

Collected Charge and Lorentz Angle Measurement on Non-irradiated and Irradiated ATLAS Silicon Micro-Strip Sensors for the HL-LHC

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Abstract

In this thesis, the collected charge and the Lorentz angle on non-irradiated and the irradiated miniature of the current test silicon micro-strip sensors (ATLAS12) of the future ATLAS inner tracker are measured. The samples are irradiated up to $5 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ and some of them also measured after short-term annealing (80 min at 60°C). The measurements are performed at the DESY II test beam, which provides the advantage of tracking to suppress noise hits.

The collected charge is measured at various bias voltages for each sample. The results are compared with the measurements performed using a Sr^{90} radioactive source. It is shown that the measurements with beam and radioactive source are consistent with each other, and the advantage of tracking at the beam measurements provides the measurement of collected charge on highly irradiated sensors at lower bias voltages.

The Lorentz angle is measured for each sample at different magnetic field strengths between 0 T and 1 T, the results are extrapolated to 2 T, which is the magnetic field in the inner tracker of the ATLAS detector. Most of the measurements are performed at -500 V bias voltage, which is the planned operation bias voltage of the future strip tracker. Some samples are also measured at different bias voltages to observe the effect of bias voltage on the Lorentz angle. The signal reconstruction of the strip sensors are performed using the lowest possible signal-to-noise thresholds. For non-irradiated samples, the measured Lorentz angle agrees with the prediction of the BFK model. On the irradiated samples, the results suggest that the Lorentz angle decreases with increasing bias voltage due to the increasing electric field in the sensor. The Lorentz angle decreases with increasing irradiation level; however, if the sample is under-depleted, the effect of electric field dominates and the Lorentz angle increases. Once the irradiation level becomes too high, hence the collected charge is small due to increasing trapping, the visible effect of the Lorentz force in the detector decreases, therefore the measured Lorentz angle decreases. Short-term annealing increases the Lorentz angle, due to the decrease in full depletion voltage. However, on the highly irradiated samples the annealing further decreases the Lorentz angle. The analysis is also re-performed using the signal threshold that will be used in the digital readout of strip sensors at the future ATLAS inner tracker. It is seen that the visible effect of the Lorentz force decreases at lower fluences due to the higher threshold.

Zusammenfassung

In dieser Arbeit werden die Messungen der gesammelten Ladungen und des Lorentz-Winkels der unbestrahlten und bestrahlten Miniaturversion des aktuellen Mikrostreifen-Testsensors (ATLAS12) des zukünftigen inneren ATLAS Trackers präsentiert. Die Testsensoren wurden bis zu einer Dosis von $5 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ bestrahlt und einige auch nach einer Kurzzeit-Ausheilung (80 min bei 60°C) getestet. Die Messungen wurden am DESY II Teststrahl ausgeführt. Dies hatte auf Grund der Möglichkeit der Spurrekonstruktion den Vorteil der Rauschunterdrückung.

Die gesammelte Ladung wurde bei jedem Testsensor für verschiedene Vorspannungen gemessen. Die Ergebnisse wurden verglichen mit den Messungen unter Verwendung einer radioaktiven Quelle (Sr^{90}). Es konnte gezeigt werden, dass die Messungen mit dem Teststrahl und der radioaktiven Quelle in guter Übereinstimmung stehen. Zudem konnte der Spurrekonstruktion genutzt werden, um die gesammelte Ladung für stark bestrahlte Testsensoren auch bei niedrigen Vorspannungen zu messen.

Der Lorentz-Winkel wurde für jeden Testsensor bei magnetischen Feldstärken von 0 T und 1 T gemessen. Die Ergebnisse wurden auf eine Feldstärke von 2 T extrapoliert, was der Feldstärke im ATLAS Detektor entspricht. Der Großteil der Messungen sind mit einer Vorspannung von -500 V durchgeführt worden, da dies der voraussichtlichen Vorspannung im zukünftigen ATLAS Mikrostreifen-Detektor übereinstimmt. Einige Testsensoren wurden bei verschiedenen Vorspannung getestet, um die Auswirkung verschiedener Spannungsstärken auf den Lorentz-Winkel zu messen.

Die Rekonstruktion des Signals der Streifensensoren ist mit dem niedrigsten möglichen Signal-Rausch-Schwellwert durchgeführt worden. Die Ergebnisse des Lorentz-Winkels bei unbestrahlten Sensoren stimmen mit den Vorhersagen des BFK Model überein. Die Messdaten der bestrahlten Testsensoren zeigen, auf Grund des wachsenden elektrischen Feldes im Sensor, eine Abnahme des Lorentz-Winkels für zunehmende Vorspannungen. Zudem, wird der Lorentz-Winkel mit zunehmender Bestrahlung kleiner. Bei einer unvollständigen Ladungsträgerverarmung dominiert allerdings der Effekt des elektrischen Feldes und der Lorentz-Winkel nimmt zu. Sobald die Dosis der Bestrahlung einen Grenzwert überschreitet und die gesammelte Ladung durch entstandene Ladungsfallen abnimmt, nimmt auch der sichtbare Effekt der Lorentzkraft ab und der Lorentz-Winkel wird kleiner. Eine Kurzzeit-Ausheilung führt zu einer Zunahme des Lorentz-Winkels durch die Zunahme der Verarmungsspannung. Bei stark bestrahlten Testsensoren führt die Ausheilung jedoch zu einer weiteren Abnahme des Lorentz-Winkels. Die Analyse der Messungen wurde mit dem Signal-Schwellwert durchgeführt, der auch im zukünftigen inneren ATLAS Tracker verwendet wird. Die Ergebnisse zeigen, dass der sichtbare Effekt der Lorentzkraft bei kleineren Teilchenfluenzen abnimmt.

To Totinim



Contents

1	Introduction	1
2	Silicon Sensors and Radiation Damage	5
2.1	Basic Properties of Silicon	5
2.2	A Silicon Sensor for High Energy Physics Application	8
2.3	Radiation Damage on Silicon Sensors	8
2.3.1	Bulk Damage	8
2.3.2	Macroscopic Effects and Annealing	9
2.4	Silicon Micro-Strip Sensors Used in this Thesis	13
2.5	Lorentz Angle	14
3	The Large Hadron Collider and the ATLAS Detector	17
3.1	The Large Hadron Collider	17
3.2	The ATLAS Detector	18
3.2.1	The Magnet System	21
3.2.2	The Inner Detector	21
3.2.3	The Calorimeter	25
3.2.4	Muon Spectrometer	27
3.2.5	The Trigger and Data Acquisition System	28
3.3	The High-Luminosity LHC and Upgrade of ATLAS Detector	29
3.3.1	Upgrade of the ATLAS detector	30
4	The Test Beam Setup	35
4.1	The DESYII Test beam	36
4.2	The Solenoid Magnet	38
4.3	The EUDET Beam Telescope	40
4.4	ALiBaVa Readout System	42
4.5	Adapting the ALiBaVa Readout System for Testbeam Usage	43
4.6	The Sensor Box	44
4.6.1	The Sensor Holder	45
4.6.2	The Cooling Plate	46
4.7	Implementation in the Telescope	46

5	Signal Reconstruction of the ALiBaVa Data	51
5.1	Raw Data from the ALiBaVa Readout System	52
5.2	Pedestal and Noise Calculation	54
5.3	Common Mode Noise Reduction	55
5.4	Signal Reconstruction	55
5.5	Signal Selection	56
5.6	Seed Clustering	57
5.7	Cross-Talk Correction	59
5.8	Calibration	61
5.9	The signal to be used in further analysis	63
6	Track Reconstruction	65
6.1	Signal Reconstruction of EUDET Beam Telescope Data	65
6.2	Forming Hits	67
6.3	Alignment and Track fitting	67
7	Measurements and Results	77
7.1	Silicon Micro-Strip Sensors for the HL-LHC ATLAS Strip Detector	77
7.2	Collected Charge Measurement	78
7.3	Lorentz Angle Measurement	80
7.4	Lorentz Angle on the Future ATLAS silicon strip sensors	95
8	Summary and Outlook	105
	Acknowledgments	107

Chapter 1

Introduction

Silicon sensors are widely used in particle physics experiments, mainly due to their excellent ability to detect charged particles passing through the sensor. They can be produced to have readout channels in the order of μm which provides fine spatial resolution. Having fine spatial resolution together with the detector geometry allow them to measure the charged particles position precisely. In a detector that has several detection layers, track of the particle can be reconstructed precisely which leads to a precise measurement of momentum of charged particles in the presence of magnetic field as well as the interaction point of the beam accurately. These characteristics of the silicon sensors makes them an excellent choice for tracking detectors.

The Large Hadron Collider (LHC) [1] is the largest and the most powerful particle accelerator in the world. The LHC is built to provide a facility for particle physics studies. There are detectors located at the interaction points of the LHC, one of which is ATLAS [2, 3], detecting the generated particles by the collision of accelerated protons. The ATLAS experiment uses a multi-layer sub-detector system to detect proton interaction point (vertex), the track direction as well as the momentum and the energy of the particles which helps to distinguish the type of the particle. One of the sub-detectors is the inner detector (ID), the closest sub-detector to the LHC beam pipe, used to track charged particles. In order to achieve the desired momentum measurement precision, the ID uses a transition radiation tracker (TRT) and high granular silicon detectors in the inner part of the ID. The data taken by the ID, with the combination of other sub-detectors in the ATLAS detector, is used to investigate the characteristics of particles and to test the existing (Standard Model) and the predicted models (such as SuperSymmetry (SUSY)).

Detectors at the LHC are subject to radiation damage due to the high luminosity ($1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$). The damage by the radiation is higher on the sub-detectors close to the beam pipe. The silicon detectors of the ID will be subject to the highest radiation. Therefore the silicon detectors are produced to be tolerant to the irradiation level that is expected during the lifetime of the LHC experiment.

By around 2022, the LHC will deliver the foreseen amount of data to the experiments

(300 fb^{-1}). In order to further increase the potential of the LHC, it is planned to be upgraded to the High-Luminosity LHC (HL-LHC) [4] to increase the recorded data by a factor of 10. Although the Higgs boson is discovered in 2012 at the LHC, its properties can be determined more precisely with a larger data set [5]. The increased amount of data by the HL-LHC will enable the precision of the Higgs boson couplings measurements by a factor of 2 to 3 with respect to the LHC [6]. The physics program of the HL-LHC includes; the precision measurements of the SM, searches for new physics by studying rare SM processes and by studying physics beyond the SM. There are still theoretical problems of the SM, such as the so-called hierarchy problem and not being to explain the Dark Matter in the universe, the HL-LHC can detect new phenomena that can explain these [6].

The HL-LHC will introduce even more harsh conditions to the detectors by increasing the luminosity to $5 - 7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The number of proton interactions per bunch crossing (pile-up) will increase which will lead to increase in number of particles created. Having more particles passing through the detectors will increase the occupancy of the detectors. The TRT will reach its occupancy limit therefore the ID will be replaced by all silicon detector system. In order to achieve the desired measurement precision, the silicon detectors should be capable of distinguish each charged particle in a high pile-up environment hence it will be designed to be more granular as well as radiation tolerant due to increased radiation.

The increased radiation at HL-LHC will cause more damage to the silicon detector compared to the LHC. The increased radiation damage will decrease the collected charge on the silicon detectors. It is essential to study the collected charge on the detector, since its decrease affects the position detection of the charged particles hence the momentum measurement of the charged particles and the interaction vertex. The Lorentz angle on the sensors, which is introduced by the presence of a magnetic field in the ID, also influences the accuracy of the ID measurements. The charge carriers in the silicon sensor are shifted by the Lorentz force which causes the change in cluster size, hence affects the calculated hit position. It is important to take the Lorentz angle into account in order to achieve precise track reconstruction. Since the radiation damages the silicon, the Lorentz angles on it also changes and it is important to investigate its behavior with radiation damage to have better knowledge of detector response during its lifetime.

This thesis focuses on the charge collection and Lorentz angle measurement on non-irradiated and irradiated test sensors of the future ATLAS silicon micro-strip detector at HL-LHC. The measurements are performed at the DESY II test beam and a dedicated setup is prepared for this measurement. The silicon micro-strip sensors are read out by the ALiBaVa analogue readout system. The analogue readout is used to achieve a precise measurement of the collected charge and the cluster size. The Lorentz angle is measured by using the cluster size dependence on the incidence angle of the track on the sensor, knowing that the minimum cluster size will be measured when the incidence angle equals to the Lorentz angle. The EUDET beam telescope is used to measure the track of the electron beams and to extract the incidence angle on the silicon strip sensors. Analysis is performed to measure the collected charge and the Lorentz angle.

The document starts with an introduction to silicon sensors, its properties and the effects of radiation damage on its properties (Chapter 2). The LHC, the ATLAS detector and the

upgrades for the HL-LHC are summarized in Chapter 3. The details of the measurement setup, which is developed to be used at the DESY II test beam, is given in Chapter 4. The analysis method, which includes the signal reconstruction on the silicon strip sensors and the particle track reconstruction using the EUDET beam telescope is described in Chapters 5 and 6, respectively. The complete overview of the measurements as well as the results are shown in Chapter 7. Finally, in Chapter 8 the results are summarized and an outlook of possible future measurements is discussed.

Chapter 2

Silicon Sensors and Radiation Damage

Silicon sensors are popular in high energy physics (HEP) detectors due to their excellent ability to detect charged particles. They can be produced with fine spatial resolution and high radiation tolerance, which makes them an excellent choice for tracking detectors that operate in high radiation environment such as the LHC.

In this chapter, basic properties of silicon will be introduced in Section 2.1 and the usage of a silicon detector in high energy physics application is illustrated in Section 2.2. Due to harsh environment of the LHC, silicon detectors are subject to high radiation, the effect of the radiation damage on the silicon detectors are discussed in Section 2.3. Finally, the Lorentz angle on the silicon detectors is explained in Section 2.5.

2.1 Basic Properties of Silicon

Semiconductors, such as silicon, are crystalline solids which show an *energy band* structure in the outer shell atomic level. While electrons in a single atom have discrete energy levels, when the atoms form a crystalline solid, the discrete energy levels are spaced closely due to the atomic interactions. These closely spaced energy levels can be considered as continuous. Comparison of the energy band structure of semiconductors with insulators and conductors is illustrated in Figure 2.1. The electrons in the *conduction band* are detached from their atoms and freely move in the crystal, whereas in the *valence band* they are bound more tightly to their atom. The *energy gap* between the valence and conduction band represents the minimum thermal energy that is needed for an electron in the valence band to break its bond and jump to the conduction band. The energy gap is determined by lattice spacing between atoms in the crystal and dependent on temperature and pressure. At normal conditions (at room temperature under atmospheric pressure) the energy gap is smaller in semiconductors than in insulators. In conductors have no

energy gap, therefore electrons in valence band can easily be excited, such as by a small electric field [7].

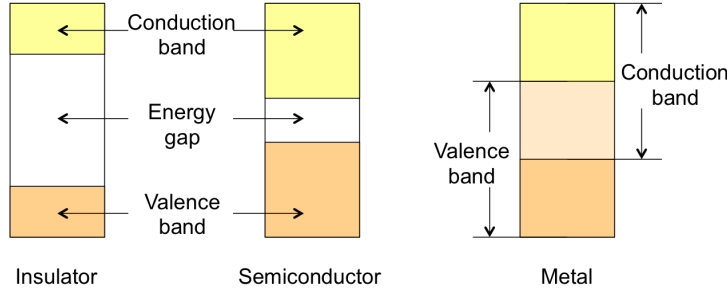


Figure 2.1: Comparison of the energy band structures of insulators, semiconductors and conductors.

Silicon, a group-IV element of the periodic table, has four valence electrons in the outer atomic shell which can contribute to the bonding process. In a pure silicon crystal, the valence electrons of a silicon atom are covalently bonded to the other silicon atoms, leaving no loosely bonded electrons or holes that can easily be freed. Introducing impurities to the silicon (doping) can provide weakly bound electron or hole. Figure 2.2 illustrates the crystal structure of the pure and the doped silicon. The silicon doped with an element of group V, such as phosphorus, has electrons as a majority of charge carrier and called n-type silicon. Whereas the element of group III, such as boron, doped silicon has holes as a majority of charge carrier and called p-type silicon.

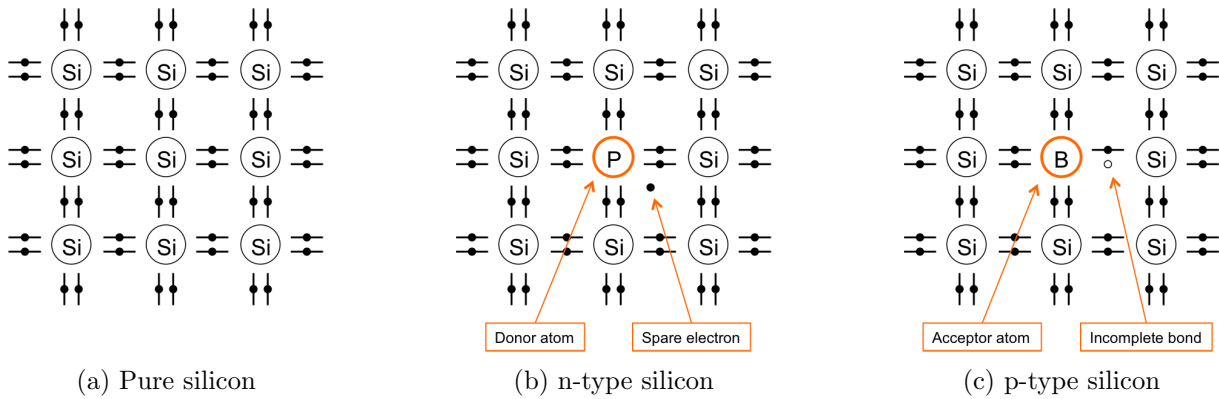


Figure 2.2: The crystal lattice structure of pure and doped silicon.

Impurities perturb the energy band structure of the semiconductor and results an additional energy level in the energy gap. Electrons or holes can be trapped (*trapping*) in these levels and be released after some time. If the releasing time is in the order of charge collection time, it decreases the charge collection efficiency, however, if it is much smaller then there is a little or no effect. This additional energy level gets closer to the conduction or valence band with higher impurities, therefore the doped silicon should be relatively pure, and the amount of doping is limited. Structural defects, such as vacancies in the lattice, in the doped silicon can also cause

trapping. These defects, among other reasons, may be caused during the crystal growth or high radiation which will be discussed in Section 2.3 [7].

The operation of silicon sensors is based on using p-type and n-type doped silicon in contact (*p-n junction*). Once the p-n junction formed, the free electrons from n-type diffuses to the p-type silicon occupying the holes. The diffusion causes the n-side of the junction to be positively charged and p-side to be negatively charged. The charged sides create an electric field which acts against the diffusion of electrons and stops the diffusion once it becomes strong enough. The stabilized p-n junction will have a small region around the junction which is depleted of free charge carriers, as shown in Figure 2.3a. This region is called *depletion zone* or *space charge region*. Any electron or hole created or entering the depletion zone drift due to the electric field and in principle can be collected on the drift side. However, since the depletion zone is thin and the electric field is not strong enough, it will not be possible to obtain a strong signal. To increase the electric field and enlarge the depletion zone, a reverse bias is applied to the p-n junction (see Figure 2.3b). The bias voltage at which the silicon volume is fully depleted is called *depletion voltage*. The enlarged depletion zone will provide larger detection volume and more efficient charge collection due to the increased electric field. However, the maximum bias voltage that can be applied to the p-n junction is limited with the resistance of the semiconductor, exceeding this limit would cause the semiconductor to breakdown and begin conducting.

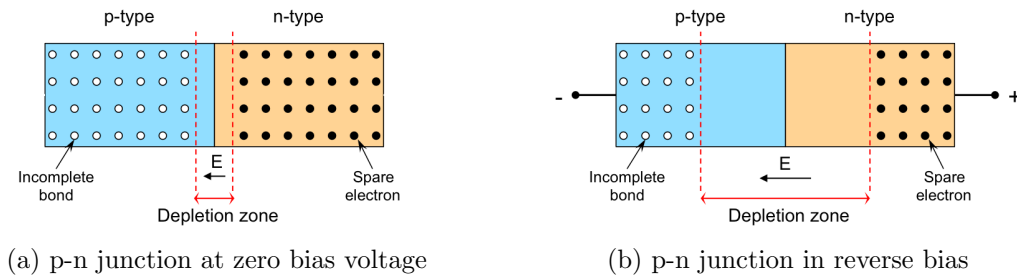


Figure 2.3: p-n junction.

Although, the reverse biased p-n junction is ideally non-conductive, a small current (*leakage current*) flows through the junction when voltage is applied. There are several sources of leakage current. One of the sources is the movement of minority carriers, for example movement of an electron from p-region to the n-region, which creates very small (few nA/cm^2) leakage current. Another source is thermally created electron-hole pairs due to the additional energy levels introduced by impurities. The additional energy levels in the energy gap can cause a creation of electrons or holes due to the trapping centers. The leakage current caused by this source depends on the number of traps in the depletion zone and usually in the order of few $\mu\text{A}/\text{cm}^2$. The other source which by far can have the largest contribution is the current through the surface channels. This source is mostly eliminated during the sensor manufacturing, and will not be discussed here. The leakage current is observed as a noise at the sensor and limits the minimum amount of signal that is detectable. Therefore, it should be kept small to reach high charge collection efficiency [7].

2.2 A Silicon Sensor for High Energy Physics Application

Figure 2.4 shows a schematic of a silicon micro-strip sensor. The p-n junction is formed between the n-type doped silicon strip and the p-type doped bulk silicon. Strips are insulated by a SiO_2 layer having opening for aluminum contact on the strips for readout. The p-n junction is operated in reverse bias. When a particle passes through the depletion zone, it ionizes the silicon and creates electron-hole pairs. Due to the electric field in the depletion zone, these electrons and holes are drifted to the n-side and p-side, respectively. Thus a current is induced and can be measured using front-end electronics. The induced current is proportional to the number of created electron-hole pairs thus to the energy deposited. The required average energy to create electron-hole pair in the silicon sensor is 3.6 eV. A minimum ionizing particle (MIP) creates approximately 80 electron-hole pairs per μm [8, 9].

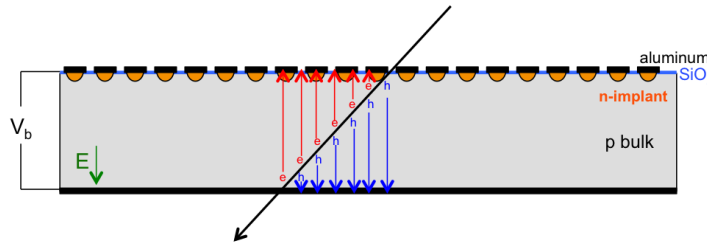


Figure 2.4: A charged particle passing through a depleted p-n junction is creating electron-hole pairs.

2.3 Radiation Damage on Silicon Sensors

The LHC and HL-LHC (see Chapter 3) aim to collect large statistical samples of particle collisions, hence they operate at high particle fluxes which lead to radiation damage. Silicon detectors at the LHC are the closest sub-detector to the collision region, thus they are be subject to high radiation damage which will be even a factor of 10 higher at HL-LHC.

When charged particles pass through the silicon detector, they ionize the lattice of silicon and also interact with the atoms in the silicon by electromagnetic and strong forces. The types of radiation damage on the silicon sensors can be classified as bulk and surface defects [10]. In this section the effects of bulk damage will be summarized, a detailed explanation as well as effects of surface damage can be found in References [10, 8, 9].

2.3.1 Bulk Damage

Traversing particles deform the silicon lattice by displacing the atom and creating interstitials (I), vacancies (V) and more complex constructs. Moreover, dispersed silicon atoms or vacancies often combine with impurity atoms. More details on the types of deformations can be found in

References [10, 8, 9]. The defects in the silicon lattice change the initial properties of silicon, therefore, this change needs to be studied in detail depending on the radiation level to predict the detector performance during its lifetime in a HEP experiment.

Different type of particles at different energies cause different level of radiation damage, which can be normalized according to the Non-Ionizing Energy Loss (NIEL) hypothesis [11]. The displacement damage $D(E)$ can be calculated as

$$D(E) = \sum_i \sigma_i(E_{kin}) \int_0^{E_{R,max}} f_i(E_{kin}, E_R) P(E_R) dE_R \quad (2.1)$$

where all possible interactions (i) are summed up. σ_i is the cross section of the process, $f_i(E, T)$ is the probability of having a collision of a particle with the energy $E = E_{kin}$, transferring a recoil energy of $T = E_R$. $P(E_R)$ is the Lindhard partition function [12] which describes the fraction of energy into silicon atom displacement. For example, this fraction is $P(E_R) \sim 50\%$ for 10 MeV protons, $P(E_R) \sim 42\%$ for 24 GeV protons and $P(E_R) \sim 43\%$ for 1 MeV neutrons [10].

Figure 2.5 shows the displacement functions of particles normalized to 1 MeV neutron equivalent fluence [$1 \text{ MeV } n_{eq}/\text{cm}^2$].

2.3.2 Macroscopic Effects and Annealing

Radiation damage causes leakage current to increase, depletion voltage to change and charge collection efficiency to decrease. At irradiation levels in the order of $10^{14} n_{eq}$ [†] increase of leakage current is the main problem of operation of the sensors. The increase in the depletion voltage becomes problematic at irradiation levels in the order of $10^{15} n_{eq}$. However; in the order of $10^{16} n_{eq}$ the major problem becomes the decrease in charge collection [10].

These properties also change with time (annealing) since interstitials and vacancies created by radiation are very mobile at temperatures above 150 K and causes possibility of defect combination. This whole process is called annealing and it is highly dependent on temperature. Controlled annealing is performed by keeping the sensor at a specific temperature for a specific time to investigate the change of sensor properties at different combination of annealing temperature and time. With annealing the leakage current always decreases, so it is always beneficial in terms of leakage current. The effect on the depletion voltage is more complicated, it depends on the detector type as well as the annealing time. For p-type sensors, which are used in this study, the depletion voltage decreases in short term annealing, so it is beneficial. However; in long term annealing the depletion voltage increases that is why it is called reverse annealing. The charge collection efficiency decreases/increases for holes/electrons [10].

[†] $1 \text{ MeV } n_{eq}/\text{cm}^2$ is denoted shortly as n_{eq}

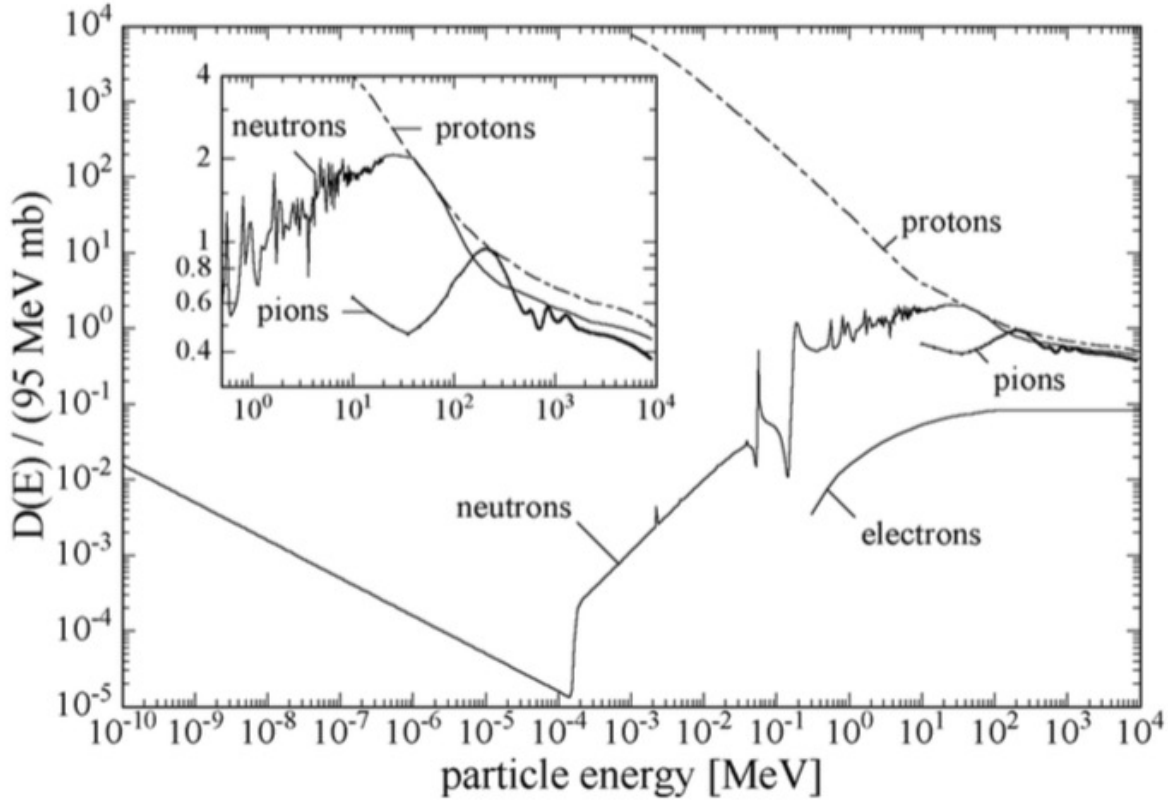


Figure 2.5: Displacement damage functions $D(E)$ normalized to $1\text{MeV } n_{\text{eq}}/\text{cm}^2$. Note that $D_{\text{neutron}}(1\text{MeV } n_{\text{eq}}/\text{cm}^2) = 95\text{ MeV mb}/\text{cm}^2$ [8]

Leakage Current

Defects in the additional energy levels in the energy band gap created by radiation degrade in time, during which electron-hole pairs are created and they increase the leakage current (ΔI) of the sensor. There is a linear relationship between leakage current (ΔI) and fluence (Equation 2.2) which makes it possible to determine the fluence a sensor exposed to using its leakage current [10].

$$\frac{\Delta I}{V} = \alpha \Phi, \quad (2.2)$$

where V is the volume that current passes through, α is the coefficient called the current-related damage rate and Φ is the 1 MeV neutron equivalent fluence.

After annealing the α parameter can be written as

$$\alpha = \alpha_0 + \alpha_I \cdot \exp\left(-\frac{t}{\tau_I}\right) - \beta \cdot \ln \frac{t}{t_0}, \quad (2.3)$$

where $\alpha_I \sim 1.25 \cdot 10^{-17}$ A/cm, $\beta \sim 3 \cdot 10^{-18}$ A/cm and $t_0 = 1$ A/cm. Parameters α_0 and τ_I depend on temperature. Detailed calculation and dependence on temperature can be found in [8]. For the measurements in this thesis, a standard annealing scenario is applied which is 80 min at 60 °C. For this scenario $\alpha \sim 4 \cdot 10^{-17}$ A/cm measured at room temperature [10]. The leakage current is temperature dependent and strongly reduced at temperatures below zero degree.

Figure 2.6 shows the linear dependence of dark current to the fluence (left) and how it changes with annealing at different temperatures (right). The dark current always decreases with annealing which is always beneficial.

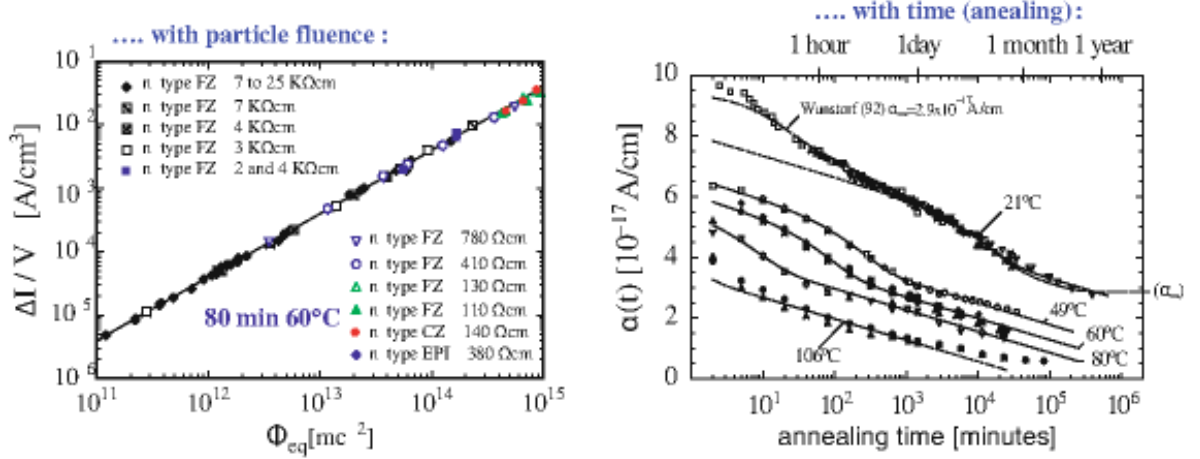


Figure 2.6: Dependence of leakage current on radiation (left) and annealing (right) [10]

Depletion Voltage

The depletion voltage is proportional to the absolute value of the effective doping concentration (N_{eff} defined as Equation 2.4) of the bulk material, which changes due to the donor and acceptor generation by irradiation.

$$N_{eff} = N_D - N_A, \quad (2.4)$$

where N_D and N_A are the donor and acceptor concentration, respectively. The acceptor creation leads to a increase in negative space charge of initial doping of the sensor. Whereas the donor creation decreases the negative space charge and increases the positive space charge. Usually both acceptors and donors are created by irradiation, however the amount of the created acceptors and donors depends on the particle type [9].

Neutrons mostly create acceptors, on p-type sensors this leads to increase in depletion voltage. However, on n-type sensors, as shown in Figure 2.7 left, an increase in negative space

charge decreases the depletion voltage up to the point where acceptors compensate the initial doping. After this point, the sensor type changes from n-type to p-type and the depletion voltage increases with irradiation [9].

The effect of annealing on depletion voltage depends on the duration of annealing. Figure 2.7 shows the change in effective space charge as a function of annealing time.

In the short term annealing, N_{eff} is increasing, this is usually associated with annealing of acceptors, but generation of donors can also cause this effect. For p-type sensors initially N_{eff} is negative, with annealing it becomes less negative so the depletion voltage decreases. That is why short term annealing is beneficial for p-type sensors. However, the depletion voltage of n-type detector increases since the N_{eff} is initially positive and it becomes more positive [8].

In the long term annealing, in contrast of the short term annealing, N_{eff} decreases, usually the reason of this effect is interpreted as building up acceptors; however, this effect can also be caused by annealing of donors. Since the absolute value of N_{eff} , so the depletion voltage, is increasing for p-type sensors, the long term annealing is called reverse annealing [8].

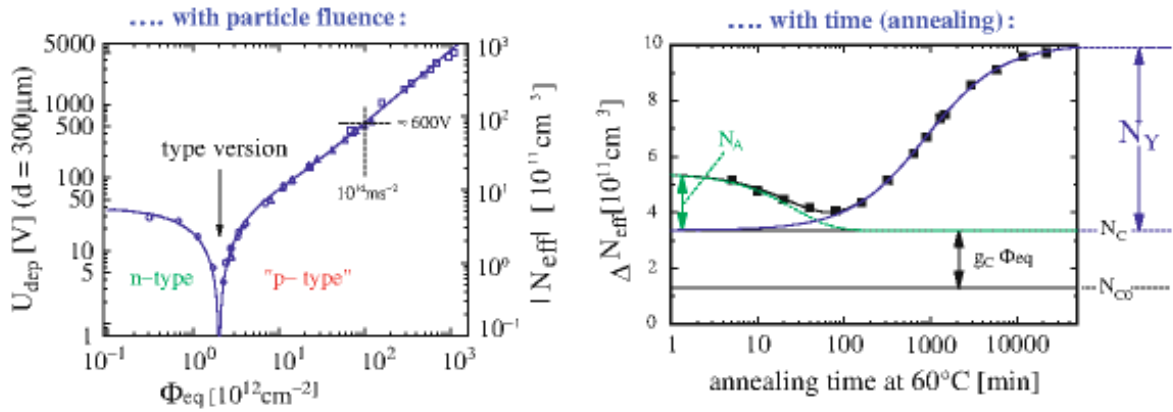


Figure 2.7: Depletion voltage and effective doping concentration as a function of irradiation (left), change in effective doping concentration as a function of annealing time (right) [10]

Charge Collection Efficiency

The charge collection efficiency is affected by irradiation since it creates trapping centers which hold the electrons/holes and reduces the signal strength. The electrons and holes are affected differently because of their different mobilities. The reduction in charge collection efficiency can be described as

$$Q_{e,h}(t) = Q_{0e,h} \exp \left(-\frac{1}{\tau_{\text{eff}e,h}} \cdot t \right) \quad (2.5)$$

where $Q(t)$ and Q_0 denotes the collected charge on an irradiated sensor with a fluence t and non-irradiated sensor, respectively. $1/\tau_{\text{eff},h}$ is proportional to the concentration of trapping centers [10]. It is possible to increase charge collection efficiency by increasing the operation voltage, however; once the depletion voltage increased too much, the decrease in charge collection efficiency becomes unavoidable.

The inverse trapping time ($1/\tau_{\text{eff}}$) decreases for electrons with annealing time, so the annealing is beneficial in terms of the charge collection efficiency [10].

One of the aims in this thesis is to measure the collected charge on future ATLAS ITK test sensors (see Section 7.1), and to investigate its the dependence on irradiation level and bias voltage.

2.4 Silicon Micro-Strip Sensors Used in this Thesis

The requirements for the HL-LHC ATLAS silicon micro-strip sensors are described in Section 3.3.1. The miniature of current test sensors, ATLAS12 [13], for the strip detector for the HL-LHC phase are used in the measurements of this thesis. The ATLAS12 sensors are chosen to be n^+ -implant readout on p -type silicon (n^+ -in- p) which is intrinsically more radiation hard than p -in- n type sensors since the depletion region develops from the readout implants. This leads to a number of advantages. First of all, it is possible to operate sensors under partial depletion, which becomes advantageous when the full depletion voltage gets too high because of the radiation damage. Moreover, n^+ -in- p sensors are collecting electrons therefore, the signal generated is higher since the drift velocity of electrons is higher and electrons are less affected by charge-trapping compared to holes [13]. Table 2.1 lists the specifications of ATLAS12 miniature sensors.

Wafer type	p-type FZ [†]
Crystal orientation	$\langle 100 \rangle$
Thickness	$310 \pm 25 \mu\text{m}$
Strip pitch	$74.5 \mu\text{m}$
Strip length	$\sim 8 \text{ mm}$
Outer dimension	$10 \times 10 \text{ mm}^2$
Number of strips	104

Table 2.1: Specifications of ATLAS12 miniature sensors.

[†]Float Zone (FZ) is a silicon growth technique which is explained in Reference [8].

2.5 Lorentz Angle

The charge carriers, created by the charged particle passing through, drift along the electric field (Figure 2.8a). However, in the presence of a magnetic field, charge carriers drift with an angle due to Lorentz force (Figure 2.8b). This angle is called ‘Lorentz angle’. Due to the Lorentz force cluster size increases, and the calculated hit position shifts, hence the spatial resolution of the detector changes. In order to achieve the best spatial resolution, the Lorentz angle should be measured and taken into account in the reconstruction of the particle tracking.

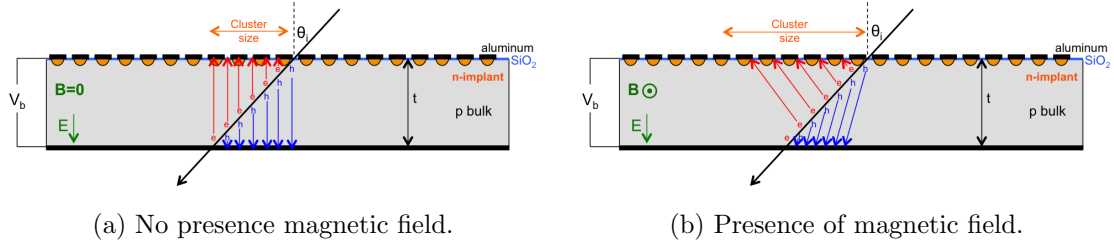


Figure 2.8: Drift of charge carriers.

