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Master Thesis

Test of High-Resolution Muon Drift-Tube Chambers for the Upgrade of the ATLAS Experiment

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Abstract

High-resolution muon drift-tube chambers were studied as a part of the planned upgrades of the ATLAS detector for the high luminosity (HL) LHC. To suppress fake muon triggers, observed in the transition region from the barrel to the end-caps of the ATLAS muon spectrometer, 16 new so-called "BIS-78" sMDT chambers will be installed in this region. As a part of this thesis, functionality tests of the eight A-side sMDT chambers are performed prior to their installation in the ATLAS detector, during the 2019/20 shutdown of the LHC. All chambers are tested in a cosmic-ray test stand. The chamber performance is characterized by measuring the noise rates, spatial resolution and the muon detection efficiency of each drift tube in the chamber. The second part of this thesis is dedicated to determination of the operational point of the amplifier-shaper-discriminator (ASD) chips for the new read-out electronics, which was developed for the operation at the HL-LHC. The noise rates, spatial resolution and muon detection efficiency are determined with two read-out cards carrying new ASD chips.

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Introduction

“What are fundamental constituents of nature ?” - the question that exists since the earliest times of the humankind. The first attempts to answer this question were given in Ancient Greece, where the atom was considered to be the smallest and an indivisible constituent of matter, which gave the foundation for the development of the particle physics. This was just the beginning of the continuous search for new elementary particles, while at the same time pushing the boundaries of our knowledge about nature with the parallel development of larger and more complex particle accelerators and detectors for these purposes.

Our curiosity to understand the world we are living in and its underlying laws led to the construction of the Large Hadron Collider (LHC) [1], the most complex experimental facility in the world, designed by the CERN¹, with the goal of investigating the structure of matter. Its 13 TeV centre-of-mass energy during the Run 2 data taking was the highest energy ever reached by a collider. Situated at the border of Switzerland and France, near the city of Geneva, LHC accelerates proton and heavy ion beams and collides them at the four crossing points. The products of the collisions are detected and analyzed with the seven different detectors, each designed for specific scientific goal.

In 2012, the successful operation of the LHC (Run 1) was followed by the discovery of a new particle, which was confirmed to be the Higgs boson, with the mass of 125.5 GeV [2, 3], the last missing part of the Standard Model, relativistic quantum field theory representing, for now, our best attempt to classify discovered elementary particles and describe three of four known interactions in the Universe between them, in a self-consistent way. Although the Standard Model is a well-tested theory and all of its predicted particles are discovered, there is experimental evidence for its incompleteness. This is the physics motivation of the many projects around the world to build higher energy colliders and develop better performance detectors which will allow the search for the answers on the many questions that still exist. In order to extend the operation of the LHC, series of upgrades are planned to increase its luminosity, with an aim to strengthen its discovery potential and search for physics beyond the Standard Model. However, at high integrated luminosity and harsh radiation environment, many detectors and read-out electronics of the LHC will reach the limit of their rate capabilities and subsequently the end of their lifetime, requiring installation of new detectors, designed to cope with newly created conditions.

¹European Organization for Nuclear Research

Contents

The main focus of this thesis is the test and comissioning of the new high-resolution muon chambers developed for the upgrade of the ATLAS detector at CERN. In the first chapter of this thesis, an introduction to the ATLAS experiment and its subdetector systems will be presented, including a brief overview of the planned ATLAS upgrades for the High Luminosity LHC. The second chapter is dedicated to explain the working principle and main characteristic of the Monitored Drift Tubes, as the main focus of this master thesis. The rest of the thesis is split into two parts. The first part deals with the tests of the BIS78 sMDT chambers with cosmic rays, to investigate noise rates, spatial resolution and muon detection efficiency of the chambers, as a part of their preparation for the installation at CERN. The experimental set-up and the method used in determining investigated quantities is described followed by the obtained results and discussion. The second part is focused on the determination of the operational point for the new read-out electronics, with the discussion of the obtained results.

1. The ATLAS experiment

The ATLAS¹ detector [4] is one of the two general-purpose detectors at the Large Hadron Collider, with the same scientific goals but different technological solutions as the CMS. With its length of 46 m and diameter of 25 m, the ATLAS detector is the largest and most complex scientific instrument ever built. To reach the desired collision energy, protons are travelling through series of preaccelerators, before they reach the 27 km long LHC tunnel, previously occupied by the Large Electron-Positron Collider (LEP) [6]. The pp collisions for LHC are chosen over LEP e^+e^- due to significant energy loss through synchrotron radiation present when accelerating electrons, which is proportional to m^{-4} . Therefore, this effect is less present when accelerating heavier particles. On the other hand, protons (or hadrons) are composite particles. They have substructure made of valence, sea quarks and gluons called partons. This means that in the hadron collisions, partons do not have defined momentum, but their momenta is distributed according to the parton distribution function.

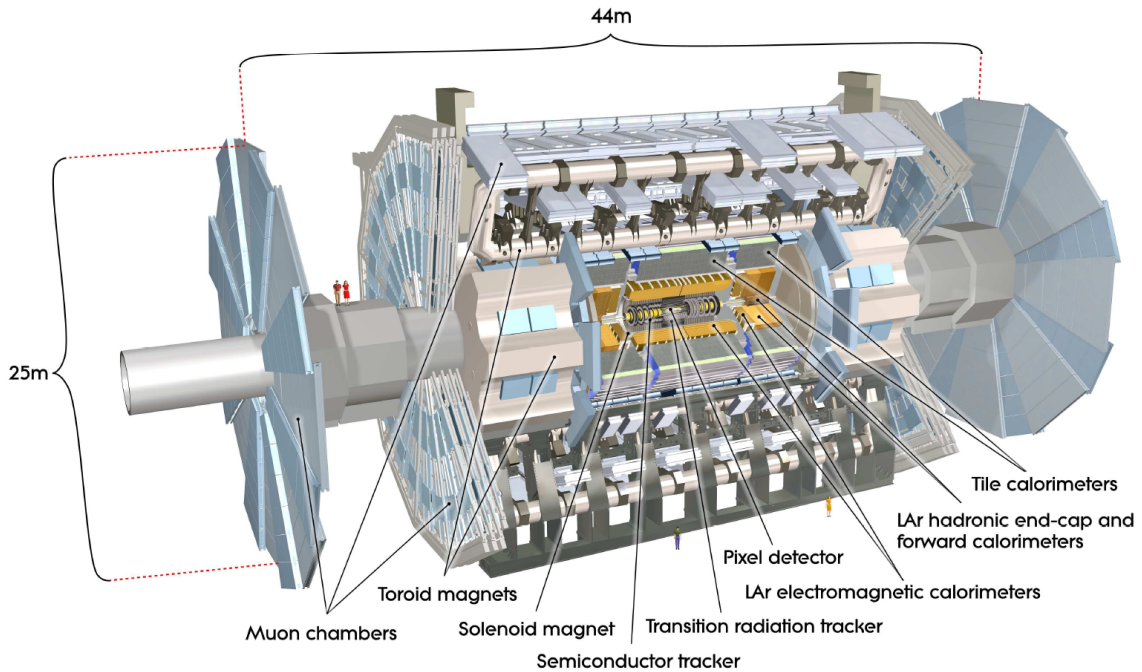


Figure 1.1.: Complete view of the ATLAS detector. [4]

After reaching the desired energy, the beams of protons are collided at four crossing

¹A Toroidal LHC Apparatus

1. The ATLAS experiment

points. The ATLAS detector, whose complete overview is given in the Figure 1.1, is located at the Interaction Point 1 of the LHC complex. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector, the beam direction defines the z -axis and the $x-y$ plane is transverse to the beam direction. The x -axis points from the interaction point to the centre of the LHC ring, while y -axis points upwards. The A -side of the detector is defined with positive z and C -side with negative z . In terms of cylindrical coordinates, (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as:

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right) \quad (1.1)$$

Transverse momentum and energy are defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively [4].

1.1. Detector components

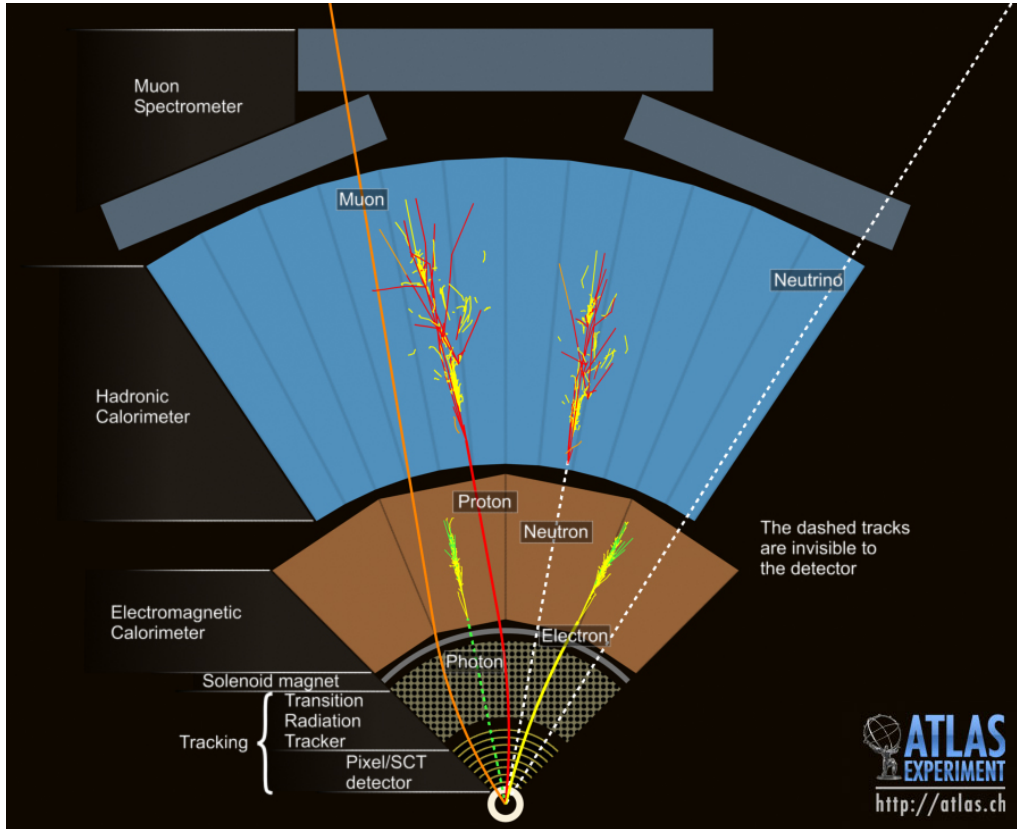


Figure 1.2.: Schematic cross-section of the ATLAS detector [4] perpendicular to the beam line, with typical signatures left by different types of SM particles, depending on their interaction with detector material [5]

Since products of pp collisions can be any particle from the Standard Model, it is not possible to use only one detector type for detection. Therefore, in the ATLAS

detector, collision products are detected with the complex system of different detector types organized around the beam line. The size of the ATLAS detector is mainly determined by the nature of the particle interactions with matter. Particles lose energy differently while travelling through a material, depending on their energy, electric charge and type of the material they are travelling through. The cross-section of the ATLAS detector perpendicular to the beam line is shown in Figure 1.2.

The ATLAS detector is divided into three main components. The closest to the beam line, immersed in homogenous 2 T magnet, is the Inner Detector with the purpose of reconstructing the trajectories of the charged particles to determine their charge and momentum as well as identification of secondary vertices. It is constructed as a combination of high-resolution Pixel and silicon microstrip (SCT) trackers and straw tubes of the Transition Radiation Tracker (TRT) tracking detectors in the outer part, enabling distinction between electrons and hadrons, such as pions, by providing additional space points [7]. It has been designed to provide a transverse momentum resolution, in the plane perpendicular to the beam axis, of $\sigma_T/p_T = 0.05\% \times p_T[GeV] \oplus 1\%$ and a transverse impact parameter resolution of $10 \mu m$ for high momentum particles in the central pseudorapidity region [4]. The ATLAS Inner Detector and its subsystems are shown in Figure 1.3a.

Typically in collider experiments, the tracking detector is surrounded by calorimeters, to measure the energy of γ , $e^\pm$ and hadrons, by creating electromagnetic and hadronic showers. The ATLAS electromagnetic calorimeter is a high granularity lead-liquid Argon (LAr) detector with accordion-shaped kapton electrodes and lead absorber plates, providing full solid angle coverage. The ionization charge is collected on copper clad Kapton electrodes. The EM calorimeter has been designed to provide energy resolution of $\sigma_E/E = 10\%/\sqrt{E[GeV]} \oplus 0.7\%$ [4]. The hadronic calorimeter is divided into three subdetectors: tile, LAr hadronic end-cap (HEC) and forward (FCal) calorimeter. The expected energy resolution [4] for the hadronic calorimeter is:

- *Barrel and end-caps*: $\sigma_E/E = 50\%/\sqrt{E[GeV]} \oplus 3\%$;
- *Forward*: $\sigma_E/E = 100\%/\sqrt{E[GeV]} \oplus 10\%$.

The complete calorimeter system of the ATLAS detector is shown in Figure 1.3b. Calorimeters have high stopping power to ensure that electromagnetic and hadronic showers are fully contained within its volume and must limit punch-through into the muon spectrometer, the final part of the ATLAS detector, which occupies the largest volume, with purpose of detecting muons, particles that transverse dense detector materials without significant energy loss.

1. The ATLAS experiment

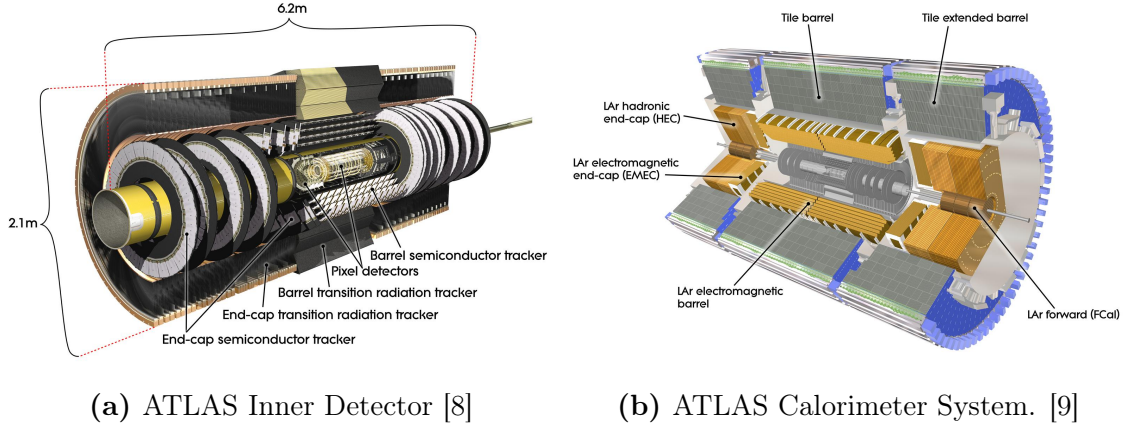


Figure 1.3.: Computer generated image of the ATLAS subdetectors

1.1.1. The muon spectrometer

The main characteristic part of the ATLAS experiment is the muon spectrometer, whose layout is shown in Figure 1.4. The muon spectrometer is the outermost part of the ATLAS experiment and occupies the largest volume. It is designed to detect and measure muon momenta by deflecting their trajectories in the large superconducting air-core toroid magnets, of approximately 0.5 T and 1 T in the central and end-cap regions, respectively [4]. The expected stand-alone transverse momentum resolution is $\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV [4]. The muon spectrometer combines different technologies of precision-tracking and triggering chambers. In the barrel regions, the chamber plane is tangential to the circles around the beam axis, while in forward and end-cap regions chambers are installed perpendicular to the beam axis, in three layers.

1.1.2. Muon chamber types

The high muon momentum resolution is achieved combining two types of the precision-tracking chambers:

- **Cathode strip chambers (CSC)** are used in the innermost tracking region ($2 < |\eta| < 2.7$) due to their high rate capability and time resolution. CSCs are multiwire proportional chambers with cathodes segmented into strips.
- **Monitored drift tubes (MDT)** are used for the precision momentum measurement, over the pseudorapidity range $|\eta| < 2.7$. Limit of their coverage is $|\eta| < 2.0$ in the innermost end-cap layer.

The important characteristic feature of the muon system is to trigger on muon tracks, therefore precision-tracking chambers are complemented with two types of fast triggering chambers:

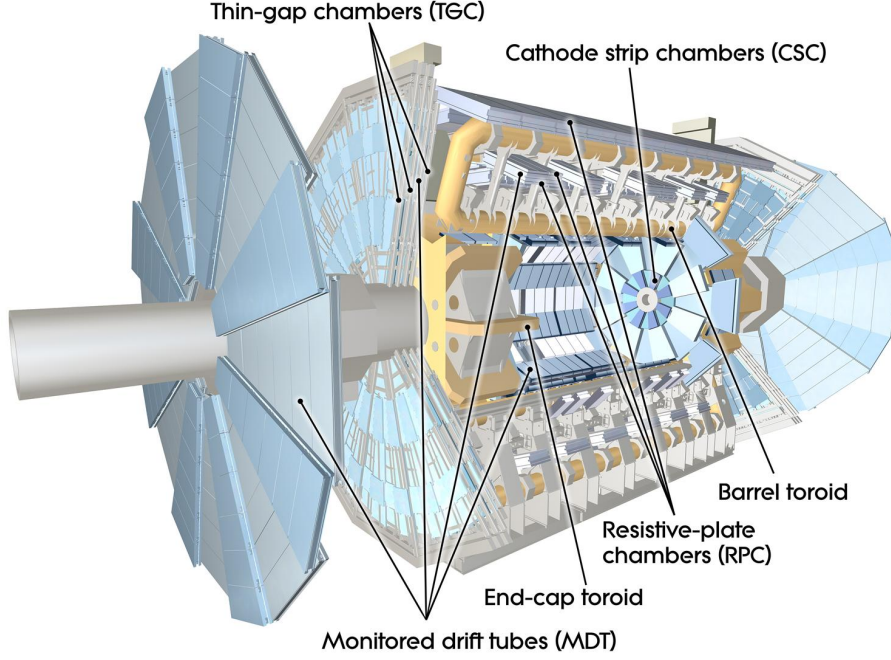


Figure 1.4.: Computer generated image of the ATLAS Muons Subsystem [10]

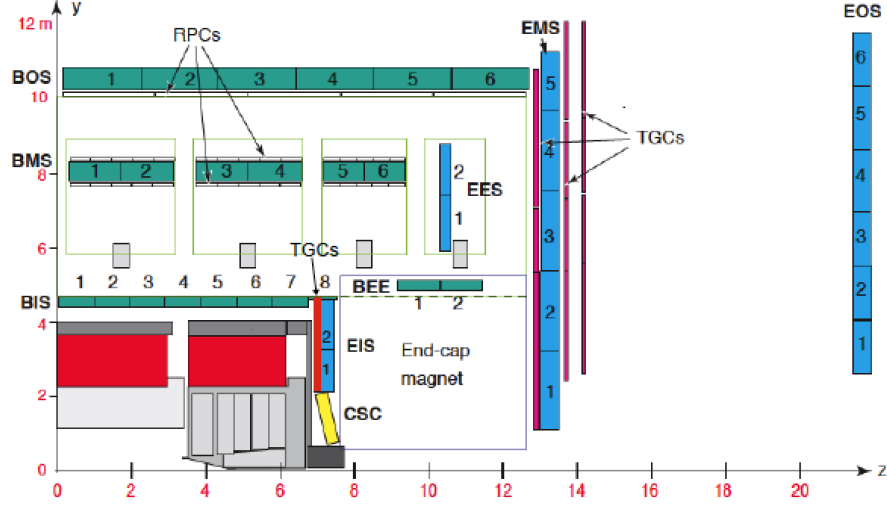
- **Resistive plate chambers (RPC)** are parallel electrode-plate gaseous detectors. They are used in the barrel region ($|\eta| < 1.05$), due to their good time resolution and high rate capability;
- **Thin gap chambers (TGC)** are used in the end-cap region ($1.05 < |\eta| < 2.4$). They operate in a similar way as multi-wire proportional chambers, providing good resolution and high rate capability.

The chambers have different shapes and dimensions in the barrel and end-cap regions, due to the optimization of the solid angle coverage. The present ATLAS muon spectrometer layout in the $r - z$ plane can be seen in Figure 1.5.

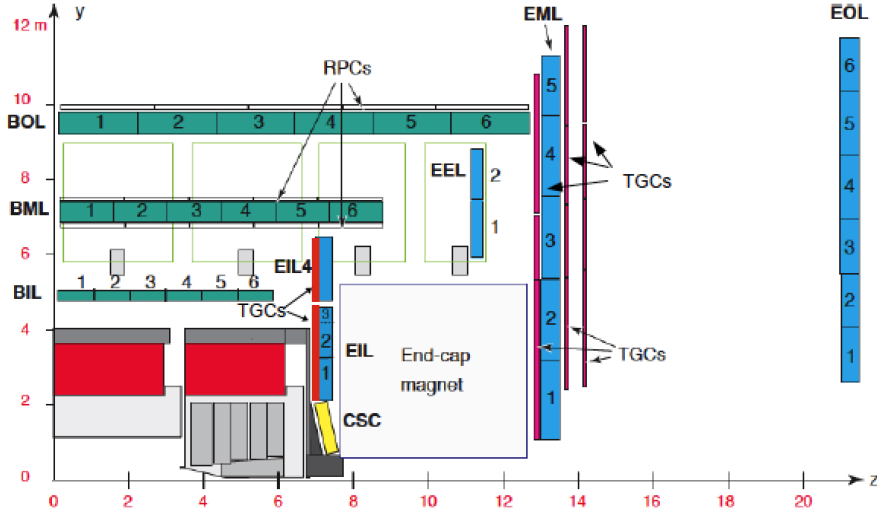
1.2. Trigger and Data Acquisition System

The ATLAS detector is designed to observe pp collision products. However, due to storage limitations and properties of the electronics, it is not possible to store every event, out of more than 40 million collisions per second. Therefore, a three step trigger system is used to reduce huge data sets to manageable levels, by selecting events for physics analysis containing interesting characteristics that can lead to future new discoveries. The level 1 (LVL1) trigger is hardware based and it reduces the data rate from 40 MHz bunch crossing down to 75 kHz using the custom build electronics, by processing the data from the calorimeters and muon detectors, searching for the events with large electromagnetic deposit or high p_T muon tracks.

1. The ATLAS experiment



(a) Small sector



(b) Large sector

Figure 1.5.: The view of the present (Run 1/2) ATLAS muon spectrometer layout in the $r - z$ plane [17]. Green (blue) chambers are MDT chambers in the barrel (endcap) regions of the spectrometer. The TGC, RPC, and CSC chambers are shown in red, white, and yellow, respectively [17]. The naming of the MDT chambers is based on their location in the barrel (B) or end-cap (E); assignment to inner (I), middle (M), outer (O) or extended (E) chamber layer; belonging to the large (L)/small (S) sector or for special chambers F, G, R, M . The sector number (1 – 16) and the sequence number of the chamber in a row are added to complete specification of the MDT chambers [4].

The level 2 (LVL2) trigger further reduces the rate down to 3.5 kHz, while the event filter (EF) at last reduces the rate down to 200 Hz. To be able to analyse the data permanently stored at the CERN computer center, a global computing network, the Worldwide LHC Computing Grid (WLCG), was created.

