines for fast electrical signals connecting the modules to the EoS card. In order to test for unintended electrical connections in these lines, pads of adjacent lines are contacted with the probes and the electrical resistance between them is recorded. If this is outside of the measuring range of the DMM, the test for shorts is considered passed for this pair of lines. The tape passes the test if no shorts could be detected.

Leakage Current As with the test for shorts, pads that should not have any electrical connection are contacted. Then, the current through both probes is measured once with the voltage source switched off and once with 1 000 V applied. The difference is the leakage current at 1 000 V, which should be less than 20 nA for all lines.

The combined number of shorts or HV failures is stored in the production database along with the total number of electrical test failures. No electrical failures must have occurred for the tape to be used further in production.

5.2 Test Results of Pre-Production B Bus Tapes

As part of ATLAS ITk PPB (Pre-Production B), 46 bus tapes were measured on the BTR at DESY, both in the bare and co-cured state. On the one hand, these tapes are used to study the production process and procedures, but on the other hand, they are also used in setups such as the System Test (see



(a) Distribution of average tape stretches $\frac{dx}{x}$ in x direction. (b) Distribution of average tape stretches $\frac{dy}{y}$ in y direction.

Figure 5.4: Average stretches of the tested tapes before and after co-curing in both dimensions.

Table 5.1: Average stretches in both dimensions before and after the co-curing process as well as the average difference.

Stretch Direction	Before Co-curing	After Co-curing	Difference
x-Dimension	$(-0.0279 \pm 0.0184) \%$	$(-0.0017 \pm 0.0194) \%$	$(0.026 \pm 0.027) \%$
y-Dimension	$(-0.1065 \pm 0.0158) \%$	$(-0.0772 \pm 0.0232) \%$	$(0.029 \pm 0.028) \%$

Section 6.2). Table A.1 and Table A.2 list the stretch and electrical test results. All results included here were already published in [97]. The tapes with serial numbers *20USEBT2000013*, *20USEBT2000021* and *20USEBT2000022* were not co-cured; the stretch test of tape *20USEBT2000035* turned out to be unusable due to an incorrectly detected fiducial. The co-cured tape *20USEBT1000033* was identified as damaged during the electrical test.

5.2.1 Stretch Test Results

In both dimensions, a sub-promille expansion of the tapes through co-curing was observed. These results are shown in Figure 5.4 and are based on the measurements in Table A.1. The average deviations in both dimensions before and after co-curing can be found in Table 5.1.

5.2.2 Electrical Test Results

The comparison of the number of short circuits, leakage currents with 1 000 V high voltage applied, and the resistance of the narrow, medium and wide lines between bare and co-cured tapes showed no statistically significant differences between the two production stages. These results are shown in shown in Table 5.2 and Figure 5.5, which refers to the measurement data in Table A.2.

5.3 Test Results of Production Bus Tapes

Since the start of production of the bus tapes, 236 co-cured tapes have been tested using the DESY BTR (see Figure 5.6). In the process, 16 tapes failed the quality control criteria. Eleven tapes showed

5.3 Test Results of Production Bus Tapes

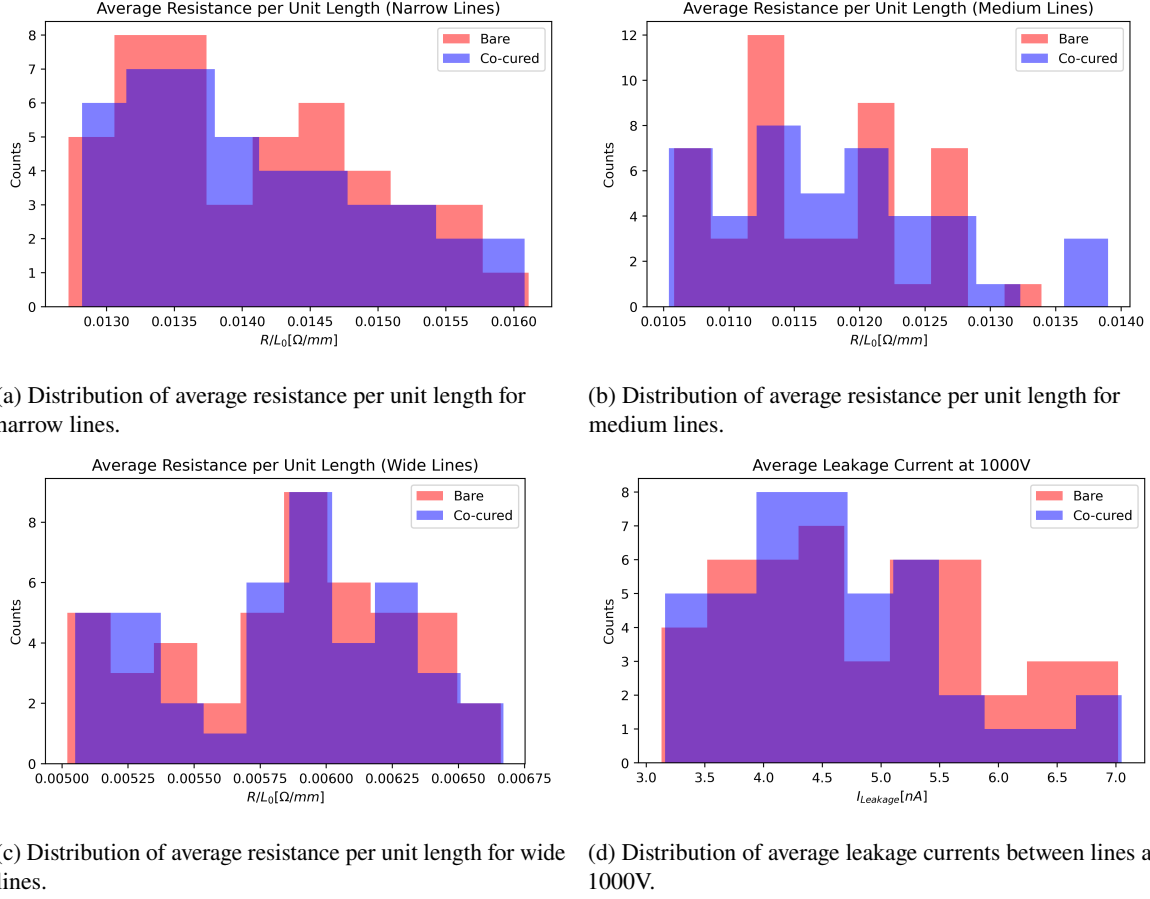


Figure 5.5: Histograms of the electrical test results obtained with the DESY BTR (based on the data in Table A.2).

Table 5.2: Average values of the leakage currents and resistances on the DESY BTR before and after co-curing of the tapes.

Measurement	Before Co-curing	After Co-curing	Difference
Leakage current at 1 000 V	$(4.9 \pm 1.0) \text{ nA}$	$(4.6 \pm 0.9) \text{ nA}$	$(-0.2 \pm 1.4) \text{ nA}$
Resistance (narrow lines)	$(0.0141 \pm 0.0009) \Omega \text{ mm}^{-1}$	$(0.0141 \pm 0.0009) \Omega \text{ mm}^{-1}$	$(0.0000 \pm 0.0013) \Omega \text{ mm}^{-1}$
Resistance (medium lines)	$(0.0117 \pm 0.0007) \Omega \text{ mm}^{-1}$	$(0.0118 \pm 0.0008) \Omega \text{ mm}^{-1}$	$(0.0001 \pm 0.0011) \Omega \text{ mm}^{-1}$
Resistance (wide lines)	$(0.0059 \pm 0.0004) \Omega \text{ mm}^{-1}$	$(0.0058 \pm 0.0004) \Omega \text{ mm}^{-1}$	$(0.0000 \pm 0.0006) \Omega \text{ mm}^{-1}$

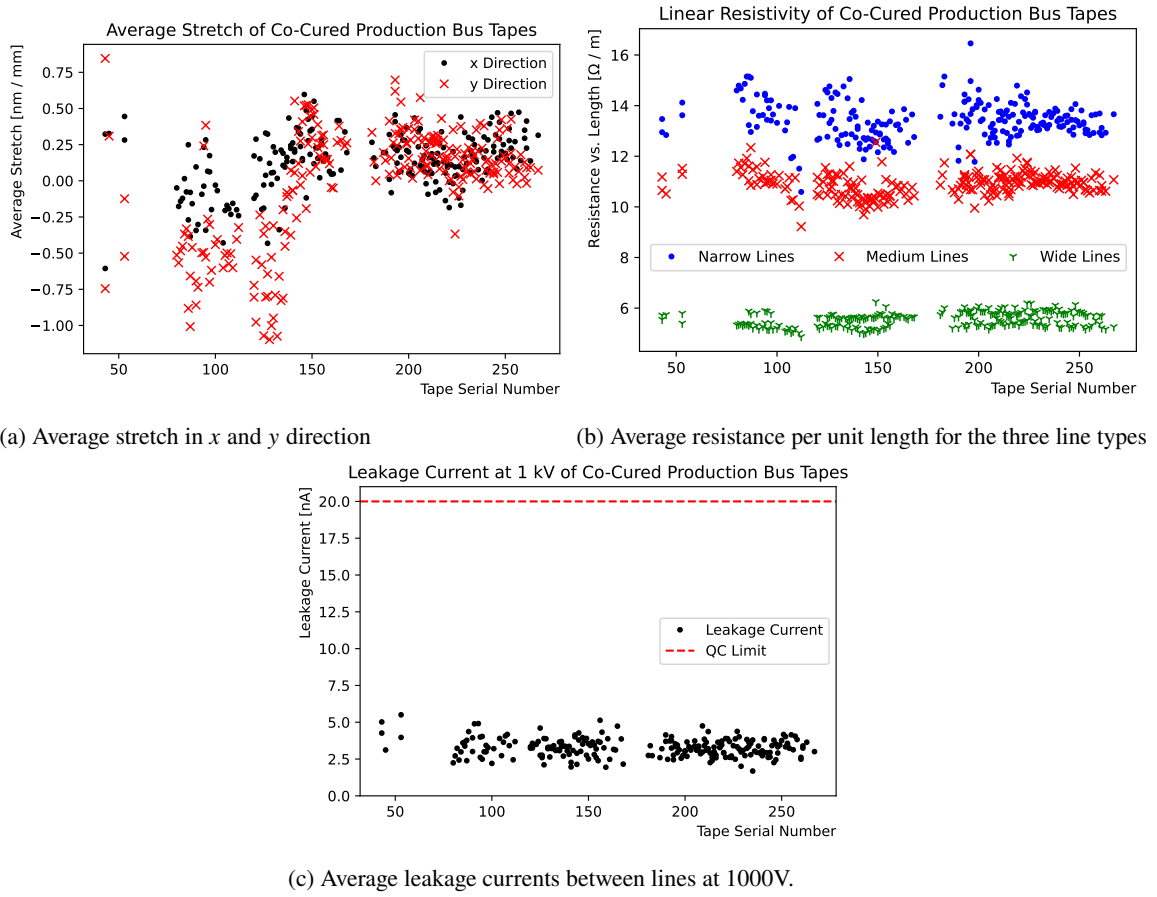


Figure 5.6: Test results of co-cured production bus tapes until March 2024.

anomalies in the electrical test, three of which were excluded from further production steps due to short circuits or increased leakage current. Five further tapes failed the stretch test, three due to the measured deviations in the x -direction and two due to the measured deviations in the y -direction. The results of the stretch test have been fed back into the production of the bare tapes, greatly reducing the observed deviations for newer tapes (see Figure 5.6(a)). A similar analysis of the tapes in the bare state has been performed by members of the ATLAS collaboration at JSI [130]. The robot has been modified to also facilitate the testing of petal cores (see Figure 5.2(b)). So far, six production cores have been subjected to double sided electrical testing, with all of them passing this quality control step.

5.4 Conclusion

The DESY BTR has been successfully prepared to test bus tapes. The results of the PPB tapes qualified DESY as a production site for the co-curing of tapes. With the testing of the PPB tapes, the ATLAS authorship qualification task was completed. The robot is now used for detector production and was successfully used for quality control of 236 co-cured tapes and the first batch of petal cores.

Experimental Setups

Over the course of this thesis, multiple measurements involving three different pre-production ITk strips end cap petals have been made. For this, two different setups, the petal coldbox and the ITk strips end cap System Test, have been developed. In this chapter, these experimental setups are explained. Furthermore, results of the drying performance of the System Test coldbox as well as the on-petal module cooling performance within the petal coldbox are presented.

6.1 Petals

Due to the highly dynamic environment of the detector pre-production, the measurements in this thesis had to be performed with the petals that were available at the time. Since these were still late-stage prototype versions of the petal mainly built to gain experience with and qualify sites for petal building, they exhibit individual features and problems that will be briefly described here. While a unique ATLAS serial number officially identifies petals, these pre-production objects have unofficial designations hinting at the institute that performed the module loading and the number of petals built by that institute. This will be how they are referred to in this thesis. The serial numbers of the module hybrid assemblies are often used to refer to the modules, they are listed in Table 6.1.

TRIUMF1 *TRIUMF1* was the first petal ever loaded with a complete set of modules. It was completed by TRIUMF (Tri University Meson Facility) in Vancouver, Canada, and received by DESY in August 2023. A thorough visual inspection revealed multiple glue remnants on the sensor surfaces, a bowed R0 sensor, and the liftoff of a R5 power board. In addition, one sensor of the secondary side R3 module showed a significant increase in leakage current and an unresponsive hybrid. During reception testing, the primary side LV circuitry of the petal was briefly exposed to 33 V instead of the specified 11 V due to a bug in the power supply control software. The linear regulator supplying the R0 power boards' AMAC chip was destroyed in the incident, leaving the module unresponsive. On arrival, multiple sensors showed noisy strips due to static surface charges that could be mitigated using ionised air, as discussed in Section 7.2. The reception test results of this petal have been presented in more detail in [131]. In October 2023, *TRIUMF1* was inserted into the System Test (see Figure 6.1).

IFIC1 *IFIC1* constitutes the first petal loaded with modules at IFIC (Instituto de Física Corpuscular) in Valencia, Spain, which was received in the DESY inventory of petals in December 2023. Its

primary side R0 module and one of the four HCCStars of the secondary side R3 module show no communication. Otherwise, the petal is functional.

DESY1 *DESY1* was the first petal loaded at DESY in Hamburg, Germany, and became available for testing in May 2024. It shows noise features on multiple modules not present before module loading, which could not be resolved using the ionised air approach (see Section 7.3.1). Also, no communication with the R3 modules on both sides could be established. This was revealed to be due to a faulty bonding scheme for this module type after the data taking for this thesis concluded and was fixed in the meantime by reworking the wire bonds.

Table 6.1: Hybrid serial numbers for the three loaded petals used in this thesis without the usual “20USEH” prefix. Hybrids with no communication during the data taking are highlighted in grey.

Module	Primary Side			Secondary Side		
	<i>TRIUMF1</i>	<i>IFIC1</i>	<i>DESY1</i>	<i>TRIUMF1</i>	<i>IFIC1</i>	<i>DESY1</i>
R0	00000245	00000262	00000252	00000250	00000268	00000251
	10000059	10000069	10000056	10000061	10000067	10000060
R1	20000037	20000033	20000027	20000041	20000026	20000046
	30000038	30000022	30000025	30000030	30000019	30000037
R2	40000057	40000059	40000082	40000048	40000073	40000072
R3	50000037	50000030	50000031	50000044	50000034	50000038
	60000036	60000030	60000029	60000040	60000031	60000037
	70000037	70000029	70000027	70000042	70000031	70000039
	60000036	80000032	80000030	80000041	80000034	80000039
R4	90000040	90000030	90000053	90000039	90000036	90000043
	A0000032	A0000033	A0000049	A0000044	A0000039	A0000050
R5	B0000026	B0000021	B0000037	B0000027	B0000018	B0000038
	C0000023	C0000017	C0000035	C0000025	C0000018	C0000036

6.2 ITk Strips End Cap System Test

The ATLAS ITk end cap System Test (from now on referred to as System Test) is intended to demonstrate the functionality of the detector’s components in an assembled system [132]. For this purpose, a one-eighth section of an end cap was constructed as a carbon fibre support structure in which up to 12 petals can be inserted. These are supplied by powering and cooling services closely resembling the systems of the final detector. In order to simulate the thermal and noise environment of the end cap, the structure is surrounded by a custom-built coldbox made of aluminium-polyurethane foam composite panels, which is constantly flooded with dry air. The DSS (Detector Safety System) of the ATLAS detector is simulated by a dedicated electrical system developed in the context of this thesis. A picture of the setup loaded with a single petal is shown in Figure 6.1.

6.2.1 LUCASZ Cooling Plant

The flow of liquid CO₂ for the System Test is provided by a LUCASZ (Light Use Cooling Appliance for Surface Zones) [133]. This integrated 2PACL (see Section 4.5) system has two cooling loops with a maximum total mass flow of 20 g s⁻¹. The flow in both cooling loops is controlled by the “local boxes”, which are to be set up separately from the main cooling plant within the DAF cleanroom to supply the end cap and the System Test with cooling. As both cooling loops are fed from the same



Figure 6.1: View of the open System Test setup loaded with the *TRIUMF1* petal.

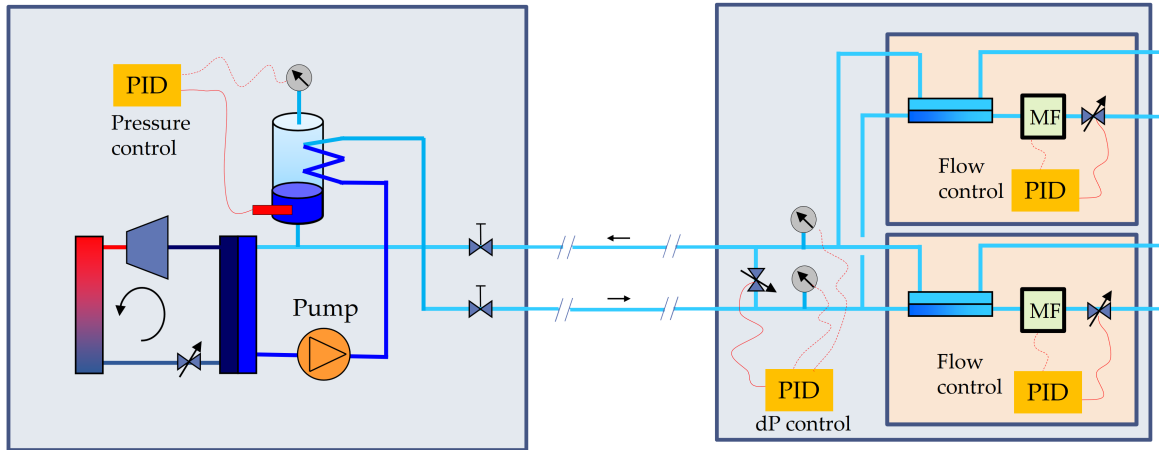


Figure 6.2: Schematic overview of the LUCASZ cooling plant (left) and its two local boxes (right) [133].

accumulator, the CO_2 setpoint of the two systems cannot be controlled independently. A schematic of the LUCASZ system is found in Figure 6.2. During the time of this thesis, both local boxes were still integrated into the LUCASZ main plant and were therefore located outside the cleanroom (see Figure 6.3). The System Test was connected to LUCASZ via flexible coolant hoses, routed through a feedthrough in the wall into the laboratory's interior. Due to DESY producing the LUCASZ units for multiple institutes involved in the ITk detector production, the unit used for the detector tests within this thesis is going to be replaced with the former being shipped to NIKHEF to be used in their end cap integration effort.

6.2.2 Coldbox

The coldbox serves as the outer enclosure of the System Test. It comprises a rear panel fixed to the carbon fibre support structure and the bulkhead, three removable side panels, and a lid, all joined with quick-release fasteners (see Figure 6.4). The outer and inner aluminium plates of all composite elements of the coldbox are electrically interconnected, and the assemblies are linked via metal contact spring strips, enclosing the System Test setup in a Faraday cage. Gaps between the assemblies are sealed with self-adhesive elastomer foam tape to increase gas tightness. Dry air is flushed into the setup via a diffuser hose mounted at the rear panel close to the lid, ensuring a dry atmosphere during cold testing to avoid issues with water condensation. The entire structure rests on a tilting table, allowing petals to be tested in horizontal and vertical orientation.

6.2.3 Interlock and Monitoring System

A crucial aspect of detector operation is personnel safety. Bias voltages of up to 550 V are applied to the silicon sensors, posing a considerable danger to personnel working on the experiment if touched. Furthermore, the detector must also be protected from environmental influences. For example, cooling the petals below the dew point would lead to the formation of condensation (or ice), which could destroy the sensitive (and very expensive) electronics of the petals. Therefore, the detector's operating status must be continuously monitored, and services such as cooling and power supplies may only be



Figure 6.3: The designated NIKHEF LUCASZ plant attached to the System Test located outside of the DAF cleanroom. Behind it, part of the DESY unit can be seen.

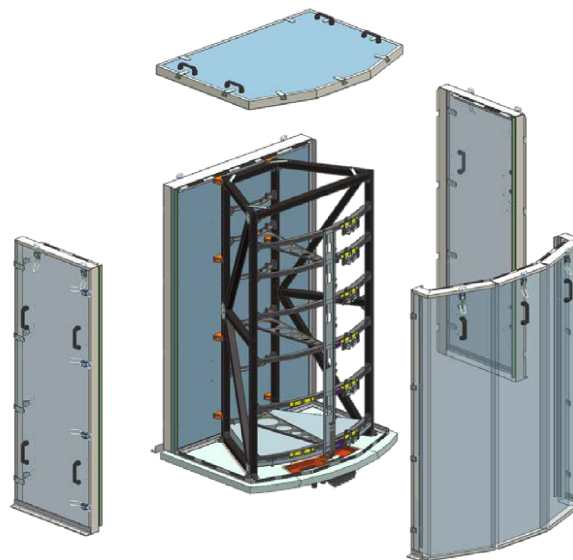


Figure 6.4: Exploded drawing of the System Test coldbox [132, Figure 12].

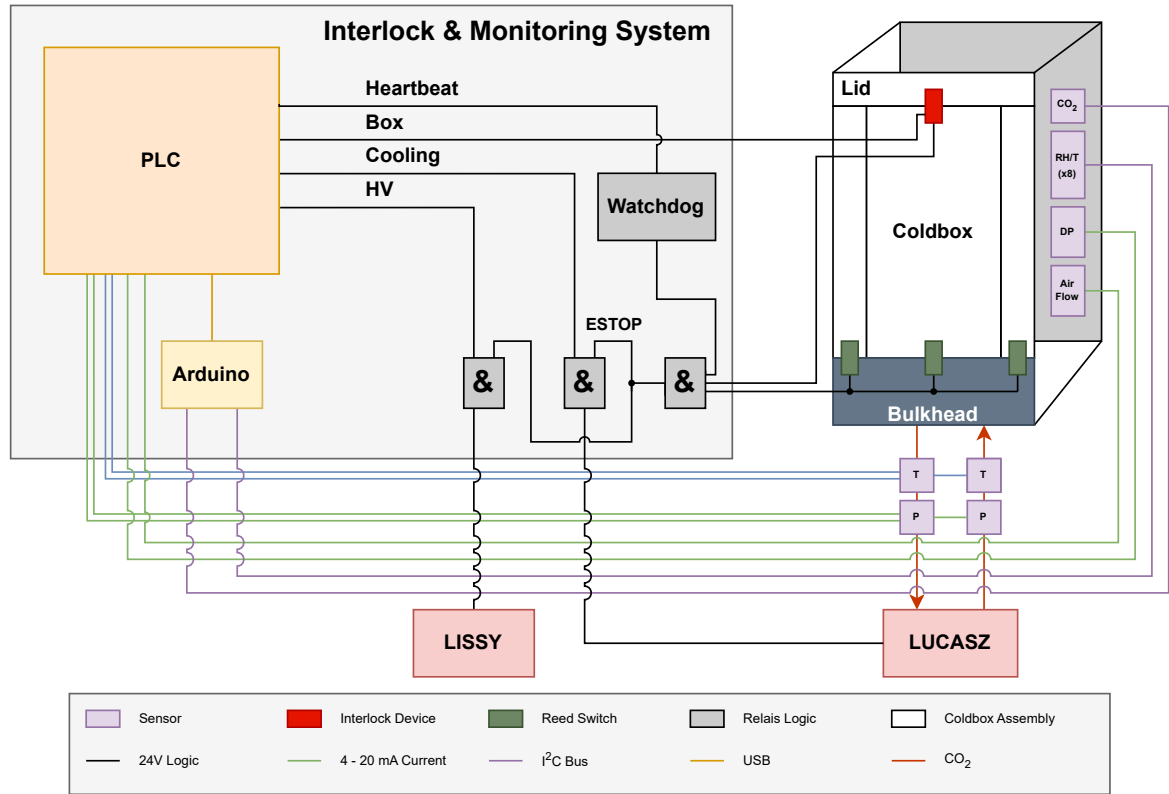


Figure 6.5: Simplified overview of the System Test IMS.

activated if the safety of people and material allows it.

As part of this thesis, an Interlock & Monitoring System (IMS) was developed to fulfil these tasks (see Figure 6.5 and Figure 6.6(a)). It is based on a RevPi (Revolution Pi) Core S PLC (Programmable Logic Controller) [134], which is an industry-standard version of the Raspberry Pi [135] with various analog and digital inputs and outputs. A Vaisala DMT143 sensor [136] is connected to monitor the dew point, producing a 4 to 20 mA current signal corresponding to the coldbox dew point with a value range of 20 to -80°C DP. In addition, eight Sensirion SHT85 [137] sensors are installed in the coldbox, which measure relative humidity and temperature. Furthermore, a Sensirion SCD30 [138] measures the current CO_2 content of the coldbox atmosphere and is intended to enable the detection of significant leaks in the cooling system. All Sensirion sensors feature an I^2C interface. Their measured values are forwarded to the PLC via USB from an Arduino microcontroller installed outside the coldbox. The IMS also features two PR3112 transducers [139], to which PT100 thermocouples can be connected with four wires, which are to be attached to the CO_2 inlet and outlet of the coldbox. The PLC digitizes the resulting 4 to 20 mA current signal. A pressure sensor is also foreseen at each of the two CO_2 connections, which will directly supply a 4 to 20 mA current signal. Furthermore, a FESTO SFAH flowmeter [140] measures the volume flow rate of dry air into the coldbox and supplies a 4 to 20 mA current signal to the PLC.

To ensure personnel safety, the coldbox was fitted with a mechanical interlock device. This device keeps the lid of the coldbox firmly closed as long as no control voltage is applied. A switch also reports

Table 6.2: Conditions for the three interlock permissions granted by the PLC.

Permission	Condition
COOLING	$\text{USER} \wedge \neg \text{ESTOP} \wedge \text{Dewpoint} \leq -45^\circ\text{C DP} \wedge \text{Dry air flow} \geq 1\,000\text{ L h}^{-1}$
HV	$\text{USER} \wedge \neg \text{ESTOP}$
BOX	$\text{USER} \wedge \text{CO}_2 \text{ Outlet Temperature} \geq 16^\circ\text{C}$

the locking mechanism’s current status to the IMS. The side panels of the coldbox are each equipped with a magnet and reed switch, reporting if the assembly is currently closed. A Relmatic WZR-1 [141] watchdog relay is installed to detect a possible failure of the PLC or the control program. It receives a pulsating “heartbeat” signal from the PLC every second. If the watchdog has not registered a pulse after 5 s, it switches its relay. The output of the watchdog relay, the reed switches, the interlock device of the coldbox, and an emergency stop switch are connected in series and form the **ESTOP** signal. If one of the switches involved opens, this means that the current operating status is not safe.

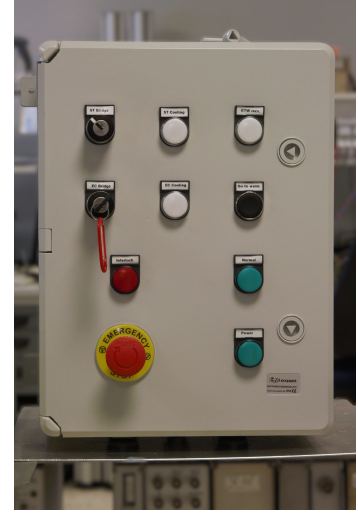
The PLC assigns three permissions based on the measurements of the connected sensors: **COOLING**, **HV** and **BOX**. The **COOLING** permission is forwarded to the DSS connection of the external cooling system via a relay logic, which allows the CO_2 setpoint to be lowered below 17°C . The **HV** permission triggers a signal to the GSS card of the LISSY-Crate (see Section 4.4.1) and allows the power supply to the detectors to be switched on. Opening the box, a PLC failure or pressing the emergency stop switch deactivates the power supply to the detector and forces the cooling system to a setpoint of 17°C . The **BOX** permission allows the interlock device of the coldbox to be opened. It is given if the temperature in the coldbox allows for opening without the risk of condensation and the HV is switched off. All three permissions can be forwarded or blocked via physical rotary switches. The interlock conditions for all three authorisations can be freely programmed; the values currently used are listed in Table 6.2. Before the PLC grants permissions based on its measured values, the user must set the **USER** permission in the OPC UA server hosted on the PLC. This server also provides all measured values from the sensors. These are also forwarded to an InfluxDB [142] instance, which saves the data as a time series and makes it available to a Grafana [143] instance, which displays monitoring data from a user-definable time period on a dashboard and makes the PLC’s interlock decisions visible.

As part of this thesis, two further copies of the system were built, which are used in the integration of the two ITk strip end caps, in which the inserted petals are tested as part of the “Segment Test” with activated CO_2 cooling. In the case of the DESY end cap, the end cap and the System Test share the same CO_2 flow and, thus, the temperature setpoint. The LIAR (LUCASZ Interlock ARbitrator) system was developed during this thesis (see Figure 6.6(b)) to take into account the interlocking decisions of both experiments. It receives the cooling interlock of the end cap and the System Test and combines them into a single interlock signal via a relay logic. In regular operating conditions, an interlock of one of the two experiments leads to a warming up of the entire cooling circuit to 17°C . Suppose one of the experiments is not to be operated. In that case, a key can be inserted into LIAR after closing the corresponding valve in the cooling circuit, which overrides the interlock decision of the experiment. Then, only interlocks of the currently active experiment are forwarded to the cooling system. In addition, a manual interlock switch and an emergency stop for the cooling system are integrated into LIAR so that it can be switched off from inside the cleanroom in the event of a malfunction.

The LISSY interlock FPGA was programmed with interlock strategy for the System Test. Both LV



(a) View of the front panel of the IMS electrical cabinet.



(b) Front panel of the LIAR electrical cabinet.

Figure 6.6: Front panels of LIAR and the IMS.

channels for a petal will be shut off if one of the two petal NTCs is registering a temperature higher than the threshold set in the T2I cards. All channels can also be interlocked by the emergency exit signal, which is received by LISSY's GSS card and acts on all channels, bypassing the interlock FPGA all together. This signal will be used to shut down the power to all modules in case of a cooling or dry air flushing failure and will be connected once LIAR is connected to the IMS boxes of both the System Test and the end cap.

6.2.4 Dry Air Flushing and Gas Tightness

As the coldbox consists of several assemblies connected via quick-release fasteners, there is a risk of air leaking into the volume of the System Test from outside. These leaks could prevent a stable atmosphere that fulfils the interlock conditions in Table 6.2 from being established at all. Secondly, if the supply of dry air fails, the moisture penetrating from outside could condense on the cooled components and cause damage to the petals.

A dry air flushing test was carried out to dispel these concerns. For this purpose, the closed coldbox was flooded with a constant volume flow of 3 m³/h dry air (dew point < -80 °C DP) in the cleanroom environment. As no dew point measuring device was installed in the coldbox at this time, the time profile of the dew point was calculated from the measured temperature and relative humidity values of the IMS SHT85 sensors.

The saturation vapour pressure of water is approximated by the Magnus formula

$$P_{\text{Saturation}}(T) = \kappa_1 \cdot e^{\kappa_2 \cdot T / (\kappa_3 + T)}, \quad (6.1)$$

where T is the ambient temperature in °C, and κ_1 , κ_2 and κ_3 are empirical parameters [144]. The measured relative humidity φ provides the partial pressure of the water at the ambient temperature T ;

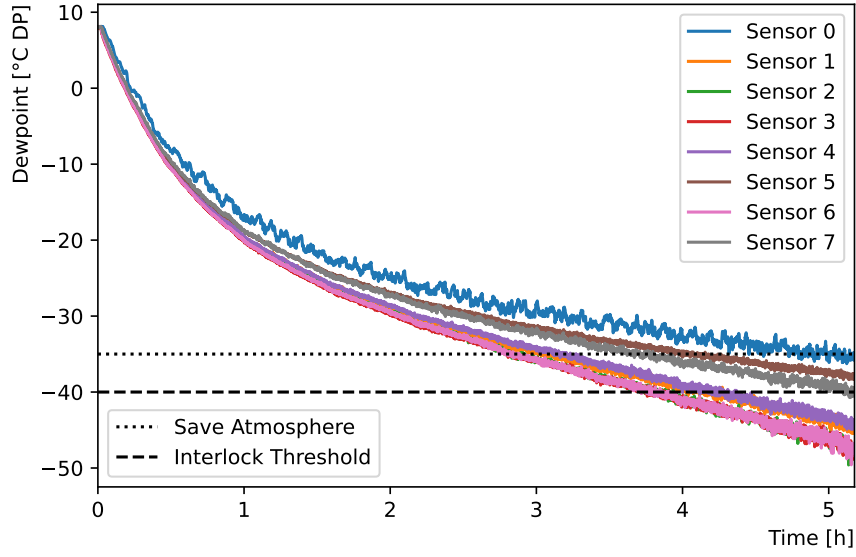


Figure 6.7: Dew point data during flushing of the System Test coldbox with 3 m³/h of dry air.

this corresponds to the saturation vapour pressure at the dew point T_{DP} via

$$P_{\text{Saturation}}(T_{DP}) = \varphi \cdot P_{\text{Saturation}}(T). \quad (6.2)$$

Together with Equation (6.1), this yields

$$\varphi \cdot e^{\kappa_2 \cdot T / (\kappa_3 + T)} = e^{\kappa_2 \cdot T_{DP} / (\kappa_3 + T_{DP})} \Leftrightarrow T_{DP} = \frac{\kappa_3 (M + \ln \varphi)}{\kappa_2 - M - \ln \varphi} \text{ with } M = \frac{\kappa_2 \cdot T}{\kappa_3 + T}. \quad (6.3)$$

The coefficients

$$\kappa_1 = 6.1037^\circ\text{C}, \kappa_2 = 17.641, \kappa_3 = 243.27^\circ\text{C} \quad (6.4)$$

from the AERG approximation given in [145, Equation (11)] were used, which is the set of parameters recommended by the authors for the temperature range 50 to -80°C .

The resulting dew point values from the flush test are shown in Figure 6.7. Within 5 hours, all sensors achieved readings below -35°C DP , which corresponds to the minimum CO₂ setpoint used in the System Test. Five of the eight sensors also fell below the interlock threshold of -40°C DP during that time, while three sensors showed a slower lowering of the moisture level. Based on these results, the strategy of flushing the coldbox with dry air overnight before switching on the cooling system was adopted to ensure no residual moisture in the entire box volume.

After the flush test, the dry airflow was interrupted, and the sealed coldbox was left in the cleanroom's stable atmosphere. The moisture from the (for practical purposes infinitely large) reservoir of the cleanroom now diffuses through the gaps in the coldbox into the volume with the lower concentration. Since the diffusion flux is proportional to the concentration gradient according to Fick's 1st law [146], the concentration of water in the atmosphere inside the coldbox approaches the value of the volume outside the coldbox exponentially.

The concentration of water vapour in the coldbox atmosphere (also referred to as the absolute

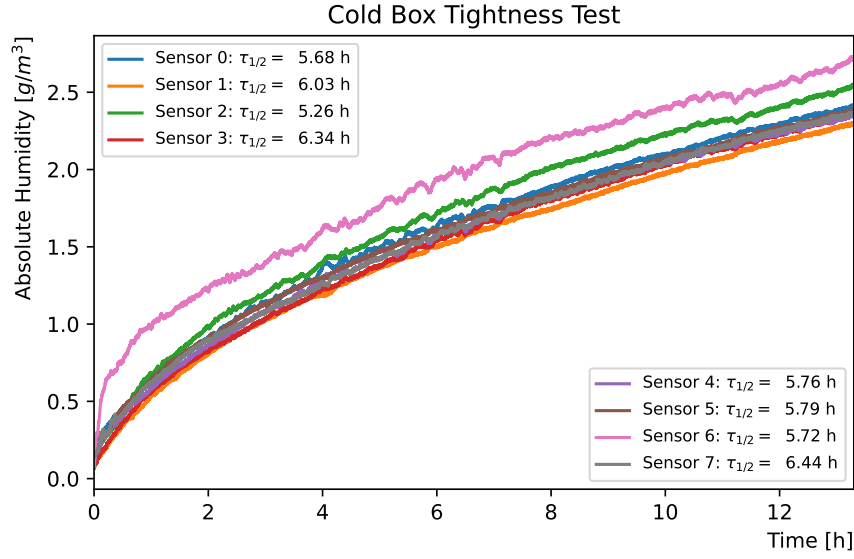


Figure 6.8: Evolution of absolute humidity after dry air flushing has stopped. The half-life $\tau_{1/2}$ was determined for every sensor using an exponential function fit and is given in the legend.

humidity AH) can be calculated from the measured values of the SHT85 sensors using the ideal gas law

$$P_{\text{Water}} \cdot V = m R_W (T + 273.15 \text{ } ^\circ\text{C}) \Leftrightarrow AH = \frac{m}{V} = \frac{\varphi \cdot P_{\text{Saturation}}(T)}{R_W \cdot (T + 273.15 \text{ } ^\circ\text{C})} \quad (6.5)$$

where $R_W = R/M_W = 461.53 \text{ J K}^{-1} \text{ kg}^{-1}$ is the specific gas constant for water vapour with the molar gas constant R [147, Table XXX] and the molar mass of water M_W [148], and the ambient temperature T in $^\circ\text{C}$. The absolute humidity values calculated from Equation (6.5) using Equation (6.1) for all sensors are shown in Figure 6.8. Their exponential approach to the outside atmosphere's value was modelled with a function of the form

$$AH(t) = p_{\text{Constant}} + p_{\text{Amplitude}} \cdot \left(1 - e^{-t/p_\tau}\right). \quad (6.6)$$

The fit parameters for all eight SHT85 sensors are listed in Table 6.3. The average half-time for all sensors is $(5.876 \pm 0.005) \text{ h}$. In case of a cut to the dry air supply, the CO_2 system would change its setpoint to $17 \text{ } ^\circ\text{C}$. Since the cooling changes setpoint at a rate of $1 \text{ } ^\circ\text{C min}^{-1}$, it would take a maximum of 43 min to reach a safe temperature above the dew point of the cleanroom air at $8 \text{ } ^\circ\text{C}$ from the coldest setpoint of $-35 \text{ } ^\circ\text{C}$. Therefore, monitoring the dry air flow rate via the IMS ensures that no condensation of cleanroom air on the petals can occur even in the worst case of an immediate cut of the dry air flushing.