The Lorentz angle on non-irradiated silicon sensors is given by

$$\tan(\theta_L) = r_H \mu_d B, \quad (2.6)$$

$$r_H = \begin{cases} 1.13 + 0.0008 \cdot (T - 273) & \text{for electrons} \\ 0.72 + 0.0005 \cdot (T - 273) & \text{for holes} \end{cases}$$

where μ_d is the drift mobility and r_H is the Hall factor, at the temperature (T in Kelvin), which depends on scattering mechanism of charge carriers in silicon. T is the temperature in Kelvin. The drift mobility, which depends on the magnetic field, bias voltage, thickness of depleted region and the temperature, can be calculated using Becker-Fretwurst-Klanner (BFK) [14] model for non-irradiated silicon sensors.

The estimated Lorentz angle for the silicon sensors in the conditions of the measurements in this study (300 μm thick p-type silicon sensor with orientation $\langle 100 \rangle$ on bias voltage -500 V at temperature -25 $^{\circ}\text{C}$) are listed in Table 2.2 for the magnetic fields 1 T (magnetic field in this study) and 2 T (magnetic field of the ATLAS inner tracker).

Lorentz angle (degrees)		
Model	1 T	2 T
BFK $\langle 100 \rangle$	3.18	6.34

Table 2.2: Estimated Lorentz angle at 1 T and 2 T using BFK $\langle 100 \rangle$ model.

The measurement of Lorentz angle is being performed on the ATLAS Semiconductor Tracker (SCT) (see Section 3.2.2) in order to have precise hit position. Prior to LHC beam operation, the Lorentz angle is measured on SCT sensors at test beams [15] and using cosmic-ray data collected in the ATLAS detector [16]. These measurements are compatible with the model predictions within uncertainties on the model predictions. Figure 2.9 [17] shows the Lorentz angle on the ATLAS Semiconductor Tracker (SCT) barrel layers measured in 2014 using the collision data of the LHC recorded in 2011 and 2012 where the magnetic field on SCT was 2 T and the bias voltage on the sensors were 150 V. The measurements are performed for each barrel layer and each sensor type ($\langle 111 \rangle$ and $\langle 100 \rangle$ crystal orientations) separately. The measured Lorentz angle values are compatible with the model predictions within at most twice the estimated uncertainties on these predictions. Although, the $\langle 100 \rangle$ sensors should have higher Lorentz angle, the measured Lorentz angles on the $\langle 100 \rangle$ sensors are approximately 1° lower than on the $\langle 111 \rangle$ sensors [17].

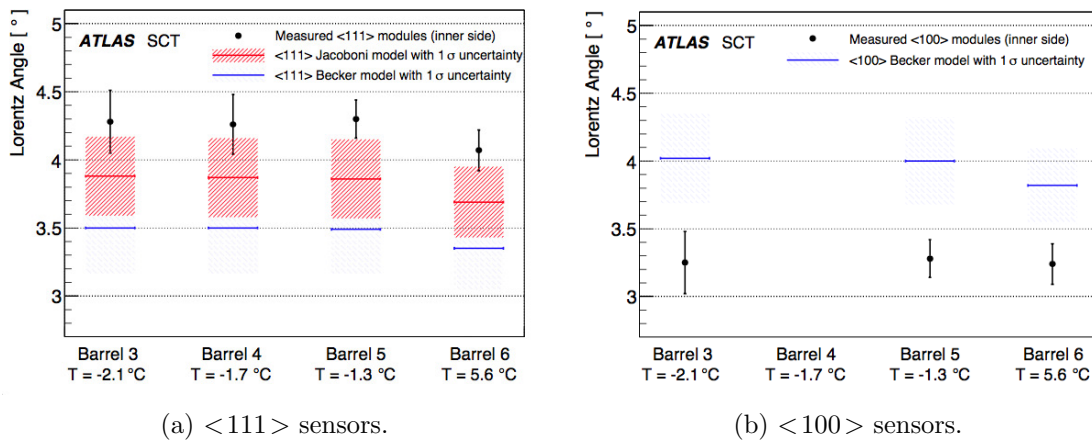
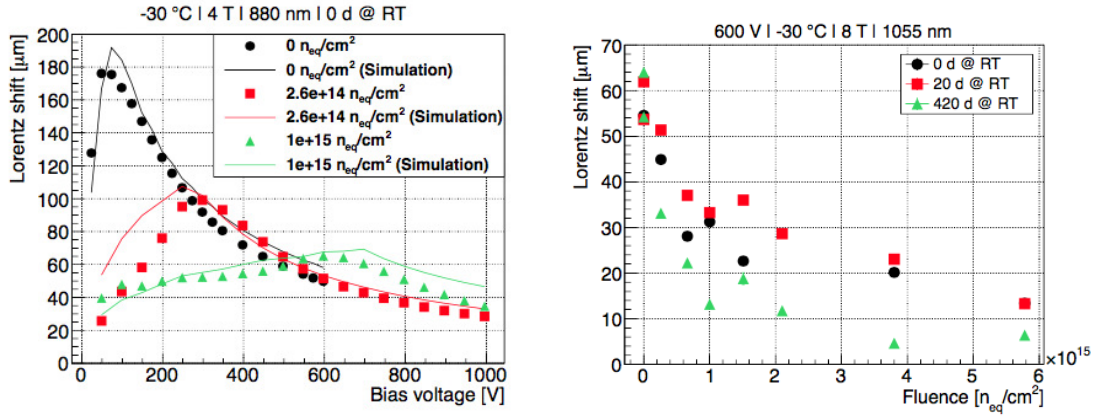


Figure 2.9: Lorentz angle measured at SCT layers and their comparison with the expected values from Jacoboni-Canali and Becker-Fretwurst-Klanner models [17].

It is challenging to compare the Lorentz angle measurements on the SCT sensors with the measurements on the sensors used in this thesis since the SCT sensors are n-type sensors, collecting holes. The holes have lower mobility therefore results in lower Lorentz angle than electrons. Moreover, the temperature and the bias voltage of the sensors measured in this thesis are different than the ones at SCT.

The shift in hit position of reconstructed cluster (Lorentz shift), which gives an estimation of the Lorentz angle, is studied on the sensors for the CMS Tracker upgrade [18]. The measurements are also performed in p-type sensors at more similar conditions with the ones in this thesis, using non-irradiated, irradiated and annealed sensors, which makes them interesting to compare with the results of the measurements in this thesis. Reference [18] measured the Lorentz shift dependence on bias voltage using 880 nm laser, the results are shown in Figure 2.10a. The Lorentz shift of electrons increases with increasing bias voltage until it reaches the full depletion since the limited depletion zone decreases the amount of shift. At the bias voltages higher than full depletion voltage the shift decreases since the electric field increases. The Lorentz angle,

unlike Lorentz shift, depends on the electric field in the depletion zone rather than its depth. Therefore, the Lorentz angle would decrease with increasing bias voltage whether it is smaller or higher than full depletion voltage. In the paper [18], the irradiated sensors up to $6 \times 10^{15} n_{eq}$ are measured without annealing, after short-term (20 days at room temperature) and long-term (40 days at room temperature) annealing using 1055 nm laser. The results are shown in Figure 2.10b. The samples measured at -600 V at which the sensors with fluences up to $1 \times 10^{15} n_{eq}$ are fully depleted. The results show that the Lorentz shift of electrons decreases with the increasing irradiation level up to $1 \times 10^{15} n_{eq}$, at higher fluences the shift is overcompensated by decreased depletion zone. The results of the measurements in this thesis are compared with the ones of this paper in Chapter 7.



(a) Lorentz shift as a function of the bias voltage for three irradiation fluences. The solid lines are representing the simulation model [19].

(b) Lorentz shift as a function of irradiation fluence and annealing time.

Figure 2.10: Lorentz shift of electrons measured on the $320 \mu m$ thick sensors for the CMS Tracker upgrade [18].

Chapter 3

The Large Hadron Collider and the ATLAS Detector

This chapter starts with a brief description of the Large Hadron Collider (LHC) [1], introducing the accelerator complex and the main experiments. The ATLAS experiment and its currently installed components are introduced. Special emphasis is put on the description on the Inner Detector, also mentioning the expected radiation damage during the data taking until 2022 (more information on radiation damage on silicon sensors can be found in Chapter 2). Subsequently, the High-Luminosity LHC [4] is introduced as well as the planned upgrades on the ATLAS sub-detectors and trigger system. Again, the focus is put on the Inner Detector upgrade.

3.1 The Large Hadron Collider

The LHC [1] at CERN is the world's largest and most powerful particle accelerator. It is located near Geneva and spans across the border between Switzerland and France. It is a 27 km two-ring-superconducting hadron accelerator and collider located 100 m underground. Figure 3.1 shows a schematic view of the LHC including the experiments located at different interaction points. There are seven experiments at the LHC: the two large experiments ATLAS and CMS, the two medium-sized experiments ALICE and LHCb, as well as the three smaller experiments TOTEM, LHCf and MoEDAL. The two large experiments, ATLAS [2] and CMS [20], are general purpose detectors designed to analyze a large range of physics processes. They are designed independently to enable the cross-confirmation of any possible new physics discoveries. One of the medium-sized experiments, ALICE [21], has a specialized detector for studying the quark-gluon plasma which is created by colliding heavy ion beams and is believed to have existed soon after the Big Bang. The other medium-sized experiment, LHCb [22], has been designed for, among other physics goals, investigating differences between matter and antimatter by studying b quarks. The smallest experiments, TOTEM [23] and LHCf [24], are designed to study forward particles (protons or heavy ions) which are coming from the elastic collision of the particles in

the beam, rather than head-on collisions. The last experiment MoEDAL [25] is searching for a hypothetical particle called the magnetic monopole [1].

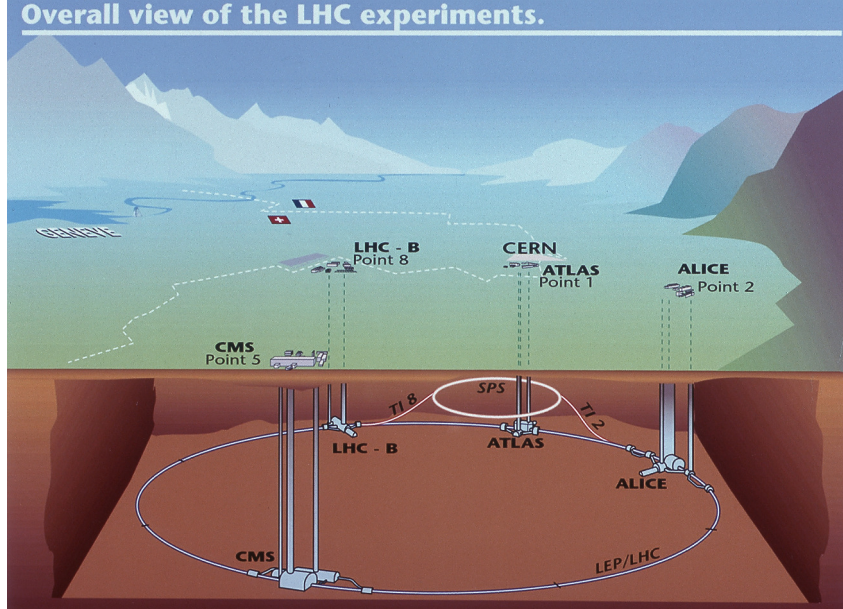


Figure 3.1: The Large Hadron Collider (LHC) [26].

The four main experiments (ATLAS, CMS, ALICE and LHCb) and the other small experiments, use data obtained by colliding proton or heavy ion beams accelerated by the LHC accelerator complex (see Figure 3.2). The protons are obtained by removing electrons from hydrogen atoms. They are accelerated to 50 MeV by a linear accelerator (LINAC2) and then injected into the Proton Synchrotron Booster (PSB) where the protons reach an energy of 1.4 GeV. The protons are further accelerated in the Proton Synchrotron (PS) to 25 GeV and then by the Super Proton Synchrotron (SPS) to 450 GeV. Finally protons are transferred to the two beam pipes of the LHC to be accelerated up to 7 TeV each. The beam circulates clockwise in one of the LHC pipes whereas it circulates anti-clockwise in the other one. The two beams are brought into collision inside the four main detectors.

3.2 The ATLAS Detector

The ATLAS (A Toroidal LHC Apparatus) detector [2] is one of the general purpose detectors at the LHC. It investigates a wide range of physics processes from the measurements of properties of the Higgs particle, to searches for extra dimensions and for particles that could make up dark matter.

At the LHC, on average twenty soft collisions occur in every beam bunch crossing with a frequency of 25 ns. Hence, fast detector response of below 50 ns and fine granularity are required

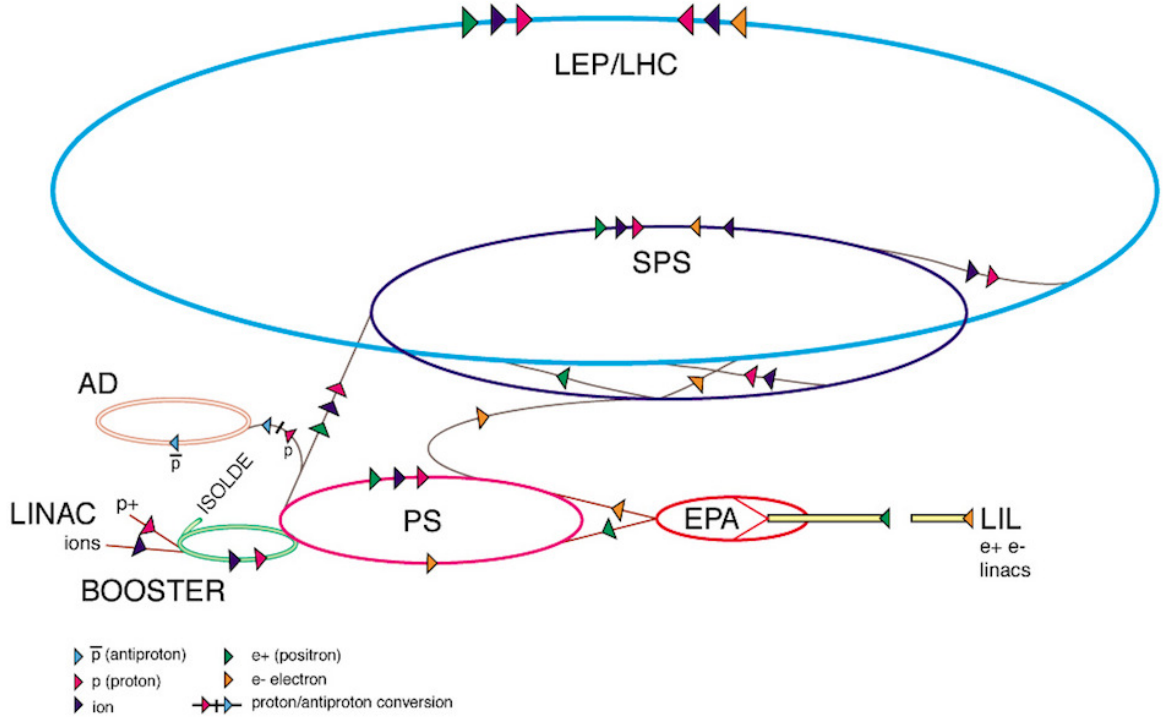


Figure 3.2: The LHC accelerator complex [27].

in order to maintain the highest possible precision on particle physics measurements. High radiation tolerance is also needed to satisfy the requirements over ten years of operation [2].

The ATLAS detector consists of four main parts: the inner detector, calorimeter, muon spectrometer and the magnet system (see Figure 3.3). Particles are detected and identified using these detector parts (see Figure 3.4). Charged particles like electrons, protons and muons leave tracks in the inner detector. Electromagnetic particles like electrons and photons deposit most of their energy in the electromagnetic calorimeter, whereas hadrons deposit most of their energy in the hadron calorimeter. All electromagnetic particles and hadrons are stopped inside the calorimeters, except muons. Muons pass through the inner detector, both calorimeters and the muon spectrometer and leave the detector. Neutrinos are not detectable by any of the detector parts; however, they are inferred by missing transverse momentum.

The sub-detectors of the ATLAS detector use a common coordinate system. The origin of the coordinate system is defined to be the interaction point. The positive x -axis points the center of the LHC ring and the positive y -axis points upward from the surface of the earth. The z -axis is defined to be along the beam line. A polar coordinate system (r, ϕ, θ) is also used. The radial axis r is the distance from the beam line and the azimuthal angle ϕ is measured from the x -axis. The polar angle θ is measured from the z -axis. Usually the polar angle is used as pseudo-rapidity (η) which is defined as $\eta = -\ln(\tan(\theta/2))$.

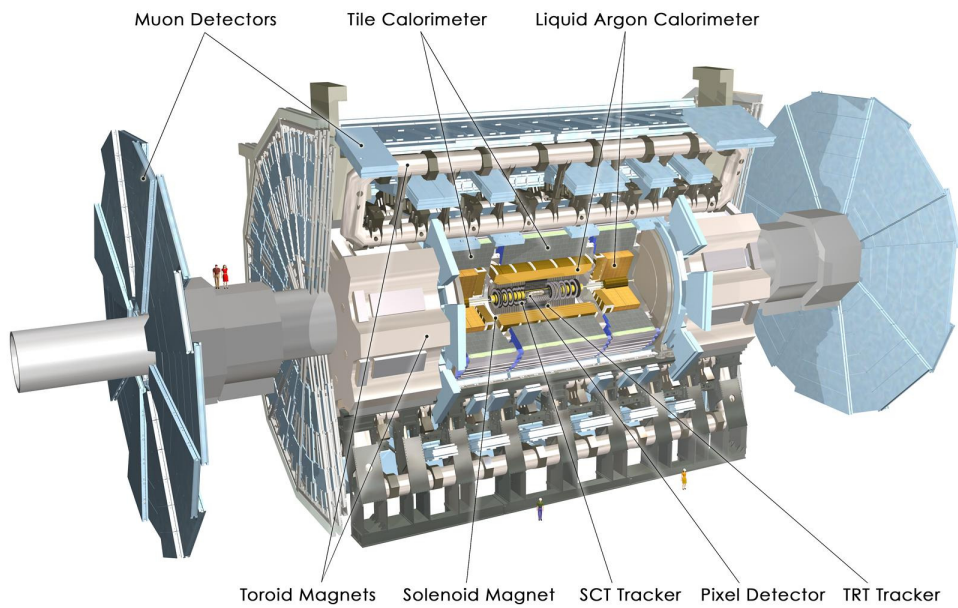


Figure 3.3: The ATLAS detector [3].

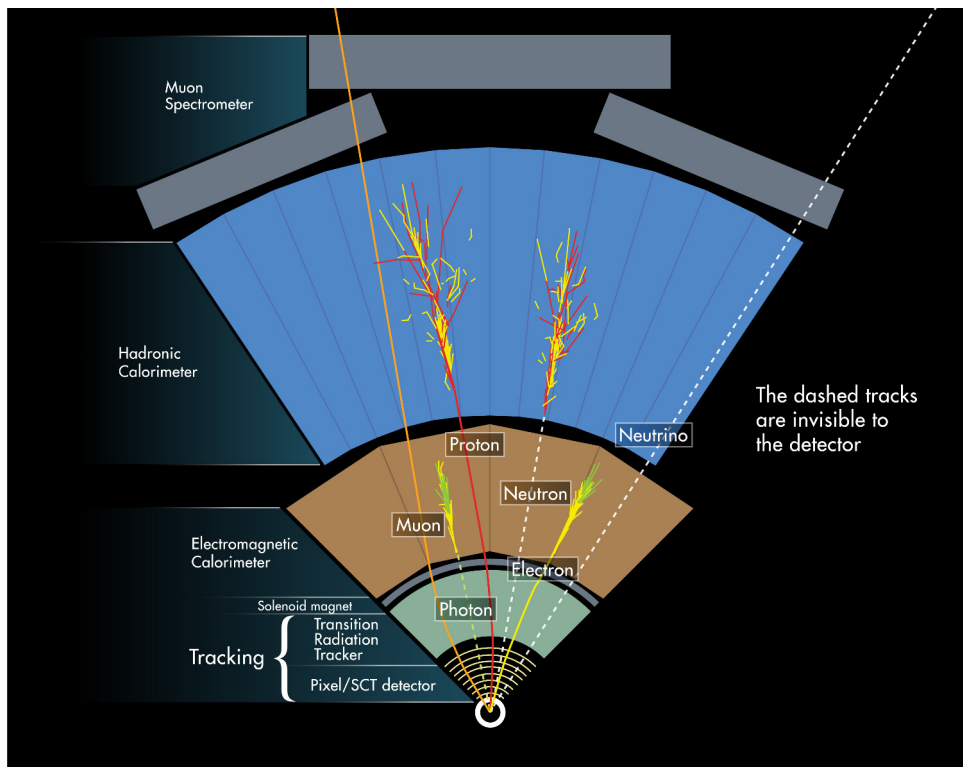


Figure 3.4: Representation of how ATLAS detects particles [3].

3.2.1 The Magnet System

The ATLAS magnet system consists of four superconducting magnets (Figure 3.5): a solenoid, a barrel toroid and two end-cap toroid magnets. The solenoid magnet is aligned with the beam axis providing a 2 T axial magnetic field for the inner detector. One of the requirements for the solenoid magnet design is to keep the material thickness as low as possible in order not to affect the performance of the calorimeters. The solenoid magnet, which is 0.1 m thick and 5.8 m long, contributes a total of approximately 0.66 radiation lengths at normal incidence. The barrel toroid and two end-cap toroids produce a toroidal magnetic field of approximately 0.5 T and 1 T for the muon detectors in the central and end-cap regions, respectively. The barrel toroid is placed in the cylindrical volume surrounding the calorimeters and both end-cap toroids. It consists of eight coils, each with a length of 25.3 m, and with inner and outer diameters of 9.4 m and 20.1 m, respectively. The two end-cap toroidal magnets are used to generate the magnetic field required for optimising the bending power in the end-cap regions of the muon spectrometer system. Each end-cap toroidal magnet consists of eight coils, each with a length of 5.0 m, and with inner and outer diameters of 1.65 m and 10.7 m, respectively [2].

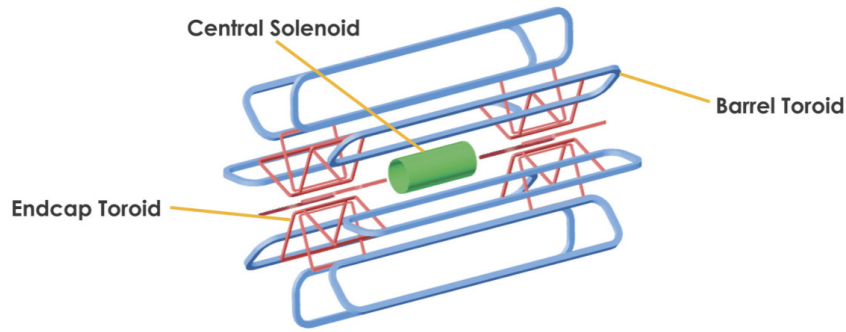


Figure 3.5: View of the ATLAS Magnets [28].

3.2.2 The Inner Detector

The Inner Detector (ID) [2] is designed to provide precise momentum measurement for charged particles. It surrounds the interaction point, has a length of 7 m and a radius of 1.15 m. It is located inside the above described solenoid magnet, which provides the magnetic field to bend the particles in order to achieve the desired momentum measurement. The ID, as shown in Figure 3.6, consists of a pixel and a silicon micro-strip (SCT) tracker, and the Transition Radiation Tracker (TRT). The pixel and the silicon micro-strip detectors cover a pseudo-rapidity range up to $|\eta| < 2.5$, whereas the TRT covers up to $|\eta| < 2$. The schematic layout of the different tracking layers is shown in Figure 3.7.

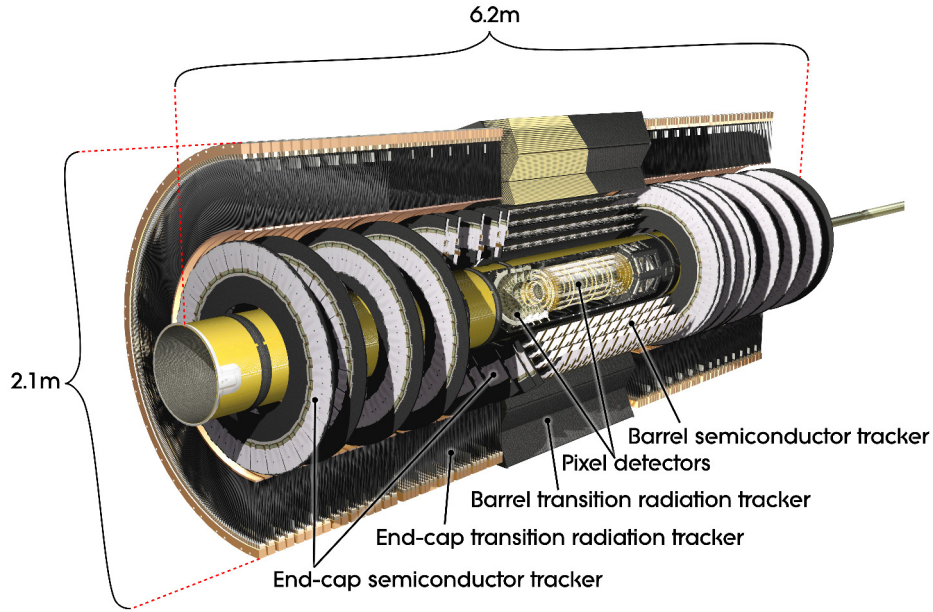


Figure 3.6: The Inner Detector of ATLAS [3].

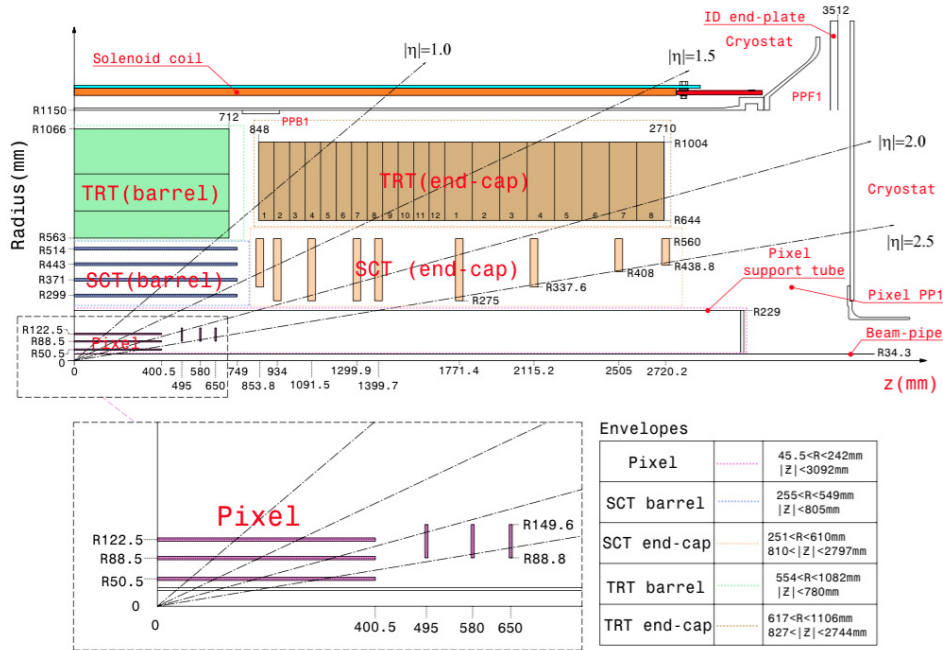


Figure 3.7: The layout of the one quarter segment of the Inner Detector [2]. The beam is in z direction and r is the radius on y axis.

The Pixel Detector

The pixel detector plays an important role for the reconstruction of charged particles and of interaction vertices. Therefore, it is designed to have a high granularity and needs to have a good spatial resolution in order to achieve a precise measurement of primary and secondary vertices. The pixel detector has approximately 80.4 million readout channels. The pixel layers are positioned in $R-\phi$ and z in a way that each track crosses at least three pixel layers. All pixel sensors are identical and have a minimum pixel size of $50 \times 400 \mu\text{m}^2$. The intrinsic resolutions in the barrel are $10 \mu\text{m}$ in $R-\phi$ and $115 \mu\text{m}$ in z and in the disks $10 \mu\text{m}$ in $R-\phi$ and $115 \mu\text{m}$ in R [2].

The pixel detector is subject to the highest radiation damage since it is the closest part of the tracking system to the beam pipe. It is developed to maintain a satisfactory performance over ten years of LHC operation. The sensors are $256 \pm 3 \mu\text{m}$ thick and have oxygenated n-type bulk with high positive (p^+) and negative (n^+) dose regions on each side of the silicon wafer. The readout pixels are located on the n^+ -implanted side of the detector. The n^+ implants and the highly oxygenated bulk material are chosen in order to have a good charge-collection efficiency after type inversion, even when operated below the depletion voltage. The sensors are initially operated at -5°C at 150 V bias voltage. After ten years of operation, due to radiation damage (see Section 2.3), depending on the integrated luminosity and the duration of warm up periods, the bias voltage will be increased up to 600 V and the temperature will be decreased down to -10°C within the detector [2, 29].

The Insertable Barrel Layer

The Insertable Barrel Layer (IBL) [30] has been inserted as a fourth layer in the barrel region of the Pixel Detector in 2013-2014 after replacing the beam pipe with a smaller one. The IBL is placed in the innermost part of the tracking system, approximately 5 mm away from the beam pipe (Figure 3.8). The motivation of adding the IBL to the barrel pixel detector is to improve tracking, vertex reconstruction and b -tagging performance in the high pile-up environment present when the peak luminosity reaches $3 \times 10^{14} \text{cm}^{-2}\text{s}^{-1}$. Since it is the closest layer to the interaction region, it will be subject to the highest radiation level. Therefore, it is designed to withstand radiation damage up to $5 \times 10^{15} \text{1MeV } n_{\text{eq}}/\text{cm}^2$ [31] (see Section 2.3).

The Semiconductor Tracker

The Semiconductor Tracker (SCT), with approximately 6.3 million readout channels, surrounds the pixel detector. It has $285 \pm 15 \mu\text{m}$ thick, single-sided p-in-n sensors designed to have identical rectangular sensors in the barrel. In the end-caps there are five different wedge-shaped geometries. The SCT has eight double layer silicon strips whose axes are tilted by 40 mrad with respect to each other in order to measure ϕ and z coordinates. The strip layers are positioned in a way that each track will cross at least four layers. In the barrel region, strip sensors have

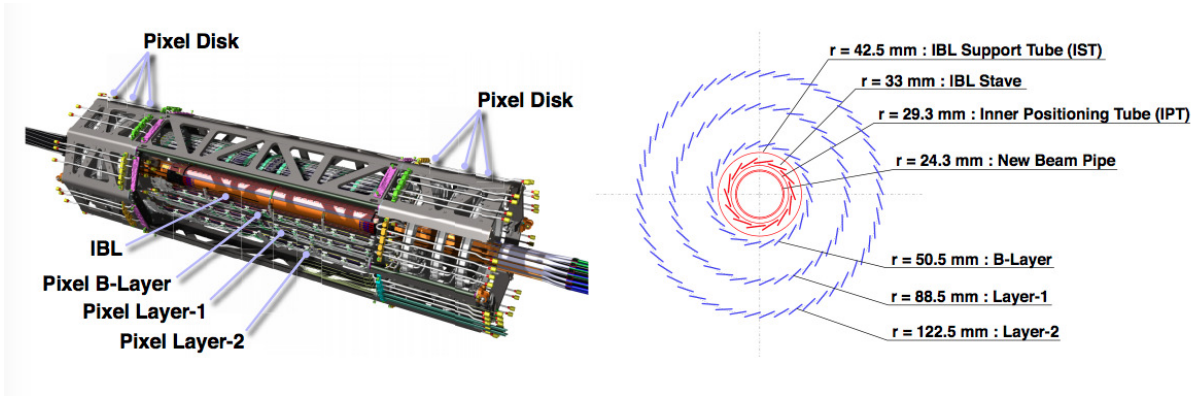


Figure 3.8: Schematic of the Pixel Detector with the IBL inserted [32].

an $80\mu\text{m}$ pitch and one set of strips in each layer is positioned parallel to the beam direction. This enables intrinsic accuracies of the pair of measurements of $17\mu\text{m}$ in $R - \phi$ and $580\mu\text{m}$ in z . In the end-cap disks, one set of strips runs radially from the beam pipe and the pitch size of the strip sensors is also approximately $80\mu\text{m}$. The achievable intrinsic accuracies in the disks are $17\mu\text{m}$ in $R - \phi$ and $580\mu\text{m}$ in R [2].

Even though the SCT is not the closest sub-detector to the beam pipe, it is still subject to quite high radiation levels and has to maintain a reasonable performance over the lifetime of the detector. It is designed to withstand radiation doses of up to a factor of two of the expected dose at the end of ten years of LHC operation, which corresponds to $2 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, normalised using the non-ionising energy loss (NIEL) cross-sections to the expected damage of 1 MeV neutrons. In order to reduce the leakage current, which increases the noise of the detector, and to prevent annealing, the SCT is to be operated at -7°C . Furthermore, an increase in bias voltage is required to keep a good charge collection efficiency. Hence, the bias voltage will be increased up to voltages between 250 and 350 V while the initial operation voltage is 150 V [2, 33].

The Transition Radiation Tracker

The Transition Radiation Tracker (TRT) is the largest sub-detector in volume in the ID. It consists of approximately 351,000 drift tubes enabling tracking up to $|\eta| = 2.0$. A non-flammable gas mixture is used in a total volume of 3m^3 . The straw tubes are 4 mm in diameter with a $30\mu\text{m}$ diameter gold-plated W-Re wire. In the barrel region, the straws are 144 cm long and oriented parallel to the beam axis, whereas in the wheels they are 37 cm long and oriented radially. Each channel provides a drift time measurement, giving a spatial resolution of $170\mu\text{m}$ per straw. The TRT also provides particle identification in addition to its tracking capabilities. Charged particles emit transition radiation photons while traversing the TRT and since, at a fixed momentum, electrons emit more transition radiation photons than charged hadrons, the TRT is capable of distinguishing them from one another. The straws are read out using two independent thresholds which allows the discrimination between tracking hits, that pass the

lower one, and transition radiation hits, that satisfy the higher threshold and are indicative of electrons [2].

3.2.3 The Calorimeter

The calorimeter is used for an accurate measurement of the energy of the particles as well as their positions. It consists of metal plates (absorbers) and sensing elements. Interactions in the absorbers transform the incident energy into a ‘shower’ of particles that are detected by the sensing elements. Its intrinsic energy resolution improves with the measured energy. At a centre-of-mass energy of 14 TeV, it is required to have good performance over an unprecedented energy range, extending from a few GeV up to the TeV scale.

The calorimeter in the ATLAS detector consists of two main parts (see Figure 3.9): the electromagnetic calorimeter (EM) and the hadronic calorimeter.

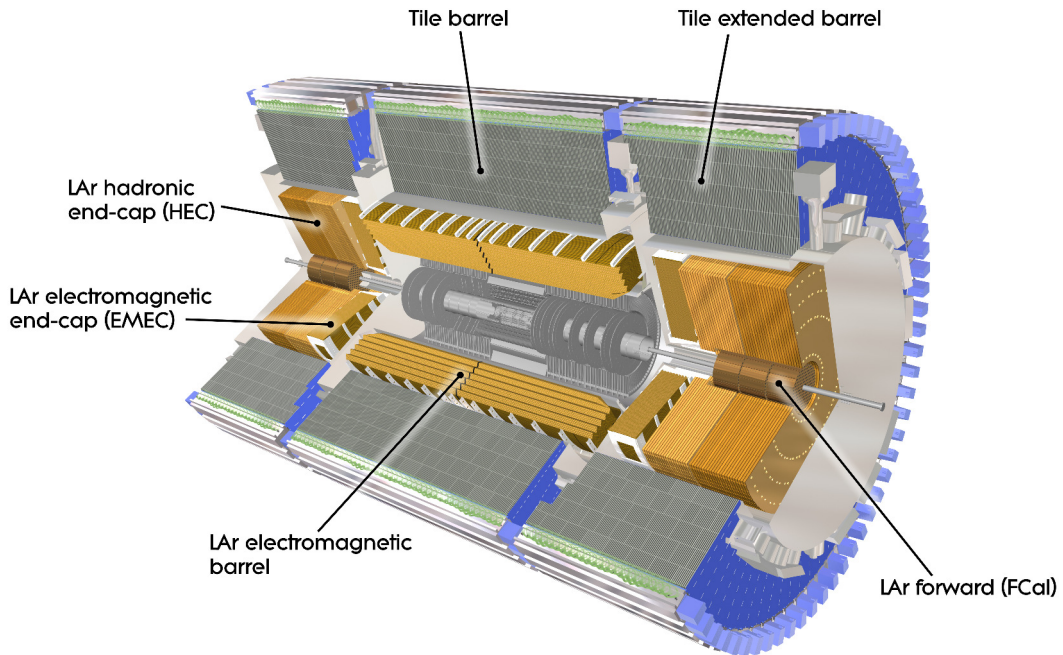


Figure 3.9: The drawing of full calorimeter of the ATLAS [34].

The Electromagnetic Calorimeter

The EM calorimeter is a lead-Liquid-Argon (lead-LAr) sampling detector with accordion-shaped kapton electrodes and lead absorber plates over its full coverage. The accordion geometry provides complete ϕ symmetry without azimuthal cracks. The calorimeter consists of a barrel

part covering the pseudo-rapidity range $|\eta| < 1.475$ and two end-caps covering the regions $1.375 < |\eta| < 3.2$. The barrel calorimeter has a small gap of 6 mm between two identical half-barrels. Each end-cap calorimeter is mechanically divided into two coaxial wheels: an outer wheel covering the region $1.375 < |\eta| < 2.5$, and an inner wheel covering the region $2.5 < |\eta| < 3.2$. The thicknesses of the lead absorber plates are chosen as a function of rapidity, as shown in Table 3.1, in order to optimize the energy resolution. In the barrel region, the LAr gap has a constant thickness of 2.1 mm. In the end-cap, the shape of the kapton electrodes and lead converter plates is more complicated, since the amplitude of the accordion waves increases with radius. The absorbers have constant thickness, and therefore the LAr gap also increases with radius [2, 35].

	Rapidity	Pb thickness	Gap thickness
Barrel	$ \eta < 0.8$	1.5 mm	2.1 mm
	$0.8 < \eta < 1.475$	1.1 mm	2.1 mm
End-cap	$1.375 < \eta < 2.5$	1.7 mm	2.8 - 0.9 mm
	$2.5 < \eta < 3.2$	2.2 mm	3.1 - 1.8 mm

Table 3.1: The thickness of lead absorber plates and LAr gap thickness in the EM calorimeter as a function of rapidity [35].

The Hadronic Calorimeter

The Hadronic Calorimeter covers the pseudo-rapidity range $|\eta| < 5$, as shown in Figure 3.9. It is arranged to have three different parts in order to match the different requirements and radiation environment best. Each part is also adjusted in depth in order to stop hadrons and not let them to pass to the muon system.

The Tile calorimeter is a sampling calorimeter using steel as the absorber and scintillator as the active material. It is located behind the LAr electromagnetic calorimeter, covering the pseudo-rapidity range $|\eta| < 1.7$. It is subdivided into a central barrel, which has a length of 5.8 m, and two extended barrel regions that each have a length of 2.6 m. The tiles are placed perpendicular to the colliding beams from an inner radius of 2.28 m to an outer radius of 4.23 m. The thickness of the active part of Tile calorimeter is approximately seven interaction lengths [2, 35].

