



Master Thesis

Production and Testing of Prototype Resistive Plate Chambers

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Abstract

The main topic of this thesis is the development of procedures for the production of thin-gap RPCs on a industrial scale. To do so the production procedures followed by the ATLAS and CMS experiments for their RPCs were used as a starting point. The procedures worked out in this thesis follow the ATLAS experiment production techniques with three main differences that ensure a better reproducible quality of the RPC.

The first part of this thesis focuses on the search for the materials and the production procedures utilized for smaller test samples. For the graphite coating which is applied on the outside of the electrodes, we chose a silk screen printing procedure that utilizes the same graphite varnish applied in the production of CMS RPCs. Additionally it was necessary to find a glue that bonds a insulating PET foil to the outside of the electrodes. The glue has to possess a sufficiently high adhesive strength, while at the same time being easy to handle in mass production and fulfilling all CERN regulations. After testing several types of glue, the best result was achieved with a compound PET foil with pre-applied EVA that fulfills all the criteria. Additionally a gluing template was introduced that allows to decouple the positioning from the gluing process of the frames and spacers in the gas gap, making it possible to safely apply the glue within its pot time. The production procedures and materials were then transferred to three companies, which produced several test samples.

The second part of the thesis focuses on testing three of the prototypes, produced by the three companies using the proposed manufacturing techniques, at MPI and the GIF++ facility at CERN, and on the data analysis involved in determining their quality and operational characteristics. The tests involved the measurement at different irradiation levels, with and without the high-energy muon beam provided at GIF++. From this data, the efficiency, the cluster size and the time resolution of these prototypes were determined. All quantities meet the required value and show the high quality of the produced RPCs.

Abstract

Das Hauptthema dieser Arbeit ist die Entwicklung von Verfahren zur Herstellung von sogenannten thin-gap RPCs in industriellem Maßstab. Dazu wurden die Produktionsverfahren, die von den ATLAS- und CMS-Experimenten für ihre RPCs verwendet wurden, als Ausgangspunkt genommen. Die in dieser Arbeit ausgearbeiteten Verfahren folgen den Produktionsmethoden des ATLAS-Experiments mit drei wesentlichen Unterschieden, die eine besser reproduzierbare Qualität der RPC gewährleisten.

Der erste Teil dieser Arbeit fokussiert sich auf die Suche nach den Materialien und auf die Produktionsverfahren, die bei der Herstellung kleinerer Handmuster erprobt worden sind. Als Ausgangspunkt wurden Verfahren und Materialien von aktuellen Lieferanten für ATLAS und CMS gewählt. Für die Graphit-Beschichtung, die auf der Außenseite der Elektroden aufgebracht wird, wurde ein Siebdruckverfahren gewählt, welches denselben Graphitlack verwendet, der für die Herstellung von CMS RPCs Verwendung findet. Um die Elektrode auf der Außenseite zu isolieren, war es notwendig, einen Klebstoff zu finden, der eine ausreichende Haftfestigkeit in Kombination mit einer PET Folie hat, einfach in der Massenproduktion zu handhaben ist und alle CERN-Vorschriften erfüllt. Nach dem Testen mehrerer Klebstoffe wurde eine Verbund-Folie aus PET mit vor-aufgetragenen EVA gefunden, die alle Kriterien erfüllt. Zusätzlich wurde eine Klebeschablone entwickelt, die es ermöglicht, die Positionierung vom Klebprozess der Rahmen und Abstandhalter in der RPC zu entkoppeln, so dass der Klebstoff sicher in der Topfzeit verarbeitet werden kann. Die Produktionsverfahren und Materialien wurden dann an drei Firmen übertragen, die mit diesen mehrere Handmuster hergestellt haben.

Der zweite Teil der Arbeit fokussiert sich auf das Testen von dreien dieser Prototypen am MPI und in der GIF++ am CERN, sowie auf die Datenanalyse, die zur Bestimmung ihrer Qualität und Betriebseigenschaften erforderlich war. Die Tests umfassten Messungen bei verschiedenen Strahlungsdosen, mit und ohne den hochenergetischen Myonenstrahl, der an der GIF++ bereitgestellt wird. Aus diesen Daten wurden die Effizienz, die Clustergröße und die Zeitauflösung dieser Prototypen berechnet. Alle Größen erfüllen den geforderten Wert und zeigen die hohe Qualität der hergestellten RPCs.

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1 The Large Hadron Collider

The Large Hadron Collider (LHC), the largest hadron-hadron collider ever constructed, is situated in a tunnel with a circumference of 26.7 km, located 50-175 m beneath the cities of Prévessin in France, and Geneva in Switzerland. The primary objective of the LHC is to accelerate and collide two proton or ion beams. The aim is to maximize the number and energy of particle interactions at the designated interaction points (IP) where experiments are located.