1.3. ATLAS detector upgrades

As a part of the High Luminosity LHC (HL-LHC) [11] project, a series of planned upgrades will gradually increase the luminosity of the LHC. Therefore ATLAS sub-detectors will undergo major modifications to be able to cope with new conditions, while exploiting the physics potential of the HL-LHC. The upgrades of the LHC are divided into two phases:

- The **Phase-I** upgrade of the LHC (during the Long Shutdown 2) is planned from 2019 to 2020, which will include upgrades of the injectors to increase LHC peak luminosity to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, with an aim of reaching the integrated luminosity of 300 fb^{-1} by the end of Run 3.
- The **Phase-II** upgrade is scheduled between 2024 and 2026 with the plan of installing new focusing magnets and crab - cavities, that will result in a total integrated luminosity for proton-proton collisions of 3000 fb^{-1} in the following years of operation.

The upgrades of the ATLAS detectors are organized in the foreseen phases.

The entire ATLAS tracking system will be replaced in the Phase-II, because of its expected sensor and front-electronics performance degradation due to the radiation damage [12]. A completely new silicon tracking system, named Inner Tracker (ITk) will consist of the Strip Detector surrounding a Pixel Detector and which must satisfy the following criteria: higher granularity, improved material budget and increased radiation hardness of the read-out components. More details about the ITk design can be found in [13, 14].

The Phase-I and Phase-II upgrades of the ATLAS LAr Calorimeter include replacement of the trigger system, read-out electronics and low-voltage power system due to limited radiation tolerance. The upgrades will provide higher-granularity and higher energy resolution, which is of importance for the trigger system, since it will give higher efficiency for identifying electrons, photons, τ leptons, jets and missing transverse energy at the high backgrounds in HL-LHC environment. During the Phase-II upgrade, the Tile Calorimeter will undergo major replacement of its on- and off-detector electronics. The details about planned ATLAS Calorimeter upgrades can be found in [15, 16].

The challenge for the ATLAS Muon Spectrometer in the harsh HL-LHC environ-

1. The ATLAS experiment

ment is to preserve its excellent muon identification, both standalone and combined with the inner detector. Therefore, during the Phase-I and Phase-II upgrades, the ATLAS Muon Spectrometer will undergo significant modifications, including the installation of new chambers. Planned upgrades include replacement of large part of front-end, trigger and read-out electronics as well as the redesign of the trigger and read-out system for RPC and TGC chambers and electronics system for the MDT chambers [17]. The New Small Wheel (NSW) project, planned for the Phase-I upgrade, includes the replacement of the CSC chambers and the MDT chambers of the innermost endcap wheels with small-strip TGC (sTGC) and Micro-Mesh Gaseous Structure chambers used for both triggering and precision tracking. In the Phase-I and Phase-II upgrade, new integrated muon tracking and triggering chambers (sMDT+RPC) are planned to be installed in the inner barrel layer of the ATLAS muon spectrometer.

Following the upgrade of the detector subsystems and facing much higher event rates and pile-up levels beyond its original design, the upgrade of the Trigger and Data Acquisition (TDAQ) system is foreseen, to support planned physics programme at HL-LHC. The TDAQ system upgrades are divided in Phase-I and Phase-II, whose details are given in [18, 19].

1.4. BIS78 upgrade project

The success of the muon spectrometer is based on high muon trigger efficiency and muon momentum resolution up to the TeV scale. However, in the transition region from the barrel to the end-caps, a non-negligible rate of the fake muon triggers has been observed. To suppress these fake muon triggers, the plan is to equip the transition region with additional Thin-Gap RPC during LHC's second long shutdown. Due to spatial constraints, MDT chambers already installed in this region (Figure 1.5a: chambers 7 and 8 in the BIS region) will be replaced by Small-Diameter Muon Drift Tube (sMDT) chambers. This Phase-I upgrade serves as a pilot project for the complete replacement of the BIS1–6 MDT chambers in LS3 by sMDT+RPC chamber modules that will have a very similar design [17]. The new chambers will be installed in the small sector of the barrel inner layer, at the ends of the toroid magnet coils.

Each BIS78 station will serve as integrated tracking and triggering detector and therefore will be composed of one sMDT chamber with two RPC triplets (BIS7 and BIS8). The scheme of the new Thin-Gap RPC chamber is shown in the Figure 1.6. Their characteristic is very fast detection and therefore are used as triggering chambers in the ATLAS muon spectrometer. New RPC chambers have twice thinner gas gaps and electrodes, as well as new highly sensitive amplifiers which improve the time resolution. Reduced operational voltage and lower achieved gas gain results in a longer lifetime, suitable for operation at HL-LHC conditions [20]. An example of the design of the new integrated sMDT+RPC chamber is shown in the Figure 1.7. There

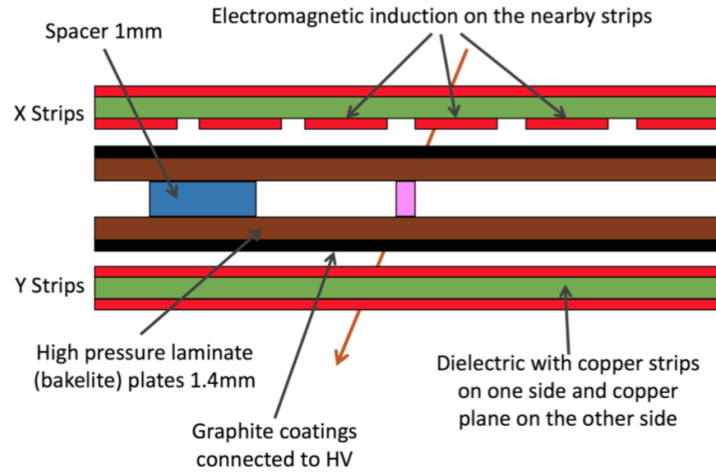


Figure 1.6.: Scheme of the Thin-Gap Resistive Plate Chambers for the new integrated tracking and triggering chambers of the ATLAS muon spectrometer [20]. The basic RPC unit consists of two parallel resistive plates forming a thin gas gap, where the primary ionization is multiplied by uniform electric field inside the gap.

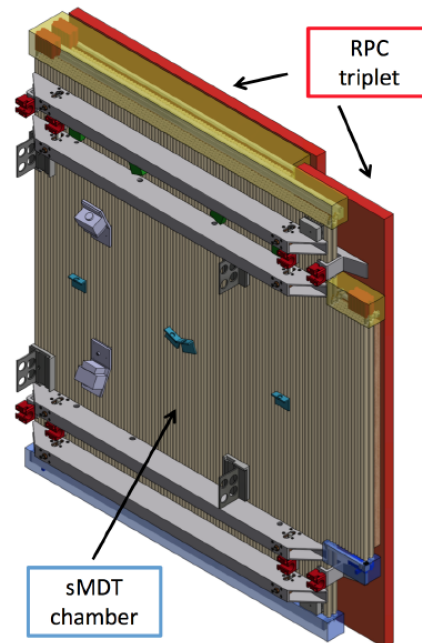


Figure 1.7.: A design of BIS78 station, consisting of a one sMDT chamber integrated with two BIS7 and BIS8 RPC triplets [20]

1. The ATLAS experiment

are 16 different types of BIS78 sMDT chambers with complex shapes, maximizing the coverage in the overlap region with the New Small Wheel, planned to be installed in the A and C side of the barrel [17]. This master thesis focuses on testing of the eight A-side BIS78 sMDT chambers, in order to check their functionality as a part of installation preparation. The details about their working principle, as well as mechanical assembly and read-out electronics will be described in the following chapter.

2. ATLAS BIS78 sMDT chambers

The Monitored Drift Tubes (MDT) as a part of ATLAS muon spectrometer, are precision drift chambers designed to provide good spatial resolution and high tracking efficiency independent of the track angle. Through the life of the LHC and ATLAS experiment, MDT chambers have demonstrated that they provide precise tracking over large areas. The goal of the ATLAS muon spectrometer upgrade is to increase the muon trigger efficiency, precise muon momentum measurement and to improve the rate capability of the muon chambers in the high-background regions of the HL-LHC [21]. To meet these requirements, small-diameter Muon Drift Tube (sMDT) chambers have been developed. In both cases, the basic detection element is a pressurized drift tube.

The muon momentum determination by ATLAS (s)MDT chambers is based on the deflection of a charged particle in the magnetic field. In the transverse plane, momentum can be determined as:

$$p[\frac{GeV}{c}] = 0.3 \cdot B[T]R[m], \quad (2.1)$$

for a particle with the electric charge $q = e$. By reconstructing the muon trajectory in the known magnetic field and determining the curvature radius R the muon momentum can be obtained. Therefore, tracking systems are organized as multiple layers of sensitive material, to provide spatial information about the particle detection in each layer, which is later used in track reconstruction. MDT and sMDT chambers in ATLAS are composed of three to four layers of drift tubes, organized in two multilayers and separated with the spacer.



Figure 2.1.: Image of the MDT (left) and the sMDT (right) tubes. [17]

The main (s)MDT parameters are listed in the Table 2.1. The major difference between MDT and sMDT chambers is the drift tube diameter (29.970 mm for MDT

2. ATLAS BIS78 sMDT chambers

and 15 mm in the case of sMDT chambers) and they are shown in Figure 2.1. As an operating gas Ar/CO_2 (93/7) mixture is chosen, at the absolute pressure of 3 bar [4].

Parameter	MDT	sMDT
Tube material	Aluminium	Aluminium
Outer tube diameter	29.970 mm	15.000 mm
Tube wall tickness	0.4 mm	0.4 mm
Wire material	gold-plated W/Re (97/3)	gold-plated W/Re (97/3)
Wire diameter	50 μm	50 μm
Gas mixture	Ar/ CO_2 (93:7)	Ar/ CO_2 (93:7)
Gas pressure	3 bar (absolute)	3 bar (absolute)
Gas gain	2×10^4	2×10^4
Wire potential	3080 V	2730 V
Maximum drift time	~ 700 ns	~ 190 ns
Average resolution per tube	83 μm	106 μm
Drift tube muon efficiency	95%	94%

Table 2.1.: Main MDT and sMDT chamber parameters [17]. Average resolution per tube and drift tube muon efficiency given in the case of no irradiation.

2.1. Functioning principle of cylindrical drift tubes

The drift tubes used in the ATLAS muon spectrometer are cylindrical gaseous detectors operating in proportional mode. The wall of the tube is grounded, while high voltage is applied to the wire in the centre of the tube (anode). When a muon transverses the drift tube, it has enough energy to ionize the gas atoms along its trajectory (Figure 2.2), resulting in the creation of free electron - positive ion pairs. The number of the electron-ion pairs created depends on the energy required to create one ion-electron pair, which is a function of the used gas.

In the gas, the motion of created free electrons and ions is described by two processes: diffusion and drift in the electric field. **Diffusion** is a characteristic uniform movement of electrons and ions in the absence of the electric field. In this process, ionization products quickly reach thermal equilibrium by losing energy in the collisions with the gas molecules [22]. To collect created primary ionization, an electric field is applied to the central wire, which results in the **drift** of charges along the field lines. Electrons drift to the anode due to the electric field in the tube, while positive ions move towards the wall of the tube. Drift velocity is given as:

$$\vec{v} = \mu \vec{E}, \quad (2.2)$$

where μ is charge mobility. Drift velocity of the electrons is higher compared to ions, since they are much lighter [22].

2.1. Functioning principle of cylindrical drift tubes

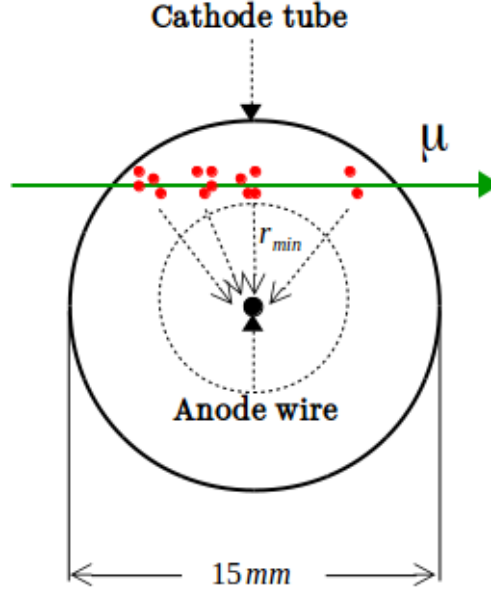


Figure 2.2.: Cross section of the sMDT.

The electric field in the tube is radially symmetric:

$$E(r) = \frac{V}{\ln \frac{R}{r_{min}}} \frac{1}{r} \quad (2.3)$$

where r_{min} is the radius of the anode wire and R is the inner radius of the tube. V refers to the potential difference between anode wire and tube wall. Due to such electric field, electron near the anode will gain sufficient kinetic energy to cause secondary ionisations which results in avalanche of the secondary electrons. This process amplifies the primary signal and enables its detection. Since electrons have greater mobility, the avalanche has a shape of a liquid drop, where electrons are grouped near the head and positive ions are trailing behind [22]. A signal is formed by the movement of the ions and electrons towards the electrodes.

Diethorn The gas amplification G , which is the ratio of charge in the avalanche and the amount of primary ionization, can be described as a function of the applied voltage using Diethorn's formula [23]:

$$\ln G = \frac{r_{min} E(r_{min}) \cdot \ln 2}{\Delta V} \cdot \ln \frac{E(r_{min})}{E_{min}(\rho_0) \frac{\rho_{gas}}{\rho_0}}, \quad (2.4)$$

where $r_{min}=0.025$ mm, $R=7.1$ mm, ΔV is the potential difference through which an electron passes between two successive ionizations, while E_{min} is the electric field needed for the avalanche to start. Both parameters have to be measured and for the used gas mixture $ArCO_2$ (93/7) their values are: $\Delta V = 34$ V and $E_{min} = 24 \frac{kV}{cm}$. The MDT and sMDT provide gas gain of $2 \cdot 10^4$ as stated in the Table 2.1, which is relatively low gas gain, but has been chosen to prevent risk of the tube ageing.

2.2. Design and working principle

In the assembled chamber, many drift tubes are glued to each other, allowing muon trajectory reconstruction. The principle is visualized in Figure 2.3.

When a muon transverses such chamber, it will ionize the atoms of the gas in each passed tube. The discriminator is used to measure the time at which signal pulse crosses the predefined threshold value, that is the time at which electrons arrive at the anode wire. However, to reconstruct the muon trajectory we need information about the time needed for electrons to reach the anode wire from their creation point in the drift tube, known as the drift time. For each tube, the electron drift time can

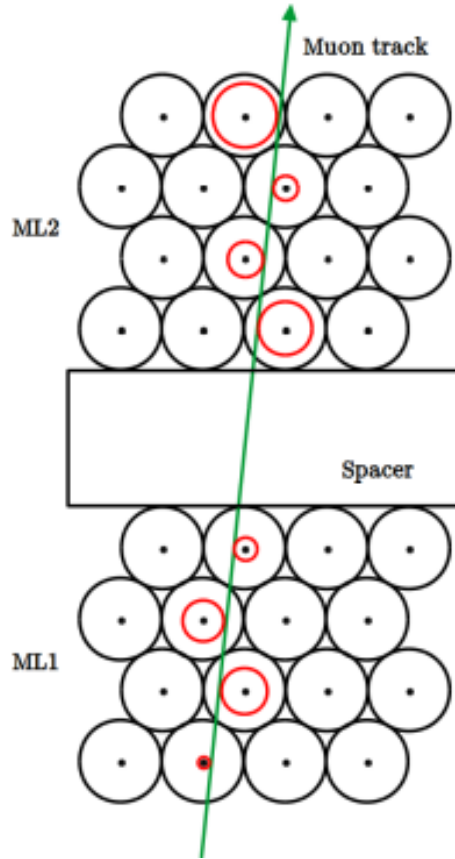


Figure 2.3.: Cross section of the sMDT chamber, with eight layers of tubes organised in two multilayers. The muon trajectory (green arrow) is reconstructed using eight drift radii, represented by red circles.

be determined as a difference between previously acquired threshold crossing time and time when the muon passed through the tube, which is obtained by additional detectors, such as scintillating counters. The drift time depends on the geometry of the drift tubes, the gas composition and pressure, as well as applied high voltage, temperature and magnetic field. The comparison of the typical drift-time spectra of the MDT and sMDT chamber is shown in the Figure 2.4. The maximum drift time of the sMDT chambers is almost 4 times smaller compared to MDT chambers.

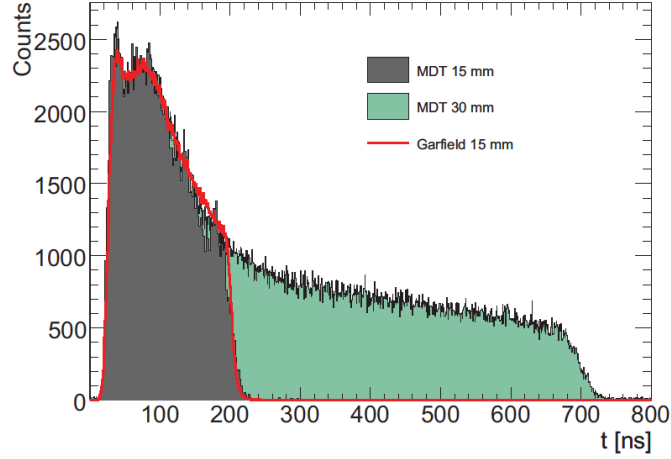


Figure 2.4.: Drift-time spectra of 30 mm and 15 mm diameter drift tubes for the same gas mixture and gain. The measurements with cosmic ray muons are compared to Garfield simulations.[24].

The drift time can be converted to drift radius, which is the shortest distance from the muon track to the anode, using the calibrated space-to-drift-time (r - t) relation, shown in Figure 2.5. The exact shape of the r - t relation depends on the temperature,

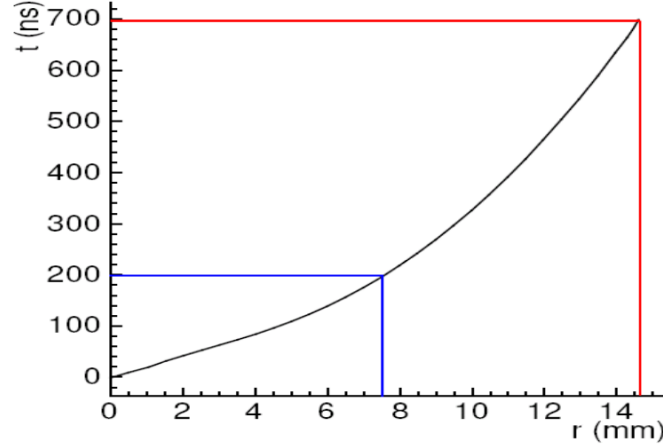


Figure 2.5.: r - t relation of the MDT chamber [17]

pressure, magnetic field and total hit rate in the tube. As shown in the Figure 2.5 the r - t relation is not linear for the chosen gas mixture of Ar/CO_2 (93/7). However, this gas mixture is chosen over more linear gas mixtures due to its good ageing properties which allows avoiding the polymerization on the wire. The advantage of the sMDT chambers comes from its dimensions, since it limits the r - t relation to the more linear region. Two methods are used for space-to-drift time relationship determination: autocalibration and integration method.

To determine space-to-drift time relationship, the integration method assumes homogenous muon hits along the drift tube. Therefore, the number of hits ΔN per

2. ATLAS BIS78 sMDT chambers

time interval Δt is given as:

$$\frac{\Delta N}{\Delta t} \approx \frac{dN}{dt} = \frac{dN}{dr} \frac{dr}{dt} = \frac{N}{r_{max}} \frac{dr}{dt}, \quad (2.5)$$

where N is the total number of entries in the drift time spectrum, and r_{max} refers to the maximum drift radius [25]. By integrating $\frac{dr}{dt} = \frac{r_{max}}{N} \frac{dN}{dt}$ in the range of $[t_0, t_{max}]$ we can obtain space-to-drift time relationship:

$$r(t) = \int_{t_0}^{t_{max}} \frac{r_{max}}{N} \frac{dN}{dt}. \quad (2.6)$$

The autocalibration method reconstructs the muon tracks using initial space-to-drift time relationship, obtained from integration method, simulation or previous measurement. After the track reconstruction, the residuals are calculated as a difference between measured drift radius (r) and distance of the reconstructed track to the wire (d), that is:

$$\Delta(t) = r(t) - d. \quad (2.7)$$

The standard autocalibration method corrects the initial space-to-drift time relationship iteratively, by subtracting the mean value of the residuals in the time interval t [25].

After obtaining a precise space-to-drift time relationship, the measured drift times can be converted to drift radii, represented with the red circles on the Figure 2.3. They are further used to reconstruct the muon trajectory as a tangent to the drift radii in the tubes with a recorded hit.

2.2.1. Advantages of small-diameter drift tubes

The performances of the MDT and sMDT chambers were studied [24, 26], showing several advantages of the sMDT chambers. Smaller maximum drift time and half size cross-section exposed to radiation results in an about eight times lower occupancy for sMDT chambers [17]. This makes sMDT chambers suitable muon precision tracking detectors not only for the conditions in the HL-LHC, but for future hadron colliders. One of the advantages of the small-diameter muon drift tubes is in the reduction of the tube diameter itself. Positive ions created in the vicinity of the wire in the ionization process have smaller mobility compared to the electrons, which result in their slow drift towards the tube walls. This will lead to the creation of space charge that can modify an electric field in the tube, which will result in the reduction of the gas amplification. Since drift velocity depends on the electric field, space charge fluctuations can cause fluctuations of the drift time and in this way affect spatial resolution of the chamber. As space charge effects are present at large radii, they are avoided in the case of sMDT chambers. On the other hand, unchanged operational parameters such as gas gain, gas mixture and pressure, but different wire potential,

allows for the sMDT chambers to share all the advantages of the MDT chambers and at the same time enables the construction of the integrated tracking and triggering sMDT+RPC chambers that can overcome spatial constraints in the ATLAS muon spectrometer.

sMDT chambers have already found their application in the ATLAS muon spectrometer. In 2014, two BME sMDT chambers with two thin-gap RPC chambers mounted on top and bottom, were installed in the bottom sector of the barrel part of the muon spectrometer and they have been in operation since the start of LHC Run 2. In the winter shutdown 2016/2017, 12 BMG sMDT chambers were installed in the detector feet in sectors 12 and 14 of the barrel [27]. The next installation of the sMDT chambers is planned for the 2019-2020 as a part of the BIS78 pilot project, following by the installation of 96 BIS1-6 chambers in the 2024–2026.