6.2.5 Power Chain

The System Test uses a power scheme similar to the concept of the final detector described in Section 4.4. However, instead of a PP3, a PP3Star patch panel developed exclusively for the barrel and end cap System Tests is used (see Figure 6.9). It divides the lines of the type III cables coming

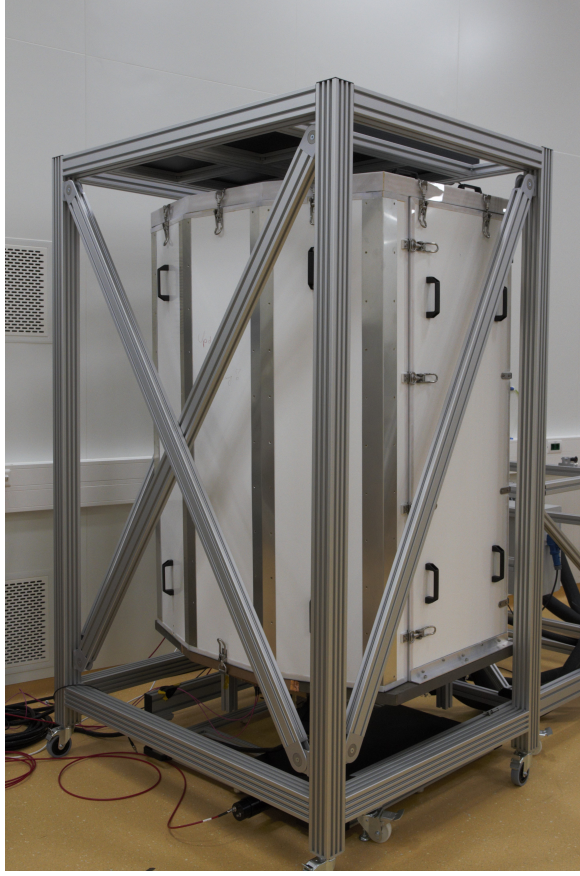


Figure 6.10: Scintillator setup for externally triggering the System Test in the event of a cosmic muon passing through the petals. In the picture, only one tile is installed at the bottom of the setup.

The scintillators above and below the petals cover an area of $l^2 = 1 \text{ m} \times 1 \text{ m}$ and are mounted at a distance of $h = 2.34 \text{ m}$. Thus

$$\Omega = 4 \arcsin \left(\frac{l^2}{h^2 + l^2} \right) = 0.62 \text{ sr} \quad (6.7)$$

is the solid angle from which cosmic muons can trigger the setup [149, Equation (3)].

6.3 Petal Coldbox

After the modules have been loaded onto a petal and wire bonding has been completed, the entire petal must be tested again before insertion into the end cap. The petal coldbox was developed to enable the testing of individual petals. It consists of a thermally insulating box made of aluminium composite panels, which is large enough to hold a single petal in its assembly frame. As with the System Test, this box forms a Faraday cage. Copper pipes feed the liquid CO_2 to the petal. They are terminated by ceramic electrical breaks to inhibit electromagnetic interference reaching the petal via the cooling

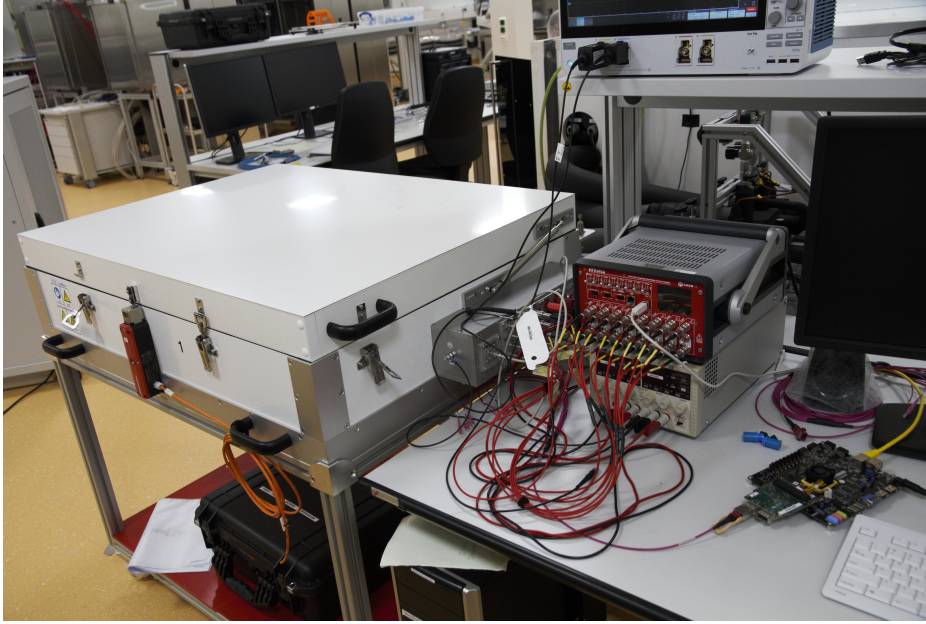


Figure 6.11: The DESY petal coldbox setup located in the DAF cleanroom.

manifold. The box is constantly flushed with dry air to prevent condensation on cooled components. A two-channel TTi CPX400DP PSU [150] supplies the petal's LV electronics, while the modules' HV is supplied by an eight-channel CAEN HiVolta DT1415ET PSU [151]. A picture of the DESY petal coldbox setup is shown in Figure 6.11.

6.3.1 MARTA Cooling Plant

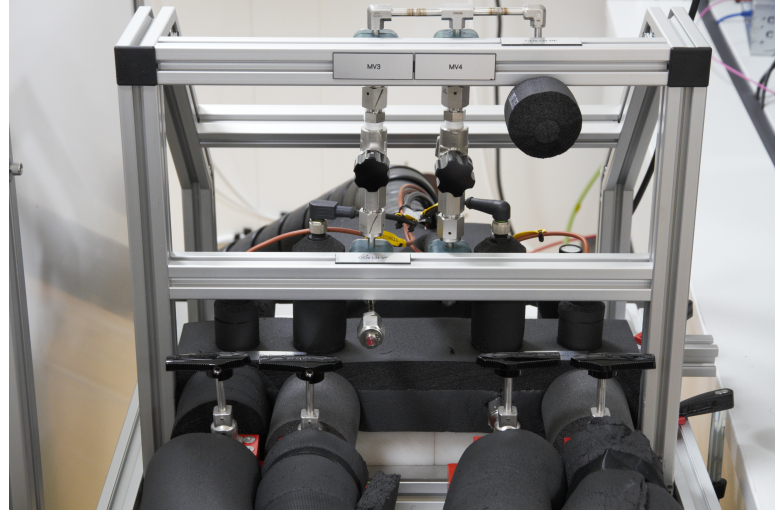
The petal coldbox features a MARTA (Monoblock Approach for a Refrigeration Technical Application) cooling system [152] (see Figure 6.12(a)), which provides a maximum cooling capacity of 200 W at a CO₂ setpoint of -30°C . MARTA is based on the 2PACL technology (see Section 4.5) and operates at a constant pump speed of 4 900 RPM during detector tests. The flow of liquid CO₂ through the petal is adjusted via a manual needle valve and reaches 4 g s^{-1} during regular operation. At DESY, MARTA also supplies a setup for the thermal investigation of the petal cores [153][154, Chapter 6]. A local box with manual valves connects both experiments to MARTA's CO₂ transfer line and allows the lines to be evacuated, for example when changing the petal in the coldbox (see Figure 6.12(b)).

6.3.2 On-Petal Cooling Performance

The temperature jump on the power boards and hybrids caused by switching on the front-end chips was investigated to study the thermal performance of CO₂-cooled petal loaded with modules. For this purpose, the *IFIC1* petal (see Section 6.1) was operated in the petal coldbox at CO₂ setpoints from 15°C to -35°C (in steps of 5°C). The temperatures on the hybrids and power boards were measured using the AMAC chip's ADCs on all modules and read out via the ITSDAQ system. After the temperatures stabilised for a CO₂ setpoint, all DC-DC converters were switched on, and all front-end chips were configured so that the petal reached its maximum power consumption. After

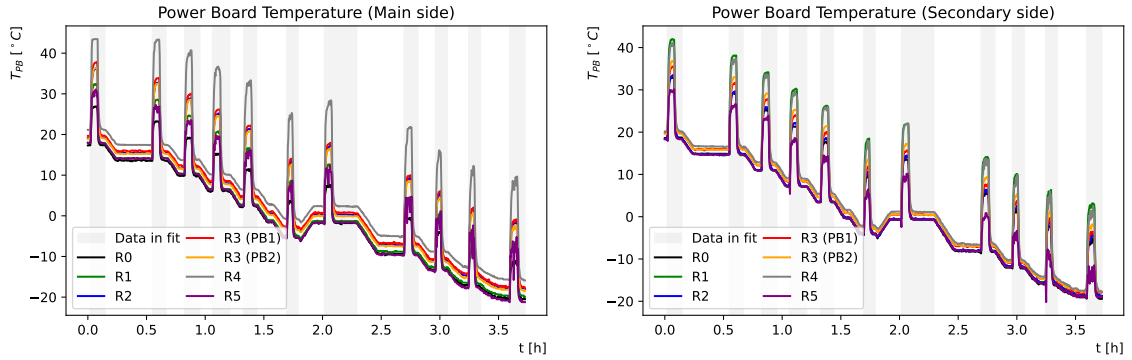


(a) MARTA plant at the DESY petal coldbox setup.



(b) MARTA local valve box connecting the coldbox and petal core thermal testing setup.

Figure 6.12: The petal coldbox MARTA system and its local valve box.



(a) Temperatures of the main side power boards.

(b) Temperatures of the secondary side power boards.

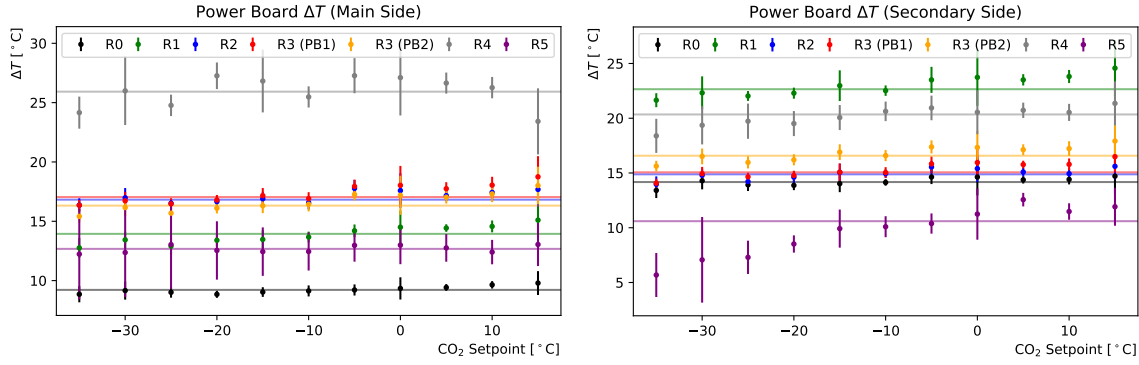
Figure 6.13: Unprocessed temperature data of the powerboard NTCs on both sides of the petal. Data included in the exponential fits are highlighted in gray.

the temperatures stabilised again, the DC-DC converters were switched off again, and the decreasing temperature curves were recorded. Finally, the CO_2 setpoint at MARTA was changed, and the measurement procedure was repeated. The resulting temperature data of the power boards are shown in Figure 6.13.

The exponential approach to the final temperature was modelled by fitting the corresponding function

$$T_{\uparrow}(t) = p_{\uparrow,1} + p_{\uparrow,2} \left(1 - e^{-t/p_{\uparrow,3}}\right) \quad (6.8)$$

to the measured data (where $p_{\uparrow,1}$, $p_{\uparrow,2}$, $p_{\uparrow,3}$ are fit parameters) in the case of warming up with DC-DC converters switched on, where $t = 0$ is the time at which the petal begins to be exposed to the increased



(a) Primary side temperature differences.

(b) Secondary side temperature differences.

Figure 6.14: Power board temperature differences due to DC-DC converters and their weighted averages for both sides of the petal for different CO₂ setpoints.

electrical power. The exponential drop in temperature was modelled analogously with the function

$$T_{\downarrow}(t) = p_{\downarrow,1} - p_{\downarrow,2}e^{-t/p_{\downarrow,3}}. \quad (6.9)$$

The total temperature difference was calculated from the fit parameters as

$$\Delta T = p_{\downarrow,1} - p_{\uparrow,1}, \quad (6.10)$$

with the uncertainty

$$\sigma_{\Delta T} = \sqrt{\sigma_{p_{\downarrow,1}}^2 + \sigma_{p_{\uparrow,1}}^2} \quad (6.11)$$

obtained via Gaussian error propagation from the fit parameter uncertainties.

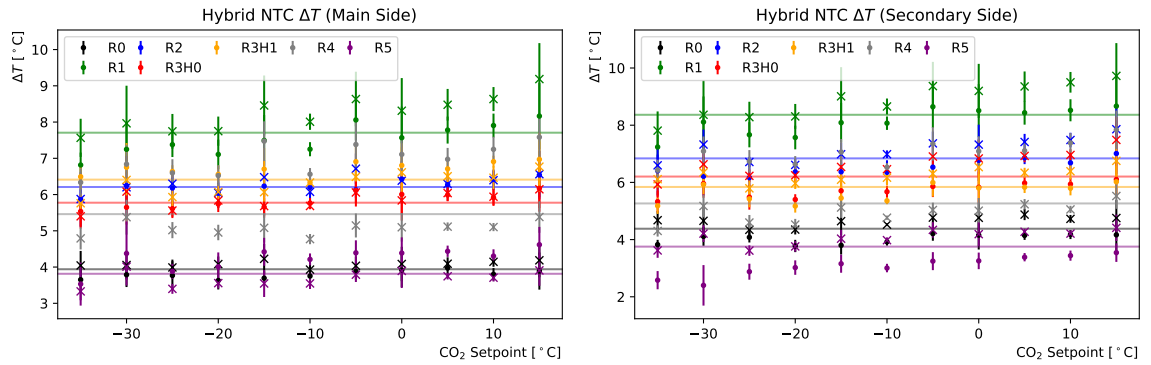
The relevant fit parameters for the power board NTCs are listed in Table A.4 and Table A.3. Together with their weighted averages, which are listed in Table 6.4, they are shown in Figure 6.14. The temperature differences on the hybrids are shown in Figure 6.15, and the weighted average values are listed in Table 6.4. As expected, the temperature jumps on the hybrids are significantly lower than on the power boards, as their electrical power density is smaller. Like in the power boards, the hybrid temperature changes also show no strong dependence on the CO₂ setpoint.

6.4 Conclusion

The System Test and petal coldbox setups located at DESY have been presented. In particular, a detector safety and interlock system was developed for the System Test. As the design has proved successful, it will now also be used for the integration of the two ITk strip detector end caps. It has been used to measure the atmosphere's behaviour within the System Test volume, proving that the current interlock strategy is safe even in the event of a sudden cut of the dry air supply to the setup. Finally, the temperature differences due to powering the modules loaded on a petal have shown to be more or less constant regardless of the CO₂ setpoint in the petal coldbox, hinting at good cooling performance with the MARTA setup over the entire temperature range.

Table 6.4: Average temperature differences of the power board and hybrid NTCs on both sides of the petal. Hybrid NTC measurements were combined per module, except for the R3, to allow comparison to the powerboard temperatures.

Module	Power Board NTCs		Hybrid NTCs	
	Main [°C]	Secondary [°C]	Main [°C]	Secondary [°C]
R0	9.22 ± 0.13	14.17 ± 0.15	3.94 ± 0.05	4.38 ± 0.03
R1	13.94 ± 0.17	22.65 ± 0.20	7.71 ± 0.09	8.36 ± 0.10
R2	16.82 ± 0.17	14.88 ± 0.17	6.21 ± 0.06	6.84 ± 0.06
R3 (PB 1)	17.04 ± 0.18	15.06 ± 0.15	5.78 ± 0.05	6.20 ± 0.05
R3 (PB 2)	16.32 ± 0.17	16.58 ± 0.19	6.41 ± 0.04	5.84 ± 0.05
R4	25.93 ± 0.37	20.35 ± 0.34	5.46 ± 0.05	5.26 ± 0.04
R5	12.68 ± 0.51	10.60 ± 0.32	3.81 ± 0.04	3.75 ± 0.04



(a) Primary side temperature differences.

(b) Secondary side temperature differences.

Figure 6.15: Hybrid temperature differences due to DC-DC converters and their weighted averages for both sides of the petal for different CO_2 setpoints. Data from the first NTC for each module is marked with a dot, for the second NTC, it is marked with a cross. The averages are combined for both NTCs for each module. The R3 hybrids are treated separately.

Petal Noise Studies

Determining a detector's noise is an essential step towards understanding its limitations in measuring physics data. Noise hits in a tracking detector can pollute the already dense collision environment, making it harder to identify real hits belonging to charged particle tracks.

During the ITk strip end cap production, modules are tested multiple times to ensure their noise levels are acceptable before they get loaded on a petal and inserted into the global support structure. These detector tests have been studied extensively on a module level. The arrival of fully loaded petals at DESY prompted further investigations into their performance, as well as the behaviour of the noise in different environments as part of this thesis. After describing the detector tests done with ITSDAQ during detector production, a study into their repeatability is presented in this chapter, and a comparison to the FELIX + YARR DAQ system is made. A treatment method for noise artefacts that can occur due to surface contamination is presented. The noise environments in both experimental setups described in Chapter 6 and the influence of loading modules onto the petal on their noise performance are studied. Finally, a measurement of noise crosstalk between both sides of the petal is presented.

7.1 Petal Tests in ITSDAQ

Tests are carried out at various points in the production process to ensure that the loaded modules on each petal meet the noise and gain requirements. In addition to a short communication test, a *full test* of the modules consists of individual test stages described below (see [10, Section 7.6.7] and [155, Section 3.2.6]).

Threshold Scan All measurements described below are based on the concept of the *threshold scan*. This can be carried out both with and without an injected charge. On the selected interval of a threshold scan, the ABCStars are read out several times for each setting of the threshold register BVT. The result is a s-curve of the form

$$O(\text{BVT}) = p_{\text{Offset}} + \frac{1}{2} \cdot \left(1 - \text{erf} \left(\frac{\text{BVT} - \text{VT}_{50}}{\sqrt{2} \cdot \sigma_o} \right) \right) \cdot p_{\text{Amplitude}}, \quad (7.1)$$

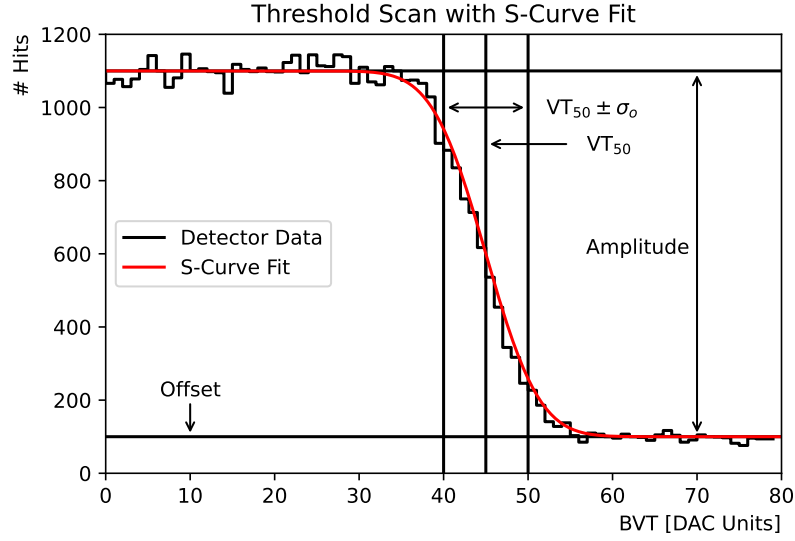


Figure 7.1: Illustration of a threshold scan result with mock hit data showing the S-curve properties $p_{\text{Amplitude}}$, p_{Offset} , VT_{50} and σ_o .

which results from the convolution of the step function of the discriminator and the Gaussian distribution of the detector noise [156, Equation (1)]. The threshold at which the measured occupancy is 50% is referred to as VT_{50} , the width σ_o of the step function is the output noise. An illustration of these relationships can be found in Figure 7.1.

7.1.1 Pedestal Trim

A TrimDAC register is assigned to each channel of the ABCStars. Its 5 bits generate a voltage via a DAC that regulates the offset of the discriminator [89]. During the pedestal trim, a scan over the available settings of the TrimDAC registers is performed without injected charge at a fixed threshold of $BVT = 15$. The TrimDAC registers of all channels are then set so that the VT_{50} response is as uniform as possible for the entire chip. The settings of the TrimDAC registers found in this way are used for subsequent scans and physics data acquisition.

7.1.2 Strobe Delay Scan

For some of the subsequent scans, a calibration pulse with a defined charge is injected into the individual channels of the ABCStars, which simulates corresponding charge signals in the strips (see Section 4.1.1). In order to determine the optimal time offset between the emission of the pulse and measurement of the signal, a charge of 4 fC is injected into the channels during the strobe delay scan at a threshold of approximately 2 fC [155, Section 3.2.6]. The number of hits measured from 32 triggers is plotted against the value of the strobe delay register for each readout channel, setting strobe delays between 0 and 80 ns with a precision of 6 bits [82, Section 11.2.5]. The location of the rising and falling edges of the resulting distribution is determined for each strip. The optimum strobe delay is defined as $SD = r + 0.57 \cdot (f - r)$, where r is the strobe delay at the rising edge of the hit occupancy

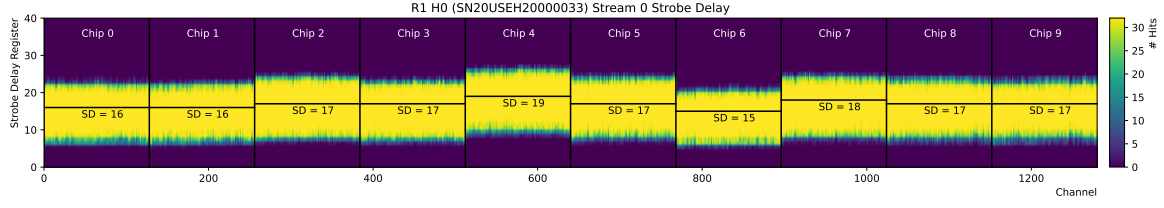


Figure 7.2: Example strobe delay scan result from a R1 hybrid. The plot shows the resulting per channel hit distribution vs the strobe delay setting and the resulting optimum strobe delay per chip.

distribution, and f is the strobe delay at the falling edge. The mean value is formed from the values calculated for all channels to find the setting of the strobe delay for each of the ABCStars, which is the setting used for all subsequent scans with charge injection. An example result of such a strobe delay scan is shown in Figure 7.2.

7.1.3 3-Point Gain and Response Curve

After TrimDAC values and strobe delay have been determined, the noise and response curves of the chips can now be measured. For this, threshold scans are performed. In the case of a 3-point gain scan, the charges 0.5, 1.0 and 1.5 fC are injected; for a response curve, the injected charges are 0.5, 0.75, 1.0, 1.25, 1.5, 2.0, 3.0, 4.0, 6.0 and 8.0 fC [10, Section 7.6.7]. The half-occupancy threshold VT_{50} and output noise σ_o are determined per channel by a fit of the S-curve; the resulting graph of VT_{50} vs injected charge is the response curve of the detector. This is fitted with an exponential function

$$VT_{50}(q) \approx \frac{p_0}{1 + \exp(-q/p_1)} + p_2, \quad (7.2)$$

where q is the injected charge, and p_0 , p_1 and p_2 are the fit parameters [156, Equation (2)]. The slope $G(q) = \frac{\partial VT_{50}(q)}{\partial q}$ is the detector gain for an injected charge q . The ENC (Equivalent Noise Charge) (see Section 3.4) is now calculated as

$$ENC(q) = \frac{\sigma_o(q)}{G(q)}. \quad (7.3)$$

Unless stated otherwise, all measurements of per-strip ENC's presented in this thesis were obtained using this method with $q = 1$ fC. An example response curve result is given in Figure 7.3.

7.1.4 Noise Occupancy

The last component of the full test is the measurement of the noise occupancy curve. For this purpose, a threshold scan is performed without injected charge with values up to $BVT = 40$ with 64 000 000 triggers in each step. If the S-curve of the noise occupancy obtained is plotted against the squared threshold charge, the ENC can be calculated from the slope of the curve via

$$\log P_n = \log \left(\frac{\Delta t}{4\sqrt{3}\tau} \right) - \frac{1}{2} \left(\frac{Q_T}{ENC} \right)^2, \quad (7.4)$$

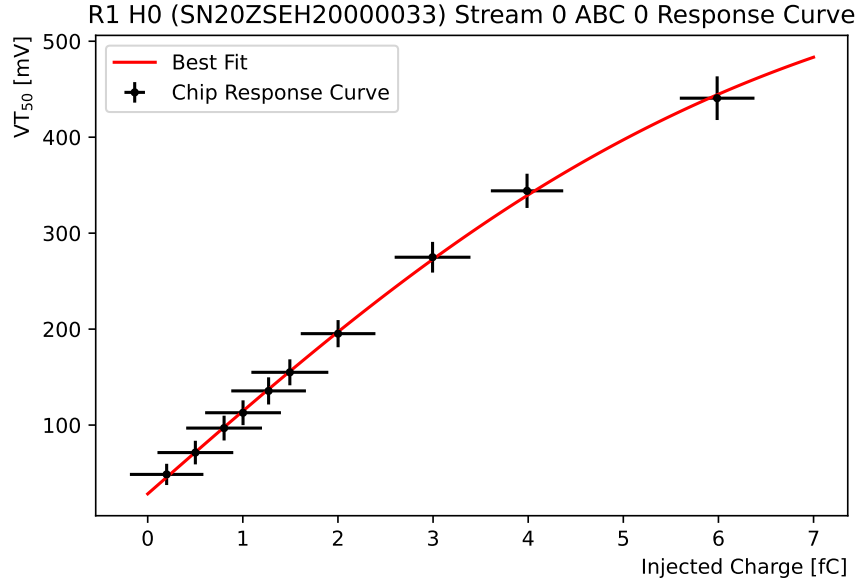


Figure 7.3: Example of a response curve result with a fit of Equation (7.2) with averaged data for a single ABCStar. The slope of the fit together with the output noise of the recorded s-curve give the ENC via Equation (7.3).

where P_n is the noise occupancy, Δt is the sampling interval, τ is the time constant of the shaper filter and Q_T is the threshold charge [157, Equation (4.68)].

7.1.5 Repeatability

Five consecutive full tests were carried out with the *IFIC1* petal (see Section 6.1) in the petal coldbox with -35°C CO_2 cooling and -350 V bias voltage, and their results were compared to verify that the ITSDAQ tests produce repeatable results.

Noise

The results of the ENC calculation from the response curve scan were compared strip by strip for all five runs. The defective R0 of the primary side was not taken into account. Likewise, two R3 hybrids (H1 and H3) on the front side were not included, as these had such a high noise level that it would have led to a rejection of the module in production (see Figure B.4). On the secondary side of the petal, the H2 hybrid of the same module did not provide any data (see Figure B.5).

The ENC at 1 fC injected charge was subtracted per strip for all non-repeating combinations of runs. The results were fitted with Gaussian distributions, the resulting fit parameters are given in Table 7.1, the distributions including the fits for all combinations are shown in Figure B.1. From these results, the mean absolute deviation between different runs can be calculated as

$$|\bar{\mu}_{\text{ITSDAQ}}| = \frac{1}{10} \sum_{i=0}^4 \sum_{j=i+1}^4 |\mu_{i,j}| = (0.711 \pm 0.023) \text{ e}^-, \quad (7.5)$$

Table 7.1: Fit parameters for the per strip noise comparison for five consecutive runs with ITSDAQ using the *IFIC1* petal.

Parameter	Run	0	1	2	3	4
Amplitude	0		1 624.1 ± 10.0	1 619.9 ± 10.1	1 538.7 ± 9.6	1 608.3 ± 9.9
$\mu_{0,j} [e^-]$			-0.93 ± 0.07	-0.88 ± 0.07	0.21 ± 0.08	-0.46 ± 0.07
$\sigma [e^-]$			15.00 ± 0.06	14.98 ± 0.06	15.59 ± 0.06	15.11 ± 0.06
$\chi^2 / \text{N.d.F.}$			552.6 / 97	672.5 / 96	601.0 / 97	508.6 / 97
Amplitude	1	1 624.1 ± 10.0		1 666.4 ± 10.2	1 550.6 ± 9.8	1 633.4 ± 10.0
$\mu_{1,j} [e^-]$		0.93 ± 0.07		0.18 ± 0.07	1.35 ± 0.08	0.62 ± 0.07
$\sigma [e^-]$		15.00 ± 0.06		14.61 ± 0.06	15.39 ± 0.06	14.92 ± 0.06
$\chi^2 / \text{N.d.F.}$		552.6 / 97		499.1 / 97	795.8 / 97	472.7 / 97
Amplitude	2	1 619.9 ± 10.1	1 666.4 ± 10.2		1 530.6 ± 9.8	1 699.0 ± 10.3
$\mu_{2,j} [e^-]$		0.88 ± 0.07	-0.18 ± 0.07		1.12 ± 0.08	0.46 ± 0.07
$\sigma [e^-]$		14.98 ± 0.06	14.61 ± 0.06		15.63 ± 0.07	14.32 ± 0.05
$\chi^2 / \text{N.d.F.}$		672.5 / 96	499.1 / 97		814.7 / 97	392.2 / 97
Amplitude	3	1 538.7 ± 9.6	1 550.6 ± 9.8	1 530.6 ± 9.8		1 553.0 ± 9.8
$\mu_{3,j} [e^-]$		-0.21 ± 0.08	-1.35 ± 0.08	-1.12 ± 0.08		-0.88 ± 0.07
$\sigma [e^-]$		15.59 ± 0.06	15.39 ± 0.06	15.63 ± 0.07		15.37 ± 0.06
$\chi^2 / \text{N.d.F.}$		601.0 / 97	795.8 / 97	814.7 / 97		639.3 / 97
Amplitude	4	1 608.3 ± 9.9	1 550.6 ± 9.8	1 699.0 ± 10.3	1 553.0 ± 9.8	
$\mu_{4,j} [e^-]$		0.46 ± 0.07	-1.35 ± 0.08	-0.46 ± 0.07	0.88 ± 0.07	
$\sigma [e^-]$		15.11 ± 0.06	15.39 ± 0.06	14.32 ± 0.05	15.37 ± 0.06	
$\chi^2 / \text{N.d.F.}$		508.6 / 97	472.7 / 97	392.2 / 97	639.3 / 97	

less than one ENC electron. For all practical purposes, this means the measurement of the ENC with the ITSDAQ full test is unbiased between runs. The average standard deviation between runs, and therefore the per-strip measurement uncertainty of the noise measurement with ITSDAQ, evaluates to

$$\bar{\sigma}_{\text{ITSDAQ}} = \frac{1}{10} \sum_{i=0}^4 \sum_{j=i+1}^4 \sigma_{i,j} = (15.092 \pm 0.019) e^-, \quad (7.6)$$

which is very small in comparison of the average ENC of the modules, and therefore of no practical importance.

Noise Occupancy

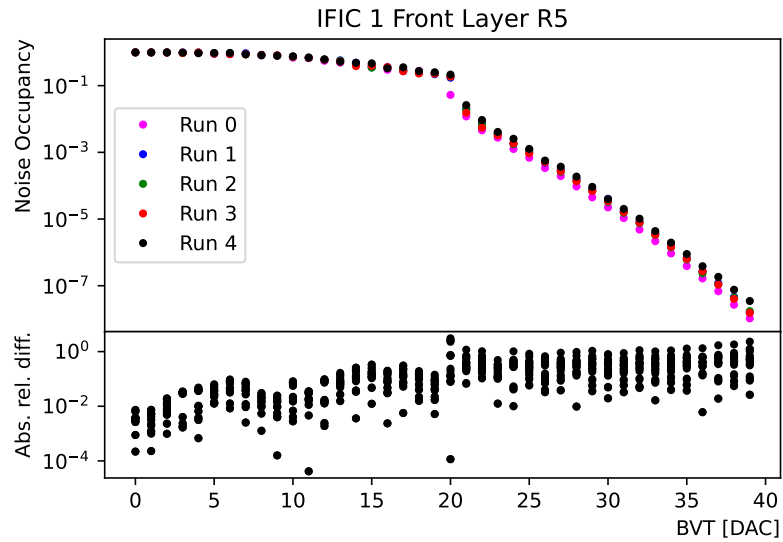
The purpose of the noise occupancy scan during detector operation is to determine the lower limit of the operating window of the modules, where $P_n \leq 1 \times 10^{-3}$ (refer to Section 4.1.2). The threshold limits reconstructed from the data were calculated for all runs and are shown in Table 7.2. A maximum deviation of 1 DAC LSB (Least Significant Bit) was found for all modules. The S-curves of the modules match very well between the runs. The primary side R5 module results are shown in Figure 7.4 as an example.

7.1.6 Comparison with the FELIX + YARR Readout System

Over the course of this thesis, the ITSDAQ software with a Genesys 2 FPGA board (see Section 4.6.1) was predominantly used for data acquisition. In order to ensure the comparability of the results with

Table 7.2: Lower bounds for the operating threshold window found with five consecutive ITSDAQ tests.

		Hybrid	Run 0	Run 1	Run 2	Run 3	Run 4
Primary	R0	0					
		1					
	R1	0	23	23	23	24	23
		1	25	26	26	26	26
	R2	0	23	23	23	23	23
		1	24	24	24	24	24
	R3	0	23	23	23	24	23
		1	27	28	27	28	28
		2	25	24	25	24	24
	R4	3	30	30	30	31	30
		0	26	26	26	27	26
	R5	1	24	25	25	25	25
		0	26	26	27	26	27
		1	25	25	25	25	25
Secondary	R0	0	22	23	23	22	23
		1	25	25	26	25	25
	R1	0	23	23	23	23	23
		1	26	25	24	25	26
	R2	0	24	23	24	24	23
		1	24	23	24	24	23
	R3	0	24	24	23	23	24
		1	24	24	24	24	24
		2					
	R4	3	26	25	25	25	26
		0	25	26	25	26	25
	R5	1	31	31	31	32	31
		0	27	25	26	26	25
		1	31	31	31	32	31

Figure 7.4: Noise occupancy S-curves of the *IFIC1* primary side R5 module for five consecutive runs in ITSDAQ.

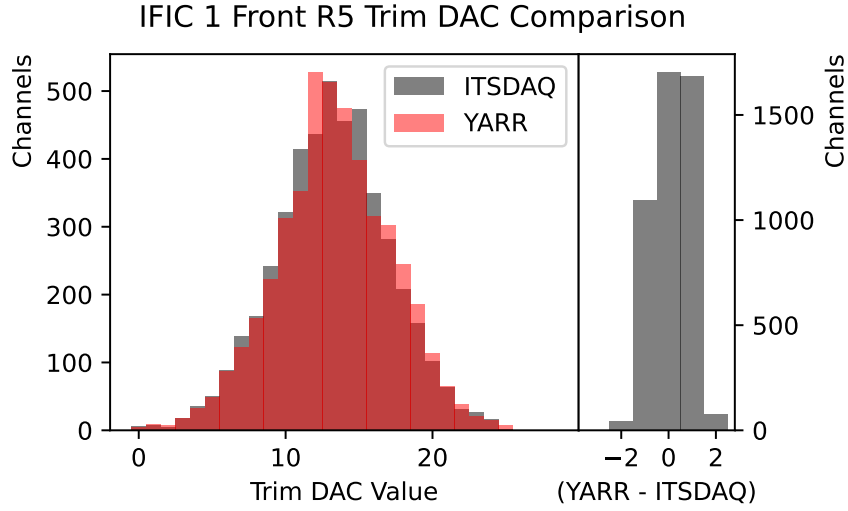


Figure 7.5: Distributions of optimal TrimDAC values obtained with the ITSDAQ and FELIX + YARR readout systems for the *IFIC1* front side R5 module as well as distribution of per-channel differences.

the FELIX data acquisition system used in the finalised detector (see Section 4.6.2), the authors of [156] carried out measurements on a stave equipped with LS (Long Strip) modules as part of the ITk strip barrel System Test. These revealed no significant deviations in the results of the pedestal trim and strobe delay scans. The noise distributions recorded using 3-point gain scans at a charge injection of 1 fC also showed no differences of any relevance to the classification of loaded modules. In order to ensure that these results can also be transferred to the end cap project, similar investigations were carried out as part of this thesis. The data presented below was obtained from the front side R5 module on the *IFIC1* petal (see Section 6.1) and was recorded at -350 V bias voltage and 0°C CO_2 cooling in the petal coldbox using both the ITSDAQ and the FELIX + YARR setup consecutively.

TrimDAC Values

In ITSDAQ, the pedestal trim scan described in Section 7.1.1 was performed. In the YARR implementation, a full trim scan is used instead, where threshold scans are performed for various TrimDAC settings. The target threshold of the scan then gets chosen as the value of VT_{50} for which the maximum number of channels can be trimmed to, given the scanned TrimDAC settings [156, Section 2.2]. Significant differences between readout systems were found in the TrimDAC values achieved in the barrel System Test, which could only be improved by implementing the ITSDAQ-style pedestal trim scan in YARR [156, Section 6.1]. In contrast, the results for the end cap module are in reasonable agreement using the full trim scan implementation in YARR. Figure 7.5 shows the distributions of the optimum TrimDAC values for both readout systems. 36.98 % of 4 608 readout channels show no deviation between readout systems at all. The value determined by YARR deviated by 1 LSB for 60.24 % of the channels. These values are compatible with the deviations determined by the ITSDAQ-adapted YARR implementation described in [156, Section 6.1]. The per-channel TrimDAC values obtained via both DAQ systems are shown in Figure B.2.

Strobe Delay

The strobe delay scan carried out with both DAQ systems showed only a minor difference of 1 LSB for four out of eighteen ABCStars; all other chips yielded no differences (see Table 7.3). This level of agreement is consistent with the results of the barrel System Test [156, Section 6.2]. The respective occupancy curves are shown in Figure B.3.

Table 7.3: Optimal strobe delay values obtained with ITSDAQ and FELIX + YARR.

	ABCStar Number									
	0	1	2	3	4	5	6	7	8	
Hybrid 0	19	17	17	18	19	19	17	21	22	YARR
	19	17	17	19	19	20	17	21	22	ITSDAQ
Hybrid 1	18	19	20	19	19	16	21	19	20	YARR
	19	19	20	20	19	16	21	19	20	ITSDAQ

Three-Point Gain

A three-point gain scan was performed using the TrimDAC and Strobe Delay values determined in the previous steps. The results obtained with both DAQ systems are shown in Figure 7.6. It is noticeable that the distribution of the VT_{50} in YARR is significantly wider than in ITSDAQ. This points to the TrimDAC values determined in the previous step not being written correctly to the registers of the ABCStars, even though the software was configured to do so. Unlike in [156, Section 6.3], no significant deviation in the mean value of the distribution was found for the tested module using the full trim scan in YARR. The distribution of the input noise, which is most relevant for evaluating the quality of the modules, is systematically about $10 e^-$ higher in YARR, which has no practical implications for any module test results. It is noteworthy that the standard deviation of the differences of noise measurements between both systems is significantly higher than what is observed when comparing multiple ITSDAQ runs. This might be due to additional uncertainty being introduced to the noise measurement with FELIX + YARR due to the TrimDAC problem.

Noise Occupancy

The results of the noise occupancy scans with both DAQ systems are shown in Figure 7.7. The noise occupancy curves agree well up to a threshold of $BVT = 19$ ($= 52.8$ mV). Above this setting, there is a significant difference between the two readout systems, leading to a drastically reduced operating window when the measurement is performed with the FELIX + YARR system ($BVT \geq 26 = 72.1$ mV for hybrid 0 and $BVT \geq 22 = 61.1$ mV for hybrid 1 with ITSDAQ, $BVT \geq 35 = 96.9$ mV for both hybrids with FELIX + YARR, see Section 4.1.2). The faster drop of the noise occupancy curve in the ITSDAQ system is consistent with the significantly narrower distribution of the strips' VT_{50} values (see above), providing further evidence for a problem with the way the TrimDAC registers are written with the FELIX + YARR setup. Further investigations into this behaviour are required before FELIX + YARR can be used to determine the modules' operating window during detector production or operations.