1.1 Accelerator Complex and hadron path

Figure 1.1.1 shows the CERN accelerator complex with the LHC and its main experiments, as well as the other accelerators and experiments. The acceleration of protons

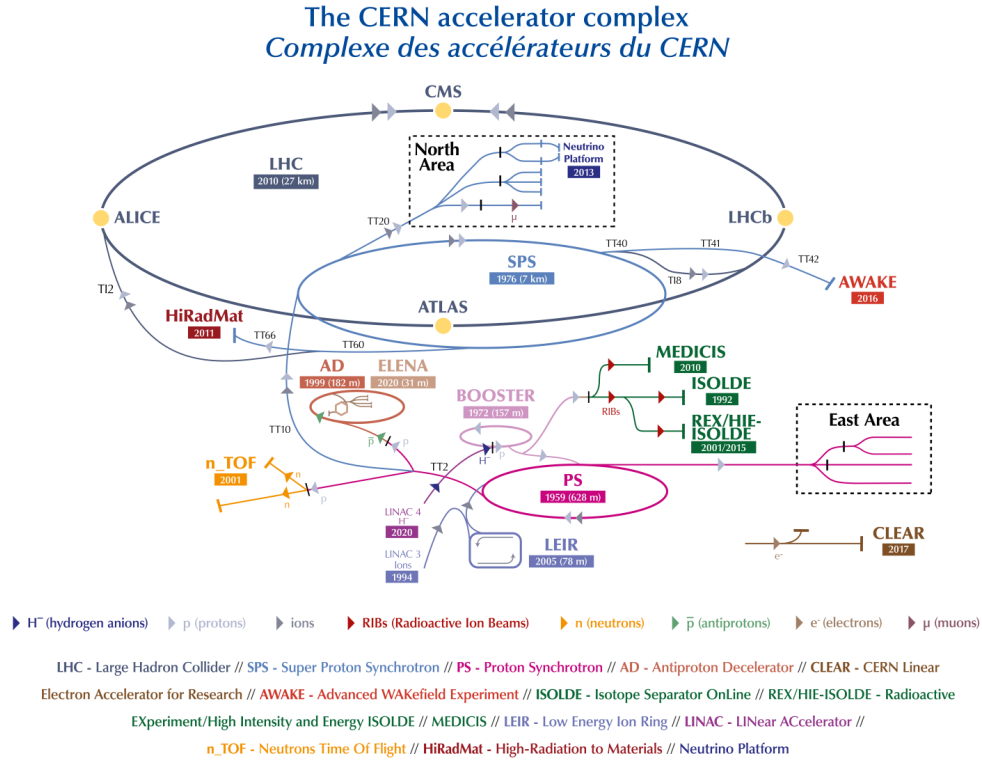


Figure 1.1.1: The CERN accelerator complex, with all accelerators and all experimental areas.

in the LHC involves several stages. Initially, protons are accelerated to an energy of 50 MeV by a linear accelerator (LINAC). Originally this was done using LINAC2 but since the long shutdown in 2017/18 LINAC 4 provides the protons for the Proton Synchrotron Booster (PSB) and thereby the LHC, increasing the brightness substantially. Subsequently, they are injected into the PSB, where their energy is increased to 1 GeV.

The Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) further accelerate the protons to energies of 26 GeV and 450 GeV, respectively. Finally, the protons are injected into the LHC and accelerated to their final energy of up to 7 TeV, which leads to a maximum center of mass energy of 14 TeV.

Ions in the LHC follow a similar path, with the difference that they originate in LINAC 3 from which they are first injected into the Low Energy Ion Ring (LEIR) which then transfers them to the PS and the rest of the accelerator chain. [1][2]

1.2 Layout of the LHC

Figure 1.2.1 illustrates the layout of the LHC. The accelerator uses two beams that circulate in opposite directions in two separate beam pipes.