The LAr Calorimeter is a copper/liquid-argon sampling calorimeter. The LAr hadronic end-cap (HEC) covers the pseudo-rapidity range $1.5 < |\eta| < 3.2$. Each HEC consists of two equal diameter wheels. In the first wheel 25 mm copper plates are used, while in the second the thickness of the plates is 50 mm. In both wheels the gap between the copper plates is 8.5 mm. The thickness of the active part of the end-cap calorimeter is approximately 12 interaction lengths. In the forward region the high-density LAr Forward calorimeter (FCal) covers the pseudo-rapidity range $3.1 < |\eta| < 4.9$. Each FCal is a high density detector since it has to have a thickness of at least 9 interaction lengths in a rather small longitudinal space. It consists of a

metal matrix with regularly spaced longitudinal channels filled with rods. The sensitive medium, liquid argon, fills the gap between the rod and matrix. The FCal has three longitudinal parts; the first one is in copper with $250\,\mu\text{m}$ gaps while the others are in tungsten with $375\,\mu\text{m}$ and $500\,\mu\text{m}$ gaps between absorbers [2, 35].

3.2.4 Muon Spectrometer

The Muon Spectrometer (Figure 3.10) is designed to detect charged particles exiting the barrel and end-cap calorimeters and to measure their momentum in the pseudo-rapidity range $|\eta| < 2.7$. The measurement is based on the magnetic deflection of charged particle tracks in the large superconducting air-core toroid magnets. The magnet configuration is chosen to have the magnetic field mostly orthogonal to the muon trajectories while minimizing the reduction of resolution due to multiple scattering.

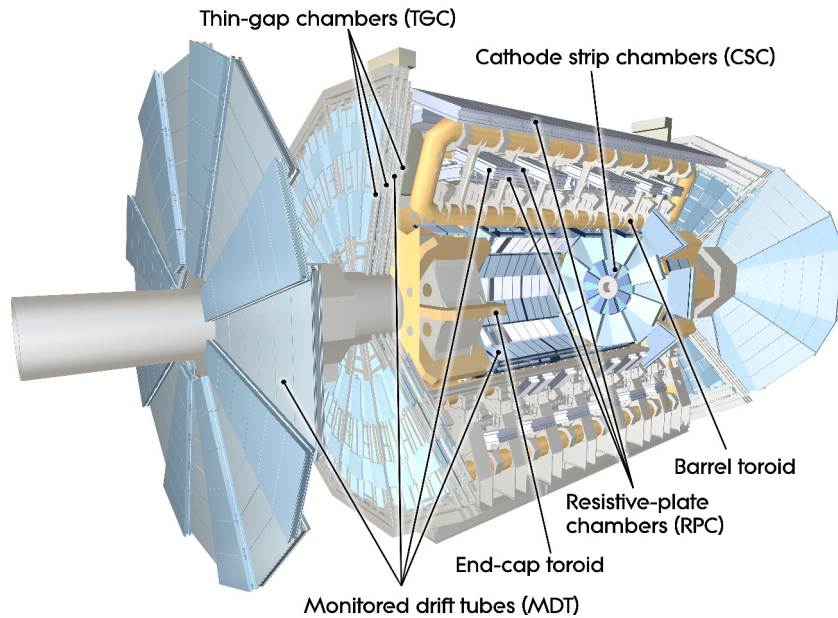


Figure 3.10: View of the ATLAS Muon Spectrometer [2].

The Muon Spectrometer has two main purposes: to provide precision measurements and a trigger system. A precision measurement of the track coordinates is provided by Monitored Drift Tubes (MDTs) in the pseudo-rapidity range $|\eta| < 2.7$ (innermost layer: $|\eta| < 2.0$). Each sense wire of the MDTs is mechanically isolated in order to provide a robust and reliable operation. At large pseudo-rapidities, $2.0 < |\eta| < 2.7$, high granularity Cathode Strip Chambers (CSCs) are used. CSCs are multi-wire proportional chambers with cathodes segmented into strips. They are chosen for this region in order to withstand the demanding rate and background conditions.

The trigger system covers the pseudo-rapidity range $|\eta| < 2.4$. Resistive Plate Chambers (RPCs) are placed in the barrel region, while Thin Gap Chambers (TGCs) are placed in the

end-cap. The purpose of the trigger chambers is to provide bunch-crossing identification and well-defined p_T thresholds as well as to measure the muon coordinates in the direction orthogonal to that determined by the precision-tracking chambers [2].

3.2.5 The Trigger and Data Acquisition System

The Trigger System

The interactions in the ATLAS detectors create an enormous amount of data, which is challenging to readout and store. The main purpose of the trigger system is to select only interesting events and reduce the dataflow. Hence, fast algorithms are implemented to select events for the readout of the detectors. The trigger system consists of three levels of event selection: Level-1 (L1), Level-2 (L2) and the event filter. The L2 and event filter together form the High-Level Trigger (HLT). Each trigger level refines the decisions made at the previous level and, where necessary, applies additional selection criteria [2].

The L1 trigger searches for signatures from high- p_T muons, electrons, photons, jets, and τ -leptons decaying into hadrons as well as events with large missing transverse energy (E_T^{miss}) and large total transverse energy. The L1 trigger uses reduced-granularity information from a subset of detectors: the Resistive Plate Chambers (RPCs) and Thin-Gap Chambers (TGCs) for high- p_T muons, and all the calorimeter subsystems for electromagnetic clusters, jets, τ -leptons, E_T^{miss} and large total transverse energy. After the bunch-crossing, the L1 must reach a decision in the front-end electronics within $2.5\,\mu\text{s}$, reducing the rate to about 75 kHz. Once the L1 trigger detects an interesting feature, it also identifies Regions-of-Interest (RoIs), which include coordinates in η and ϕ , the type of the feature and the criteria passed. The RoI information is used by the HLT system [2].

In order to perform its selection, L2 uses information from all available detector data at full granularity and precision within RoIs passed down from L1. The data processed by L2 corresponds to approximately 2% of the total event data. The L2 trigger reduces the trigger rate to approximately 3.5 kHz, with an event processing time of about 40 ms [2].

The event filter uses offline analysis procedures on fully-built events selected by the L2 trigger. It selects events further down to a rate which can be recorded for subsequent offline analysis. It processes an event in approximately 4 s, and reduces the event rate to approximately 200 Hz [2].

In order to refine the trigger selections, the HLT algorithms use the full granularity and precision of the calorimeter and muon chamber data, as well as the data from the inner detector. Improving the information on energy depositions improves the threshold cuts. Using the data from the inner detector provides track reconstruction which significantly increases particle identification capabilities [2].

The Data Acquisition System

The Data Acquisition System (DAQ) performs data transmission over point-to-point Readout Links (ROLs). It receives and buffers the event data from the detector specific readout electronics at the L1 trigger rate. Then it transmits the data requested to the L2 trigger, typically the data corresponding to RoIs. For the events passing the L2 selection it performs event-building and moves the information to the event filter. Finally, the events selected in the event filter are moved to permanent event storage for offline processing [2].

In addition to the data transmission between trigger levels, the DAQ system is also used to configure, control and monitor the ATLAS detector during data taking. The Detector Control System (DCS) provides supervision of the detector hardware such as the gas systems, power-supply voltages, cooling systems, magnetic field, temperatures and humidity [2].

3.3 The High-Luminosity LHC and Upgrade of ATLAS Detector

The LHC is planned to run in its current form until 2024. At the end of 14 years of operation, some detectors will reach the end of their lifetime due to radiation damage. However, it is required to collect more data in order to further increase the discovery potential of the LHC by being able to observe rare events and have more accurate measurements on discovered particles like the Higgs boson [36, 5]. To achieve this, the LHC will eventually need to be upgraded to increase the total number of collisions by a factor of 10. The High Luminosity LHC (HL-LHC) is designed to serve this purpose.

Figure 3.11 shows schedule for the upgrades of the LHC. The first upgrade (phase 0) of the LHC was done during long shutdown 1 (LS1) in 2013-2015 after collecting 30 fb^{-1} at 75% of its nominal luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) with bunch crossings every 50 ns. After this upgrade the luminosity was increased to the nominal luminosity and the bunch crossing time was decreased to 25 ns. By the time LS2 (upgrade phase 1) starts in 2018, the LHC will deliver 100 fb^{-1} to ATLAS and CMS each. In 2020, the LHC will start taking data again and increase its luminosity to twice the nominal luminosity. By the end of 2024, it is expected to have delivered 300 fb^{-1} .

In 2024-2026 (LS3), the upgrade for the HL-LHC (phase 2) will start. At around 2026, the HL-LHC is planned to start collisions, it will provide a leveled instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with the aim of delivering an additional 3000 fb^{-1} to ATLAS and CMS each over ten years of operation. Assuming a bunch crossing time of 25 ns, the increase in instantaneous luminosity will increase the mean number of interactions per bunch crossing from 55 at $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to 140 at $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. As a result the integrated luminosity will increase drastically which requires a detector that can withstand large particle fluences. This will lead to increased occupancy and radiation damage in the detector. Allowing a safety margin, the detector upgrades are designed assuming a maximum instantaneous luminosity of

$7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 200 pile-up events and an integrated luminosity of 3000 fb^{-1} over ten years of operation [36].

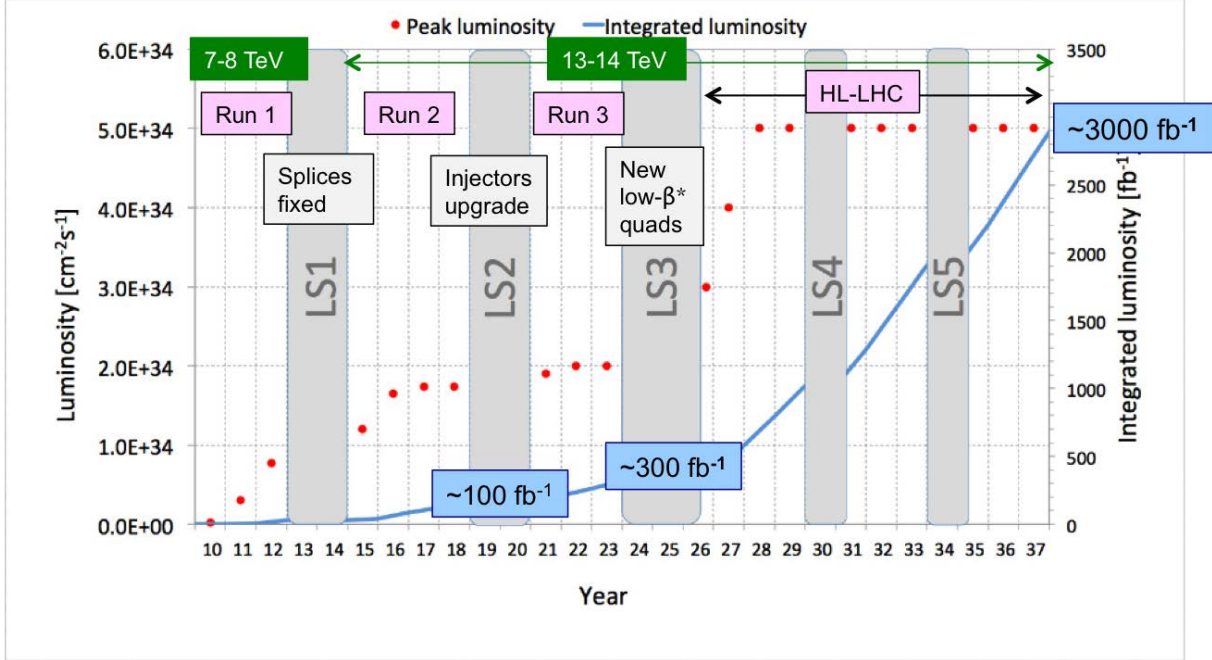


Figure 3.11: The time schedule of the road to HL-LHC [4].

3.3.1 Upgrade of the ATLAS detector

The harsh environment at the HL-LHC will introduce challenges in terms of high radiation levels, high rate and a high number of pile-up events. In order to satisfy the performance requirements, it is planned to perform upgrades of several sub-detectors of ATLAS as well as the trigger and DAQ system.

Upgrade of the Inner Detector

At HL-LHC, the Inner Detector will be subject to much harsher radiation levels and occupancy. Hence, it is necessary to remove the current ID and replace it by all silicon tracking detector which will meet performance requirements.

The TRT detector is not part of the new ID design since its straws would approach 100% occupancy in the high pile-up conditions. In the barrel, the pixel system is planned to be extended out to larger radii and the TRT will be removed and the new strip detector, with 47.8 mm long silicon strips, will be extended to the magnet. In the end-cap region, more pixel layers will be placed to improve tracking in this dense region. In order to increase the granularity,

smaller pixels and 23.8 mm long strips are planned to be used. The baseline layout of the future ID can be found in Figure 3.12 [36].

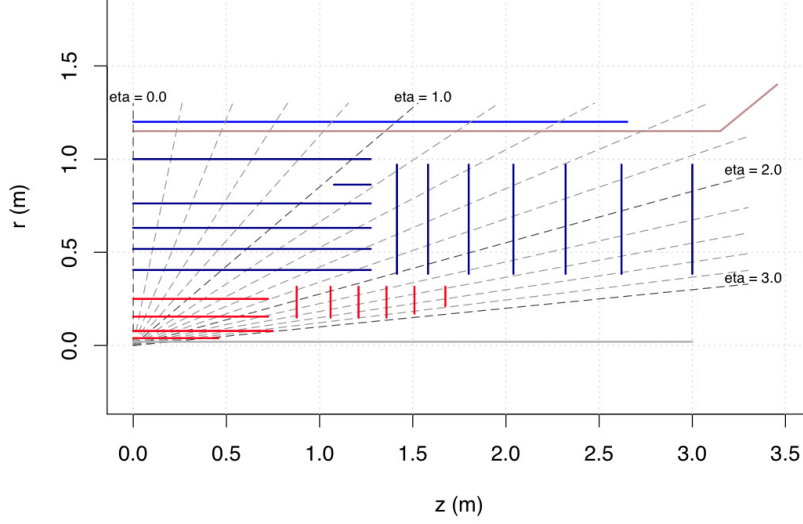


Figure 3.12: The baseline quarter segment layout of the future ID [36].

The front-end electronics of both the current pixel and SCT detectors are designed to cope with a number of pile-up events of up to 50, whereas the expected number of pile-up events at the HL-LHC is about 140. The current detectors would reach bandwidth saturation with the current design, which would cause major data losses. That is why the readout links of the new detector system are designed to have much greater bandwidth. In addition, with the expected pile-up at HL-LHC, the SCT would be unable to resolve close-by particles. The new sensors will have a higher granularity which will enable it to cope with very high pile-up [36].

One of the most challenging conditions in HL-LHC is the high radiation damage. The current pixel detector is designed to survive up to a fluence of 10^{15} 1MeV n_{eq}/cm^2 which approximately corresponds to 400 fb^{-1} . The IBL can operate up to an integrated luminosity of 850 fb^{-1} . The SCT is able to withstand a fluence of 2×10^{14} 1MeV n_{eq}/cm^2 . All are significantly lower than the values expected in HL-LHC when it reaches an integrated luminosity of 3000 fb^{-1} . For this reason the new sensors are designed to be more radiation tolerant in order to withstand the high radiation environment expected in HL-LHC. The expected fluences can be found in Figure 3.13 [36].

Upgrade of the Calorimeters

The challenging HL-LHC environment requires more selective and advanced trigger algorithms based on high granularity and high precision calorimeter information, which requires both an increased bandwidth and a longer latency of the readout systems. In order to satisfy these requirements the calorimeter electronics will be upgraded to allow 40 MHz read-out and back-end buffering while ensuring good performance through the HL-LHC life time [5].

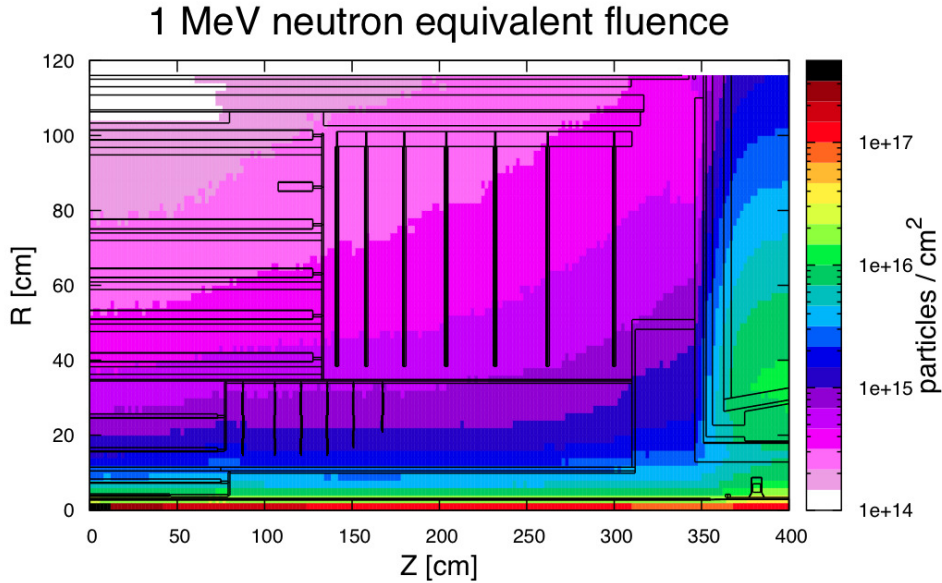


Figure 3.13: Expected 1MeV n_{eq}/cm^2 fluences in HL-LHC (normalised to 3000 fb^{-1}) [36].

The increased luminosity will require the calorimeter to be more radiation tolerant to the radiation levels they will receive. The radiation levels increase with $|\eta|$ so the barrel calorimeters will receive relatively low radiation and they are sufficiently radiation tolerant to the expected radiation doses. The end-cap and forward calorimeters are based on LAr technology which is intrinsically radiation tolerant. However, their performance might suffer from space-charge effects [37] due to the high instantaneous rates. The performance of the electromagnetic calorimeter will not be affected significantly, some degradation will be observed in the inner wheel of the ECAL ($2.4 < |\eta| < 3.2$), which will be compensated by offline corrections. The space-charge effects will be more significant in the FCAL and may cause performance degradation. The magnitude of this degradation and its effects on ATLAS physics are still under investigation [5, 38].

Upgrade of the Muon System

The Muon System is the sub-detector which will least suffer from higher radiation levels except in the most forward regions. The main challenges the HL-LHC pose to the muon system are due to the increased rate and much greater precision information needed in the triggering system. The expected trigger rate at the HL-LHC exceeds the capabilities of the current muon system electronics. Due to this, the entire read-out and trigger electronics will be re-designed and replaced. In addition, the triggering system for HL-LHC requires an improved p_T measurement. In order to satisfy this need, the new small wheel (NSW), which covers $1.3 < |\eta| < 2.7$ and has finer granularity, is planned to be installed in the end-cap region [5].

Upgrade of the Trigger System

The conditions at the HL-LHC will pose a challenge to the trigger and DAQ system in terms of rates and increased data size. Hence, ATLAS trigger and DAQ systems will need to be upgraded. First of all, a Level-0 trigger will be introduced. It will function in the same way as the L1 trigger before the HL-LHC upgrade (after phase-1 upgrade, see Figure 3.11) in the sense that it will be using high granularity data from the previously upgraded calorimeters and muon system [39]. The new L0 trigger will reach a decision within $6\mu\text{s}$ at a rate of at least 500 kHz. The L1 trigger will be upgraded to use track information within regions of interest (RoI) in addition to calorimeter and muon trigger objects within the same RoI. The L1 trigger will reduce the rate to 200 kHz and introduce an additional latency of $14\mu\text{s}$. The increase in L1 trigger rate will require more CPU power and higher readout rates in the High-Level Trigger (HLT). In order to cope with the increased rate the HLT readout rate will be increased to 5-10 kHz [36, 5].

Chapter 4

The Test Beam Setup

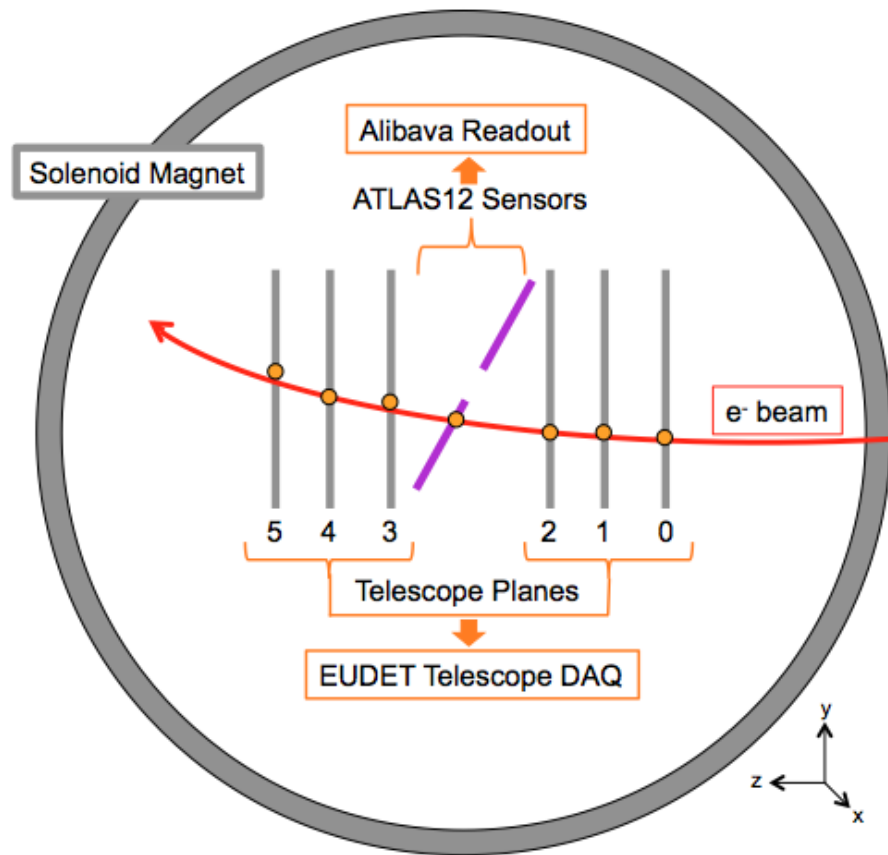


Figure 4.1: Schematic drawing of the setup.

In this chapter, the test beam setup (Figure 4.1), used for the measurements presented in the following chapters, is explained. The setup is designed to be multi-purpose and flexible enough to adapt it to other sensor measurements, especially the ones that need magnetic field present.

In this work, the setup is used to measure the Lorentz angle (LA) and the charge collection efficiency (CCE) of silicon micro-strip sensors.

The test beam facility of DESYII, which is introduced in Section 4.1, provides an electron beam up to 6 GeV for the measurements. The LA measurement requires a magnetic field to be present. A solenoid magnet present at the DESYII test beam facility which provides magnetic field up to 1 T is used. More information on the magnet is given in Section 4.2. The EUDET beam telescope, which consists of 6 high resolution pixel sensors, is used to track particles passing through the system. The telescope is introduced in Section 4.3. Finally in Section 4.4 the ALiBaVa analogue readout system is introduced, which is used to read out the strip sensors.

In order to use the ALiBaVa readout system at the testbeam measurements efficiently, modifications had to be implemented to its firmware, which are explained in Section 4.5 in detail. In order to avoid leakage current and annealing of the irradiated samples, the sensors had to be cooled. A sensor box designed for this purpose is described in Section 4.6. Finally in Section 4.7, the assembly of all components is explained and the monitoring of the setup is described.

4.1 The DESYII Test beam

The test beam facility at DESY [40] is of great importance for current and future detector development. The DESYII accelerator, which is responsible for injecting accelerated electrons to PETRA [41], also provides an electron beam to the test beam hall.

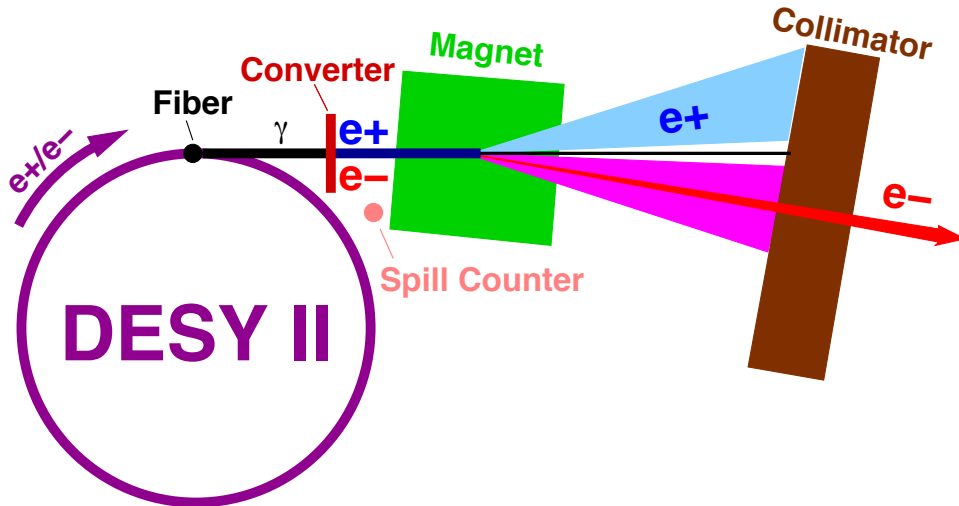


Figure 4.2: Schematic layout of a test beam line at DESYII [40].

The electrons/positrons for the test beam are provided as shown in Figure 4.2. Bremsstrahlung photons are generated from the circulating beam in DESYII hitting a carbon fibre. These photons are converted to electron/positron pairs by using a metal converter. Then a dipole magnet is used to spread the beam and select the desired beam energy and type (either electrons or

positrons). The electron beam energy that can be obtained from the DESYII test beam is in the range of 1-6 GeV, which corresponds to minimal ionizing particles (MIPs) [42].

There are four test beam areas using the electron beam coming from DESYII: T21, T22, T24 and T24/1. The beam rate in the areas is influenced by many parameters: the current in the machine, the operation mode, the position of the carbon fibre, the converter target, the selected beam energy, and the opening of the collimators [43]. Typically, the maximum rate is around 5 kHz, which can be obtained for a 3 GeV beam energy using a 3 mm Cu converter and a $5 \times 5 \text{ mm}^2$ collimator opening when DESYII is running at 7 GeV with no beam extraction. The rates as a function of the beam energy for various targets at the T24 beam line are shown in Figure 4.3.

All measurements presented in this thesis are recorded in TB24/1 where the solenoid magnet is located. The TB24/1 area is behind the area T24, so the electron beam has to pass through the T24 area. The beam energy was set to 4.4 GeV for most of the measurements and the collimator size on the wall was $2 \times 2 \text{ cm}^2$.

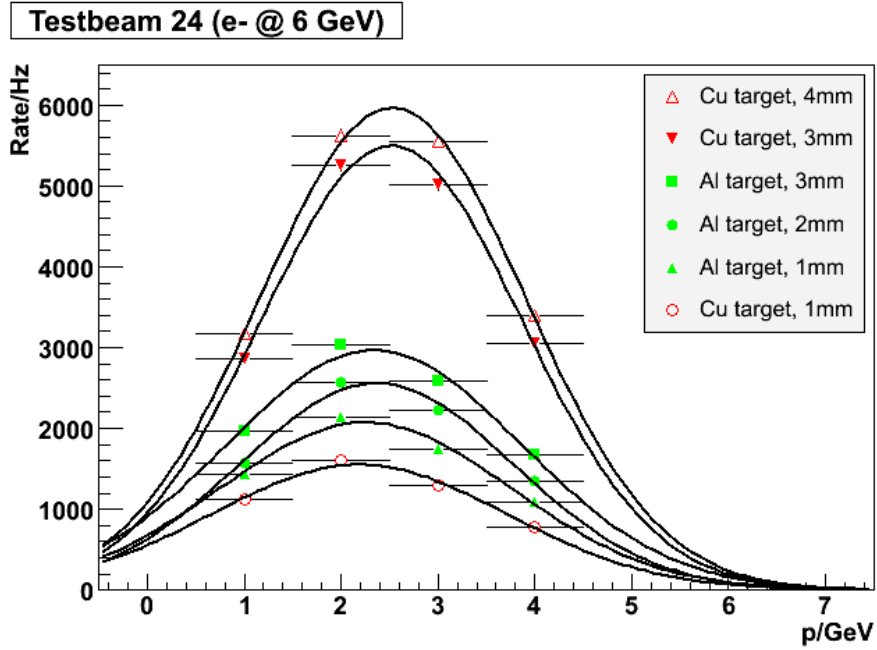


Figure 4.3: The dependence of rate on the test beam energy at Testbeam 24 [40].

4.2 The Solenoid Magnet

The solenoid magnet (PCMAG) [44] located in area T24/1 of the DESYII testbeam (see Figure 4.4) is used to obtain the uniform magnetic field needed for the Lorentz angle measurement. The magnet is mounted on a movable stage, which provides horizontal and vertical movement perpendicular to the beam axis and also rotations up to $\pm 45^\circ$ in the horizontal plane. This feature of the magnet enables users to align the magnet precisely to the desired position.

The PCMAG has a superconducting coil which can provide a magnetic field of up to 1 T in its centre at an operational current of 431 A. The magnetic field is adjustable to the strength desired with an error of ± 0.0002 T by changing the current in the coil. Figure 4.5 shows the magnetic field strength as a function of the current monitored and current set in the power supply unit (PSU) [45]. A technical drawing of the PCMAG is shown in Figure 4.6, its wall has a radiation length of $20\% X_0$ (the mean distance over which a high-energy electron loses all but $1/e$ of its energy by bremsstrahlung), and its coil has a diameter of 1.0 m and a length of 1.3 m. The usable inner bore has a diameter of 0.85 m and a length of 1.0 m. Along the length of the inner bore a rail is placed so that one can easily place a setup in the middle of the PCMAG where the magnetic field is uniform. The main parameters of PCMAG can be found in Table 4.1.

Since the ATLAS Inner Tracker is in a 2 T magnetic field and the PCMAG is capable of providing only up to 1 T, the Lorentz angle measurement in this thesis are carried out at various magnetic fields (0, 0.25, 0.50, 0.75, 1.0 T) in order to be able to extrapolate the results to 2 T.



Figure 4.4: The PCMAG on the movable stage in testbeam area T24/1 [46].

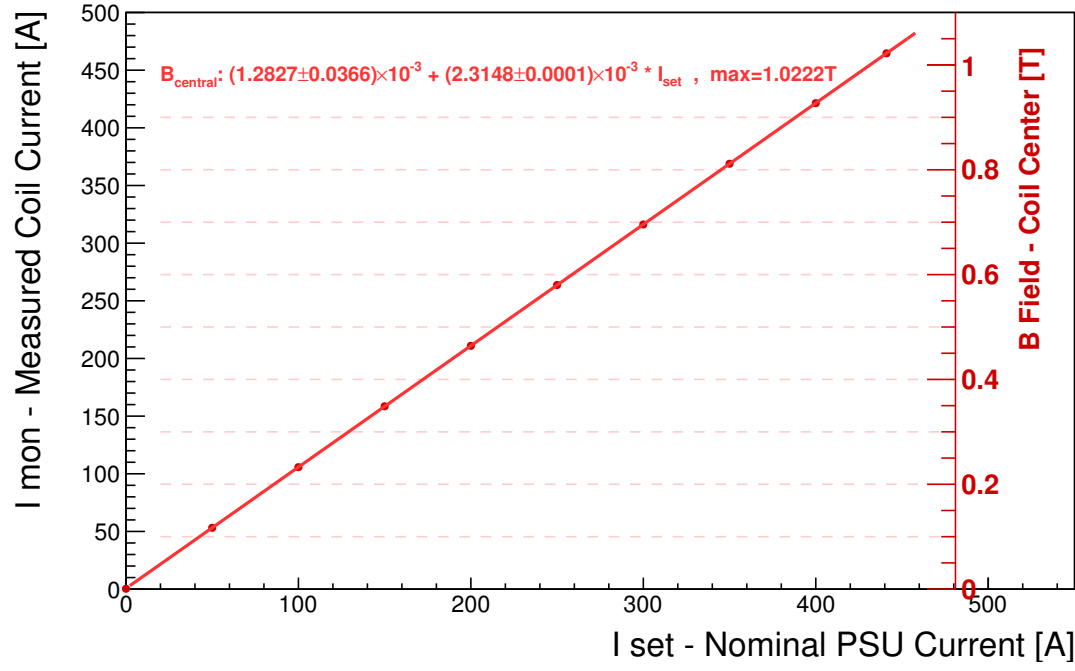


Figure 4.5: Magnetic field strength at the centre of the PCMAG as a function of the current in the coil [45].

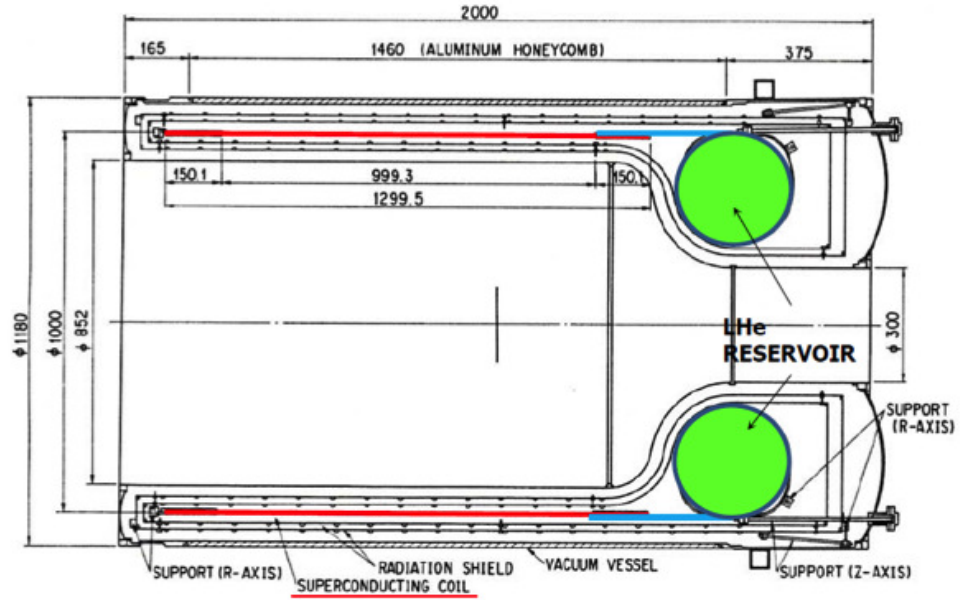


Figure 4.6: Technical drawing of the PCMAG [46].

Central magnetic field (operational)	1 T
Central magnetic field (maximum)	1.25 T
Operational current at 1T field	431 A
Coil length	1.3 m
Coil diameter	1.0 m
Radiation length (wall including coil)	$0.2 X_0$
Inner bore diameter	0.85 m
Inner bore length	1.0 m
Weight	430 kg

Table 4.1: Main parameters of the PCMAG solenoid magnet [44].

4.3 The EUDET Beam Telescope

The EUDET beam telescope [47], which was developed by the EUDET consortium, is used in this study in order to obtain track information. The track information is essential for LA measurement to determine the incidence angle of the track on the sensor. It is also used for both the LA and CCE measurements, to select the hit on the sensor which is associated with the track.

The EUDET beam telescope consists of six planes of Mimosa26 monolithic active pixel sensors (MAPS) with 576×1152 pixels, a pitch of $18.4 \mu\text{m}$ in both directions, an active area of $10.6 \times 21.2 \text{ mm}^2$, and a thickness of $50 \mu\text{m}$. Using a EUDET beam telescope, a track-pointing resolution of better than $2 \mu\text{m}$ can be obtained at the device under test (DUT) [48].

Figure 4.7a shows the EUDET telescope installed at the DESY testbeam area. The Mimosa26 sensors are placed in aluminum boxes which are connected to a water cooling system. On top of each sensor plane an auxiliary board is fixed. The auxiliary boards read out the sensors and send the data to the data acquisition (DAQ) system. The EUDET beam telescope DAQ (EUDAQ) system is based on the National Instruments PXI express bus [49] (Figure 4.7b) which allows to read out all six sensors with a rate up to $\sim 9 \text{ kHz}$ [50].

The trigger for the EUDET beam telescope is provided by four scintillators, two located at the upstream and two at the downstream. The trigger logic unit (TLU) [51] (Figure 4.7c) is used to process the signals from the trigger detectors in a desired logic combination of AND, OR. There are three ways of using the TLU with DUTs.

No-Handshake

This is the basic way of using the TLU. In this mode, the TLU receives the trigger signal from the beam scintillators and generates a trigger signal, which is distributed to the telescope and DUTs.

Simple Handshake

The difference of this mode from the No-Handshake mode is that after distributing the

trigger signal, the TLU waits for a BUSY signal from the DUTs and does not produce any trigger until the BUSY signals are de-activated.

Trigger Data Handshake

In this mode the TLU introduces trigger clock data (time stamp) in addition to the Simple Handshake mode features. In Trigger Data Handshake mode, the TLU sends the time stamp right after the trigger signal. The DUT should process the time stamp and then de-activate the BUSY signal when it is ready to process a new trigger.

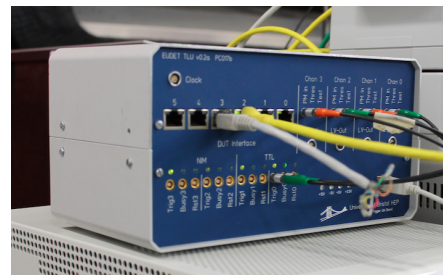
With the help of these features of the TLU, the user can choose the mode that fits to their need and synchronize the data taken by the telescope and their DUTs. In order to synchronize the DUT used in the measurements of this study with the telescope, the Simple Handshake mode is used.



(a) The EUDET telescope installed at the DESY testbeam area [50].



(b) The National Instruments PXI crate [49].



(c) The trigger logic unit (TLU) [50].

Figure 4.7: The EUDET beam telescope setup.

4.4 ALiBaVa Readout System

The ALiBaVa analogue readout system [52] is chosen in order to measure the cluster size of the deposited charge for the LA measurement and calculate the collected charge for the CCE measurement precisely.

The ALiBaVa analogue readout system is a compact and portable tool to readout micro-strip detectors. The analogue measurement of the front-end pulse shape and the charge collected in the sensor are its two main purposes [53]. Originally, the ALiBaVa readout system was designed for measurements inside a laboratory with a radioactive source or a laser.

In order to protect sensitive electronics from extreme environments, such as radiation or low temperatures, the readout electronics of the ALiBaVa system are divided into two parts. Figure 4.8 shows these parts: a daughter board and a mother board. The daughter board (Figure 4.9) is a small board with the minimum components needed to operate the readout chips and a temperature sensor. There are two Beetle front-end chips [54] on the daughter board. The Beetle chips integrate a charge sensitive amplifier, a shaper and a buffer with each channel and samples the output with 40 MHz clock frequency. The sensors are connected to the channels of the Beetle chips by micro wire-bonding ($25\text{ }\mu\text{m}$ diameter) via metal-on-glass "pitch adapters". Each chip is capable of reading out up to 128 channels of a strip sensor. The sampled analogue signals are forwarded to the mother board using a twisted ribbon cable. The mother board converts the analogue signal into a digital signal, processes the trigger input signal, and stores the readout frame in the internal memory. In order to reconstruct the Beetle chip analogue pulse shape, the ALiBaVa mother board stores the readout frame within a 100 ns time window once it receives the trigger input signal. The Time to Digital Converter (TDC), placed on the mother board, is used to measure the time between the trigger input signal and the time when the frame is read out. Finally, all data is sent to a PC. The software on the PC receives the data from the mother board, processes it, monitors the data and stores it. The general user interface software also enables the communication between the user and the system [53].



Figure 4.8: The ALiBaVa readout system [52]: the mother board is placed in the box in black and the daughter board is in the aluminium box in front.

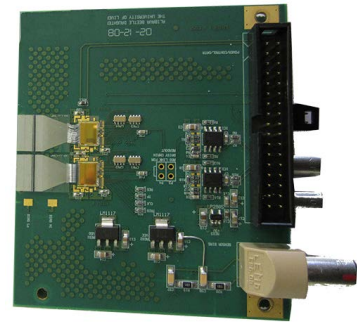


Figure 4.9: The daughter board of the ALiBaVa system [52].