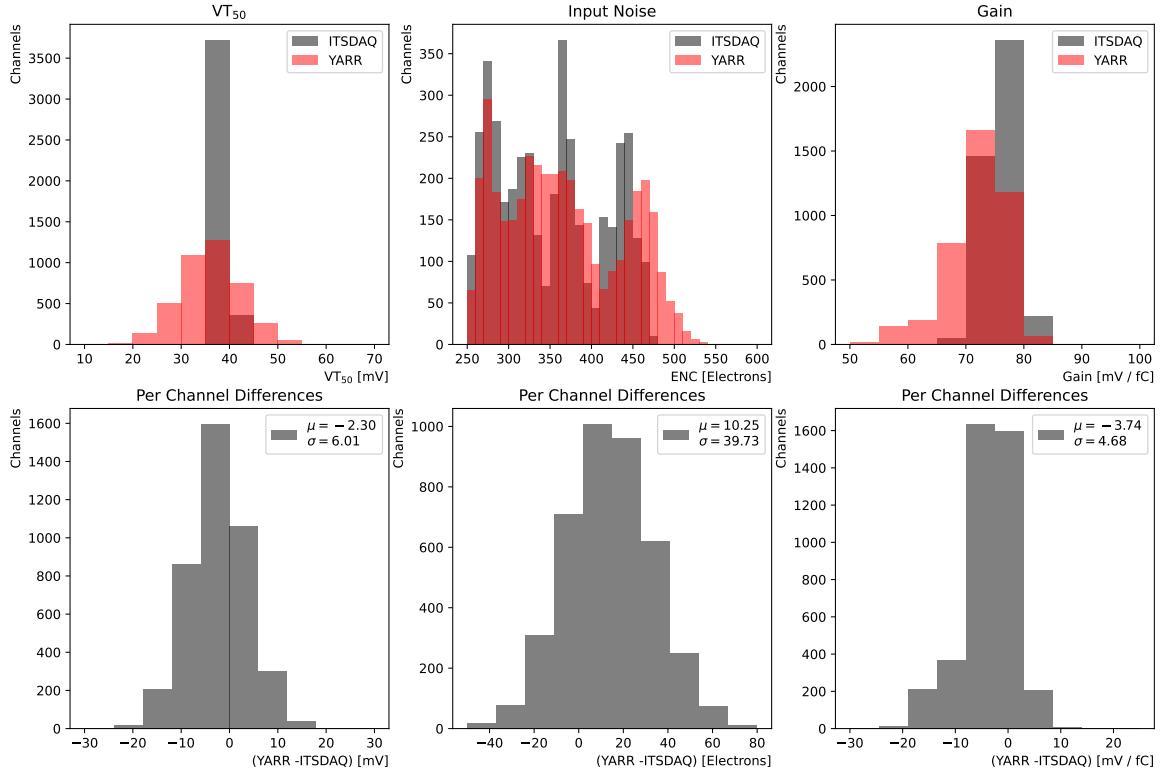


Figure 7.6: Comparison of VT_{50} , input noise and gain between the ITSDAQ and FELIX + YARR DAQ setups for the *IFIC1* front side R5 module with an injected charge of 1 fC.

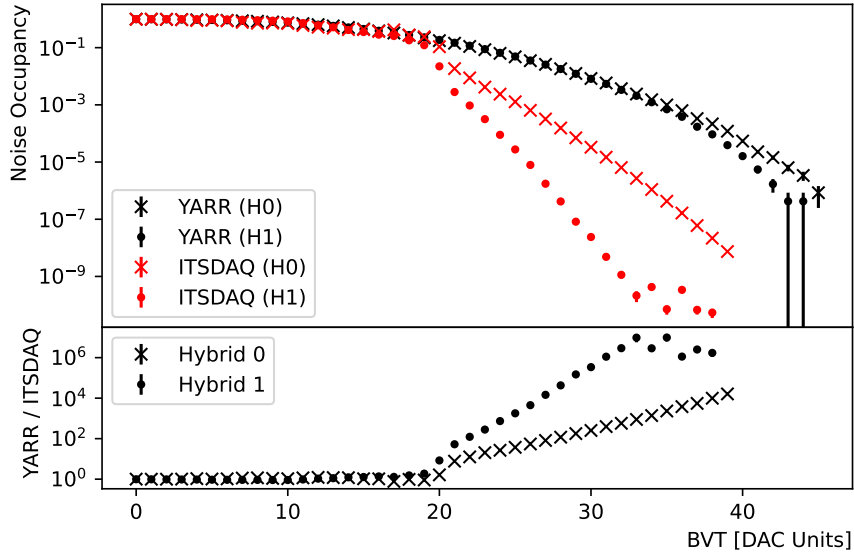


Figure 7.7: Comparison of relative noise occupancy between the ITSDAQ and FELIX + YARR DAQ setups for the *IFIC1* front side R5 module with no injected charge.

7.2 Surface Charges

The *TRIUMF* petal (see Section 6.1) exhibited high noise in several modules after delivery to DESY, which was not detected in the prior measurements at TRIUMF. It quickly became apparent that the effect was limited to the primary side of the petal, which points upwards both when the petal is transferred from the transport to the loading frame and during testing in the petal coldbox. A possible static charge from the temporary plexiglass cover could be ruled out as the noise source by conducting comparative measurements. After consultation with the experts in Vancouver, a SCS 980E [158] ionised air gun was used to clean the surface of the silicon sensors of dust and accumulated static charges (see Figure 7.8(a)). This process indeed removed the areas of increased noise on the petal (see Figure 7.9). These results have already been presented in [159].

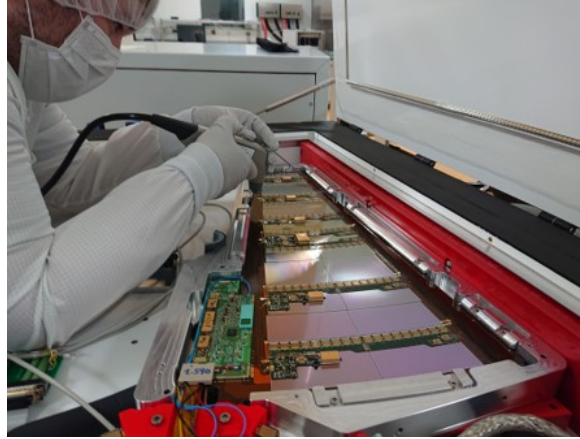
The petal grabber, which was used to transfer the petals between the frames, was identified as a possible source for these charges. The grabber must be placed over the petal and is then closed. The petal is carefully lifted by the grabber's handle and placed in the new frame. The grabber is then released and removed from the petal. So far, the grabber used consisted of aluminium plates, to which a 3D-printed mechanism is attached, which engages the grabber locations in the closeouts of the petal cores (see Figure 7.8(b)). The aluminium plates feature cutouts to reduce weight. These allow dust particles from the operator's sleeve and gloves, as well as dust and material abrasion from the grabber mechanism itself, to get directly onto the sensors' surface. Due to the petal's sensitive (and prohibitively expensive) nature, no further attempt was made to prove this hypothesis by re-using the petal grabber. Instead, a modified version of the insertion hand (see Section 4.3.1) is foreseen as a replacement (see Figure 7.8(c)). It has a mechanism made of low-abrasion plastic and completely covers the silicon surface so that no external material can fall onto the silicon sensor surfaces during the transfer procedures.

7.3 Noise Environment Comparisons

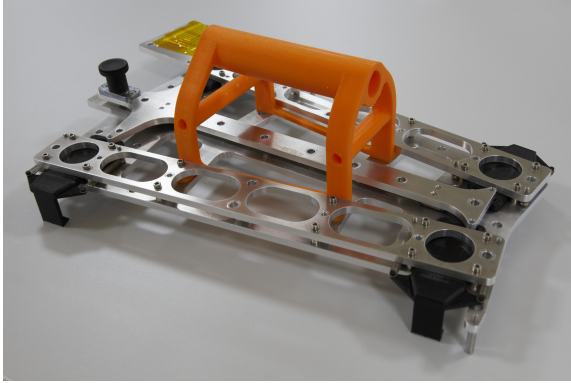
The ITSDAQ noise tests allow for a comparison of the noise level exhibited by the modules in different environments. For this thesis, measurements of the noise level of modules before and after they have been loaded onto a petal have been performed. Also, comparative measurements of the noise inside of both the petal and the System Test coldbox have been carried out.

7.3.1 Module Loading

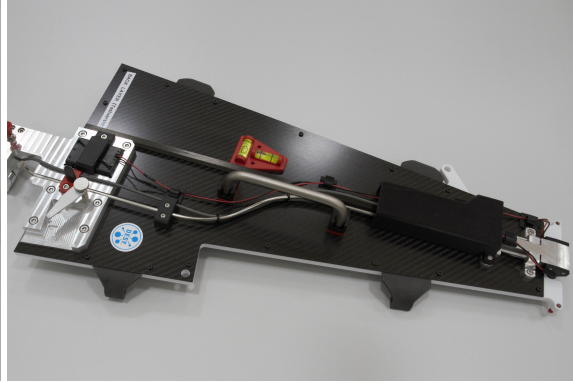
The modules for the *DESY* petal (see Section 6.1) have been subjected to a reception test at DESY without activated cooling before they have been loaded onto the petal. In order to emulate these conditions, a test has been repeated with 17 °C CO₂ cooling and a HV bias of −350 V, the resulting noise for both sides of the petal is shown in Figure B.6 and Figure B.7. The resulting distributions of per-strip differences are shown in Figure 7.10. Their mean and standard deviation per module are listed in Table 7.4. Combined for all modules, the modules average noise appears to lessen by 85.2 e[−] during the loading process. A closer look at the data reveals that this is not uniform for all modules; the mean values per module vary over 200 e[−], which is an effect far exceeding the results of any other noise comparison studies that were conducted during this thesis. It is, therefore, likely that instead of the loading procedure, the significant noise reduction between the measurements stems from the fact that during the reception tests, the noise was artificially increased due to the lack of



(a) The author of this thesis during the removal of surface charges with an ionised air gun.



(b) The old petal grabber tool.



(c) Petal insertion hand, which serves as a template for the design of the new tool.

Figure 7.8: Use of the ionised air gun as well as the petal grabber tool and the petal insertion hand.

cooling. Because the power density varies from module to module, some modules should be more susceptible to this effect than others. Before drawing conclusions on the effect of the petal loading procedure on electrical noise, more data for petals before/after loading should therefore be gathered, with the explicit requirement to use proper cooling during reception testing to avoid introducing a large systematic uncertainty to the noise measurement.

7.3.2 System Test and Petal Coldbox

For the measurements with the loaded petals, both the petal coldbox and the System Test were used throughout this thesis (see Chapter 6). Full tests were carried out with the *TRIUMF1* petal (see Section 6.1) at a CO_2 setpoint of -35°C , first in the petal coldbox and again after insertion in the System Test, to assess whether the results measured in the two setups are comparable. The acquired noise data is shown in Figure B.9 and Figure B.10.

Due to the limitations of the *TRIUMF1* petal, it was impossible to compare the measurement data of the R0 and R3 modules on the primary side and the R3 and R5 modules on the secondary side

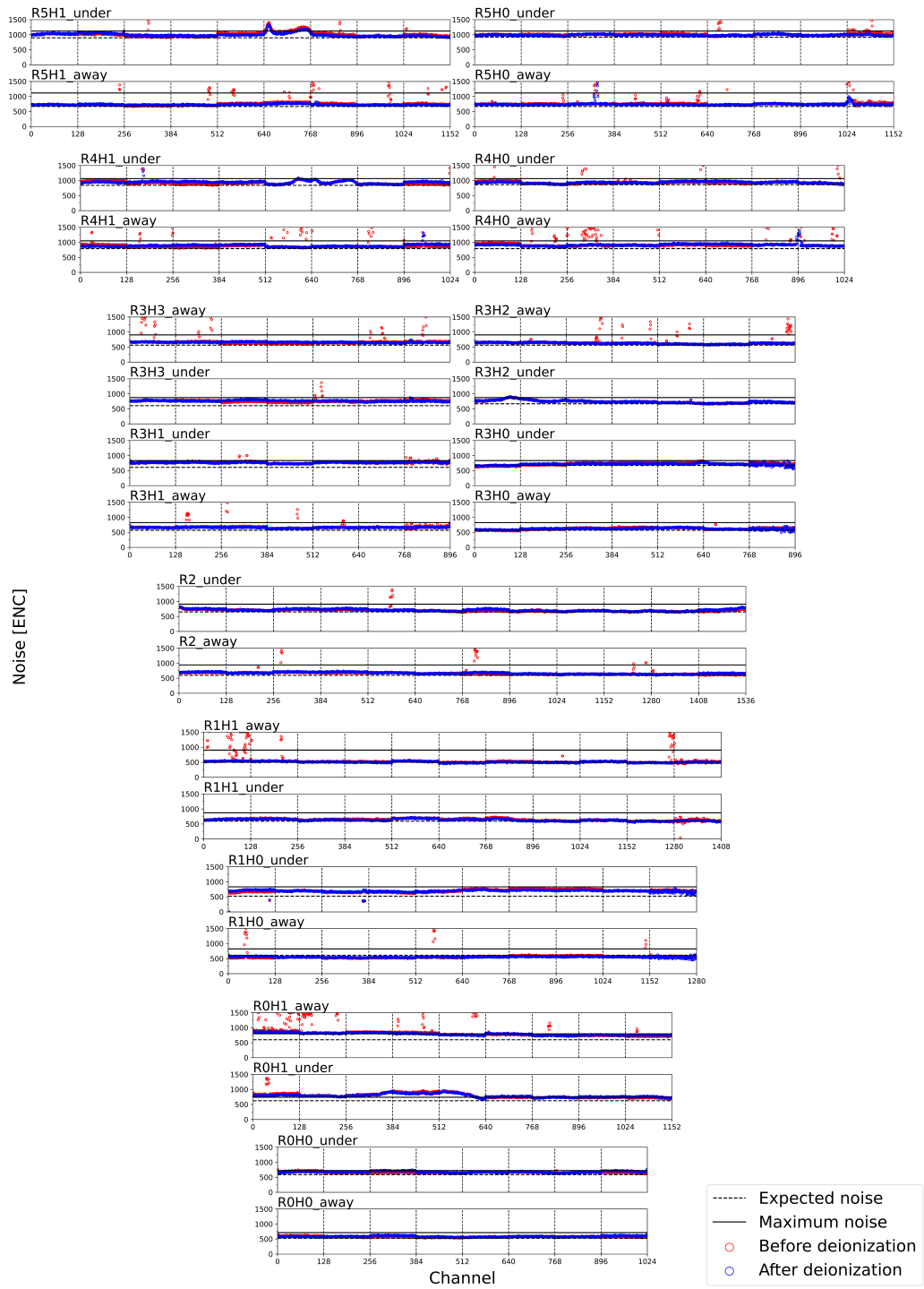


Figure 7.9: Equivalent noise charge at 1 fC injected charge at -35°C CO_2 setpoint before and after deionisation of the *TRIUMF1* petal's primary side.

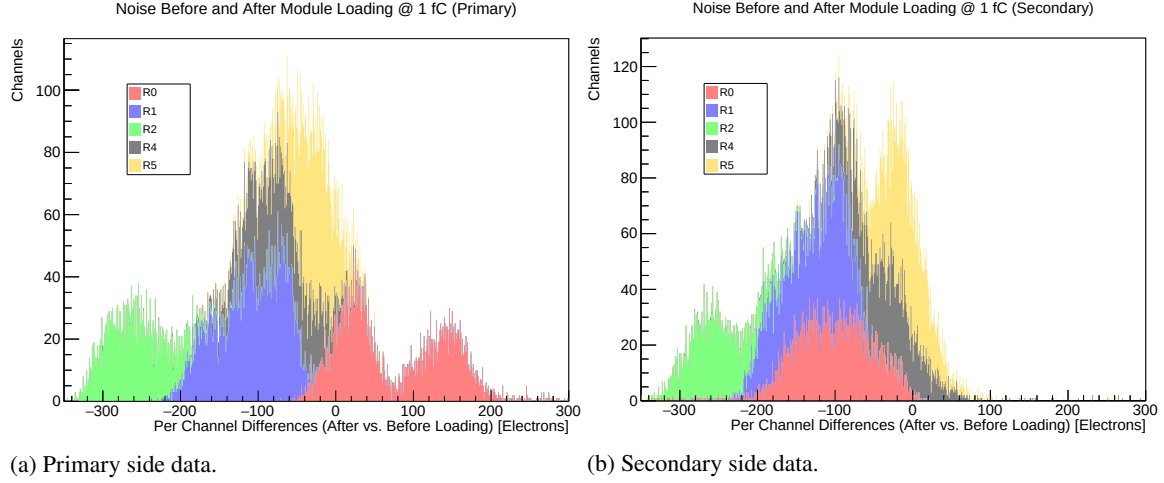


Figure 7.10: Comparison of noise with an injected charge of 1 fC at room temperature before and after loading the modules onto the *DESYI* petal.

Table 7.4: Mean and standard deviation of module noise before and after module loading.

	Primary Side		Secondary Side	
	μ [e^-]	σ [e^-]	μ [e^-]	σ [e^-]
R0	74.7	67.2	-102.1	50.6
R1	-110.0	42.1	-131.1	39.8
R2	-255.5	37.6	-247.0	39.3
R3	-	-	-	-
R4	-71.4	51.4	-40.7	46.4
R5	-31.4	32.9	-16.5	39.1
Combined (Side)	-69.9	110.9	-100.2	85.9
Combined (Petal)	$\mu = -85.2 e^-$		$\sigma = 100.3 e^-$	

Table 7.5: List of individual ABCStars not used in the noise environment comparison with the *TRIUMF1* petal due to data acquisition issues.

Petal Side	Module	Hybrid	ABCStar ID [0..11]
Primary	R1	0	9
	R5	1	9
Secondary	R1	0	9
	R2	0	3
	R2	0	9
	R4	0	5

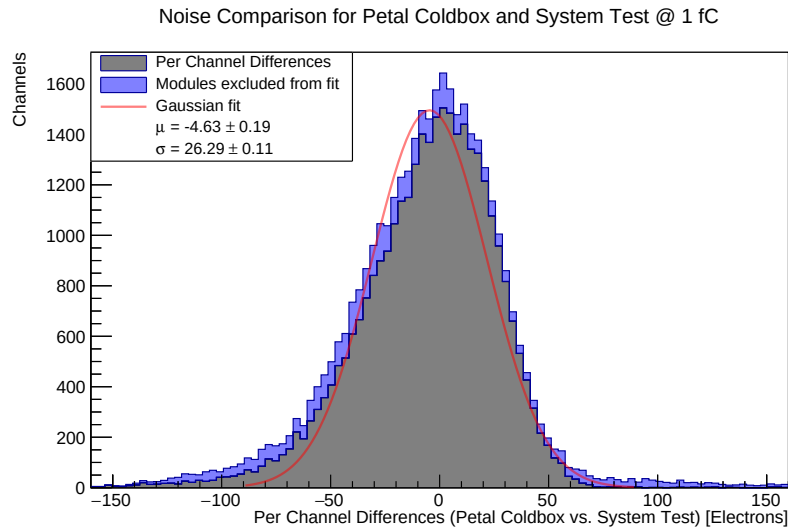


Figure 7.11: Histogram of the per-channel noise differences between the petal coldbox and the System Test as measured with the *TRIUMF1* petal with -35°C CO_2 cooling at 1 fC injected charge together with a Gaussian fit. Data from modules not included in the fit is marked blue.

of the petal. In addition, the data of the ABCStars of some modules listed in Table 7.5 were not used. These chips were not configured correctly due to an error in the data acquisition software and exhibited increased or irregular noise. Although the error was fixed with a later commit in the ITSDAQ repository [160], it was not feasible to retake the data in the petal coldbox because the petal had been inserted into the System Test in the meantime.

The strip-wise differences between both measurements are shown in Figure 7.11. They were fitted with a Gaussian distribution, whose resulting fit parameters are given in Table 7.6. The petal coldbox turned out to yield $\mu = (4.63 \pm 0.19) e^-$ less ENC than the System Test coldbox, which is not relevant for real-life detector performance. Notably, the standard deviation of this distribution is higher than what was determined for the ITSDAQ measurement itself in Section 7.1.5. This suggests either a non-uniform response of the modules to the different noise environments, or is a remaining artifact of the DAQ problems discussed above. It is therefore advisable to repeat this measurement with the fixed ITSDAQ version once a new petal becomes available for insertion into the System Test.

Table 7.6: Parameters of the Gaussian fit to the petal coldbox / System Test noise environment comparison data with the *TRIUMFI* petal.

Parameter	μ [e^-]	σ [e^-]	Amplitude	$\chi^2/\text{N.d.F.}$
Value	-4.63 ± 0.19	26.29 ± 0.11	$1\,496 \pm 10$	$1\,937 / 90$

Table 7.7: Parameters of the Gaussian fit to the primary/secondary side noise crosstalk data of the *IFIC1* petal.

Parameter	μ [e^-]	σ [e^-]	Amplitude	$\chi^2/\text{N.d.F.}$
Value	11.25 ± 0.12	17.05 ± 0.09	675 ± 6	$130.8 / 90$

7.4 Noise Crosstalk between Petal Sides

A potential concern in constructing a detector is the increase in the noise of the modules due to the coupling of electromagnetic interference from neighbouring detector components. The System Test will, therefore, test for precisely this type of noise crosstalk. For this purpose, comparative tests are carried out in which one group of modules acts as an aggressor and the other as an observer. A noise crosstalk from aggressor to observer can be detected if the observer systematically measures more noise with the aggressor switched on than in comparative measurements without the aggressor.

In the context of this dissertation, the potential for noise crosstalk between the primary and secondary sides was investigated. At -35°C CO_2 cooling, a full test of the *IFIC1* petal was first performed with the secondary side unpowered. The test was then repeated, and the secondary side of the petal was operated as an aggressor while powered and read out. No data was taken for the R0 module of the primary side since it was broken in a over-voltage incident; the data of the R3 hybrids 2 and 3 was not read out during this run due to communication issues with their respective HCCStars (see Figure B.8). A strip-by-strip comparison of the primary side's detector noise at 1 fC injected charge resulted in the histogram shown in Figure 7.12. This data were fitted with a Gaussian distribution, which yielded the parameters listed in Table 7.7. On average, turning on the aggressor increased the equivalent noise charge in the observer strips by (11.3 ± 0.1) electrons. This lies well outside of the expected deviations of the ITSDAQ system determined in Section 7.1.5, but has no practical implications for detector operations.

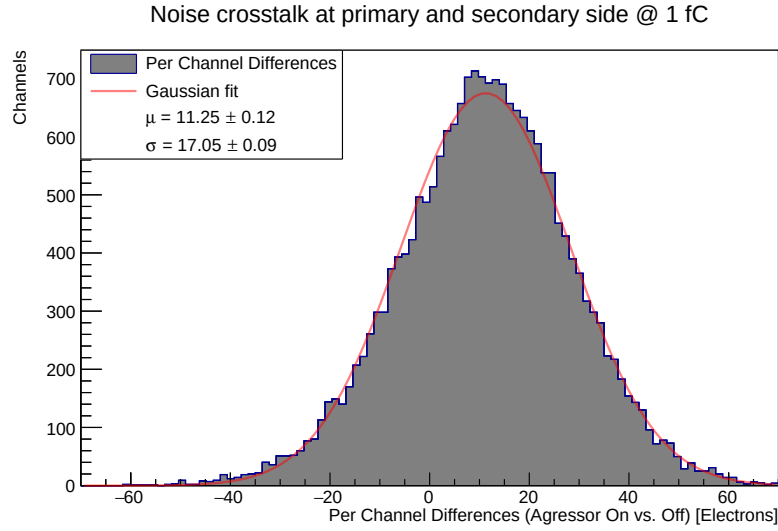


Figure 7.12: Noise crosstalk between primary and secondary side of the *IFIC1* petal as observed by its primary side with Gaussian fit.

7.5 Conclusion

The detector tests performed at multiple steps during the detector production process have been presented. The ITSDAQ full test was repeated five times in the same environment, showing that the noise measurements provide repeatable results between runs. Comparisons between the ITSDAQ and the FELIX + YARR readout systems have been made, providing evidence of issues with the propagation of the TrimDAC values to the ABCStars with the latter. A removal process for noisy regions caused by foreign bodies on the surface of the silicon sensors was successfully tested. The comparison between noise levels of modules before and after loading on a petal was inconclusive, probably because of the lack of cooling during module reception tests. The noise differences between the System Test and the petal coldbox and the noise crosstalk between petal sides have been measured to be negligible for practical detector tests.

Cosmic Muons

As early as 1912, Viktor Franz Hess discovered cosmic radiation during measurements from a hot air balloon [161], for which he received the Nobel Prize in Physics in 1936 [162]. In the same year, his co-winner, Carl David Anderson, studying this radiation, discovered particles “less massive than protons but more penetrating than electrons” [163], which would later become known as muons.

8.1 Origin of Cosmic Muons

Although their name may suggest otherwise, cosmic muons are not particles that directly originate outside our planet. Instead, they are tertiary collision products of much more energetic hadrons that collide with atoms in the Earth’s atmosphere. A general overview of cosmic rays can be found in [63, Chapter 30].

8.1.1 High-Energy Cosmic Rays

The cosmic ray spectrum contains all stable particles and nuclei at the upper end of our atmosphere. These particles originate from the Sun and sources outside the solar system, such as supernovae or the jets from black holes and pulsars. Moving interstellar clouds, such as the shock waves from supernovae, can further accelerate particles by first and second-order Fermi acceleration (see [164] for an overview). The resulting energy spectrum, shown in Figure 8.1, is usually parameterised as a power law [165][166, Equation (1.1)] of the form

$$\frac{dN}{dE} \propto E^{-\gamma}, \quad \gamma \approx \begin{cases} 2.75 & E < 4 \times 10^{15} \text{ eV} \\ 3.05 & 4 \times 10^{15} \text{ eV} \leq E \leq 1 \times 10^{19} \text{ eV} \\ 2.75 & E > 1 \times 10^{19} \text{ eV} \end{cases} . \quad (8.1)$$

In the region around 4×10^{15} eV, the slope of the spectrum becomes steeper; this is called the “knee”; at 1×10^{19} eV it flattens out again in the region of the “ankle”. For protons with an energy above 5×10^{19} eV, it is assumed that they lose energy due to interactions with photons of the cosmic background radiation, forming pions. Thus, their energy has a natural soft upper limit [167, 168]. Data from the Pierre Auger Observatory [169] and the Telescope Array Project [170] confirm the existence of this so-called GZK (Greisen, Zatsepin & Kuzmin) cutoff of the cosmic ray spectrum.

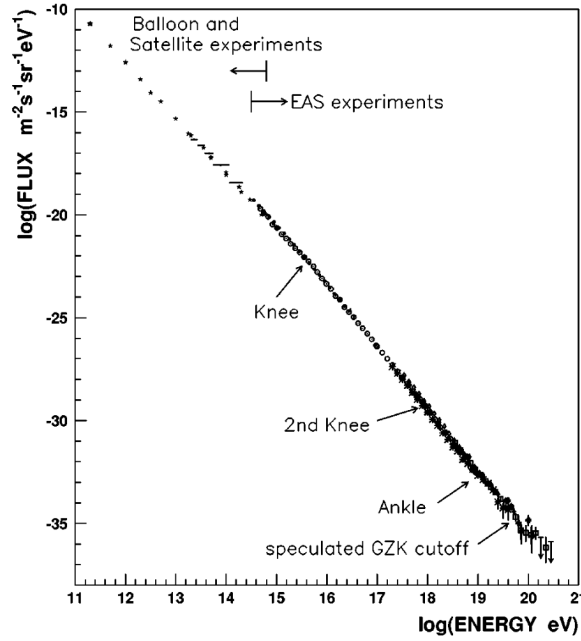


Figure 8.1: The energy spectrum of primary cosmic rays [165, Figure 1].

8.1.2 Extensive Air Showers

Through initial collision with an atomic nucleus in the atmosphere, a primary cosmic ray triggers a whole cascade of reactions, creating a multitude of new particles. The start of such an EAS (Extensive Air Shower) is exemplified in Figure 8.2. The simplest model for such cascades is a Heitler model [171, Chapter 24], in which new interactions occur after each radiation length in the medium. In the process, the hadronic interactions, through which mainly pions, protons and neutrons are produced, continue to develop through collisions with atomic nuclei in the atmosphere until there is no longer sufficient kinetic energy left to sustain the production of new particles. Meanwhile, the electromagnetic part of the cascade, which progresses through pair formation, Bremsstrahlung and annihilation of positrons with electrons from the atmosphere, is supplied with new particles by the decay of the neutral pions. At the same time, most of the charged pions decay via the channel [63, p. 38]

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \Gamma_{\pi^\pm \rightarrow \mu^\pm + \nu} / \Gamma = (99.98770 \pm 0.00004) \%, \quad (8.2)$$

with the resulting muons being observable on the Earth's surface.

8.1.3 Modelling of Cosmic Rays in the Atmosphere

Due to the high number of particles in a single EAS, it is not economical to simulate the complete shower. Instead, pre-simulated distributions are often used for applications only involving the EAS final state particles. For this purpose, the CRY (Cosmic-ray Shower Library) framework [172] was used in this thesis. This software was initially developed by the Lawrence Livermore National Laboratory for homeland security applications and can interface with common Monte Carlo simulation frameworks such as Geant4. CRY provides a predefined number of particles on a square area as its

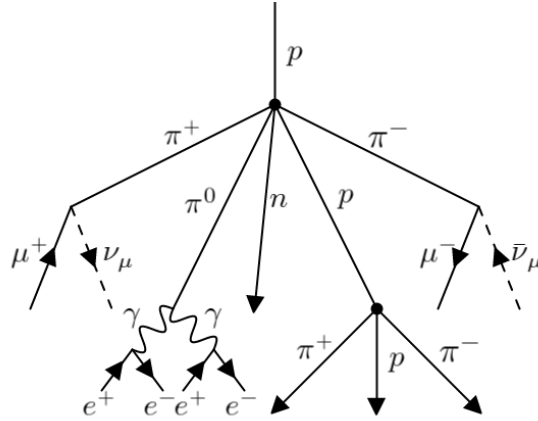


Figure 8.2: Example of a primary cosmic ray proton starting an EAS. The resulting neutral pions are feeding the electromagnetic cascade, while the charged pions are mainly generating cosmic ray muons as well as neutrinos.

output. All types of shower particles can be generated, and the simulated height above sea level, the latitude and the calendar date are variable. In addition to the simulated particles, the user receives the corresponding time, which allows a comparison with experimentally measured count rates or fluxes of EAS muons.

8.2 Cosmic Muon Flux

The cosmic muon flux is defined as

$$\Phi = \frac{\partial^3 N_\mu}{\partial t \partial \Omega \partial A}, \quad (8.3)$$

where $\frac{\partial N_\mu}{\partial t}$ is the measured particle rate, Ω is the solid angle, and A is the detector area. The flux of muons on the Earth's surface is influenced by their creation spectrum, the number of particles that decay along the way, and the energy lost in interactions with the air.

8.2.1 Energy Distribution

There is no generally accepted first principle model for the cosmic muon flux. However, a widely used approximation is

$$\frac{\partial \Phi}{\partial E_\mu} \approx \frac{0.14 E_\mu^{-2.7}}{\text{cm}^2 \text{ s sr GeV}} \cdot \left(\frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{850 \text{ GeV}}} \right) \quad (8.4)$$

for high-energy muons ($E_\mu > 100/\cos \theta$ GeV) and a flat atmosphere ($\theta < 70^\circ$) [63, Equation (30.4)]. The authors of [173] provide a model that also considers the energy loss in the atmosphere during the transport of low-energy muons at variable zenith angles. This results in a muon flux of

$$\frac{\partial \Phi}{\partial E_\mu} = I_0 N (E_0 + E_\mu)^{-n} \left(1 + \frac{E_\mu}{\varepsilon} \right)^{-1} D(\theta)^{-(n-1)}, \quad (8.5)$$

where $I_0 = \Phi(\theta = 0)$ is the vertical muon flux, $N = (n - 1)(E_0 + E_{\text{cutoff}})^{(n-1)}$ is a normalisation, E_0 a parameter that accounts for energy loss in the atmosphere, n is a parameter of the assumed initial E^{-n} power law distribution of the muons, ε a modification parameter to the power law to account for finite pion and kaon lifetimes, and $D(\theta)$ the ratio of path lengths between vertical and inclined muons [173, Equation (10)].

8.2.2 Angular Distribution

Neglecting the Earth's curvature, the ratio of path length becomes $D(\theta) = 1/\cos(\theta)$. In this case, the energy-integrated form of Equation (8.5) is [173, Equations (9), (11)]

$$\Phi(\theta) = I_0 D(\theta)^{-(n-1)} = I_0 \cos^{n-1} \theta. \quad (8.6)$$

With $n = 3$, this is consistent with the approximate $\Phi \propto \cos^2 \theta$ distribution found experimentally [63, p. 512][174, 175].

8.2.3 East-West Effect

It was observed by Compton in 1932 that the measured cosmic ray rate decreases around the equator [176]. The theory of Lemaitre and Vallarta explains this with a deflection of low-energy particles in the Earth's magnetic field. It also predicts an asymmetry of the incident radiation from the east and west directions in the region of 20 to 30° latitude [177]. In 1933, Johnson verified this prediction via measurements with Geiger-Müller coincidence counters [178]. In the early 1940s, Johnson published a paper explaining cosmic muons' east-west asymmetry with the EASs' development [179]. During the evolution of the shower, particles become slower and slower and are deflected more and more by the Earth's magnetic field; positively charged particles, therefore, tend to reach an observer more from the west, while negatively charged particles tend to come more from the east. The fact that more positively charged particles than negatively charged particles are involved in the cascade results in an asymmetry in the azimuth distribution of the shower particles.

8.2.4 Effective Detector Area

The area of a flat detector mounted parallel to the Earth's surface is $A(\theta) = A_0 \cdot \cos \theta$ from the point of view of a non-vertical incoming cosmic ray. The definition of an "effective" area with respect to a region of solid angle is more beneficial for a three-dimensional detector. Particles are generated on a surface A_{MC} and their interaction with the detector is simulated. For a region of the sky defined by the zenith and azimuth angle intervals $[\theta_l, \theta_h] \times [\phi_l, \phi_h]$, the effective detector area is defined as

$$A_{\text{eff}} = A_{\text{MC}} \cdot \frac{N_{\text{Tracks}}}{N_{\text{MC}}}, \quad (8.7)$$

where N_{Tracks} is the number of tracks registered by the detector from this direction of the sky, and N_{MC} is the number of simulated particles originating there [180, Equation (6.1)].

Cosmic Muons at the System Test

The ATLAS ITk strip end cap System Test serves as a test bench for all functions and the operation of the final detector. Therefore, an essential goal of this work from the outset was data acquisition with cosmic muons to demonstrate the measurement of an actual particle signal with the setup. The measurement of the cosmic muon flux, which was initially envisioned, would have required a higher number of petals in the System Test than were available during the period of this thesis. This discrepancy resulted from unforeseen changes in the production schedule. Nonetheless, the detector readout's functionality with muons could be demonstrated using a single petal; these results are presented in this chapter.

9.1 Cosmic Ray Setup

The ATLAS ITk strip end cap System Test (as described in Section 6.2) was prepared for experiments with cosmic muons as part of the thesis. For this purpose, the signals of the scintillators of the cosmic ray trigger setup were connected to an AIDA-2020 TLU (Trigger Logic Unit) [116] (see Figure 9.1). The TLU converts every signal that drops below a threshold value of -0.1 V into a 100 ns long pulse and generates a trigger signal based on the logic function

$$\text{Trigger} = \left(S_{\text{Top}}^{\text{Left}} \vee S_{\text{Top}}^{\text{Right}} \right) \wedge \left(S_{\text{Bottom}}^{\text{Left}} \vee S_{\text{Bottom}}^{\text{Right}} \right), \quad (9.1)$$

where S are the digitised signals from the four scintillators. This trigger signal is forwarded to the external trigger input of the Genesys-II board via an HDMI cable (see Section 4.6.1). Data acquisition is controlled via the EUDAQ framework [181], which handles the timestamp synchronisation between the TLU and the ITSDAQ hardware and allows for the execution of user-defined parameter scans.

9.2 Noise Occupancy

To verify the functionality of the data acquisition setup with ITSDAQ and the TLU, a noise occupancy scan (see Section 7.1) was carried out with both R5 modules of the *TRIUMFI* petal (see Section 6.1) loaded in the System Test with 17°C CO_2 cooling and a bias voltage of -350 V. First, the regular full test was conducted with ITSDAQ. Then, a scan was created in EUDAQ that records data from at

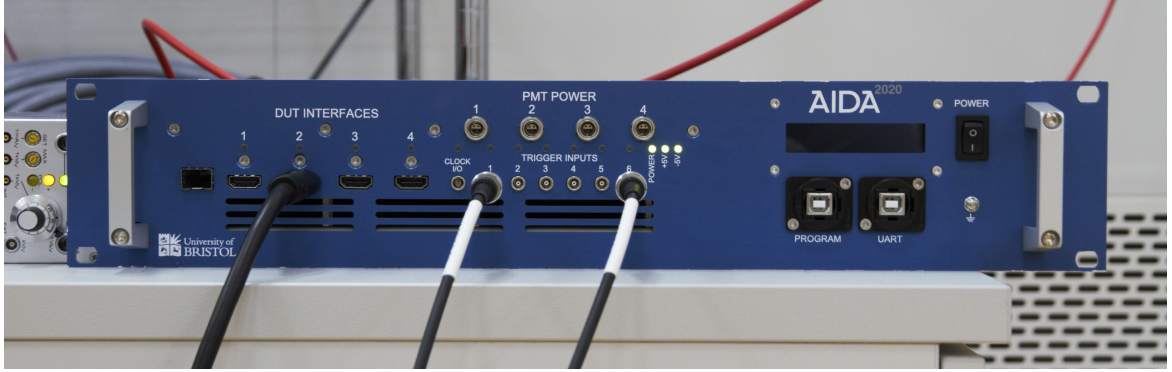


Figure 9.1: The AIDA-2020 Trigger Logic Unit used with the System Test with the photomultiplier tube output signals of two scintillator tiles and the trigger output HDMI cable connected.

Table 9.1: Comparison of the lower operating window threshold where the noise occupancy dips below 1×10^{-3} for both R5 modules on the *TRIUMF1* petal at 17°C CO_2 cooling with -350 V bias voltage.

Side	Module Serial Number	Operating Window BVT > [DAC Counts]	
		ITSDAQ	EUDAQ
Main	20USEHB0000026	26	27
Main	20USEHC0000023	25	24
Secondary	20USEHB0000027	25	30
Secondary	20USEHC0000025	26	24

least 2 048 events at threshold values from 0 to 44 DAC counts using the trim data obtained during the full test. The internal *auto trigger* of the TLU with a frequency of 500 Hz was used instead of the scintillator signals. The resulting data are shown in Figure 9.2.