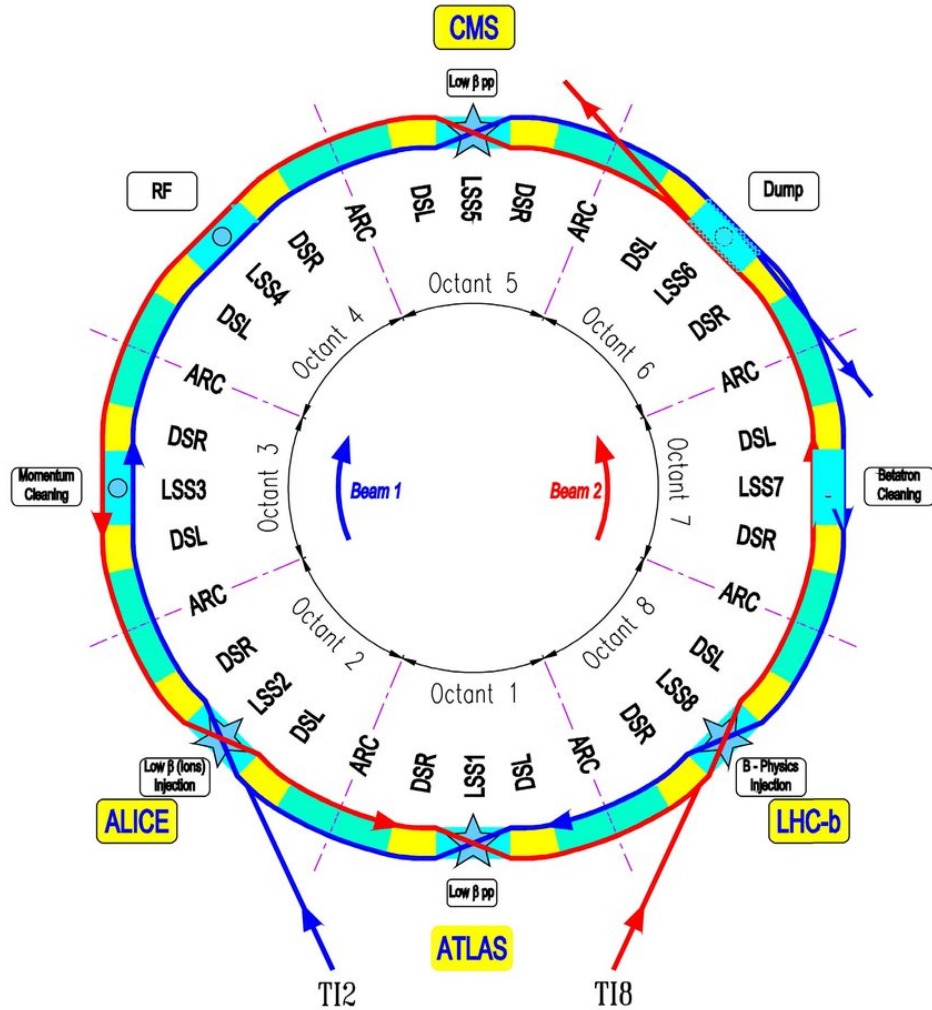


Figure 1.2.1: The layout of the LHC and its subcomponents. [3]

It comprises eight arcs, each equipped with 154 superconducting dipole magnets made of NbTi stabilized with copper. These magnets operate at temperatures as low as 1.9 K,

achieved by cooling them in an atmospheric bath of superfluid Helium, and with maximum currents of almost 13 kA at maximum field generating a field of up to 8.33 T. [4] Their primary function is keeping the two proton beams in the ring. Additionally, there are eight straight sections positioned between the arcs, each uniquely designed to cater to specific use cases. Furthermore, the accelerator incorporates 392 superconducting quadrupole magnets, along with several other multipole magnets strategically placed in it. These magnets act as lenses, focusing and optimizing the beam properties for the interaction points and experiments. [1]

The RF section of the accelerator is responsible for accelerating the hadron beams to high energies. It consists of 8 single-cell cavities for each beam, which are arranged in two cryomodules containing the cooling and power delivery. Each single cell can reach a maximum voltage of 2 MV, leading to a nominal 16 MV per beam intensity-modulating it to a frequency of 400 MHz. [5]

The betatron and momentum cleaning sections of the LHC are equipped with specialized beam optics and collimators that enhance specific beam parameters. The betatron cleaning section is designed to absorb particles from the primary beam halo, which consists of out-of-focus particles surrounding the main beam. Without this cleaning, these particles could potentially collide with parts of the accelerator and damage them. [6] The momentum cleaning section, on the other hand, serves to remove particles that have deviated significantly from the main beam's momentum. [7]

The dump section of the Large Hadron Collider accommodates the beam dump, which consists of an 8 m long graphite absorber. Given the enormous amount of kinetic energy carried by the beam, the beam dump plays a critical role in safely dissipating the beam when required. Its purpose is to provide a mechanism for the safe disposal of the beam, ensuring the controlled dissipation of its energy into the graphite absorber.[8]

With this configuration, the accelerator provides the hadron beams that are collided in the interaction regions (IR) where the experiments are located. [9][10]

1.3 The LHC Luminosity

The *Luminosity* is a measure proportional to the number of collisions per second for a given cross-section. For two colliding beams, it is described by the following formula:

$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi\beta^* \epsilon_n} \cdot \frac{1}{\sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}}} = \gamma \frac{n_b N^2 f_{rev}}{4\pi\beta^* \epsilon_n} \cdot S \quad (1.3.1)$$

with

γ being the proton beam energy in units of rest mass ($\gamma = \frac{E_{tot}}{m_0 c^2}$),

n_b the number of bunches in the accelerator (1380 for a spacing of 50 ns or 2808 for 25 ns),

1 The Large Hadron Collider

N the number of protons in the bunch, the bunch population ($1.15 \cdot 10^{11}$ protons/bunch),

f_{rev} the revolution frequency (11.25 kHz),

β^* the beam beta function at the collision point (55 cm for the LHC),

ϵ_n the transverse normalized beam emittance (nominal design: 3.75),

θ_c the full crossing angle of the colliding beams at the IP (285),

σ the transverse RMS beam size at the IP (16.7),

σ_z the RMS bunch length (7.7 cm),

S the geometrical reduction factor (0.835 at $\beta^* = 0.55$ m),

In total, this gives a peak luminosity of around $10^{34} \text{cm}^{-2} \text{s}^{-1}$. [11][12]

When integrating the Luminosity over time, the result is the so-called *integrated luminosity*:

$$\mathcal{L}_{int} = \int L dt = [\text{fb}^{-1}] \quad (1.3.2)$$

This integrated luminosity is a measure for the collected data size. Figure 1.3.1 shows the luminosity delivered to ATLAS during the past years of operation.