2.3. BIS78 sMDT chamber assembly

The chamber assembly methods have been optimized for mass production, minimizing manpower and time needed for construction while ensuring high mechanical accuracy of the wire positioning. The sense wires with a diameter of $50\ \mu\text{m}$ are inserted into tube with 0.4 mm thick aluminium chromated walls and fixed in the insulating plastic endplugs at both ends of the tubes. The detailed view of the individual tube can be seen in the Figure 2.6 while the more details about the design and fabrication can be found in [17]. After successful quality assurance tests, the

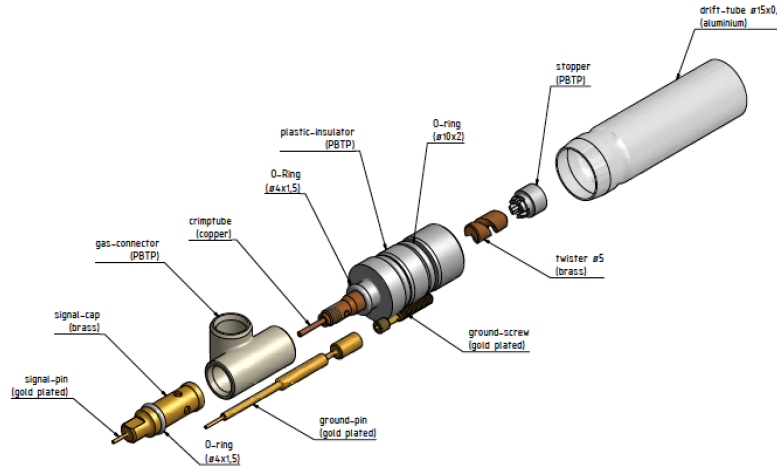


Figure 2.6.: Exploded view of an sMDT endplug with interfaces for precise wire positioning and measurement, for gas and high-voltage supplies, and for read-out electronics [21]

drift tubes are assembled into chambers in a climatized clean room. The chamber assembly consist of the following steps:

2. ATLAS BIS78 sMDT chambers

- Gluing the tubes to each other (to form multilayer) and onto the support frame and spacer using two-component epoxy glues (as for the MDT chamber construction) applied by an automated glue dispenser. The alignment sensor platforms are used for precise mounting.
- Insertion of the gold-plated ground connection screws to enable reliable electrical contact.
- Mounting of the chromatized aluminium ground foils of 0.2 mm thickness on the multilayers, which serve as backplanes of the Faraday cages and provide common grounding for the tubes of a multilayer close to the tube walls.
- Mounting of the gas connections.
- Addition of the ground pins onto previously inserted ground screws to allow connection to read-out and high-voltage distribution boards, after which chamber undergoes wire positioning measurement.
- Mounting of the parallel gas distribution system (Figure 2.7).

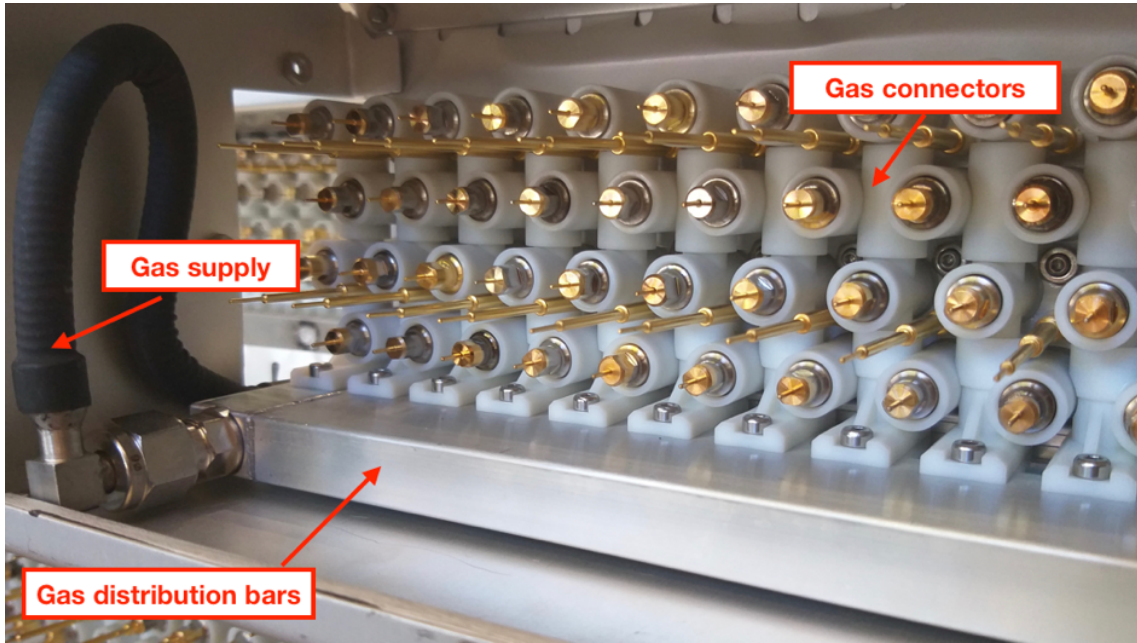


Figure 2.7.: Gas distribution system made of interconnected plastic gas connectors and gas distribution bars.

The gas distribution system is needed to fill drift tubes with the chosen gas mixture. The gas for each tube is provided by injection molded plastic gas connectors, that are interconnected in the direction perpendicular to the chamber plane, connecting drift tubes to the aluminium gas bars mounted on the read-out and high-voltage side of the chamber. The gas leakage rate is required to be below $2n \cdot 10^{-8} \text{ bar} \frac{\text{l}}{\text{s}}$, for a chamber with n tubes at the 3 bar pressure [17].

2.3. BIS78 sMDT chamber assembly

An in-plane alignment system consisting of two CCD cameras covered in boxes, four lenses in the middle of the chamber surface and two LEDs, is used to monitor the deformation of the chamber during its operation [28].

Mechanical chamber assembly is followed by the installation of the hedgehog and mezzanine cards and mounting of the Faraday cage, whose details will be presented in the following section. The assembled chamber, before mounting the gas system and electronics, is shown in the Figure 2.8.

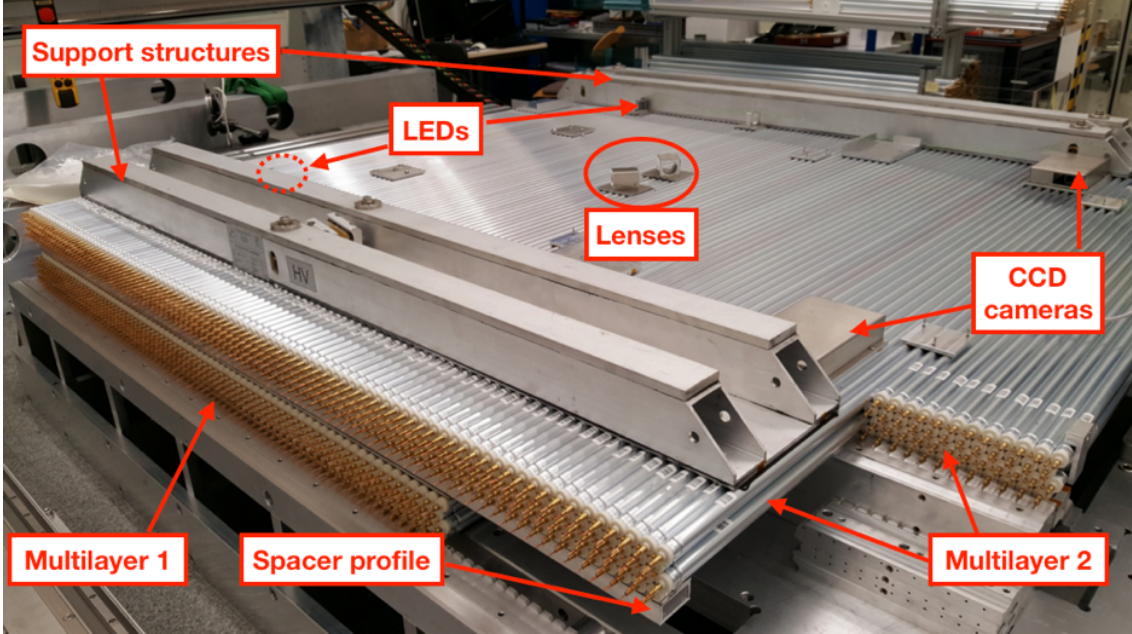


Figure 2.8.: An assembled sMDT chamber, with two multilayers of drift tubes separated by the spacer. The elements of the in-plane alignment system are marked [28].

Complete details about BIS-78 chambers such as the number of the tubes or length of tubes in each chamber can be found in sMDT Parameter Book [29].

2.4. BIS78 sMDT chamber electronics

2.4.1. High voltage side

Two high voltage (HV) lines dedicated to each multilayer are split into eight using a HV splitter box. To eliminate possible electromagnetic pick-up by the cables, from the HV power supply to the splitter box, low-pass filters are implemented in the box. HV is distributed to the drift tubes via two on-chamber boxes, one for each multilayer, shown in the Figure 2.10a. From the on-chamber box, the HV is

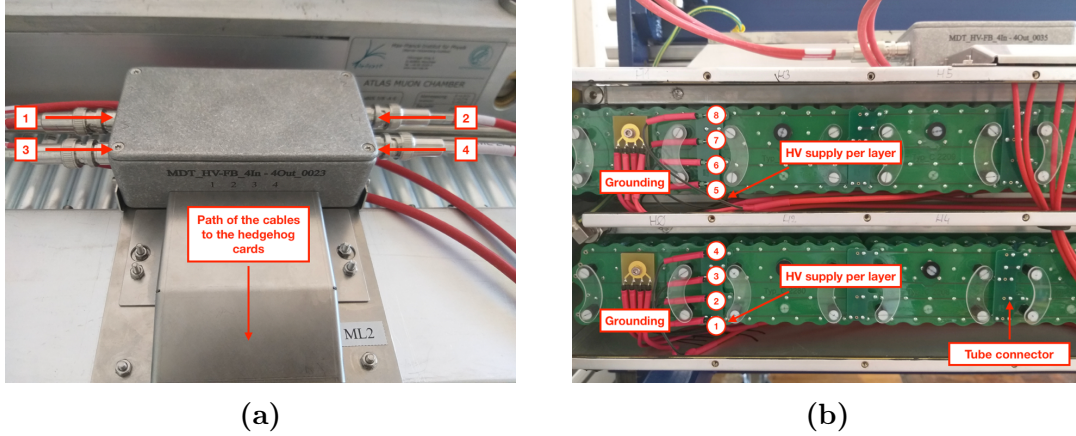


Figure 2.9.: HV side of the chamber: (a) One of boxes mounted to the chamber to distribute HV to each layer, (b) Red cables providing HV and ground connection.

distributed to each layer of drift tubes, by connecting the brought HV lines to the HV hedgehog cards, shown in the Figure 2.10. Each HV line is used for one layer of the tubes, therefore $4 \text{ layers} \times 6 \text{ cards}$ are connected to single hedgehog card.

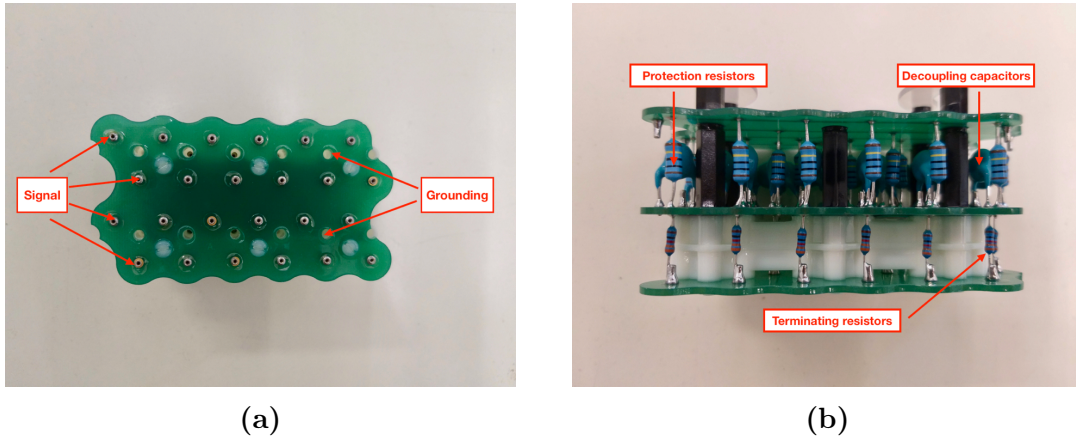


Figure 2.10.: HV hedgehog card (a) Connecting side to the tubes, with marked openings for the signal and grounding pins, (b) Components of the HV hedgehog card

Beside providing necessary HV supply to the drift tubes, hedgehog cards enable secure grounding. HV is further carried from one card to the other with the connectors mounted to the hedgehog cards. Each hedgehog card contains terminating resistor, that suppresses signal reflection at the end of the open wire. It contains capacitors to prevent a short-circuit between the anode and the cathode by the termination resistor and protection components to ensure HV stability. The mounted hedgehog cards are enclosed in the Faraday cage.

2.4.2. Read-out side

On the read-out side, signal distribution boards with mezzanine cards are mounted and enclosed in the Faraday cage. The cross-section of the Faraday cage is shown in

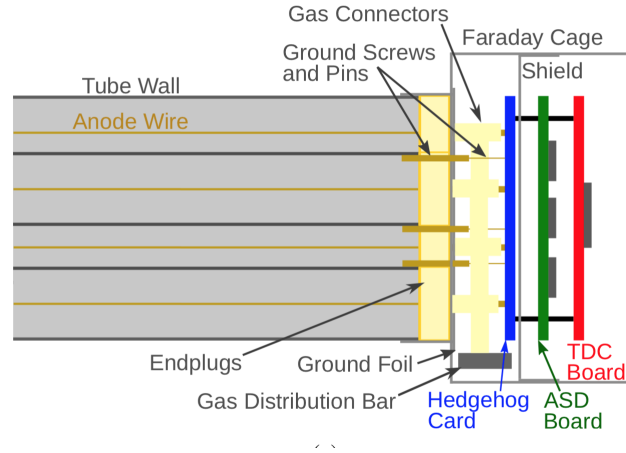


Figure 2.11.: The layout of the Faraday cage on the RO side for BIS chambers [28]

the Figure 2.11. It consist of 0.5 mm thick chromatized aluminium walls, a 0.2 mm thick chromatized aluminium ground foil as a backplane of the Faraday cage and chromatized aluminium shielding plates placed between hedgehog and mezzanine cards on the read-out side. The ground screws between the tube layers as well as the ground pins enabling the connection to the signal distribution cards are indicated.

A single signal distribution hedgehog card capacitively decouples signal from 24 drift tubes and leads them to active read-out electronics component called mezzanine card (Figure 2.12), placed on the top of the hedgehog cards. The active read-out component consist of a board in the middle layer, carrying 3 ASD¹ chips [30] and TDC ² chip with FPGA placed on the top layer. When a muon passes through the chamber, it generates the signal through the ionization process described in Section 2.1.

A block diagram of one of the eight channels in the ASD chip is shown in the Figure

¹Amplifier - Shaper - Discriminator

²Time to Digital Converter

2. ATLAS BIS78 sMDT chambers

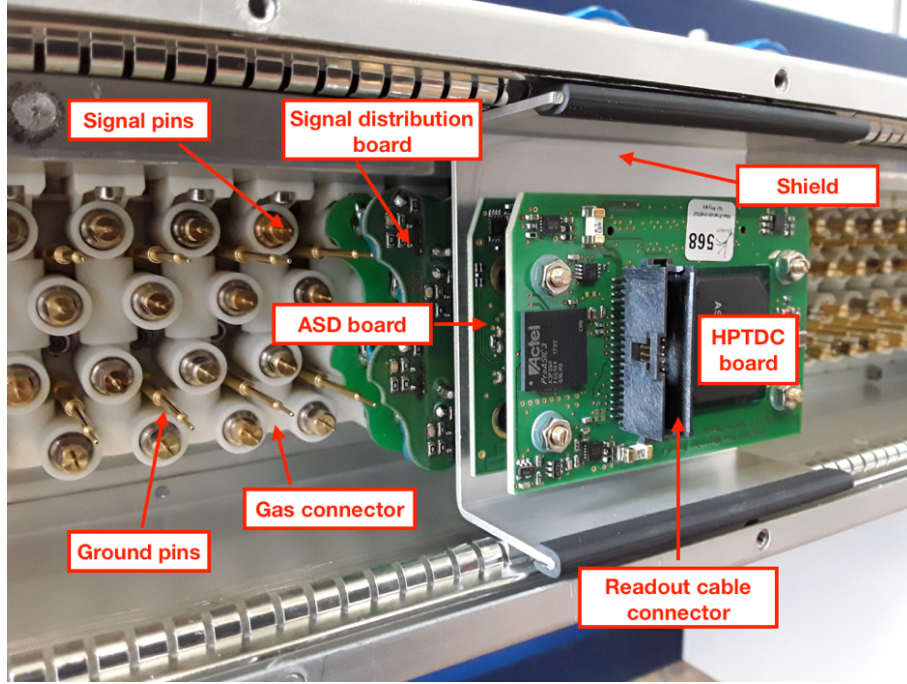


Figure 2.12.: Readout side of the sMDT chamber

2.13. On the mezzanine cards, each ASD chip amplifies and shapes the raw signals from 8 sMDT tubes before sending it to the discriminator. The ASD chip can

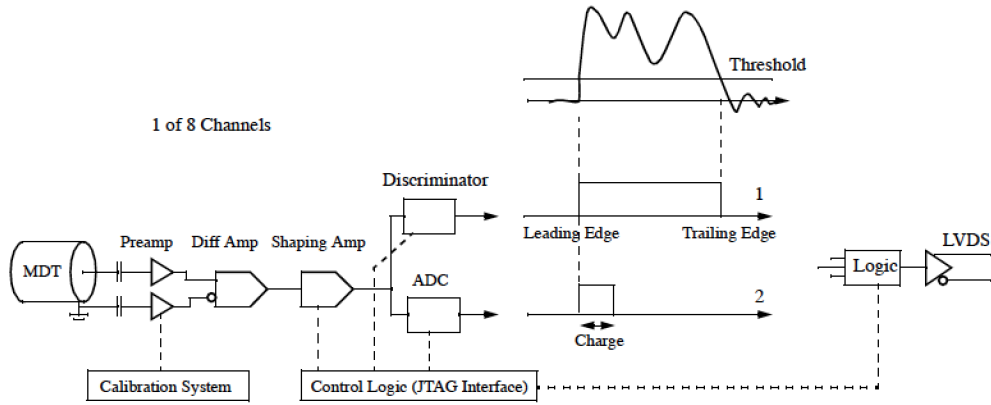


Figure 2.13.: Block diagram of one ASD channel [31]

operate in two [30] modes:

- **ADC mode (default)** in which the width of the output signal represents the charge measured in the leading edge of the signal from the sMDT. The rising edge contains the timing information.
- **Time-over-threshold (TOT mode)** where the output logic signal is high as long as the shaped signal from the sMDT tube is above the chosen threshold value. Multiple threshold crossings are possible, while the rising edge of the first (main) pulse contains the timing information for the event.

Parameter	Nominal value	ATLAS value	Range	Units
DISC1 Threshold	-39	-39	-255 - +255	mV
DISC1 Hysteresis	2.5	8,75	0–19	mV
Wilkinson ADC int. gate	20	18.5	8-45	ns
DISC2 threshold	30	94	32–256	mV
Wilkinson discharge current	5.9	4.5	2.4–7.3	μA
Channel mode	ON	ON	ON, HI, LO	-
Operation mode	ADC	ADC	ADC, ToT	-

Table 2.2.: Programmable parameters of the ASD chip with nominal [30] and ATLAS value [26]

The programming of the ASD chip is done via a JTAG serial string that is passed from the CSM³ via the TDC chip. Discriminator threshold and hysteresis can be adjusted. Programmable parameters and nominal/ATLAS values are given in the Table 2.2, while more details about their settings can be found in the ASD Users Manual [30].

If the signal exceeds the pre-defined threshold value, a digital signal is sent to TDC to stop time measurement that was started when the particle passed through the detector. The TDC stores the arrival times of both leading and trailing edges of the signal in a buffer memory of 256 words. However, the leading edge of the pulse is important for the drift time measurement. To avoid multiple crossing of the threshold caused by the electrons arriving late from the same track, discriminator can be disabled for a chosen time (dead time).

The mezzanine cards are connected via the blue shielded twisted-pair cable to the on-chamber multiplexer known as the CSM which among others has functions of receiving the trigger, timing, and control signals from the TTC⁴ system and further delivering these signals to all mezzanine boards on the sMDT chamber. From the maximum 18 mezzanine cards, CSM multiplexes the serial data into a single output stream and delivers it via an optical fibre cable to the Data Acquisition (DAQ) system. [31].

Every MDT chamber has MDT-DCS module, which monitor chamber's temperature, magnetic field and is used to programme and configure front-end electronics on the CSM and Mezzanines Boards. The communication between computer and MDM module is established via a CAN-bus.

³Chamber Service Module

⁴Timing, Trigger and Control

Part I.

BIS-78 sMDT chamber tests

Introduction

The sMDT chambers are designed with the purpose of precisely tracking muons, particles that can reach outer parts of the detector without significant energy loss. To verify chamber functionality, the detector can be exposed to muon beams, produced at accelerator facilities. Similar tests can be performed using cosmic rays. Primary cosmic rays, reaching Earth's atmosphere from outside the Solar system, are mainly composed of high energy protons. In the interaction with the atmosphere, where atmosphere serves as a calorimeter, they create a shower of particles that reach Earth's surface and are detectable. At the sea level, muons and neutrinos are the most abundant particles and they can be studied with different experiments. Muons are created typically in the atmosphere at the height of 15 km and they lose about 2 GeV in the ionisation processes on their way to the surface. The mean energy of muons at the Earth's surface is ≈ 4 GeV. The integral intensity of vertical muons above 1 GeV/c at sea level is $I \approx 1\text{cm}^{-2}\text{min}^{-1}$ for horizontal detector. The angular distribution of muons is a function of their energy. For muons with the energy of about 3 GeV the angular distribution at the surface is proportional to $\cos^2(\theta)$, where θ is the zenith angle. For lower energies the distribution becomes steeper, while it flattens at the higher energies [32].

For the purposes of this thesis, cosmic ray muons are used to verify functionality of the sMDT chambers. The main disadvantage of cosmic ray muons for such test is longer required measurement time due to the muon rates at the ground level, as well as the large number of low energy muons which can be prone to larger multiple scattering angles in the detector.

The measured quantities are:

- Noise rates, without and with applied high voltage;
- Spatial resolution of the chamber;
- Muon detection efficiency of each tube in the chamber.

3. Experimental set-up

3.1. Cosmic test stand

Eight A-side sMDT chambers are individually tested in the cosmic stand at Max Planck Institute for Physics in Munich, whose schematic detection set-up is shown in the Figure 3.1. The cosmic stand provides a computer controlled HV power supply. Each chamber is equipped with a HV distribution on one side and a read-out system on the other side. Scintillating counters, needed to provide muon triggers, were placed in the direction perpendicular to the tubes at about 30 cm above the tested chamber. The test stand is equipped with a gas system to provide chosen ratio of the

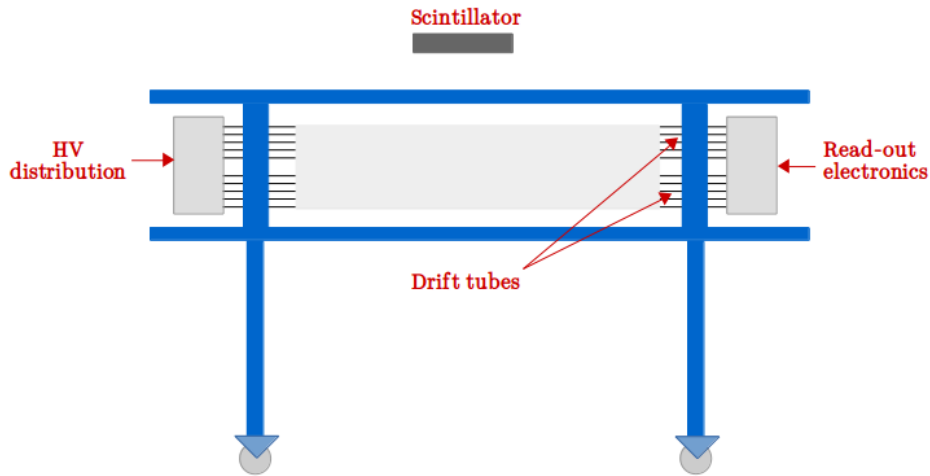


Figure 3.1.: Schematic drawing of the cosmic stand at MPI for Physics.