As can be seen in Figure 9.3, the results from the pure ITSDAQ and TLU + EUDAQ + ITSDAQ setups do not line up well in the threshold region of $10 < \text{BVT} < 20$. While the noise occupancy curves then converge around $\text{BVT} = 20$, the noise occupancy for two out of four hybrid assemblies (serial numbers 20USEHB0000026 and 20USEHB0000027) starts to diverge again shortly after. This is especially pronounced for the secondary side R5 module, where several noisy strips exist in the region under the hybrid over the entire scan range for the first of the ABCStars, causing the noise occupancy to plateau for high thresholds. When masking the channels in this ABCStar, the plateau is no longer present. Notably, for the other three HCCStars, the lower operating window threshold (where the noise occupancy is $< 1 \times 10^{-3}$) found in both the full tests and externally triggered noise occupancy scan match closely (see Table 9.1).

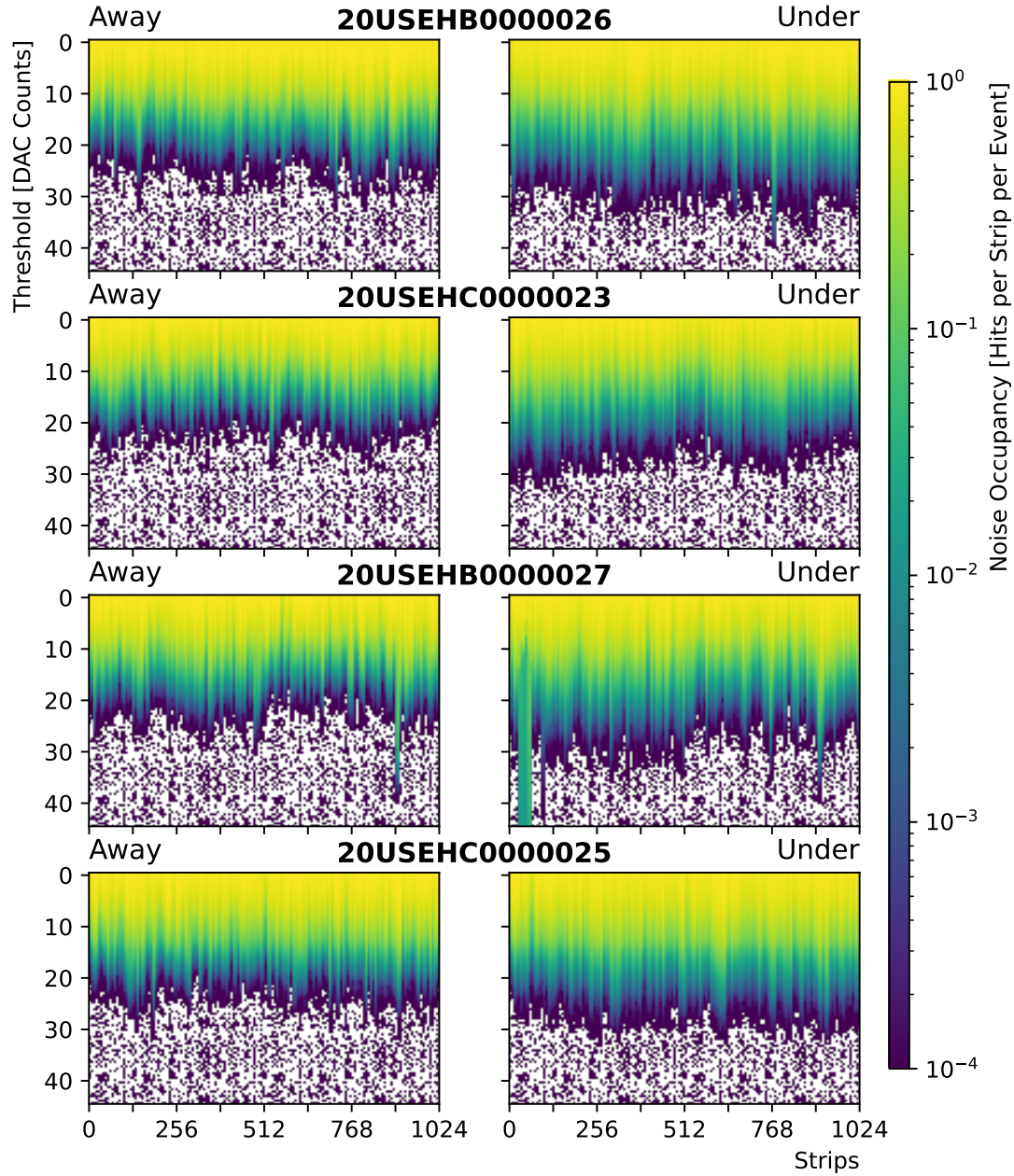
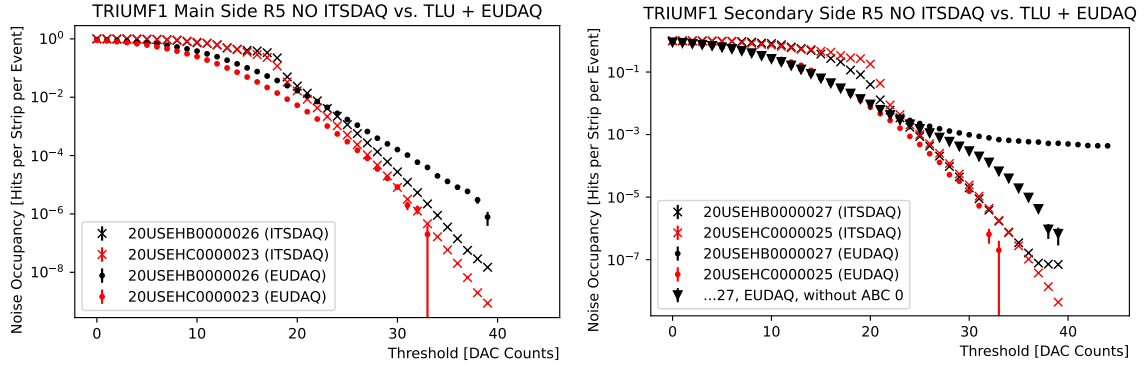


Figure 9.2: Noise occupancy map of both R5 modules on the *TRIUMF1* petal obtained with the EUDAQ setup using the TLU auto trigger. Strips in the *under* region are located underneath the hybrid, whereas the *away* region strips are located in the row next to the hybrid.



(a) Main side R5 module.

(b) Secondary side R5 module.

Figure 9.3: Comparison of noise occupancy results between the pure ITSDAQ scan (crosses) and the externally triggered ITSDAQ + EUDAQ based system (dots) for both R5 modules of the *TRIUMF1* petal. The data for one secondary side module was analysed again without considering noise hits in the first ABCStar (black triangles).

9.3 Trigger Latency

The time delay between recording a hit in the detector and the subsequent arrival of a trigger signal is called *latency*. The ABCStars store hit data for all channels in a shift register with a length of 512 events so that the detector can process triggers with a maximum time delay of $12.8 \mu\text{s}$ [82, Section 11.8.1]. In order to be able to measure cosmic muons with the *TRIUMF1* petal inserted into the System Test, the latency must be set to the delay of the external trigger signal, which is determined by the reaction times of the scintillator material and the photomultiplier tubes, the propagation times of the signals in the cables, the digitisation and processing of the signals in the TLU, the runtime of the TLU output signals in the HDMI cable, the processing of the triggers within the Genesys-II board, the runtime of the trigger signal in the downlink fibre to the IpGBT, and the signal runtimes on the petal itself. If the latency is not set correctly, the hits received are not correlated with an external particle, so one obtains the noise occupancy. If the latency is set correctly, on the other hand, an increased number of hits should be detected, as signals from real particles are now also being digitised.

To determine the latency valid for the System Test cosmics setup, a latency scan was first carried out in the value range 25 to 39 of the corresponding ABCStar register with a threshold of $\text{BVT} = 40$ with a minimum of $N_{\text{Target}} = 250$ events per latency setting. Both R5 modules were used on the *TRIUMF1* petal with a bias voltage of -350V at 0°C CO_2 cooling. The data from the strips of the first ABCStar in the *20USEHB0000027* half module were not considered as they exhibited exceptionally high noise (see above). This scan only resulted in hits for latency settings of 35 to 36. Due to the very low statistics of this scan, another scan was performed with latencies 34 to 37, this time with $\text{BVT} = 36$ and at least $N_{\text{Target}} = 2500$ events per latency setting. The resulting hit occupancy is shown in Figure 9.4. The number of events and hits per scan point can be found in Table 9.2.

Both scans consistently show a peak of the hit occupancy at a latency of $35 \cdot 25 \text{ ns} = 875 \text{ ns}$, which successfully demonstrates the detection of cosmic muons with the setup. The second scan was recorded at a lower threshold, where both the efficiency of muon detection and the noise occupancy are higher, resulting in a significantly higher overall hit occupancy. The composition of the hit occupancy at different thresholds will be analysed below.

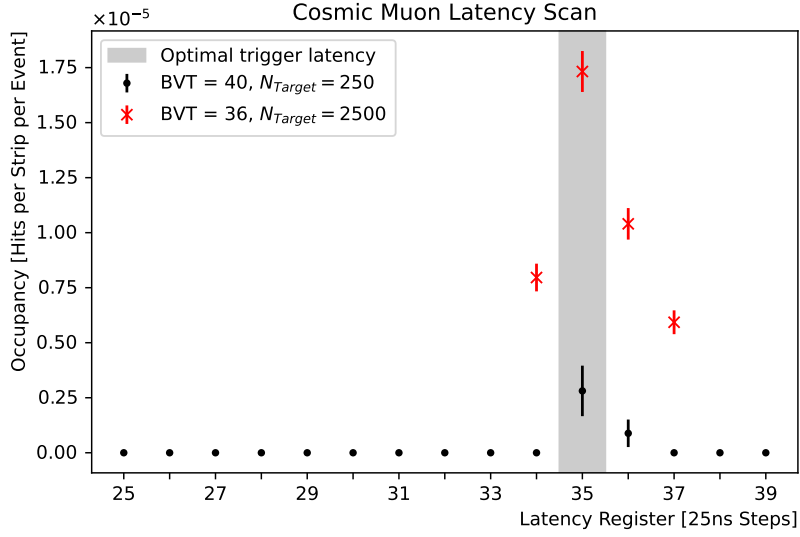


Figure 9.4: Results of both latency scans with the System Test cosmics setup. The grey area marks the latency setting of $35 \cdot 25 \text{ ns} = 875 \text{ ns}$ which was found to be optimal in both scans.

Table 9.2: Number of events and hits of both latency scans conducted with the System Test cosmics setup.

Latency	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Hits	0	0	0	0	0	0	0	0	0	0	6	2	0	0	0
Events	283	266	271	279	278	292	282	268	278	270	269	285	283	272	273
Hits										160	347	211	120		
Events										2532	2524	2556	2550		

9.4 Threshold Scan with Cosmic Muons

Once the correct trigger latency for the detection of cosmic muons had been determined, a threshold scan of the signal generated by the muons could be recorded. For this purpose, at least $N_{\text{Target}} = 5000$ events were recorded at threshold values between $\text{BVT} = 20$ to 126 with the same settings used during the latency scan. To illustrate the difference between the signal correlated with the cosmic muons obtained using the external scintillator trigger and the uncorrelated detector noise, a noise occupancy scan was also recorded with the same settings using the internal auto trigger of the TLU at 500 Hz. Since only one petal was installed in the System Test during this measurement, a set of one scintillator tile on the top and on the bottom of the trigger setup covering the entire area of the petal was used in coincidence instead of the full trigger defined in Equation (9.1), resulting in a cosmic muon trigger frequency of about 5 Hz. The combined results for both R5 modules of both scans are shown in Figure 9.5.

For low thresholds ($\text{BVT} < 40$), the hit occupancy matches the noise occupancy closely. For $\text{BVT} \geq 40$, the signal of the externally triggered modules displays a broad, pronounced muon plateau. The noise occupancy at lower thresholds and the hit occupancy in the muon signal region are well

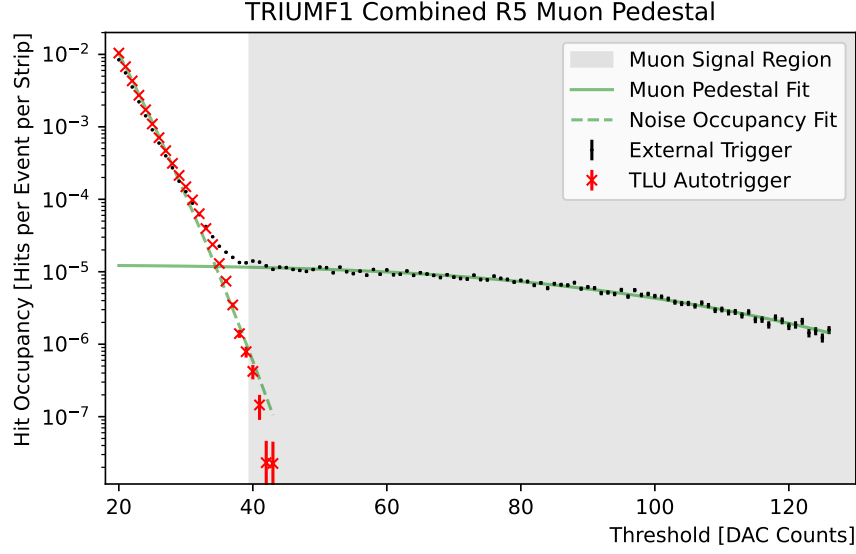


Figure 9.5: Hit occupancy found in the threshold scans using the uncorrelated TLU autotrigger at 500 Hz (red crosses) and the external cosmic ray trigger (black dots). Also shown are fits of the noise occupancy (dashed line) and muon signal (solid line) regions. The muon signal region used for the fit is marked light grey.

described by an S-curve as defined in Equation (7.1) with $p_{\text{Offset}} = 0$. A corresponding fit was applied to both signals. For the fit of the noise occupancy data, $p_{\text{Amplitude}} := 1$ was chosen to reflect that for low thresholds, the hitmap of the detector will always be full for every event. The resulting fit parameters are listed in Table 9.3. The amplitude of the S-curve caused by the muons can be described by

$$HO = \frac{g \cdot \bar{s} \cdot \varepsilon(\text{BVT})}{\# \text{ Strips}} + NO, \quad (9.2)$$

where g is the fraction of external triggers for which a muon has hit the active area of the silicon modules under study, $\bar{s}$ is the average number of hits caused by a muon passing the sensor (or $\bar{s} = 1$ if the cluster occupancy is considered instead), $\varepsilon(\text{BVT})$ is the threshold-dependent efficiency of the modules and NO is the noise occupancy. If the detector- and setup-dependent variables were known, the efficiency curve of the modules could be directly calculated from the data of the threshold scan. In practice, however, g is heavily dependent on the noise and efficiency of the scintillators and photomultiplier tubes, as well as the exact alignment of the scintillator plates and the modules. Therefore, an alternative method for determining the absolute module efficiency curve, which utilises the correlation between hits on both sides of the petal, is proposed in Section 10.5 and tested in a Monte Carlo simulation.

Table 9.3: Fit parameters to the muon signal obtained with the external trigger and the noise occupancy data taken using the TLU auto trigger at 500 Hz.

	Muon Signal Region			Noise Occupancy		
Parameter	$P_{\text{Amplitude}}$	VT_{50}	σ_O	$P_{\text{Amplitude}}$	VT_{50}	σ_O
Value	$(1.24 \pm 0.04) \times 10^{-5}$	87.2 ± 1.7	32.4 ± 1.4	$:= 1$	3.49 ± 0.37	7.08 ± 0.14
R^2	96.90 %			99.71 %		

9.5 Conclusion

Data taking with the System Test using the EUDAQ framework with the AIDA TLU was successfully demonstrated. A noise occupancy scan was performed and compared to the pure ITSDAQ implementation, showing discrepancies subject to further investigation by the ITk DAQ community. The correct trigger latency was determined. Finally, a threshold scan with cosmic muons was taken, which showed a clear plateau stemming from the cosmic muon signal. This constitutes the first measurement of a real particle signal with a fully loaded ITk strips petal and an important step towards more complex measurements of cosmic muons with the System Test setup, such as a measurement of the cosmic muon flux. Simulations for tracking cosmic muons in the System Test setup with multiple petals are presented in the next chapter.

Simulations

After the arrival of more petals and their eventual insertion into the System Test, the setup is foreseen to be used as a cosmic muon telescope to demonstrate data taking in physics mode with multiple petals and an external trigger, as well as tracking. In order to reconstruct the flux of cosmic muons from the detector data, a detailed understanding of the geometric acceptance of the detector is necessary first. For this purpose, Monte Carlo simulations were carried out with the software package Allpix² [182]. This chapter explains the simulation and reconstruction tools used while also exploring the geometry of the end cap sensors. It also presents simulation results for cosmic muon measurements with a possible arrangements of petals in the System Test. A proposal for measuring the efficiency curve of modules using cosmic muons exploiting the double-sided layout of the petals is made, and its feasibility is studied using Monte Carlo simulations.

10.1 Radial Strip Geometry

The sensors of the ATLAS ITk strip end cap (see Chapter 4) feature radial strips. Measured from the interaction point, all strips in the same row start and end at the same radii. From a specified centre point of the sensor, the vector pointing to the interaction point is rotated by the stereo angle $\varphi_S = 20$ mrad. All strips in a particular row have the same angular pitch measured from the resulting point focus point F . A schematic overview of this geometry is shown in Figure 10.1. The design parameters in Table 10.1 define the geometry of the sensors belonging to the end cap modules R0 - R5. The radial strip geometry was recently implemented in the silicon sensor simulation software Allpix² [183].

10.1.1 Transformation to Cartesian Coordinates

If a strip (i, j) of a radial sensor detects a signal, the centre of the strip can be specified by its radius

$$R = \frac{r_{i+1} + r_i}{2} \quad (10.1)$$

and its angle

$$\varphi = \varphi_{i,0} + j \cdot \Delta_{\varphi,i}, \quad (10.2)$$

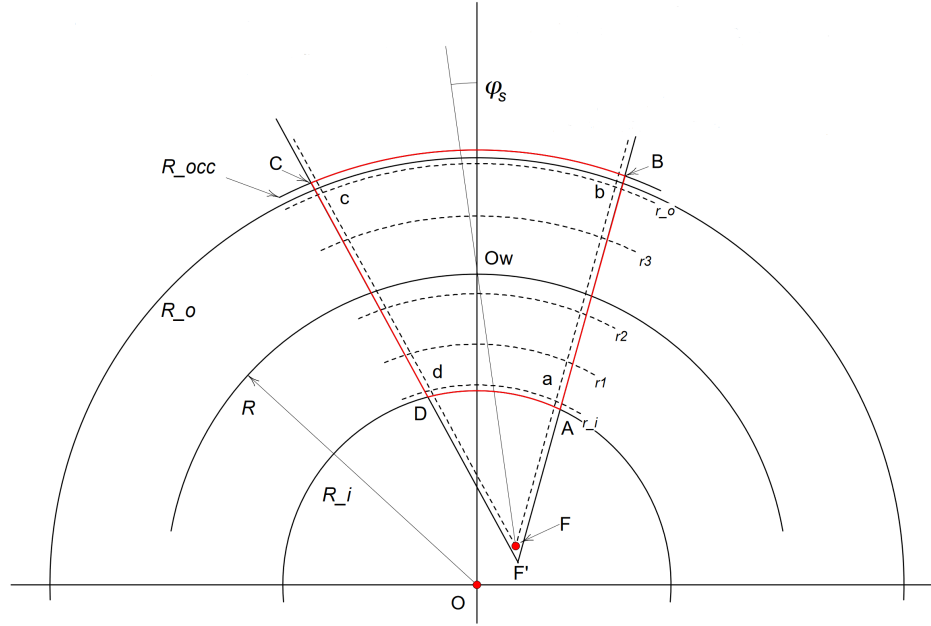


Figure 10.1: Definitions of the radial strip coordinate system [87, Figure 15]. The outer shape of the sensor (red outline) is obtained by adding a distance dR around the active sensor area.

Table 10.1: Design parameters of the ITk strip end cap sensors R0 - R5 [87, Table 2]. The number of strips includes the two outermost strips of each row, which are only present for shaping the electric field, but are not connected to the front-end chips.

Module	R0	R1	R2	R3	R4	R5
R_i [mm]	384.0500	489.3730	575.1440	638.1590	756.4510	867.0120
R_o [mm]	488.8730	574.6440	637.6590	755.9510	866.5120	968.2350
R_{occ} [mm]	488.8826	574.6553	637.6715	755.9547	866.5162	968.2397
R_C [mm]	438.6140	534.6390	609.4050	697.8990	812.4710	918.7490
r_i [mm]	384.5000	489.8230	575.5940	638.6090	756.9010	867.4620
r_1 [mm]	403.4810	507.9160	606.4020	664.8320	811.4820	907.6230
r_2 [mm]	427.4620	535.0090		697.0550		
r_3 [mm]	456.4420	559.1010	606.4020	729.2780	811.4820	907.6230
r_o [mm]	488.4230	574.1940	637.2090	755.5010	866.0620	967.7850
Number of strips (Row 0)	1026	1282	1538	898	1026	1154
(Row 1)	1026	1282		898		
(Row 2)	1154	1410		898		
(Row 3)	1154	1410	1538	898	1026	1154
Δ_φ [μ rad] (Row 0)	193.0863	154.7122	129.0774	109.5053	96.1753	85.7429
(Row 1)	193.0863	154.7122		109.5053		
(Row 2)	171.6880	140.6774		109.5053		
(Row 3)	171.6880	140.6774	129.0774	109.5053	96.1753	85.7429

where r_i are the inner and outer row radii, $\varphi_{i,0}$ is the angle of the first strip centre in the i^{th} row, and $\Delta_{\varphi,i}$ is the angular pitch of the same row. This position can be reconstructed in Cartesian coordinates as

$$\begin{pmatrix} X \\ Y \end{pmatrix} = r' \cdot \begin{pmatrix} \sin(\varphi + \varphi_S) \\ \cos(\varphi + \varphi_S) \end{pmatrix} - R_C \cdot \begin{pmatrix} \sin(\varphi_S) \\ \cos(\varphi_S) \end{pmatrix} \quad (10.3)$$

using the substitutions

$$b = -4R_C \cdot \sin(\varphi_S/2) \sin(\varphi_S/2 + \varphi), \quad (10.4)$$

$$c = (2R_C \cdot \sin(\varphi_S/2))^2 - R^2 \quad (10.5)$$

$$r' = (-b + \sqrt{b^2 - 4c}) / 2, \quad (10.6)$$

where R_C denotes the radius of the sensor center O_w [87, Section 3.1.3.3].

10.1.2 Detector Resolution

For the track reconstruction in Corryvreckan (see Section 10.2.2), the detector resolution in global Cartesian coordinates is needed in addition to the position of the hits. Here, the case of a single binary hit is considered. This hit is located at radial coordinates (R, φ) and has known radial and angular resolutions Δ_R and Δ_φ . Using the transformation in Equation (10.3), Gaussian error propagation can be used to transfer the detector resolution into Cartesian coordinates:

$$\Delta_X = \sqrt{\left(\frac{\partial X}{\partial \varphi}\right)^2 \Delta_\varphi^2 + \left(\frac{\partial X}{\partial R}\right)^2 \Delta_R^2} \text{ and } \Delta_Y = \sqrt{\left(\frac{\partial Y}{\partial \varphi}\right)^2 \Delta_\varphi^2 + \left(\frac{\partial Y}{\partial R}\right)^2 \Delta_R^2}. \quad (10.7)$$

The derivatives evaluate to

$$\frac{\partial X}{\partial R} = \frac{R \sin(\varphi + \varphi_S)}{K}, \quad \frac{\partial Y}{\partial R} = \frac{R \cos(\varphi + \varphi_S)}{K}, \quad (10.8)$$

$$\frac{\partial X}{\partial \varphi} = M \cdot \left(L \cos\left(\varphi + \frac{\varphi_S}{2}\right) \sin(\varphi + \varphi_S) + K \cos(\varphi + \varphi_S) \right) \text{ and} \quad (10.9)$$

$$\frac{\partial Y}{\partial \varphi} = M \cdot \left(L \cos\left(\varphi + \frac{\varphi_S}{2}\right) \cos(\varphi + \varphi_S) - K \sin(\varphi + \varphi_S) \right) \quad (10.10)$$

using the substitutions

$$K = \sqrt{R^2 - 4R_C^2 \sin^2\left(\frac{\varphi_S}{2}\right) \cos^2\left(\varphi + \frac{\varphi_S}{2}\right)}, \quad L = 2R_C \sin\left(\frac{\varphi_S}{2}\right) \text{ and} \quad (10.11)$$

$$M = \left(1 + \frac{L}{K} \sin\left(\varphi + \frac{\varphi_S}{2}\right) \right). \quad (10.12)$$

For all simulations presented in this thesis, an approach using the resolution transformation presented here after clustering in the (R, φ) plane (see Section 10.2.2) was used to obtain the cluster positions in Cartesian coordinates.

10.2 Simulation Toolchain

All simulations presented have been performed with the Allpix² software [182], which simulates the charge creation by ionising particles within silicon sensors and generates the corresponding hit information. The Corryvreckan framework [184], initially intended to reconstruct test beam data from pixel sensors, was modified to allow for track reconstructions with radial strip detectors utilizing the coordinate and resolution transformations presented in Section 10.1.1 and Section 10.1.2. It was then used to reconstruct the tracks of the simulated particles in the detector.

10.2.1 Allpix²

The Allpix² software was developed as a generic simulation framework for semiconductor detectors. It has a modular structure and can be adapted to the respective simulation scenario through configuration files. The modules required to simulate the ATLAS ITk strip modules and their specific settings are explained below.

Energy Deposition in Silicon

The motion and energy loss of particles in matter are calculated in Allpix² by using the Geant4 simulation software [70–72]. For investigations with a directed particle beam, the module *DepositionGeant4* was used, which simulates the charge deposition in the specified geometry. For simulations with particles from EASs (see Chapter 8), the module *DepositionCosmics* is available, which invokes CRY (Cosmic-ray Shower Library) [172]. Thus, cosmic muon events with typical angular and energy distributions can be generated at atmospheric heights of 0, 2 100 and 11 300 m on a square area. Furthermore, the software also takes into account the geographic latitude. The total simulated time can also be read out to compare the obtained particle flux with experimental data.

Charge Transport

The modules of the ITk strip detector (see Section 4.1) are designed to have a depletion voltage of < 350 V and to operate at a voltage of 500 V [87, p. 20]. Assuming that a detailed consideration of the effects at the edges of the strips is not necessary for a simulation of cosmic ray runs, the electric field in the sensor was approximated as linear using the *ElectricFieldReader* module. A depletion voltage of –300 V and a bias voltage of –500 V were assumed. The *GenericPropagation* module was used to simulate the transport of charges in the silicon bulk. It uses the Jacoboni-Canali model [185], which parametrises the charge carrier mobility in silicon in dependence of the electric field as

$$\mu(E) = \frac{v_m}{E_C} \frac{1}{\left(1 + (E/E_C)^\beta\right)^{1/\beta}}, \quad (10.13)$$

with E_C , v_m and β being the temperature dependent empirical parameters found in [185, Table 5]. A temperature of 243 K $\equiv$ –30.15 °C, which is the approximate temperature of the liquid CO₂-cooled modules in the detector, was assumed during all simulations. Charges located within a depth of 15 μ m of the strips were assigned to the respective readout channels using the *SimpleTransfer* module.

Hit Digitization and Histogramming

The charge collected in the channels was converted into digital hit information by the *DefaultDigitizer* module. A Gaussian noise of 700 e^- was added to the signal (as specified as the maximum input noise of the front end chips in [10, Section 6.2.1]) and then compared to a threshold charge of 0.2 fC (estimated from [10, Figure 8.8, right, short strips]) using a discriminator. The resulting hit data is binary. For each event, the direction of incidence of the EAS particles in (θ, ϕ) was histogrammed using a custom Allpix² module. This information is later needed to calculate the effective detector area. In addition, all hits were saved by the module *CorryvreckanWriter* in a file format compatible with the Corryvreckan framework.

10.2.2 Corryvreckan

The detectors' hit information must first be imported before track reconstruction. In the case of events simulated with Allpix², this was done using the *FileReader* module.

Clustering

A particle can deposit charge in several strips as it passes through a silicon detector. If several strips are identified as belonging to the same particle, this group is called a cluster. The *ClusteringSpatial* module follows the *touching-neighbors* approach, in which adjacent hits are added to a cluster until none of the neighboring strips contain a hit. This algorithm is repeated for the entire detector until every hit belongs to a cluster. If no additional charge information is available, the cluster's centre is set to the arithmetic mean of the Cartesian centres of its assigned strips for rectangular detector geometries. However, since in the case of radial strip geometry the strips do not have a uniform pitch in x and y , the centre point is therefore first calculated in the (R, φ) plane, taking into account the respective resolution of the strips. This *radial weighting* algorithm developed for this thesis averages over the positions of all associated strips in a cluster in R and φ . With binary hit information, the cluster center and resolution evaluate to

$$R = \frac{\sum_{i=1}^N w_{R,i} \cdot R_i}{\sum_{i=1}^N w_{R,i}}, \sigma_R^2 = \frac{1}{\sum_{i=1}^N w_{R,i}}, w_{R,i} = \frac{12}{\Delta_{R,i}^2}, \quad (10.14)$$

$$\varphi = \frac{\sum_{i=1}^N w_{\varphi,i} \cdot \varphi_i}{\sum_{i=1}^N w_{\varphi,i}}, \sigma_\varphi^2 = \frac{1}{\sum_{i=1}^N w_{\varphi,i}}, w_{\varphi,i} = \frac{12}{\Delta_{\varphi,i}^2}, \quad (10.15)$$

where $p_{R/\varphi,i}$ are the pitches of the i^{th} strip in the cluster in R/φ respectively. Finally, the position and resolution of the clusters are transformed into Cartesian coordinates using the transformation described in Section 10.1.2.

Correlations

Correlations in the i^{th} detector element are defined as

$$x_{\text{Correlation}, i} = x_{\text{Cluster, REF}} - x_{\text{Cluster}, i} \text{ and } y_{\text{Correlation}, i} = y_{\text{Cluster, REF}} - y_{\text{Cluster}, i} \quad (10.16)$$

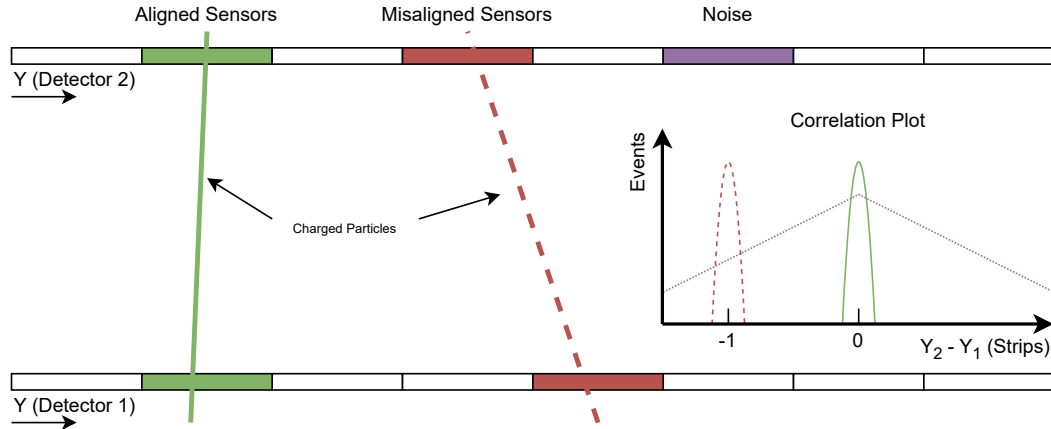


Figure 10.2: Illustration of the basic features of a correlation plot. Here, the correlation between two layers of strips is shown. Particles hitting the sensors orthogonally (green line) cause a peak in the plot. Are the tracks not orthogonal to the sensors, or the sensors misaligned from their intended positions, a peak is produced at a position different from $y = 0$ (red dashed line). Noise hits, or multiple hits not caused by the same particle, cause a triangular background (purple dotted line), since both Y_1 and Y_2 are independently uniformly distributed.

by comparing all clusters with all clusters of a reference detector. Their distribution will show a peak for “correlated” clusters belonging to the same particle track, while “uncorrelated” clusters will produce a triangular background due to the position of both clusters contributing to the correlation following a continuous uniform distribution. Calculating the correlations allows valuable insights into the data even before the actual track reconstruction is undertaken. For example, the position of the peak of the distribution can indicate the misalignment of the respective detector in the x/y plane. For an illustration showing these relationships, see Figure 10.2.

Tracking

A *track* is a function that reproduces the path of a particle that has produced a signal in the detector. In the simplest case, this is a linear function fitted to the clusters in multiple detector planes. However, as more than one cluster per event can occur in each detector element, a decision must first be made regarding which clusters should be assigned to which track. The *Tracking4D* module takes the approach of first selecting two reference clusters, between which a provisional linear track is formed. All clusters that lie within a defined spatial cut of this track are then added to the track. The linear track model can now be fitted to the clusters found. With this procedure, it is possible that several track candidates are found that contain the same cluster. In this case, the track with the smaller $\chi^2/N.d.F.$ is retained. To ensure that the track contains all detector planes, it is also required that it consists of at least $2N - 1$ clusters (for a detector consisting of N stereo module planes). Unlike Corryvreckan’s usual test beam-like applications, cosmic ray telescopes exhibit multiple detectors in the same z -plane. Since only single clusters from each side of a petal should contribute to a track, track candidates with multiple clusters with the same z coordinate were therefore rejected. The module *AnalysisParticleFlux* [186] was newly developed during this thesis to obtain the angular distribution necessary for calculating the particle flux. It creates histograms of the azimuth and zenith angles of all analysed tracks.

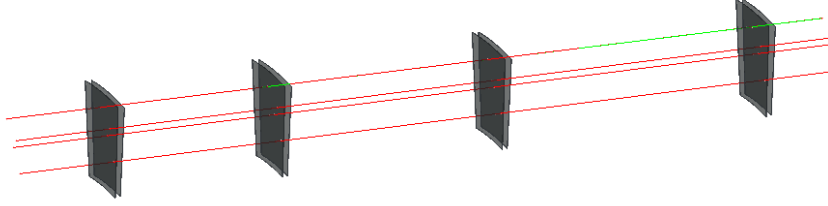


Figure 10.3: Setup of the R0 telescope shown in the Allpix² visualisation tool.

10.3 R0 Telescope Studies

In order to verify the functionality of the implementations discussed above and to gain an impression of the performance of the System Test when tracking cosmic muons, simulations were first carried out with a beam telescope-type setup consisting of R0 sensors. The modules were arranged at distances of 100, 290, 540 and 840 mm from the source in planes of two sensors each (as shown in Figure 10.3); sensors in the same plane are separated in z by 6.43 mm. This is consistent with the distances of the modules in the first four discs in the ATLAS ITk end cap. One of each plane's sensors is rotated by 180° around its R -axis to obtain a superposition of the strips via their stereo angle. The particle source is configured as a 5.078 GeV electron beam with a 10 mm wide Gaussian profile. Its energy spread is 0.163 GeV, and its divergence is 1 mrad. This is equivalent to the beam parameters at the DESY II electron test beam facility [187].

10.3.1 Aligned Telescope

To verify the results of simulation and reconstruction chain step by step, a simulation was first carried out with an aligned telescope, meaning that the exact positions of all modules are known to the reconstruction chain. A total of one million source electrons were simulated for this configuration.

Strip Association and Residuals in Allpix²

As the implementation of the radial strip geometry in Allpix² was a new addition to the framework at the time of this thesis, it was first necessary to check that the association of hits to the strips works correctly. For this purpose, the strips in columns 500 and 501 were selected from row 2 of the telescope's first plane front sensor, and the position at which the simulated particle hit the silicon was recorded for all single-hit clusters found. In Figure 10.4, this is plotted against the actual position of these strips, together with the information as to which strip the associated hit was assigned to. In addition, the Python package *shapely* [188] (using the GEOS geometry library [189]) was used to create polygons from the four outer corner points of both strips and the correct assignment of all hits was checked. Hits assigned to a strip with MC particle positions within the associated polygon were classified as correctly assigned.

A total of 1821 hits were recorded in the 500th strip of the second row, for 1747 of which the position of the MC particle was within the associated polygon. For strip 501, 1826 hits were registered, of which 1719 were classified as correctly assigned. One hit in strip 500 with the MC particle

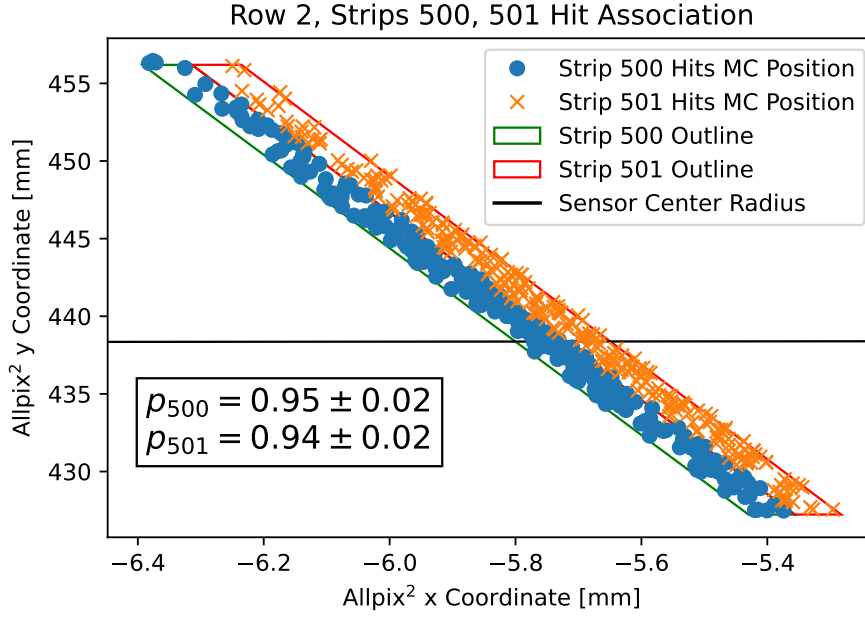


Figure 10.4: Position of incoming MC particle hits vs. the strip they have been reconstructed in for two strips of the telescope’s front sensor. The number of hits has been limited to 250 points per strip for the plot. p_{500} and p_{501} are the probabilities for a correct reconstruction for both strips respectively. Note that the coordinate origin in Allpix² coordinates is not in the sensor center, but rather at $R = 0$.

Table 10.2: Assumed radial resolutions of the R0 module.

Strip Row	0	1	2	3
$\sigma_{\varphi}^{\text{reco}} = \Delta_{\varphi,i}/\sqrt{12}$ [μrad]	5.4793	6.9227	8.3658	9.2321
$\sigma_R^{\text{reco}} = \Delta_{R,i}/\sqrt{12}$ [mm]	55.7392	55.7392	49.5621	49.5621

position $(-91.310, 458.487)\text{mm}$, and two hits in strip 501 with positions $(-586.038, 1132.68)\text{mm}$ and $(14.8169, 447.447)\text{mm}$ were classified as outliers and not taken into account due to the extreme deviation of their positions from all other reconstructed hits. Therefore, the probability that a hit registered in strip 500 was correctly assigned is 0.95 ± 0.02 ; for strip 501, this probability is 0.94 ± 0.02 . Since the position of the simulated particle is calculated as the average between its entry and exit point for the silicon volume, the misattributed hits should be mainly located in the border regions between the strips. The residuals between the position of the MC particles and the reconstructed hit were also calculated. These are plotted in radial coordinates in Figure 10.5. In φ , the standard deviation of the residuals evaluated to $\sigma_{\varphi} = 46.38 \mu\text{rad}$; in R , it was $\sigma_R = 7.679 \text{ mm}$. These standard deviations represent the detector resolution in the respective coordinate. The detector resolutions assumed naively in the reconstruction algorithm are depending on the strip row and are listed in Table 10.2. While the resolution in R is consistent with the calculated values, the real resolution of the detector in φ is even slightly better.