4.5 Adapting the ALiBaVa Readout System for Testbeam Usage

As mentioned before, the ALiBaVa readout system was designed to be used in a laboratory. Using the ALiBaVa system at the testbeam integrated with the EUDET beam telescope required modifications to the firmware.

The most crucial problem that had to be solved was the synchronization of the ALiBaVa readout system with the EUDET beam telescope. The EUDAQ is designed to be synchronized with DUTs easily. The TLU serves this purpose by creating a timestamp for each generated trigger as well as by communicating with the DUTs in order not to send a trigger while it is busy. For synchronization using a timestamp, a DUT should either be capable of reading the TLU's timestamp via the RJ45 DUT interface of the TLU, or have its own timestamp to be processed and used with the timestamp of the TLU. The ALiBaVa system had neither a RJ45 connection nor a timestamp as required for the use with the TLU, so synchronization via timestamp was not suitable for this case. The other option the TLU offers for synchronization is via handshake communication. For this option, the TLU expects a busy signal back from DUTs to ensure no events are missed by any of the DUTs since it will not generate a new trigger while any of the DUTs is not capable of processing it.

The ALiBaVa system was not generating a signal while busy; however, it could easily be implemented in the firmware. So one of the modifications, requested by us for testbeam use, was to generate a busy signal and send it through the LEMO connector present on the mother board.

Moreover, since the ALiBaVa system was designed to reconstruct the front-end pulse shape, the data is sampled within a time window of 100 ns after the trigger signal is received. After reconstruction of the pulse shape, only the data sampled within a time window of ± 5 ns around the peak value of the pulse is used for further analysis. This is increasing the data taking time drastically to collect the desired number of events usable in the analysis. Although this might not cause problems for most of the laboratory measurements, it is definitely an issue for the testbeam measurements because of having limited time of beam which makes testbeam campaign schedules tight. Therefore, the other modification requested for the new firmware release was to reduce the time window in which the data sampled after receiving the trigger signal to 25 ns, which corresponds to one clock cycle.

At the time this study started, the last release of the ALiBaVa system had the firmware version v2.0. Modifications to the firmware for integration with the EUDET beam telescope were suggested to ALiBaVa Systems. These modifications, the busy signal and the shorter data taking time window, are implemented in the ALiBaVa firmware version v2.0a. This version was not officially released, but is used for all measurements presented in this document. The ALiBaVa Systems further implemented a timestamp in the firmware and released this version as v3.0 [52]. The modifications are now available as a default part of the system.

4.6 The Sensor Box

The sensor box, shown in Figure 4.10, is designed to be as adaptable as possible for future studies while satisfying the needs of the measurements presented here. First, it is required to have a good cooling capability since some the measurements are also performed on highly irradiated sensors. A cooling plate is located inside the box to cool the sensors down to -25°C , which is the expected operation temperature at the HL-LHC. A rotation axis is attached to the cooling plate since the box should be rotatable for the Lorentz angle measurement. Two sensors are placed in the box to measure them at the same time, and the rotation axis is situated in the middle of the two sensors.

The box has a size of $110\text{ mm} \times 150\text{ mm} \times 54\text{ mm}$, is made of plastic and has a $40 \times 25\text{ mm}^2$ window on both sides, where the beam will pass through. The windows are covered with $25\text{ }\mu\text{m}$ black kapton foil to keep the sensors in the dark. The box is covered with styrofoam for thermal insulation. In order to keep the humidity low inside the box to prevent condensation, it is flushed with nitrogen. A temperature sensor and a humidity sensor are placed to monitor the environment inside the box.

The sensor holder and the cooling plate are explained in the following subsections.

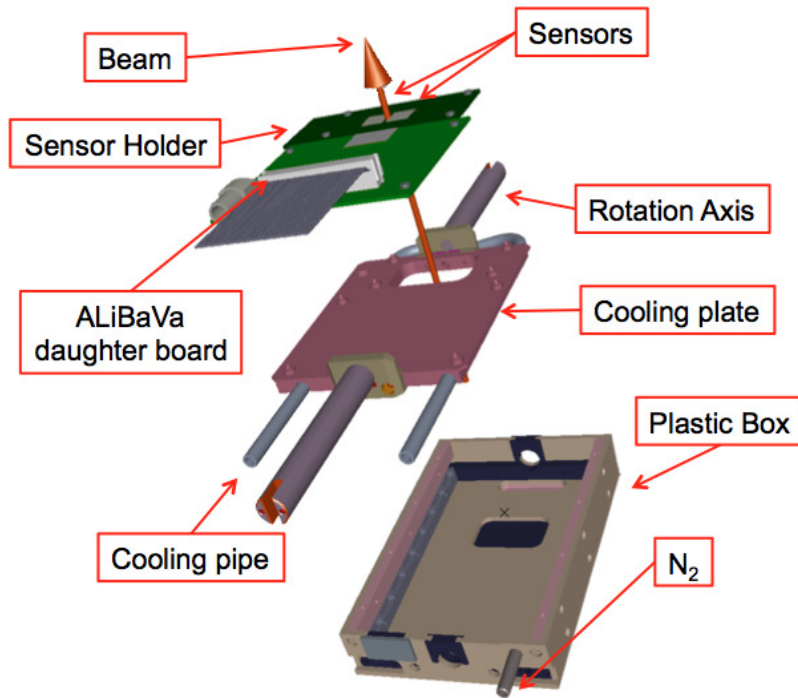


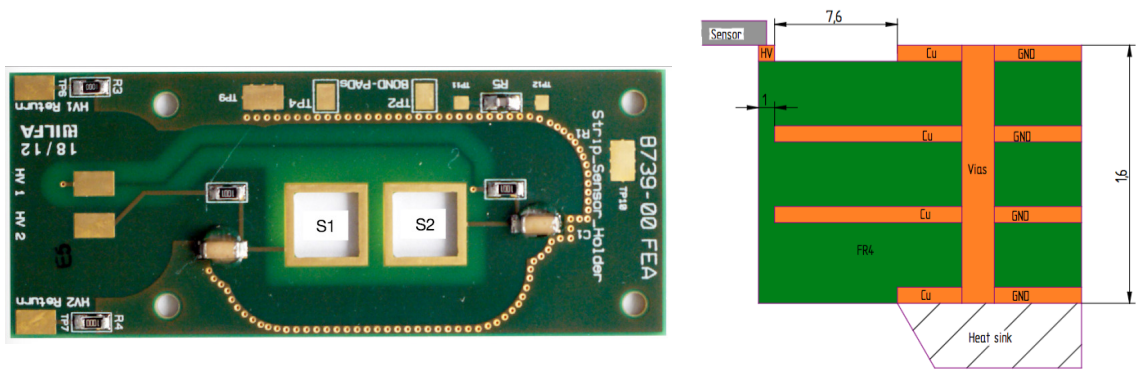
Figure 4.10: The sensor box.

4.6.1 The Sensor Holder

The sensor holder is designed to hold two $10\text{ mm} \times 10\text{ mm}$ sensors, so that two sensors can be measured at the same time, which decreases the data taking time. A good thermal conductivity is desired to cool the irradiated sensors to prevent uncontrolled annealing and avoid high leakage currents. For charge collection efficiency (CCE) measurements of irradiated sensors, the bias voltage has to be increased up to 1000 V . For this reason, the sensor holder is designed to be protected against high voltage (HV) up to 1000 V .

A picture of the sensor holder is shown in Figure 4.11a. It has a size of $82\text{ mm} \times 33\text{ mm}$. The four pads on the left are used to bias the sensors, two are connected to each sensor. In this way it is possible to set the bias voltage of each sensor separately. The sensors are positioned at the points labelled "S1" and "S2". In order to reduce the amount of material a particle impacting the sensor has to traverse, a square of $8\text{ mm} \times 8\text{ mm}$ has been cut out in the area where the sensors are placed. The 1 mm thick rim of the cut-out has a connection to the HV pad so that the bias voltage can be applied from the back side of the sensor using a conductive glue. There are two ground pads (TP2 and TP4) each connected to the bias ring of each respective sensor via a wire-bond. Between the sensors and the ALiBaVa daughter board, there is some space left for the fan-ins which will be wire-bonded to the sensor. The connections between the Beetle chips and the sensors are established via wire-bonding the fan-ins on the sensor holder to the ones on the ALiBaVa daughter board. A temperature sensor is located on the top-right of the sensor holder in order to measure the temperature in the vicinity of the sensor.

Figure 4.11b shows the inner layers of the sensor holder. There are four copper layers increasing the area used for heat transfer. These layers are connected to the heat sink using vias, so that the heat on the inner layers can easily be transferred to the heat sink. In this way a good thermal conductivity is achieved. The distance of the layers to the HV points is adjusted to be able to operate safely at up to 1000 V .



(a) The sensor holder.

(b) A cross section through the different layers of the sensor holder.

Figure 4.11: The sensor holder.

4.6.2 The Cooling Plate

The cooling plate is designed to hold the sensor holder and the ALiBaVa daughter board, as shown in Figure 4.12a. It is aimed to have a good thermal contact with the sensor holder in order to improve the heat removal from the sensors. The cooling plate is made of copper and has a cooling pipe, which is used by the cooling system with the silicone coolant. As depicted in Figure 4.12b, a 40 mm $\times$ 25 mm window is left in order to reduce the radiation length in the beam path.

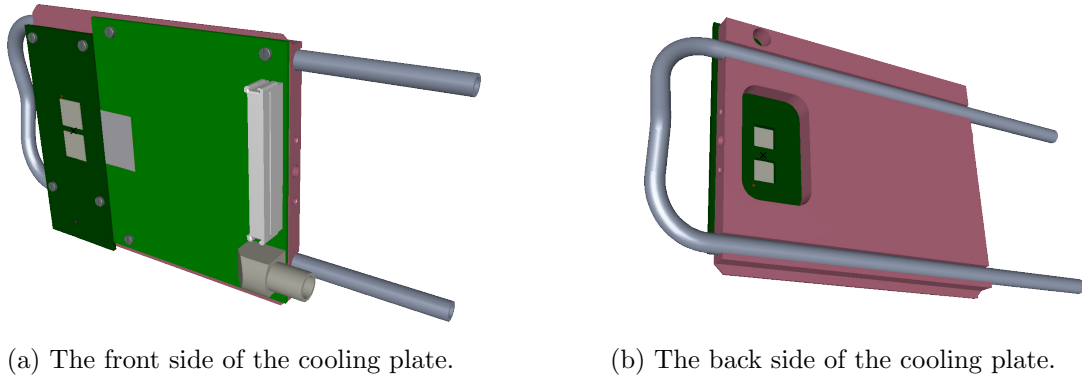


Figure 4.12: The cooling plate with the sensor holder and the ALiBaVa daughter board attached.

4.7 Implementation in the Telescope

In order to assemble the setup, a carriage was built to hold the sensor box and the EUDET beam telescope planes inside the PCMAG. The front and back views are shown in Figure 4.13. The carriage holds a 32 cm support base for the telescope planes. As mentioned in Section 4.3, the size of telescope sensors is 10.6 mm $\times$ 21.2 mm. In order to have the longest side of the telescope sensors in the bending direction of the beam, the telescope planes are rotated by 90° compared to their standard configuration in the EUDET telescope. Aiming at a minimum deviation of the beam in the presence of a magnetic field over the length of telescope, the distance between the first and last telescope plane is kept as short as possible. For the same reason the carriage places the telescope planes close to the wall of magnet where the beam enters. In the middle of the telescope support base, a plastic holder is placed to hold one end of the rotation axis of the sensor box. The other end of the rotation axis is attached to the rotation stage which is fixed to the carriage, as shown in Figure 4.13a. Although the rotation stage has a scale to measure the rotation angle, in order to achieve better precision an inclinometer [55] is attached to the rotation stage. The sensor box is located such that the centre between the two sensors on the sensor holder is aligned with the centre of the telescope sensors. The legs of the carriage are holding the rails located inside the PCMAG; this provides freedom to slide the setup inside the magnet. The height of the carriage is designed in a way that the telescope sensors are located

in the centre of the PCMAG in the vertical direction. A picture of the carriage assembled is shown in Figure 4.14.

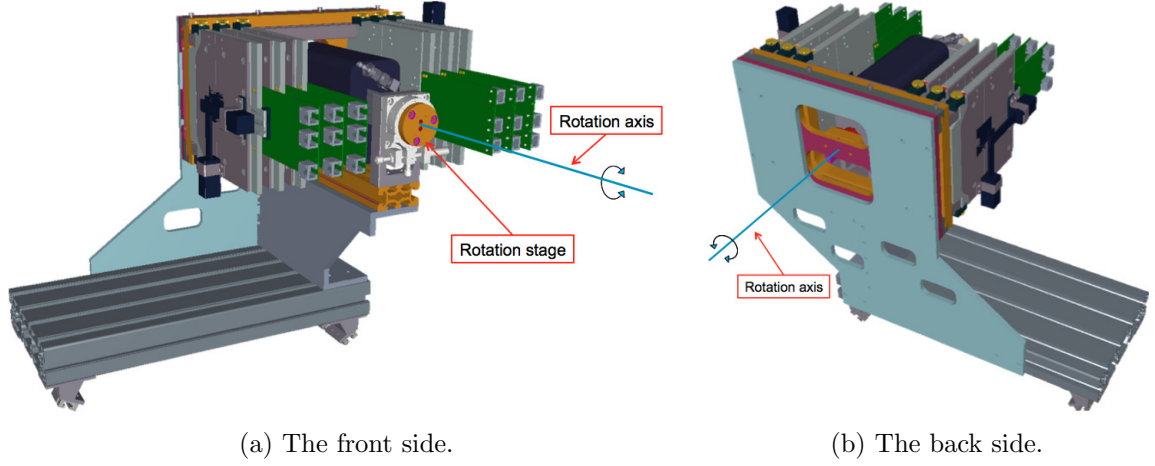


Figure 4.13: Drawings of the carriage that positions the sensor box and the EUDET beam telescope planes inside the PCMAG.

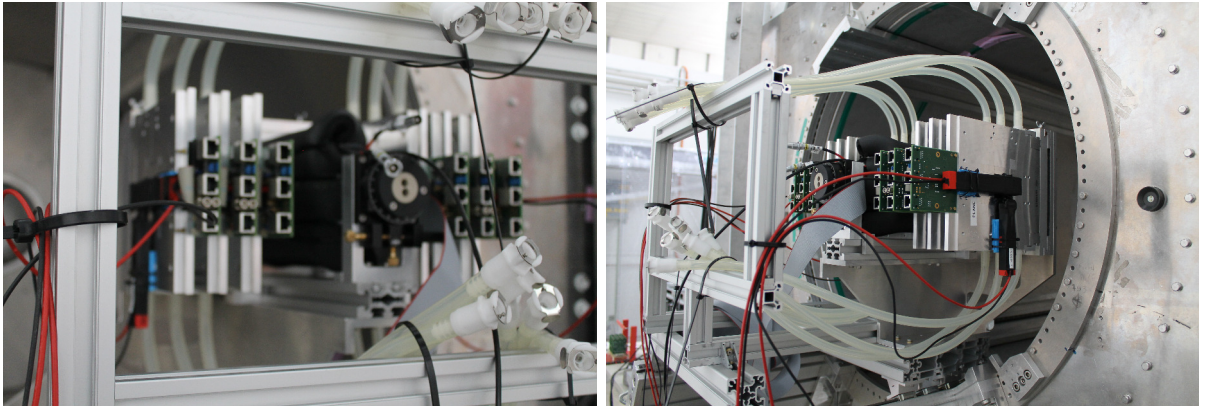


Figure 4.14: The carriage assembled inside the magnet.

The scintillators used as the trigger of the EUDET beam telescope are read out by photomultiplier tubes (PMTs), which are not suitable for use in a magnetic field. Therefore, the PMTs are replaced by silicon photomultipliers (SiPMs).

The operation in the magnetic field also introduces challenges to the cooling system. Due to the magnetic field, the chiller had to be placed in a distance from the magnet where the magnetic field is low (0.1 mT), which required using long cooling pipes as shown in Figure 4.15. Using long pipes increases the resistance to the liquid flow and the heat gain on the way. To reduce the resistance to the liquid, a 4 m long rigid pipe with a diameter of $\phi 12 \text{ mm} \times 1 \text{ mm}$ made of stainless steel is installed on the wall. It is followed by a 3 m flexible pipe made of stainless steel with the same diameter used to get closer to the DUT and then a 1 m hose is used to reach

the DUT. There is another 1 m hose to connect the pipes on the wall to the chiller. In total, counting from the outlet of the chiller to its inlet 18 m of pipes were present, which is why it was difficult to keep the temperature constant. The temperature of the system was increasing approximately 1°C in 3 days. UniStat 705 chiller [56] is used with an additional pump Unipump I DC[57] to increase the pressure and the flow rate. The chiller has a cooling capacity of 0.3 kW at -60°C and a circulation pump with a capacity of 55 l/min ; 0.9 bar. The external pump has a capacity of 55 l/min ; 1 bar.

In order to reach a temperature of -25°C on the sensors, a procedure is developed to cool down the the system. First, the temperature on the chiller is set to -40°C . Once the temperature on the chiller stabilizes, the chiller was set to -65°C . Finally the pump was turned on to increase the circulation in the system. Since the cooling capacity of the chiller was not enough to eliminate the heat gain from pipes, the system was warming up slowly (1°C in 3 days). It was observed that the heat produced on the irradiated samples does not affect the cooling system since it is small compared to the heat gain from pipes.



Figure 4.15: The setup at the testbeam.

The measurement of the air temperature and humidity inside the box as well as the temperature on the sensor is carried out using a National Instruments (NI) PXI crate to read out the humidity and temperature sensors. A PC based digital multimeter (NI PXI DMM) and a multiplexer for multiple readings (NI PXI switch) is used with the NI PXI crate. A LabView interface, shown in Figure 4.16, is used to monitor the values. The tilt angle of the sensor box is measured attaching the inclinometer on the rotation stage.

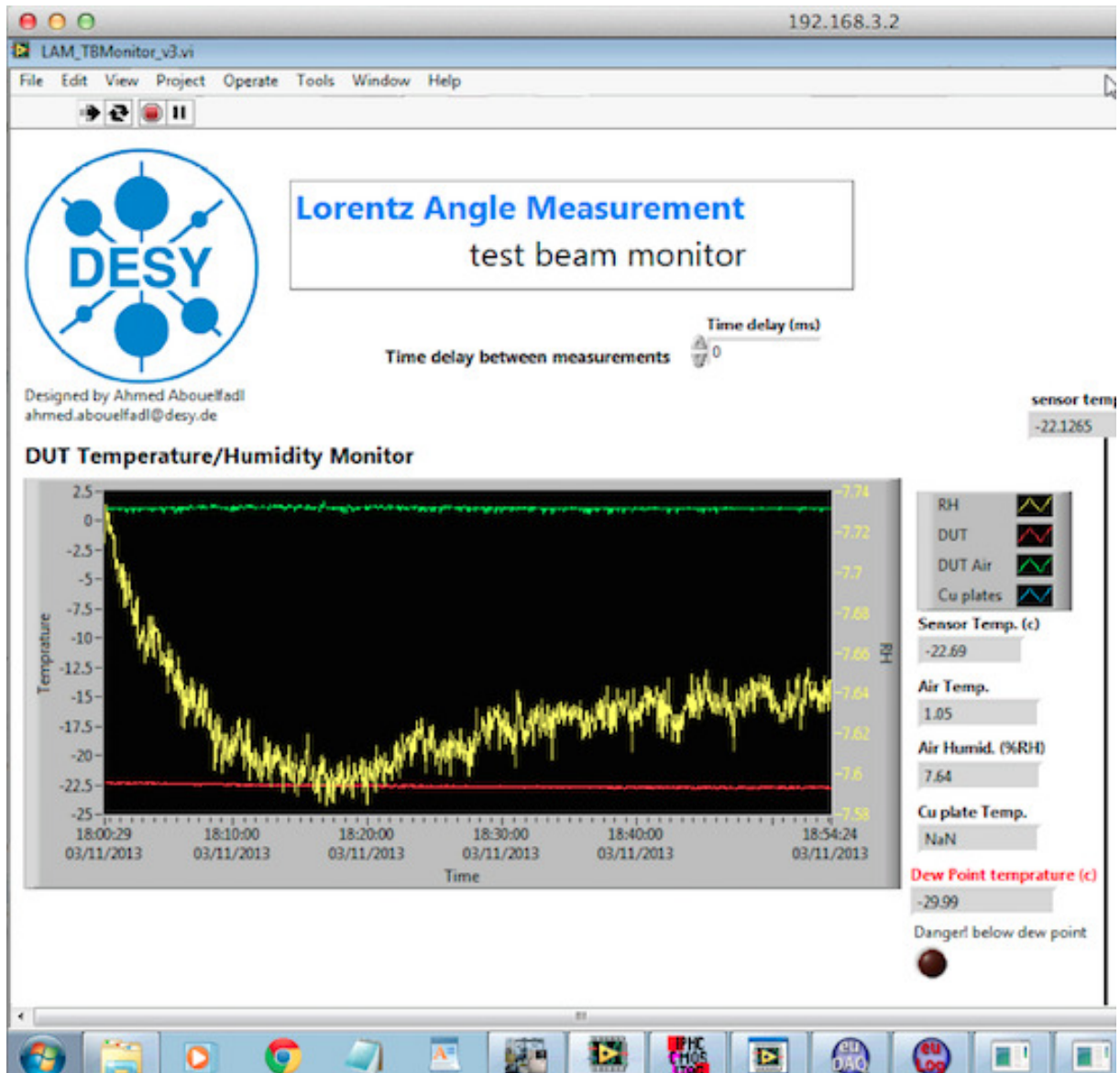


Figure 4.16: The LabView interface of the monitoring setup.

Chapter 5

Signal Reconstruction of the ALiBaVa Data

In this chapter the procedure to reconstruct the signal of a particle passing through a silicon strip sensor that is readout by the ALiBaVa system is described step-by-step.

The analysis is performed within the EUTelescope framework which is used for the analysis and reconstruction of data taken with pixel beam telescopes. The analysis chain from raw data to obtain the signal and form the clusters is shown in Figure 5.1. The details will be given in the following sections. The raw data of a pedestal run and a radioactive source or beam data is first converted to LCIO (Linear Collider Input/Output) [58] format, which is an event data model designed for linear collider detector studies. The raw data distributions are shown in Section 5.1. Then using pedestal data, the calculation of pedestal and noise values is performed (Section 5.2). The common mode noise correction is applied to both pedestal and source data (Section 5.3). The final pedestal and noise values are obtained by re-performing the pedestal and noise calculation on the common mode noise corrected raw data. The common mode noise correction for the source raw data is done after subtracting final pedestal values (Section 5.4). After obtaining common mode noise corrected signal values, in order to select signal usable for further analysis, a TDC time cut and signal to noise ratio (SNR) cut is applied (Section 5.5). In Section 5.6, the clustering method used in this thesis is explained. After that, the evidence of cross-talk between the channels is shown and the procedure to correct this effect is explained in Section 5.7. Having the selected and cross-talk corrected signal in units of analogue to digital count (ADC) in order to obtain the corresponding charge values the signal is multiplied with the calibration constant of the corresponding readout chip. In Section 5.8, the setup used to calibrate the readout chips as well as the calibration method is introduced. To conclude, the final signal and cluster plots to be used in further analysis are shown in Section 5.9.

In this chapter, beam data taken with a non-irradiated sensor at zero tilt angle and at zero magnetic field and pedestal data taken with the same sensor and same conditions are shown. The same procedure is applied for each data set that are used in the next chapters.

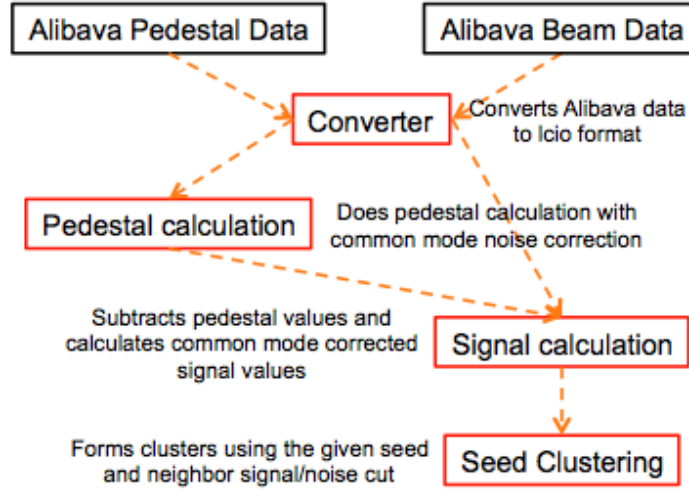


Figure 5.1: The analysis chain to obtain clusters from raw data of the ALiBaVa system.

5.1 Raw Data from the ALiBaVa Readout System

The ALiBaVa readout system stores the data in a binary file with the format shown in Table 5.1 for firmware version 2 and 3. Since the EUTelescope framework is working with LCIO format, this binary data is first converted to a LCIO file.

File Header	Date
	Data Type
	File Header Length
	File Header (includes firmware version)
	Pedestal values for channels in both chips
	Noise values for channels in both chips
For Each Event	Event Header
	Event Size
	A value that stores charge and delay in calibration mode
	Clock (only in version 3)
	TDC Time
	Temperature
	Header of chip 0
	Raw data for each channel in chip 0 (128 channels)
	Header of chip 1
	Raw data for each channel in chip 1 (128 channels)

Table 5.1: The ALiBaVa readout binary data format.

The signal distribution of the raw data collected by the ALiBaVa readout system is shown

in Figure 5.2a for a pedestal run and in Figure 5.2b for a run with beam data. The pedestal data is taken by turning the beam off, therefore it contains the readout response when there is no particle passing through the sensor. While signal distribution of the pedestal data forms a gaussian shape, the signal distribution of the beam data also has signal with lower strength in addition to the pedestal peak. Comparing the raw data distribution of the pedestal and the beam data, the signal can clearly be seen in the beam data. The TDC time dependence of the raw data is shown in Figure 5.3a for the pedestal run and in Figure 5.3b for the run with beam data. The ALiBaVa readout system takes data within a certain time window in order to reconstruct the Beetle chip pulse shape (see Sections 4.4 and 4.5). For the studies in this thesis, in order to increase the data taking efficiency, the width of the time window is set to 25 ns. In Figure 5.3b, the pulse shape can be seen clearly. The pedestal data is taken with auto-triggering, since there is no particle passing through the sensor the signal strength does not depend on time, therefore, the data taking time in pedestal data is in 1 ns as shown in Figure 5.3a.

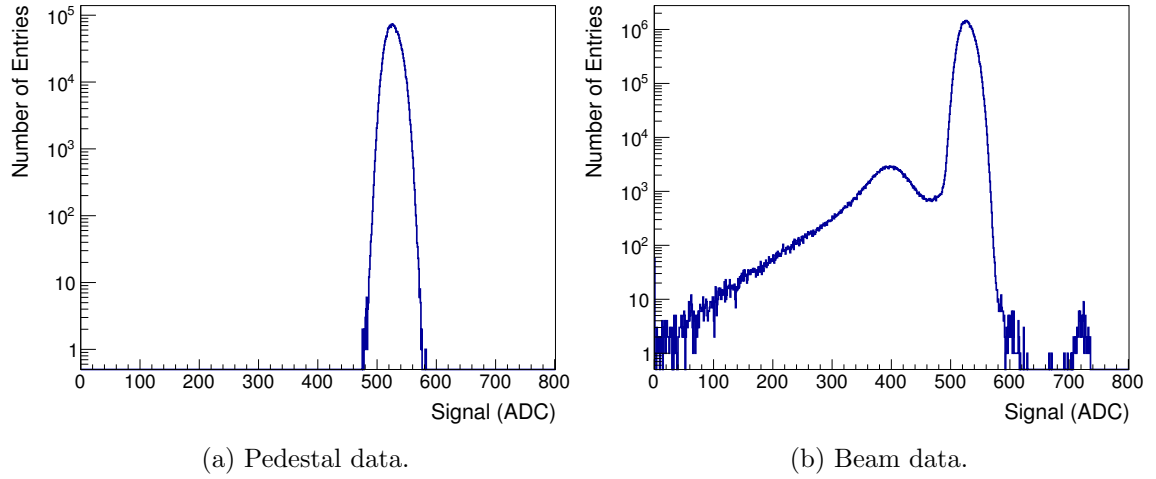


Figure 5.2: Raw data distribution.

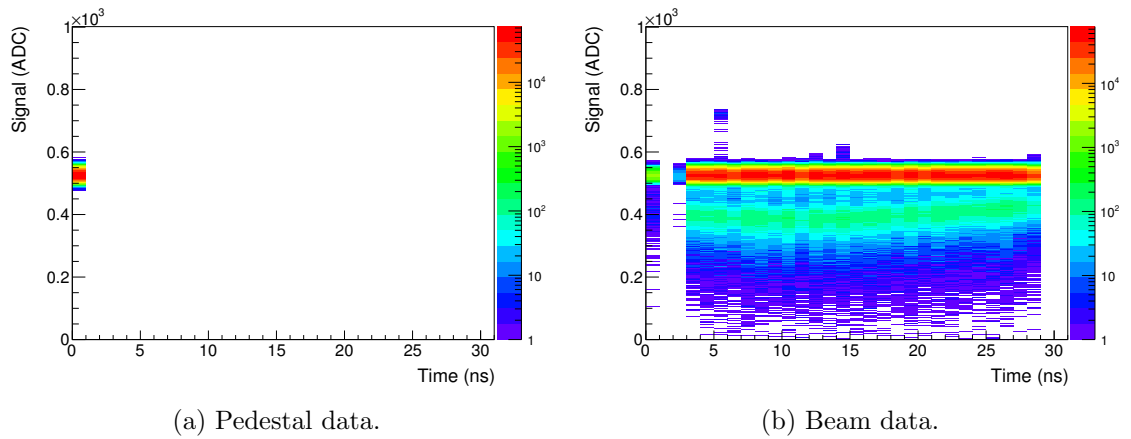


Figure 5.3: Raw data signal distribution dependence on TDC time.

5.2 Pedestal and Noise Calculation

The pedestal and noise values are calculated for each channel in each chip. The pedestal value of a channel corresponds to the mean value of the raw data distribution and the noise corresponds to its standard deviation. Figure 5.4 shows the raw data distribution for a channel and the gaussian fit from which its mean and standard deviation is calculated. By applying the same procedure to each channel in a chip one calculates the pedestal and noise distribution per channel, which is shown in Figure 5.5a and 5.5b, respectively. The channels which have no entry are the channels that are not connected to the sensor.

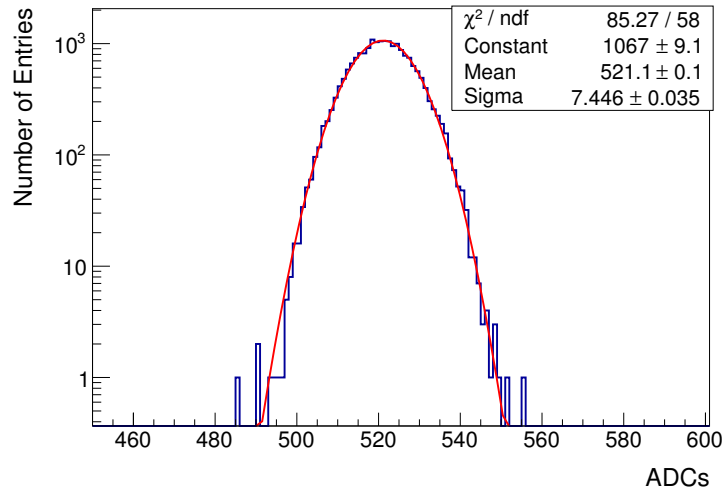


Figure 5.4: Raw data distribution in pedestal data for a single channel and Gaussian fit to the distribution.

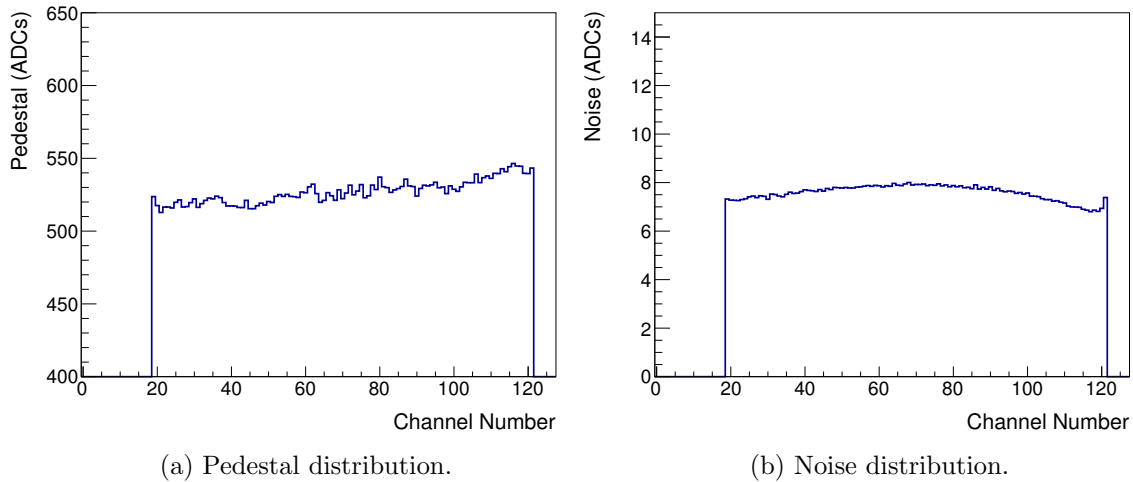


Figure 5.5: Pedestal and noise distributions for each channel in a chip.

5.3 Common Mode Noise Reduction

After the pedestal calculation and pedestal subtraction from pedestal data one expects to have only noise in an event. However, in some events, a common shift in the baseline of noise is seen (see Figure 5.6). This shift is called common mode noise. The source of the common mode noise might be instability of the reference ground of the power supply or picking-up noise at the inputs of front-end chips. In addition, the analogue cable and the sensors can act as an antenna and cause common mode noise. In the event shown, the common mode noise is negative. Assuming the common mode noise is constant, it is calculated and subtracted from each event and each chip. The calculated common mode noise distribution is shown in Figure 5.7.

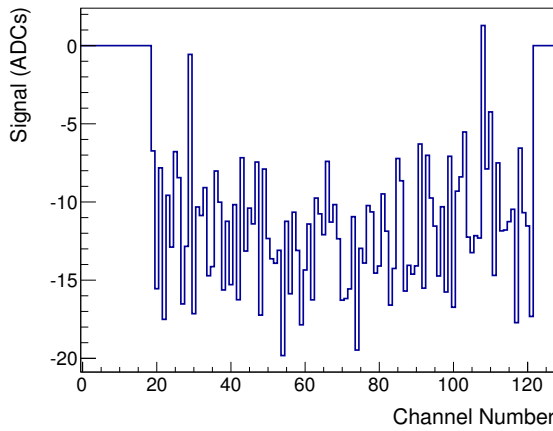


Figure 5.6: Signal on channels of a chip after pedestal subtraction.

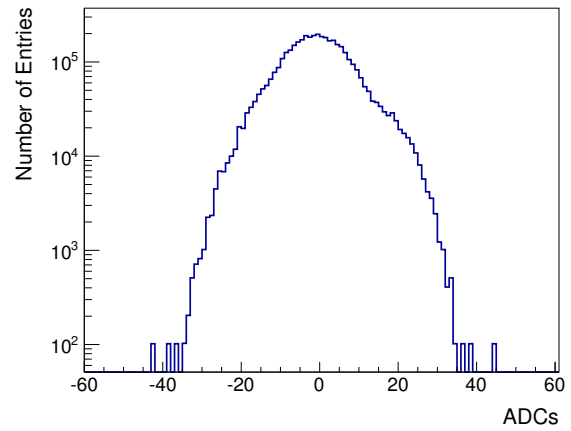


Figure 5.7: Corrected common mode noise values.

After subtracting the common mode noise from the raw data of pedestal run, pedestal and noise values are re-calculated, the results are shown in Figure 5.8a and 5.8b, respectively. The noise values are reduced drastically whereas the pedestals values did not change much as expected.

5.4 Signal Reconstruction

In order to obtain a signal from the raw data, re-calculated pedestal values are subtracted from each channel in each event and then the common mode noise correction is applied. The signal to noise ratio (SNR) values are also calculated by dividing each signal by its corresponding channel noise. The signal and SNR distribution is shown in Figure 5.9 and their dependence on the TDC time is shown in Figure 5.10. The signal values are multiplied by -1 to show the quantitative values.

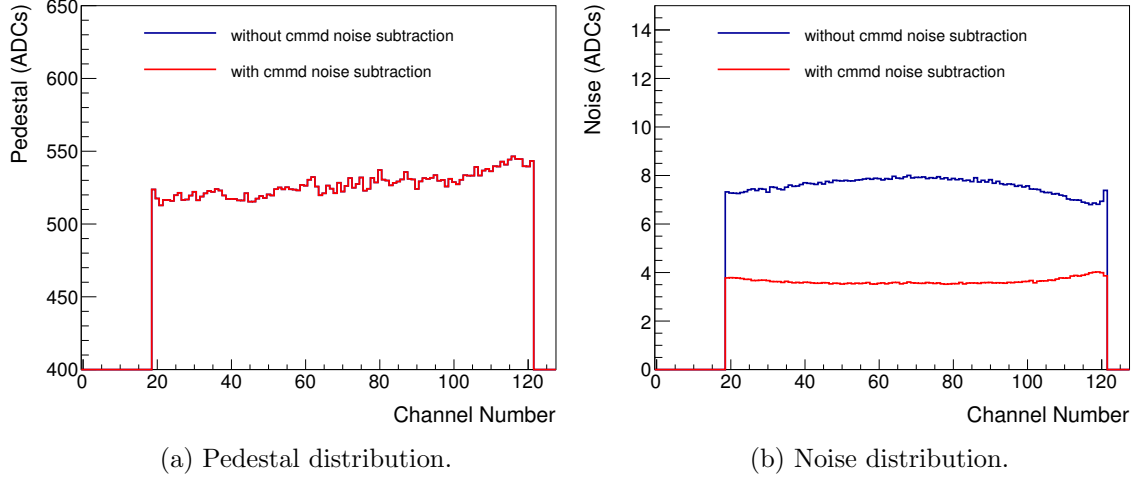


Figure 5.8: Common mode noise corrected pedestal and noise distributions for each channel in a chip.

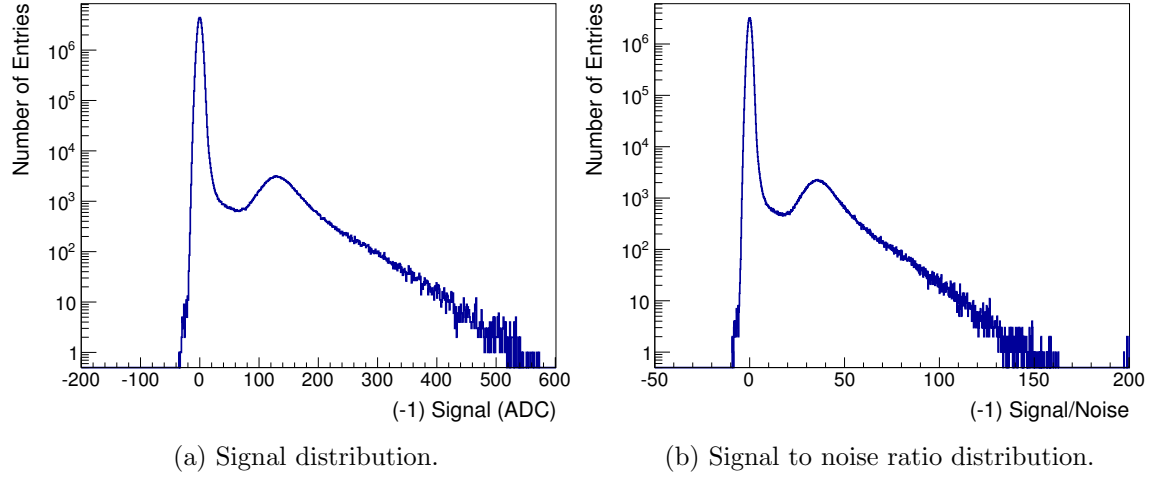


Figure 5.9: Signal and signal to noise ratio distribution of beam data.