Ar/CO_2 gas mixture and manometer to monitor the pressure. In order to avoid the contamination of the gas in the chamber, since it significantly can change maximum drift time, chambers are first evacuated and then filled with the operational gas mixture, till the pressure in the chamber reaches 3 bar.

The set-up contains modules providing the trigger, a computer controlled HV supply for scintillating counters and manually controlled low voltage supplies needed for the read-out electronics.

3. Experimental set-up

3.1.1. Trigger and Read-Out Scheme

The trigger system of the experimental set-up consist of the types of triggers:

- Random trigger used for determination of the noise rates,
- Cosmic muon trigger used for spatial resolution and detection efficiency determination.

The trigger scheme of the cosmic muon trigger at MPI is given in the Figure 3.2.

Two scintillating counters are used in coincidence to provide trigger on cosmic muons. Trigger logic is based on a set of Nuclear Instrument Modules (NIM) in the cosmic test stand set-up:

- *16 Channel Low Threshold Discriminator* (Mod. N845) [33] which accepts 16 inputs, and provides 2×16 NIM outputs and 16 negated outputs. The discriminator thresholds are adjustable for every channel, in a range of -1 mV to -255 mV in the steps of 1 mV ,
- *Triple 4- Fold Logic Unit* (Mod. N405) [34] divided into three independent sections, each accepting up to four standard NIM inputs. Logic functions AND/OR and MAJORITY are available for each section. Each section provides VETO input and 4 outputs: 2 normal, 1 negated and 1 linear.
- *Dual Timer* (Mod. N93B) [35] containing two identical trigger pulse generators. The start of the trigger can be provided as an external signal or with the *START* switch, giving a standard NIM logic signal of -0.8 V , while timer re-triggering is done by *END MARKER* funcion.

If signals from scintillating counters cross the chosen threshold value, the discriminator sends logic signals to the logic unit. A trigger is generated only if two signals from the discriminator and the negated output of the previous trigger from the dual timer are in coincidence. The generated trigger signal is further sent to the TTC system with an internal clock of 40 MHz.

The read-out electronics scheme for the experimental set-up is given in the Figure 3.3. The TTC system distributes trigger signal and control information through the CSM to the chamber front-end electronics, which starts the data aquisition. Programming and configuration of the CSM and mezzanine cards is done via the so-called ELMB module. A single BIS78 chamber may have either 648 or 744 drift tubes which corresponds to 27 to 31 mezzanine cards. Data are read out of each TDC individually via a 40 Mbit/sec serial link to two CSMs, where each multiplexes the 18 serial links into a single optical fiber used to transmit the data to the DAQ PC. Therefore, every chamber is tested with cosmic rays separatelly for each CSM.

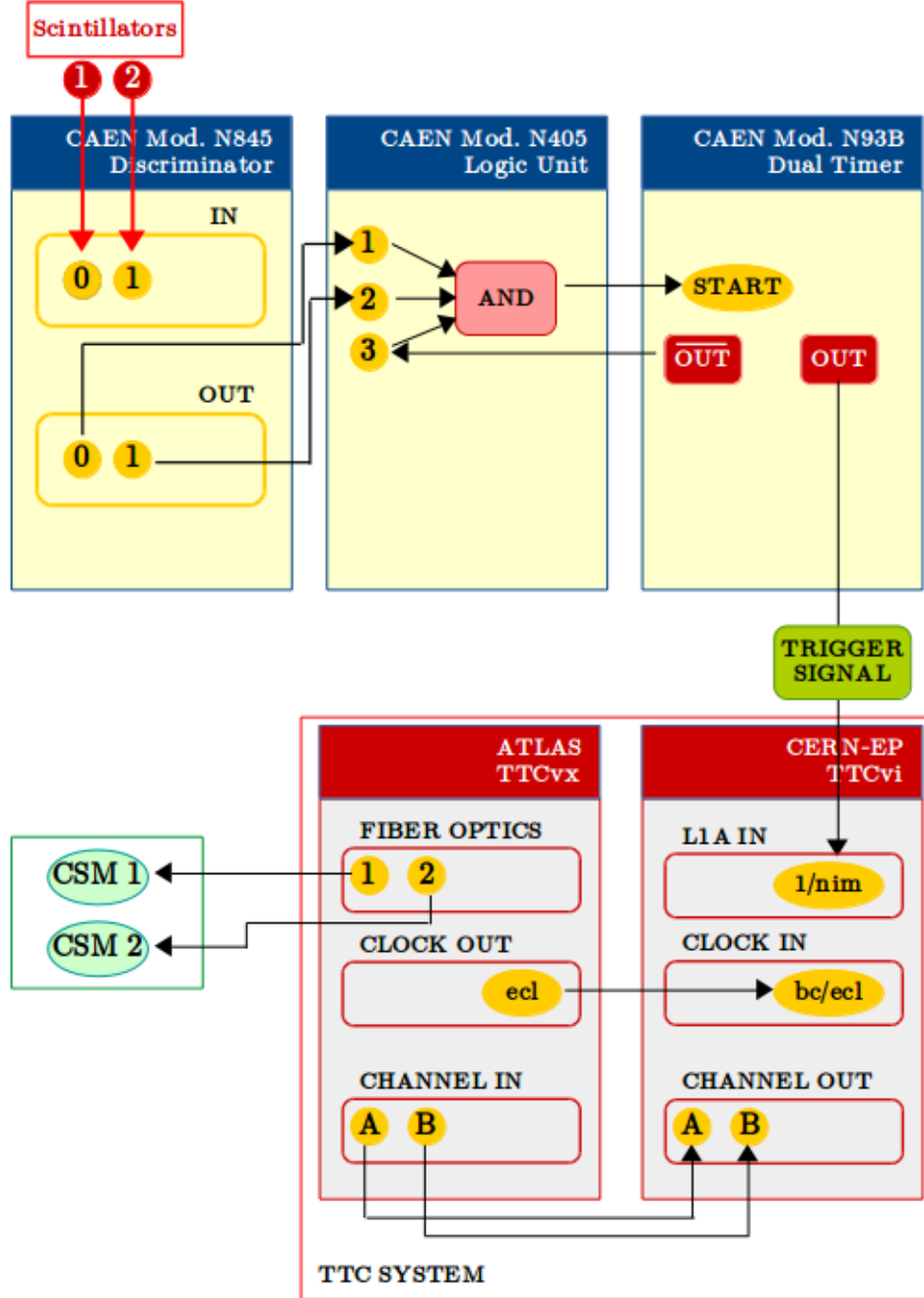


Figure 3.2.: Trigger scheme of the MPI test stand

3. Experimental set-up

The random trigger for the noise measurement is provided directly from the dual timer, with fixed length and frequency, to the TTC system.

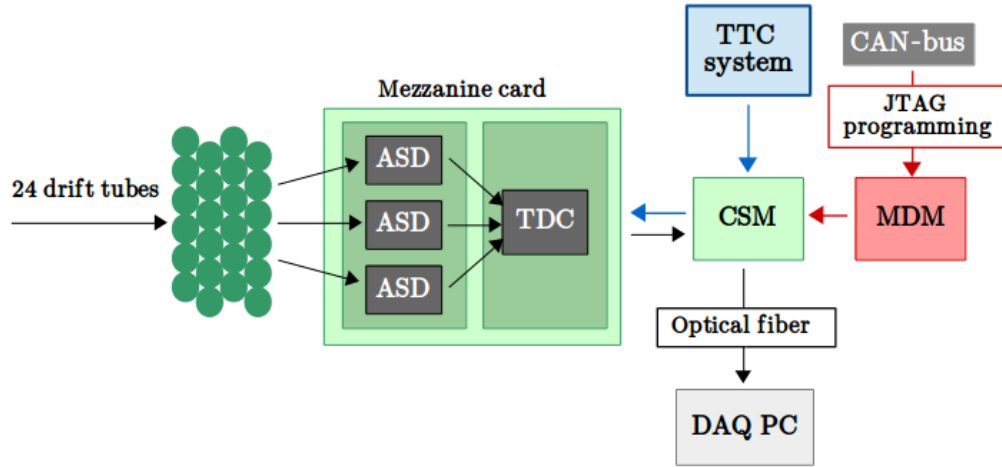


Figure 3.3.: The scheme of the sMDT read-out electronics

4. Noise rate measurement

Noise rates are determined as a function of different threshold and hysteresis values, by providing random trigger signals to the CSM, which starts the measurement. Signals exceeding pre-defined threshold value are counted. The measurement for the noise rates is performed for different thresholds, first without and then with applied high voltage, listed in the table 4.1.

Code	Threshold value (mV)
103	-49
106	-43
108	-39
110	-35
112	-31
114	-27

Table 4.1.: Codes and corresponding threshold values used for noise studies.

The discriminator threshold values can be computed using following expression:

$$\text{Threshold [mV]} = (2 * N - 255), \quad (4.1)$$

where N is code number [30].

The noise rates are defined as:

$$\text{noise rate per tube} = \frac{\text{events per tube}}{\text{active time window} \times \text{total number of triggers}} \quad (4.2)$$

and are determined for each tube in a chamber.

In addition to the predefined threshold value, adjustable hysteresis for the timing discriminator, based on a Schmitt trigger, is used to increase noise immunity. In circuits with only one threshold input, noisy input signal near the predefined threshold value can cause multiple threshold crossings. With the discriminator hysteresis applied, the effective threshold is higher and multiple threshold crossings are avoided. The hysteresis is set by a 4-bit code in following way:

$$\text{Hysteresis} = 1.25 \text{ mV} \cdot N, \quad (4.3)$$

where $N = 0, 1, \dots, 15$ [30]. Default hysteresis is given by code 2, while ATLAS settings correspond to hysteresis 7. A threshold of -39 mV at a hysteresis of 2.5 mV corresponds to the signal created by 20 primary electrons [30]. The noise measurements are performed for both hysteresis in off-chamber and on-chamber measurement.

4. Noise rate measurement

4.1. Off-chamber measurements

The ASD chips on mezzanine cards have threshold variations due to the production process. Therefore, to determine intrinsic noise levels, each card is tested individually before the chamber assembly. The testing set-up is shown in the Figure 4.1. The set-up consist of the HV and signal distribution system (hedgehog cards) and

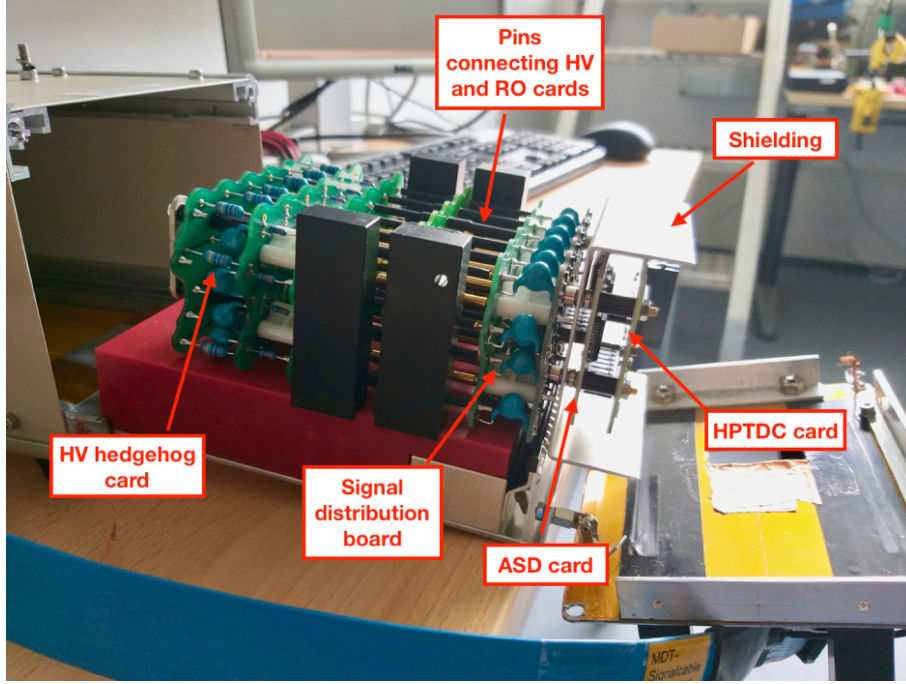


Figure 4.1.: Testing set-up for the off-chamber noise determination

array of pins to establish connection between HV and read-out card and recreate on-chamber conditions. The entire set-up is placed in a Faraday cage, which provides shielding from external influences that can have impact on measured values. The test is performed for two hysteresis settings and six different thresholds listed in the Table 4.1.

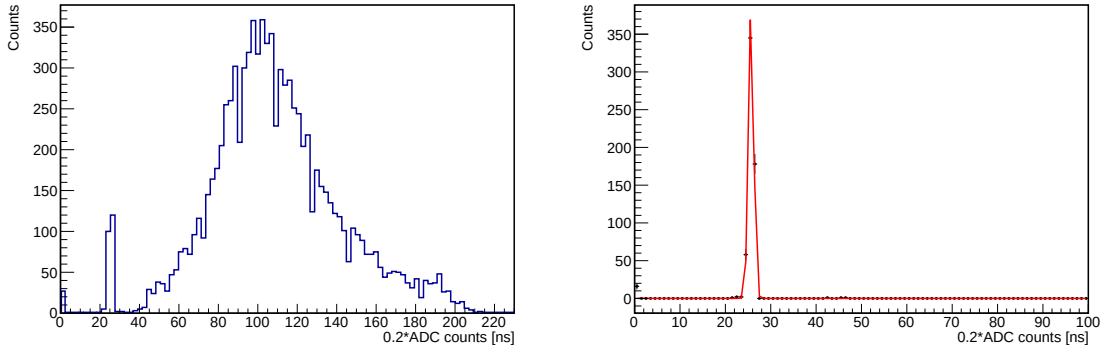
4.2. On-chamber measurements

Once a chamber is fully assembled, the noise measurement is performed for the entire chamber in the cosmic ray test stand (Figure 3.1), for the first five thresholds from the Table 4.1. For comparison of the data with the off-chamber test, it is necessary to know the location of each mezzanine card on the chamber, which is ensured by knowing the identification code of each mezzanine card mounted to the chamber.

5. Drift tube calibration

5.1. Pedestal determination

The drift time spectrum measured with the chambers contained recorded incoming muons and noise component. Before determining the drift time, as a crucial step for the track reconstruction, the electronics noise contribution has to be eliminated. This can be done using the ADC spectrum (Figure 5.1a), which corresponds to the collected charge. The majority of the electronics noise has a peak before the ADC spectrum. Therefore, the noise pedestal can be determined by fitting the ADC spectrum for the lowest threshold (-31 mV) obtained during noise measurement of each tube in the chamber with a Gaussian function, where the mean of the distribution represents the noise pedestal.



(a) ADC spectrum recorded for one tube in the A4 chamber (b) Pedestal determination for one tube of the BIS-78 A4 chamber.

Figure 5.1.

The example of the ADC pedestal determination for one tube of the A4 chamber is shown in the Figure 5.1b, with $\mu_{ped} = 25.54$ and $\sigma_{ped} = 0.68$. For tubes with lower statistics in the ADC spectrum, where a pedestal determination fails, the mean of all other tubes in the chamber is used. Determined values are used to subtract the noise from the drift time spectra, by requiring that $ADC\ count > \mu_{ped} + 3 \cdot \sigma_{ped}$, leaving only detected muon hits in the measured spectrum.

5.2. The drift time spectrum

To accurately measure drift radii it is required to have high drift time resolution. However, the drift time t_{drift} is not measured directly. It is obtained from the time measured by the TDC chip t_{TDC} , which in used experimental set-up consists of several components:

$$t_{TDC} = t_{drift} + t_{delay} - t_{trigg}, \quad (5.1)$$

where:

- t_{delay} refers to the delay in the propagation of the sMDT signal in the tube from the track along the wire to the read-out electronics, as well as delay contributions due to the to the cabling and front-end electronics;
- t_{trigg} is the time when the coincidence signal of several trigger detectors gives the start pulse for the read-out electronics.

The term $t_0 = t_{delay} - t_{trigg}$ is the same for all tubes. However, variations of few nanoseconds in t_0 values from tube to tube can exist. Therefore to determine drift time as $t_{drift} = t_{TDC} - t_0$, t_0 has to be determined for each tube individually. In order to do so, a fitting procedure for the drift spectra of the sMDT chambers has been developed to determine the start time of the measured time spectrum.

The rising edge fitting

The rising edge is fitted with the modified Fermi function:

$$G(t) = p_0 + \frac{A_0}{1 + e^{-\frac{t-t_0}{T}}}, \quad (5.2)$$

where A_0 corresponds to the amplitude of the spectrum, $1/T$ corresponds to the slope of the function and p_0 refers to uncorrelated noise due to accidental hits [36]. Drift-time spectra synchronization of the tubes in a muon chamber requires fitting this function $G(t)$ to the rising edge of the drift-time spectrum for each individual tube and shifting it by $-t_0$.

The falling edge fitting

The maximum drift time t_m is determined by fitting the falling edge of the drift-time spectrum for each individual tube with the function:

$$H(t) = p_{max} + \frac{A_{max} + \alpha_m \cdot t}{1 + e^{\frac{t-t_m}{T_{max}}}}, \quad (5.3)$$

where slowly falling region $t < t_m$ is modelled by a straight line with intercept A_{max} and slope α_{max} , which is significantly smaller than the slope of the rising edge [36].

5.2. *The drift time spectrum*

The functions $G(t)$ and $H(t)$ describe only rising and falling edge of the drift-time spectra and therefore cannot be used to fit the complete spectrum, but only chosen range. The maximum drift time depends on several environmental parameters including gas mixture and temperature and for its determination quality of the falling edge fit is important.

6. Spatial resolution

The spatial resolution determination is based on the difference in the measured drift radius and distance of the reconstructed muon track from the tube wire. Therefore, the first step is to reconstruct the trajectories of the detected cosmic muons.

6.1. Track reconstruction

To reconstruct the muon trajectory, the drift time is converted to the drift radius using rt function, which is represented as a circle with center on the anode, marking the surface corresponding to the measured position of the particle passage through the tube. Drift radii are marked as red dashed circles in the Figure 6.1. The drift radii are connected from each hit SMDT by a straight line that represents a tangent on each drift radius circle, to obtain the candidates for the muon track, since there can be more than one track fulfilling the previous condition. The track is defined as a line that minimizes the track residuals, which is the difference between drift radius (r) and the distance of the reconstructed muon track to the anode wire of the drift tube (d).

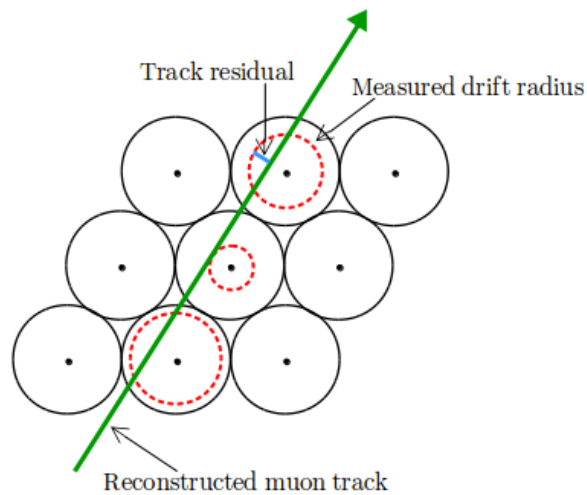


Figure 6.1.: Visualisation of the muon track reconstruction.

6.2. Spatial resolution determination

The spatial resolution of the chamber is determined as a function of the measured drift radius. For precise determination of the spatial resolution, it is necessary to know relative wire positions in the chamber. In the coordinate system of the chamber, the reconstructed track is given by the equation:

$$y = m \cdot z + b, \quad (6.1)$$

where m represents the slope of the track ($m = \frac{dz}{dy}$) and b is intercept on the y axis. Therefore, from the Figure 6.2, the distance of the reconstructed muon track in the k -th tube from the wire y_k , can be computed as:

$$d_k = |y - y_k| \cdot \cos \alpha. \quad (6.2)$$

where the $\cos \alpha$ can be written as:

$$\cos \alpha = \frac{1}{\sqrt{1 + \tan^2 \alpha}} = \frac{1}{\sqrt{1 + m^2}}. \quad (6.3)$$

After replacing expressions for y and $\cos \alpha$, distance of the reconstructed track from the wire can be computed as:

$$d_k = \frac{|mz_k + b - y_k|}{\sqrt{1 + m^2}}. \quad (6.4)$$

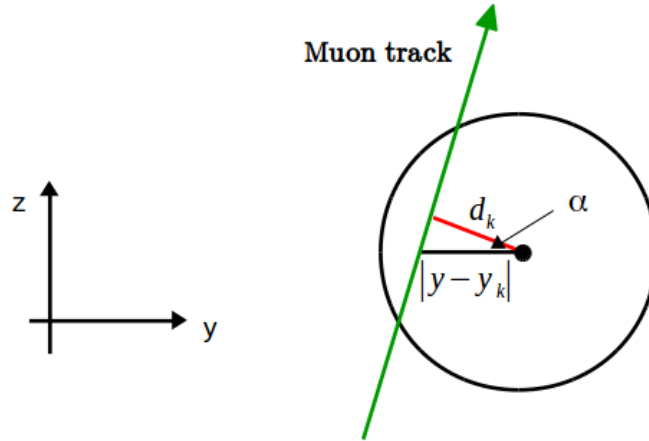


Figure 6.2.: Distance of the reconstructed track (greem arrow) from the tube wire.