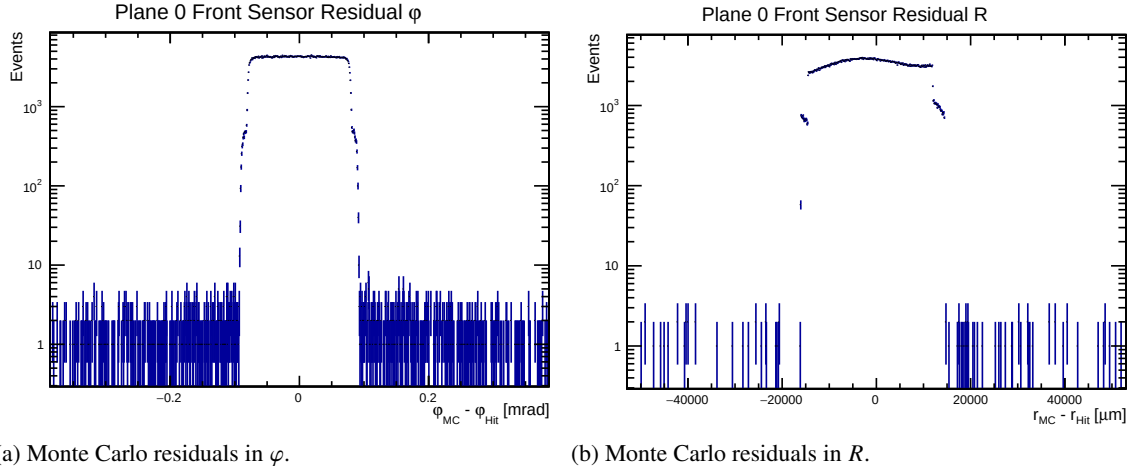


Figure 10.5: Residuals between Monte Carlo particle and reconstructed hit in radial coordinates for the first telescope sensor.

Table 10.3: Number of Hits and radii used to reconstruct the beam spot position (radii calculated from the data presented in Table 10.1).

Strip Row	0	1	2	3
Number of Hits	525	151236	963573	45358
$r_{center,i}$ [mm]	393.9905	415.4715	441.952	472.4325
Δr_i [mm]	18.9810	23.9810	28.9800	31.9810

Hitmaps and reconstructed Beam Spot

The telescope planes are arranged so that the beam hits the centre of the R0 sensor ($\varphi = 0$, $R = R_C$). Thus, most hits should lie in the middle of strip row 2, which is consistent with the recorded hitmaps (see Figure 10.6(a)). Proper reconstruction of the position and size of the beam spot was demonstrated using the front sensor of the first plane as an example. The reconstructed R coordinates are plotted in Figure 10.6(b). As the resolution of the detector in R is very low, only an approximate reconstruction of the beam spot was possible in this dimension. The number of hits per strip row can be obtained from the hit map and are listed in Table 10.3. With these, the R coordinate of the beam spot can be reconstructed as

$$R = \sum_{i=0}^3 \frac{12 \cdot n_{hits,i}}{(\Delta_{R,i})^2} \cdot r_{center,i} \bigg/ \sum_{i=0}^3 \frac{12 \cdot n_{hits,i}}{(\Delta_{R,i})^2} = (438.050 \pm 0.008) \text{ mm} \quad (10.17)$$

by weighting each hit according to the radial resolution, analogous to the algorithm described in Section 10.2.2. The result is a position close to the R0 center radius of $R_C = 438.6140$ mm. The standard deviation of reconstructed cluster radii is 11.11 mm, slightly larger than the real beam spot size, once again hinting at the bad resolution of the detector in that dimension.

Concerning the φ -coordinate, the distribution shown in Figure 10.6(c) results. Since the original binning in the Corryvreckan analysis was too fine and led to significant aliasing, the further evaluation

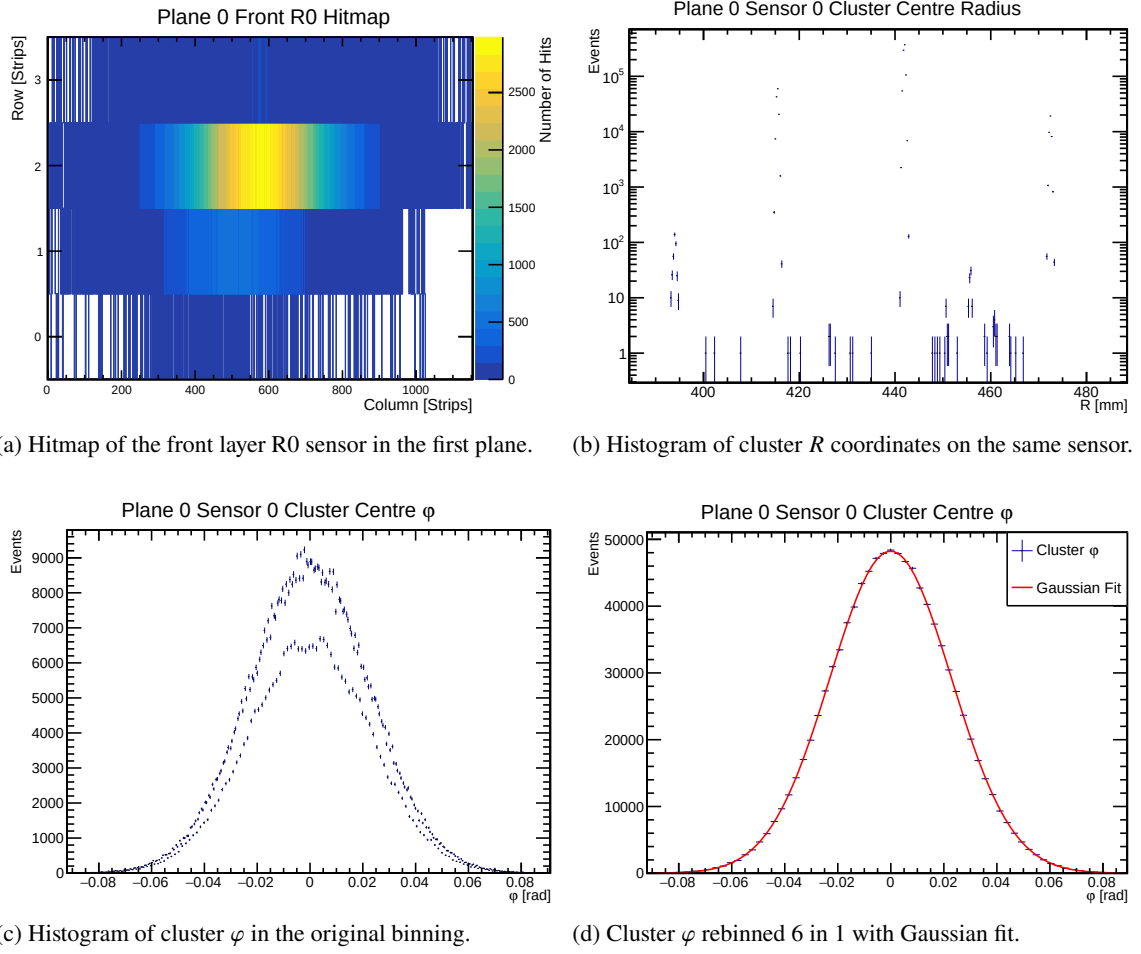


Figure 10.6: Telescope front sensor hitmap and clustering histograms.

 Table 10.4: Parameters of the Gaussian fit to the reconstructed φ coordinate.

Parameter	μ	σ	Amplitude	$\chi^2/\text{N.d.F.}$
Value	$(-66 \pm 23) \mu\text{rad}$	$(22.904 \pm 0.016) \text{ mrad}$	$48\,250 \pm 59$	144.58 / 63

was carried out with a binning reduced by a factor of 6. A Gaussian fit to the resulting histogram has the parameters listed in Table 10.4 and is shown in Figure 10.6(d). The mean of the fitted distribution differs less than one strips pitch in φ from 0, meaning that the result is consistent with the beam center being correctly reconstructed at $\varphi = 0$. Using the small angle approximation

$$\sigma_{\varphi}^{\text{Cartesian}} = R_C \cdot \sigma_{\varphi}^{\text{radial}} = (10.046 \pm 0.007) \text{ mm}, \quad (10.18)$$

reasonable agreement with the simulated beam spot size is found.

Table 10.5: Parameters of the fit to the standard deviations of cluster correlations in x according to Equation (10.19).

Parameter	$\sigma_{\text{uncorrelated}}$	σ_{beam}	$\chi^2/\text{N.d.F.}$
Value	$(0.57008 \pm 0.00160) \text{ mm}$	$(1.059 \pm 0.004) \text{ mrad}$	$1.057 \times 10^{-5} / 2$

Correlations

For each detector, the correlations $x_{\text{Ref}} - x$ were calculated for all clusters in reference to the front sensor of the first telescope plane. A clear peak is expected for correlated clusters, and a triangular background for uncorrelated clusters. Since the beam is divergent in this simulation, a distance-dependent peak broadening is also anticipated. As can be seen in Figure 10.7, this is consistent with the data¹. The standard deviation of the correlations is composed of a distance-independent part $\sigma_{\text{uncorrelated}}$ and a distance-dependent part σ_{beam} and follows

$$\sigma(z) = \sqrt{\sigma_{\text{uncorrelated}}^2 + (z \cdot \sigma_{\text{beam}})^2}, \quad (10.19)$$

where z is the distance between the sensor and the reference plane. A fit of this equation to the measured standard deviations is shown in Figure 10.8 and has the parameters listed in Table 10.5. The obtained beam divergence σ_{beam} is consistent with the simulation input of 1 mrad and small amounts of additional scattering on the detector material.

The deviation between the first and last detector plane caused by a straight path with an angle of 1 mrad to the beam axis is 740 μm . Since the strips in the R direction (and thus in Cartesian coordinates in the y direction) are several cm in size, the detector is not sensitive enough in this direction to make the same effect visible as in x . Two exemplary correlation plots in this dimension can be found in Figure B.12.

Since a front layer sensor was chosen as a reference for the correlations, distributions for back layer sensors show more complex features in the x -direction due to the rotation of the sensor around the y -axis. While the triangular background originating from the uncorrelated clusters is still present, the distributions now exhibit a wide peak (see Figure 10.9). Because of the stereo angle, hits are reconstructed in a position offset from the actual particle hit when the hit is not located close to the centre of the strip. This offset in x is the same for sensors with the same rotation, thus cancelling the effect in the correlation plots for the front-side sensors.

Tracking

999801 tracks were reconstructed from the simulated detector data after clustering. The histogram of angles between the x -axis and reconstructed tracks were fitted with a Gaussian distribution on the interval -4 to 4 mrad. A plot of the data with the fitted curve is found in Figure 10.10(a), the parameters of the Gaussian fit are shown in Table 10.6. Note that the binning was reduced by a factor of 10 because of aliasing in the original dataset (a plot of the original track angle data is found in Figure B.13). It follows from the fit result that the angular resolution in x of this R0 based beam

¹ Once again, the binning in the original Corryvreckan analysis was too fine, leading to significant aliasing effects. Therefore, a $\frac{1}{4}$ rebinned version of the histograms was used in the analysis. Plots of the original histograms are found in Figure B.11.

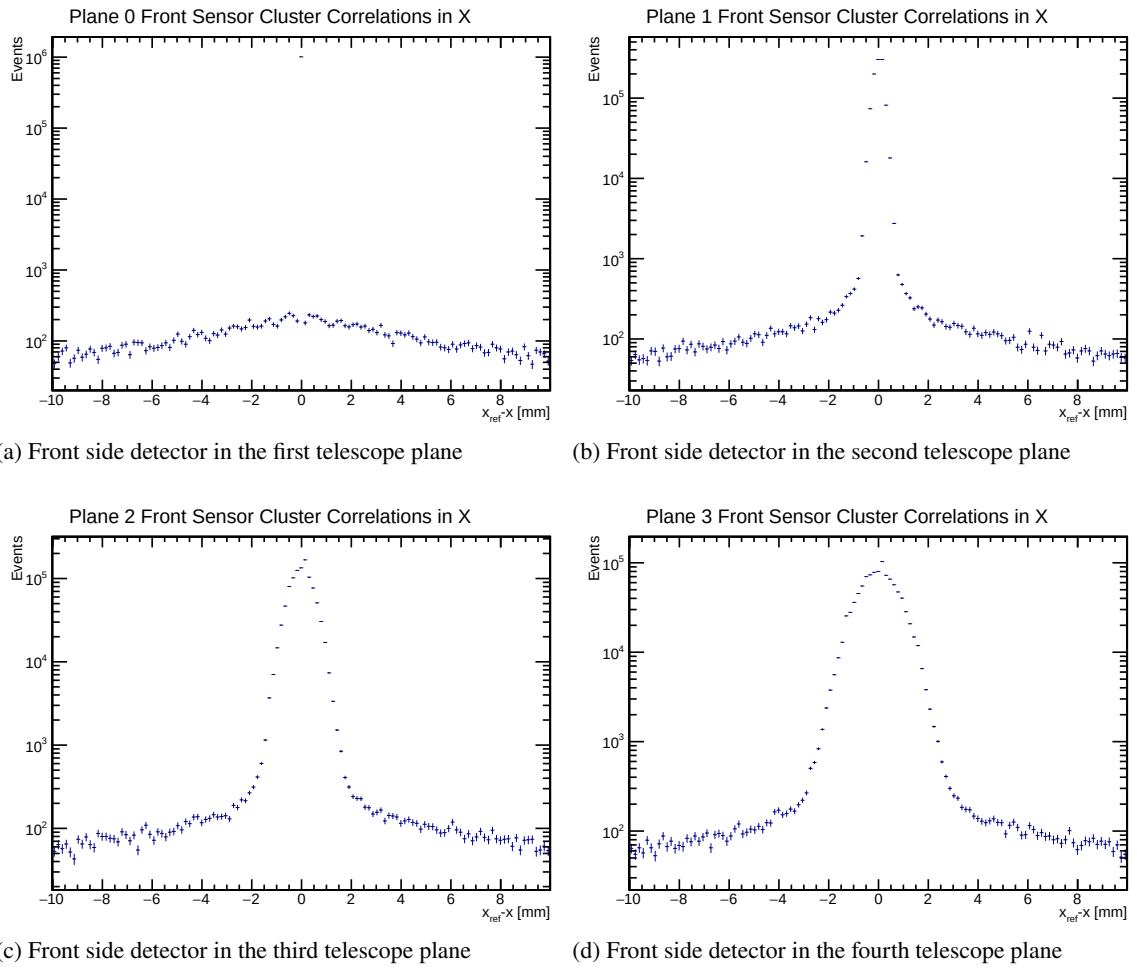


Figure 10.7: Histograms of cluster correlations in x .

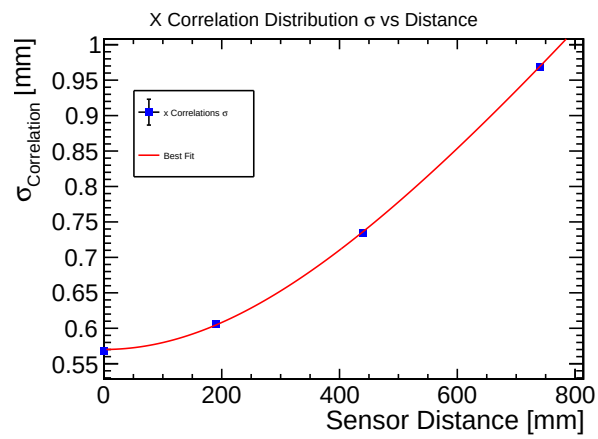
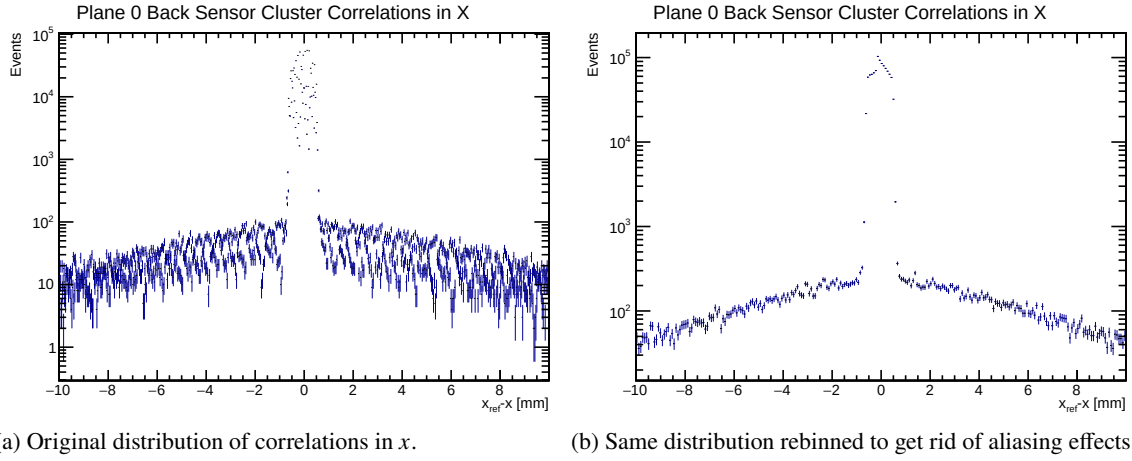


Figure 10.8: Standard deviation of cluster correlations in x vs sensor distance in z with best fit according to Equation (10.19).

Figure 10.9: Histograms of cluster correlations in x for a back side sensor.Table 10.6: Parameters of the Gaussian fit to the reconstructed track angles in x .

Parameter	$\mu_{\text{Tracks}, X}$	$\sigma_{\text{Tracks}, X}$	Amplitude	$\chi^2/\text{N.d.F.}$
Value	$(0.26 \pm 1.04) \mu\text{rad}$	$(1.0392 \pm 0.0007) \text{ mrad}$	$38\,332 \pm 47$	$574.14 / 77$

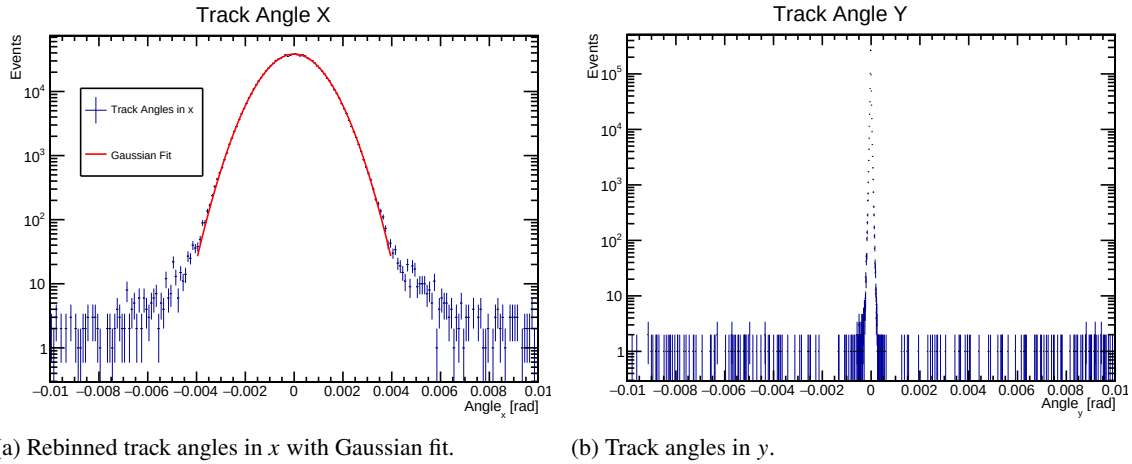


Figure 10.10: Track angles reconstructed from the R0 telescope simulation data.

telescope is

$$\sigma_{\text{telescope}, X} = \sqrt{\sigma_{\text{Tracks}, X}^2 - \sigma_{\text{Beam}, X}^2} = (282.8 \pm 2.7) \mu\text{rad}. \quad (10.20)$$

In the y direction, the standard deviation of the track angles is $92.28 \mu\text{rad}$, which again shows that the detector resolution is insufficient to correctly reconstruct the beam divergence in this axis. A histogram of these track angles is shown in Figure 10.10(b).

In the x -direction, the track residuals are defined as $x_{\text{Cluster}} - x_{\text{Track}}$. They indicate the precision of the tracking on the respective sensor plane. For the first sensor of the telescope, they are plotted for

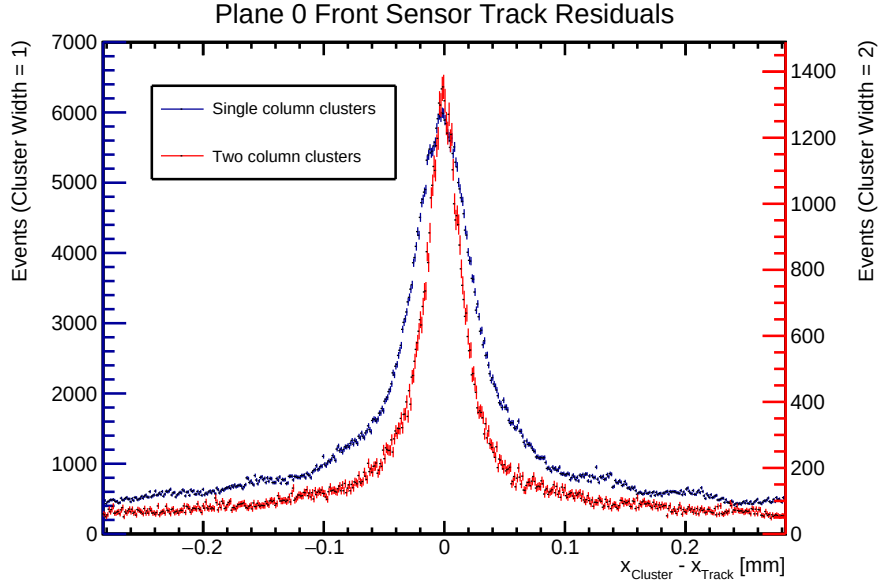


Figure 10.11: Distribution of track residuals in x for width 1 and 2 clusters.

cluster column widths 1 and 2 in Figure 10.11. The corresponding tracking resolutions on the sensor evaluate to

$$\sigma_{\text{Tracking}, X}^{\text{Width}=1} = (111.05 \pm 0.09) \mu\text{m} \text{ and } \sigma_{\text{Tracking}, X}^{\text{Width}=2} = (105.80 \pm 0.24) \mu\text{m}. \quad (10.21)$$

Thus, it is demonstrated that the radial clustering algorithm improves the local resolution for multi-column clusters. The relatively bad local tracking resolution compared to the width of the strips is due to the type of reconstruction algorithm selected. An overlay of the front and back layer strips is not used to calculate a more precise position of the hits. Instead, two positions are reconstructed in the respective centre of the strip, which are then included in the track fitting with equal weighting. Ideally, the track is reconstructed precisely in the centre of these two hits, such that the offsets of both planes cancel each other out. The maximum offsets in x that can result from this approach in the individual sensor plane evaluate to

$$\frac{\Delta R, i}{2} \sin \varphi_S = 189.797, 239.794, 289.781 \text{ and } 319.789 \mu\text{m} \quad (10.22)$$

for strip rows $i = 0$ to 3, respectively. The tracking resolution for all clusters in x is $(110.35 \pm 0.08) \mu\text{m}$, and the corresponding distribution is plotted in Figure B.14(a). As previously stated, most of the tracks in the y -direction are reconstructed as passing straight through the centres of the strips, which leads to an artificially narrow distribution of residuals in this coordinate. This is shown in Figure B.14(b) and does not provide a realistic estimate of the resolution in y .

The distribution of the reduced χ^2 of the individual track fits is usually expected to peak at $\chi^2/\text{N.d.F.} = 1$. However, in this case, the telescope cannot resolve the track angles in y . Also, according to the Monte Carlo residuals, the actual sensor resolution in φ is slightly better than estimated in the definition of the reconstruction algorithm. Therefore, “over-fitting” occurs during the fitting of the straight-line track models, leading to the non-peaked distribution shown in Figure B.15.

10.3.2 Alignment of Detector Positions

So far, the correct simulation and reconstruction chain behaviour have been demonstrated using a setup whose detector positions were precisely known to the reconstruction software. In real particle detectors, deviations that are significant enough to influence the track reconstruction occur in the placement of the silicon sensors. The correct position of the sensors must be reconstructed from the recorded detector data to obtain correct track fits. The model of the R0 beam telescope was used again to verify that the methods built into Corryvreckan also work for the radial strip geometry.

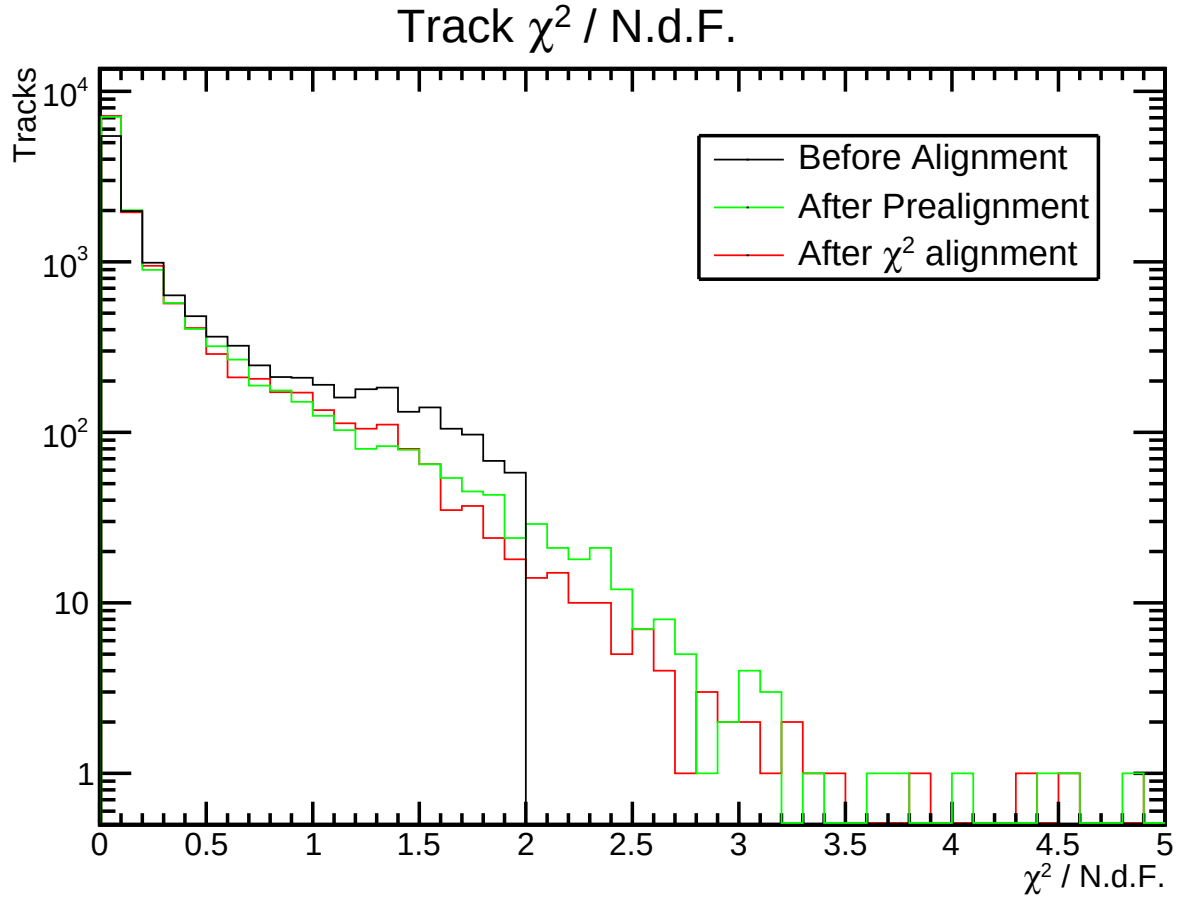
In the ATLAS ITk strip end cap, petal cores are mounted on locking points who are mounted to a precision of $300\text{ }\mu\text{m}$. However, after mounting, the position of these locking points is measured to a precision of $\sigma_{\text{Locking Point}} = 100\text{ }\mu\text{m}$ [101, p. 17]. On the petal core, the tolerance on the position of the locators (which determine the position in the kinetic mount of the end cap) are manufactured to a tolerance of $\sigma_{\text{Locator}} < 25\text{ }\mu\text{m}$ in any direction [92, p. 12]. The modules themselves are then mounted onto the petal with a tolerance of $\sigma_{\text{Loading}} = 50\text{ }\mu\text{m}$ in both x and y direction [190, p. 8]. In total, this means individual module positions in the end cap are known to a precision of

$$\sigma_{\text{Modules}} = \sqrt{\sigma_{\text{Locking Point}}^2 + \sigma_{\text{Locator}}^2 + \sigma_{\text{Loading}}^2} \approx 115\text{ }\mu\text{m} \quad (10.23)$$

in both x and y direction. The precision of the module angle is not specified, but it can be estimated that $\sigma_{\alpha} \approx \sigma_{\text{Modules}}/R_C \approx 0.3\text{ mrad}$. A simulation run of 100 000 input particles was performed with the same setup as before, but with a beam spot size of 10 cm. Apart from the first sensor module, which serves as a reference plane, Gaussian misalignment with precision σ_{Modules} was added in x , y , as well as a misalignment in the module rotation α with precision σ_{α} . The usual Corryvreckan telescope alignment procedure [191, Chapter 7] was then applied: First, all modules were shifted according to the displacement shown in the mean of their correlation plots with the *Prealign* module. Based on this rough alignment, the module *AlignmentChi2* was then used to minimize the track χ^2 further. The resulting positions can be found in Table 10.7. For all modules, the alignment does not really change the y coordinate, since the added misalignment is significantly smaller than the detector resolution in that direction. However, in x , all but one module moved closer to their simulated position due to the prealignment procedure. Before alignment, the average $\chi^2/\text{N.d.F.}$ of reconstructed tracks was 0.5078. After prealignment it improved to 0.2576. While the χ^2 -based alignment step was able to reduce the average $\chi^2/\text{N.d.F.}$ down to 0.2471, the module placement actually worsened for all modules. This, and the fact that with a perfectly aligned telescope, the average $\chi^2/\text{N.d.F.}$ was higher at 0.2574 than after the alignment, speak in favor of the algorithm not being able to find an actual improvement on the positions found in the prealignment due to the detector resolution. A comparison of the track χ^2 distributions at all steps is shown in Figure 10.12.

Table 10.7: Positions of the misaligned modules shown at different steps of the alignment process.

Module	Real Positions		After Prealignment		After χ^2 Alignment	
	$x_{\text{Real}} [\mu\text{m}]$	$y_{\text{Real}} [\mu\text{m}]$	$x_{\text{Real}} - x [\mu\text{m}]$	$y_{\text{Real}} - y [\mu\text{m}]$	$x_{\text{Real}} - x [\mu\text{m}]$	$y_{\text{Real}} - y [\mu\text{m}]$
Layer 0, Front	0	0	0	0	0	0
Layer 0, Back	-128.08	227.61	79.31	226.76	164.77	226.76
Layer 1, Front	24.45	-268.42	-4.64	-267.04	-31.12	-267.04
Layer 1, Back	131.79	72.89	80.75	72.45	148.59	72.45
Layer 2, Front	-54.17	-126.92	-2.52	-126.33	-47.80	-126.33
Layer 2, Back	3.55	17.82	79.65	17.38	125.79	17.38
Layer 3, Front	5.02	-173.62	-2.63	-173.60	-63.16	-173.60
Layer 3, Back	179.59	47.37	87.02	46.81	105.17	46.81

Figure 10.12: Track χ^2 / N.d.F. before alignment, after prealignment and after χ^2 -based alignment.

10.4 System Test Cosmic Ray Setup

Since the expected functionality of the simulation of the radial strip geometry has been demonstrated using the R0 telescope, more complex arrangements of modules were simulated. In this section, the performance of a possible detector configuration in the ITk strip end cap System Test (see Section 6.2) is evaluated for measuring the flux of cosmic muons.

10.4.1 Procedural Generation of the ITk Strip End Cap Geometry

The System Test has a support structure in which petals can be inserted in various positions. To enable simulating the cosmic ray flux for different configurations, a procedural geometry generator calculating the correct module positions was created for this thesis. The positions of the centre point O_W of the individual front side modules on a petal were determined in relation to the centre point O using the official ATLAS CAD (Computer Aided Design) model [192] and are listed in Table 10.8. From these, the positions of the modules on the back of the petal are determined by a shift by its total thickness of -6.430 mm in the z direction and rotating all modules 180° around their y axis. The petal constructed in this way corresponds to a petal in segment 0 of disc 5. Each disc consists of 32 petals, arranged in two layers of 16 petals each with a distance of 17 mm. For the other segments, the modules must therefore be rotated by an amount of

$$\Delta\alpha = n_{\text{segment}} \cdot 22.5^\circ + \begin{cases} 11.25^\circ, & \text{if back layer petal} \\ 0, & \text{if front layer petal} \end{cases} \quad (10.24)$$

around the centre point, so their new positions and rotations in the xy plane evaluate to

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos(\Delta\alpha) & -\sin(\Delta\alpha) \\ \sin(\Delta\alpha) & \cos(\Delta\alpha) \end{pmatrix} \cdot \begin{pmatrix} x_0 \\ y_0 \end{pmatrix}, \quad \alpha = \alpha_0 + \Delta\alpha. \quad (10.25)$$

Additionally, the modules must be moved by

$$\Delta z = \Delta z_{\text{layer}} + \begin{cases} 0, & \text{if back layer petal} \\ 17 \text{ mm}, & \text{if front layer petal} \end{cases} \quad (10.26)$$

in z depending on the disc; the offsets Δz_{layer} of the different layers of the end cap are listed in Table 10.9. Finally, the centre of gravity of the generated modules in the xy plane is estimated by averaging the position of all modules. All modules are then moved as a group so that their centre of gravity in the xy plane lies at the origin of the coordinates.

10.4.2 Cosmic Ray Flux Measurement

A potential cosmic ray telescope setup that could be realized in the System Test consists of four petals arranged vertically in discs 0 to 3. In order to better recreate the conditions in the laboratory environment, a 5 cm thick square concrete ceiling was added to the simulation geometry, which is placed at a distance of 10 cm from the surface of the first petal. The *DepositionCosmics* module generated cosmic muons in Allpix² on an area of 1 m^2 , which hit the modules after passing through the concrete layer. This simulation setup is shown in Figure 10.13. A total of one million events were

Table 10.8: Front module positions relative to the beam axis O together with rotation α around the module centre.

Module	x [mm]	y [mm]	z [mm]	α_0 [°]
R0	1.535167	438.608598	3.215	-0.203829
R1	1.871244	534.632891	3.215	-0.203851
R2	2.132949	609.398478	3.215	-0.203887
R3	37.596466	696.882840	3.215	-3.091339
	-32.717383	697.128877	3.215	2.683739
R4	43.752278	811.289297	3.215	-3.090189
	-38.072132	811.575665	3.215	2.682580
R5	49.479329	917.412896	3.215	-3.090438
	-43.056181	917.736753	3.215	2.682817

Table 10.9: Layer offsets in z of the ITk strip end cap.

Layer	0	1	2	3	4	5
Δz_{layer} [mm]	1338	1148	898	613	318	0

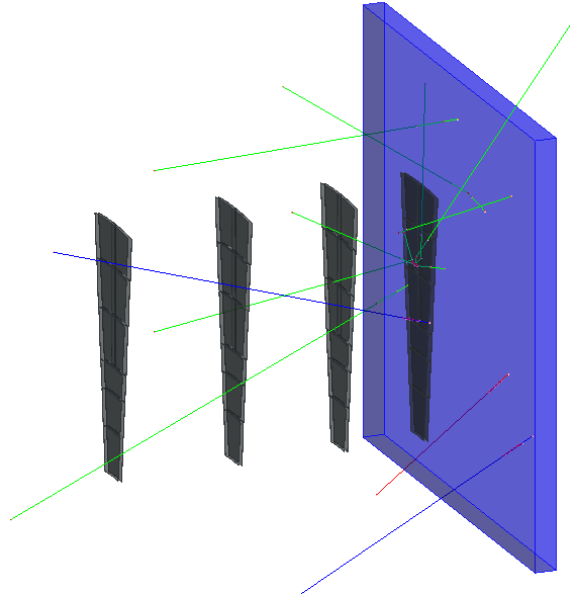


Figure 10.13: Simulation setup for the four petal cosmic ray telescope. The muons are generated such that they pass through the concrete layer (blue) before reaching the petals.

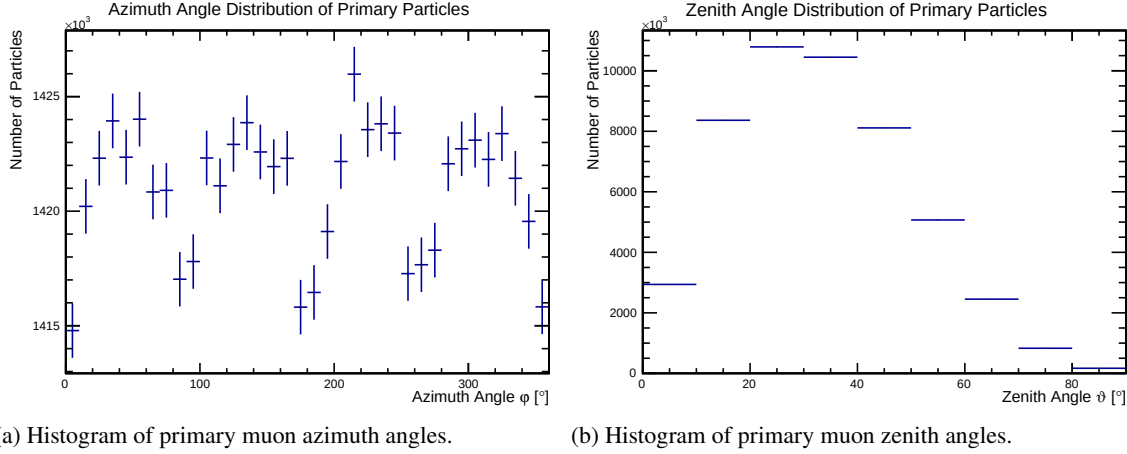


Figure 10.14: Angles of simulated primary cosmic ray particles.

simulated, with 50 cosmic muons being generated simultaneously per event. This corresponds to the number of cosmic muons that occur at sea level over a period of $t_{\text{Sim}} = 175\,870$ s. After clustering, 116 520 tracks with at least seven associated clusters could be reconstructed in Corryvreckan from the Allpix² data. The $\chi^2/\text{N.d.F.}$ distribution of those tracks shows a clear peak close to $\chi^2/\text{N.d.F.} = 1$ (see Figure 10.15(a)), indicating that, as opposed to the R0 telescope setup, the telescope is sensitive to the track angles in both x and y .