5.5 Signal Selection

As seen from Figure 5.10a, the signal amplitude depends on TDC time. To minimize the effect of TDC time on the analysis, a TDC time cut is applied. Since the change in signal amplitude is smaller around the peak value of the signal, the usual cut applied to the TDC time is ± 5 ns around the TDC time corresponding to the peak value of the signal. In the case of this run this corresponds to approximately $5 \text{ ns} < \text{TDC time} < 15 \text{ ns}$. The applied cut is shown in Figure 5.11. The distributions of the selected signals and their SNRs are shown in Figure 5.12a and 5.12b, respectively.

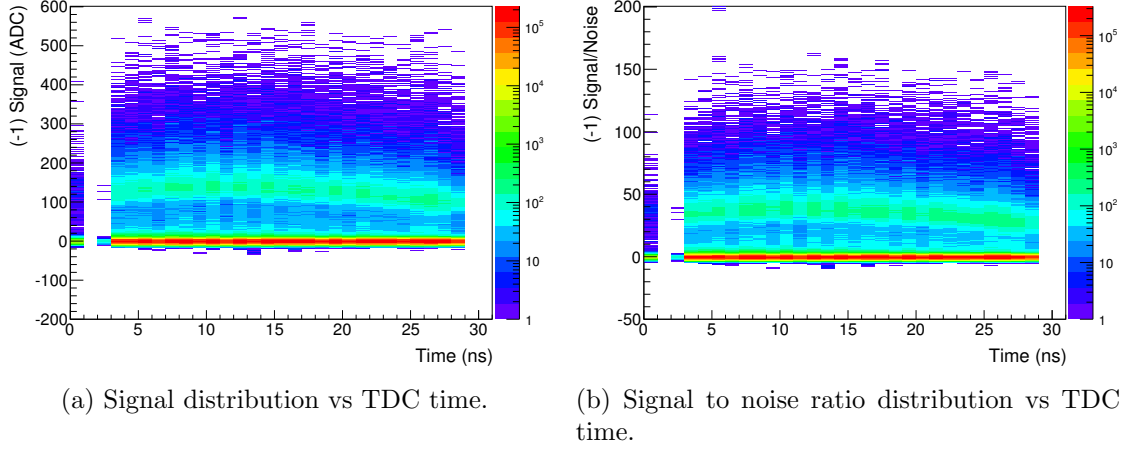


Figure 5.10: Signal and signal to noise ratio distribution of beam data vs TDC time.

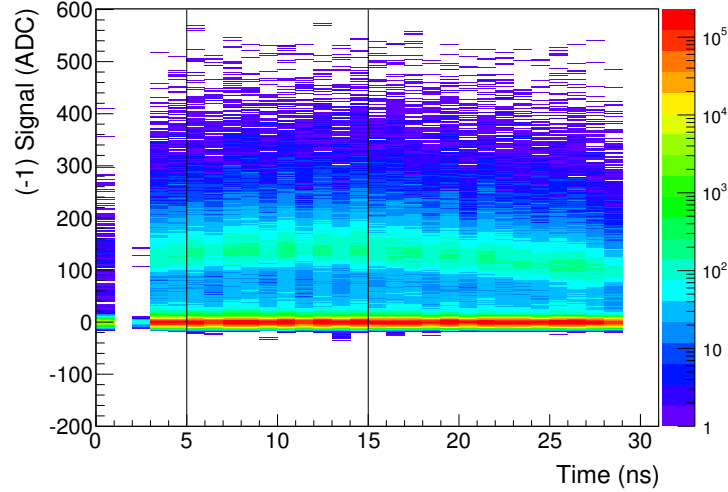


Figure 5.11: The selected TDC time window (approximately $5 \text{ ns} < \text{TDC time} < 15 \text{ ns}$).

5.6 Seed Clustering

Clustering is performed to add up the charges that are deposited by the same particle. In the clustering algorithm, it is required to have at least one channel that has 3.5 times more signal than its noise. This channel is called the seed channel. If there are more than one channel satisfying this condition, the one that has the highest signal to noise ratio is considered as the seed channel. Neighboring channels are clustered with the seed channel if they have signal to noise ratio greater than 1.8. Figure 5.13 illustrates the thresholds of the clustering algorithm. In this example, the seed channel is the y channel since it is the only channel that has $\text{SNR}_{\text{seed}} > 3.5$, the neighbor channel z is clustered with the seed channel since it satisfies the $\text{SNR}_{\text{neigh}} > 1.8$ cut. However, channel x is not included in the cluster since it doesn't satisfy the neighbor cut.

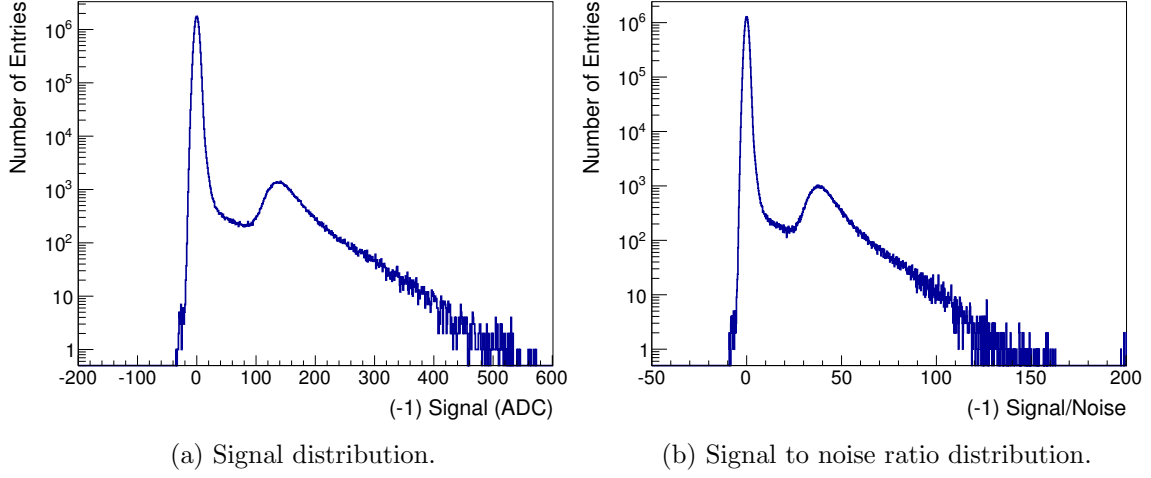


Figure 5.12: Signal and signal to noise ratio distribution of beam data after TDC time cut.

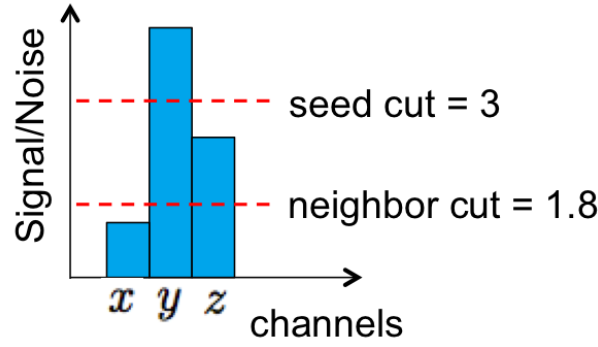


Figure 5.13: The illustration of the seed clustering thresholds ($\text{SNR}_{\text{seed}} > 3.5$, $\text{SNR}_{\text{neigh}} > 1.8$).

The clusters which are next to the channels that are not connected to the readout system or next to a noisy channel are not included in the analysis. Figure 5.14 shows the number of channels in a cluster (cluster size) distribution.

The η -distribution of clusters gives information on the charge distribution within strips. η is defined as:

$$\eta = \frac{Q_{\text{left}}}{Q_{\text{left}} + Q_{\text{right}}} ,$$

where Q_{left} is the charge on the left channel and Q_{right} is the one on the right channel. In this analysis, to define the left and right channels, neighbors of the seed channels are compared. The seed channel and its neighbor that has the highest signal are used to calculate the η . The channel that has smaller channel number is considered to be the left channel.

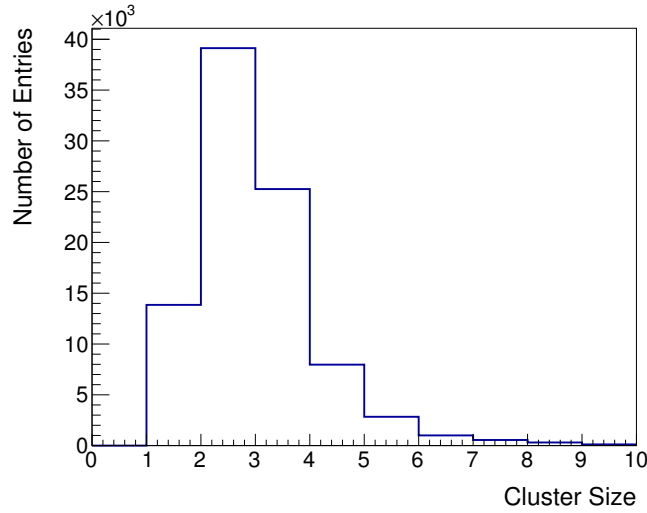


Figure 5.14: Cluster size distribution using $\text{SNR}_{\text{seed}} > 3.5$, $\text{SNR}_{\text{neigh}} > 1.8$.

In the case where there is no magnetic field present and no cross-talk in the readout system, the η -distribution should be symmetric with two peaks close to 0 and 1. If η is close to 0, this means that the seed is the right channel and the left neighbor channel has very small charge compared to the seed channel. If η is close to 1, the seed is the left channel and the right neighbor channel has a small signal.

Figure 5.15 shows the η -distribution of data run taken at zero magnetic field. The asymmetry in the η -distribution can be clearly seen. Since there is no magnetic field present, the asymmetric should be caused by the cross-talk in the readout. Other studies using the ALiBaVa readout system also observed cross-talk in their data [59, 60], it is shown that the amount of cross-talk can be decreased by shortening [60] and shielding [59] the ribbon cable between the ALiBaVa daughterboard and motherboard.

5.7 Cross-Talk Correction

Cross-talk refers to any phenomenon that causes signal transmission from one channel to another due to the electromagnetic (inductive) or electrostatic (capacitive) coupling. In silicon detectors, the cross-talk term refers to the dependence of the response of the neighboring channels on a certain channel in the silicon that is hit by a particle [61].

An asymmetric cross-talk means that some of the signal of a channel passes either to the left or to the right neighbor. In the analogue readout systems asymmetric cross-talk can be caused either within the readout chip or through the cable. The cross-talk in the Beetle chip [54] of the ALiBaVa readout system is less than 1%, which does not explain the cross-talk we observe in Figure 5.15. Hence the majority of the cross-talk should come from the coupling within the cable.

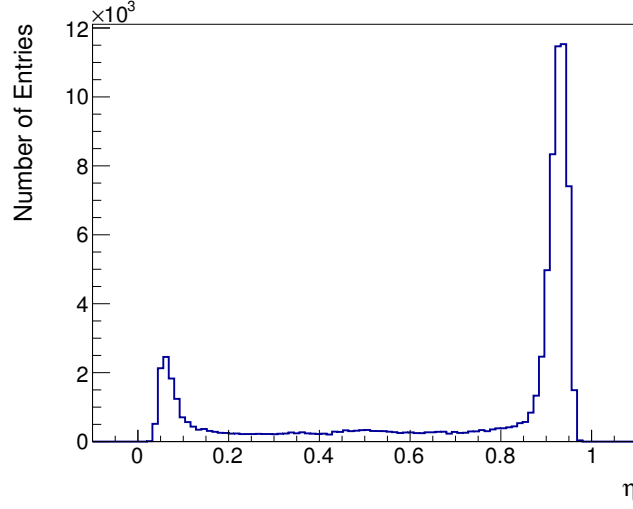


Figure 5.15: η -distribution of clusters.

The cross-talk in the readout system affects the signal distribution in the channels and therefore the cluster size. In order to achieve a precise measurement of the particle track, it is crucial to correct the cross-talk effect and restore the correct signal distribution of the channels.

The cross-talk can be corrected using finite impulse response (FIR) [62]. Equation 5.1 shows the formulation the cross-talk correction of the order of N .

$$y[n] = \sum_{i=0}^N b_i \cdot x[n - i], \quad (5.1)$$

where $x[n - i]$ is the measured signal, b_i is the cross-talk coefficient and $y[n]$ is the cross-talk corrected signal.

In this study the cross-talk correction is applied by using FIR filter of the order of 2 as shown in Equation 5.2.

$$y[n] = x[n] - b_1 \cdot x[n - 1] - b_2 \cdot x[n - 2], \quad (5.2)$$

where $b_1 \cdot x[n - 1]$ and $b_2 \cdot x[n - 2]$ denotes the amount of cross-talk signal contributed to the measurement of the signal on $x[n]$ from the left channel and the second left channel, respectively. By subtracting the cross-talk signal from the measured signal ($x[n]$), the cross-talk corrected signal ($y[n]$) is obtained.

The cross-talk coefficients b_1 and b_2 is calculated as shown in Equation 5.3 using data taken with zero magnetic field and applied to all data sets used in this thesis.

$$b_1 = \sum_n \frac{Q_{\text{left}}}{Q_{\text{seed}}} - \sum_n \frac{Q_{\text{right}}}{Q_{\text{seed}}}, \quad (5.3)$$

$$b_2 = \sum_n \frac{Q_{\text{second left}}}{Q_{\text{seed}}} - \sum_n \frac{Q_{\text{second right}}}{Q_{\text{seed}}}, \quad (5.4)$$

5.8 Calibration

The calibration is needed in order to calculate the deposited charge on the channels by the particle passing through the silicon. This information is important especially for the charge collection efficiency (CCE) measurement in this thesis. The calibration is done for each chip used for the measurements, using a Strontium-90 (Sr^{90}) source in the laboratory with a setup designed for this purpose which can be seen on the left of Figure 5.16.

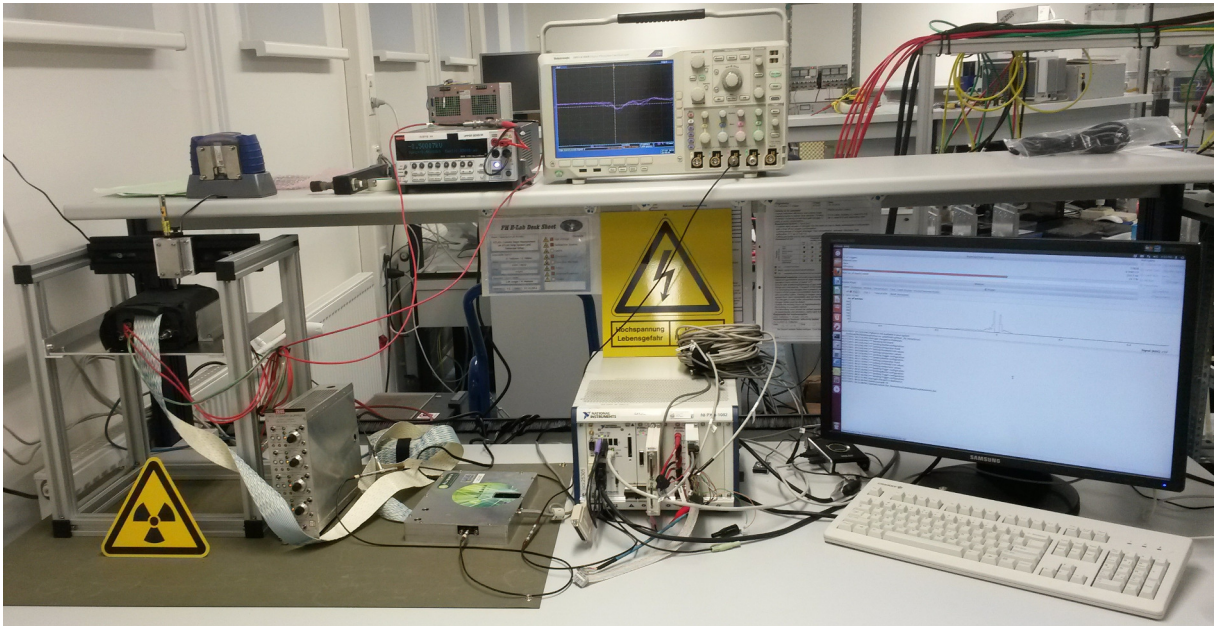


Figure 5.16: The laboratory setup for calibration measurements.

The setup consists of a radioactive source, non-irradiated ATLAS12 miniature sensors wire bonded to each chip on the ALiBaVa daughterboard and a scintillator used for triggering. A holder for the radioactive source is placed on top of the setup, the sensor box introduced in Section 4.6 is placed under the radioactive source and the scintillator is placed under the sensors in the sensor box. To calibrate a single chip, the source with a 6 mm diameter collimator and the 22×40 mm scintillator is aligned with the sensor connected to that chip. The sensor is

cooled down to the desired temperature using the same cooling system used at the test beam setup.

In order to calculate the calibration constant, i.e. the deposited charge per ADC, the data is taken with a fully depleted sensor since the active thickness and hence the expected deposited charge is known. To find the full depletion bias voltage of the ATLAS12 miniature sensors, data is taken at different bias voltages and analyzed with the procedure explained in this chapter. Using the seed clustering method with $\text{SNR}_{\text{seed}} > 3.5$ and $\text{SNR}_{\text{neighbour}} > 1.8$ the hit amplitude is calculated. The most probable hit amplitude versus bias voltage is shown in Figure 5.17. It is clearly seen that the sensor is fully depleted with a reverse bias voltage more than 350 V. The calibration constant is calculated with the knowledge of the sensor active thickness at full depletion ($300\text{ }\mu\text{m}$) and the deposited charge in the silicon with that thickness (32k electrons). The calculation is done with the reverse bias voltages of 400 V, 450 V, 500 V and 550 V and the mean value of the results is used as the calibration constant. Table 5.2 shows the calculated calibration constants for each Beetle chip used in this measurement. The error on the calibration constants are calculated from the uncertainty of the most probable value of the hit amplitude.

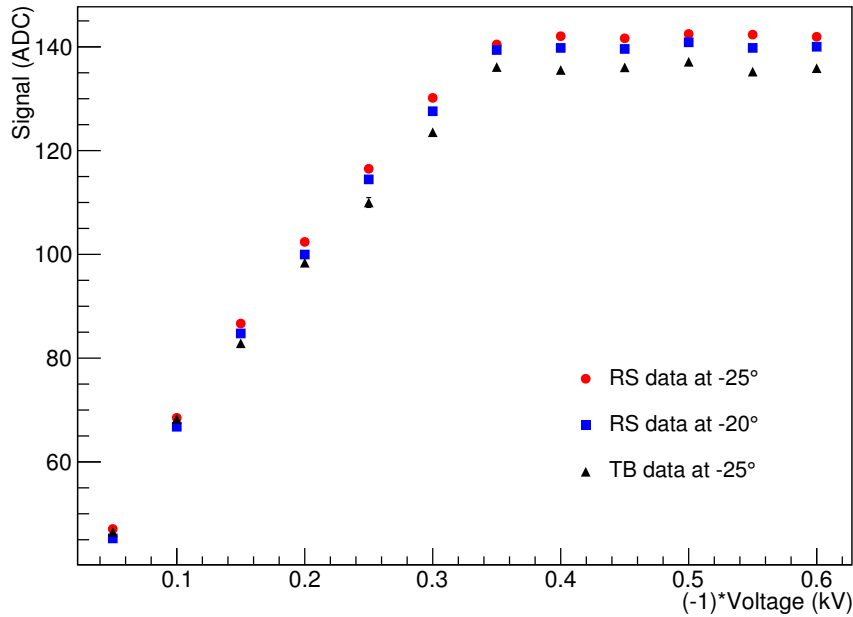


Figure 5.17: The bias voltage scan for the calibration constant calculation.

Alibava daughter board number	Readout chip number	Calibration constant (<i>electrons/ADC</i>)
Board 1	Chip 0	163.69 ± 0.25
	Chip 1	160.47 ± 0.25
Board 2	Chip 0	154.33 ± 0.36
	Chip 1	156.12 ± 0.41
Board 3	Chip 0	166.24 ± 0.35
	Chip 1	163.60 ± 0.43
Board 4	Chip 0	169.93 ± 0.36
	Chip 1	165.31 ± 0.37

Table 5.2: The calibration constant of each ALiBaVa readout chip used in the measurements.

5.9 The signal to be used in further analysis

In this section, the distribution of noise, signal, cluster size and the total charge in the clusters (hit amplitude) of the non-irradiated sample are compared with the irradiated samples. For the comparison the data taken with the samples at zero tilt angle and at zero magnetic field are used. The fluences of the samples are labeled on the plots with the unit n_{eq} which denotes $1\text{MeV } n_{\text{eq}}/\text{cm}^2$.

Figure 5.18 shows the comparison of the noise distribution of the chips used to measure each sample. The distributions are labelled with the fluence of the measured sample. It is seen that the noise distributions are similar for the chips used in this study. Figure 5.19 shows the signal distribution of the non-irradiated and irradiated samples. The gaussian peaks around zero correspond to the noise signal, and the remaining is the measured signal. As expected the most probable value of the signal distribution decreases with increasing fluence. It should be noted that the signal amplitude of the highest irradiated samples () is close to the noise values. Figure 5.20 shows the normalized distribution of the cluster size. As the fluence increases, number of clusters with cluster size of one increases due to the smaller signal collected on the samples. The total charge in the clusters (hit amplitude) is shown in Figure 5.21. The charge of the clusters decreases with the increasing fluence as expected.

The signal reconstruction procedure described in this chapter is applied to all data runs to be used in the further analysis.

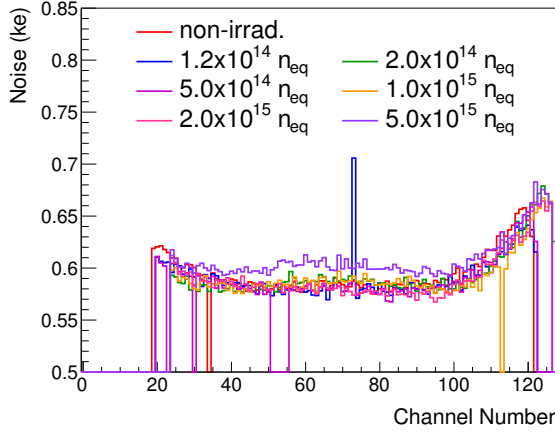


Figure 5.18: Comparison of noise distribution of each chip used to measure the irradiated samples.

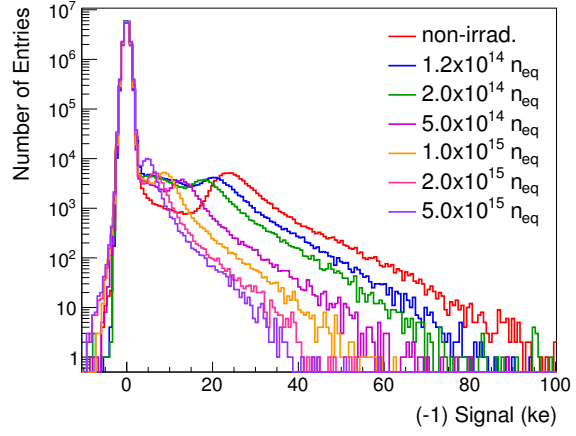


Figure 5.19: Comparison of signal distribution of the irradiated samples.

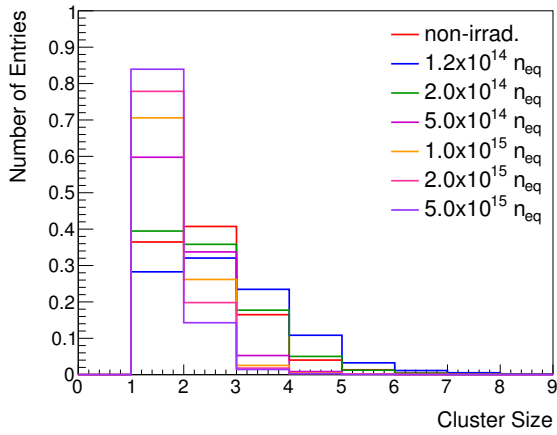


Figure 5.20: Comparison of cluster size distribution of the irradiated samples.

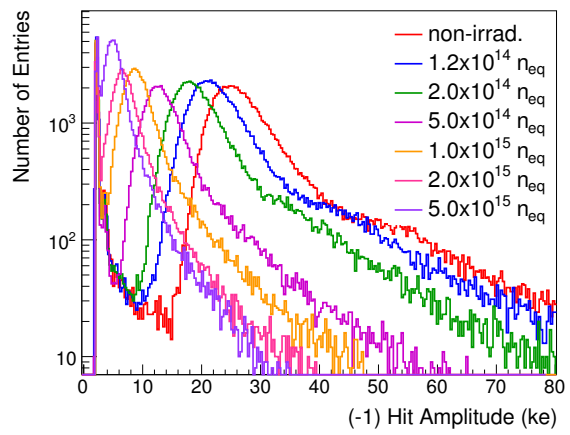


Figure 5.21: Comparison of hit amplitude distribution of the irradiated samples.

Chapter 6

Track Reconstruction

This chapter describes the rest of the analysis chain to obtain particle tracks. For completeness, the whole analysis chain is summarized in Figure 6.1. The first part of the analysis chain which is obtaining clusters of signals from the silicon strip sensors which are readout by the ALiBaVa system was described in Chapter 5. The charge collection and Lorentz angle analysis will be explained in Chapter 7. The processes shown in blue boxes are the default processors from the EUTelescope framework, the ones in red boxes are written for this analysis. All processors are put into the EUTelescope framework [63] and available for public use.

This chapter starts with describing the clustering of the EUDET beam telescope [63] (also called telescope) signals (Section 6.1) and focuses on finding the track of particles passing through all detectors. In order to obtain tracks, first the hit position of the particle on each detector layer is calculated using the clustered signals (Section 6.2). Then track candidates are found using telescope and strip sensors. The trajectory of track candidates are re-fitted by the General Broken Lines (GBL) algorithm [64] and the alignment parameters are calculated by Millepede-II [65]. After performing alignment the tracks which are also fitted by the GBL algorithm are stored to be used in the further analysis. The alignment and track fitting processes are explained in Section 6.3. As the first part, the rest of the analysis is performed within the EUTelescope framework.

6.1 Signal Reconstruction of EUDET Beam Telescope Data

Reconstruction of EUDET beam telescope signals is straight forward thanks to the EUTelescope framework, which has been developed to provide easy-to-use telescope data reconstruction.

Converter

The telescope sensors are read out in digital form and raw data is saved in a binary file. This binary data is converted to LCIO format by the process which is called the converter. During this conversion also the noisy pixels are identified and saved in a database file to be used in the

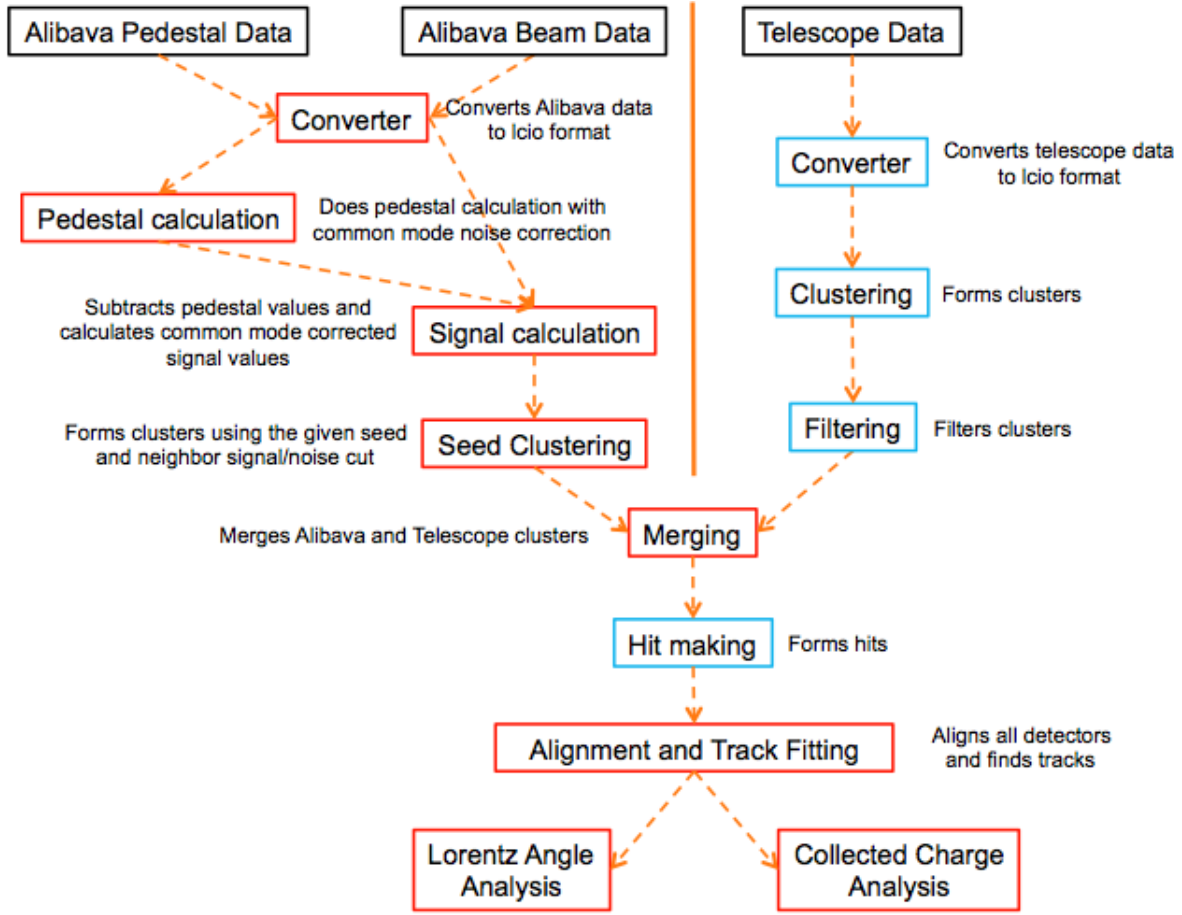


Figure 6.1: The analysis chain used to obtain the results presented in this work.

clustering process. The noisy pixels are defined by their firing frequency which is set by the user. For this analysis, pixels that have fired more than 10 times per 10000 events are labelled as noisy pixels.

Clustering

In this step, pixels are clustered with the neighboring pixels. Since the telescope layers are read out digitally no cut on the pixels are used. Clusters that contains noisy pixels are ignored in order to suppress noise.

Filtering

In this process, a Region Of Interest (ROI) is defined by the user for each telescope sensor. ROI cuts are useful to exclude specific parts of the sensors. In this analysis, the edges of sensors as well as noisy columns and rows are excluded using ROI cuts. This process removes the clusters which contain pixels that are not in the ROI.

6.2 Forming Hits

After obtaining clusters from telescope and strip sensors, they are merged into a single LCIO file. Then hit positions are derived in local coordinates using the charge weighted center of gravity algorithm. Since the telescope data are digital, the charge weighted algorithm is not necessary. However, for the ALiBaVa data it is crucial to use this algorithm since it provides a more precise determination of the hit position for the analogue signal.

Having the hits from all sensors, the synchronization of the telescope and the ALiBaVa events is checked. Figure 6.2 shows the x position difference (dx) between the hit of the strip sensor and the hit of the telescope sensor versus event number. The fact that the change in dx is small and similar for each event proves that the events are synchronous. In case the events were not synchronous, one would see a scattered dx . The offset in dx comes from the mis-alignment.

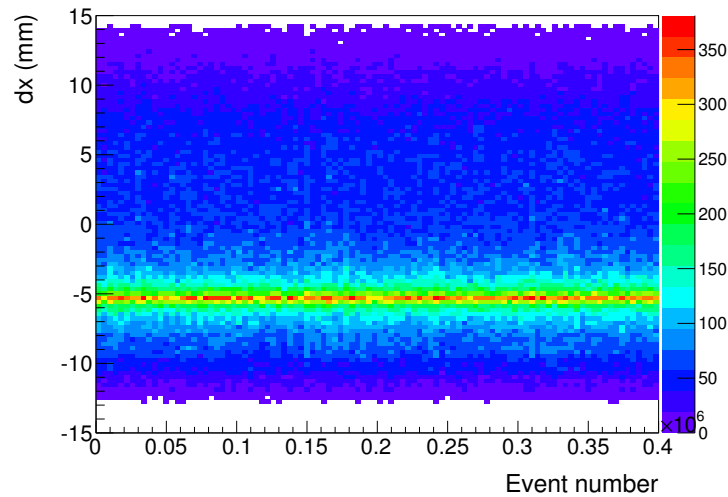


Figure 6.2: Synchronization of detector events.

6.3 Alignment and Track fitting

Once the events are synchronized and hits from all sensors are obtained, track candidates are found and then the detectors are aligned and track fitting is performed. The General Broken Lines (GBL) [64, 66, 67] algorithm is used to determine the tracks. The GBL is a track model where a proper description of the multiple scattering in the detector material is implemented in track fitting algorithm. This model enables a fast track based alignment. Once the track candidates are found, the track-based alignment is performed by Millepede-II.

For this analysis, a new software is developed which brings together the GBL algorithm with LCIO format [68]. This software is written in the python programming language, and can be

found in the EUTelescope framework. This software will be called "gblpython" in the rest of this document.

Track finding procedure

The alignment process starts with transforming the local hit coordinates to global coordinates. For this a geometry file, also called GEAR file, with estimated detector positions (x , y and z) in global coordinates is supplied to the gblpython. Using this geometry file, hit positions are transformed to the estimated global coordinates. Then track candidates are searched in the events that have at least one hit on each telescope layer.

In order to illustrate this procedure, a schematic of detector layout is shown in Figure 6.3, where sensors with sensor IDs 0, 1, 2, 3, 4 and 5 are the sensors of telescope ordered from upstream to downstream, and sensors with ID 6 and 7 are the strip sensors, which have strips along the y axis. The full schematic of the test beam layout is shown in Figure 4.1.

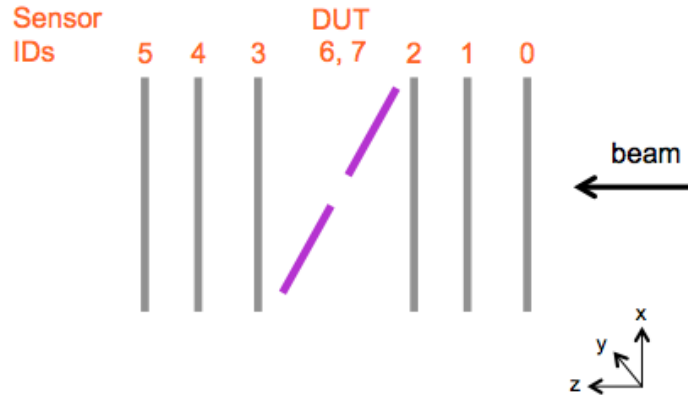


Figure 6.3: Schematic of detector layout (not to scale).

The data used for in this section to illustrate the procedure is taken at 4.4 GeV and 1 T magnetic field, and as DUT two non-irradiated strip sensors are used. The strip sensors are tilted approximately by 10° .

Doublet search

The track search algorithm starts forming so called "doublets" by pairing the hits of sensors (0 and 2) and (3 and 5) of the telescope layers. In this step, hits that are close to each other in x and y positions are paired by applying a cut on the position difference (dx and dy). Figure 6.4 shows the doublet dx and dy distribution within the cut range. Since the Lorentz force due to the magnetic field is along the x -direction, an asymmetric distribution of dx is observed in Figure 6.4a, as expected.

Triplet search

The second step in the track search is to pair hits from layers 1 and 4 with the doublets of (0 and 2) and (3 and 5), respectively and form so called "triplets". A curve passing through each doublet is estimated by taking into account the magnetic field, nominal beam energy and position of hits in the doublet. Then a cut on the distance of the third hit to the doublet curve is calculated and a cut on this distance is applied. Figure 6.5 shows the distance in x and y (dx , dy) distribution within the cut range. The asymmetric distribution of dx seen in Figure 6.5a is due to using the nominal beam energy. The real beam energy is reduced due to bremsstrahlung or energy loss while passing through the material, and therefore, the curvature increases. The underestimation of curvature causes the asymmetric distribution of dx .

Triplet match

In the third step, the curves formed by the triplets from each arm of the telescope are extrapolated to the middle of two arms of telescope layers in z . Figure 6.6 illustrates this step. Cuts are applied to the slope and position difference of the triplet curves on the intersection point, to form tracks using the matched triplets. Figure 6.7 and 6.8 shows the slope and position difference distribution within the cut range. In order to avoid fake tracks, triplets that match with only one triplet on the other arm of the telescope are accepted.

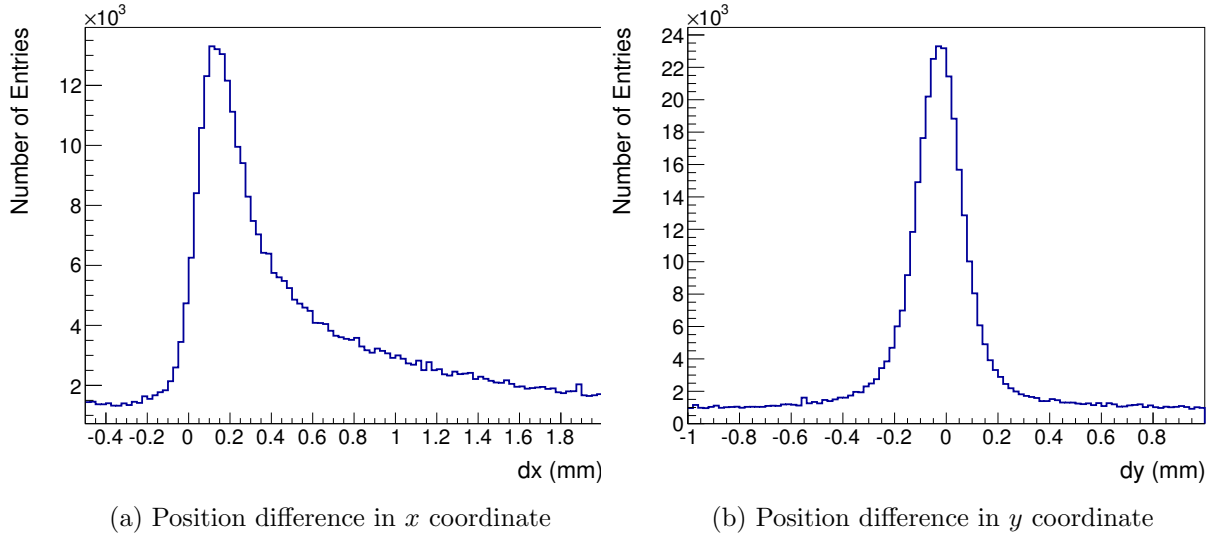


Figure 6.4: Doublet position difference for x and y coordinates.