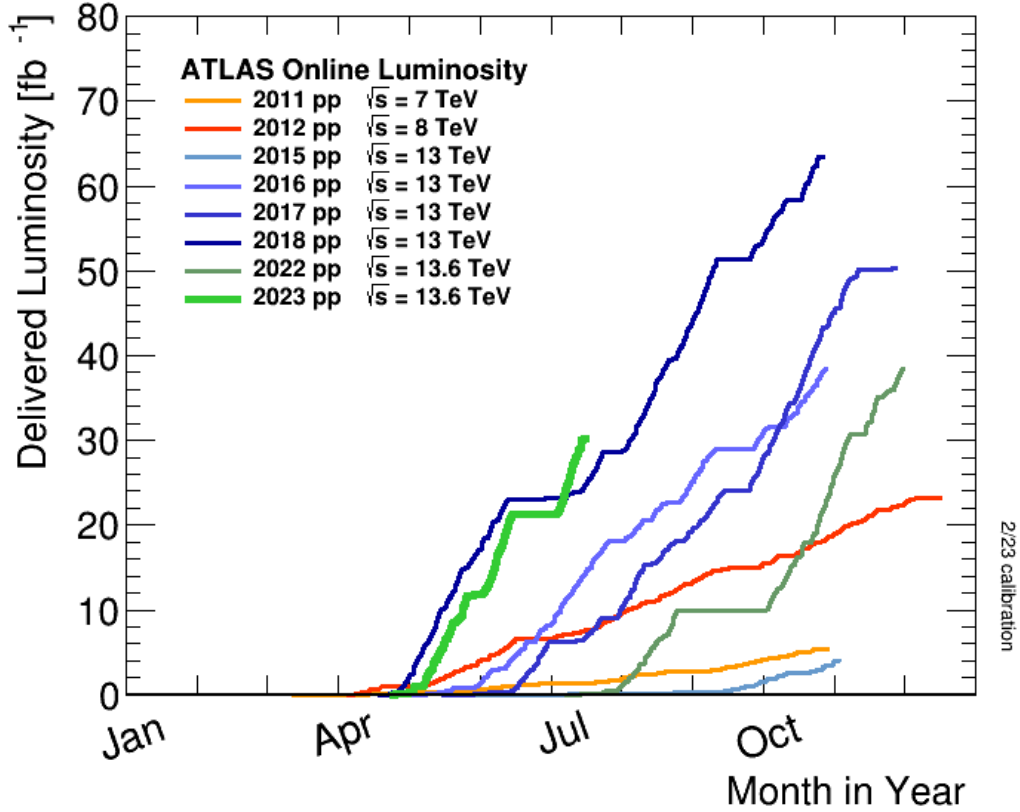


Figure 1.3.1: Integrated luminosity delivered to ATLAS, plotted against time for several years.[13]

2 High-Luminosity Upgrade

In order to become more sensitive to rare events, the LHC is going to be upgraded to the High Luminosity-LHC (HL-LHC) increasing its luminosity by about one order of magnitude during the planned long shutdown 3 (LS3) reaching an integrated luminosity of 300 fb⁻¹ within ten years of operation. Figure 2.0.1 shows the timeline of the upgrades for the HL-LHC.

2 High-Luminosity Upgrade

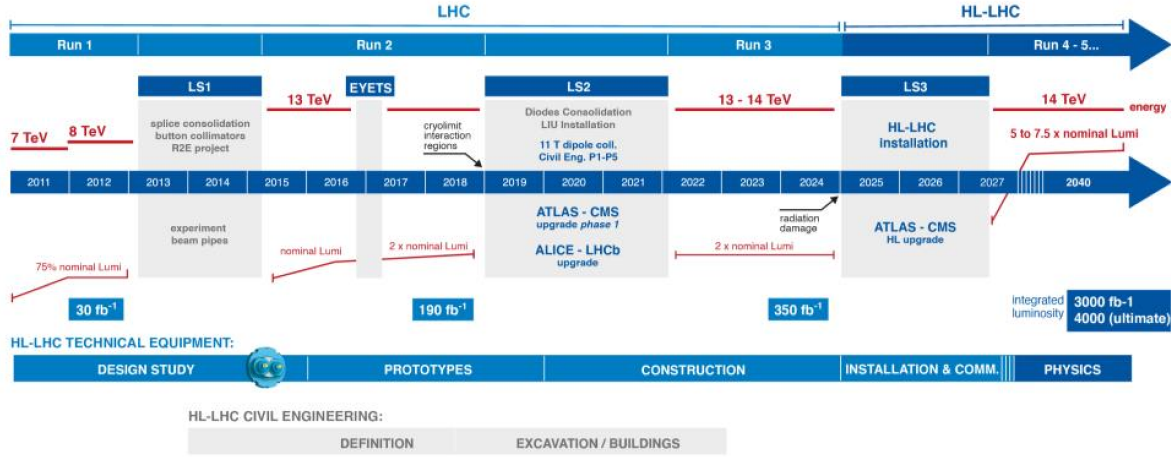


Figure 2.0.1: The timeline for the LHC upgrades, as well as the collision energy (red line in the upper part of the image) and the luminosity (red line in the lower part of the image).[14]

2.1 Luminosity increase

In order to increase the luminosity of the LHC, the main upgrades concern the beam current, the beam brightness and the reduction of the luminosity reduction factor S and the β^* . Reducing β^* corresponds to a reduction of the beam size in the transverse direction. When operating with a crossing angle, not with a perfect head-on collision, this reduction in β^* leads to an increase of the crossing angle θ_c . This increase in θ_c leads to a reduction of the geometrical reduction factor S .