Spatial resolution can be determined as:

$$\sigma = \sqrt{\text{Var}(\delta)} = \sqrt{\text{Var}(r_k - d_k)}, \quad (6.5)$$

where δ represents track residuals. To derive the relation for the spatial resolution determination, two tubes are considered, such that they are above one another in

alternating layers (tubes marked with yellow in Figure 6.3). For this method only vertical muon tracks are used. The difference between drift radii for two tubes right above one another is given as:

$$r_2 - r_1 = d_2 - d_1 + \delta_2 - \delta_1, \quad (6.6)$$

where we are interested in the difference $\Delta = \delta_2 - \delta_1$:

$$\Delta = \delta_2 - \delta_1 = r_2 - r_1 - (d_2 - d_1). \quad (6.7)$$

Difference between distance of the reconstructed tracks in the case of two observed

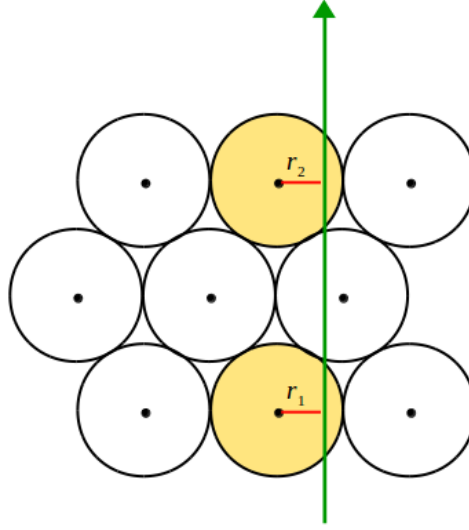


Figure 6.3.: Tubes marked with yellow are considered for the spatial resolution determination, in the case of vertical muon tracks.

tubes $d_2 - d_1$ has different sign depending on the position of the reconstructed tracks, right or left from the anode wire:

- Tracks passing right from the wire ($d_{1/2} > 0$):

$$d_2 - d_1 = \frac{m \cdot (z_2 - z_1)}{\sqrt{1 + m^2}}. \quad (6.8)$$

- Tracks passing left from the wire ($d_{1/2} < 0$):

$$d_2 - d_1 = -\frac{m \cdot (z_2 - z_1)}{\sqrt{1 + m^2}}. \quad (6.9)$$

After plugging in expression for $d_2 - d_1$:

$$\Delta = r_2 - r_1 \mp \left(\frac{m}{\sqrt{1 + m^2}} (z_2 - z_1) \right) \quad (6.10)$$

6. Spatial resolution

To obtain spatial resolution we need $Var(\Delta) = Var(\delta_2 - \delta_1)$:

$$Var(\Delta) = Var(\delta_2 - \delta_1) = Var(r_2 - r_1 \mp (\frac{m}{\sqrt{1+m^2}}(z_2 - z_1))), \quad (6.11)$$

Using the properties of the variance, where $Var(\delta_2 - \delta_1) = Var(\delta_2) + Var(\delta_1)$ and $Var(\delta_2) = Var(\delta_1)$:

$$Var(\delta_{1/2}) = \frac{1}{2} \cdot Var(r_2 - r_1 \mp (\frac{m}{\sqrt{1+m^2}}(z_2 - z_1))). \quad (6.12)$$

Therefore, combining the Equation 6.5 and assuming perfectly vertical track, spatial resolution could be computed as:

$$\sigma(r_{1/2}) = \sigma\left(\frac{r_2 - r_1}{\sqrt{2}}\right). \quad (6.13)$$

However, since reconstructed muon tracks have non-zero inclination, in the expression above additional term is added, giving final expression for the spatial resolution determination, which can be used for tracks with incident angle close to 0 (requiring $|m| < 0.01$):

$$\sigma(r_{1/2}) = \sigma\left(\frac{r_2 - r_1}{\sqrt{2}} \mp \frac{m \cdot (z_2 - z_1)}{\sqrt{2} \cdot (1 + m^2)}\right). \quad (6.14)$$

The error on $\frac{m \cdot (z_2 - z_1)}{\sqrt{2} \cdot (1 + m^2)}$ is small compared to the error on $\frac{r_2 - r_1}{\sqrt{2}}$, because m is measured with all tubes across the muon track, i.e. with a lever arm significantly larger than $z_2 - z_1$. The method used for the resolution determination has also the advantage that the trigger time t_{trigg} does not have to be known precisely as it cancels out in the expression $r_2 - r_1$ in the first order:

$$\begin{aligned} r_2 - r_1 &= r(t_2) - r(t_1) \\ &= r(t_1 + (t_2 - t_1)) - r(t_1) \\ &= r(t_1) + \dot{r}(t_1)(t_2 - t_1) - r t_1 \\ &= \dot{r}(t_1)(t_2 - t_1). \end{aligned} \quad (6.15)$$

t_{trigg} cancels out in $t_2 - t_1$ and $\dot{r}(t_1)$ varies only slowly with t_1 so that t_{trigg} does not have to be known with high precision.

7. Muon detection efficiency

An important quantity, when describing performances of the chamber, is the muon detection efficiency, which is the probability that drift tube will record hit, if a reconstructed track is passing through the tube. The muon detection efficiency can be determined for each tube in the chamber. To determine efficiency the following steps are performed:

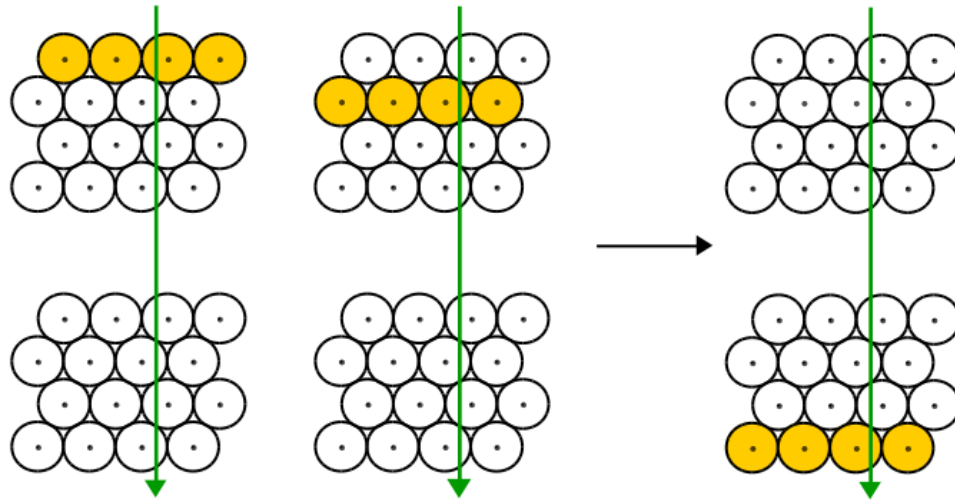


Figure 7.1.: Visualisation of the efficiency determination. The excluded layer, containing the tube through which reconstructed track (green arrow) is passing and for which detection efficiency should be determined is represented in yellow.

- Reconstruction of the muon trajectory using recorded hits in the all tubes in an event;
- Exclusion of the one tube layer;
- Muon track reconstruction using the hits from the rest of the tubes in an event;
- Check if the tube in the excluded layer, through which reconstructed track is passing, has a hit;
- Repetition of the process for every tube in an excluded layer;
- Repetition of the process for every layer in a chamber.

7. Muon detection efficiency

The muon tracks are reconstructed by requiring minimum of four hits. The single tube efficiency ϵ_{tube} is calculated as:

$$\epsilon_{tube} = \frac{\text{nr. of detected hits in tube matching the reconstructed tracks}}{\text{number of all reconstructed tracks crossing the tube}}, \quad (7.1)$$

where each reconstructed track crossing the investigated tube increases the denominator by one, while additional detected hit in same tube belonging to the reconstructed track increases the numerator by one. Together with the single tube efficiency, average chamber efficiency is determined as an mean of all single tube efficiencies in the chamber.

8. Results

8.1. Noise measurement

Off-chamber and on-chamber noise measurements allow the comparison of noise rates for individual channel/tube in the chamber, enabling fluctuation observation in noise levels from channel to channel and finding noisy tubes. Drift tubes, whose noise rates from the on-chamber test are twice higher compared to off-chamber test, are isolated and further investigated.

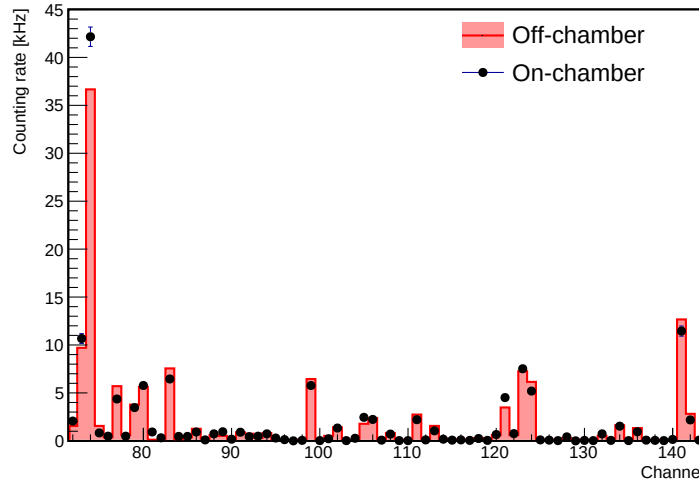


Figure 8.1.: Noise rates for the chamber BIS78-A2: Nominal ASD configuration (hysteresis 2, threshold 108).

In the Figures 8.1 and 8.2 results of the noise study are presented for the segment of three mezzanine cards (72 tubes) of the A2 chamber, at the nominal threshold value of -39 mV. The result shown for two hysteresis and same threshold values allows to observe the impact of different hysteresis settings on noise levels. Smaller hysteresis settings correspond to effectively lower thresholds, resulting in measured ≈ 43 kHz for the 74th channel. However, this channel showed higher intrinsic noise rates, as seen in the off-chamber test. For both hysteresis expected fluctuations in measured noise levels from one tube to the other were observed, as a characteristic of used ASD chips, while still following the expected noise rates obtained from the off-chamber test. By applying larger hysteresis, the resulting effective threshold is 6.25 mV higher, compared to the previous case, which reduced noise rates for

8. Results

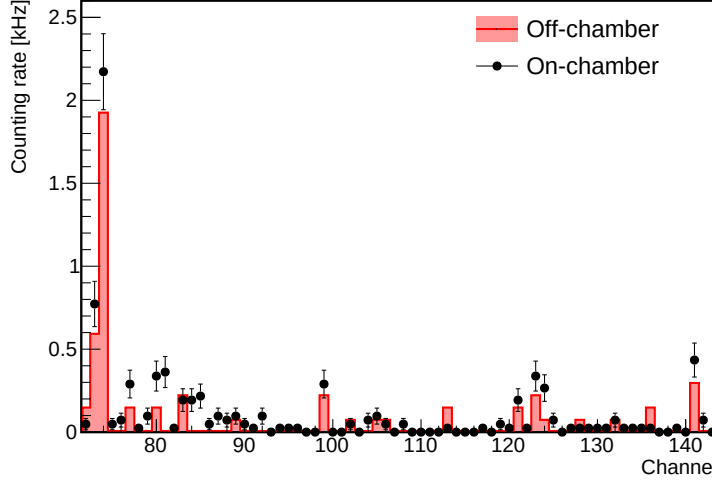


Figure 8.2.: Noise rates for the chamber BIS78-A2: Hysteresis 7; Threshold 108.

around 20 times in the presented segment of drift tubes. Figure 8.2 shows noise rates in the case of ATLAS settings, where measured noise rates for all channels, except mentioned channel 74, are below 1 kHz. Average noise rates per tube were determined for each tested chamber for both hysteresis settings and the nominal threshold value. Obtained average values were compared with expected average values from the off-chamber test.

For the expected average value per tube, the average of all channels from the off-chamber test was found, taking into consideration number of tubes per chamber. This number differs between chambers due to their design and can be either 648 or 744. On the other side, average noise rate per tube for one chamber was calculated by excluding individual noisy tubes. Excluded tubes satisfied following conditions:

- Hysteresis 2: $Noise_i^{on} > 25 \text{ kHz}$ and $Noise_i^{on} > 2 \cdot Noise_i^{off}$;
- Hysteresis 7: $Noise_i^{on} > 5 \text{ kHz}$ and $Noise_i^{on} > 2 \cdot Noise_i^{off}$,

where $Noise_i^{on}$ and $Noise_i^{off}$ correspond to the determined noise levels of the i -th tube in a chamber from on and off chamber test, respectively. This step was performed due to individual tubes in the chamber with significantly high noise rates, which have an impact on average noise rates per tube. One example of the noisy tube in the chamber A4 is given in Figures 8.3a and 8.3b for hysteresis 2 and 7, respectively. The channel 590 satisfied previous conditions and showed noise rates of 141.93 kHz, for hysteresis 2 in comparison to the expected 0.07 kHz from the off-chamber measurement, while all other presented channels did not show noise rates higher than 18 kHz. Larger hysteresis resulted in reduced noise rates in all channels, except channel 590, which showed high noise rates of 132.37 kHz. Tubes showing the same behaviour were excluded from the average noise per tube calculation. The number of excluded tubes per chamber is below 4 and makes up less than 1% of the

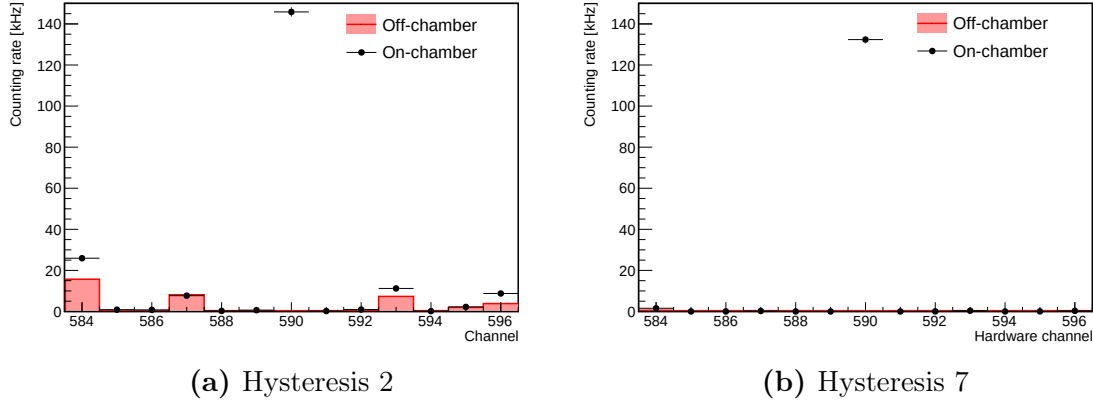


Figure 8.3.: Example of the noisy tube in the chamber A4.

total number of tubes in the chamber.

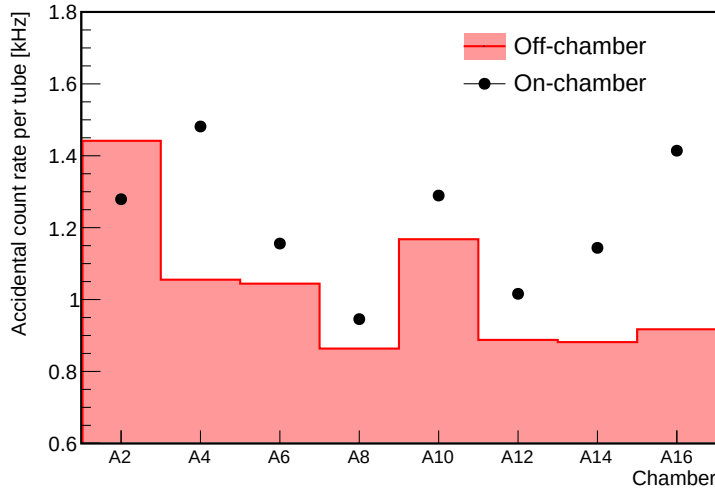


Figure 8.4.: Average noise rates per tube for nominal threshold and hysteresis 2.

The average noise rates per tube for all tested chambers are shown in Figures 8.4 and 8.5 for both hystereses. In the case of the hysteresis 2, measured values were all within the factor of 2 compared to the expected values from the off-chamber test. The highest measured value belongs to the chamber A4 which was 1.48 kHz. Therefore, all tested chambers showed noise rates below 1.5 kHz for the hysteresis 2. In the case of the ATLAS settings, all tested chamber showed more uniform noise rates, in the range of 40 Hz - 60 Hz. The exception is chamber A16, with measured 110 Hz, but still well below 1 kHz.

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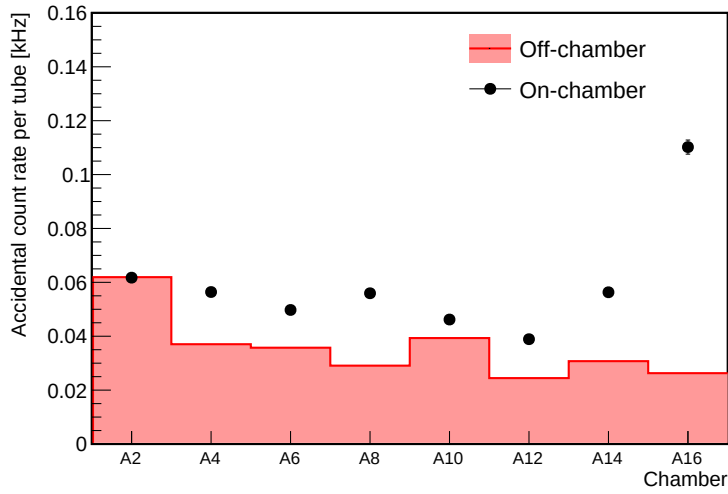


Figure 8.5.: Average noise rates per tube for nominal threshold and hysteresis 7.

8.1.1. Noisy tubes

Although the tested chambers show acceptable noise levels, there were several individual noisy tubes per chamber, as well as tubes that drove too high currents. One way to deal with tubes showing these characteristics was to check the existence of the high noise rates when measuring without the high voltage. Isolated bad tubes can be investigated individually, by applying the high voltage only to the specific tube, as it can be seen in the Figure 8.6. During the testing, there were several cases when this method was used with an attempt to recover bad tubes.

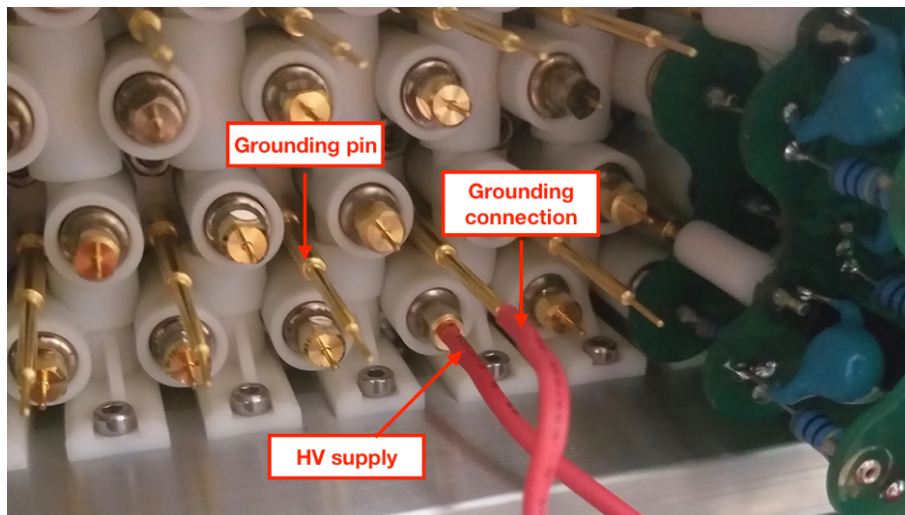


Figure 8.6.: Providing individual HV supply to the investigated tube

A2

Initial testing of the A2 chamber showed high current and loud noise when ramping up high voltage. The current was within the normal limits up to 2300 V, beyond which it suddenly rose with additional sound noise. After inspecting tubes individually, the problematic tube was found and was disconnected from the high voltage supply.

A4

The 150th channel of the A4 chamber was a candidate for the noisy tube, with measured 211.31 kHz compared to the expected 0.3 kHz. However, this channel was successfully recovered by applying -2.73 kV to the wire. HV reversal can remove deposits on the anode wire if they exist and reduce the high noise rates. The comparison of the noise rates for this channel is shown in the Table 8.1, where the expected value from the off-chamber measurement was 3.62 kHz.

Before HV reversal	211.31 kHz
After HV reversal	4.56 kHz

Table 8.1.: Noise rates of the channel 150, measured with the hysteresis 2



(a) Burnt resistor on the hedgehog card

(b) Broken wire

Figure 8.7.

A6

A very high current of $\approx 1.9 \mu\text{A}$ was measured the first layer of the A6 chamber, compared to the $\approx 0.35 \mu\text{A}$ measured in the entire second multilayer. The bad tube was found to belong to the 12th mezzanine card in the first multilayer. The high current was caused by broken wire, which resulted in a burnt protecting resistor of this tube, as shown in the Figure 8.7a. The broken wire was taken out (see Figure 8.7b).

8. Results

A16

During operation, the current of the second multilayer was showing the current of $\approx 10 \mu\text{A}$, where the expected current rate should be below $0.5 \mu\text{A}$. By connecting layer per layer to the HV, the tube that drives high current was found to be in the 5th layer. Two tubes are found with current values shown in the Table 8.2. HV

Layer	Tube	Current [μA]
5	11	1.5
5	12	4.5

Table 8.2.: The current values for the bad tubes in the fifth layer of the A16 chamber.

reversal was not successful in this case and two mentioned tubes were disconnected from the HV supply.

8.2. Maximum drift time

The typical drift-time spectrum of the sMDT chamber is shown in the Figure 8.8 with fitted rising and falling edge.

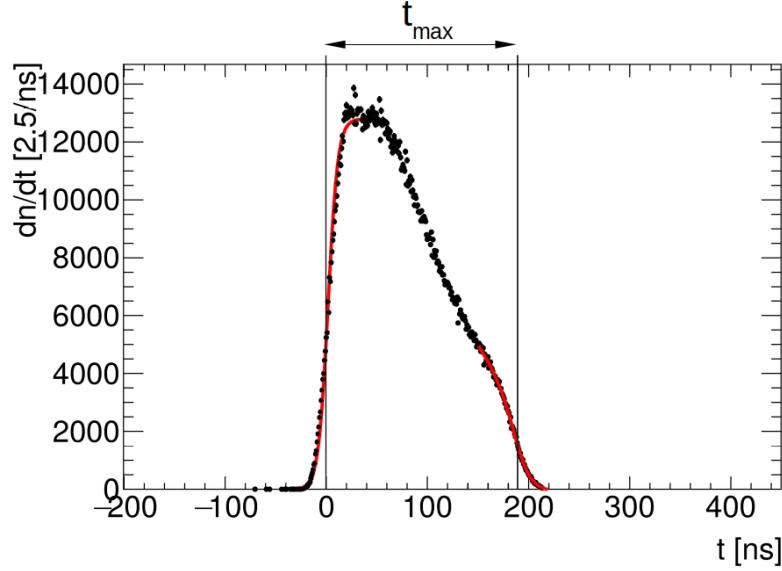


Figure 8.8.: Drift-time spectrum of the BIS-78 A4 sMDT chamber.

The maximum drift time of tested chambers was determined as a difference between fit parameters corresponding to t_m from the falling edge fit and t_0 obtained from the raising edge fit of the drift time spectra. At the same operational parameters, maximum drift time for every tube in a chamber should be the same.

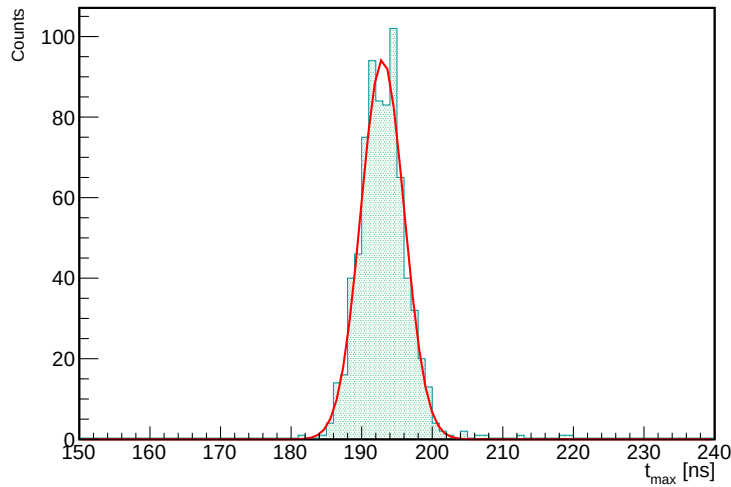


Figure 8.9.: Maximum drift time distribution of the BIS-78 A4 sMDT chamber.