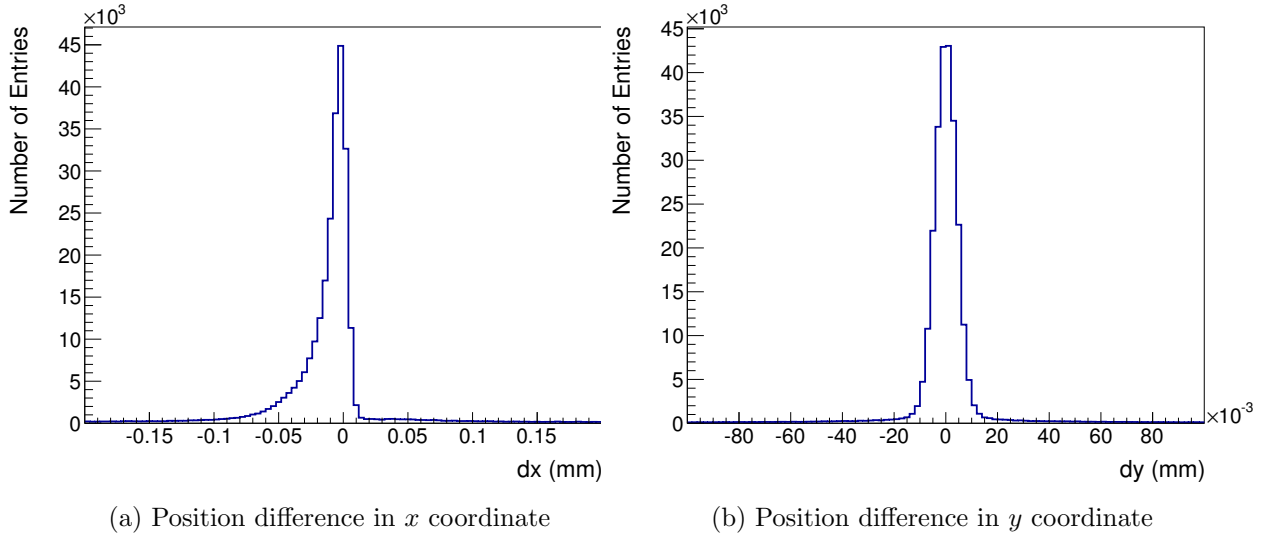


Figure 6.5: Triplet position difference for x and y coordinates.

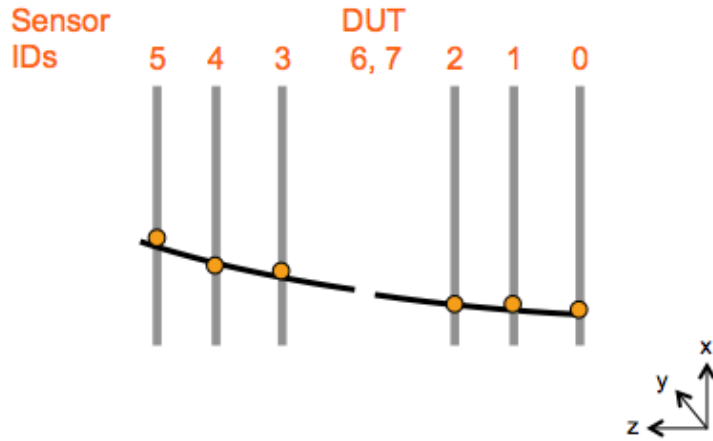


Figure 6.6: Schematic of extrapolation of triplet curves (not to scale).

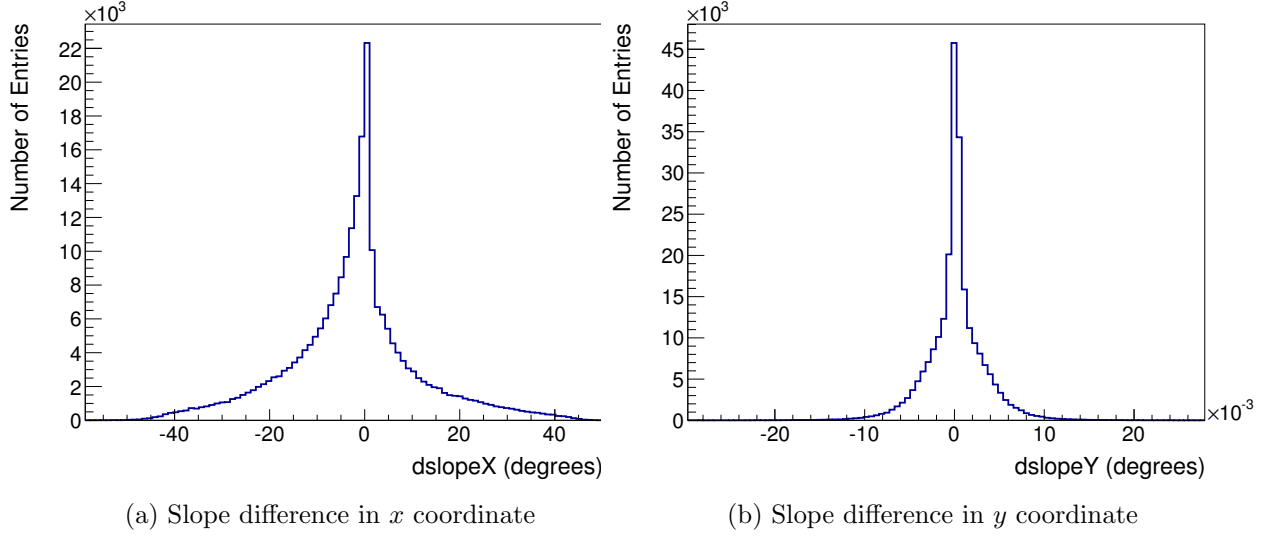


Figure 6.7: Slope difference of triplet curves.

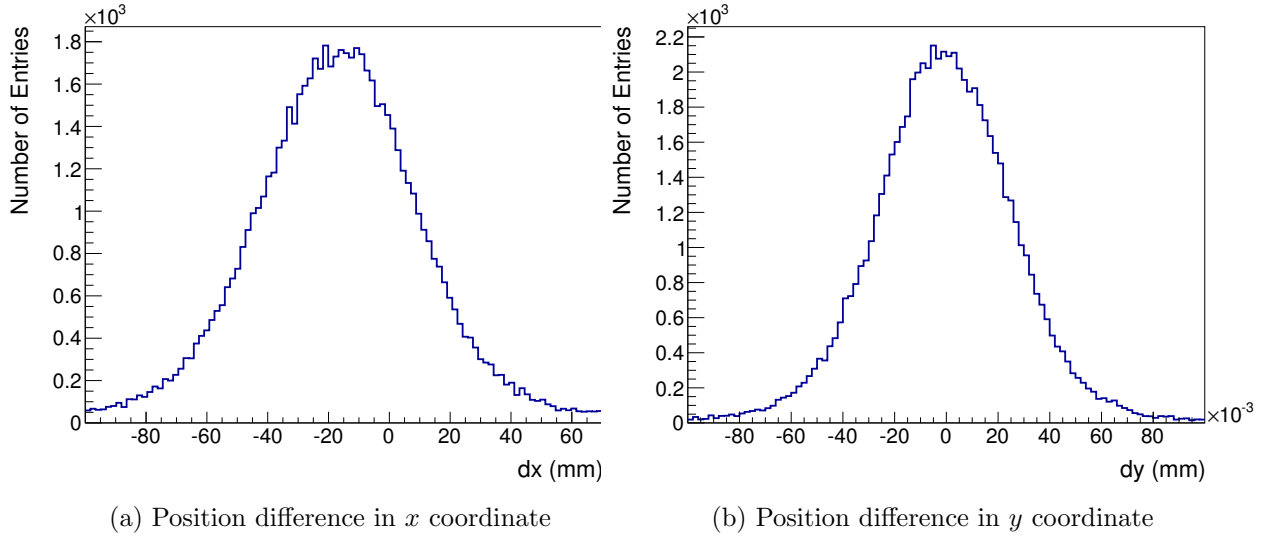


Figure 6.8: Position difference of triplet curves.

DUT hit match

Finally, the track candidates found using the telescope are matched with DUT hits. As illustrated in Figure 6.9, intersection point of the track with the DUT layer is calculated. A cut on the distance of the measured hit and the estimated hit position (dx) is applied for each sensor separately. Since the strips of the DUT are along the y -axis, no cut is applied on dy . Figure 6.10 shows the dx distribution of DUT sensors 6 and 7 within the cut range. Tracks that do not match with any DUT hits are ignored.

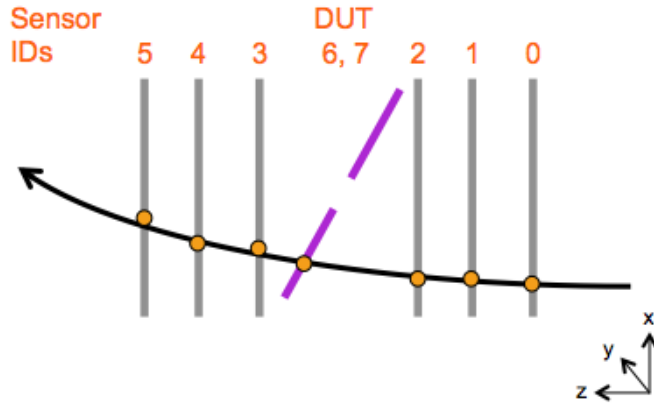


Figure 6.9: Schematic of matching DUT hits with track candidates (not to scale).

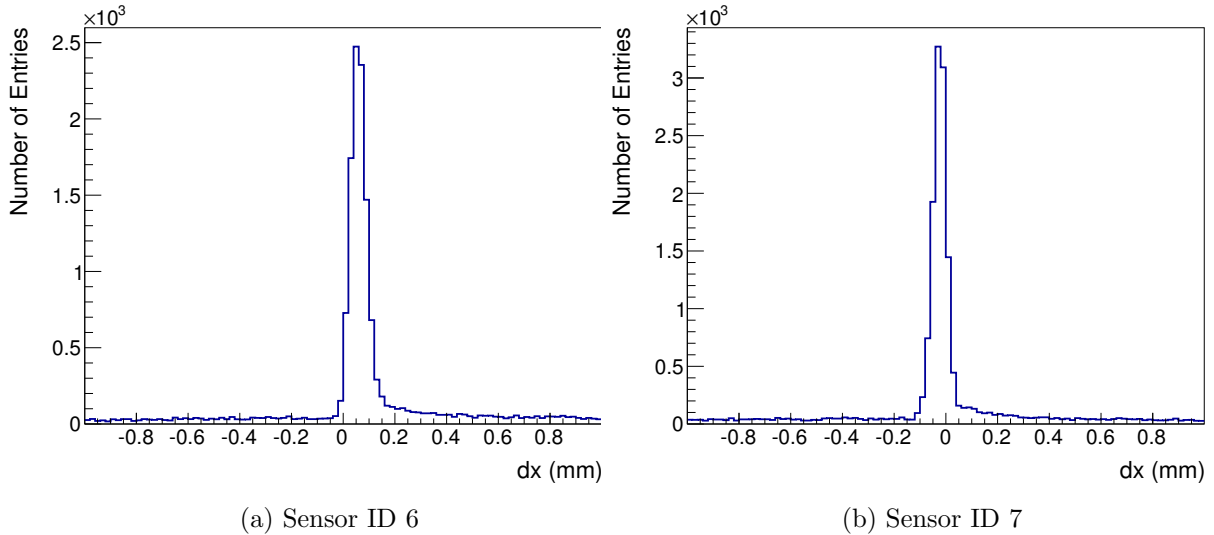


Figure 6.10: Position difference of estimated and measured hit positions on DUT layers.

Alignment procedure

The track-based alignment is a least squares minimization problem (χ^2 minimization) which can be formulated as [66].

$$\chi^2(p, q) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} r_{ij}^T(p, q_j) V_{ij}^{-1} r_{ij}(p, q_j) \quad (6.1)$$

where r_{ij} is the difference between the expected and measured hit position for a given hit i on a given track j . V_{ij} is the covariance matrix of each measurement. The χ^2 is minimized by Millepede-II [65, 69] with respect to the alignment parameters p and the track parameters q of all tracks. The Millepede-II algorithm fits a large number of tracks simultaneously and determine the alignment corrections Δp to the detector positions and orientations. According to the alignment corrections obtained by Millepede-II, the initial geometry file used to determine track candidates is corrected and saved to be used by further analysis.

In order to obtain a precise alignment of the detector positions and orientations, an iterative alignment is performed until the alignment errors are larger than the alignment corrections. In this analysis, first the telescope layers are aligned with respect to a global coordinate, which is defined by the first layer (sensor ID 0) of the telescope. In order to obtain a large number of tracks, all data taken with the same telescope geometry are the combined and DUT matching step is skipped. Then using the precisely aligned telescope geometry, the DUT layers are aligned with respect to the global coordinate of the telescope, while the positions of the telescope layers are fixed.

The cut values used for the track finding procedure for the data taken with and without the presence of magnetic field are listed in Table 6.1. As an example using data taken in the presence of magnetic field, the distributions of the parameters, which are used to form tracks, after the final iteration of alignment are shown in Figures 6.11, 6.12, 6.13, 6.14 and 6.15.

The track reconstruction procedure, described in this chapter, is applied separately to each data run that is taken in different setting (tilt angle and/or magnetic field). The reconstructed and the aligned tracks are used for the charge collection and Lorentz angle measurements (Chapter 7).

Final track selection cuts		
parameter	Magnetic Field (B)	
	$B = 0$	$B \neq 0$
Doublet search	$-1.00 \text{ mm} < dx < 1.00 \text{ mm}$ $-1.00 \text{ mm} < dy < 1.00 \text{ mm}$	$-0.50 \text{ mm} < dx < 2.00 \text{ mm}$ $-0.40 \text{ mm} < dy < 0.40 \text{ mm}$
Triplet search	$-0.02 \text{ mm} < dx < 0.02 \text{ mm}$ $-0.02 \text{ mm} < dy < 0.02 \text{ mm}$	$-0.10 \text{ mm} < dx < 0.05 \text{ mm}$ $-0.01 \text{ mm} < dy < 0.01 \text{ mm}$
Triplet match	$-0.02 \text{ mm} < dx < 0.02 \text{ mm}$ $-0.02 \text{ mm} < dy < 0.02 \text{ mm}$ $-0.10 \text{ rad} < dslope_x < 0.10 \text{ rad}$ $-0.10 \text{ rad} < dslope_y < 0.10 \text{ rad}$	$-0.06 \text{ mm} < dx < 0.05 \text{ mm}$ $-0.06 \text{ mm} < dy < 0.06 \text{ mm}$ $-0.08 \text{ rad} < dslope_x < 0.04 \text{ rad}$ $-0.10 \text{ rad} < dslope_y < 0.10 \text{ rad}$
DUT match	$-0.15 \text{ mm} < dx < 0.15 \text{ mm}$ $-10.0 \text{ mm} < dy < 10.0 \text{ mm}$	$-0.40 \text{ mm} < dx < 0.40 \text{ mm}$ $-10.0 \text{ mm} < dy < 10.0 \text{ mm}$

Table 6.1: Final track selection cuts.

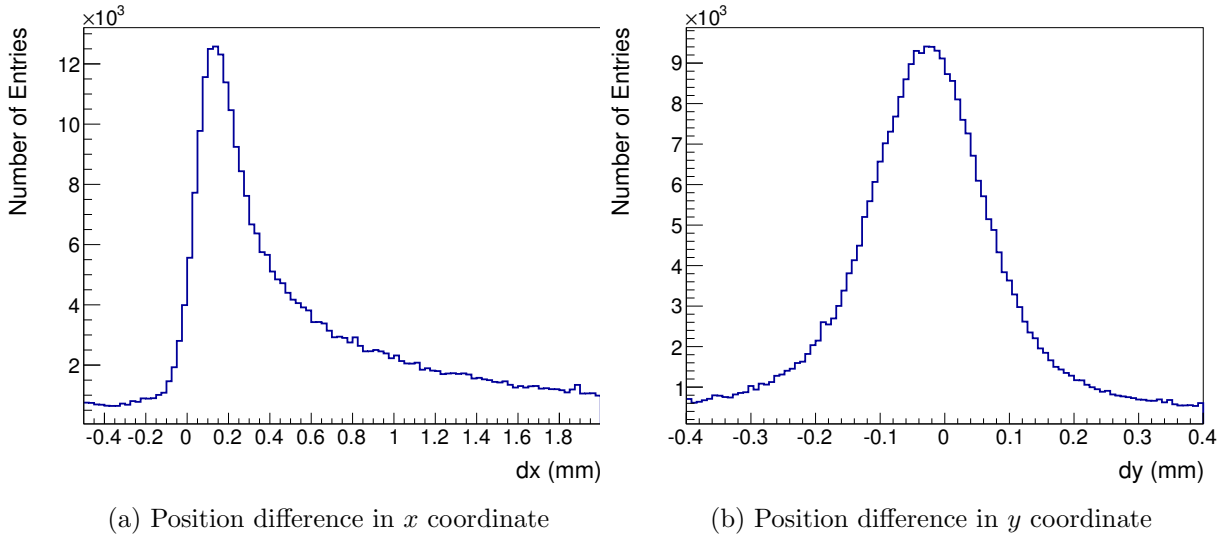


Figure 6.11: Doublet position difference of selected tracks.

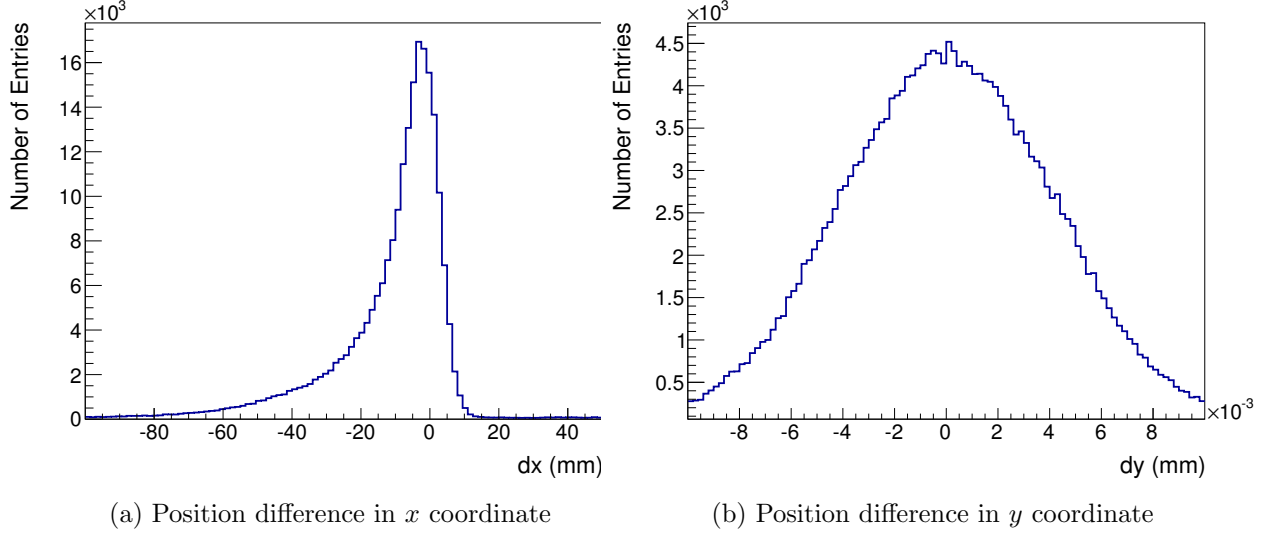


Figure 6.12: Triplet position difference of selected tracks.

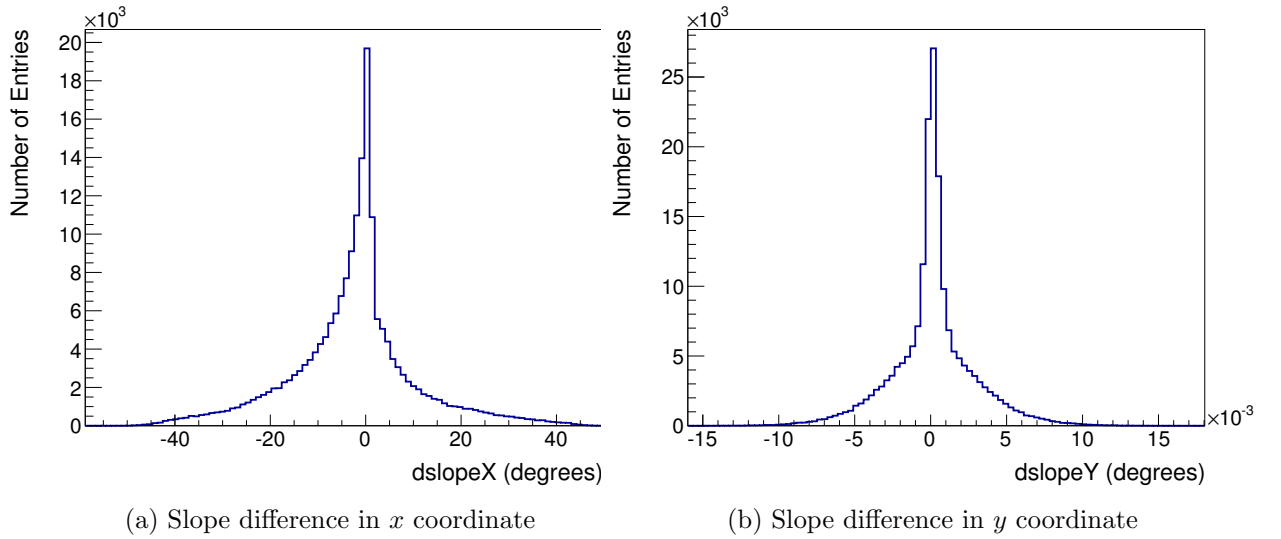


Figure 6.13: Slope difference of triplet curves of selected tracks.

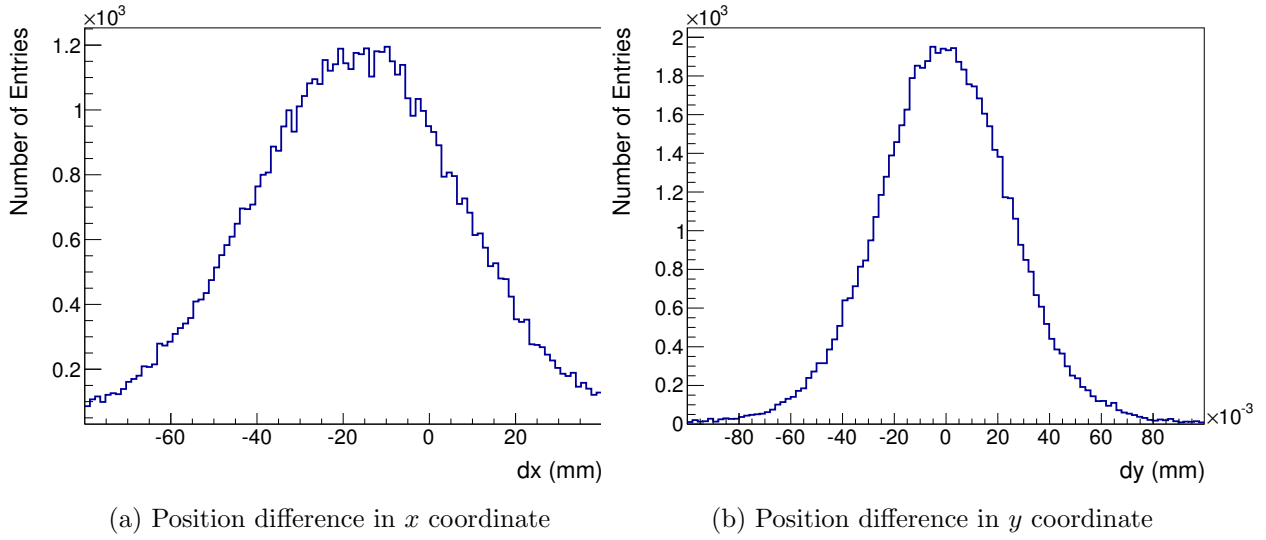


Figure 6.14: Position difference of triplet curves of selected tracks.

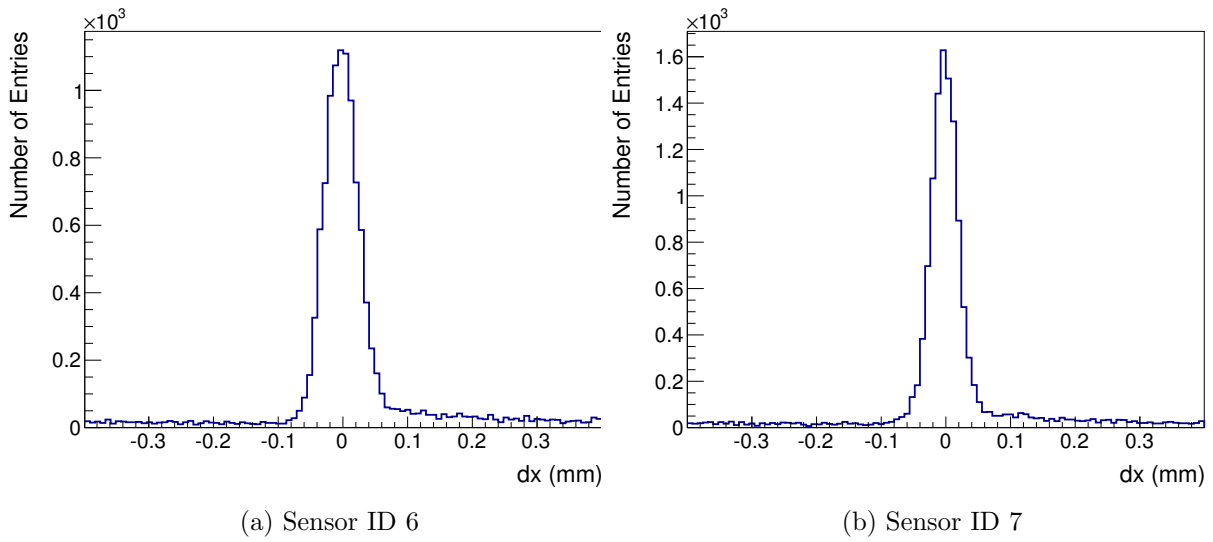


Figure 6.15: Position difference of estimated and measured hit positions on DUT layers of selected tracks.

Chapter 7

Measurements and Results

This chapter begins with introducing the sensors that are used in this study and continues with showing the results of the collected charge and the Lorentz angle measurements. In this chapter, the irradiation unit $1\text{MeV } n_{\text{eq}}/\text{cm}^2$ will be denoted shortly as n_{eq} .

7.1 Silicon Micro-Strip Sensors for the HL-LHC ATLAS Strip Detector

Multiple samples of ATLAS12 miniature sensors (see Section 2.4) are used for this study. Two non-irradiated sensors are used to confirm the results among each other. There are six neutron irradiated samples with different fluences between $1.2 \times 10^{14} n_{\text{eq}}$ and $5 \times 10^{15} n_{\text{eq}}$. Most of these samples are also measured after annealing at 60°C for 80 min. Measurements are performed at the DESY II test beam with a 4.4 GeV electron beam and the setup introduced in Chapter 4. During the measurements, all sensors are kept at -25°C in order to avoid high leakage current and uncontrolled annealing.

For all samples, the collected charge is measured at zero magnetic field and setting the tilt angle to zero. Non-irradiated samples are measured at bias voltages from -50 V to -600 V varying in steps of 50 V and irradiated samples from -100 V to -1000 V in steps of 100 V . Details of the collected charge measurement and its results are discussed in Section 7.2.

The Lorentz angle measurement is performed at various conditions. It is performed on all samples at -500 V bias voltage at different magnetic fields to be able to extrapolate the results to 2 T. For the $1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$ samples, the measurements are also done with different bias voltages at 1 T magnetic field to study the Lorentz angle dependence on the bias voltage. Full list of measured samples and measurement conditions are shown in Table 7.1, where the samples with ‘ * ’ are also measured at the same conditions after annealing.

		Magnetic Field (T)				
		0.00	0.25	0.50	0.75	1.00
Bias Voltage (V)	-300					1.2×10^{14} 2.0×10^{14}
	-500	non-irrad. $1.2 \times 10^{14} *$ $2.0 \times 10^{14} *$ $5.0 \times 10^{14} *$ $1.0 \times 10^{15} *$ 2.0×10^{15} 5.0×10^{15}		non-irrad. $1.2 \times 10^{14} *$ $2.0 \times 10^{14} *$ $5.0 \times 10^{14} *$ $1.0 \times 10^{15} *$ 2.0×10^{15} 5.0×10^{15}	non-irrad. $1.2 \times 10^{14} *$ $2.0 \times 10^{14} *$ $5.0 \times 10^{14} *$ $1.0 \times 10^{15} *$ 2.0×10^{15} 5.0×10^{15}	non-irrad. $1.2 \times 10^{14} *$ $2.0 \times 10^{14} *$ $5.0 \times 10^{14} *$ $1.0 \times 10^{15} *$ 2.0×10^{15} 5.0×10^{15}
	-700					1.2×10^{14} 2.0×10^{14}
	-1000					1.2×10^{14} 2.0×10^{14}

Table 7.1: List of the Lorentz angle measurements. The samples marked with ‘ $*$ ’ are also measured after annealing at 60°C for 80 minutes.

7.2 Collected Charge Measurement

Measuring the collected charge on irradiated sensors is crucial to determine the life time of the detector, operation conditions and the response of the sensor. Especially in the harsh operation conditions like at HL-LHC where the integrated irradiation levels (fluence) increase extremely over the life time of the inner detector, it is crucial to determine the behavior of the sensors during the life time of the detector. The charge that can be collected from the sensors decrease with increasing fluence, this might lead to not being able to detect hits. Therefore, to increase the signal on the sensor, the operation voltage has to be increased and/or the threshold should be lowered. The collected charge on irradiated samples is measured with different bias voltages to investigate the collected charge dependence on the bias voltage and the fluence of the sensor.

Using the setup introduced in Chapter 4, data are taken with different bias voltages at zero magnetic field and approximately zero tilt angle. During the measurements, all sensors are kept at about -25°C in order to avoid high leakage current and uncontrolled annealing. The data are analyzed using the analysis procedure described in Chapters 5 and 6. The results are shown in Figure 7.1.

As expected, the collected charge decreases with irradiation level and short term annealing increases the collected charge. As seen in Figure 7.1, at low fluences such as $1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$, all deposited charge can be collected by increasing the reverse bias voltage. However, at higher fluences most of the deposited charge cannot be collected even increasing

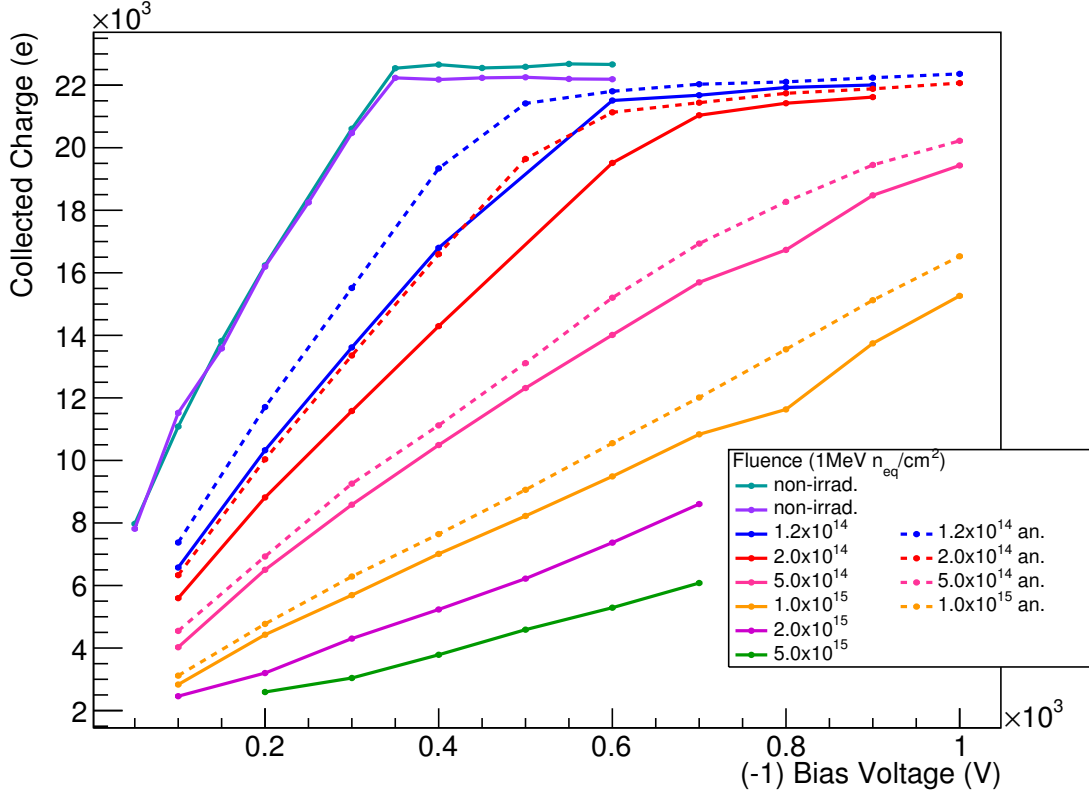


Figure 7.1: Collected charge on ATLAS12 sensors as a function of the bias voltage.

the reverse bias voltage up to 1 kV. The sample irradiated to $2.0 \times 10^{15} n_{eq}$ went to breakdown at reverse bias voltages higher than 700 V, since the $2.0 \times 10^{15} n_{eq}$ and $5.0 \times 10^{15} n_{eq}$ samples were on the same board (see Section 4.6) reliable measurements could not be done for these two sensors at higher reverse bias voltages. Since the collected charge on the $5.0 \times 10^{15} n_{eq}$ sample is too low at 100 V reverse bias voltage, it cannot be distinguished from the noise, and therefore could not be measured.

The collected charge on the test sensors are usually measured using a radioactive source in a laboratory. In this study, the current test sensors of the ITK are measured for the first time at the test beam. Therefore, in order to compare the beam measurements with the radioactive source measurements, the collected charge on some of the samples are also measured in the laboratory setup (see Section 5.8) using a Strontium-90 (Sr^{90}) radioactive source. The comparison, shown in Figure 7.2, shows that the results of the measurements with Sr^{90} are consistent with the electron beam measurements. The deviation of the Sr^{90} measurements from the electron beam measurements is less than 16%. The difference comes from the noise "hits", since the measurements with Sr^{90} have no noise suppression, the noise hits which have lower signal reduce the average collected charge. However, this comparison shows that collected charge measurements using Sr^{90} radioactive source gives very close results to the electron beam measurements. On

the samples $2.0 \times 10^{15} n_{\text{eq}}$ and $5.0 \times 10^{15} n_{\text{eq}}$ the collected charge could not be measured at reverse bias voltages lower than 300 V and 400 V, respectively, since the signal could not be distinguished from noise. However, it is possible to measure it at beam measurements due to noise suppression using tracking. These results are published in Reference [70].

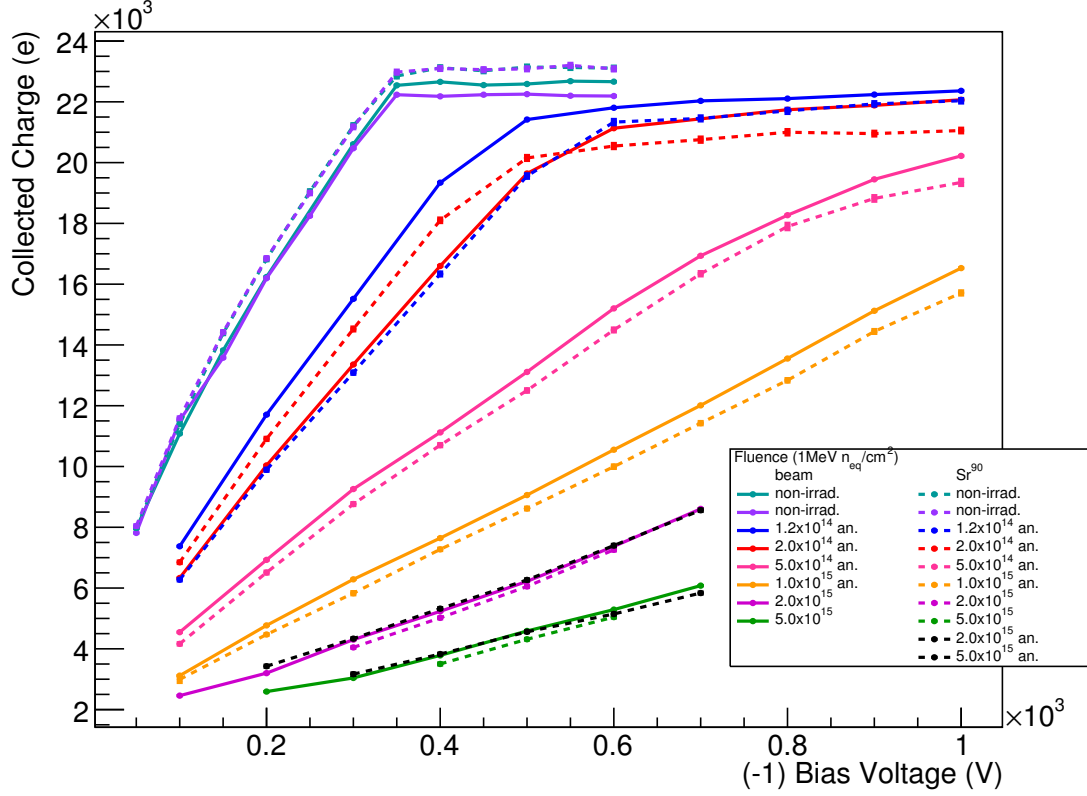


Figure 7.2: Collected charge comparison of beam and Sr^{90} measurements as a function of the bias voltage.

7.3 Lorentz Angle Measurement

The measurement of the Lorentz angle is important to achieve a precise measurement of the position of a charged particle passing through the sensor, which allows to measure its trajectory as well as the interaction point of the protons in the LHC precisely. The measurement of the Lorentz angle provides important information to estimate the detector performance, hence it is important to have knowledge of the expected Lorentz angle on the detector and its behavior after irradiation.

The measurement procedure is based on the knowledge that the number of strips in a cluster (cluster size) depends on the incidence angle of the track on the sensor and the Lorentz angle.

In the case of the incidence angle of the track being equal to the Lorentz angle, the electrons drift along the Lorentz angle direction, which is illustrated in Figure 7.3, hence, the minimum cluster size is measured. In this study, the Lorentz angle is measured by searching the minimum cluster size and its corresponding incidence angle. In order to search for the minimum cluster size, data is taken at different tilt angles between -20 and +20 degrees for each Lorentz angle measurement.

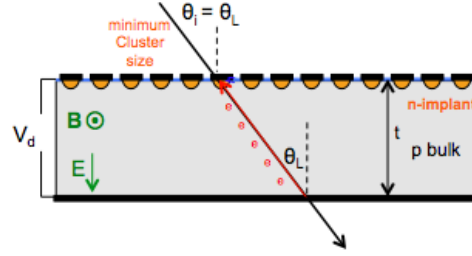


Figure 7.3: Drift of charge carriers when the incidence angle of the track is equal to the Lorentz angle.

Measurement Method

The analysis of the data is performed as described in Chapters 5 and 6. Once the data are analyzed and the tracks are obtained from each data set of a Lorentz angle measurement at a given bias voltage and magnetic field setting, the profile of the cluster size as a function of the incidence angle on the strip sensor is obtained. The profile is fitted, and the parameter θ_L , which corresponds to the Lorentz angle, is extracted from the fit function given by

$$f(\theta) = (a \cdot |\tan(\theta) - \tan(\theta_L)| + b) \otimes \text{Gaussian}(\theta) \quad (7.1)$$

$$= \int_{-\infty}^{\infty} (a \cdot |\tan(\theta') - \tan(\theta_L)| + b) \cdot \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\theta' - \theta)^2}{2\sigma^2}\right) d\theta',$$

where $\otimes$ indicates the convolution operator. The values of a and b , the standard deviation of the Gaussian, and the Lorentz angle value θ_L are the free parameters of the fit. The term $a \cdot |\tan(\theta) - \tan(\theta_L)| + b$ represents the geometrical projection of the charge carriers on the sensor surface. The parameter a varies with how rapidly the cluster size increases with the incident angle [71].

The statistical error on the Lorentz angle comes from the error of the profile fit (Equation 7.1). The major systematic error on the Lorentz angle measurement is the error on the alignment of sensors with respect to the telescope. There are multiple data runs, which differ in tilt angle, taken at specific magnetic field that contribute to the Lorentz angle measurement. Each data

run, taken under a specific conditions, is aligned separately. Therefore a weighted average of the alignment errors of each data run is calculated using Equation 7.2 and used as the systematic error on the corresponding Lorentz angle measurement. Although the track fitting of the particle would also bring a systematic error, it should be much smaller than the alignment error, therefore it is neglected in this study.