To combat this, the main upgrade for the HL-LHC luminosity will be the installation of the so-called “crab cavities”. These are superconducting RF cavities, which are meant to rotate the bunches in the beam by applying an electrical field to them longitudinally by $\frac{\theta_c}{2}$, in order to increase the cross-section of the two beams colliding in the center. Figure 2.1.1 shows the change in S as a function of β .

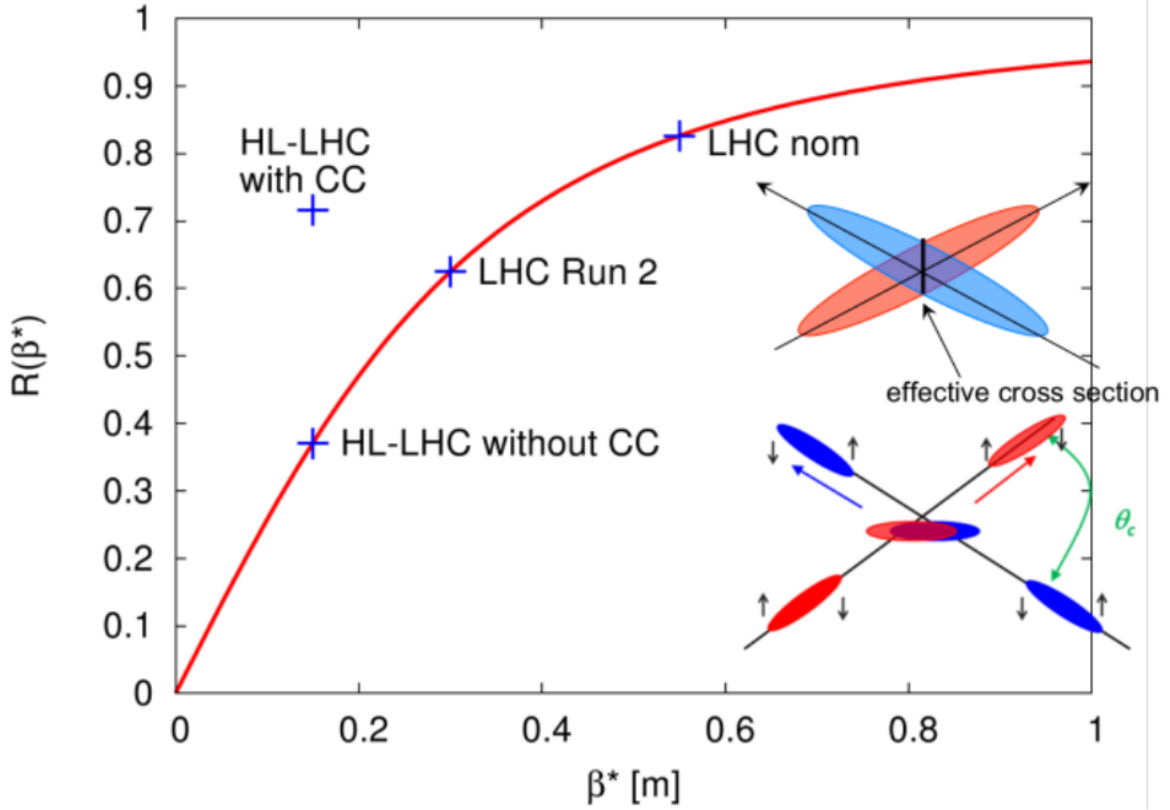


Figure 2.1.1: The geometrical reduction factor S as a function of $\beta^{(*)}$ for a constant normalized beam separation; marked are the nominal LHC operation point, the LHC Run 2 and the HL-LHC with and without crab cavities (CC). On the right is an illustration of a beam bunch with (lower illustration) and without the CC (upper illustration). [15]

2.2 Impact of the upgrade on the Experiments

In order to be able to utilize this increase in luminosity, the detectors have to be upgraded as well. The detectors need to be able to handle higher pileups, higher particle rates and a higher radiation dose as during operation a fairly uniform background, consisting of low energy neutrons, photons and electrons, is present in the detectors, that is generated by the interaction and decay of particles created in the collisions. After several collisions and decays, these particles are uncorrelated from the event itself and are of no interest for the science at the detectors. However they still can cause damage and issues with the performance of the detectors if not accounted for.

3 ATLAS Detector

ATLAS (**A** Toroidal **LHC** **A**pparatu**S**) is one of the two main general-purpose experiments at the LHC. It is located at the interaction point (IP) 1 and shares scientific goals with its counterpart **CMS** (**C**ompact **M**uon **S**olenoid), located at the second high luminosity IP 5, trying to achieve these goals using a different approach.