The distributions of the zenith and azimuth angles of the primary particles are shown in Figure 10.14. The 2D distribution is homogeneous in ϕ as can be seen in Figure B.16(a). Together with the angular distributions of the reconstructed tracks shown in Figure B.17, the effective detector area can be calculated as described in Section 8.2.4. The error of the effective area is calculated as

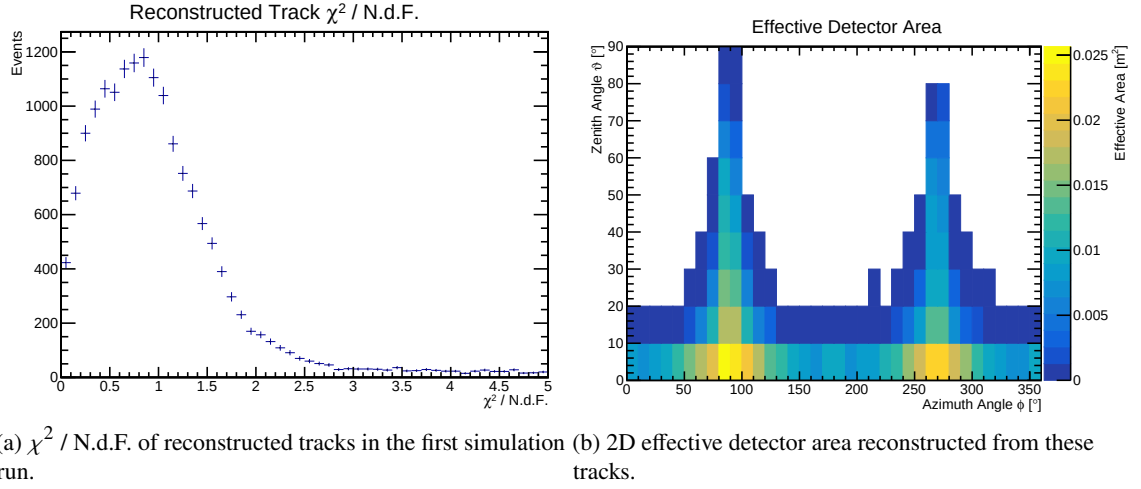
$$\sigma_{A_{\text{eff}}} = \sqrt{\left(\frac{\partial A_{\text{eff}}}{\partial N_{\text{Tracks}}}\right)^2 \sigma_{N_{\text{Tracks}}}^2 + \left(\frac{\partial A_{\text{eff}}}{\partial N_{\text{MC}}}\right)^2 \sigma_{N_{\text{MC}}}^2} = A_{\text{eff}} \cdot \sqrt{\frac{1}{N_{\text{Tracks}}} + \frac{1}{N_{\text{MC}}}} \quad (10.27)$$

since the error of the number of primary particles is $\sigma_{N_{\text{MC}}} = \sqrt{N_{\text{MC}}}$ and $\sigma_{N_{\text{Tracks}}} = \sqrt{N_{\text{Tracks}}}$ for the reconstructed tracks. The effective detector area calculated from the simulation results is plotted as a function of the zenith and azimuth angle in Figure 10.15(b) and Figure B.18. For $\phi = 90^\circ$ and $\phi = 270^\circ$, the detector area is significantly larger than for other azimuth angles. This is due to the petal being much longer in the y -direction than in the x -direction. Therefore, particles at these angles have a higher chance of passing through all layers of the cosmic ray telescope, causing the reconstruction of a track.

If the data from the same simulation from which the effective area was calculated were used to calculate the cosmic ray flux, it would cancel the n_{Tracks} contribution as in

$$\Phi = \frac{N_{\text{Tracks}}}{A_{\text{eff}} \cdot t_{\text{sim}} \cdot \Omega} = \frac{N_{\text{MC}}}{A_{\text{MC}} \cdot t_{\text{sim}} \cdot \Omega}, \quad (10.28)$$

thus only reproducing the flux directly from the distribution of primary Monte Carlo particles. Therefore, a second run with 100 000 Events was performed with the same parameters with a different


 Figure 10.15: Track χ^2 and 2D effective detector area in the first simulation run.

random seed, corresponding to a simulation time of $t_{\text{sim}} = 17\,589.2\text{ s} \approx 4.9\text{ h}$. From this run, 11 689 tracks were reconstructed, whose distributions in ϕ and ϑ are shown in Figure B.17(c) and Figure B.17(d). The cosmic muon flux for each bin $[\vartheta_l, \vartheta_h) \times [\phi_l, \phi_h)$ in azimuth and zenith angle evaluates to

$$\Phi = \frac{N_{\text{Tracks}}^{\text{Run 2}}}{A_{\text{eff}}^{\text{Run 1}} \cdot t_{\text{sim}}^{\text{Run 2}} \cdot \Omega}, \quad (10.29)$$

where $N_{\text{Tracks}}^{\text{Run 2}}$ refers to the number of tracks reconstructed in simulation run 2 in the bin, $t_{\text{sim}}^{\text{Run 2}}$ to the simulation time of run 2, $A_{\text{eff}}^{\text{Run 1}}$ to the effective detector area in that solid angle bin that was calculated using the run 1 results, and

$$\Omega = \int_{\phi_l}^{\phi_h} d\phi \int_{\vartheta_l}^{\vartheta_h} d\vartheta \sin(\vartheta) = (\phi_h - \phi_l) \cdot (\cos(\vartheta_l) - \cos(\vartheta_h)) \quad (10.30)$$

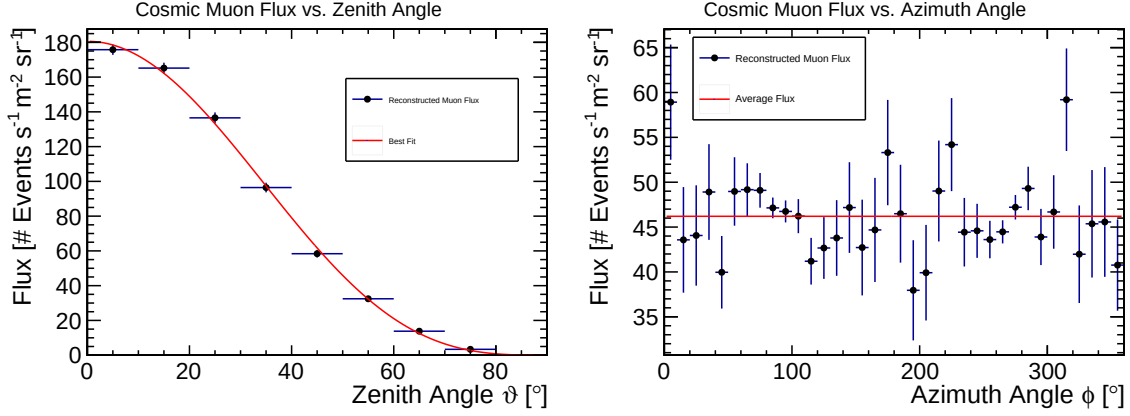
the total solid angle covered by the bin. The error of the particle flux in each bin of solid angle is thus given by

$$\sigma_{\Phi} = \sqrt{\left(\frac{\partial \Phi}{\partial N_{\text{Tracks}}^{\text{Run 2}}}\right)^2 \sigma_{N_{\text{Tracks}}^{\text{Run 2}}}^2 + \left(\frac{\partial \Phi}{\partial A_{\text{eff}}^{\text{Run 1}}}\right)^2 \sigma_{A_{\text{eff}}^{\text{Run 1}}}^2} = \Phi \cdot \sqrt{\frac{\sigma_{A_{\text{eff}}}^2}{A_{\text{eff}}^2} + \frac{1}{N_{\text{Tracks}}^{\text{Run 2}}}}. \quad (10.31)$$

The reconstructed cosmic muon flux in dependence of zenith angle ϑ is shown in Figure 10.16(a). A cosine power law as in Equation (8.6) was fitted to the data with good agreement, the fit results are listed in Table 10.10. In dependence of the azimuth angle, the flux is expected to be constant. Fitting a constant value to the simulated flux data in ϕ , the mean particle flux in the hemisphere $[0^\circ, 360^\circ) \times [0^\circ, 90^\circ]$ evaluates to $(46.20 \pm 0.45) \text{ Events/s/m}^2/\text{sr}$ with $\chi^2/\text{N.d.F.} = 38.4/35$ (see Figure 10.16(b)).

Table 10.10: Parameters of the cosine model fit to the reconstructed zenith angles.

Parameter	I_0	n	$\chi^2/\text{N.d.F.}$
Value	$(180.588 \pm 2.129) \text{ Events/s/m}^2/\text{sr}$	4.09887 ± 0.06484	$6.59988 / 6$

(a) Muon flux vs. ϑ with cosine model fit.(b) Muon flux vs. ϕ with average flux.Figure 10.16: Cosmic muon flux reconstructed from run 2 simulation data vs. ϑ and ϕ .

10.4.3 Detector Resolution

The detector resolution in ϑ and ϕ must be estimated to ensure that the reconstructed angular distributions are accurate. For this purpose, simulations were created for all combinations from the parameter space

$$(\vartheta \in \{0^\circ, 5^\circ, \dots, 50^\circ\}) \times (\phi \in \{0^\circ, 5^\circ, \dots, 355^\circ\}) \quad (10.32)$$

in which a 10 cm wide beam of μ^- with an energy of 10 GeV without angular divergence was simulated as passing through the detector's geometric centre of gravity $(0, 0, z_{\text{COM}})$ from the direction of (ϑ, ϕ) . z_{COM} was found by simply averaging all module z positions. Ten thousand particles were simulated for each set of parameters, from which tracks were then reconstructed. Their number and the mean value and standard deviation of ϑ and ϕ were measured. The efficiency in dependence of particle incidence angle (shown in Figure B.20(a)) again shows the two characteristic peaks for $\phi = 90$ and 270° .

The resulting detector resolutions σ_ϑ and σ_ϕ are shown in Figure 10.17. In particular, the poor azimuth resolution for $\vartheta \leq 5^\circ$ is striking and can be explained by the fact that particles moving approximately parallel to the z -axis are reconstructed on the other side of the axis in extreme cases due to the nonzero resolution in ϑ , i.e. with a maximum measurement error of 180 deg. The relative biases

$$\frac{\vartheta' - \vartheta}{\sigma_\vartheta} \text{ and } \frac{\phi' - \phi}{\sigma_\phi}, \quad (10.33)$$

where ϑ' and ϕ' are the mean angles of the reconstructed tracks, are shown in Figure B.19. Except at the edges of the sensitive range, the detector bias in ϑ is less than 1, i.e. the measurement error is smaller than the resolution. For small ϕ , the detector bias is also increased for $\vartheta \leq 5^\circ$.

To get a better picture of the detector resolution and its associated uncertainty, one hundred

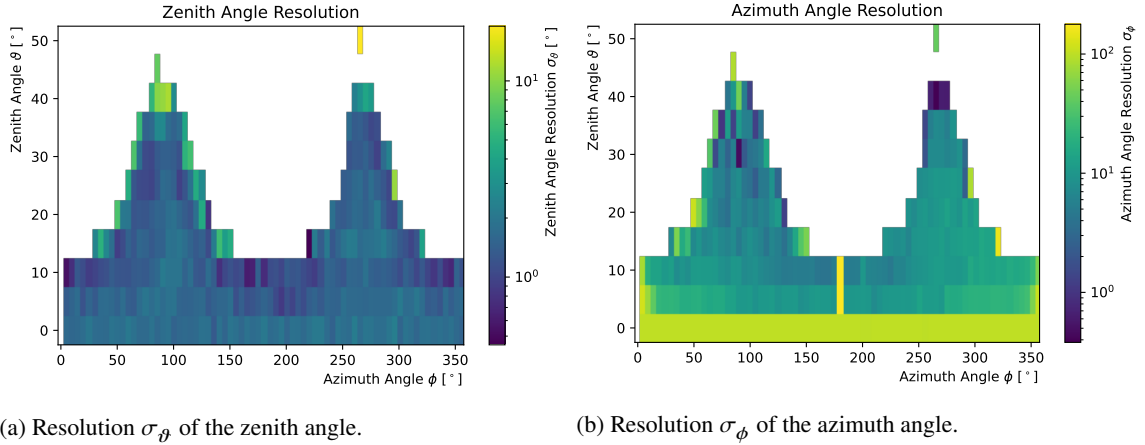


Figure 10.17: Track angle resolutions vs. azimuth and zenith angle.

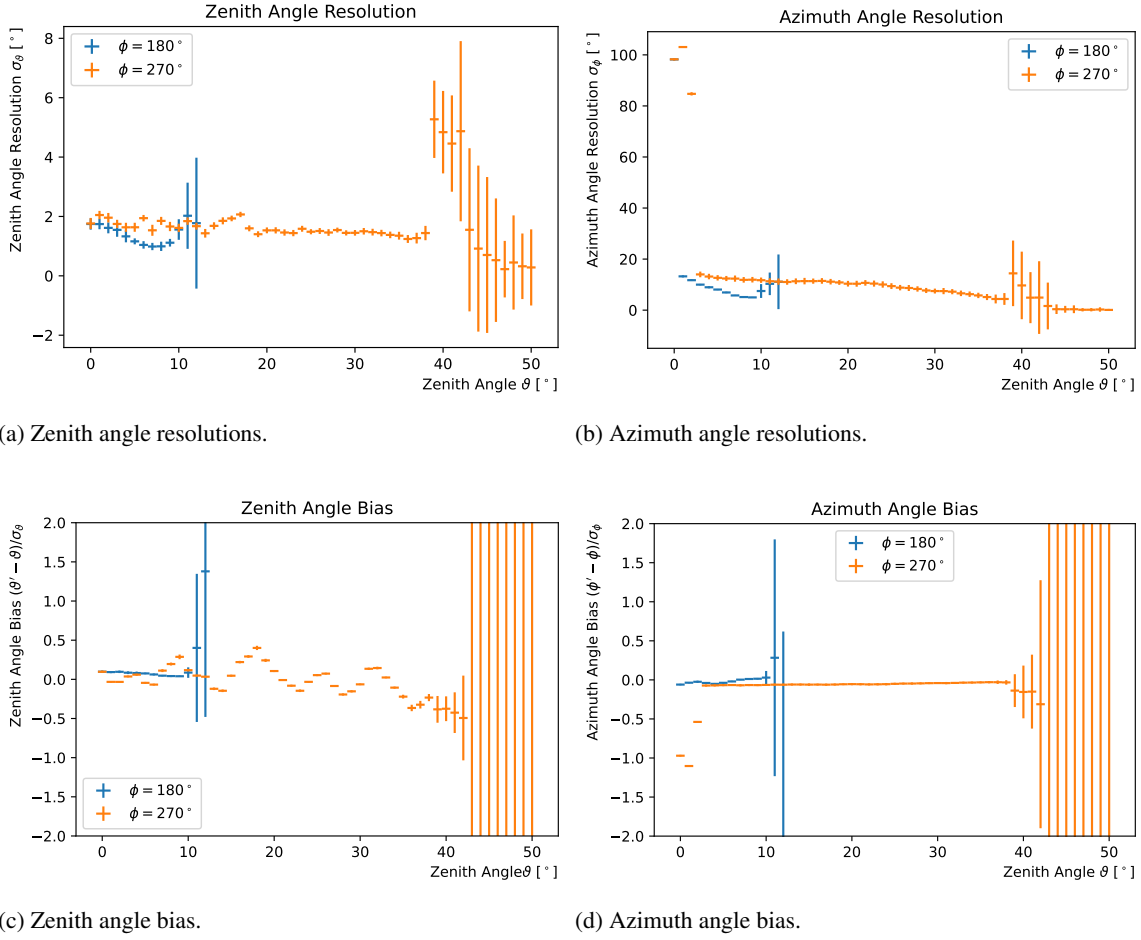
simulations per value of θ with ten thousand particles with $\phi = 180^\circ$ and ten simulations with $\phi = 270^\circ$ were carried out on the parameter space $\theta \in \{0^\circ, 1^\circ \dots 50^\circ\}$. From this, the detector resolutions' mean value and standard deviation as well as the reconstructed track angles were determined. The detector shows no significant bias in θ , it is also unbiased in ϕ except for $\theta \leq 3^\circ$. Its resolution is significantly smaller than the binning of $\Delta\theta = 10^\circ$ previously used in the simulation of the cosmic muon flux, therefore allowing for an accurate reconstruction of the flux in θ . In ϕ , the resolution is larger than 10° for $\theta \leq 3^\circ$ at $\phi = 180^\circ$, and for $\theta \leq 25^\circ$ at $\phi = 270^\circ$ (see Figure 10.18). For $\theta \leq 3^\circ$, the order of the resolution in ϕ is consistent with tracks being reconstructed from any random direction (which would mean $\sigma_\phi = 360^\circ/\sqrt{12} \approx 104^\circ$). For a plot of the detector's efficiency in dependence of the track zenith angle, refer to Figure B.20(b). In conclusion, the detector is unbiased and shows good resolution in θ , but the resolution in ϕ is not good enough to justify a fine binning over a large portion of the sensitive solid angle.

10.5 Estimation of Efficiency Curves with Cosmic Rays

Before the modules are loaded onto the petal, the lower limit of the operating window (see Section 4.1.2) is determined using a noise occupancy scan (see Section 7.1). The upper limit specified by the efficiency curve was determined for each module type in a high-energy test beam facility (see e.g. [90, 91]). As such, a test beam is very time-consuming, so only occasional checks of the modules' efficiency will be carried out during detector production. One possibility for measuring the efficiency curve for more modules would be to use cosmic muons, as they are abundant and independent of the detector production facility. The method described below allows the efficiency of a module on a petal to be estimated by comparing it with hit information from the module on the opposite side.

10.5.1 Proposed Method

As the strips on both sides of the petal overlap, one side of the petal can be used as a reference detector. It operates with a threshold above the operating window, meaning that the noise occupancy can be assumed to be very low compared to the front-side module. If a threshold scan is now performed on


 Figure 10.18: Resolutions and biases in ϑ and ϕ for $\phi = 180^\circ$ and $\phi = 270^\circ$.

the front side and both sides of the petal are only read out when an external trigger signal indicates a cosmic muon passing through the detector, the module's efficiency can be estimated from the correlation of the hits on both detectors. For this purpose, the hits of the reference plane per event are first clustered to prevent hits of a single particle from being considered multiple times. An overlapping strip hit on the other module is then searched for all strip hits in these reference clusters. If such a hit is found, it is assumed to be correlated with the cluster. It is likely that a passing charged particle caused both hits when both the noise occupancy on the reference plane and the hit occupancy from real particles are low. With this method, one expects a much higher systematic error in measuring the efficiency since both hits belonging to a real passing charged particle could only be definitely verified using external tracking.

Since the inner and outer radii of the rows of strips are very large compared to the length of the strips and the width of the overlapping area caused by the stereo angle φ_S , the overlapping of the strips can also be considered in a first approximation as a overlapping of strips of length

$$\Delta R = R_{\text{outer}} - R_{\text{inner}}$$

starting and ending at the same y -coordinates, where R_{inner} , R_{outer} are the inner and outer radius of the row of strips. The length of the overlap thus results in

$$\Delta x = \frac{\Delta R}{2} \tan \varphi_S. \quad (10.34)$$

The external trigger setup's solid angle of acceptance determines the maximum angle in x to the normal vector of the petal surface at which cosmic muons can reach the detector. In the case of the scintillator trigger of the System Test (see Section 6.2.6), the most oblique possible straight line, which triggers a scintillator above and below the petals, has a shift in x of $l = 1$ m over $h = 2.34$ m in z . According to the intercept theorem, a maximum displacement in x of

$$\Delta x_{\text{Trigger}}^{\text{Max}} = \frac{l \cdot d}{h} = 2.71 \text{ mm} \quad (10.35)$$

is produced over the distance of the petal thickness $d = 6.43$ mm between the two sensors.

10.5.2 Monte Carlo Feasibility Study

Monte Carlo simulations were carried out using the ATLAS ITk strip end cap module implemented in the Allpix² software package presented in Section 10.2.1 to test the feasibility of the proposed method for determining the module efficiency curve. First, a baseline efficiency curve was simulated with a single R0 module (from now on referred to as the DUT (Device Under Test)). For this purpose, a beam of μ^- with 10 GeV was directed at the DUT. Its diameter was limited to 10 mm to ensure that every particle hits the DUT. The other settings of the simulation software correspond to those discussed in Section 10.2.1. Only the threshold of the hit digitisation was varied between 0 and 95 ke⁻ in steps of 5 ke⁻. $N_{\text{Events}} = 100\,000$ particles were simulated per threshold value. The efficiency was calculated from this threshold scan as

$$\varepsilon = \frac{N_{\text{DUT}}}{N_{\text{Events}}} \text{ with error } \sigma_{\varepsilon} = \frac{\sqrt{N_{\text{DUT}}}}{N_{\text{Events}}}, \quad (10.36)$$

where N_{DUT} is the number of events in which at least one cluster was found on the DUT. Concerning the statistical error, only confidence intervals with $\varepsilon \leq 1$ are physical.

In addition, an efficiency curve was created using the new method proposed above. For this purpose, two R0 modules were simulated at a distance of 6.43 mm (corresponding to the distance between both sides of a petal), whereby the rear module was rotated by 180° around the z -axis in its centre point O_W . This rear module was operated with a threshold of 25 ke⁻ and served as the reference plane. To compensate for the selection of events requiring a hit in the reference detector, a total of 300 000 events were simulated. Since Allpix² does only add noise to hits during the digitisation step, there are no pure noise hits. Hence, the threshold of the reference plane should not affect the result of the scan in any significant way, since there is no noise occupancy. In a real experiment, a large threshold with low noise occupancy needs to be chosen, significantly slowing data taking due to the low efficiency of the reference plane. The analysis was performed using the Corryvreckan framework with the clustering algorithm described in Section 10.2.2. For all clusters on the reference detector, it

was checked whether a strip hit exists on the DUT for which

$$|x_{\text{Reference}}^{\text{Strip}} - x_{\text{DUT}}^{\text{Strip}}| \leq \Delta x + \Delta x_{\text{Trigger}}^{\text{Max}} \text{ and } |\text{Row}_{\text{Reference}}^{\text{Strip}} - \text{Row}_{\text{DUT}}^{\text{Strip}}| \leq 1 \quad (10.37)$$

applies by iterating over the strips of the reference cluster. This criterion considers the overlapping of strips discussed above and the possibility that a particle triggers a strip in a different row of the front sensor due to particles passing close to the radial border of the strip rows. The efficiency is then calculated as

$$\varepsilon = \frac{N_{\text{Correlated}}}{N_{\text{DUT}}} \text{ with error } \sigma_{\varepsilon} = \varepsilon \cdot \sqrt{\frac{1}{N_{\text{Correlated}}} + \frac{1}{N_{\text{Reference}}}}, \quad (10.38)$$

with $N_{\text{Reference}}$ being the number of events with at least one cluster registered in the reference plane, and $N_{\text{Correlated}}$ the number of reference clusters for which a correlated strip hit in the DUT was found.

The calculated efficiency curves obtained with both methods are shown in Figure 10.19, and the corresponding data are listed in Table 10.11. In comparison, the curve of the two-sided method deviates downwards systematically by around one percentage point in the area relevant for determining the operating window of $\varepsilon > 99\%$. The direct method for determining the efficiency provides threshold $\leq 10 \text{ ke}^-$ as the upper limit of the operating window. For the proposed method, no data point satisfies the criterion. However, several confidence intervals overlap the specification of 99%. Considering the statistical errors, this results in the same operating window as with the reference method.

This result suggests the method is feasible for estimating the efficiency of modules loaded on the petal. However, the results from the proposed method did not align perfectly with the simulated efficiency curve. For the determination of the module's operating window, the efficiency has to be measured with a precision much better than 1%. Therefore, comparison of real world data from the petal with efficiency curves obtained in the testbeam, ideally with the same modules, should be undertaken before the results can be used for quality control during detector production.

10.6 Conclusion

The new implementation of the ATLAS ITk strip end cap module geometry within the Allpix² and Corryvreckan frameworks was evaluated. Using a beam telescope-like setup of R0 modules, the hit association, clustering and basic track reconstruction could be confirmed functional. While the usual prealignment procedure using the correlation data improved the alignment of most telescope modules, the results with the χ^2 based approach were inconclusive.

A simulation of the System Test with four inserted petals revealed that a measurement of the cosmic muon flux with a good resolution is possible with this setup.

Finally, a proposal was explored to measure the efficiency curves with loaded petals using cosmic muons. Reasonable agreement with the simulated module efficiency was achieved.

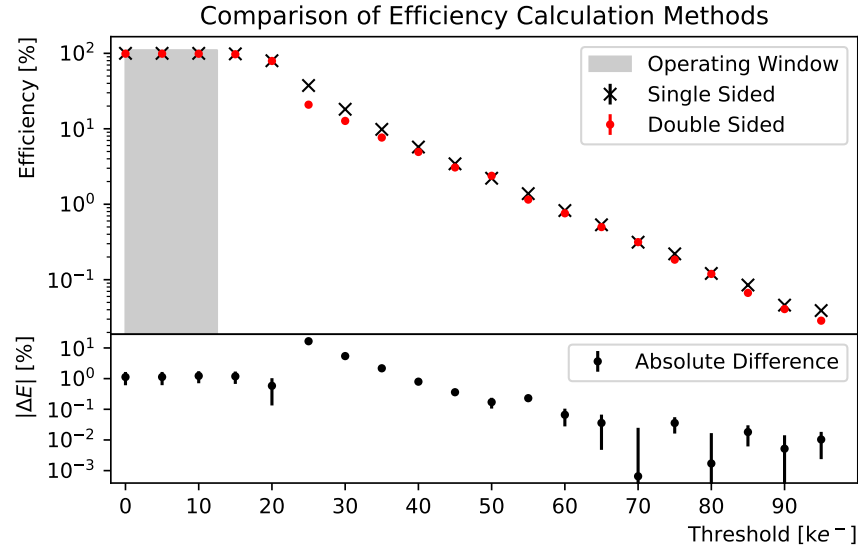


Figure 10.19: Comparison of the proposed method of double sided efficiency estimation (red dots) with the efficiency curve obtained directly from the Monte Carlo data (black crosses) together with the mean absolute difference. The grey area is the operating window determined with both simulation methods.

Table 10.11: Monte Carlo simulated efficiency with the single and double module method. The resulting operating window is marked by the greyed out cells.

Threshold [ke^-]	Single Module Efficiency [%]	Double Module Efficiency [%]
0	$100.0^{+0.00}_{-0.3}$	98.9 ± 0.4
5	$100.0^{+0.00}_{-0.3}$	98.9 ± 0.4
10	$99.9^{+0.1}_{-0.3}$	98.7 ± 0.4
15	98.4 ± 0.3	97.3 ± 0.4
20	79.8 ± 0.3	79.2 ± 0.4
25	37.4 ± 0.2	20.9 ± 0.1
30	18.1 ± 0.1	12.7 ± 0.1
35	9.83 ± 0.10	7.65 ± 0.08
40	5.73 ± 0.08	4.93 ± 0.07
45	3.43 ± 0.06	3.07 ± 0.05
50	2.21 ± 0.05	2.38 ± 0.05
55	1.38 ± 0.04	1.15 ± 0.03
60	0.825 ± 0.030	0.759 ± 0.030
65	0.534 ± 0.020	0.498 ± 0.020
70	0.314 ± 0.020	0.315 ± 0.020
75	0.22 ± 0.01	0.184 ± 0.010
80	0.121 ± 0.010	0.119 ± 0.010
85	0.085 ± 0.009	0.0669 ± 0.0080
90	0.046 ± 0.007	0.0408 ± 0.0060
95	0.039 ± 0.006	0.0286 ± 0.0050

Conclusion and Outlook

This chapter summarises the most important results of this thesis and presents an outlook on the next steps with the System Test in the context of the ongoing detector production.

During the start of petal production, the DESY BTR was finalised, which allows the testing of bus tapes for electrical defects and dimensional deviations. As part of an ATLAS authorship qualification task, the entire Pre-Production B of the bus tapes was tested in the bare and co-cured state. In addition, all tapes that have been co-cured at DESY to date were successfully tested with the setup.

The ITk strip end cap System Test at DESY is a test bench for all detector components and services. An Interlock & Monitoring System was developed for this setup, which records environmental data from the dry air atmosphere and the cooling system. It also controls access to the interior of the setup and the operation of the cooling system and power supply, keeping personnel away from the modules' high voltage and preventing moisture condensation on sensitive detector components. By measuring the dew point inside of the closed dry atmosphere, it was possible to show that even in the event of a sudden failure of the dry air supply, there is enough time to warm up the setup using the cooling system without penetrating moisture damaging the detector. Within the System Test, physics data of cosmic muons was taken for the first time using realistic electrical and cooling services as present in the final ATLAS ITk detector. During this measurement campaign, which lasted several days, the cooling, power supply, and DAQ systems all ran stably. It represents the most prolonged continuous operation of a petal at DESY to date.

The petal coldbox was built as a second setup for testing individual petals during detector production. Extensive studies were carried out on the behaviour of the modules with the first three available PPB petals. It was shown that the ITSDAQ system, which is used in detector production for testing individual hybrid assemblies and modules, but also entire petals, provides repeatable results with loaded petals for the noise of the strips and the noise occupancy curves relevant for determining the operating window. A comparison with the FELIX + YARR DAQ system revealed that the latter suffers from a problem with the trimming of the individual channels, which leads to strongly deviating measurement results. Based on these findings, the ITk strips DAQ community is working on improving the system to achieve results comparable to those of ITSDAQ. Instances of new noise features occurred after the reception of a petal at DESY. They could be attributed to foreign bodies on the surface of the silicon sensors and were successfully removed using ionised air. The petal grabber was identified as a possible source of these disturbances, for which a replacement is now being designed based on the petal insertion hand. The influence of module loading on the noise was investigated but could not be

conclusively elucidated due to the lack of cooling during the module reception test. A comparison of the noise in the System Test and the petal coldbox showed that there were no experimentally relevant differences between the two environments. The noise crosstalk between the two sides of the petals was measured. It was found not to be a relevant source of interference for the final detector.

The implementation of the radial strips geometry in the simulation software Allpix² and the reconstruction framework Corryvreckan was first tested in simulations using a fictitious beam telescope consisting of R0 modules. Among other things, a way of carrying out the clustering in radial coordinates was presented to subsequently transform it into Cartesian coordinates, taking the respective strip resolutions into account. As it was demonstrated using the beam telescope that this method is effective, a possible cosmic muons telescope setup based on the System Test geometry was then investigated. From the simulated data, the flux of the cosmic muons was successfully reconstructed, and the angular resolution of this setup was determined by means of simulations. Finally, a method for measuring the module efficiency as a function of the threshold for modules on the petal was presented, which is based on the correlation of hits with the rear-mounted module. Using a Monte Carlo simulation, it was shown that the method could be suitable for determining the upper limit of the operating window of the modules. In ongoing detector production, more petals will become available to be inserted into the System Test. This will make it possible to measure the noise crosstalk between petals in the front and back layers in the same disc, as well as in between the discs. Once enough petals have been installed, data collection of more useful cosmic muon samples will be possible. Tracking cosmic muons will not only allow comparison with the simulations undertaken in this thesis, but will also enable the measurement of the efficiencies of all modules in the System Test. If modules tested in a high-energy test beam campaign should find their way onto a petal, the method for determining the operating window presented in this thesis could also be tested experimentally.

As soon as the first petals are installed in the global support structure of the end cap, the transfer of the knowledge gained from the System Test will be a high priority. In the so-called Segment Test, the petals will be operated with CO₂ cooling and read out; the services used and tests carried out will, for the most part, correspond to those of the System Test.

Appendix

APPENDIX **A**

Additional Tables

Additional tables not part of the main body of the thesis can be found in this appendix.

Appendix A Additional Tables

Table A.1: Test results for all pre-production bus tapes tested both in the bare and the co-cured state with the DESY BTR.

Serial Number	Before Co-curing			After Co-curing		
	Stretch X	Stretch Y	Debugged Lines	Stretch X	Stretch Y	Debugged Lines
20USEBT1000005	-0.00014	-0.00084	4	-0.00016	-0.00062	1
20USEBT1000006	-0.00019	-0.00115	1	0.00020	-0.00051	2
20USEBT1000007	-0.00035	-0.00127	2	-0.00005	-0.00045	1
20USEBT1000009	-0.00029	-0.00068	3	-0.00003	-0.00003	1
20USEBT1000010	-0.00011	-0.00082	1	0.00008	-0.00033	1
20USEBT1000012	-0.00054	-0.00121	2	-0.00022	-0.00094	2
20USEBT1000014	-0.00037	-0.00097	2	0.00002	-0.00070	3
20USEBT1000015	-0.00043	-0.00101	1	-0.00016	-0.00079	1
20USEBT1000016	-0.00063	-0.00127	1	-0.00048	-0.00108	0
20USEBT1000017	-0.00049	-0.00104	1	-0.00022	-0.00082	1
20USEBT1000018	-0.00042	-0.00097	4	-0.00031	-0.00088	1
20USEBT1000019	-0.00048	-0.00107	3	-0.00025	-0.00091	0
20USEBT1000020	-0.00027	-0.00092	1	-0.00001	-0.00072	0
20USEBT1000021	-0.00040	-0.00108	1	-0.00010	-0.00084	0
20USEBT1000022	-0.00056	-0.00106	1	-0.00030	-0.00081	1
20USEBT1000023	-0.00015	-0.00093	1	0.00011	-0.00075	0
20USEBT1000024	-0.00033	-0.00121	1	-0.00009	-0.00099	1
20USEBT1000025	-0.00001	-0.00093	1	0.00025	-0.00078	0
20USEBT1000027	-0.00022	-0.00102	2	0.00009	-0.00081	0
20USEBT1000028	-0.00002	-0.00084	1	0.00022	-0.00069	1
20USEBT1000031	-0.00015	-0.00100	1	0.00020	-0.00067	0
20USEBT1000032	-0.00013	-0.00099	1	0.00011	-0.00075	0
20USEBT1000033	-0.00028	-0.00121	1	-0.00008	-0.00094	
20USEBT2000006	-0.00014	-0.00077	5	-0.00015	-0.00043	1
20USEBT2000009	-0.00011	-0.00100	3	0.00005	-0.00037	5
20USEBT2000010	-0.00006	-0.00087	2	0.00011	-0.00034	1
20USEBT2000011	-0.00026	-0.00134	0	-0.00003	-0.00055	2
20USEBT2000012	-0.00010	-0.00128	2	0.00029	-0.00071	1
20USEBT2000013	-0.00010	-0.00093	1			
20USEBT2000014	-0.00023	-0.00117	0	0.00007	-0.00079	4
20USEBT2000017	-0.00019	-0.00113	1	0.00005	-0.00094	1
20USEBT2000018	-0.00063	-0.00134	3	-0.00039	-0.00109	0
20USEBT2000020	-0.00053	-0.00134	1	-0.00034	-0.00107	5
20USEBT2000021	-0.00053	-0.00118	2			
20USEBT2000022	-0.00059	-0.00113	2			
20USEBT2000023	-0.00025	-0.00102	10	0.00013	-0.00072	0
20USEBT2000024	-0.00055	-0.00135	2	-0.00020	-0.00105	1
20USEBT2000025	-0.00044	-0.00113	1	-0.00026	-0.00108	1
20USEBT2000027	-0.00017	-0.00111	1	0.00012	-0.00087	0
20USEBT2000028	-0.00012	-0.00103	1	0.00019	-0.00083	1
20USEBT2000029	-0.00005	-0.00099	1	0.00019	-0.00102	1
20USEBT2000031	-0.00025	-0.00119	1	-0.00001	-0.00095	0
20USEBT2000032	-0.00022	-0.00096	1	0.00006	-0.00079	0
20USEBT2000033	-0.00013	-0.00108	1	0.00012	-0.00099	1
20USEBT2000034	0.00006	-0.00108	1	0.00026	-0.00091	0
20USEBT2000035			1	0.00020	-0.00083	3

Table A.2: Electrical test results for all PPB bus tapes tested with the DESY BTR.

Serial Number	Before Co-curing				After Co-curing			
	Resistance Slope [Ω / mm]			Leakage [nA]	Resistance Slope [Ω / mm]			Leakage [nA]
	Narrow	Medium	Wide		Narrow	Medium	Wide	
20USEBT1000005	0.01611	0.01339	0.00629	6.45	0.01608	0.01361	0.00628	5.015
20USEBT1000006	0.01358	0.01137	0.00551	3.485	0.0136	0.01171	0.00552	7.05
20USEBT1000007	0.01339	0.01157	0.00539	5.4	0.01314	0.01146	0.00533	4.455
20USEBT1000009	0.01441	0.01222	0.00596	4.19	0.01442	0.01198	0.00587	4.745
20USEBT1000010	0.01453	0.0127	0.00589	6.93	0.01442	0.01235	0.00579	4.1
20USEBT1000012	0.0128	0.01094	0.00541	3.38	0.01282	0.01113	0.00535	3.76
20USEBT1000014	0.01388	0.01121	0.00553	4.85	0.01399	0.012	0.00551	5.21
20USEBT1000015	0.01472	0.01188	0.00581	4.115	0.01542	0.01265	0.0058	5.25
20USEBT1000016	0.01492	0.01224	0.00611	6.54	0.01507	0.01382	0.00615	3.54
20USEBT1000017	0.01472	0.01204	0.00577	4.115	0.01473	0.0119	0.00576	4.81
20USEBT1000018	0.01479	0.01223	0.00579	5.165	0.01477	0.01198	0.00575	3.88
20USEBT1000019	0.01557	0.01263	0.00634	6.685	0.01573	0.01263	0.00638	4.01
20USEBT1000020	0.01465	0.0122	0.0059	3.13	0.01479	0.0139	0.00592	4.7
20USEBT1000021	0.0144	0.01205	0.00616	4.365	0.01454	0.01217	0.00623	4.28
20USEBT1000022	0.01483	0.01233	0.006	5.115	0.015	0.01225	0.00604	5.16
20USEBT1000023	0.01293	0.0106	0.00503	4.125	0.01306	0.01054	0.00505	4.37
20USEBT1000024	0.0132	0.01083	0.00512	5.8	0.0132	0.01073	0.0051	3.16
20USEBT1000025	0.0128	0.01058	0.00502	5.71	0.01292	0.01067	0.00506	5.4
20USEBT1000027	0.01414	0.01142	0.00528	3.745	0.01382	0.01125	0.00526	4.8
20USEBT1000028	0.01381	0.01128	0.00519	5.655	0.01393	0.01125	0.00524	4.25
20USEBT1000031	0.01345	0.01081	0.00508	3.775	0.01359	0.01082	0.00513	4.54
20USEBT1000032	0.0142	0.0114	0.00521	3.73	0.01431	0.01129	0.00526	4.19
20USEBT1000033	0.01324	0.01069	0.00504	3.97				
20USEBT2000006	0.01408	0.01167	0.00621	4.585	0.01403	0.01285	0.00616	5.83
20USEBT2000009	0.01327	0.01133	0.00591	3.365	0.01322	0.01175	0.00586	6.22
20USEBT2000010	0.0151	0.01277	0.00666	7.02	0.01515	0.01235	0.00661	3.5
20USEBT2000011	0.01333	0.01126	0.00597	5.16	0.01341	0.01133	0.00592	3.535
20USEBT2000012	0.01369	0.01199	0.00607	4.445	0.01361	0.01159	0.00597	4.075
20USEBT2000013	0.01468	0.01224	0.00635	5.785				
20USEBT2000014	0.01319	0.01112	0.00592	4.365	0.0133	0.01137	0.00598	3.84
20USEBT2000017	0.01509	0.01192	0.00611	4.865	0.0152	0.01197	0.00619	3.27
20USEBT2000018	0.01571	0.01271	0.0064	5.875	0.01578	0.01278	0.00636	6.57
20USEBT2000020	0.01466	0.01222	0.00632	4.355	0.01463	0.01292	0.00623	5.265
20USEBT2000021	0.01549	0.01274	0.00636	4.35				
20USEBT2000022	0.01519	0.01269	0.00641	4.765				
20USEBT2000023	0.01407	0.01155	0.00629	5.435	0.0142	0.01166	0.00639	4.16
20USEBT2000024	0.01533	0.01267	0.00662	3.88	0.0155	0.01237	0.00667	6.88
20USEBT2000025	0.01344	0.01127	0.00606	3.63	0.01341	0.01111	0.00602	5.74
20USEBT2000027	0.01342	0.01174	0.00624	5.295	0.01351	0.01203	0.00631	4.52
20USEBT2000028	0.0128	0.01103	0.00586	6.02	0.01289	0.01149	0.00588	4.5
20USEBT2000029	0.01335	0.01131	0.0061	4.26	0.0135	0.01143	0.00622	3.89
20USEBT2000031	0.01309	0.01086	0.0058	6.255	0.01318	0.01075	0.00588	4.28
20USEBT2000032	0.01341	0.01125	0.00595	5.52	0.01375	0.01103	0.00606	5.31
20USEBT2000033	0.01272	0.01062	0.00548	5.785	0.01285	0.01063	0.00554	4.69
20USEBT2000034	0.01372	0.01118	0.00565	3.825	0.0138	0.01112	0.0057	4.34
20USEBT2000035	0.01371	0.0113	0.00573	4.635	0.01367	0.01168	0.00578	4.75

Appendix A Additional Tables

Table A.3: Fit parameters relevant for temperature jump calculation for main and secondary side modules R3 - R5.