The maximum drift time distribution of the A4 chamber is shown in the Figure

8. Results

8.9. The distribution is fitted with the Gaussian function where the mean of the distribution corresponds to the maximum drift time. The obtained value for the A4 chamber was $t_{max} = 192.96$ ns. The maximum drift time distribution does now show outliers, indicating that all tubes in the chamber have the same space-to-drift time relationship. The standard deviation of the distribution corresponds to the statistical accuracy of the maximum drift time determination and is largely dominated by the statistical error in determining the t_{max} .

The values of the maximum drift time determined for all tested chambers are shown in the Figure 8.10, where the error bars represents the spread around the mean value. Individual maximum drift times did not deviate more than 1.5% from the

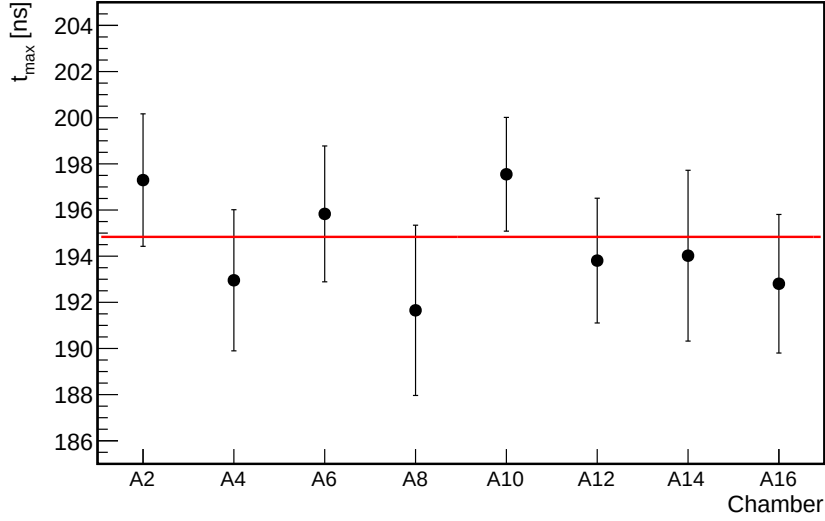


Figure 8.10.: Maximum drift time of tested sMDT chambers

mean maximum drift time of all tested chambers, which is determined to be:

$$t_{max} = (194.84 \pm 1.05) \text{ ns}$$

8.3. Spatial resolution

Cosmic ray test is used to determine spatial resolution of every chamber for ATLAS hysteresis and threshold settings. The data are taken separately for CSM 1 and CSM 2, with the same data taking time of 15 hours. The muon tracks are reconstructed by requiring minimum of four hits in the chamber. The result for the dependency of the spatial resolution of the drift radius for all tested chambers is shown in the Figure 8.11. The presented data are before subtracting the contribution of the multiple scattering, obtained from Monte Carlo simulation [37]:

$$\sigma_{MS} = (120 \pm 10) \mu\text{m}.$$

For the determination of the spatial resolution two multilayers are required, there-

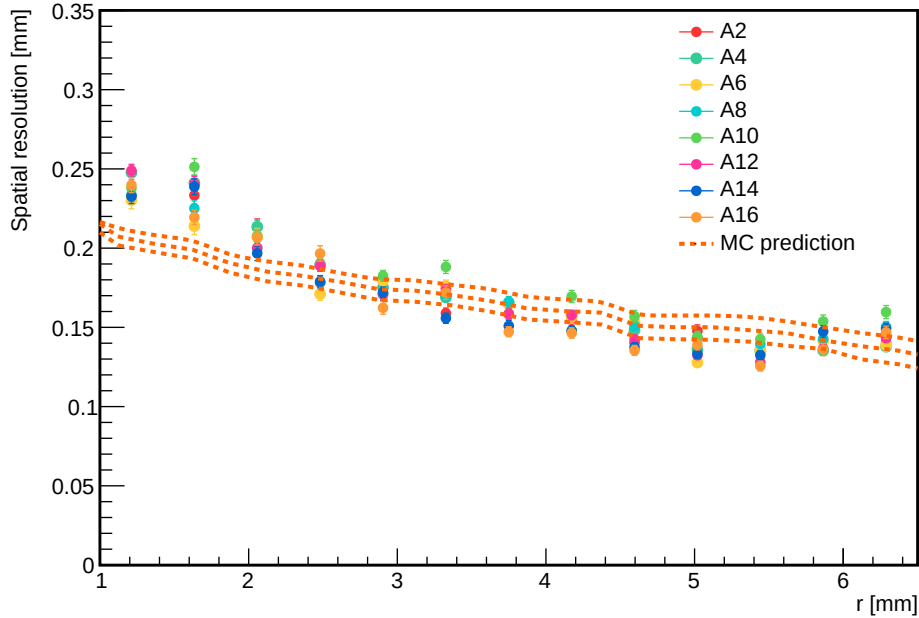


Figure 8.11.: Spatial resolution as a function of the measured r of the all tested chambers, at the threshold of -39 mV and hysteresis of -8.75 mV. Results presented for the data taken with the CSM 1.

fore in Figure 8.11 data taken with CSM 1 are presented. The good agreement of the measured spatial resolution between different chambers as well as the agreement with Monte Carlo prediction within the multiple scattering uncertainty band was observed. The resolution depends on the measured drift radius r and is the worst near the wire. Therefore, the results of the spatial resolution for the drift radii below 1 mm were not shown. The reason for bad spatial resolution close to the anode wire comes from the geometry of the drift tubes. The variations in the drift path length (Δr) are larger for the muons transversing close to the anode wire (Figure 8.12). With increasing drift radius, spatial resolution improves. The last half millimeter of the tube radius was not considered, since the Δ distribution in this region deviated

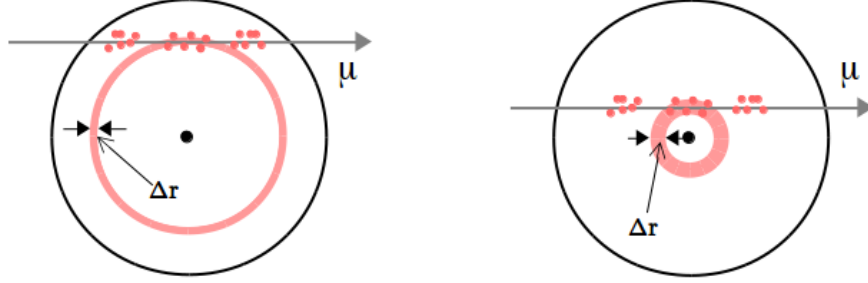


Figure 8.12.: The improvement of the spatial resolution with increasing drift radius is due to the variation of the drift path length, depending on the fluctuation in position of the primary ionisation clusters.

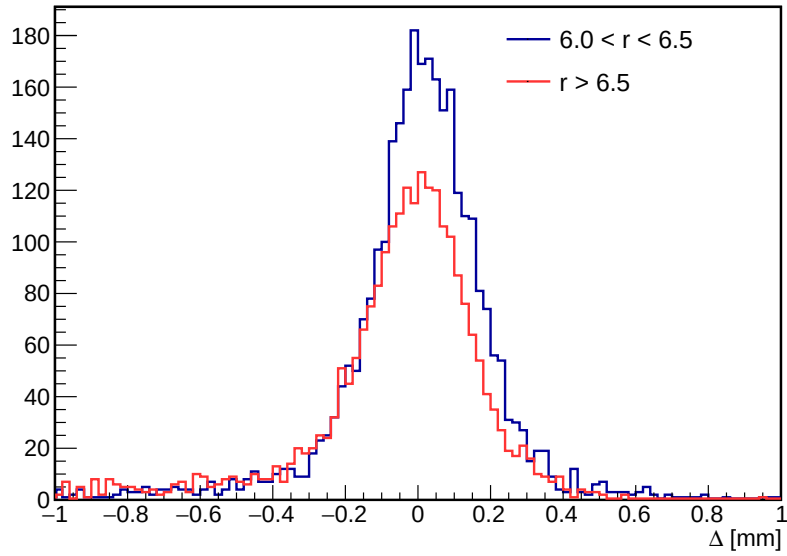


Figure 8.13.: Δ distribution for the last mm of the drift tube radius for the A4 chamber. Separate distributions are shown for the drift radii belonging to two different segments: $r > 6.5$ mm and r in the interval $[6.0, 6.5]$

from the Gaussian distribution (Figure 8.13) and therefore it was difficult to obtain reliable value of the spatial resolution. Additional contribution to the degradation of the spatial resolution in this region is observed decrease in the efficiency (Section 8.4.1).

To obtain the value for the spatial resolution the Δ distribution was fitted with double Gaussian function:

$$G(x) = g_1 + g_2 = N_1 \cdot e^{-\frac{(x-\mu)^2}{2 \cdot \sigma_1^2}} + N_2 \cdot e^{-\frac{(x-\mu)^2}{2 \cdot \sigma_2^2}}, \quad (8.1)$$

with common mean value μ and σ_1, σ_2 being corresponding standard deviations. The measured spatial resolution was computed as the weighted mean of the standard deviations:

$$\sigma_{meas} = \frac{N_1 \cdot \sigma_1 + N_2 \cdot \sigma_2}{N_1 + N_2}. \quad (8.2)$$

The final spatial resolution of the chamber was obtained by subtracting the contribution of the multiple scattering:

$$\sigma = \sqrt{\sigma_{meas}^2 - \sigma_{MS}^2}. \quad (8.3)$$

The example of this procedure is shown in the Figure 8.14 for the chamber A6. The

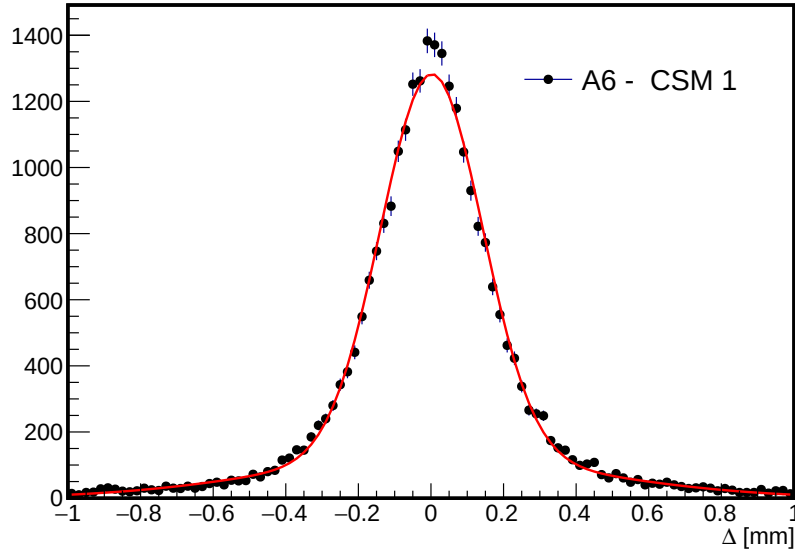


Figure 8.14.: The Δ distribution of the A6 chamber, fitted with the double Gaussian function to obtain spatial resolution.

obtained values for this chamber were:

$$\sigma_{meas} = (169 \pm 3) \mu\text{m} \quad \text{and} \quad \sigma_{A6} = (119 \pm 11) \mu\text{m},$$

which is in agreement with previous measurement at the muon beam facilities [38], using the same analysis method:

$$\sigma = (125 \pm 4) \mu\text{m},$$

8. Results

The spatial resolution was computed using this method for all tested chambers and is shown in the Figure 8.15. The uncertainty was mainly dominated by the multiple

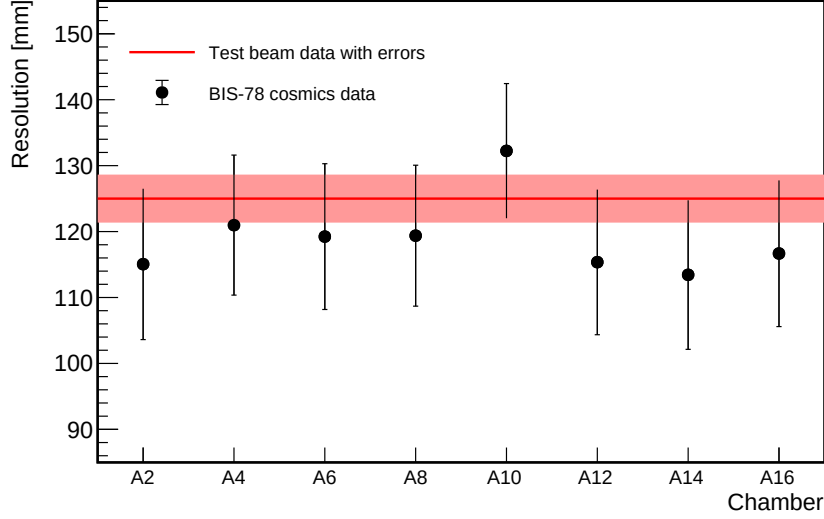


Figure 8.15.: Determined spatial resolution of the all tested chambers. Error bars consist of statistical error and multiple scattering uncertainty.

scattering uncertainty. All tested chambers have same spatial resolution within measurement uncertainties. The average single tube resolution of all chambers is:

$$(119.403 \pm 3.85628) \mu\text{m}.$$

8.3.1. Spatial resolution at different hysteresis and threshold

The effect of lower threshold and hysteresis were investigated with chambers A16 and A4, respectively. The dependency of the measured resolution of the drift radii is shown in the Figure 8.16. Data were taken for the 6.25 mV lower hysteresis with the chamber A4, while keeping nominal threshold. In addition, the measurement was performed with 8 mV lower threshold with unchanged ATLAS hysteresis settings with the chamber A16. The data points were fitted with the polynomial of the third order. In the case of lower applied hysteresis, the spatial resolution was improved over the entire tube for around $20 \mu\text{m}$. The improvement was more significant for the $r < 4 \text{ mm}$. The same effect was seen when using lower threshold. The corresponding spatial resolutions were calculated by fitting the Δ distribution with double Gaussian function. In the case of A4 chamber, obtained spatial resolutions were:

$$\sigma_{hyst_2} = (102 \pm 12) \mu\text{m} \quad \text{and} \quad \sigma_{hyst_7} = (120 \pm 10) \mu\text{m}.$$

For the chamber A16, calculated values were:

$$\sigma_{112} = (104 \pm 12) \mu\text{m} \quad \text{and} \quad \sigma_{108} = (117 \pm 11) \mu\text{m}.$$

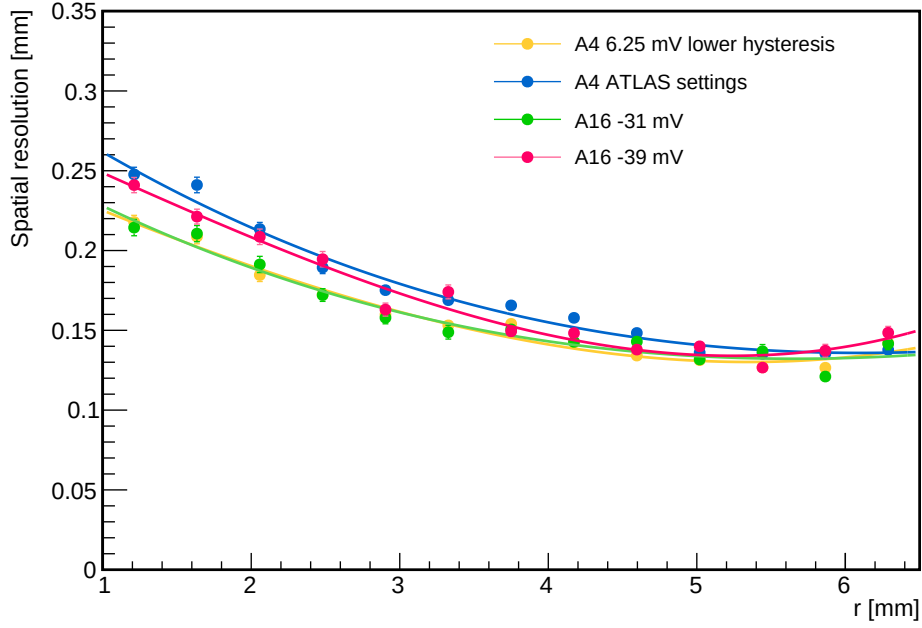


Figure 8.16.: Comparison of the spatial resolution for two threshold settings for chamber A16 and two hysteresis settings for the chamber A4, as a function of measured drift radii.

The degradation of the spatial resolution comes from the uncertainty in determining the time when signal crosses predefined threshold by the ASD chips, which indicates the start of the measurement for the TDC chip. In the case of signals with higher amplitude, the threshold will be crossed at earlier times compared to lower amplitude signals (Figure 8.17). However this difference in threshold crossing times is smaller

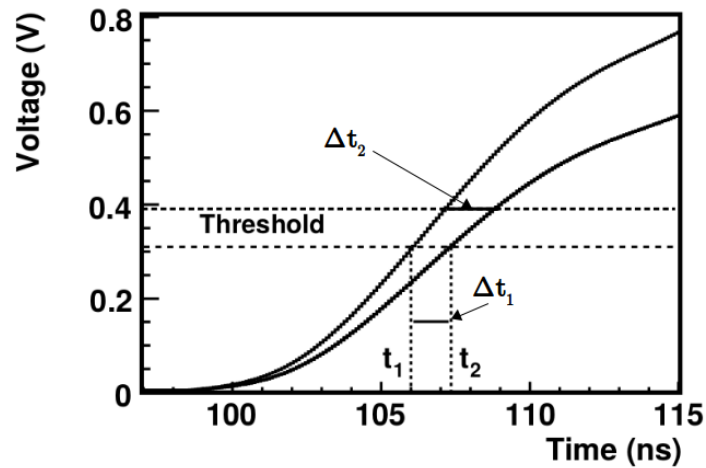


Figure 8.17.: Difference in the threshold crossing times for signals of different amplitudes (Modified [39]).

in the case of lower threshold and therefore results in better spatial resolution.

8.4. Muon detection efficiency

To have maximal angle coverage, BIS78 sMDT chambers are designed with two multilayers of tubes, covering the area of present BIS7 MDT chambers and a segment consisting of one tube multilayer for the area of currently installed BIS8 MDT chambers.

The average efficiency obtained for the part of the chamber with only one multilayer was compared with the average efficiency of the part with two multilayer, as well as the entire chamber and is presented in Table 8.3. The average efficiency of the BIS7

Average efficiency of the BIS8 part	$(96.44 \pm 0.04)\%$
Average efficiency of the BIS7 part	$(98.48 \pm 0.01)\%$
Average chamber efficiency	$(98.40 \pm 0.01)\%$

Table 8.3.: Efficiency of the different parts of the A4 chamber.

part of the chamber where tracks are determined with two multilayers of drift tubes was $\approx 2\%$ better compared to the average efficiency of the BIS8 part, indicating the systematic uncertainty of the efficiency measurement. However, when compared to the average efficiency of the entire chamber, this improvement was only $\approx 0.1\%$. In order to obtain a forecast for the measured tube efficiency which takes into account the measurement procedure, Monte Carlo simulated data were used. The average chamber efficiency is in an agreement with Monte Carlo prediction of 98.76 %.

Single tube efficiency for the part of A4 chamber with two multilayers is shown in the Figure 8.18, where channels on the x-axis corresponds to the read-out mapping of the drift tubes. Therefore, the result is segmented in 8 layers, with the gaps belonging to the drift tubes that either do not exist due to geometry or are belong the the BIS8 part of the chamber. Due to the design of the A4 chamber, in each layer

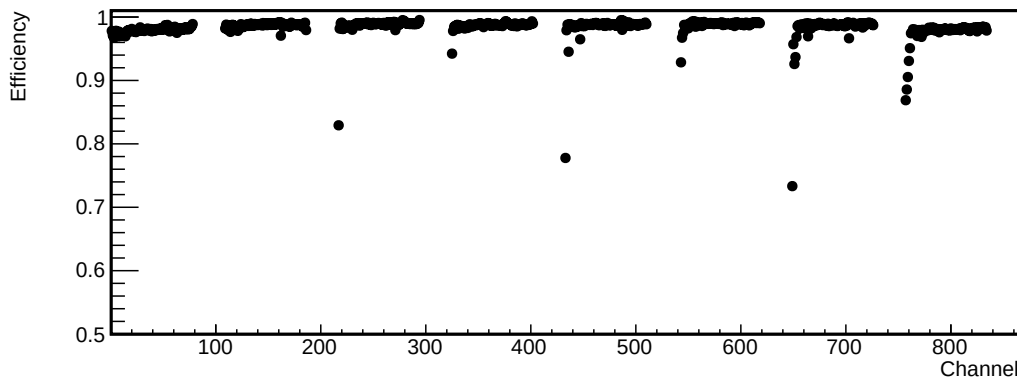


Figure 8.18.: Single tube muon detection efficiency for the A4 chamber.

exist 78 drift tubes. The result shows the uniformity of the chamber performance, with the efficiency close to 100%. However, there are several places with decreased

detection efficiency and this pattern was observed in the determined efficiency of all chambers.

In the second layer of the A4 chamber, the drop in efficiency was seen for the tube 162, with the efficiency of 97% compared to the neighbouring tubes with efficiency of 99%. The reason for this lays in the fact that this tube is the last tube read-out by CSM 1. Therefore, for an incoming muon track with an angle such that it transverses tubes read-out by both CSM 1 and CSM 2 (Figure 8.19a), when recording the cosmic rays with CSM 1, hits belonging to the CSM 2 will not be detected, which can lead to the efficiency drop in this region. Same can be observed for layers 3, 5 and 7 of this chamber.

In addition, the efficiencies of the tubes at the beginning of each layer, especially in the second multilayer showed the drop in efficiency, in some cases below 80 %. This is most significant for the last tube layer of the A4 chamber. The efficiency of the first five tubes in this layer increased from $\approx 86\%$ to $\approx 95\%$. This efficiency drop comes from the geometry of the set-up, where the scintillating counter with its coupled photomultiplier tubes was mounted ≈ 30 cm above the tested chamber. Since the active area of the scintillator does not cover the beginning to the chamber (Figure 8.19b), in order to cross drift tubes in these locations, while at the same time passing through the scintillator, muon has to arrive at large incidence angle. This problem can be mitigated by placing the scintillator counter with larger active

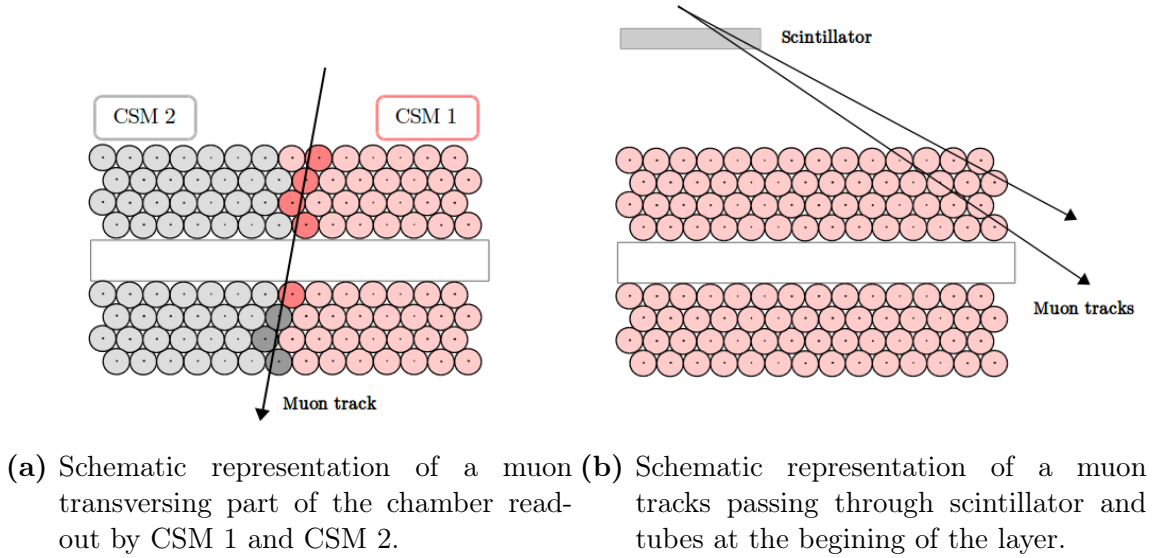


Figure 8.19.

area, which will allow full coverage of the chamber.