The systematic uncertainty is estimated as

$$\sigma_{LA}^2 = \sum_{i=1}^n w_i^2 \sigma_i^2, \quad (7.2)$$

where n is the number of data runs that contribute to the specific Lorentz angle measurement, w_i is the ratio of the number of tracks in the i^{th} data run to the number of tracks in the Lorentz angle measurement and σ_i it the alignment error of the i^{th} data run.

Lorentz Angle on Non-irradiated Samples

The results for the non-irradiated samples are shown in Figure 7.4. The errors plotted on the cluster size are the statistical uncertainties. For the Lorentz angle the statistical errors come from the fit is written on the plot. The measured values including the systematic error on the Lorentz angle on non-irradiated sensors are listed in Table 7.2.

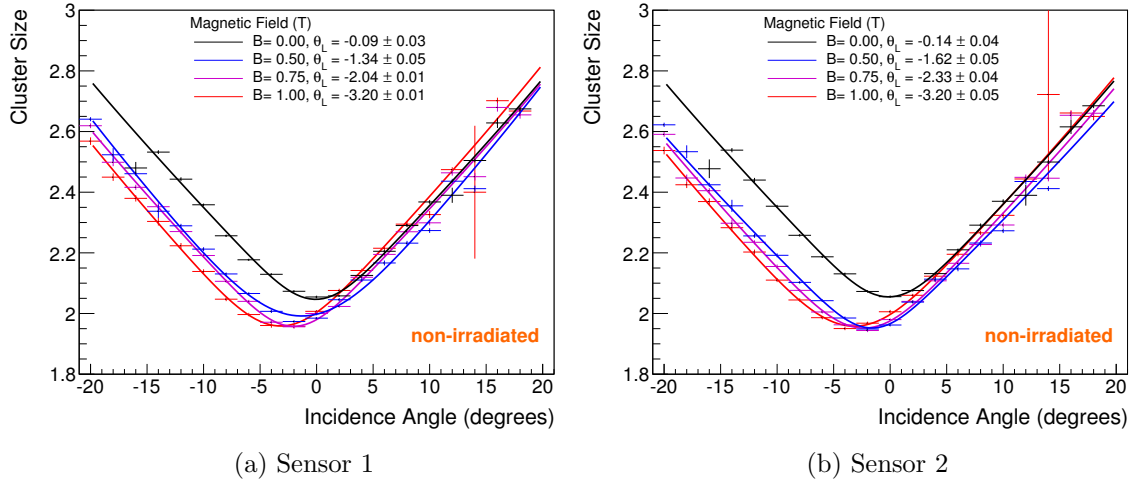


Figure 7.4: Lorentz angle measurement on non-irradiated sensors. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

The measured Lorentz angle at 1 T on two non-irradiated sensors agree with each other and also with the calculated value using the BFK model, which predict the Lorentz angle to be 3.18 degrees, as described in Section 2.5. The measured Lorentz angles at 0.5 T and 0.75 T are slightly

Sensor	B-field (T)	Lorentz angle (°)
Sensor 1	0.00	$-0.09 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$
	0.50	$-1.34 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$
	0.75	$-2.04 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$
	1.00	$-3.20 \pm 0.01(\text{stat}) \pm 0.14(\text{syst})$
Sensor 2	0.00	$-0.14 \pm 0.04(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.62 \pm 0.05(\text{stat}) \pm 0.05(\text{syst})$
	0.75	$-2.33 \pm 0.04(\text{stat}) \pm 0.06(\text{syst})$
	1.00	$-3.20 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$

Table 7.2: Lorentz angle measurement on non-irradiated sensors.

different on the sensors. This might be due to an additional error on the alignment, for example not accurate initial value of the tilt angle given to the alignment procedure might cause an error on the alignment of the sensor. Further studies are needed to have a better understanding of the reason for this difference. In order to estimate the expected Lorentz angle on the future ATLAS Inner Tracker where the magnetic field is 2 T the measurement results are extrapolated using a linear fit. In Figure 7.5, the red line shows the linear fit, the fit parameters and the estimated Lorentz angle values at 2 T are written on the plot. The BFK model predicts the Lorentz angle at 2 T to be 6.34° . The extrapolated results are close to the predictions of the model, the small difference may come from the error caused by extrapolation.

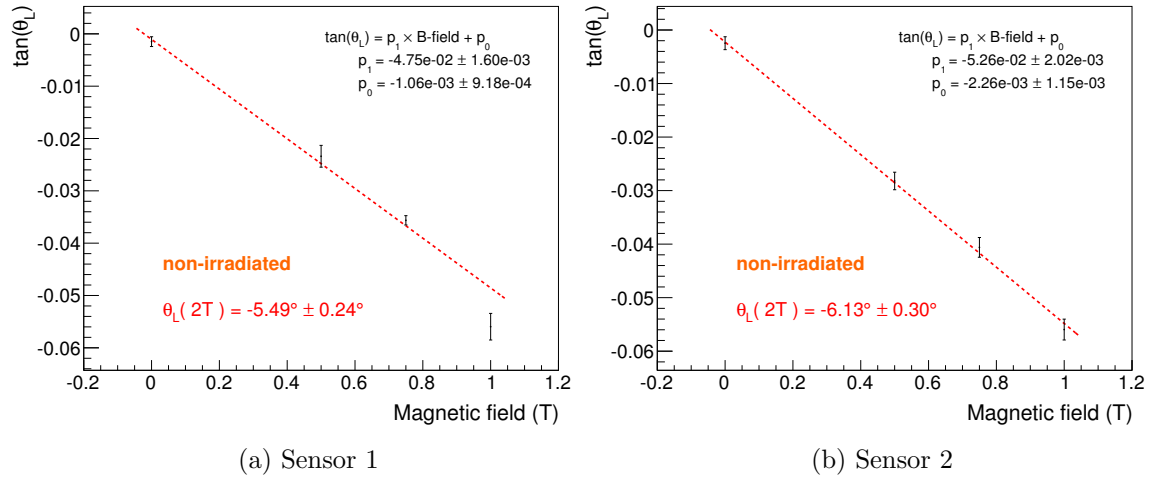


Figure 7.5: Extrapolation of the Lorentz angle to 2 T for non-irradiated sensors. The uncertainty is calculated from the uncertainty of the fit parameters.

It is observed that the minimum cluster size measured in the presence of magnetic field is lower than the one measured without magnetic field. This can be explained with the charge spread due to the Lorentz force. In the presence of the magnetic field the amount of charge carriers, created by a charged particle passing through the sensor, will slightly increase due to longer path inside the sensor. At 1 T magnetic field, the increase in the path length would be $\sim 4 \mu\text{m}$ in a $\sim 300 \mu\text{m}$ thick silicon sensor, this would correspond to a charge increase of $\sim 200 e^-$ which is smaller than the noise of the readout channels in our sensors. Therefore the change in the collected charge would not be detectable and the collected charge can be assumed to be same as the case where there is no magnetic field. However, due to the Lorentz force inside the sensor, the charge will spread into a larger area causing a collected charge shape of a gaussian with a long tail with a very low signal on some strips. Since the low signal will not pass the neighbor cut this would decrease the cluster size. The effect of the tail vanishes once the signal-to-noise ratio cuts are increased as can be seen in Section 7.4 where the foreseen ITK thresholds are used to form clusters. Hence, in order to have a better understanding of this behavior, one can study the charge spread in the presence of the magnetic field and adjust the signal-to-noise ratio requirements for the clusters.

Lorentz Angle on Irradiated Samples

The Lorentz angle measurement results for irradiated samples are shown in Figures 7.7 to 7.15 where on the left plots show the dependence of the cluster size on the incidence angle and the distributions are fitted by Equation 7.1, the measured Lorentz angle (LA) values are shown on the plot with only statistical error. On the right plots, the dependence of the tangent of the Lorentz angle (θ_L) on the magnetic field are shown. The Lorentz angle errors in these plots include both statistical and systematic errors. The distributions are fitted by a linear function (shown in red) to estimate the Lorentz angle at the magnetic field of 2 T. The estimated Lorentz angle (given in degrees) as well as the fit parameters are shown on the plots. The uncertainty is calculated from the uncertainty of the fit parameters. Table 7.3 shows the Lorentz angle values with the statistical and systematic errors for all measured samples.

For some of the measurements at $B = 0 \text{ T}$, the fitted value of the Lorentz angle (θ_{L0}) is non-zero although there is no magnetic field. The θ_{L0} values are shown in Figure 7.6. The θ_{L0} values of the non-irradiated sensors, the $5.0 \times 10^{14} n_{\text{eq}}$ and $1.0 \times 10^{15} n_{\text{eq}}$ irradiated samples are close to zero. However, for the $1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$ irradiated samples the θ_{L0} values are different than zero. The data runs that contribute to these measurements are checked in detail; the signal, cluster size and η -distributions are as expected. The alignments of these data runs are also checked and no abnormality is found. Since here is no visible pattern of θ_{L0} values seen through the samples and since the data taken for the Lorentz angle measurements at different magnetic fields are independent of each other, these values are not considered as a systematic error. Since the Lorentz angle at zero magnetic field has to be zero, further studies are needed to understand these results.

As can be seen on Figure 7.15, the Lorentz effect on the $2.0 \times 10^{15} n_{\text{eq}}$ and $5.0 \times 10^{15} n_{\text{eq}}$ samples is not visible due to reduced collected charge, which is mostly measured on a single

readout channel. Hence, the Lorentz angle on those samples could not be measured. It might be possible to measure it by increasing the collected charge on the samples by increasing the depletion region using higher reverse bias voltages. However, since the planned reverse bias voltage is around 500 V during the ITK operation, it can be concluded that the Lorentz force will not influence the hit position on the sensors when the irradiation level reach about $2.0 \times 10^{15} n_{eq}$.

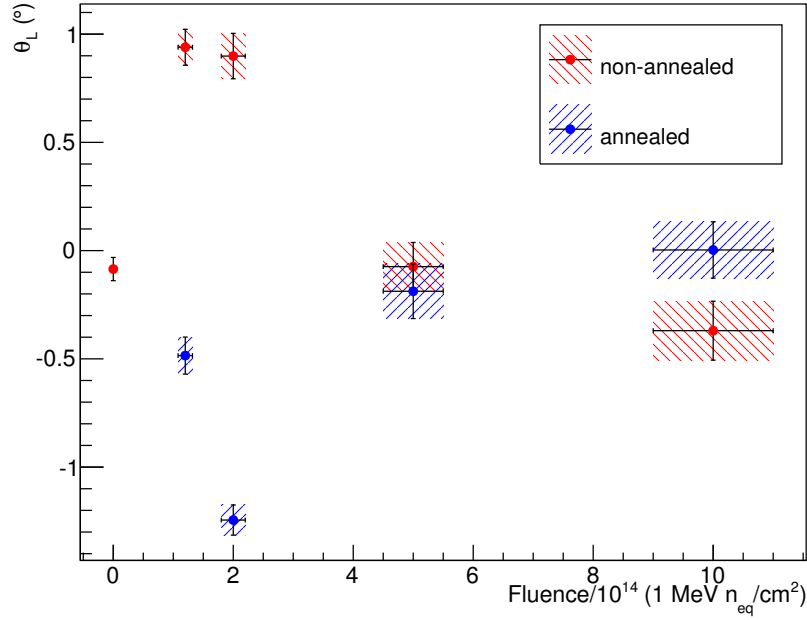


Figure 7.6: Lorentz angle fit results at zero magnetic field. Bias voltage set to -500 V .

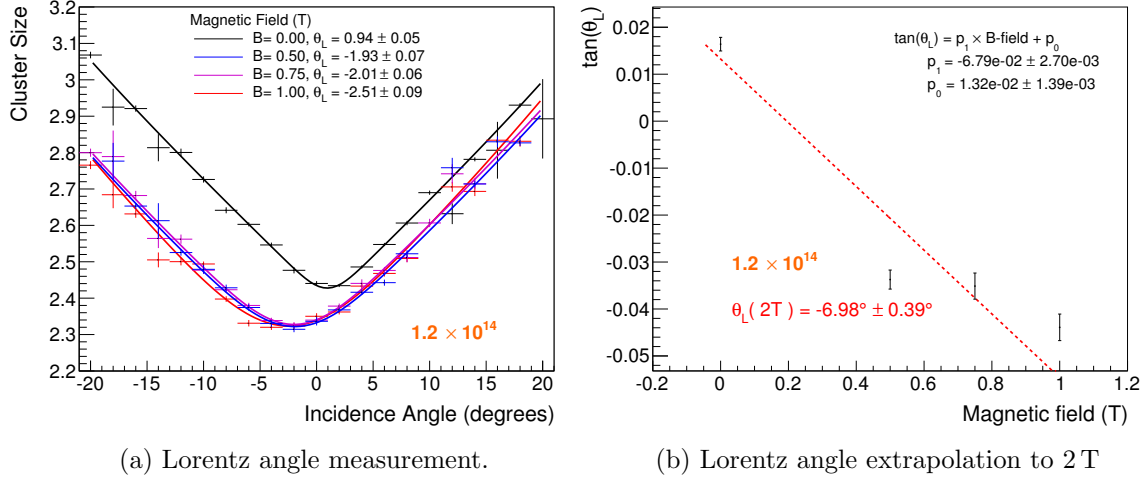


Figure 7.7: Lorentz angle measurement and its extrapolation to 2 T on the $1.2 \times 10^{14} n_{\text{eq}}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

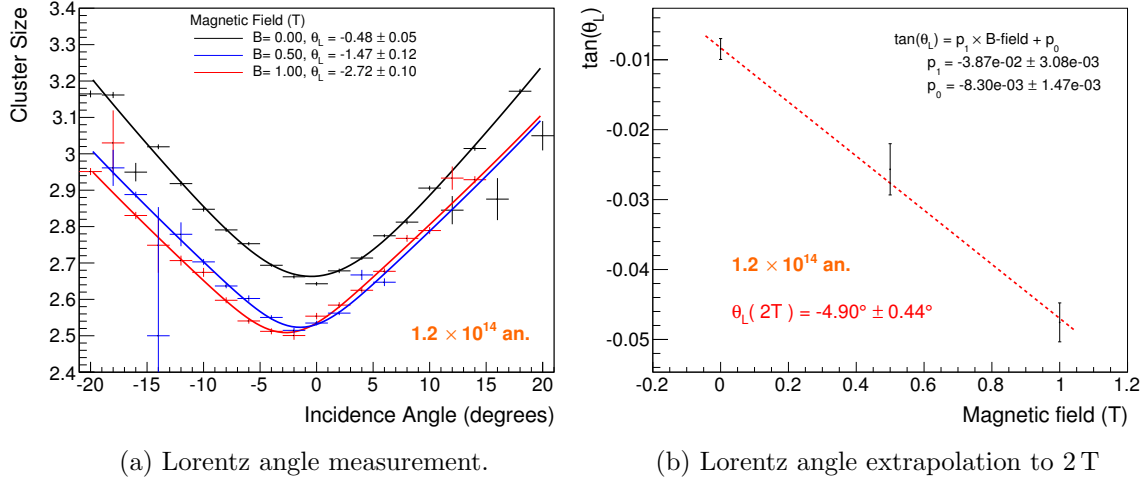


Figure 7.8: Lorentz angle measurement and its extrapolation to 2 T on the annealed $1.2 \times 10^{14} n_{\text{eq}}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

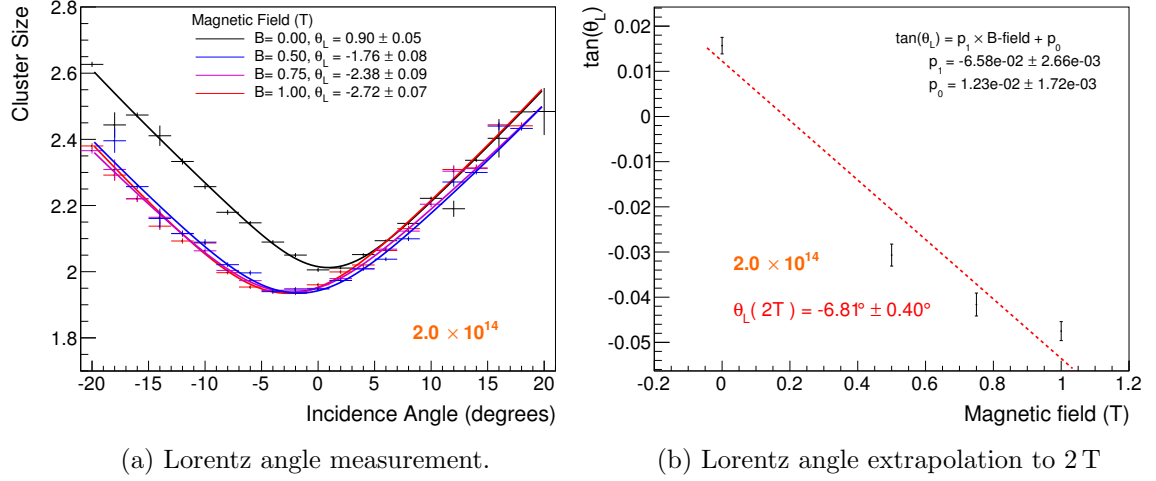


Figure 7.9: Lorentz angle measurement and its extrapolation to 2 T on the $2.0 \times 10^{14} n_{eq}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

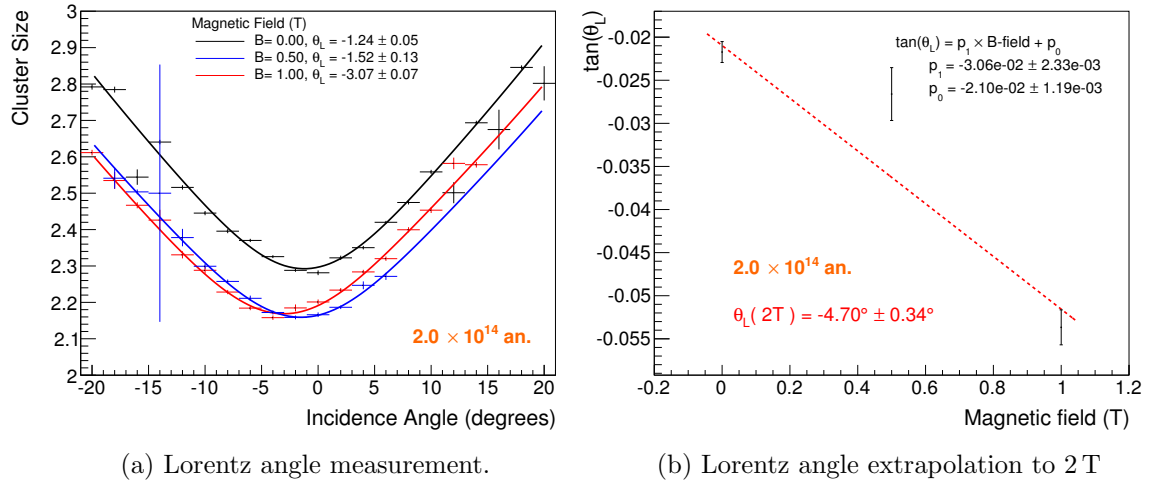


Figure 7.10: Lorentz angle measurement and its extrapolation to 2 T on the annealed $2.0 \times 10^{14} n_{eq}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

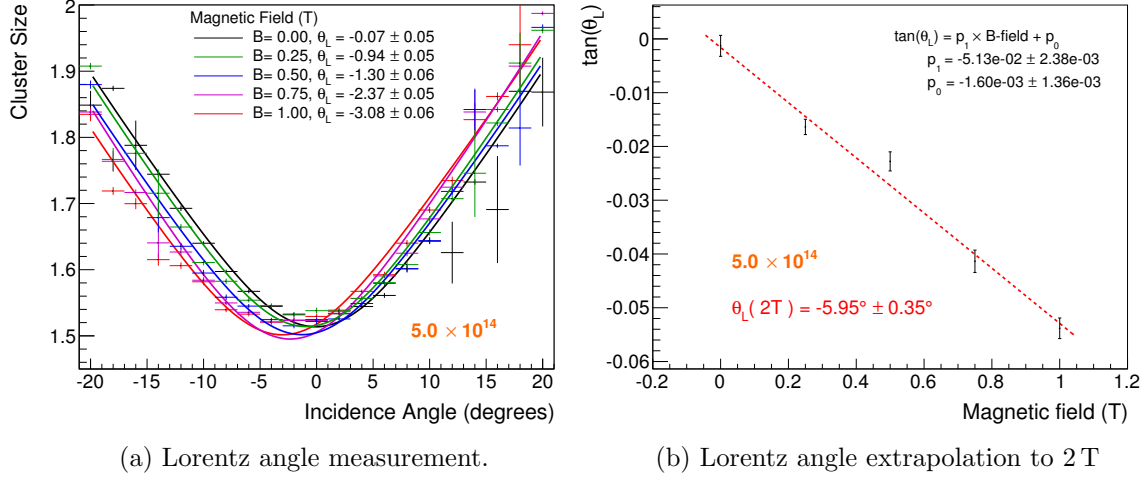


Figure 7.11: Lorentz angle measurement and its extrapolation to 2 T on the $5.0 \times 10^{14} n_{\text{eq}}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

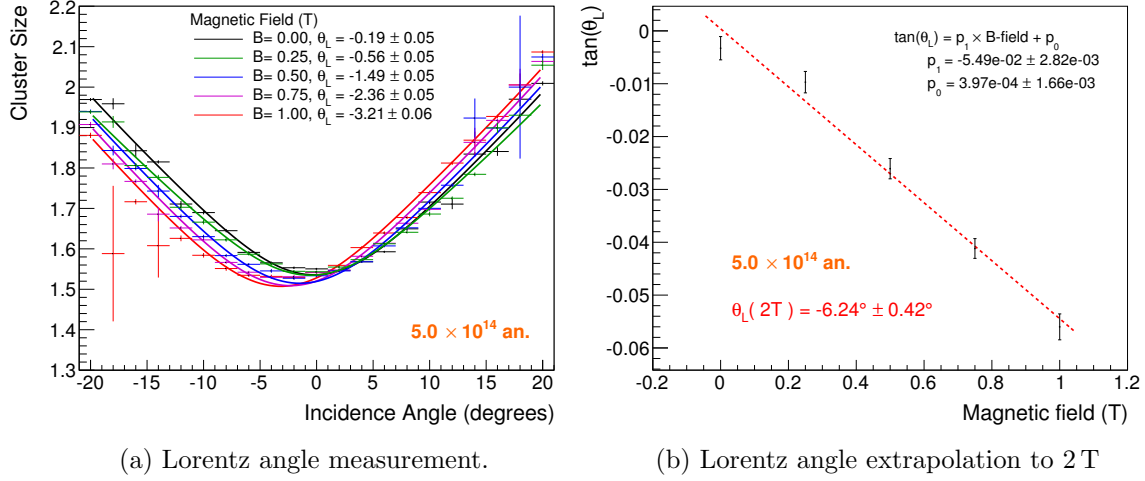


Figure 7.12: Lorentz angle measurement and its extrapolation to 2 T on the annealed $5.0 \times 10^{14} n_{\text{eq}}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

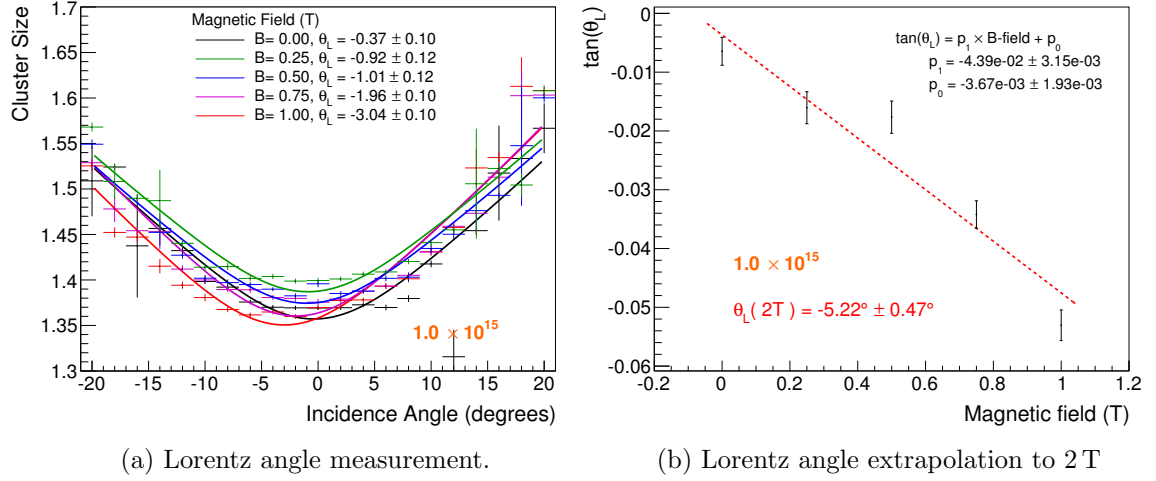


Figure 7.13: Lorentz angle measurement and its extrapolation to 2 T on the $1.0 \times 10^{15} n_{eq}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

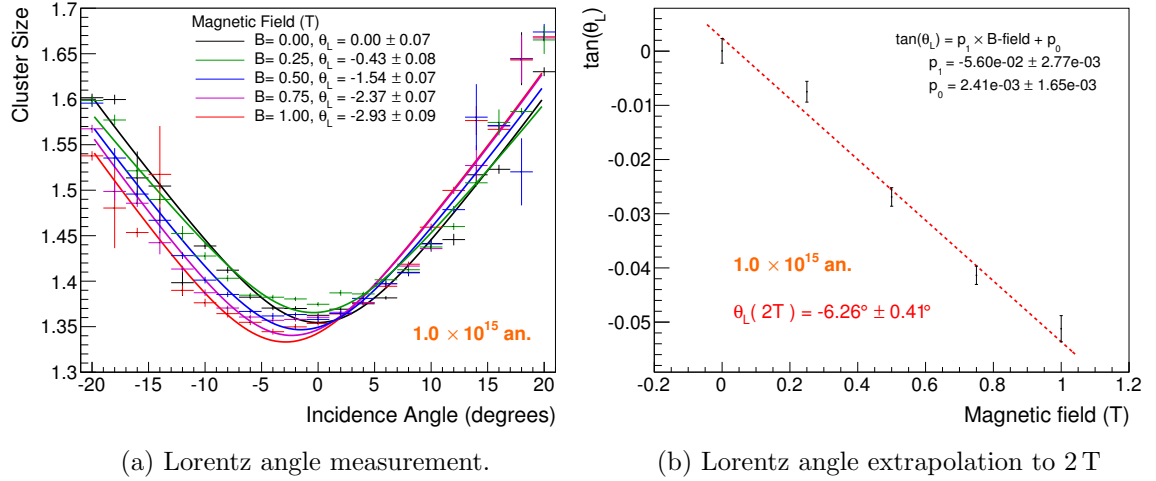
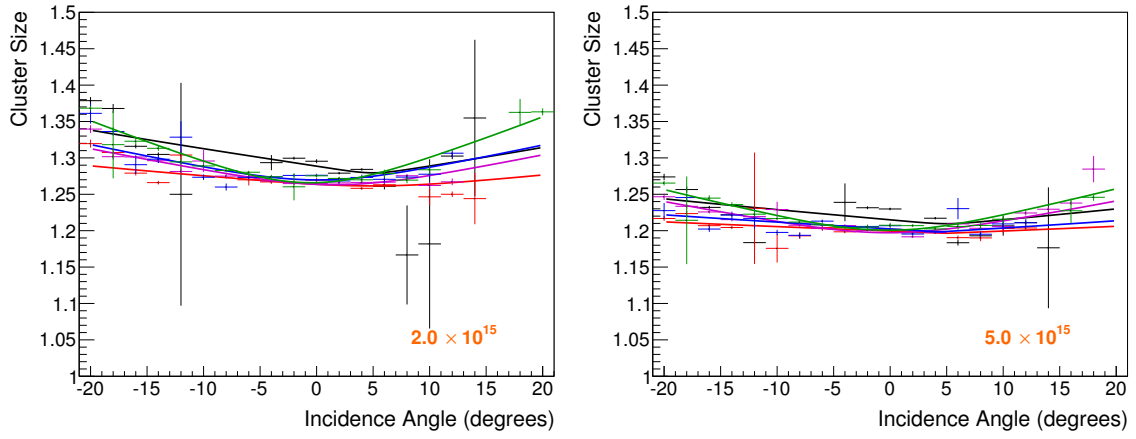


Figure 7.14: Lorentz angle measurement and its extrapolation to 2 T on the annealed $1.0 \times 10^{15} n_{eq}$ sample. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.



(a) Lorentz angle measurement on $2.0 \times 10^{15} n_{\text{eq}}$ sample.

(b) Lorentz angle measurement on $5.0 \times 10^{15} n_{\text{eq}}$ sample.

Figure 7.15: Lorentz angle measurement on the $2.0 \times 10^{15} n_{\text{eq}}$ and $5.0 \times 10^{15} n_{\text{eq}}$ samples.

Fluence	B-field (T)	Lorentz angle (°)
0.0 (sensor 1)	0.00	$-0.09 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$
	0.50	$-1.34 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$
	0.75	$-2.04 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$
	1.00	$-3.20 \pm 0.01(\text{stat}) \pm 0.14(\text{syst})$
0.0 (sensor 2)	0.00	$-0.14 \pm 0.04(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.62 \pm 0.05(\text{stat}) \pm 0.05(\text{syst})$
	0.75	$-2.33 \pm 0.04(\text{stat}) \pm 0.06(\text{syst})$
	1.00	$-3.20 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$
$1.2 \times 10^{14} n_{\text{eq}}$	0.00	$0.94 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.93 \pm 0.07(\text{stat}) \pm 0.05(\text{syst})$
	0.75	$-2.01 \pm 0.06(\text{stat}) \pm 0.10(\text{syst})$
	1.00	$-2.51 \pm 0.09(\text{stat}) \pm 0.08(\text{syst})$
$1.2 \times 10^{14} n_{\text{eq}}^*$	0.00	$-0.48 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.47 \pm 0.12(\text{stat}) \pm 0.09(\text{syst})$
	1.00	$-2.72 \pm 0.10(\text{stat}) \pm 0.06(\text{syst})$
$2.0 \times 10^{14} n_{\text{eq}}$	0.00	$0.90 \pm 0.05(\text{stat}) \pm 0.05(\text{syst})$
	0.50	$-1.76 \pm 0.08(\text{stat}) \pm 0.06(\text{syst})$
	0.75	$-2.38 \pm 0.09(\text{stat}) \pm 0.06(\text{syst})$
	1.00	$-2.72 \pm 0.07(\text{stat}) \pm 0.05(\text{syst})$
$2.0 \times 10^{14} n_{\text{eq}}^*$	0.00	$-1.24 \pm 0.05(\text{stat}) \pm 0.02(\text{syst})$
	0.50	$-1.52 \pm 0.13(\text{stat}) \pm 0.05(\text{syst})$
	1.00	$-3.07 \pm 0.07(\text{stat}) \pm 0.04(\text{syst})$
$5.0 \times 10^{14} n_{\text{eq}}$	0.00	$-0.07 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$
	0.25	$-0.94 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.30 \pm 0.06(\text{stat}) \pm 0.04(\text{syst})$
	0.75	$-2.37 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$
	1.00	$-3.08 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})$
$5.0 \times 10^{14} n_{\text{eq}}^*$	0.00	$-0.19 \pm 0.05(\text{stat}) \pm 0.08(\text{syst})$
	0.25	$-0.56 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$
	0.50	$-1.49 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$
	0.75	$-2.36 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$
	1.00	$-3.21 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$
$1.0 \times 10^{15} n_{\text{eq}}$	0.00	$-0.37 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$
	0.25	$-0.92 \pm 0.12(\text{stat}) \pm 0.04(\text{syst})$
	0.50	$-1.01 \pm 0.12(\text{stat}) \pm 0.04(\text{syst})$
	0.75	$-1.96 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$
	1.00	$-3.04 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$
$1.0 \times 10^{15} n_{\text{eq}}^*$	0.00	$0.00 \pm 0.07(\text{stat}) \pm 0.06(\text{syst})$
	0.25	$-0.43 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.54 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$
	0.75	$-2.37 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$
	1.00	$-2.93 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$

Table 7.3: Lorentz angle measurement on non-irradiated and irradiated samples. The samples marked with ' * ' are measured after annealing at 60 °C for 80 minutes.

Lorentz Angle dependence on fluence

Since the sign of the Lorentz angle depends on the definition of the coordinate system and the direction of the magnetic field, the absolute value of the Lorentz angle ($|\theta_L|$) is of importance to understand its behaviour. Therefore, the dependence of $|\theta_L|$ on irradiation level at 1 T magnetic field strength is shown in Figure 7.16. The measurements are taken at 500 V reverse bias voltage, which is higher than the full depletion voltage of the non-irradiated samples, close to the full depletion voltage of the $1.2 \times 10^{14} n_{eq}$ and $2.0 \times 10^{14} n_{eq}$ irradiated samples, and lower than the full depletion voltage of the higher irradiated samples (see Figure 7.1).

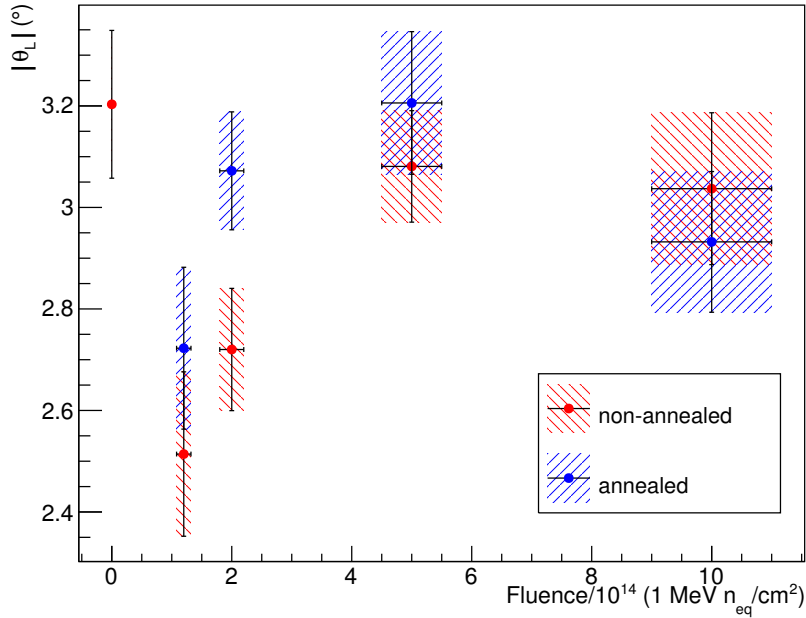


Figure 7.16: Lorentz angle dependence on the irradiation level.

For non-irradiated samples, the $|\theta_L|$ is measured to be 3.20° . Since the sample is measured at over-depletion, one would measure a larger Lorentz angle if the sensor would be biased at full depletion voltage. The $|\theta_L|$ is smaller for the irradiated sensors. For the lowest irradiated sample ($1.2 \times 10^{14} n_{eq}$), the $|\theta_L|$ is decreased compared to the non-irradiated samples. For the $1.2 \times 10^{14} n_{eq}$ sample, the bias voltage was close but slightly lower than the full depletion voltage, therefore one could expect a slightly smaller $|\theta_L|$ at full depletion bias voltage. These results are consistent with the measurements in Reference [18].

Following the previous knowledge [18], the $|\theta_L|$ should decrease with irradiation when the

samples are at full depletion voltage. However, the measurements in this thesis show that the $|\theta_L|$ increases with increasing fluence between $1.2 \times 10^{14} n_{eq}$ and $5.0 \times 10^{14} n_{eq}$. It is known that the full depletion bias voltage increases with the increasing irradiation levels. Since the bias voltage is kept constant at -500 V, the electric field is decreased by irradiation compared to the electric field in the samples at full depletion bias voltage. The decrease in electric field will cause an increase in $|\theta_L|$. Hence, it is hard to conclude if the $|\theta_L|$ is increased due to the irradiation or due to the decrease in electric field. It is also possible that the $|\theta_L|$ still decrease with irradiation, but the increase of $|\theta_L|$ due to the decreasing electric field dominates. Further measurements on these samples at full depletion voltage are needed to understand the reason for the increase in $|\theta_L|$.

The $|\theta_L|$ is slightly decreased for the $1.0 \times 10^{15} n_{eq}$ sample compared to the one irradiated to $5.0 \times 10^{14} n_{eq}$. As mentioned earlier for the samples $2.0 \times 10^{15} n_{eq}$ and $5.0 \times 10^{15} n_{eq}$ the effect of the Lorentz force is not visible anymore at a bias voltage of -500 V due to the low collected charge. The decrease of $|\theta_L|$ for the $1.0 \times 10^{15} n_{eq}$ sample can also be due to the decrease in collected charge, which would suggest the $|\theta_L|$ would decrease with irradiation at higher fluences and finally would not be visible at $2.0 \times 10^{15} n_{eq}$. However, more samples need to be measured in this region in order to have a complete understanding of the behavior of $|\theta_L|$ at these fluences.

The $|\theta_L|$ increases with short-term annealing (at 60°C for 80 min) for the samples with fluences lower than $10^{15} n_{eq}$, this is due to the decrease of the full depletion voltage with short-term annealing and hence the increase of the electric field compared to the non-annealed samples. This behavior is also consistent with the results in Reference [18]. It is observed that the $|\theta_L|$ for the annealed sample of $1.0 \times 10^{15} n_{eq}$ is decreased with a large error bar, which is also overlapping with the non-annealed result. It is possible that the increase in the electric field is not large to have a visible effect on the $|\theta_L|$ value. To have a better understanding one needs to measure more samples on the fluences in the order of $10^{15} n_{eq}$ with smaller errors on the measurement.

Lorentz Angle dependence on bias voltage

The dependence of the Lorentz angle on the bias voltage is investigated using the $1.2 \times 10^{14} n_{eq}$ and $2.0 \times 10^{14} n_{eq}$ samples. The bias voltage varies from -300 V to -1000 V, and the Lorentz angle is measured at a magnetic field of 1 T. The measured Lorentz angle values are listed in Table 7.4 and shown in Figure 7.17. As expected the absolute value of the Lorentz angle decreases with the increasing bias voltage, due to the increased electric field, which increases the drift velocity of the charge carriers.

Fluence	(-1) Bias voltage (V)	Lorentz angle ($^{\circ}$)
$1.2 \times 10^{14} n_{\text{eq}}$	300	$-3.96 \pm 0.18(\text{stat}) \pm 0.08(\text{syst})$
	500	$-2.51 \pm 0.09(\text{stat}) \pm 0.08(\text{syst})$
	700	$-2.16 \pm 0.10(\text{stat}) \pm 0.12(\text{syst})$
	1000	$-1.82 \pm 0.14(\text{stat}) \pm 0.07(\text{syst})$
$2.0 \times 10^{14} n_{\text{eq}}$	300	$-4.31 \pm 0.27(\text{stat}) \pm 0.06(\text{syst})$
	500	$-2.72 \pm 0.07(\text{stat}) \pm 0.05(\text{syst})$
	700	$-2.34 \pm 0.09(\text{stat}) \pm 0.06(\text{syst})$
	1000	$-1.96 \pm 0.13(\text{stat}) \pm 0.05(\text{syst})$

Table 7.4: Lorentz angle dependence on bias voltage on the $1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$ samples at the 1 T magnetic field.