Module	T_{CO_2} [°C]	Main side			Secondary side		
		$p_{\uparrow,1}$ [°C]	$p_{\downarrow,1}$ [°C]	ΔT [°C]	$p_{\uparrow,1}$ [°C]	$p_{\downarrow,1}$ [°C]	ΔT [°C]
R3 PB2	15	18.87 ± 0.38	36.88 ± 1.54	18.01 ± 1.59	19.42 ± 0.40	37.34 ± 1.40	17.92 ± 1.45
	10	15.11 ± 0.42	32.42 ± 0.55	17.31 ± 0.69	15.70 ± 0.42	32.93 ± 0.52	17.23 ± 0.67
	5	11.41 ± 0.31	28.44 ± 0.43	17.03 ± 0.53	11.94 ± 0.33	29.06 ± 0.37	17.13 ± 0.49
	0	7.60 ± 0.33	24.79 ± 1.62	17.19 ± 1.65	8.21 ± 0.33	25.55 ± 1.47	17.34 ± 1.50
	-5	3.56 ± 0.48	20.83 ± 0.17	17.27 ± 0.51	4.08 ± 0.55	21.47 ± 0.24	17.38 ± 0.60
	-10	-0.12 ± 0.08	16.31 ± 0.60	16.43 ± 0.60	0.45 ± 0.08	17.04 ± 0.50	16.59 ± 0.51
	-15	-3.72 ± 0.33	12.59 ± 0.53	16.31 ± 0.62	-3.27 ± 0.36	13.63 ± 0.62	16.91 ± 0.72
	-20	-7.74 ± 0.29	8.36 ± 0.33	16.10 ± 0.44	-7.13 ± 0.31	9.07 ± 0.40	16.20 ± 0.51
	-25	-11.44 ± 0.10	4.24 ± 0.35	15.68 ± 0.37	-10.89 ± 0.10	5.08 ± 0.54	15.97 ± 0.55
	-30	-15.64 ± 0.39	0.52 ± 0.60	16.16 ± 0.71	-15.22 ± 0.46	1.29 ± 0.56	16.51 ± 0.72
	-35	-18.27 ± 0.05	-2.85 ± 0.52	15.41 ± 0.52	-17.68 ± 0.06	-2.06 ± 0.48	15.63 ± 0.49
R4	15	20.71 ± 0.79	44.13 ± 2.67	23.42 ± 2.78	19.98 ± 0.51	41.33 ± 1.95	21.36 ± 2.02
	10	16.99 ± 0.74	43.25 ± 0.52	26.27 ± 0.90	16.30 ± 0.51	36.83 ± 0.59	20.53 ± 0.78
	5	13.50 ± 0.58	40.15 ± 0.68	26.65 ± 0.89	12.62 ± 0.42	33.35 ± 0.55	20.73 ± 0.70
	0	9.83 ± 0.54	36.93 ± 3.14	27.11 ± 3.19	8.80 ± 0.38	29.35 ± 1.97	20.55 ± 2.01
	-5	5.42 ± 1.13	32.69 ± 0.95	27.27 ± 1.48	4.84 ± 0.72	25.78 ± 0.86	20.94 ± 1.13
	-10	2.26 ± 0.13	27.74 ± 0.88	25.48 ± 0.89	1.08 ± 0.12	21.71 ± 0.88	20.63 ± 0.89
	-15	-1.46 ± 0.65	25.36 ± 2.56	26.82 ± 2.64	-2.59 ± 0.47	17.47 ± 1.04	20.06 ± 1.14
	-20	-5.40 ± 0.53	21.87 ± 0.99	27.26 ± 1.12	-6.61 ± 0.39	12.90 ± 1.07	19.51 ± 1.14
	-25	-9.23 ± 0.34	15.54 ± 0.84	24.77 ± 0.90	-10.49 ± 0.15	9.24 ± 1.60	19.73 ± 1.61
	-30	-13.46 ± 0.74	12.53 ± 2.79	26.00 ± 2.88	-14.75 ± 0.42	4.61 ± 1.70	19.36 ± 1.75
	-35	-15.84 ± 0.18	8.32 ± 1.34	24.16 ± 1.35	-17.68 ± 0.17	0.71 ± 1.55	18.39 ± 1.56
R5	15	17.70 ± 0.35	30.75 ± 1.79	13.05 ± 1.82	18.25 ± 0.21	30.17 ± 1.72	11.92 ± 1.74
	10	14.04 ± 0.31	26.45 ± 0.98	12.40 ± 1.03	14.58 ± 0.34	26.07 ± 0.67	11.48 ± 0.75
	5	10.19 ± 0.13	22.95 ± 1.16	12.76 ± 1.16	10.84 ± 0.13	23.41 ± 0.60	12.57 ± 0.62
	0	6.30 ± 0.25	19.29 ± 1.59	12.99 ± 1.60	7.04 ± 0.20	18.29 ± 2.33	11.25 ± 2.34
	-5	2.23 ± 0.46	15.20 ± 1.30	12.97 ± 1.37	3.40 ± 0.16	13.78 ± 0.91	10.38 ± 0.92
	-10	-1.67 ± 0.07	10.78 ± 1.60	12.45 ± 1.60	-0.68 ± 0.04	9.41 ± 0.96	10.09 ± 0.96
	-15	-5.47 ± 0.11	6.98 ± 2.04	12.44 ± 2.04	-4.19 ± 0.27	5.74 ± 1.72	9.92 ± 1.74
	-20	-9.71 ± 0.13	2.83 ± 2.46	12.54 ± 2.46	-8.33 ± 0.31	0.18 ± 0.72	8.52 ± 0.79
	-25	-13.47 ± 0.06	-0.43 ± 3.74	13.04 ± 3.74	-12.09 ± 0.21	-4.79 ± 1.50	7.30 ± 1.52
	-30	-17.98 ± 0.26	-5.61 ± 3.75	12.37 ± 3.76	-16.32 ± 0.17	-9.25 ± 3.91	7.07 ± 3.91
	-35	-20.98 ± 0.09	-8.75 ± 3.81	12.23 ± 3.81	-19.07 ± 0.09	-13.39 ± 2.01	5.68 ± 2.01

Table A.4: Fit parameters relevant for temperature jump calculation for main and secondary side modules R0 - R3.

Module	T_{CO_2} [°C]	Main side			Secondary side		
		$p_{\uparrow,1}$ [°C]	$p_{\downarrow,1}$ [°C]	ΔT [°C]	$p_{\uparrow,1}$ [°C]	$p_{\downarrow,1}$ [°C]	ΔT [°C]
R0	15	17.24 ± 0.26	27.03 ± 0.97	9.79 ± 1.01	18.51 ± 0.37	33.21 ± 1.59	14.71 ± 1.64
	10	13.51 ± 0.27	23.15 ± 0.17	9.64 ± 0.31	14.64 ± 0.39	29.06 ± 0.23	14.41 ± 0.45
	5	9.67 ± 0.19	19.09 ± 0.21	9.42 ± 0.28	10.80 ± 0.30	25.18 ± 0.14	14.37 ± 0.34
	0	5.98 ± 0.20	15.32 ± 0.92	9.34 ± 0.94	6.94 ± 0.33	21.57 ± 1.64	14.63 ± 1.67
	-5	2.09 ± 0.34	11.30 ± 0.32	9.21 ± 0.47	2.98 ± 0.50	17.61 ± 0.41	14.63 ± 0.64
	-10	-1.81 ± 0.06	7.32 ± 0.46	9.13 ± 0.46	-0.74 ± 0.08	13.40 ± 0.29	14.14 ± 0.30
	-15	-5.53 ± 0.19	3.51 ± 0.36	9.03 ± 0.41	-4.39 ± 0.28	9.64 ± 0.73	14.03 ± 0.78
	-20	-9.57 ± 0.18	-0.72 ± 0.24	8.84 ± 0.30	-8.45 ± 0.28	5.42 ± 0.34	13.87 ± 0.44
	-25	-13.13 ± 0.04	-4.12 ± 0.45	9.01 ± 0.45	-12.29 ± 0.08	1.62 ± 0.55	13.92 ± 0.56
	-30	-17.47 ± 0.25	-8.30 ± 0.72	9.16 ± 0.76	-16.48 ± 0.32	-2.20 ± 0.72	14.29 ± 0.78
	-35	-20.34 ± 0.07	-11.49 ± 0.68	8.85 ± 0.68	-19.17 ± 0.08	-5.76 ± 0.69	13.41 ± 0.70
R1	15	17.68 ± 0.32	32.78 ± 1.51	15.10 ± 1.54	18.09 ± 0.53	42.67 ± 2.51	24.57 ± 2.56
	10	13.91 ± 0.34	28.48 ± 0.36	14.57 ± 0.50	14.26 ± 0.53	38.07 ± 0.28	23.81 ± 0.60
	5	10.22 ± 0.23	24.65 ± 0.22	14.43 ± 0.32	10.64 ± 0.42	34.15 ± 0.30	23.51 ± 0.52
	0	6.40 ± 0.26	20.90 ± 1.38	14.50 ± 1.41	6.84 ± 0.46	30.58 ± 2.56	23.74 ± 2.60
	-5	2.38 ± 0.38	16.58 ± 0.38	14.20 ± 0.53	2.86 ± 0.63	26.37 ± 1.01	23.50 ± 1.19
	-10	-1.35 ± 0.07	12.32 ± 0.45	13.67 ± 0.46	-0.64 ± 0.12	21.88 ± 0.46	22.52 ± 0.48
	-15	-5.07 ± 0.19	8.40 ± 0.76	13.47 ± 0.78	-4.40 ± 0.35	18.58 ± 1.36	22.97 ± 1.40
	-20	-9.19 ± 0.21	4.21 ± 0.44	13.40 ± 0.49	-8.32 ± 0.38	13.98 ± 0.33	22.29 ± 0.51
	-25	-12.86 ± 0.07	0.05 ± 0.72	12.91 ± 0.73	-12.04 ± 0.12	9.99 ± 0.43	22.03 ± 0.45
	-30	-16.96 ± 0.27	-3.52 ± 0.63	13.44 ± 0.69	-16.13 ± 0.49	6.19 ± 1.43	22.32 ± 1.51
	-35	-19.72 ± 0.05	-6.96 ± 0.83	12.76 ± 0.83	-18.87 ± 0.05	2.77 ± 0.64	21.65 ± 0.64
R2	15	19.00 ± 0.42	36.69 ± 1.41	17.69 ± 1.47	18.20 ± 0.35	33.82 ± 1.14	15.61 ± 1.19
	10	15.15 ± 0.47	32.58 ± 0.48	17.43 ± 0.68	14.54 ± 0.37	29.48 ± 0.30	14.94 ± 0.48
	5	11.59 ± 0.33	28.75 ± 0.31	17.16 ± 0.45	10.80 ± 0.31	25.89 ± 0.24	15.09 ± 0.40
	0	7.79 ± 0.36	25.37 ± 1.41	17.59 ± 1.46	6.98 ± 0.28	22.38 ± 1.20	15.40 ± 1.24
	-5	3.73 ± 0.60	21.50 ± 0.37	17.77 ± 0.71	3.06 ± 0.47	18.60 ± 0.31	15.54 ± 0.56
	-10	0.24 ± 0.09	16.80 ± 0.55	16.56 ± 0.56	-0.63 ± 0.07	14.31 ± 0.37	14.94 ± 0.37
	-15	-3.31 ± 0.37	13.58 ± 0.45	16.90 ± 0.58	-4.40 ± 0.31	10.65 ± 0.74	15.05 ± 0.80
	-20	-7.47 ± 0.32	9.19 ± 0.31	16.66 ± 0.45	-8.39 ± 0.29	6.23 ± 0.44	14.62 ± 0.53
	-25	-11.11 ± 0.13	5.42 ± 0.28	16.52 ± 0.31	-12.06 ± 0.13	2.16 ± 0.50	14.22 ± 0.52
	-30	-15.19 ± 0.46	1.79 ± 0.68	16.98 ± 0.82	-16.10 ± 0.35	-1.31 ± 0.49	14.79 ± 0.60
	-35	-17.85 ± 0.07	-1.49 ± 0.57	16.36 ± 0.57	-18.65 ± 0.08	-4.69 ± 0.72	13.96 ± 0.73
R3 PB1	15	19.48 ± 0.43	38.23 ± 1.68	18.75 ± 1.74	19.51 ± 0.37	36.00 ± 1.33	16.49 ± 1.38
	10	15.67 ± 0.45	33.71 ± 0.54	18.05 ± 0.70	15.72 ± 0.41	31.51 ± 0.36	15.79 ± 0.54
	5	12.04 ± 0.34	29.79 ± 0.43	17.75 ± 0.55	11.98 ± 0.31	27.75 ± 0.17	15.77 ± 0.35
	0	8.37 ± 0.36	26.40 ± 1.60	18.03 ± 1.64	8.22 ± 0.31	24.17 ± 1.26	15.96 ± 1.30
	-5	4.32 ± 0.50	22.26 ± 0.27	17.94 ± 0.57	4.15 ± 0.49	19.98 ± 0.45	15.83 ± 0.66
	-10	0.73 ± 0.09	17.64 ± 0.54	16.91 ± 0.55	0.46 ± 0.08	15.50 ± 0.48	15.04 ± 0.49
	-15	-3.00 ± 0.30	14.16 ± 0.57	17.16 ± 0.64	-3.19 ± 0.32	11.89 ± 0.73	15.08 ± 0.79
	-20	-7.03 ± 0.28	9.77 ± 0.32	16.80 ± 0.42	-7.28 ± 0.27	7.50 ± 0.33	14.78 ± 0.43
	-25	-10.49 ± 0.07	5.98 ± 0.47	16.47 ± 0.47	-11.10 ± 0.11	3.55 ± 0.35	14.65 ± 0.37
	-30	-14.75 ± 0.49	1.98 ± 0.57	16.73 ± 0.76	-15.28 ± 0.41	-0.34 ± 0.47	14.94 ± 0.62
	-35	-17.46 ± 0.05	-1.11 ± 0.44	16.35 ± 0.44	-17.90 ± 0.05	-3.83 ± 0.39	14.07 ± 0.40

APPENDIX **B**

Additional Figures

Additional figures not part of the main body of the thesis can be found in this appendix.

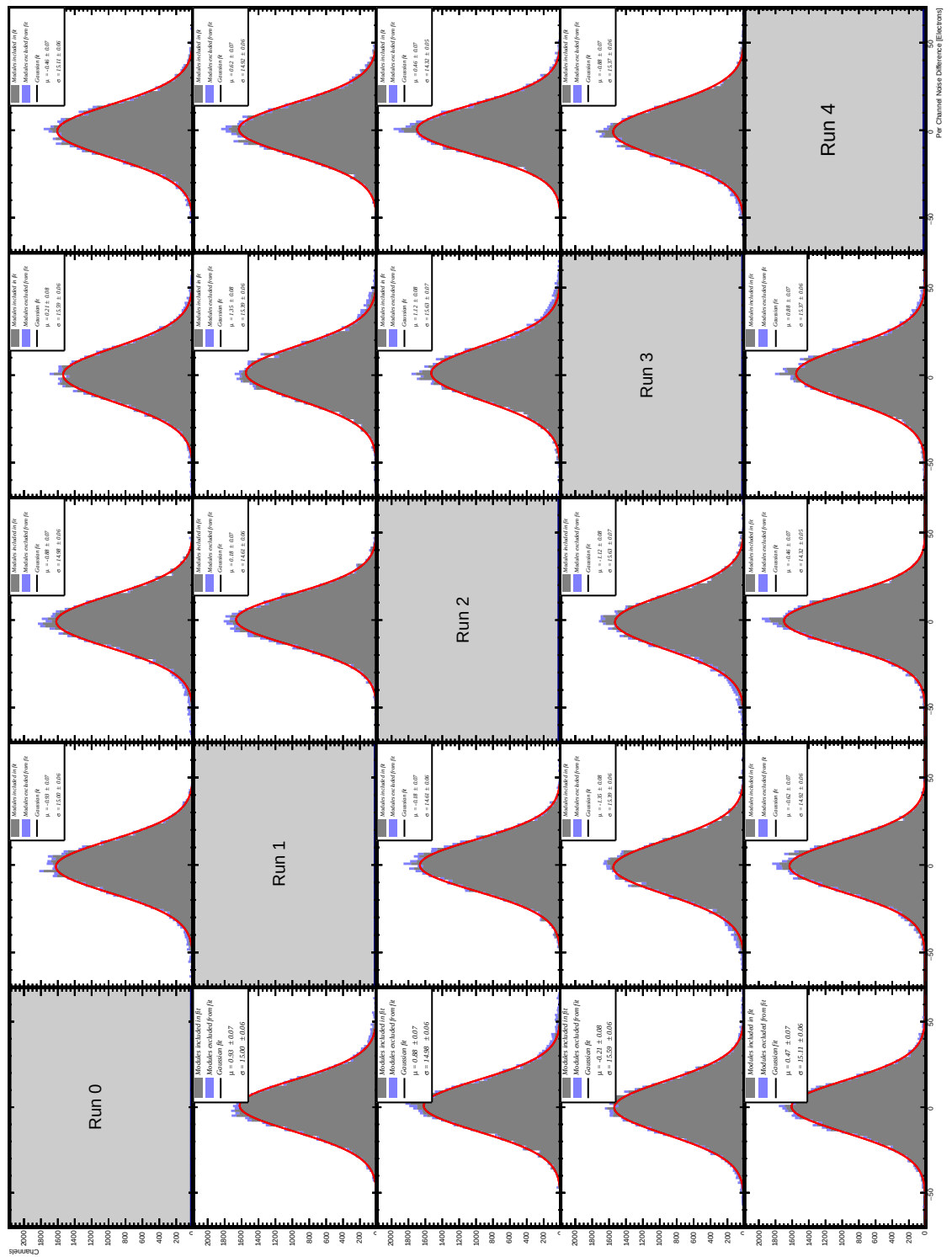


Figure B.1: Comparison of the channel noise for a 1 fC injected charge for five consecutive full test runs in ITSDAQ with the *IFIC1* petal at -35°C .

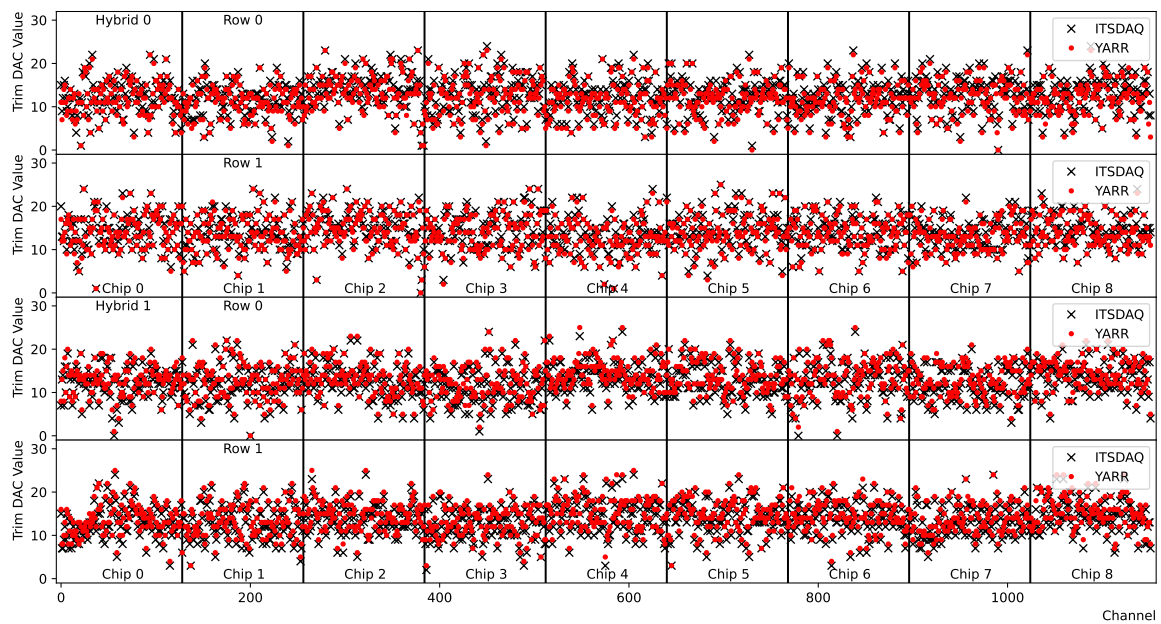
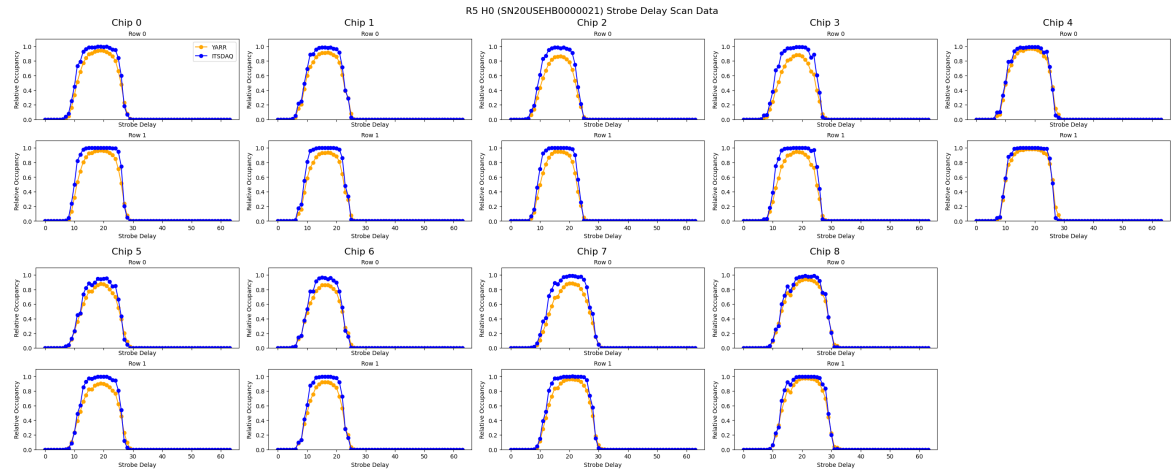
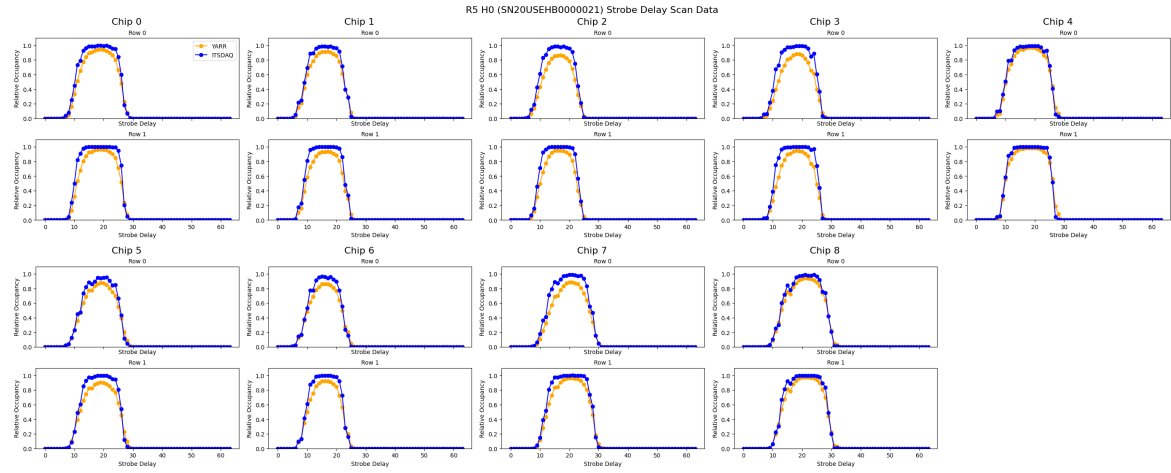


Figure B.2: Trim DAC values obtained with ITSDAQ and FELIX + YARR.

Appendix B Additional Figures



(a) Data for half-module *SN20USEHB0000021*.



(b) Data for half-module *SN20USEHC0000017*.

Figure B.3: Strobe delay data comparison between ITSDAQ and FELIX + YARR.

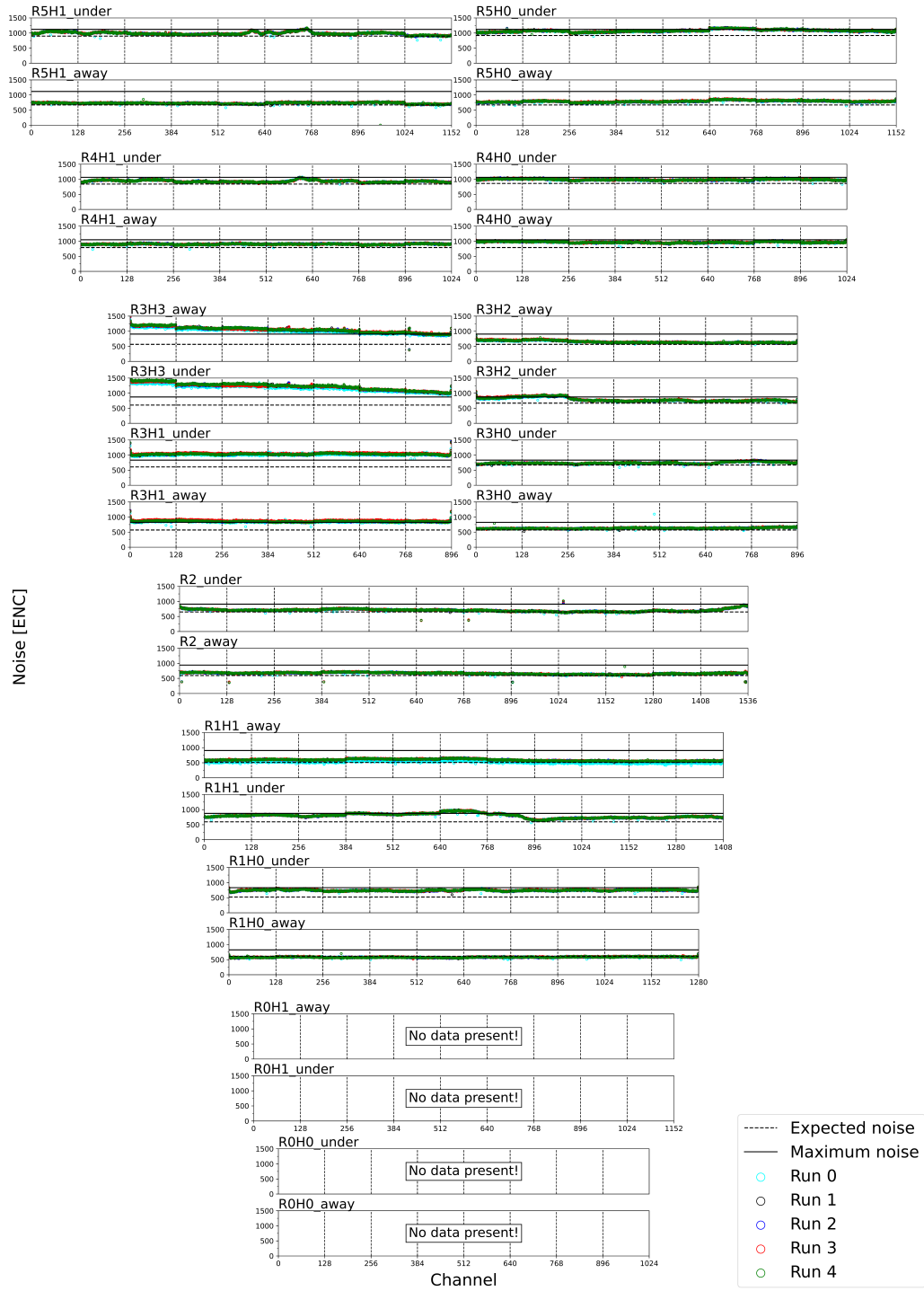


Figure B.4: Equivalent noise charge at 1 fC injected charge for five consecutive full tests at 0°C for the primary side of the *IFIC1* petal.

Appendix B Additional Figures

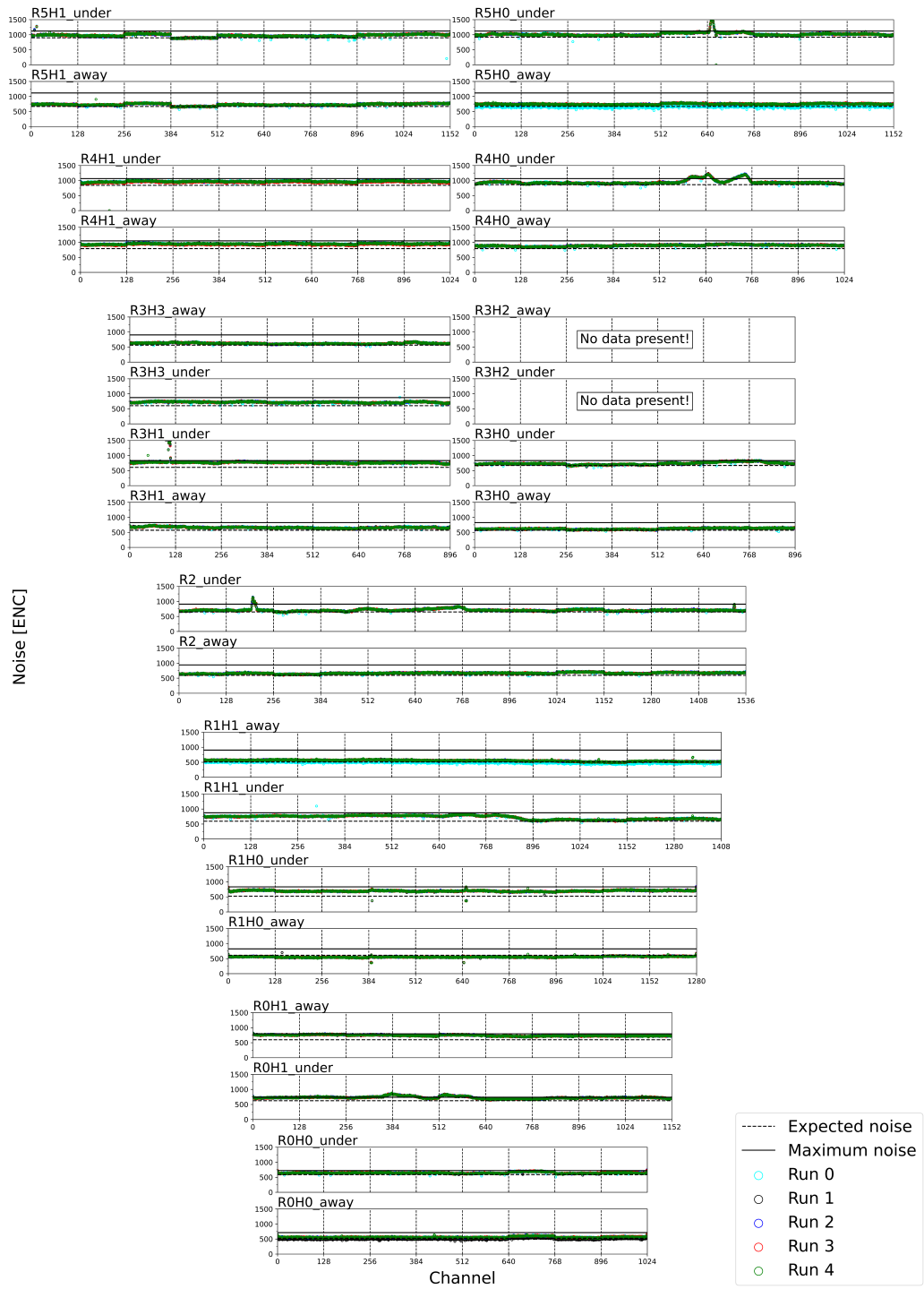


Figure B.5: Equivalent noise charge at 1 fC injected charge for five consecutive full tests at 0 °C for the secondary side of the *IFIC1* petal.

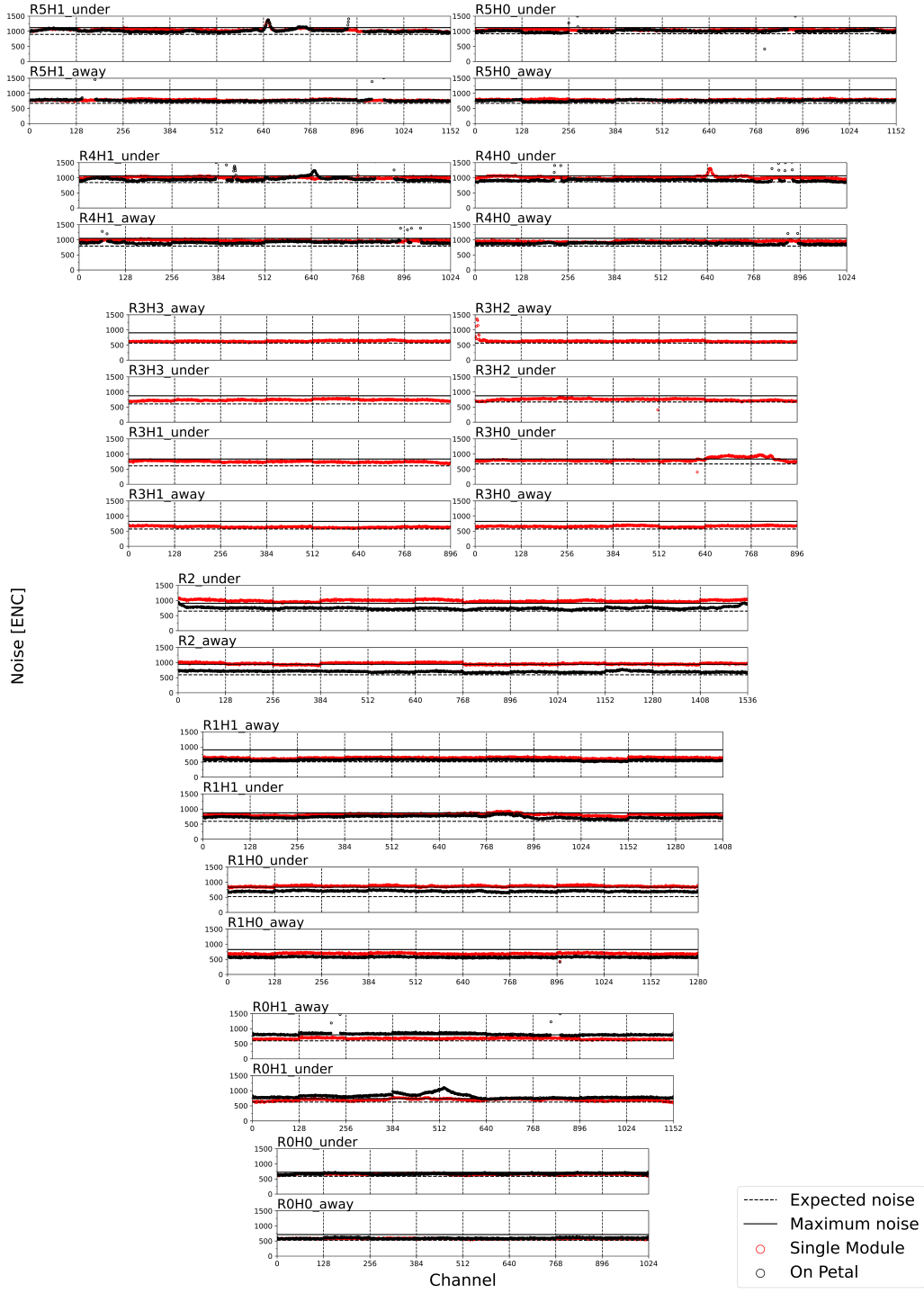


Figure B.6: Equivalent noise charge at 1 fC injected charge before and after loading of the primary side modules of the *DESY1* petal.

Appendix B Additional Figures

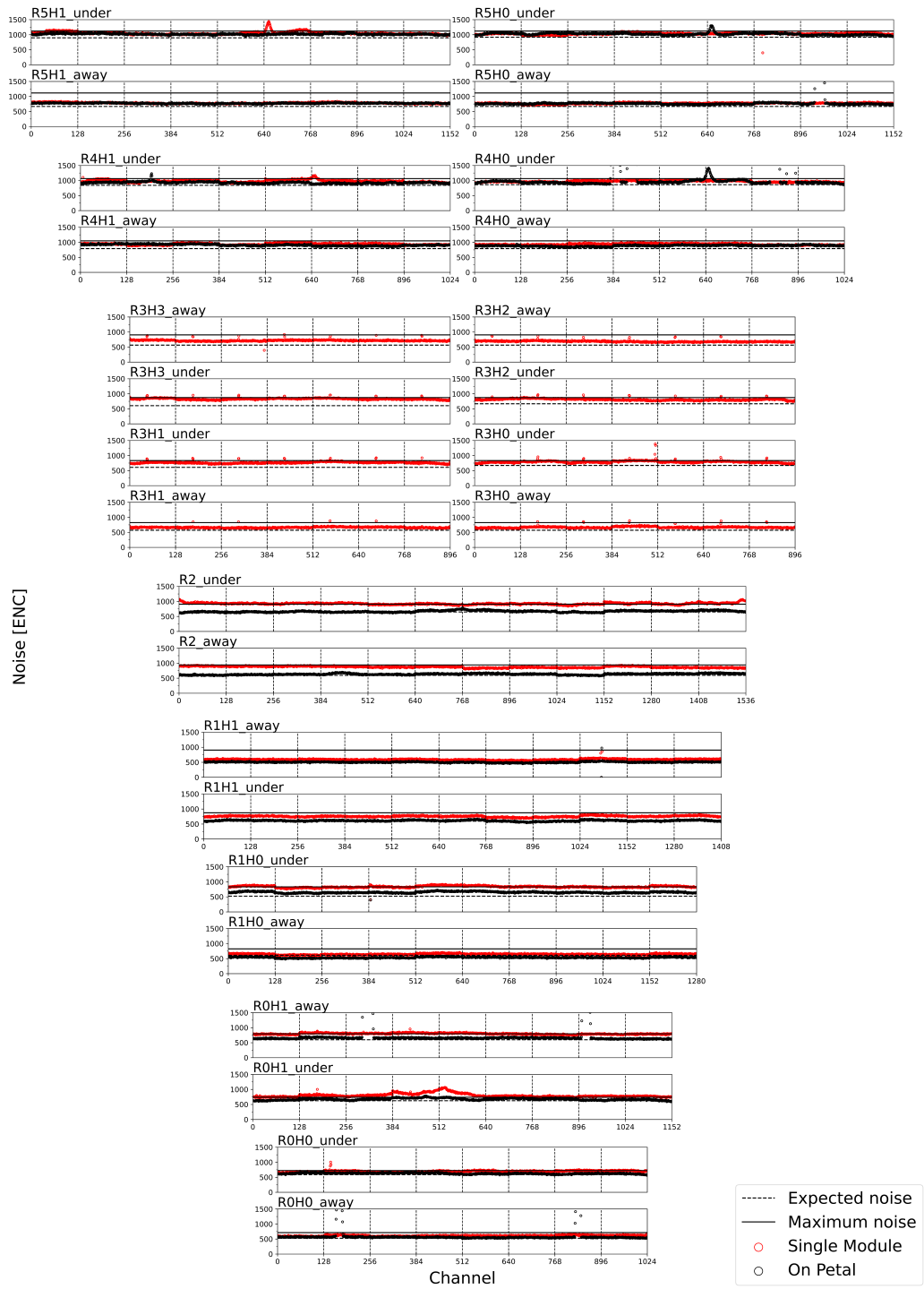


Figure B.7: Equivalent noise charge at 1 fC injected charge before and after loading of the secondary side modules of the *DESYI* petal.