The single tube efficiency of the A4 chamber, after the exclusion of the tubes with decreased efficiency at the beginning of each tube layer, is shown in Figure 8.20, with the average efficiency of 98.77 %.

8. Results

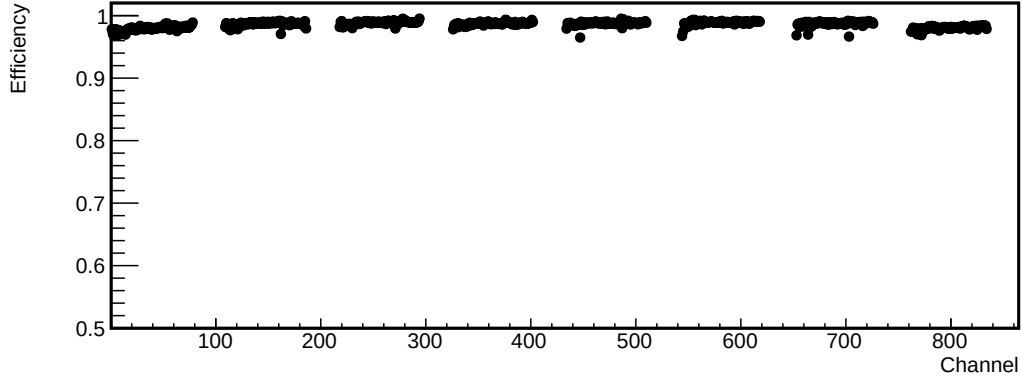


Figure 8.20.: Single tube muon detection efficiency for the A4 chamber.

The average chamber efficiency, after the exclusion of the tubes at the beginning of each layer, was computed for all chambers, and is shown in the Figure 8.21. Efficiencies of the all tested chambers are within measurement errors, except for chambers A6 and A12. Chamber A12 is the only tested chamber whose geometry correspond to the design of C-side chambers. Therefore, in experimental set-up, the chamber was fully under the active area of the scintillator, resulting in the higher efficiency, since the drop in efficiency at the beginning of each layer was avoided. The lower efficiency of the A6 chamber is due to dead tubes. Determined efficiency of all tested chambers was higher than 98%, with the mean value of 98.76%, which agrees with the value obtained from Monte Carlo.

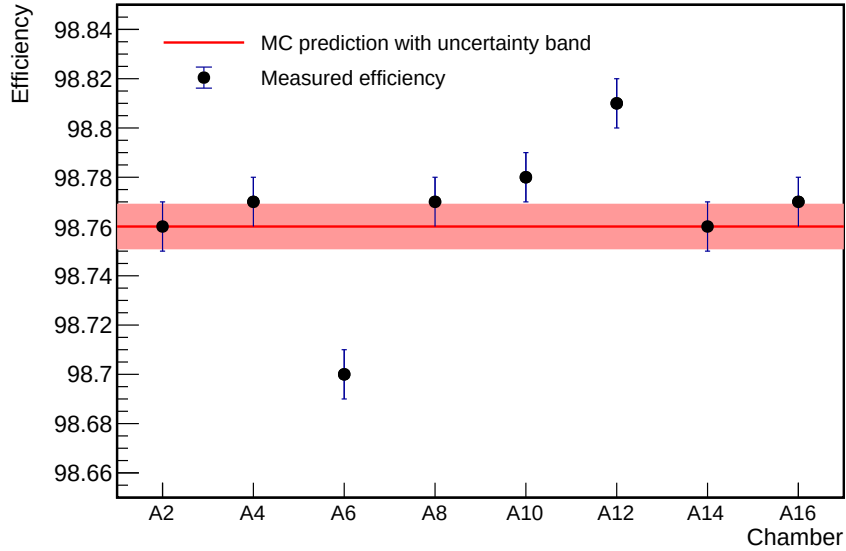


Figure 8.21.: Average chamber efficiency for all tested chambers

8.4.1. Efficiency as a function of drift radius

The dependency of the efficiency to the measured drift radii was investigated. The results for all tested chamber is shown in the Figure 8.22.

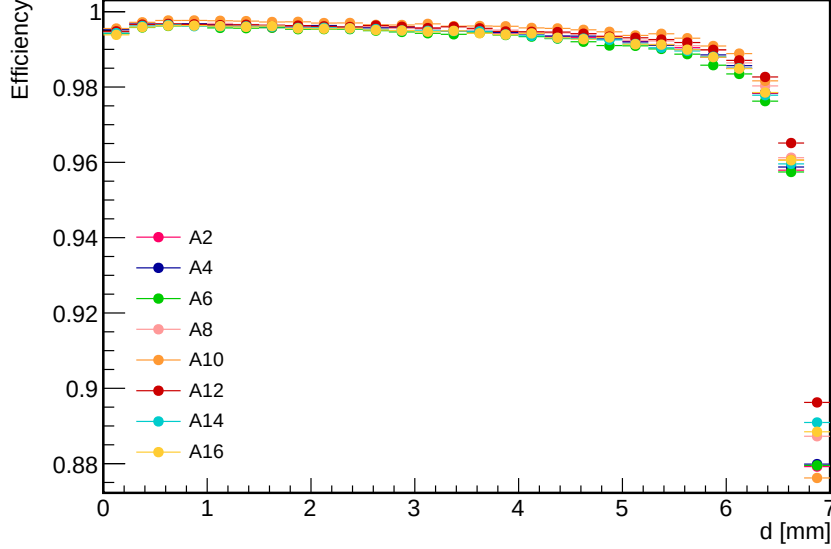


Figure 8.22.: Muon detection efficiency as a function of measured drift radius for all tested chambers.

All tested chambers showed same behaviour of the efficiency as a function of measured r . For $r < 4$ mm the efficiency reached more than 99.5%, then it gradually decreased to 99.0% at $r = 5.5$ mm. In the last millimeter of the tube the drop in efficiency was more significant. However up to $r = 6.5$ mm efficiency was still higher than 96%, with sudden drop in the last half millimeter to 88%. The reason for this

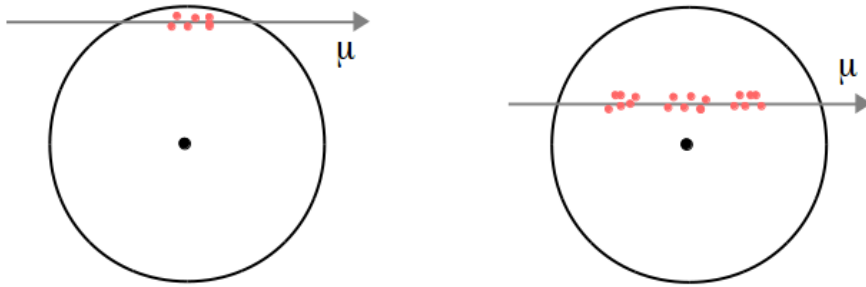


Figure 8.23.: The path of the muon through the drift tube at different locations results in different number of created primary ionisation clusters.

lies in the tube geometry and length of the muon path in the drift tube (Figure 8.23).

8. Results

To create a detectable signal, it is necessary to create sufficient number of the primary ionisation pairs. However, close to the tube walls, due to circular geometry of the tube, the muon path through the gas is smaller compared to the size of the path through the central part of the tube, resulting in smaller number of primary ionisation clusters, which create the signals that cannot cross the predefined threshold value and therefore are not detected, which lastly results in the efficiency drop.

8.4.2. Efficiency as a function of high voltage

The set-up for the testing of BIS-78 sMDT chambers can be used for obtaining further informations about chamber properties. The dependency of the efficiency on the high voltage was investigated by keeping the first chamber multilayer on a operational voltage of 2730 V, while varying the voltage of the second multilayer. For each voltage point cosmic ray data were taken and the efficiency of the upper multilayer was determined. This test was performed for chambers A8 and A16 and results are shown in the Figure 8.24. Both chambers showed similar behaviour when

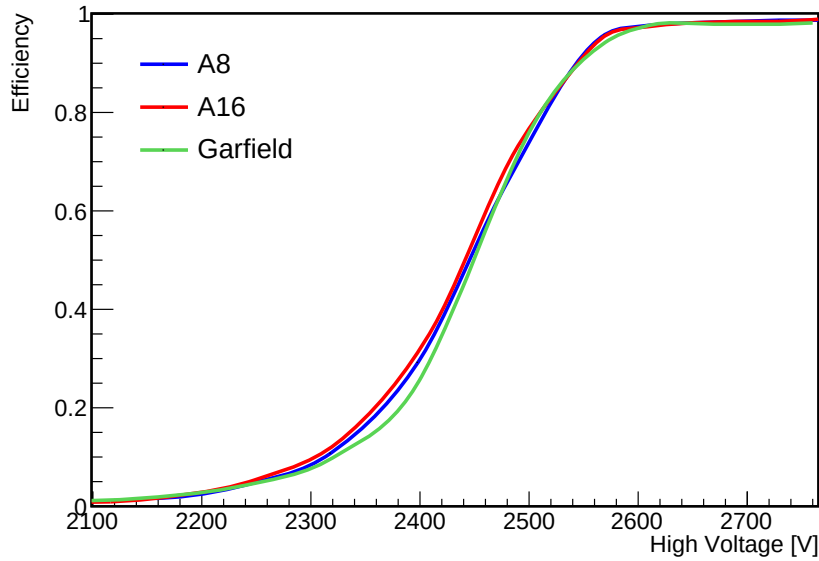


Figure 8.24.: Dependency of the muon detection efficiency of applied high voltage for A8 and A16 chamber, compared to the Garfield simulation.

tested at different applied voltages, with the muon detection efficiency falling to 0 below 2100 V. The efficiency slowly rose with increased high voltage reaching efficiency plateau after ≈ 2570 V. The results were compared to the data simulated by Garfield. Garfield [40] is a programme that allows detailed simulation of the drift chambers behaviour, including the creation of the primary ionisation and avalanche formation as a result of a charge particle passage. As an input to the simulation, operational parameters (pressure, temperature, gas mixture, applied voltage and gas gain), as well as the dimension of the drift tubes were given. Provided gas gain at ap-

plied high voltage was calculated using Diethorn's formula (Eq. 2.4). The simulation was performed for same voltage values at which cosmic ray data were taken and for each point expected efficiency was obtained. The results of the measurement were in good agreement with simulated data. The efficiency of the plateau region was comparable to previously determined chamber efficiencies and it was in agreement with the efficiency of $(97.7 \pm 0.2)\%$ expected by the simulation. The comparison of the efficiency dependency to the distance of the reconstructed muon track from the anode was performed for the operational voltage and 2570 V which is the point at the beginning of the efficiency plateau. The result at operational voltage followed

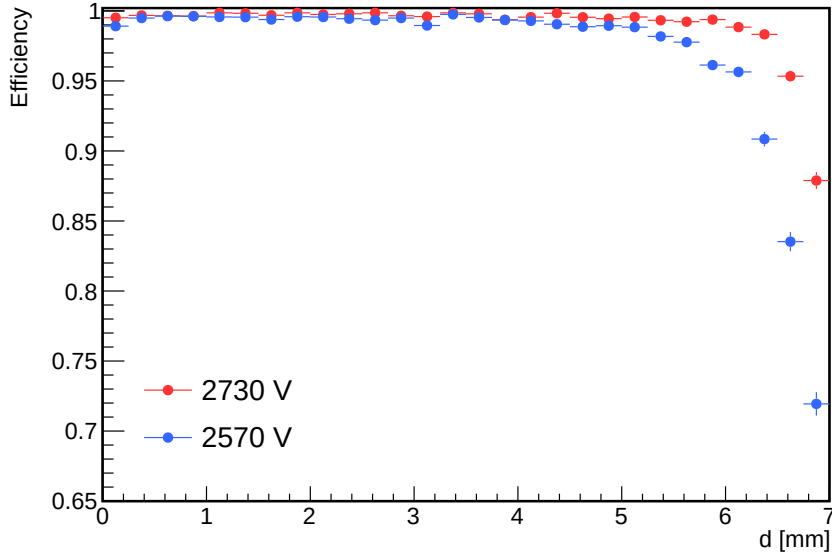


Figure 8.25.: Muon detection efficiency as a function of the track distance from the wire for operational voltage and voltage point at the beginning of the efficiency plateau.

the expected behaviour explained in the previous section 8.4.1. However the effect was more significant when upper multilayer was operated at 2570 V. The decrease of the efficiency below 95% started at 6 mm, reaching $\approx 70\%$ for tracks at $d \approx 7$ mm, which was significantly lower compared to the same point at the operational voltage. The main reason for this stronger effect at large d values comes from the fact that at this voltage points the gas gain is lower compared to operational gas gain.

For comparison, the gas gains of the points at the plateau was determined, using the calibration function, which converts ADC counts to collected charge (Figure 8.26). Such calibration curve can be obtained by providing a known value of the input signal charge to the ASD chip and measure the corresponding output value of the ADC counts. To determine most probable value of the collected charge, the distribution was fitted with exponentially modified Gaussian function:

$$f(x; \mu, \sigma, \lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2x)} \operatorname{erfc}\left(\frac{\mu + \lambda\sigma^2 - x}{\sqrt{2}\sigma}\right), \quad (8.4)$$

8. Results

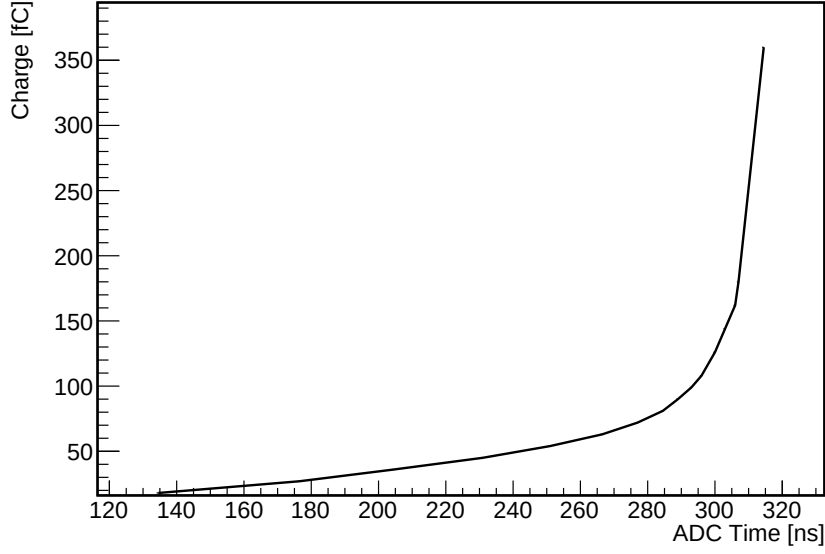


Figure 8.26.: Calibration function used to convert ADC counts to collected charge [41]

where μ and σ^2 are mean value and variance of the Gaussian function, while λ is the exponential decay constant. The erfc is the complementary error function defined as:

$$\text{erfc}(x) = 1 - \text{erf}(x) = \frac{2}{\sqrt{2\pi}} \int_{\pi}^{\infty} e^{-t^2} dt. \quad (8.5)$$

The example of the performed fit is shown in the Figure 8.27 for the operational voltage. The relative gas gain $\frac{G(V)}{G(2730V)}$ was computed for points at the plateau (Fig-

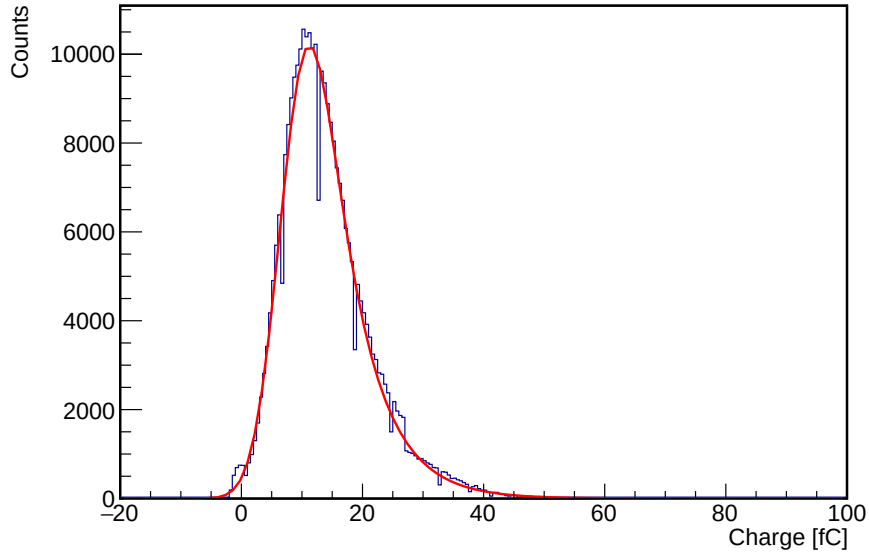


Figure 8.27.: Collected charge distribution fitted with the exponentially modified Gaussian function.

ure 8.28), where $G(V)$ and $G(2730V)$ refers to peak position of the points at the plateau and at operational voltage, excluding the point at the 2570 V, since the distribution at this point was already deviating from expected shape and therefore was not possible to perform the fit. The obtained points were fitted with the exponential

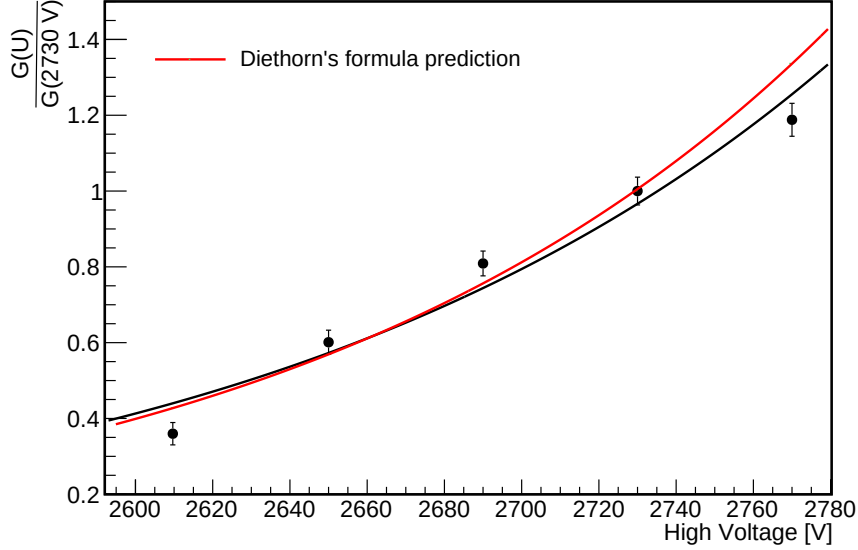


Figure 8.28.: Relative gas gain for the voltage points at the efficiency plateau, compared to the expectation based on Diethorn's formula (Eq. 2.4.)

function and compared to the gain ration according to the Diethorn's formula (Eq. 2.4). In both cases, the gas gain at 2570 V was computed to be $\approx 30\%$ of the gas gain at the operational voltage. This gas multiplication factor at large d was not enough to create detectable signals, resulting in the larger efficiency drop effect in this region.

8.4.3. Efficiency as a function of threshold

In addition, the effect of the lower threshold to the efficiency curve was investigated with the A16 chamber. Besides for the nominal threshold of -31 mV, the data were taken for 8 mV lower threshold.

The obtained efficiency curve in both cases was fitted with Fermi-Dirac function:

$$f(V) = \frac{p_0}{1 + e^{-\frac{V-p_1}{p_2}}} + p_3, \quad (8.6)$$

where p_0 corresponds to the value of the plateau region, p_1 is the edge or the position of the turnon of the fitting function, p_2 is related to the slope of the function and p_3 represents the offset of the fitting curve.

8. Results

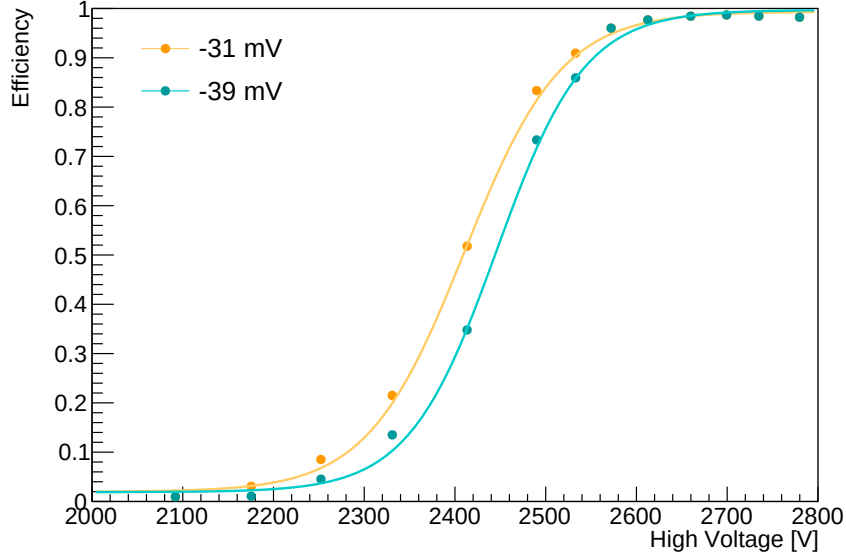


Figure 8.29.: The efficiency turn-on curve at two different threshold settings for A16 chamber.

The efficiency plateau values for two curves differed only less than 1%. However, in the case of lower threshold, the efficiency obtained at same voltage points were higher compared to the efficiency reached at nominal threshold value, which resulted in the shift of turn-on curve to the lower applied voltages. This effect was visible for voltages below 2570 V. Although the gas gain at lower voltage points drops compared to required gas gain to detect signal created by incoming muon, the 8 mV lower threshold allowed smaller signals to cross this threshold value and were detected, resulting in increase efficiency in these points.

Part II.

New read-out electronics
operational point determination

9. Overview

In order to cope with 10 times higher instantaneous luminosity and exploit full discovery potential of the ATLAS experiment at the HL-LHC, a new first-level muon track trigger with increased maximum rate capability to 400 kHz hit rate per tube, based on tracking (s)MDT chambers with triggerless read-out, is planned. The TDC chips on the current front-end electronics of the ATLAS MDT chambers do not fulfill these requirements. Therefore, new front-end boards are needed. This includes octal ASD2 ASIC in modern 130 nm IBM/Global Foundries CMOS technology [42].