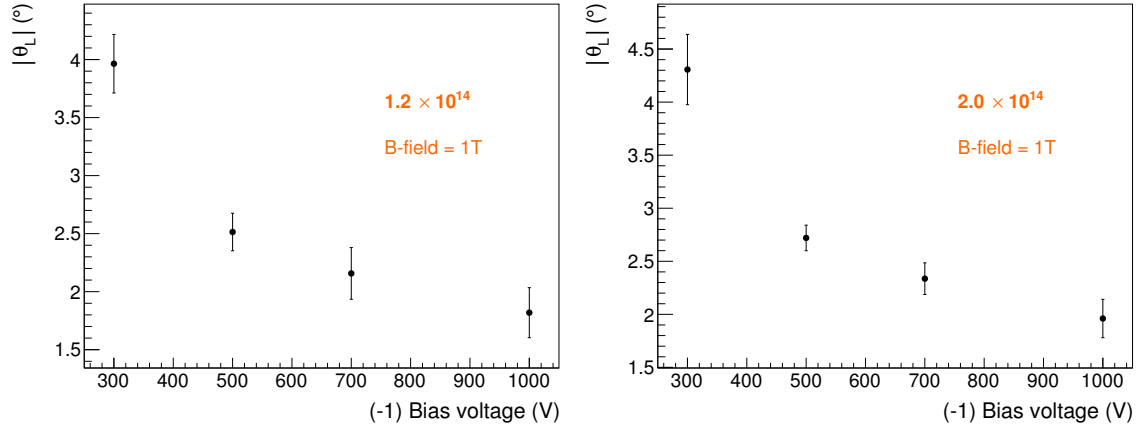


Figure 7.17: Lorentz angle measurement on the $1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$ samples at different bias voltages.

7.4 Lorentz Angle on the Future ATLAS silicon strip sensors

The ITK will have a digital readout and the threshold will be set to approximately 3 ke, which is much higher than the thresholds used in this study. Increasing the signal threshold will cause a decrease in cluster size, which will decrease the effect of the Lorentz force on irradiated samples.

The analysis is performed as described in Chapters 5 and 6. After obtaining the tracks, the cluster size is re-calculated requiring the collected charge on each strip to be higher than the ITK threshold (3 ke). The alignment of the DUT, hence the incidence angle, would change slightly, due to the small change in the hit position on the DUT. The small change in the incidence angle would not cause a large differences of the result of the Lorentz angle measurements, therefore this effect is neglected. With the re-definition of the clusters, it is possible that none of the strips passes the new criteria, so the cluster size is zero. In this case, the cluster and the corresponding track are ignored and removed from the analysis. This might cause the systematic error calculation to change; however, since the number of tracks in each data run is similar, the effect on the weighted average error calculation would be very small. Hence the systematic error is not re-calculated.

Lorentz Angle measurement using the ITK threshold

The Lorentz angle measurement results are shown in Figures 7.18 to 7.28 and the measured values are listed in Table 7.5. As expected, the behavior of the $|\theta_L|$ is consistent with the one observed using lower thresholds. However, the decrease in the effect of the Lorentz force can already be seen from the irradiation level of $5.0 \times 10^{14} n_{eq}$, where the cluster size does not change for small incidence angles. The effect of the Lorentz force decreases with irradiation level and becomes almost invisible on the $1.0 \times 10^{15} n_{eq}$ sample, since the change in cluster size is too small in the incidence angle region around the expected Lorentz angle.

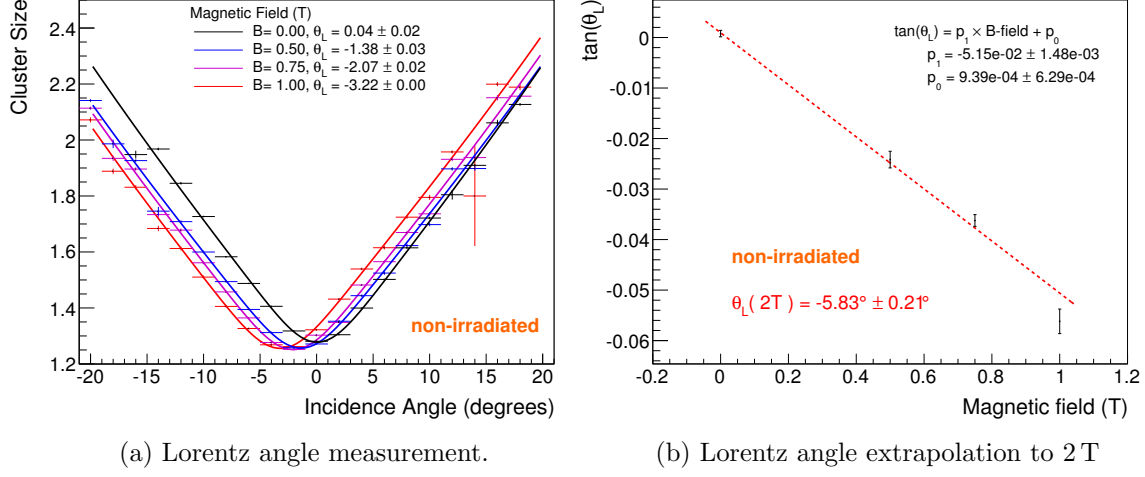


Figure 7.18: Lorentz angle measurement and its extrapolation to 2 T on the non-irradiated sample sensor 1 samples using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

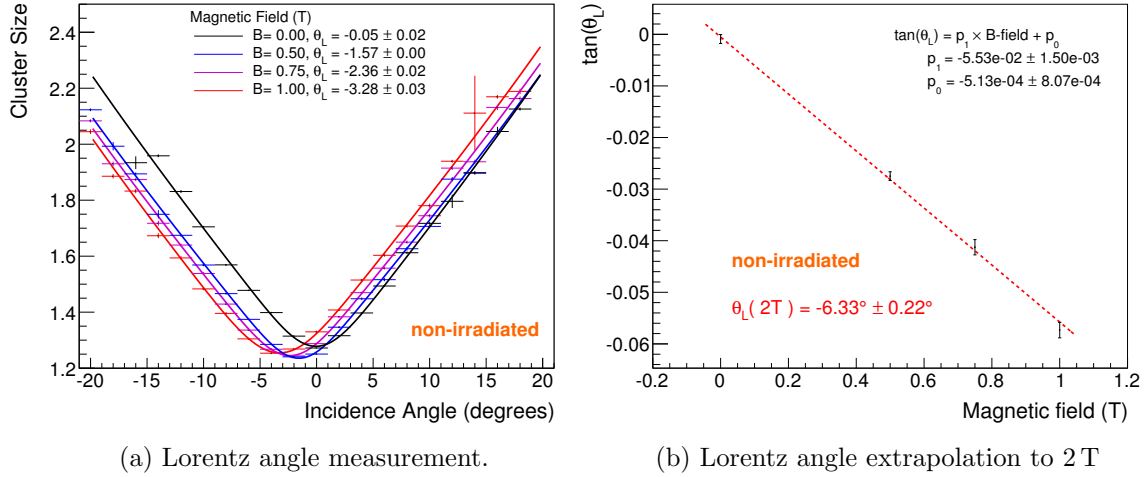


Figure 7.19: Lorentz angle measurement and its extrapolation to 2 T on the non-irradiated sample sensor 2 samples using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

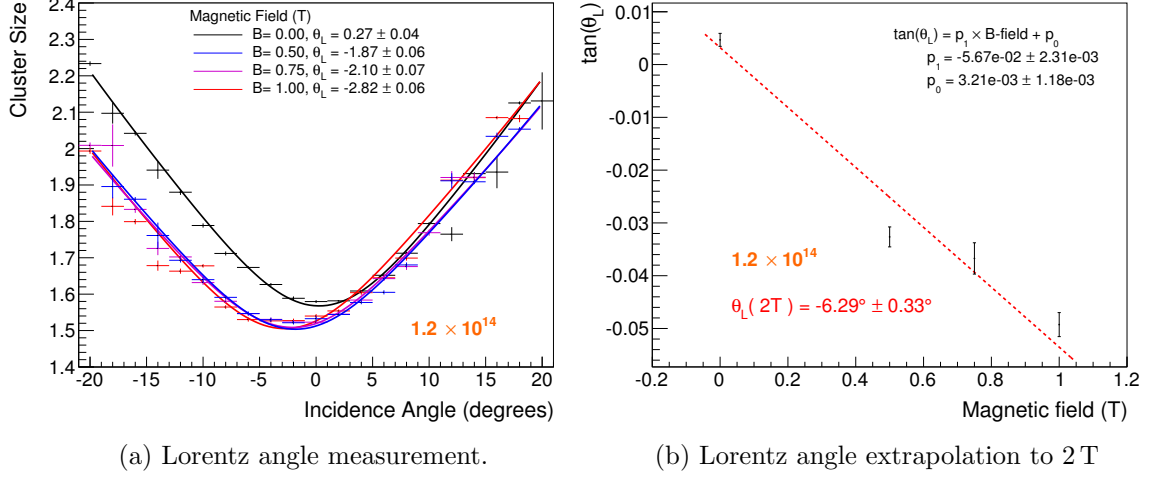


Figure 7.20: Lorentz angle measurement and its extrapolation to 2 T on the $1.2 \times 10^{14} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

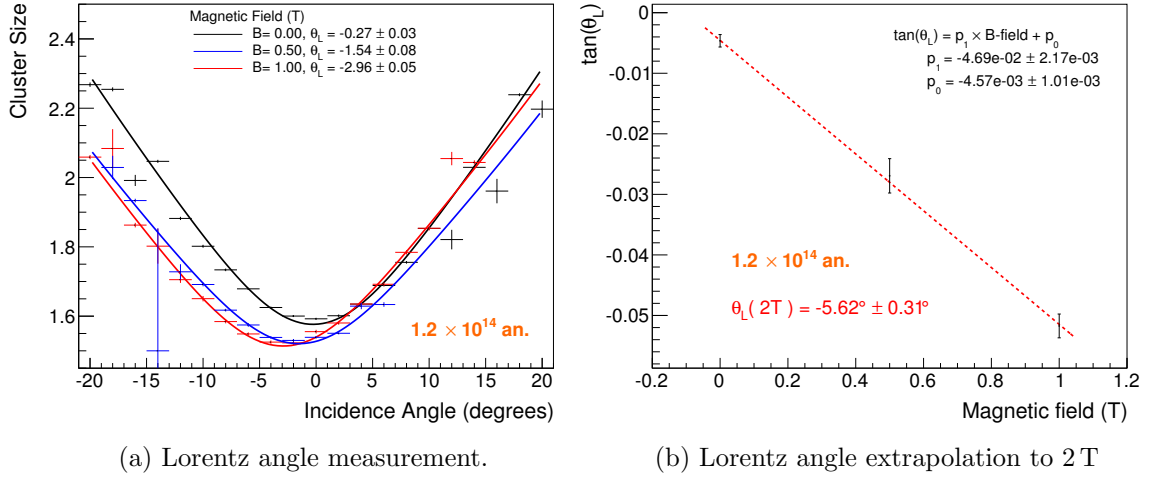


Figure 7.21: Lorentz angle measurement and its extrapolation to 2 T on the annealed $1.2 \times 10^{14} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

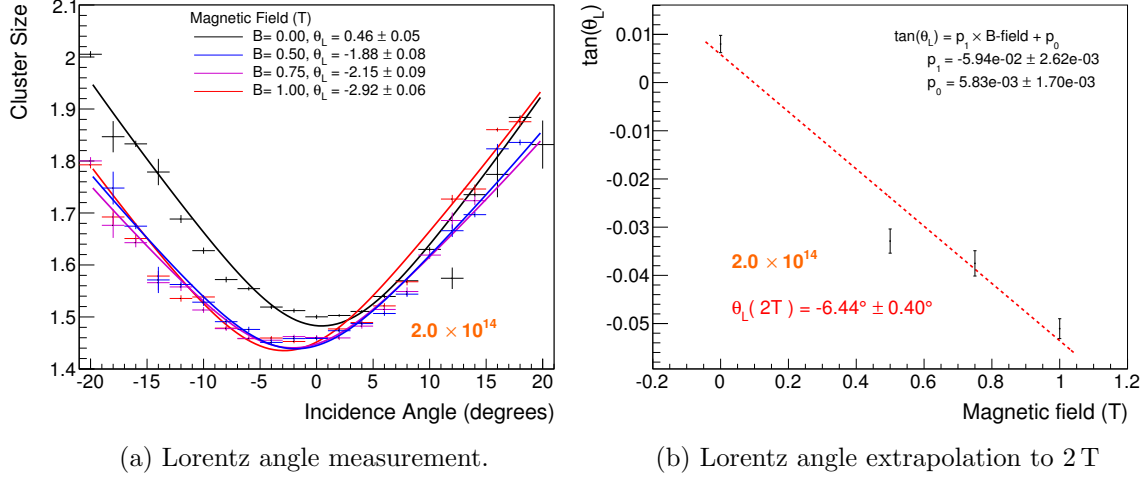


Figure 7.22: Lorentz angle measurement and its extrapolation to 2 T on the $2.0 \times 10^{14} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

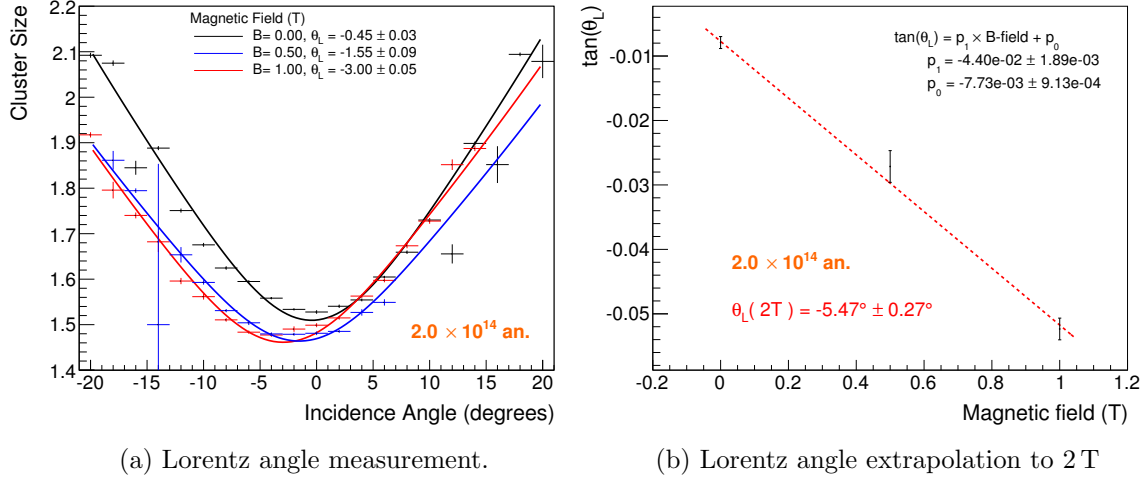


Figure 7.23: Lorentz angle measurement and its extrapolation to 2 T on the annealed $2.0 \times 10^{14} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

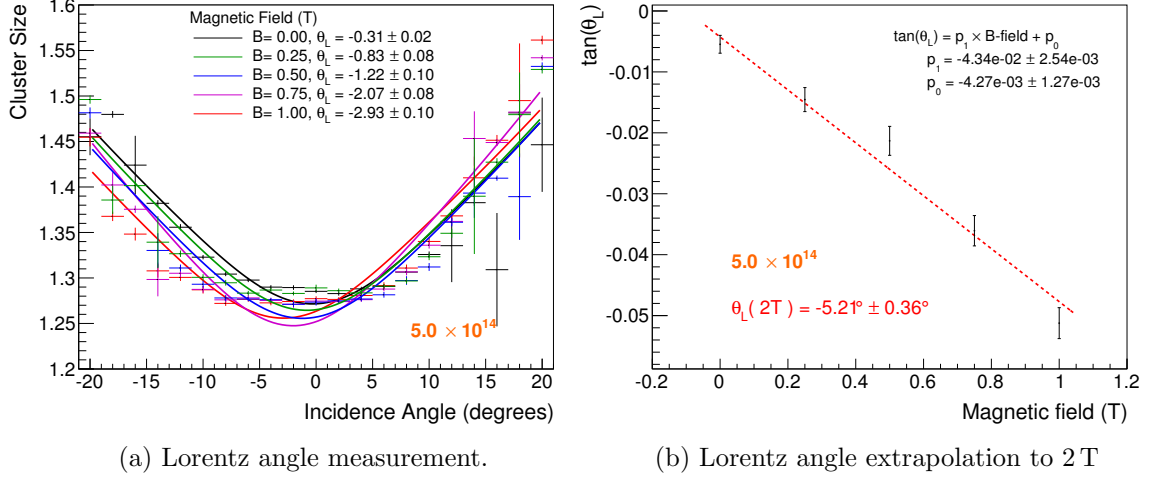


Figure 7.24: Lorentz angle measurement and its extrapolation to 2 T on the $5.0 \times 10^{14} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

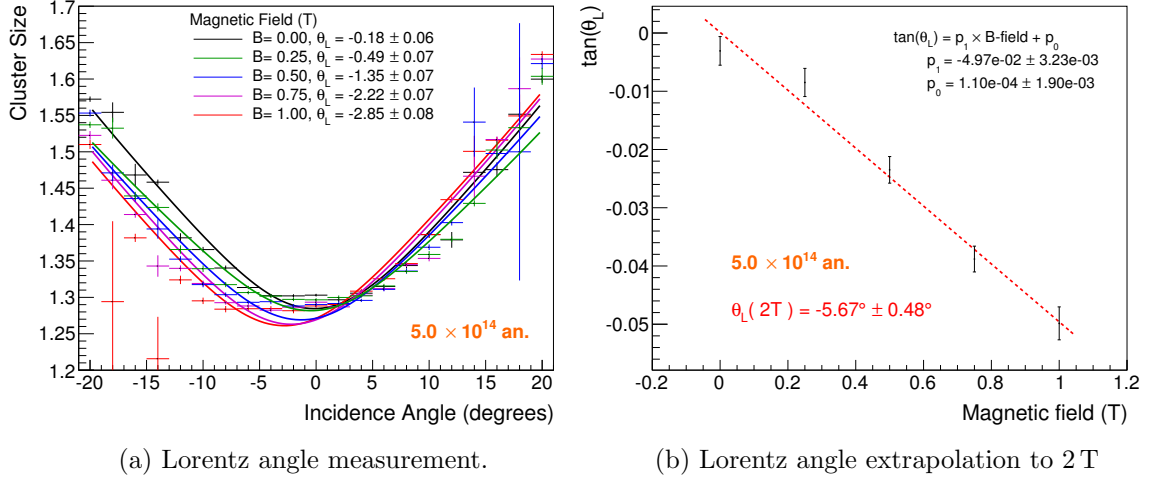


Figure 7.25: Lorentz angle measurement and its extrapolation to 2 T on the annealed $5.0 \times 10^{14} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

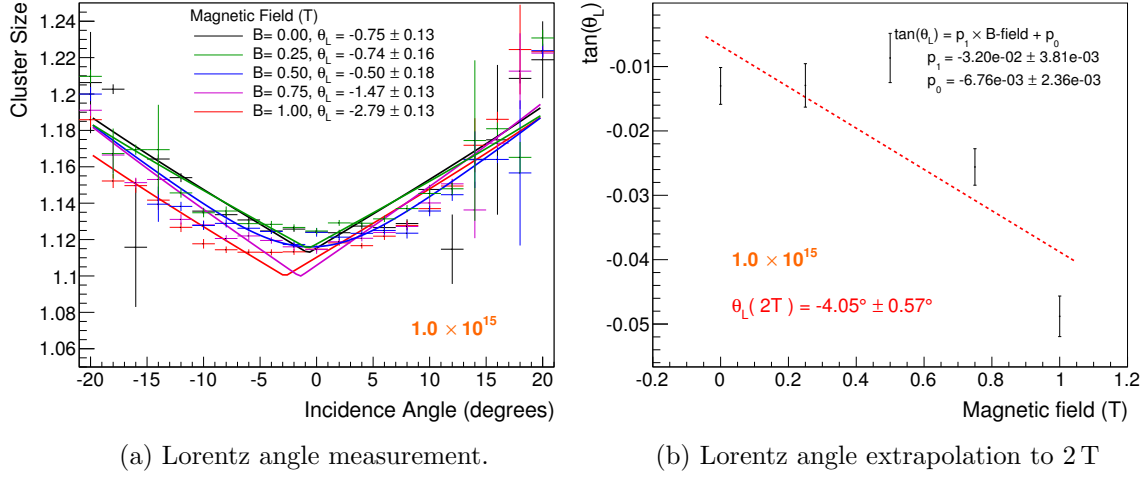


Figure 7.26: Lorentz angle measurement and its extrapolation to 2 T on the $1.0 \times 10^{15} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.

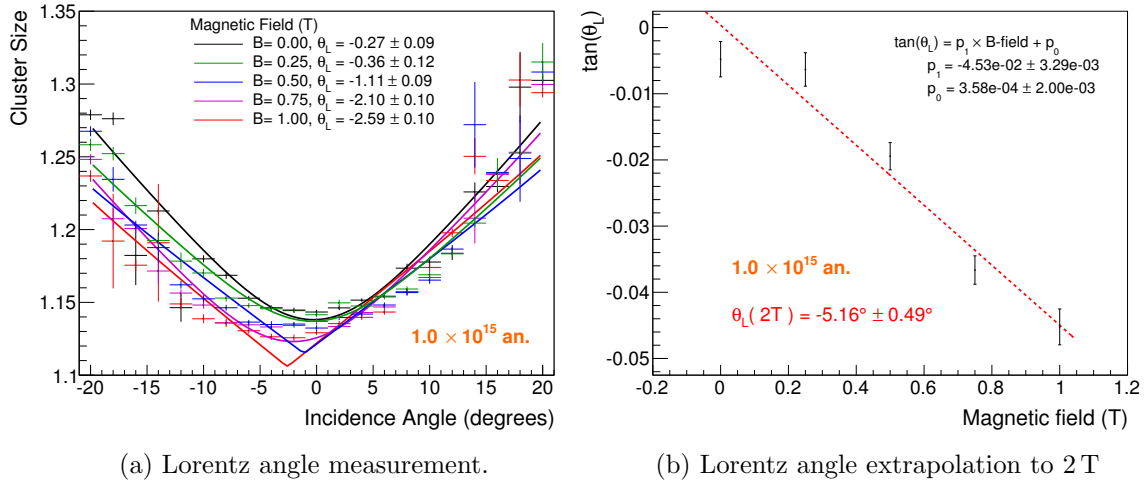
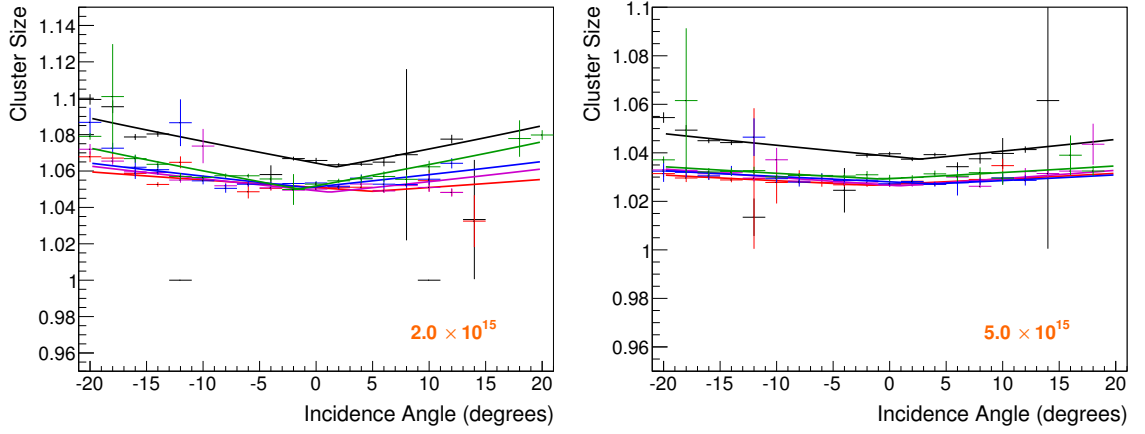


Figure 7.27: Lorentz angle measurement and its extrapolation to 2 T on the annealed $1.0 \times 10^{15} n_{\text{eq}}$ sample using the ITK thresholds. The values of the magnetic field (B) and the Lorentz angle (θ_L) are given in Tesla and degrees, respectively.



(a) Lorentz angle measurement on $2.0 \times 10^{15} n_{eq}$ sample.

(b) Lorentz angle measurement on $5.0 \times 10^{15} n_{eq}$ sample.

Figure 7.28: Lorentz angle measurement on the $2.0 \times 10^{15} n_{eq}$ and $5.0 \times 10^{15} n_{eq}$ samples using the ITK thresholds.

Fluence	B-field (T)	Lorentz angle ($^{\circ}$)
0.0 (sensor 1)	0.00	$0.04 \pm 0.02(\text{stat}) \pm 0.02(\text{syst})$
	0.50	$-1.38 \pm 0.03(\text{stat}) \pm 0.07(\text{syst})$
	0.75	$-2.07 \pm 0.02(\text{stat}) \pm 0.04(\text{syst})$
	1.00	$-3.22 \pm 0.00(\text{stat}) \pm 0.14(\text{syst})$
0.0 (sensor 2)	0.00	$-0.05 \pm 0.02(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.57 \pm 0.00(\text{stat}) \pm 0.05(\text{syst})$
	0.75	$-2.36 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$
	1.00	$-3.28 \pm 0.03(\text{stat}) \pm 0.06(\text{syst})$
$1.2 \times 10^{14} n_{\text{eq}}$	0.00	$0.27 \pm 0.04(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.87 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})$
	0.75	$-2.10 \pm 0.07(\text{stat}) \pm 0.10(\text{syst})$
	1.00	$-2.82 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$
$1.2 \times 10^{14} n_{\text{eq}}^*$	0.00	$-0.27 \pm 0.03(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.54 \pm 0.08(\text{stat}) \pm 0.09(\text{syst})$
	1.00	$-2.96 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$
$2.0 \times 10^{14} n_{\text{eq}}$	0.00	$0.46 \pm 0.05(\text{stat}) \pm 0.05(\text{syst})$
	0.50	$-1.88 \pm 0.08(\text{stat}) \pm 0.06(\text{syst})$
	0.75	$-2.15 \pm 0.09(\text{stat}) \pm 0.06(\text{syst})$
	1.00	$-2.92 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})$
$2.0 \times 10^{14} n_{\text{eq}}^*$	0.00	$-0.45 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$
	0.50	$-1.55 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$
	1.00	$-3.00 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$
$5.0 \times 10^{14} n_{\text{eq}}$	0.00	$-0.31 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$
	0.25	$-0.83 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.22 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$
	0.75	$-2.07 \pm 0.08(\text{stat}) \pm 0.07(\text{syst})$
	1.00	$-2.93 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$
$5.0 \times 10^{14} n_{\text{eq}}^*$	0.00	$-0.18 \pm 0.06(\text{stat}) \pm 0.08(\text{syst})$
	0.25	$-0.49 \pm 0.07(\text{stat}) \pm 0.07(\text{syst})$
	0.50	$-1.35 \pm 0.07(\text{stat}) \pm 0.06(\text{syst})$
	0.75	$-2.22 \pm 0.07(\text{stat}) \pm 0.06(\text{syst})$
	1.00	$-2.85 \pm 0.08(\text{stat}) \pm 0.08(\text{syst})$
$1.0 \times 10^{15} n_{\text{eq}}$	0.00	$-0.75 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$
	0.25	$-0.74 \pm 0.16(\text{stat}) \pm 0.04(\text{syst})$
	0.50	$-0.50 \pm 0.18(\text{stat}) \pm 0.04(\text{syst})$
	0.75	$-1.47 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$
	1.00	$-2.79 \pm 0.13(\text{stat}) \pm 0.05(\text{syst})$
$1.0 \times 10^{15} n_{\text{eq}}^*$	0.00	$-0.27 \pm 0.09(\text{stat}) \pm 0.06(\text{syst})$
	0.25	$-0.36 \pm 0.12(\text{stat}) \pm 0.03(\text{syst})$
	0.50	$-1.11 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$
	0.75	$-2.10 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$
	1.00	$-2.59 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$

Table 7.5: Lorentz angle measurement on non-irradiated and irradiated samples using the ITK threshold. The samples marked with ' * ' are measured after annealing at 60 $^{\circ}\text{C}$ for 80 minutes.

Lorentz Angle dependence on fluence using the ITK threshold

The Lorentz angle versus fluence is shown in Figure 7.29. As also seen with the low signal-to-noise ratio requirements (see Figure 7.16), the $|\theta_L|$ decreases for the irradiated sample $1.2 \times 10^{14} n_{eq}$ compared to the non-irradiated one and $|\theta_L|$ increases for $2.0 \times 10^{14} n_{eq}$ compared to $1.2 \times 10^{14} n_{eq}$. The $|\theta_L|$ for these samples increases after short-term annealing. Since the effect of the Lorentz force started to decrease already on the sample $5.0 \times 10^{14} n_{eq}$ the $|\theta_L|$ value decreases with the irradiation for the samples $5.0 \times 10^{14} n_{eq}$ and $1.0 \times 10^{15} n_{eq}$. The annealing decreases the $|\theta_L|$. The behavior of the $|\theta_L|$ dependence on irradiation is consistent with the results we get using the low thresholds. However, with this analysis it is seen that increasing the signal threshold causes a decrease on the effect of the Lorentz force.

Lorentz Angle dependence on bias voltage using the ITK threshold

Figure 7.30 shows the decrease in the $|\theta_L|$ with the increase in absolute value of the bias voltage, and Table 7.6 shows the measured values. As expected the $|\theta_L|$ decreases with the increasing electric field.

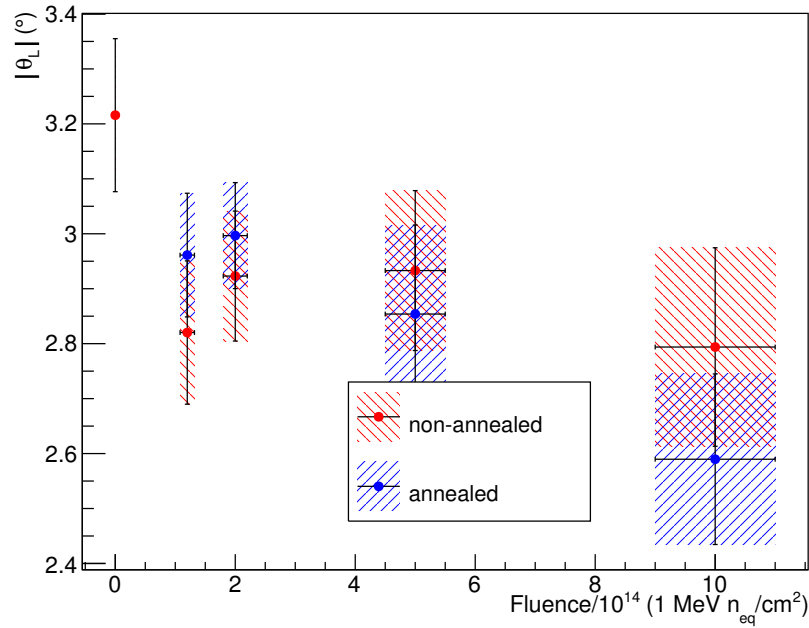
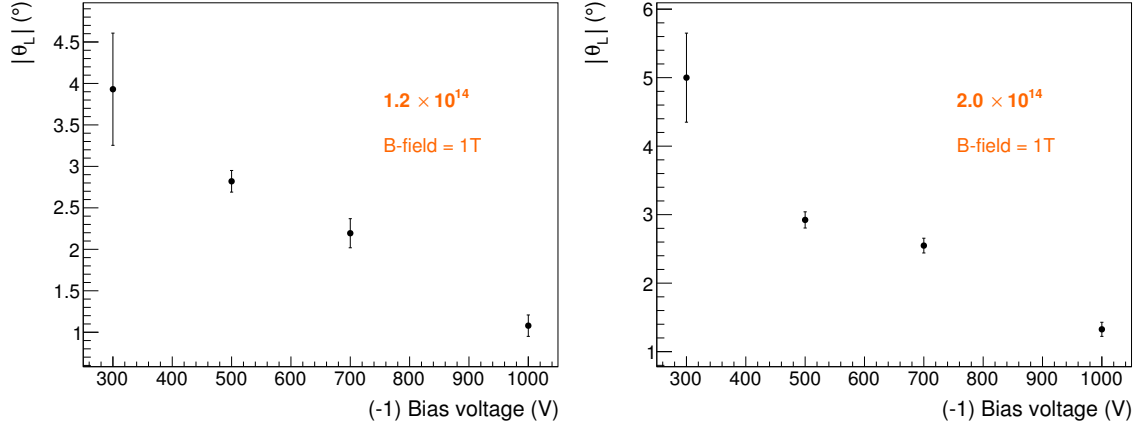


Figure 7.29: Lorentz angle dependence on the irradiation level using ITK threshold.



(a) Lorentz angle measurement on the $1.2 \times 10^{14} n_{\text{eq}}$ sample at different bias voltages using the ITK threshold.

(b) Lorentz angle measurement on the $2.0 \times 10^{14} n_{\text{eq}}$ sample at different bias voltages using the ITK threshold.

Figure 7.30: Lorentz angle measurement on the $1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$ samples at different bias voltages using the ITK threshold.

Fluence	(-1) Bias voltage (V)	Lorentz angle (°)
$1.2 \times 10^{14} n_{\text{eq}}$	300	$-3.93 \pm 0.08(\text{syst}) \pm 0.60(\text{stat})$
	500	$-2.82 \pm 0.08(\text{syst}) \pm 0.06(\text{stat})$
	700	$-2.19 \pm 0.12(\text{syst}) \pm 0.05(\text{stat})$
	1000	$-1.08 \pm 0.07(\text{syst}) \pm 0.06(\text{stat})$
$2.0 \times 10^{14} n_{\text{eq}}$	300	$-5.00 \pm 0.06(\text{syst}) \pm 0.59(\text{stat})$
	500	$-2.92 \pm 0.05(\text{syst}) \pm 0.06(\text{stat})$
	700	$-2.55 \pm 0.06(\text{syst}) \pm 0.05(\text{stat})$
	1000	$-1.33 \pm 0.05(\text{syst}) \pm 0.05(\text{stat})$

Table 7.6: Lorentz angle dependence on bias voltage on the $1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$ samples at 1 T magnetic field using the ITK threshold.

Chapter 8

Summary and Outlook

The collected charge and the Lorentz angle are measured on the miniature of future ATLAS12 sensors, which are the current test sensor for the ITK upgrade. The measurements are performed on non-irradiated sensors and on six neutron irradiated sensors where the irradiation levels vary from $1.2 \times 10^{14} n_{\text{eq}}^{\ddagger}$ to $5.0 \times 10^{15} n_{\text{eq}}$. Some of the irradiated samples are also measured after short term annealing (at 60°C for 80 min). The measurements are carried out at the DESY II test beam using the setup designed for this measurement but flexible enough to be used for other measurements. The analogue readout ALiBaVa is used to record the signal from the strip sensors. A dedicated software is developed for the analysis of the data taken with the ALiBaVa readout system in the EUTelescope framework. For the precise hit reconstruction seed clustering is applied using the minimum possible signal requirements. Millepede II and GBL are used for the alignment and track fitting.

The collected charge measurement results show that, as expected, the collected charge decreases with increased irradiation, and short-term annealing increases the collected charge. Since the collected charge is measured for the first time at the test beam for these samples, some of the samples are also measured in the laboratory using a Strontium-90 (^{90}Sr) radioactive source. It is shown that the collected charge measured with the radioactive source and the beam are consistent with each other. The advantage of the test beam measurement using tracking shows itself on the highly irradiated samples. On the samples $2.0 \times 10^{15} n_{\text{eq}}$ and $5.0 \times 10^{15} n_{\text{eq}}$ the collected charge is too small at low reverse bias voltages (such as bias voltages higher than -200 V and -300 V , respectively) to distinguish the signal from the noise, therefore the collected charge on these samples could not be measured using the radioactive source. However, the measurements taken using the beam allow noise hit reduction using tracking. Therefore, it is possible to measure the collected charge on the $2.0 \times 10^{15} n_{\text{eq}}$ and $5.0 \times 10^{15} n_{\text{eq}}$ samples at bias voltages of -100 V and -200 V , respectively, at the test beam.

The Lorentz angle is measured on the samples by varying the incidence angle of the track on the sensor between -20° and 20° , searching for the incidence angle equals to the Lorentz

^{$\ddagger$} $1\text{MeV } n_{\text{eq}}/\text{cm}^2$ is denoted shortly as n_{eq} .

angle, which results a minimum cluster size. The measurements are performed on all samples at different magnetic fields up to 1 T and the results are extrapolated to 2 T, which is the magnetic field on the ITK. The measurements are taken at -500 V bias voltage which is the planned operation bias voltage at the HL-LHC; however, for two samples ($1.2 \times 10^{14} n_{\text{eq}}$ and $2.0 \times 10^{14} n_{\text{eq}}$) the Lorentz angle is also measured by varying the bias voltage between -300 V and -1000 V.

The Lorentz angle measurements on non-irradiated samples agree with the prediction of BFK model within errors. The measurements show that the Lorentz angle decreases with increasing electric field in the samples as expected. It is observed that the $|\theta_L|$ is decreased on the $1.2 \times 10^{14} n_{\text{eq}}$ due to the irradiation. The previous knowledge predicts the $|\theta_L|$ to increase with decreasing electric field and to decrease with increasing irradiation level. For the irradiated samples ($2.0 \times 10^{14} n_{\text{eq}}$ and $5.0 \times 10^{14} n_{\text{eq}}$) where the bias voltage is lower than the full depletion voltage, the $|\theta_L|$ increases compared to the lower irradiated full depleted samples. This result suggests that the effect of electric field on the $|\theta_L|$ dominates the other effects of the irradiation. To have a better understanding of the behavior of $|\theta_L|$ on these samples, further measurements at full depletion bias voltages are needed. On the higher irradiated samples, the results suggest that the effect of the Lorentz force is decreasing due to the decrease in collected charge. Therefore the $|\theta_L|$ decreases on the sample $1.0 \times 10^{15} n_{\text{eq}}$ compared to the sample $5.0 \times 10^{14} n_{\text{eq}}$. For the highly irradiated samples ($2.0 \times 10^{15} n_{\text{eq}}$ and $5.0 \times 10^{15} n_{\text{eq}}$) the effect of the Lorentz force becomes too small to measure the Lorentz angle for these samples.

The analysis is also performed using the threshold for the clustering that is planned to be used in the ITK (3 ke), it is seen that the decrease in $|\theta_L|$ already starts on the $5.0 \times 10^{14} n_{\text{eq}}$ sample and the effect of Lorentz force becomes invisible at the fluence $2.0 \times 10^{15} n_{\text{eq}}$. To determine the minimum fluence at which the Lorentz effect is not visible, more measurements are needed on the sensors irradiated between $1.0 \times 10^{15} n_{\text{eq}}$ and $2.0 \times 10^{15} n_{\text{eq}}$. However, with the measurements in this thesis, it is shown that for the fluences higher than $5.0 \times 10^{14} n_{\text{eq}}$ small incidence angles do not change the size of the clusters in the ITK.

Short-term annealing (at 60°C for 80 min) on irradiated sensors decreases the full depletion voltage, so increases the electric field in the sample at a given bias voltage. The $|\theta_L|$ is increased by short-term annealing on the samples $1.2 \times 10^{14} n_{\text{eq}}$, $2.0 \times 10^{14} n_{\text{eq}}$ and $5.0 \times 10^{14} n_{\text{eq}}$. However, on the samples where the $|\theta_L|$ decreases with increasing fluence due to the low collected charge, it is observed that the short-term annealing does not increase the $|\theta_L|$. The measurement on these samples gives smaller $|\theta_L|$ with large error bars, which are also overlapping with the non-annealed results. Further measurements on these samples with smaller errors are needed to conclude the effect of short-term annealing on these samples.

On some of the samples, the measured Lorentz angle at zero magnetic field is different from zero. Although the alignment procedure and the error on the alignment has been checked, an additional error on the alignment might come from a non-accurate initial tilt angle given to the alignment procedure. Further studies are needed to understand the source of this bias. However, the results show that the Lorentz angle can be measured using the test beam setup designed and produced within the scope of this thesis.

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