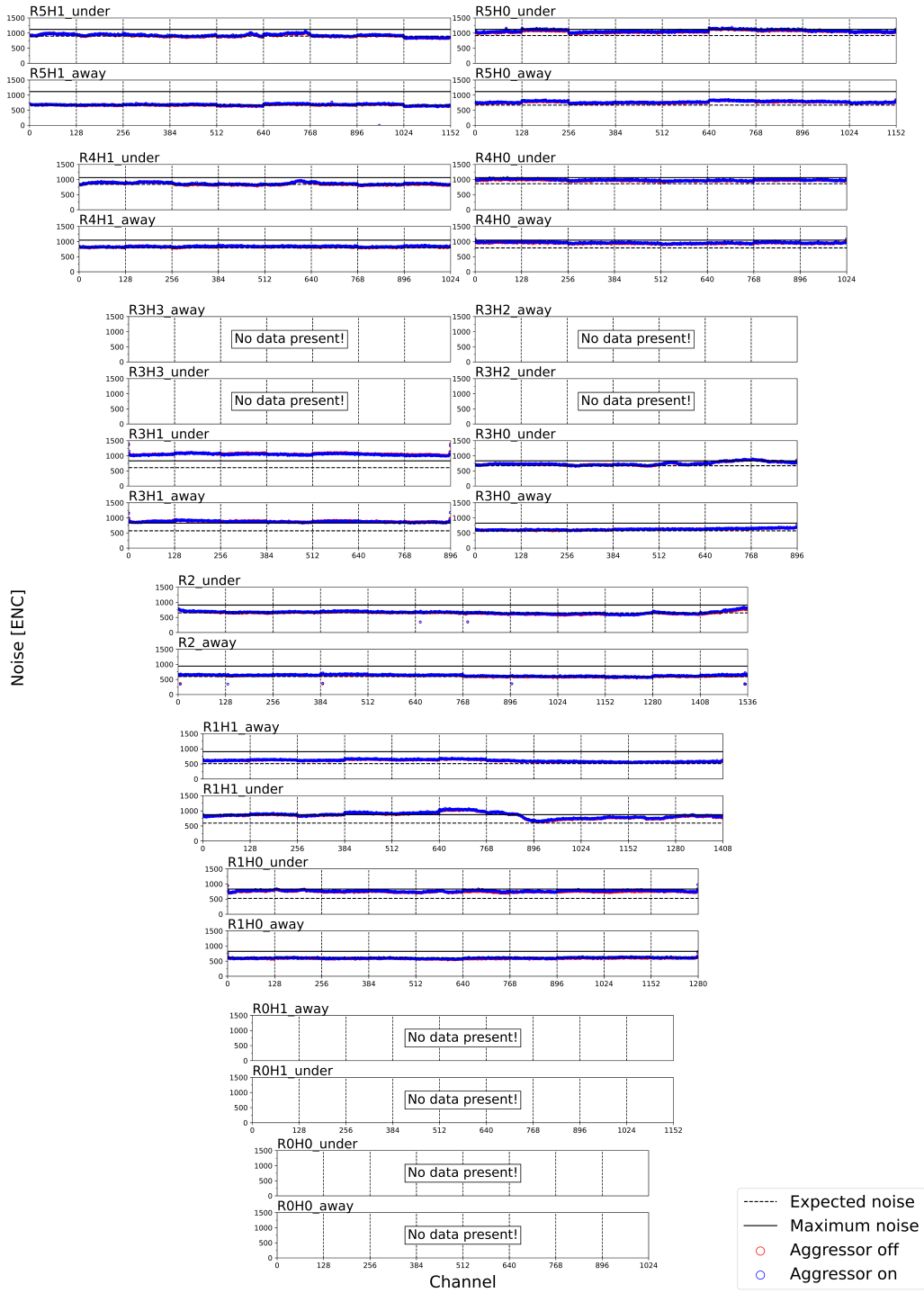


Figure B.8: Equivalent noise charge at 1 fC injected charge with and without activated secondary side at -35°C for the primary side of the *IFIC1* petal.

Appendix B Additional Figures

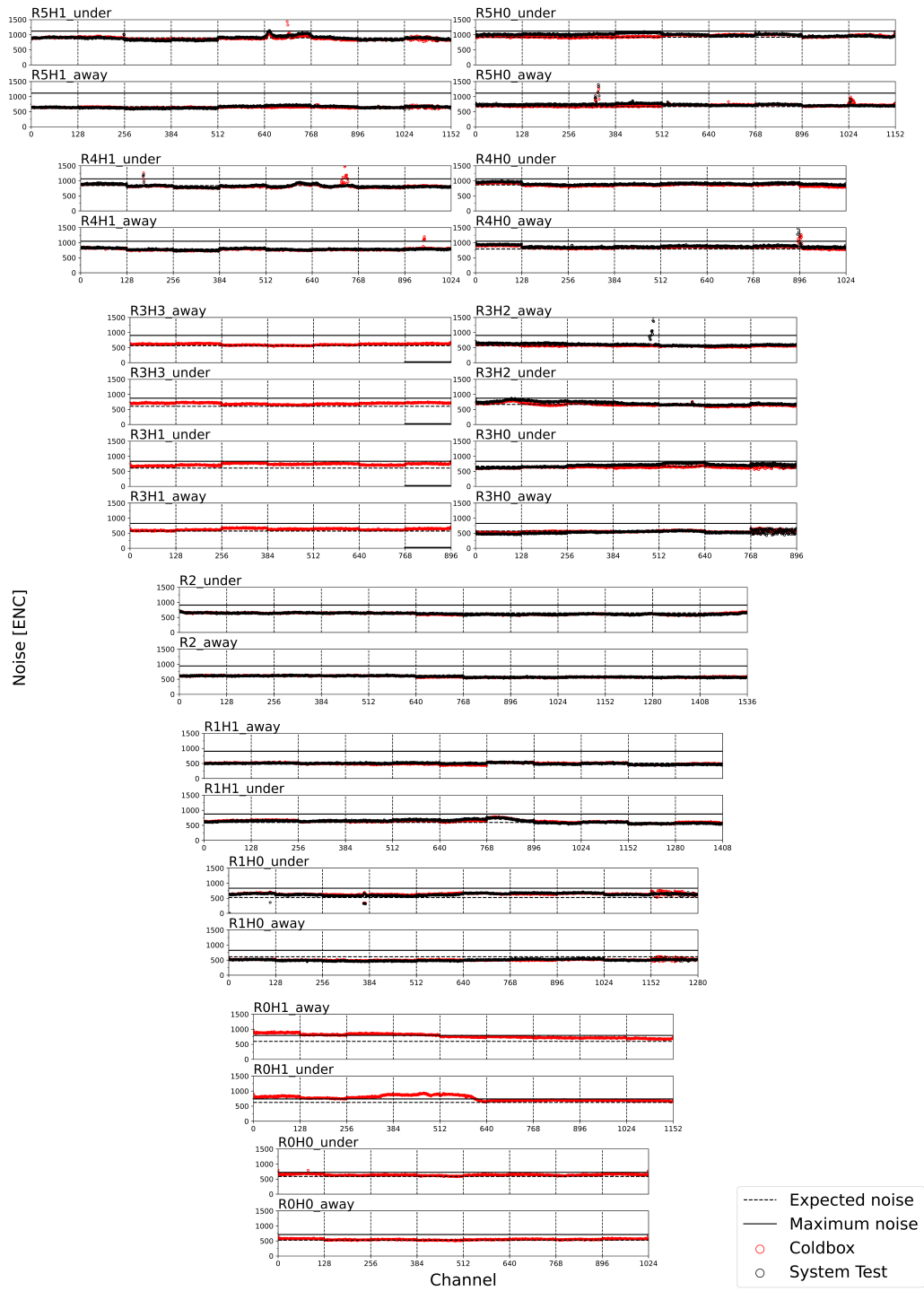


Figure B.9: Equivalent noise charge at 1 fC injected charge in the petal coldbox and the System Test at -35°C for the primary side of the TRIUMF1 petal.

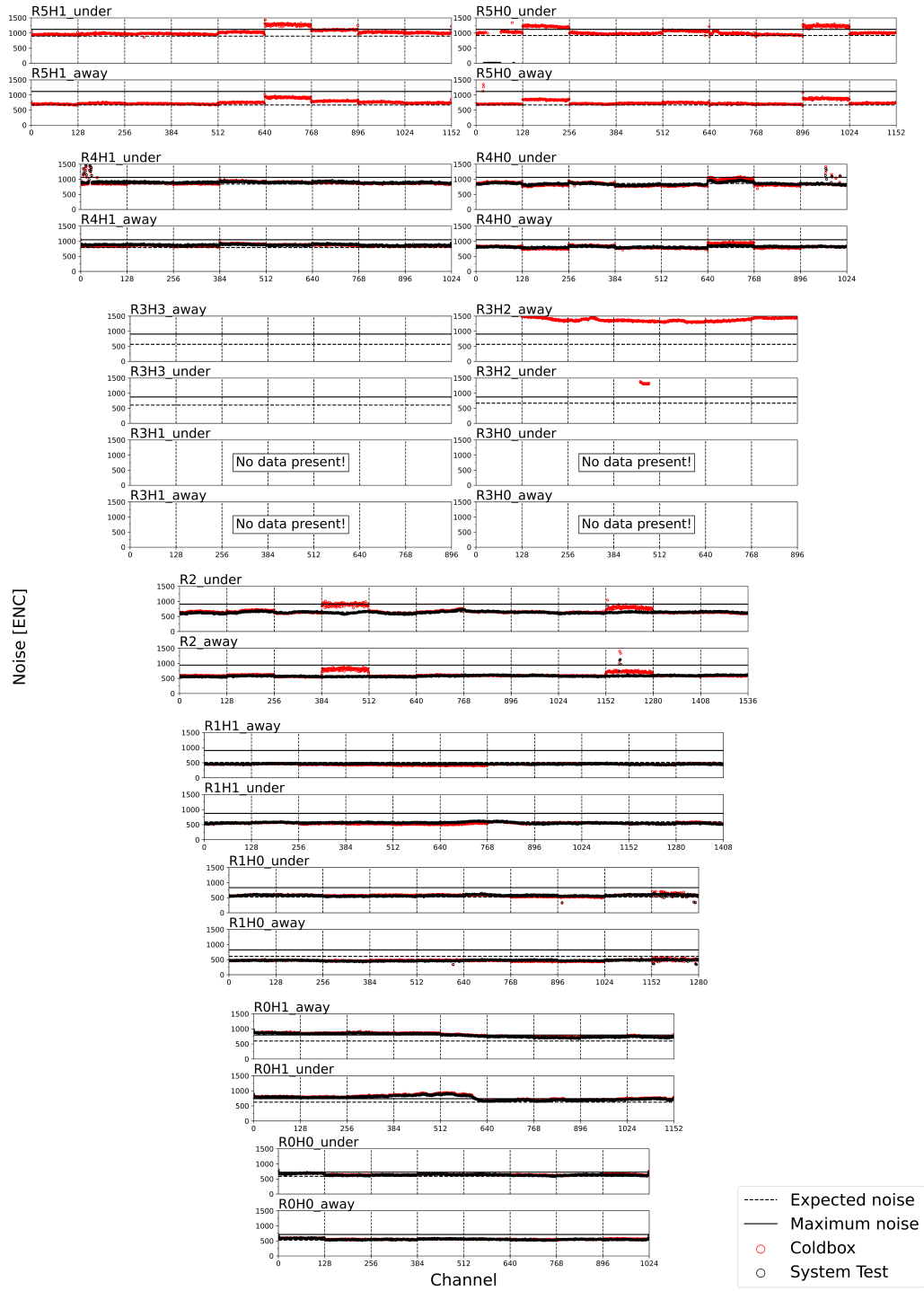


Figure B.10: Equivalent noise charge at 1 fC injected charge in the petal coldbox and the System Test at -35°C for the secondary side of the *TRIUMF1* petal.

Appendix B Additional Figures

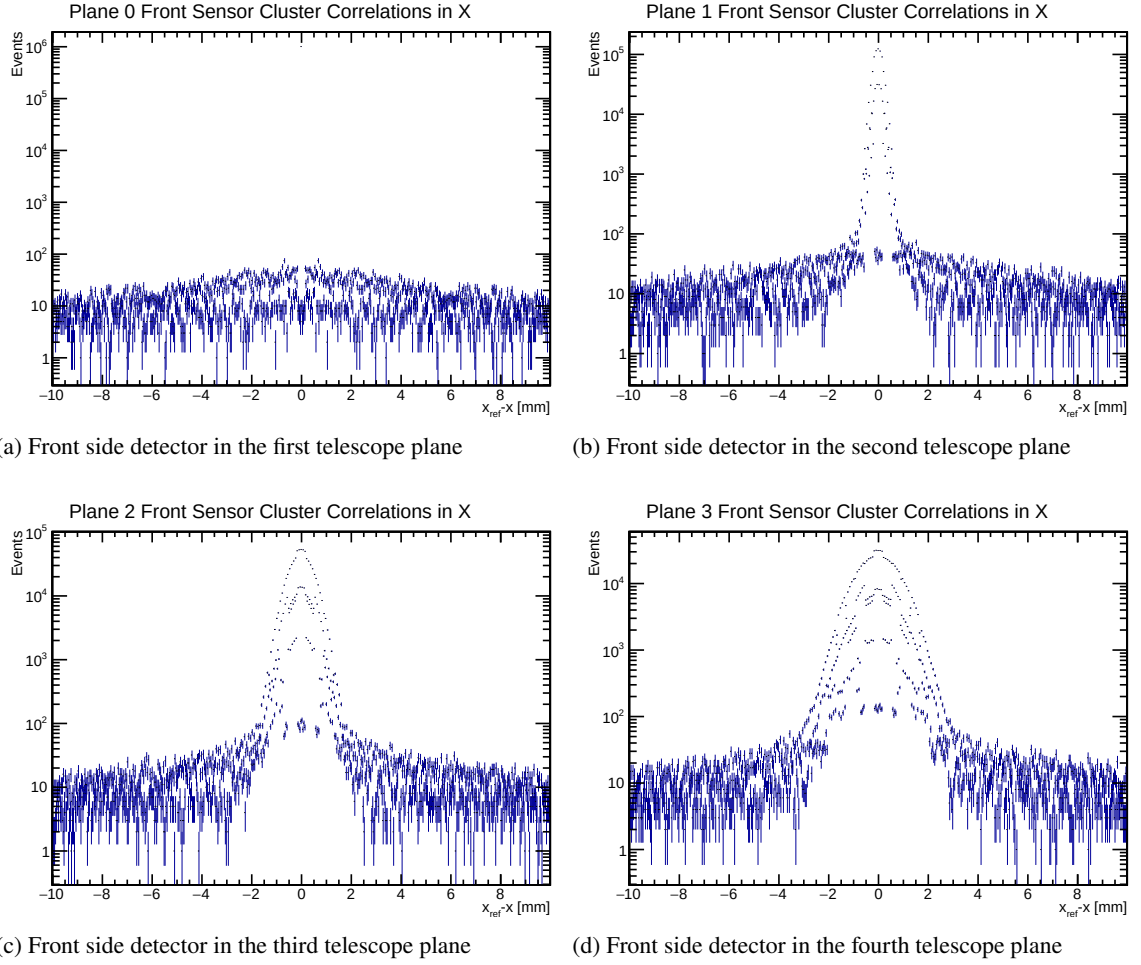


Figure B.11: Histograms of cluster correlations in x in the original binning.

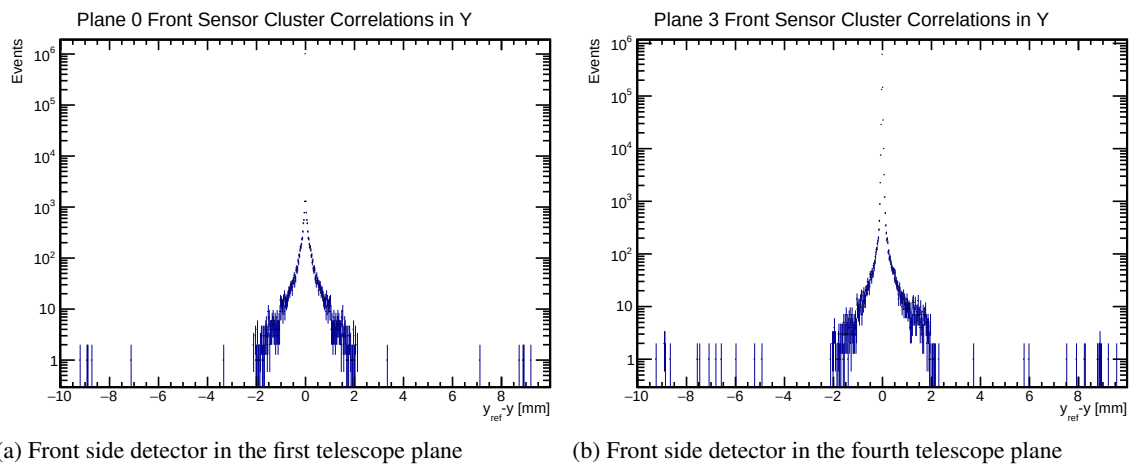


Figure B.12: Histograms of cluster correlations in y .

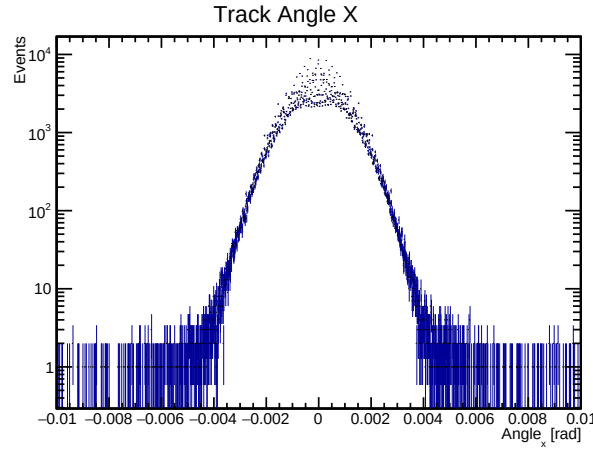


Figure B.13: R0 telescope x track angles in the original binning.

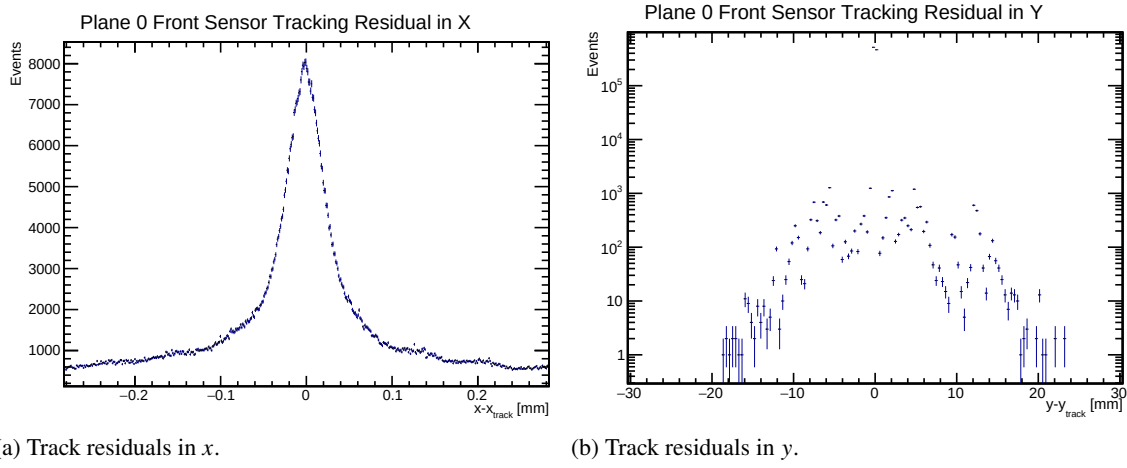


Figure B.14: Histograms of track residuals for the R0 telescope's front side sensor.

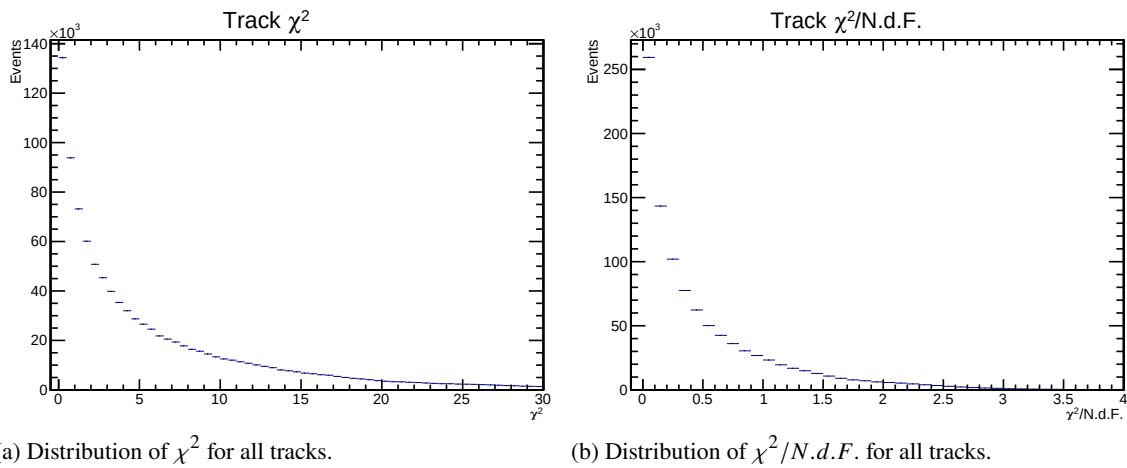
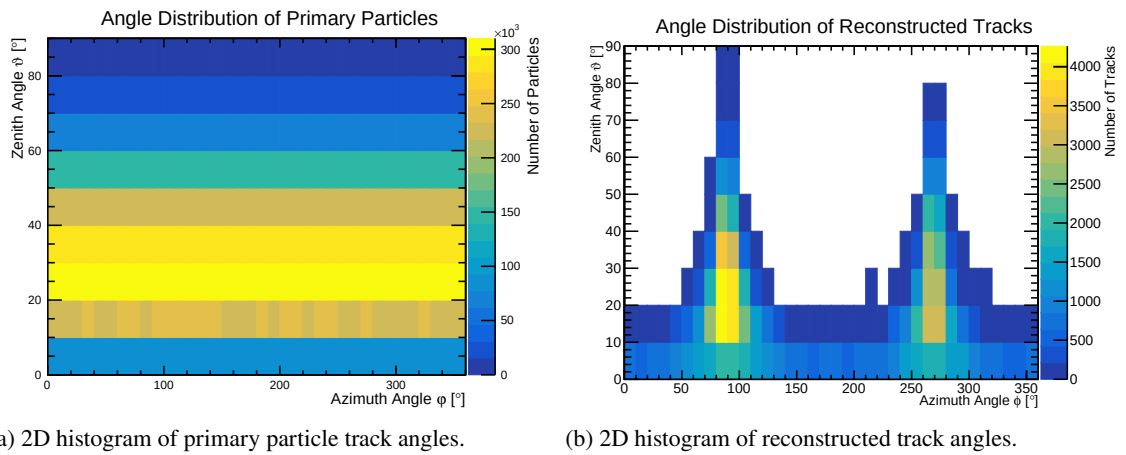


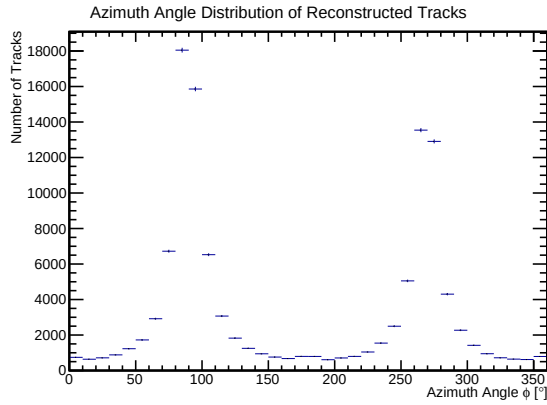
Figure B.15: Distributions of the goodness of fit measures for all tracks of the R0 telescope setup.



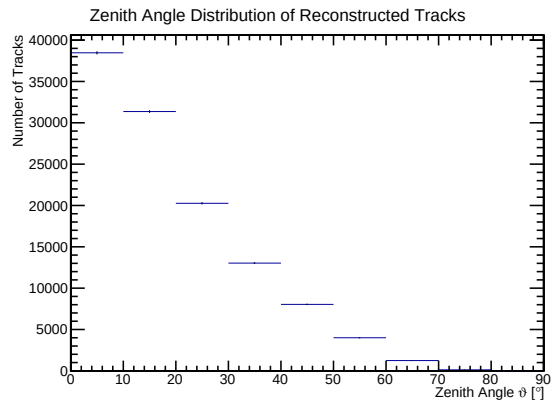
(a) 2D histogram of primary particle track angles.

(b) 2D histogram of reconstructed track angles.

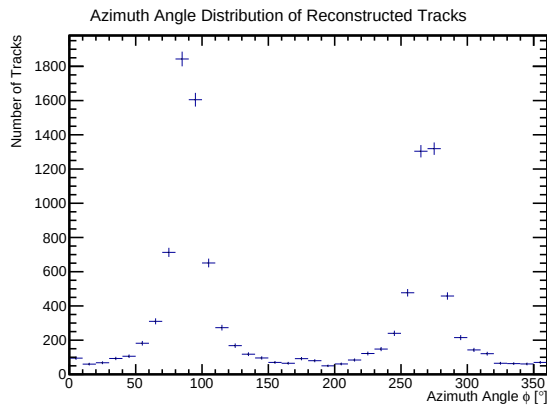
Figure B.16: 2D histograms of primary and reconstructed track angles in the first run of the 4 petal cosmic ray telescope simulation.



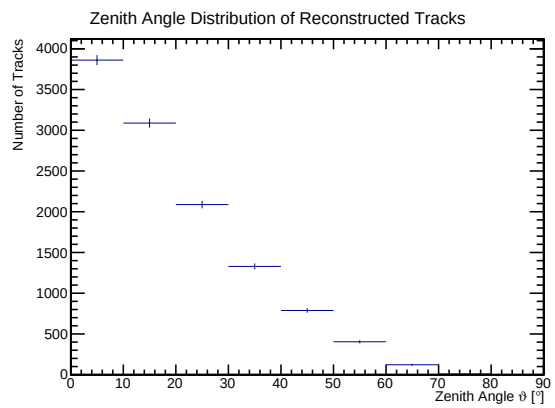
(a) Histogram of reconstructed track azimuth angles from the first simulation run.



(b) Histogram of reconstructed track zenith angles from the first simulation run.

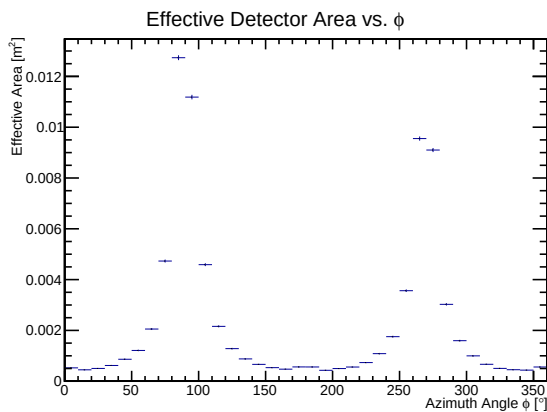


(c) Histogram of reconstructed track azimuth angles from the second simulation run.

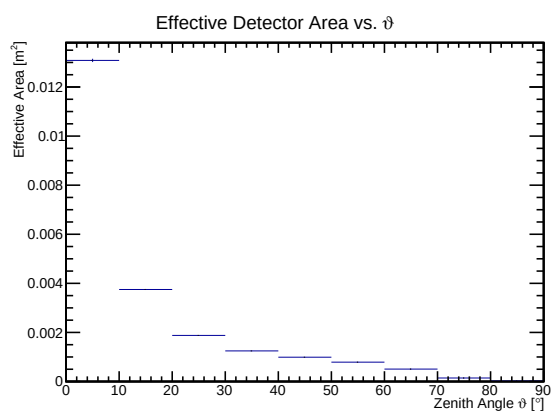


(d) Histogram of reconstructed track zenith angles from the second simulation run.

Figure B.17: Angles of reconstructed tracks from the 4 petal cosmic ray telescope simulation during both simulation runs.

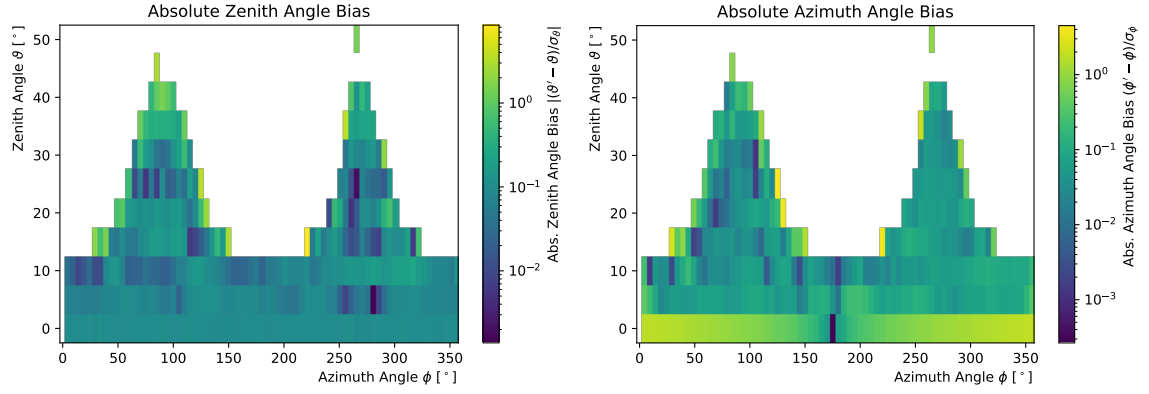


(a) Effective detector area vs. azimuth angle ϕ .



(b) Effective detector area vs. zenith angle ϑ .

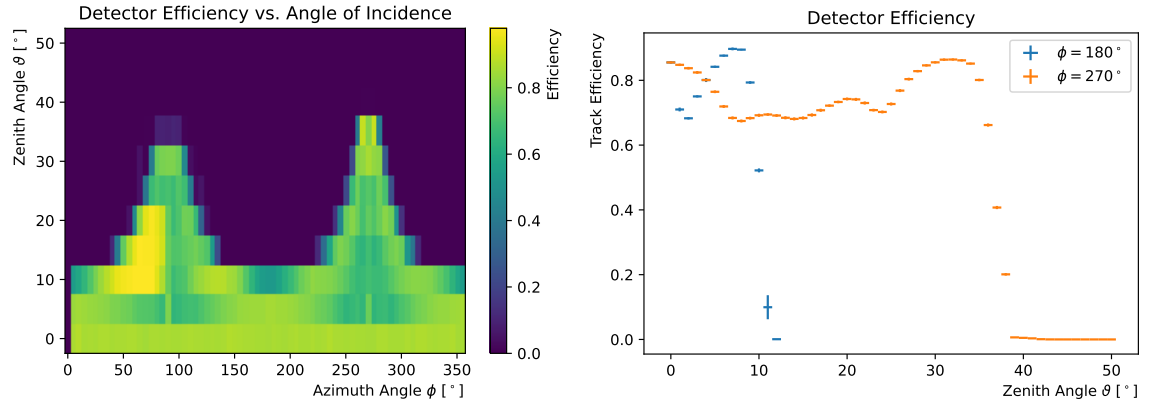
Figure B.18: Effective detector area vs. ϕ and ϑ reconstructed from the first simulation run.



(a) Reconstructed zenith bias.

(b) Reconstructed azimuth bias.

Figure B.19: 2D maps of absolute detector biases.



(a) 2D track reconstruction efficiency in the detector resolution study.

(b) Tracking efficiency for $\phi = 180^\circ$ and $\phi = 270^\circ$.

Figure B.20: Simulated track reconstruction efficiency of the 4 petal cosmic ray detector.

Bibliography

The online availability of all material was last checked on the 8th of July 2024. Access to some material is restricted to members of the ATLAS ITk project. These references are marked accordingly.

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Acronyms

- 2PACL** Two-Phase Accumulator Controlled Loop. 35, 36, 46, 57
- ABCStars** ATLAS Binary Chips. 25, 26, 27, 30, 61, 62, 63, 68, 74, 76, 82, 84
- ADC** Analog-to-Digital Converter. 21, 25, 33, 57
- ALICE** A Large Ion Collider Experiment. 7
- ALTI** ATLAS Local Trigger Interface. 38
- AMAC** Autonomous Monitor and Control. 25, 30, 45, 57
- ATLAS** A Toroidal LHC ApparatuS. 1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 20, 22, 35, 37, 39, 40, 44, 46, 81, 89, 92, 95, 103, 105, 112, 113, 115
- BC** Bunch Crossing Clock. 37
- BCID** Bunch Crossing ID. 26, 37
- BCR** Bunch Counter Reset. 37
- BIS** Beam Interface System. 33
- BTR** Bus Tape Testing Robot. 39, 40, 41, 42, 43, 44, 115, 120, 121
- BVT** ABCStar Threshold Setting in DAC Units. 26, 61
- CAD** Computer Aided Design. 105
- CERN** Organisation européenne pour la recherche nucléaire. 1, 3, 6, 7
- CMS** Compact Muon Solenoid. 6, 7, 8, 20
- CRY** Cosmic-ray Shower Library. 78, 92
- CSCs** Cathode Strip Chambers. 13
- CTP** Central Trigger Processor. 38
- DAC** Digital-to-Analog Converter. 65, 82
- DAF** Detector Assembly Facility. 25, 46, 49, 57

- DAQ** Data Acquisition. 14, 37, 38, 61, 67, 68, 69, 74, 87, 115
- DCS** Detector Control System. 25, 28, 34
- DESY** Deutsches Elektornen-Synchrotron. 1, 2, 11, 25, 29, 31, 38, 39, 41, 42, 43, 44, 45, 46, 48, 49, 51, 57, 58, 59, 61, 70, 95, 115, 120, 121
- DIDIS** DESY ITk Database Interaction Script. 38
- DMM** Digital Multimeter. 39, 40
- DSS** Detector Safety System. 33, 46, 51
- DUT** Device Under Test. 112, 113
- EAS** Extensive Air Shower. 78, 79, 80, 92, 93
- ECR** Event Counter Reset. 37
- EF** Event Filter. 14
- EM** electromagnetic. 12
- ENC** Equivalent Noise Charge. 21, 63, 64, 65, 74
- EOs** End of Substructure. 30, 32, 33, 38, 41
- FE** Front-End. 14
- FELIX** Front-End LIInk eXchange. 14, 36, 37, 61, 67, 68, 69, 76, 115, 127, 128
- FPGA** Field Programmable Gate Array. 33, 34, 35, 36, 37, 51, 52, 65
- GSS** Global Safety System. 33, 51, 52
- GUT** Grand Unified Theory. 5
- GZK** Greisen, Zatsepin & Kuzmin. 77
- HCCStars** Hybrid Controller Chips. 25, 27, 30, 46, 75, 82
- HL-LHC** High-Luminosity Large Hadron Collider. 7, 8, 9, 11, 12, 13, 14, 23
- HV** High Voltage. 26, 29, 32, 33, 34, 35, 51, 55, 57, 70
- HV TAB** HV Tape Automated Bond. 26
- IBL** Insertable B-Layer. 10, 11, 35
- ID** Inner Detector. 10, 11, 12, 13, 35
- IFIC** Instituto de Física Corpuscular. 45

IMS Interlock & Monitoring System. 2, 50, 51, 52, 54, 115

ITk Inner Tracker. 1, 2, 11, 12, 13, 14, 25, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39, 40, 41, 45, 46, 48, 51, 59, 61, 67, 81, 87, 89, 90, 92, 95, 103, 105, 106, 112, 113, 115

ITSDAQ ITk Strips DAQ. 36, 37, 57, 61, 64, 65, 66, 67, 68, 69, 70, 74, 75, 76, 81, 82, 84, 87, 115, 126, 127, 128

JSI Jožef Stefan Institute. 39, 44

L1A Level-1 Trigger Accept. 37

LAr Liquid Argon. 12, 13

LEP Large Electron-Positron Collider. 8

LHC Large Hadron Collider. 1, 2, 3, 6, 7, 8, 9, 37

LHCb LHC beauty. 7

LIAR LUCASZ Interlock ARbitrator. 51, 52

Linac4 Linear Accelerator 4. 6

LISSY Local Interlock & Safety System. 33, 34, 51, 52, 55

IpGBT low power GigaBit Transmitter. 30, 84

LS Long Strip. 67

LSB Least Significant Bit. 65, 67, 68

LUCASZ Light Use Cooling Appliance for Surface Zones. 46, 48, 49

LV Low Voltage. 25, 29, 32, 33, 34, 35, 45, 51, 55, 57

MARTA Monoblock Approach for a Refrigeration Technical Application. 57, 58, 59

MDTs Monitored Drift Tubes. 13

MIC Main Interlock Crate. 33

NIKHEF Nationaal Instituut voor Kernfysica en Hoge-EnergieFysica. 31, 48, 49

NTC Negative Temperature Coefficient resistor. 30, 32, 33, 52, 55, 58, 59, 60

OPC UA Open Platform Communications Unified Architecture. 33, 35, 51

ORB Beam Orbit. 37

PCB Printed Circuit Board. 25, 28, 30

PLC	Programmable Logic Controller. 50, 51
PP1	Patch Panel I. 32, 34
PP2	Patch Panel II. 32, 34, 55
PP3	Patch Panel III. 32, 54, 55
PPB	Pre-Production B. 41, 44, 115, 121
PS	Proton Synchrotron. 7
PSB	Proton Synchrotron Booster. 6
PSU	Power Supply Unit. 32, 33, 34, 35, 55, 57
QCD	Quantum Chromodynamics. 5
RevPi	Revolution Pi. 50
RPCs	Resistive Plate Chambers. 13
SCT	SemiConductor Tracker. 10
SEUs	Single Event Upsets. 22
SLAC	Stanford Linear Collider. 8
SPS	Super Proton Synchrotron. 7
T2I	Temperature to Interlock. 33, 52
TASSO	Two Arm Spectrometer SOlenoid. 1
TDAQ	Trigger and Data Acquisition. 13, 14
TGCs	Thin Gap Chambers. 13
TID	Total Ionising Dose. 22
TIG	Tungsten Inert Gas. 32
TLU	Trigger Logic Unit. 37, 81, 82, 83, 84, 85, 86, 87
TMR	Triple Modular Redundancy. 22
TRIUMF	Tri University Meson Facility. 45, 70
TRT	Transition Radiation Tracker. 10
TTC	Trigger, Timing, and Control. 14, 29, 30, 37, 38
VTRx+	Versatile Transceiver. 30
YARR	Yet Another Rapid Readout. 36, 37, 61, 67, 68, 69, 76, 115, 127, 128