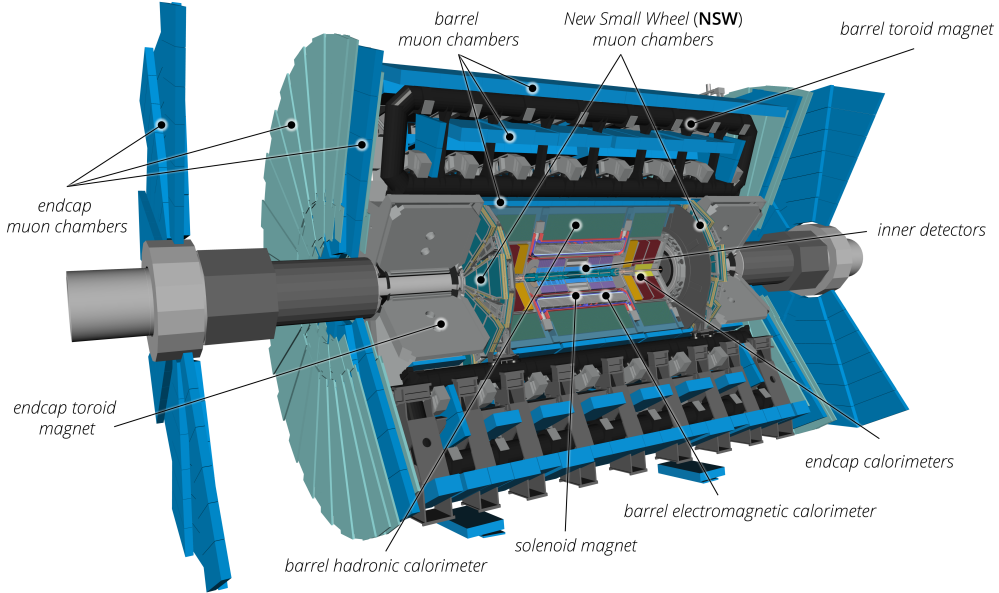


Figure 3.0.1: A Cut-way rendering of the ATLAS detector in the current run 3 configuration, with the larger detector sub-systems marked.[16]

3.1 The ATLAS Coordinate System

The coordinate system in ATLAS is right-handed, with its origin located in the nominal interaction point in the center of the detector. Its z-axis is defined by the beam direction, while the x-y-plane is transverse to the beams' direction, with the x-axis pointing toward the center of the ring and the y-axis pointing upward from the interaction point. Side A of the detector is defined as the positive z, the C side the negative and the B side is the plane with $z=0$.

In order to make the tracking of the trajectories of particles easier in the cylindrical detector, a cylindrical coordinate system is used with (r, ϕ) the coordinates in the transverse plane (x-y-plane) with ϕ being the azimuthal angle around the beam pipe. In the y-z-plane instead the angle θ the so-called pseudorapidity is used, which is defined as

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \quad (3.1.1)$$

as it is an invariant quantity.

The momentum and energy are defined as $p_T = p \cdot \sin(\theta)$ and $E_T = E \cdot \sin(\theta)$. [16]

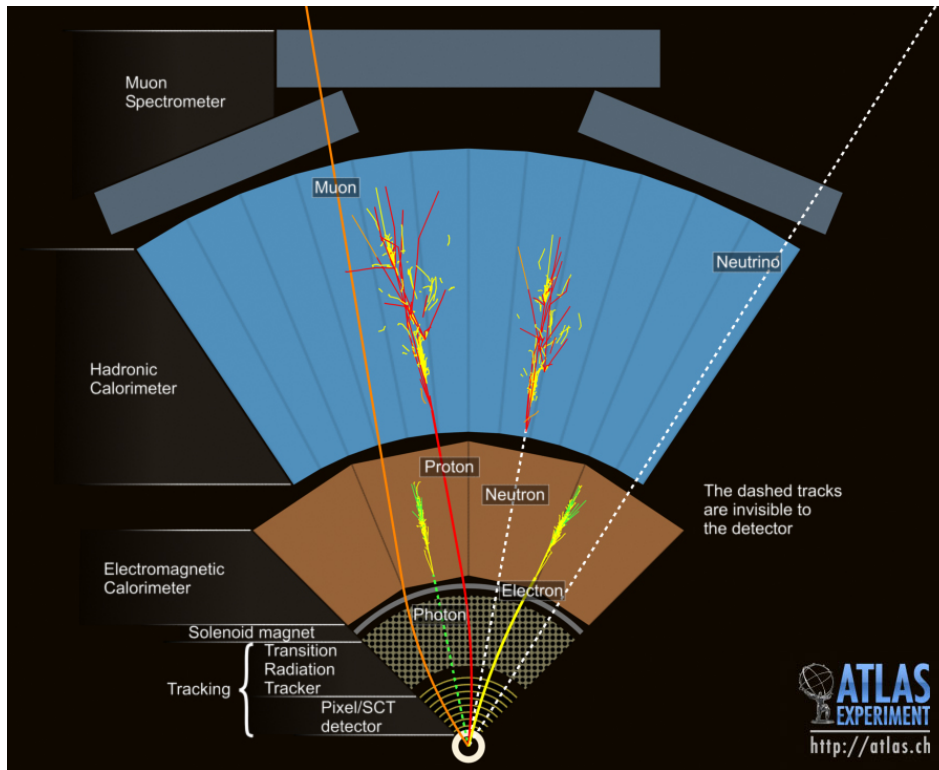


Figure 3.1.1: The picture shows a computer-generated image of an event cross-section in the ATLAS detector, illustrating which parts of the detector are sensible to which kind of particle.[17]

3.2 Detector structure

As the proton-proton collisions in ATLAS can produce any particle in the standard model (SM) and potentially even some unknown particles beyond the SM, scattering them in all directions, it is not possible to just build one detector type capable to measure all the particles and their properties. Instead the ATLAS detector is made out of several sub-detector systems. The three main components are the inner detector, the calorimeters, and the muon spectrometer.