As demonstrated in the previous section, the cosmic-ray test stand at MPI (Figure 3.1) is a set-up that can be used for investigating features of the muon chambers. Furthermore, it can be used to test new ASD chips. To determine the operational point for the new read-out electronics, two read-out cards, consisting of TDC and ASD boards, where each ASD board carries 3 new ASD chips (Figure 9.1) are mounted to the operational C10 chamber and tested in the cosmic test stand.

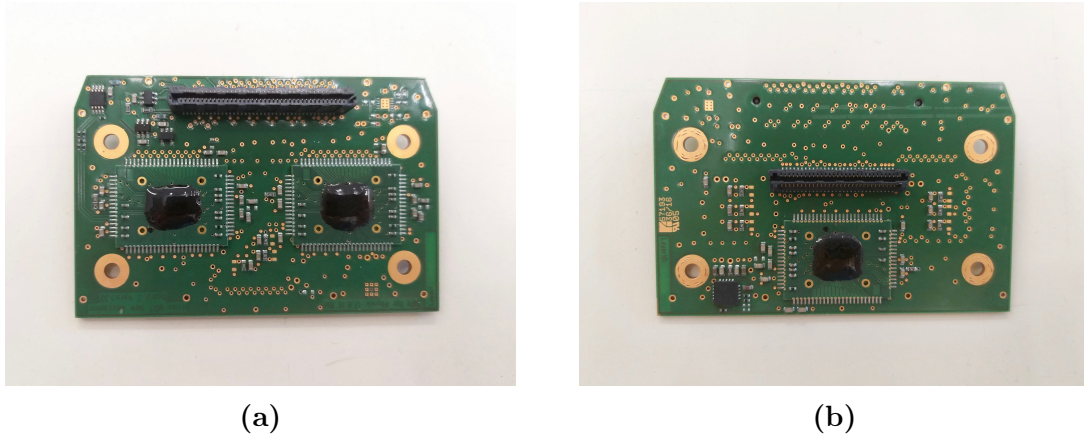


Figure 9.1.: 2 sides of the ASD board carrying 3 new ASD chips

Cards are placed one above another, as shown in Figure 9.2. The rate of the muon triggers was increased by placing additional scintillating counter next to the existing one. The trigger signal is now generated only if discriminated signal from one of the scintillating counters and the negated output of the previous trigger from the dual timer are in coincidence.

Measured quantities include noise rates, spatial resolution and muon detection efficiency which are compared to the values obtained with the old ASD chip. All

9. Overview

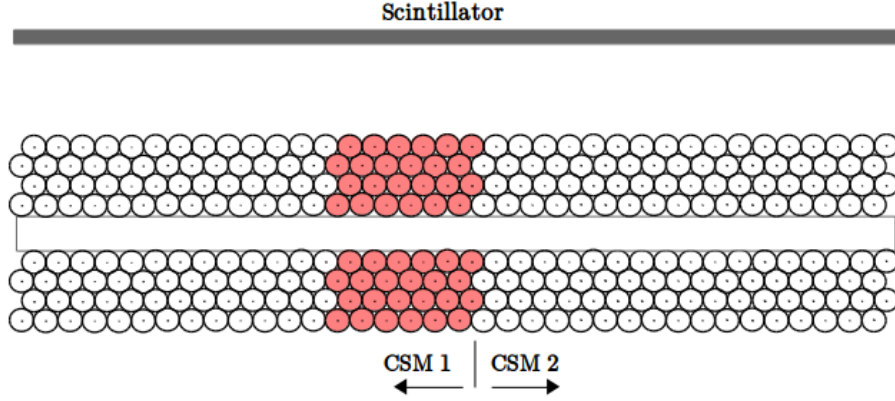


Figure 9.2.: Schematic drawing of the experimental set-up for electronics study for the new ASD chip.

quantities are determined using the same testing procedure as described for the BIS78 sMDT chambers tests.

The noise rates are investigated for the nominal parameters of the current ASD chip, as well as for additional lower thresholds, as listed in Table 9.1. Due to expected

Code	Threshold value (mV)
108	-39
110	-35
112	-31
114	-27
115	-25
116	-23

Table 9.1.: Codes and corresponding threshold values used for noise studies.

lower noise rates compared to the current ASD chip, the data taking time is increased by a factor of 3 to obtain enough accidental hits.

Cosmic ray data, needed for the spatial resolution and muon detection efficiency determination, are taken for different thresholds. Spatial resolution and efficiency determination follow the methods described in Chapters 6 and 7.

10. Results

10.1. Noise study

The average noise rates per channel were determined for each tested mezzanine card, at different discriminator thresholds and hysteresis 7.

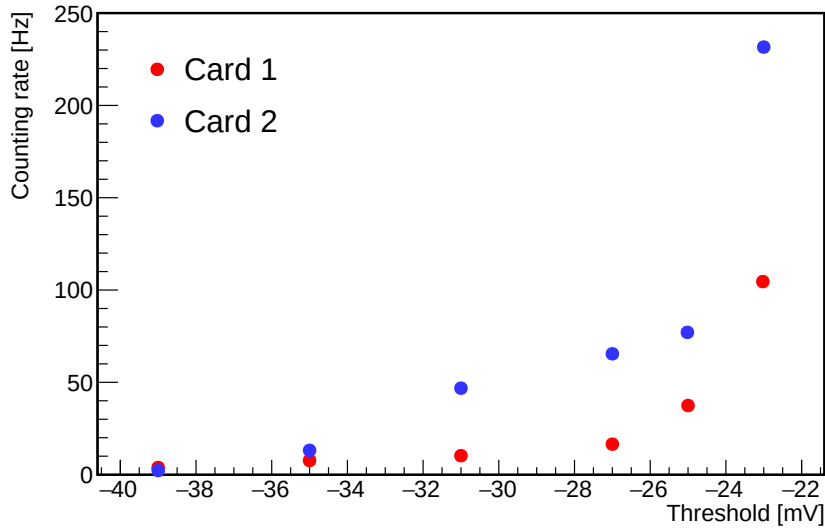


Figure 10.1.: The average noise rates per channel for two tested read-out cards, measured with new ASD chips at different discriminator thresholds.

Performed tests showed that the new ASD chip has higher noise immunity compared to old ASD chip, even at very low thresholds. The measured noise levels for two tested mezzanine cards were below 5 Hz for ATLAS settings (Figure 10.1), compared to noise levels of ≈ 60 Hz measured by the current ASD chips (Figure 8.5), at the same parameters.

New ASD chips could be operated at the threshold of -27 mV, which is 12 mV lower compared to the ATLAS settings, while achieving similar noise rates measured with current ASD chips below 100 Hz. This is compatible with the fact that the amplifier intrinsic noise was reduced from 8 mV RMS in the old chips to 4 mV RMS in the

10. Results

new chips. The other unchanged source of the noise is the thermal noise of the termination resistor on the HV side.

10.2. Cosmic rays test

10.2.1. Spatial resolution

The obtained value of the spatial resolution for ATLAS settings using the new ASD chips was

$$\sigma = (102 \pm 5)\mu\text{m},$$

which represents an improvement in spatial resolution of $20\ \mu\text{m}$, and is in agreement with the test beam measurement:

$$\sigma_{TB} = (105 \pm 2)\mu\text{m},$$

determined using the same method. The improvement in spatial resolution is caused by the twice higher amplification and slightly smaller peaking time of the new compared to the old chip. As described in Section 8.3.1, operation at lower thresholds

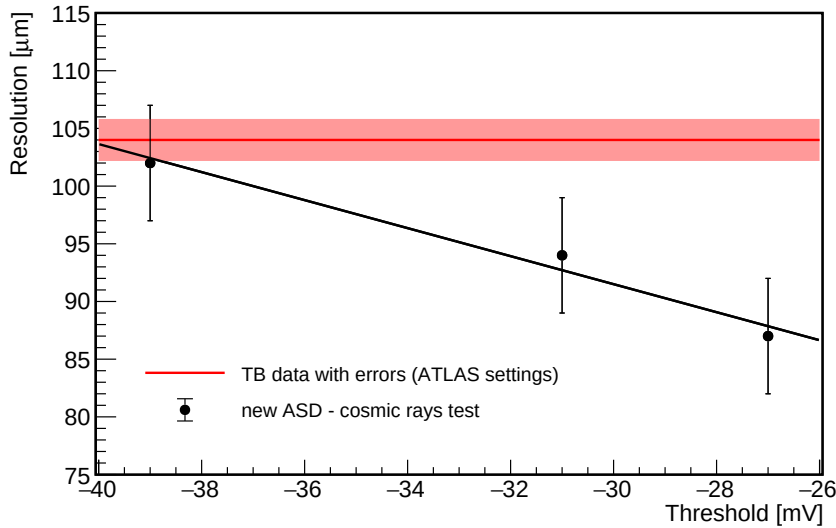


Figure 10.2.: Average spatial resolution measured with new ASD chip at different discriminator thresholds. The red line represents the test beam results obtained with new ASD chip for ATLAS settings. The error bars represent statistical error.

leads to an improvement in the spatial resolution. Spatial resolution was determined for thresholds -31 mV and -27 (Figure 10.2) leading to the additional improvement:

$$\sigma_{112} = (94 \pm 5)\mu\text{m} \quad \text{and} \quad \sigma_{114} = (87 \pm 5)\mu\text{m}.$$

10.2.2. Muon detection efficiency

The muon detection efficiency was determined for each of the 48 tested drift tubes, at ATLAS settings and two lower thresholds: -31 mV and -27 mV. The example of the obtained results is shown in Figure 10.3 for one of the tested cards at -31 mV. Overall, all tested drift tubes with new ASD chips were confirmed to be efficient, with the efficiency above 98.5 %, as measured with an old ASD chip.

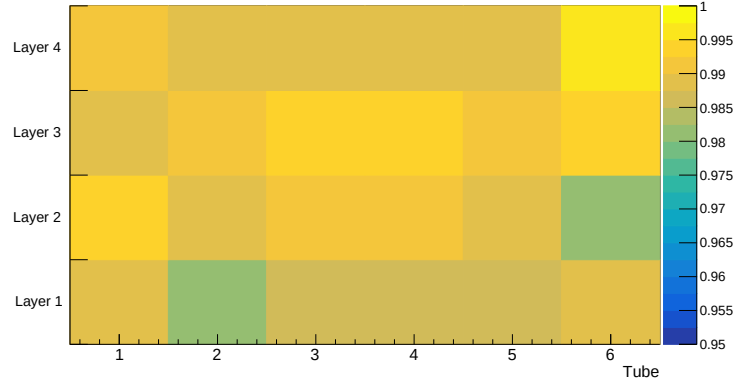


Figure 10.3.: Efficiency per tube of the one tested mezzanine card with new ASD chips at discriminator thresholds of -31 mV.

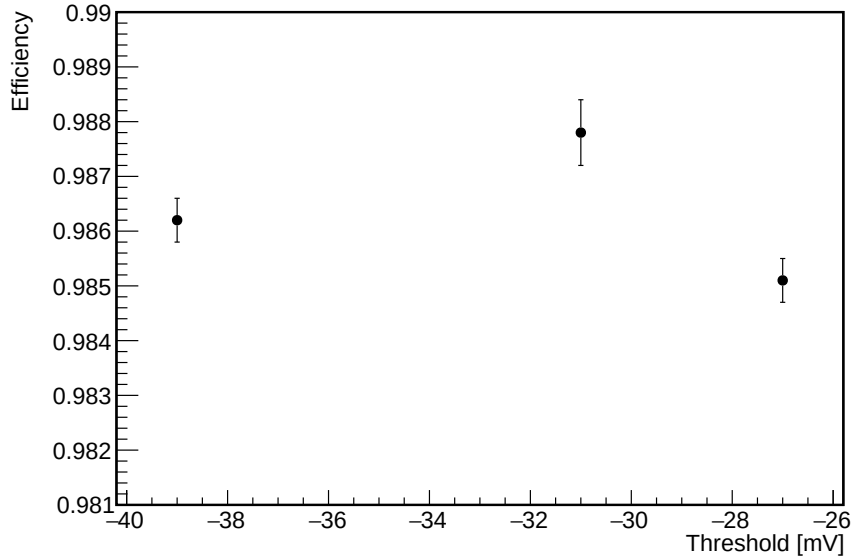


Figure 10.4.: Average muon detection efficiency measured with new ASD chip at different discriminator thresholds.

The average efficiency per tube was determined for each threshold (Figure 10.4), with mean value of 98.6 %, which is comparable to the value measured with old ASD chip of 98.76 %.

10.3. Operational point of the new ASD chip

Based on the obtained result for the noise rates, spatial resolution and efficiency at different threshold values, the proposed new operational point of the new ASD chip for the new read-out electronic is:

Parameter	Value
Discriminator threshold	-27 mV
Discriminator hysteresis	8.75 mV

Table 10.1.: Proposed operational point of the new ASD chip.

Reduced noise rates of the new ASD chip allow the reduction of the discriminator threshold for 12 mV compared to the ATLAS settings which leads to the improvement of the spatial resolution of $\approx 30 \mu\text{m}$, while staying at the average noise rates per tube of $\approx 60 \text{ Hz}$ as measured with the current ASD chip and maintaining full efficiency of the drift tubes.

Summary

Newly created conditions expected at the HL-LHC represent the challenging environment for the ATLAS muon spectrometer, which will undergo series of upgrades with an aim to preserve its excellent muon identification. Two aspects of the planned upgrades were investigated as a part of this thesis.

BIS-78 sMDT chamber tests

In the first part of this thesis, the testing of the eight new BIS78 sMDT chambers was performed, to verify their performance before the installation in the ATLAS detector, as a part of the muon spectrometer upgrade. All chambers were constructed and tested in a cosmic-ray test-stand at MPI for Physics. The investigated quantities included the measurement of the noise rates, as well as the determination of muon detection efficiency and spatial resolution by exposing the chamber to the cosmic muons:

- The noise rates were determined per drift tube of the chamber and were found to be in the agreement with previously determined intrinsic noise levels of each channel on the read-out cards, which depend on the individual threshold on the ASD chips. Average noise rates per tube are determined to be around 60 Hz for all tested chambers for ATLAS settings.
- The spatial resolution of the tubes in a chamber was determined using the method that considers almost vertical cosmic muon tracks. Measured values were found to be in agreement with the Monte Carlo prediction and the expectations from previous test beam measurements.
- The muon detection efficiency was determined for each tube in a chamber, showing full efficiency and uniform performance of the tested chambers. Obtained values were in agreement with the Monte Carlo prediction.

The tested chambers satisfy the performance requirements and can be installed in the ATLAS detector.

New ASD chip tests

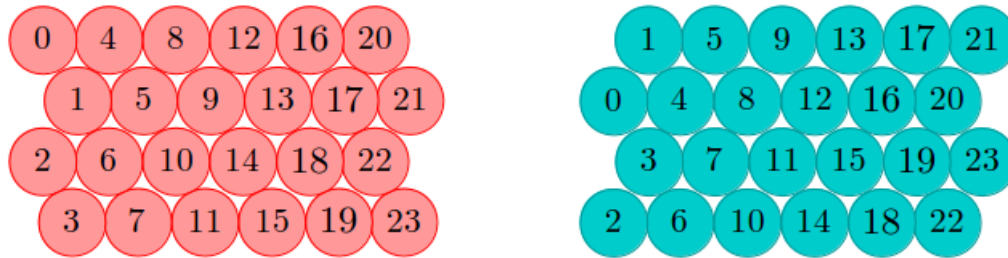
The second part of this thesis was dedicated to the determination of the operational point for the new ASD chips, developed for the new front-end boards of the MDT chambers which will be installed during the 2024/2026 shutdown of the LHC. Two read-out cards carrying new ASD chips were tested in the same experimental set-up used for certifying of the BIS78 sMDT chambers. Noise rates, spatial resolution and muon detection efficiency were investigated for the hysteresis parameter 7 of the discriminator (8.75 mV):

- The noise rates were determined per drift tube of the each card at different threshold values. The new ASD chips showed lower noise levels for all investigated thresholds, allowing the reduction of the threshold for 12 mV, while staying at the same noise levels measured with the old ASD chips.
- The spatial resolution determined with the new ASD chip at ATLAS settings was already better compared to the measurements with current front-end electronics. The reduction of the threshold to the -27 mV allows the additional improvement in the spatial resolution.
- The drift tubes read-out with new electronics showed constant efficiency, comparable to the values obtained with the old ASD chips.

Therefore, the proposed operational point for the new ASD is -27 mV, allowing better spatial resolution determination while keeping full efficiency of the drift tubes.

A. Tube numbering and channel mapping

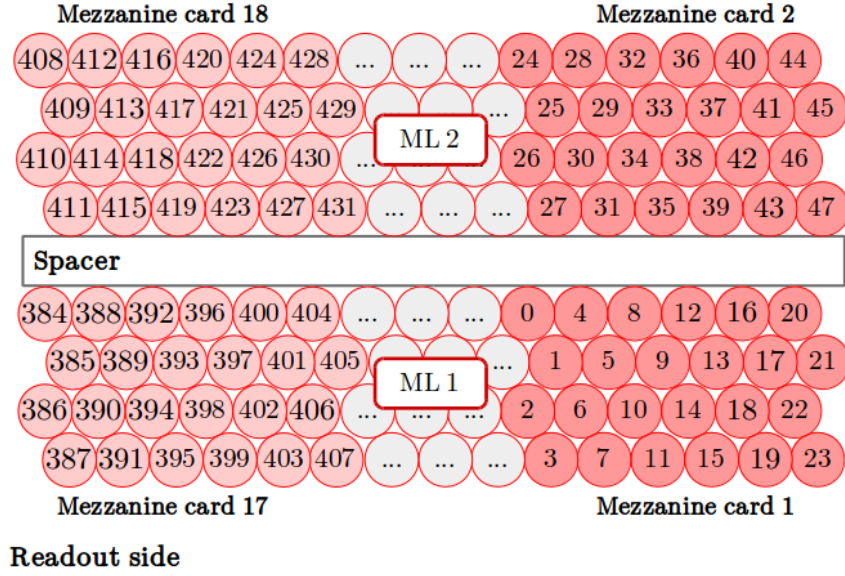
A.1. Mezzanine cards



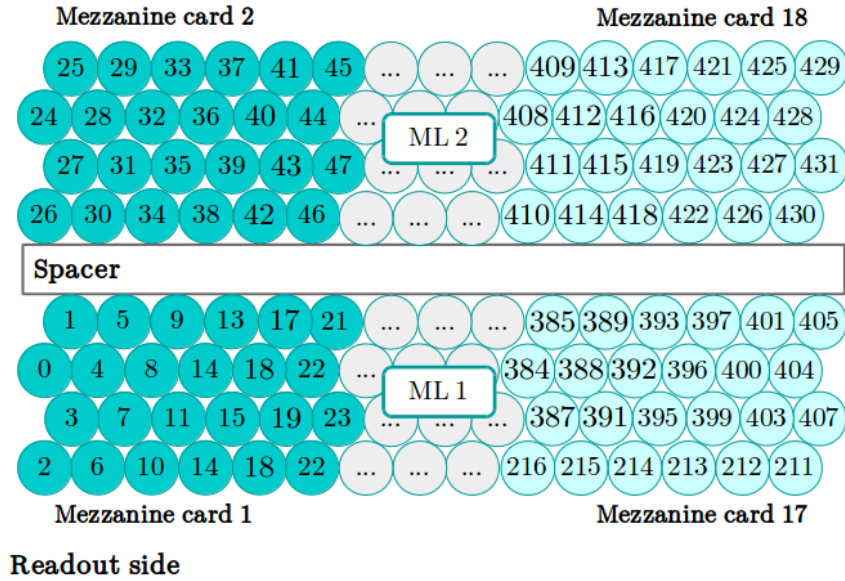
(a) Tube numbering of the C type mezzanine card seen from the read-out side (b) Tube numbering of the A type mezzanine card seen from the read-out side

Figure A.1.: Two types of the mezzanine cards used for BIS78 sMDT chambers

A.2. Mezzanine card tube numbering



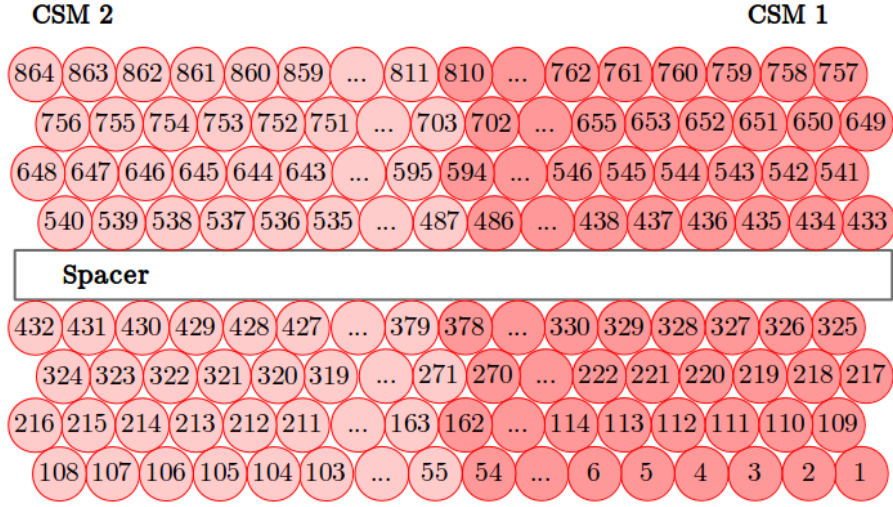
(a) Chambers with C type mezzanine cards



(b) Chambers with A type mezzanine cards

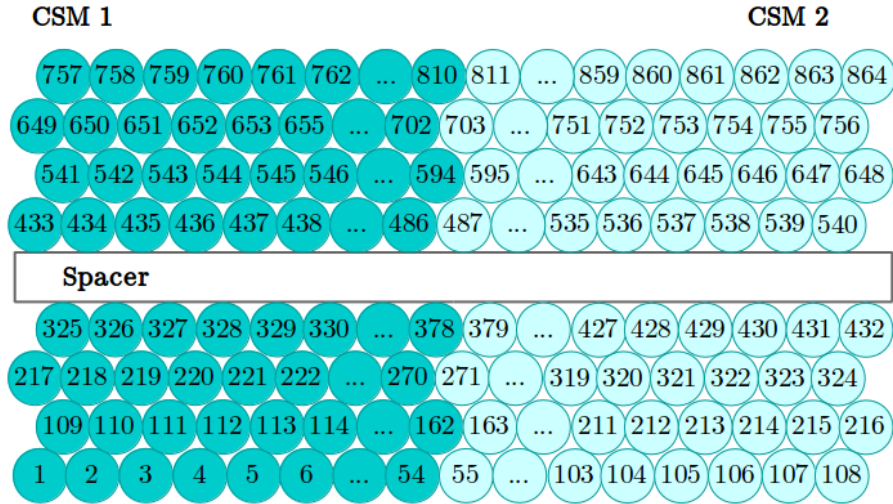
Figure A.2.: Mezzanine card tube numbering per CSM seen from the read-out side

A.3. Read-out channel mapping



Readout side

(a) Chambers with C type mezzanine cards



Readout side

(b) Chambers with A type mezzanine cards

Figure A.3.: Readout channel mapping for entire chamber seen from the read-out side

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