The main design goals for the ATLAS detector are:

- Very accurate electromagnetic calorimetry for electron and photon identification
- Very good, full coverage hadronic calorimetry for jet and missing transverse energy measurements
- Good tracking at high luminosity for high- p_t lepton-momentum measurements, electron/photon identification and τ lepton/heavy flavor identification as well as full event reconstruction at low luminosity

- Wide acceptance in η with almost full ϕ coverage everywhere
- Triggering and measurements of particles at low- p_t thresholds. [16]

3.2.1 The Inner Detector

The inner detector is designed to reconstruct the trajectories of charged particles, in order to determine their charge and momentum. For this purpose, the detector is immersed in a 2 T magnetic field generated by the central solenoid. Its location in the ATLAS detector can be seen in Figure 3.0.1 while a more detailed view of the inner detector itself is shown in Figure 3.2.1.

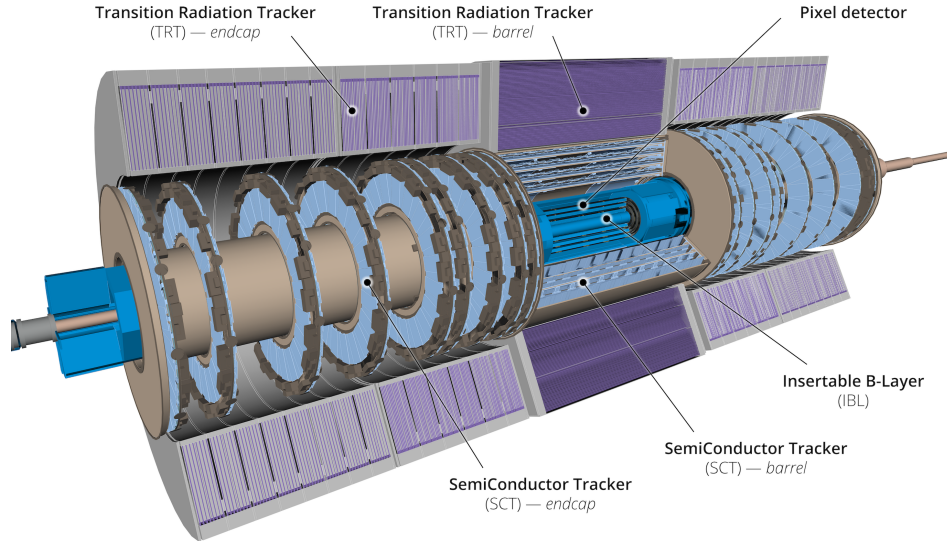


Figure 3.2.1: A cut-away view of the ATLAS inner detector showing the positions of the silicon Pixel detector in the center surrounded by silicon microstrip detectors (SCT) and straw-tube (the TRT) detectors. [16]

The inner detector is composed of a high-resolution pixel and silicon microstrip detectors covering an $|\eta| \leq 2.5$, as well as of Transition Radiation Tracker (TRT) made of gas-filled straw tubes, interleaved with transition radiation material, in the outer part. The pixel detector is made of three barrel layers and three discs on each side, with the pixels being segmented in $r\phi$ and z . For the three outer layers, the detector is made of identical pixels with a size of $50 \times 400 \mu\text{m}$. In the barrel section, the intrinsic accuracy is $10 \mu\text{m}$ ($r\phi$) and $115 \mu\text{m}$ (z) and in the discs, they are $10 \mu\text{m}$ and $115 \mu\text{m}$. A fourth layer (Insertable B-Layer IBL) installed during LS1 and operating since Run 2 is made of pixels with a size of $50 \times 2550 \mu\text{m}$. With this upgrade, the pixel detector operates with a total of 92 million channels.

The SemiConductor Tracker (SCT) is made of eight strip layers that are crossed by each track. In the inner barrel region, it is constructed of stereo strips with an angle

of 40 mrad measuring $r\phi$ and z while in the endcap the detector uses strips running radially and a set of stereostrips angled at 40 mrad. The pitch of all these strips is approximately $80\text{ }\mu\text{m}$. The intrinsic accuracy per module in the barrel is $17\text{ }\mu\text{m}$ in $r\phi$ and $580\text{ }\mu\text{m}$ in z while in the discs the accuracy is $17\text{ }\mu\text{m}$ in $r\phi$ and $580\text{ }\mu\text{m}$ in r . In total, the SCT has 66.3 million readout channels.

The 300 000 thin-walled straw tubes in proportional mode provide on average 30 points for charged particle tracks in $r\phi$ with a resolution of $130\text{ }\mu\text{m}$. The TRT covers $|\eta| < 2$ for $p_T > 50$. Additionally, the TRT provides electron identification through the detection of transition radiation X-rays. Figure 3.2.2 shows the layout of the ID.

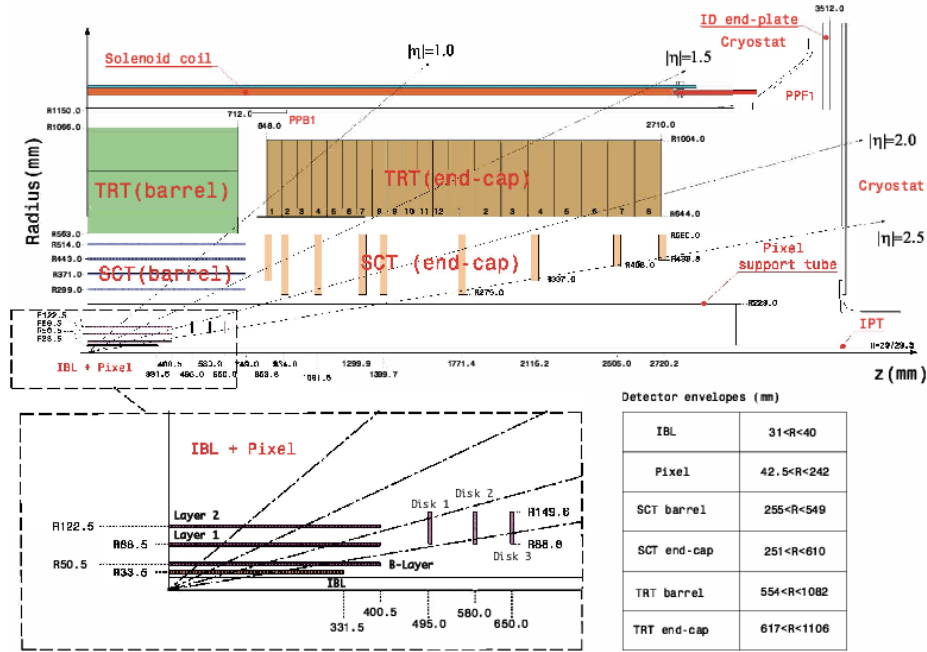


Figure 3.2.2: The graphics show the layout of the ATLAS inner detector (ID). [16]

3.2.2 The calorimeter system

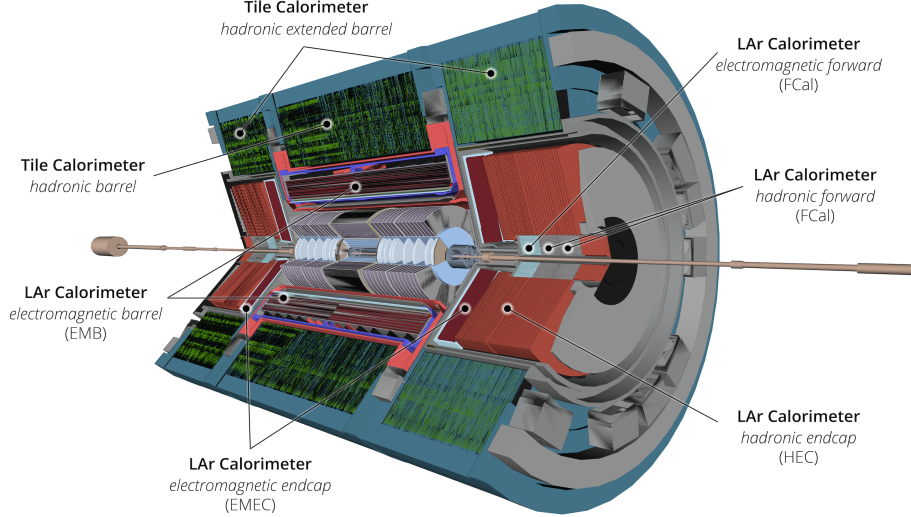


Figure 3.2.3: The picture shows a cut-way rendering of the ATLAS calorimeter system with its subcomponents marked. [16]

To measure the energy of the particles generated by the LHC, ATLAS utilizes so-called sampling calorimeters. These detectors use layers of absorbing high-density materials to stop the incoming particles with intervals of active media that measure the particles' deposited energy. The electromagnetic barrel calorimeters (EBM), the electromagnetic endcap calorimeter (EMEC), the LAr Hadronic Endcap Calorimeter (HEC), and the LAr Forward Calorimeter (FCal) are LAr based. They are designed to measure the energy of electrons, photons τ and hadron jets that are developing in the dens calorimeter material. Additionally, it also is capable of contributing to the identification of these particles, as the system is capable of reconstructing the size and shape of the shower, which is characteristic of some particles, as well as to the calculation of missing transverse energy (E_T^{miss}).

The tile calorimeter system, which covers the region of $|\eta| < 1.7$, uses pseudo-projective calorimeter towers composed of scintillating tiles in a steel matrix, that are read out by wavelength-shifting fibers. The system is composed of a cylindrical barrel section surrounding the LArEMB cryostat and two extended barrels that surround the LAr endcap cryostats. It is designed to monitor the luminosity and correct for energy losses in the outer wall of the barrel cryostat and ID services, as in this region a larger amount of passive material is present that can absorb significant amounts of energy. Another system that is considered as part of the TileCal as it shares the same readout system is the Minimum Bias Trigger Scintillators (MBTS) which covers the range $2.0 < |\eta| < 4.0$. This system is used for triggering and luminosity monitoring.

The table in Figure 3.2.4 shows the coverage of the calorimeter and its subcomponents, while Figure 3.2.3 shows the calorimeter system as it is integrated into ATLAS.[16]

		Barrel	Endcap	
EM calorimeter				
Number of layers and $ \eta $ coverage				
Presampler	1	$ \eta < 1.52$	1	$1.5 < \eta < 1.8$
Calorimeter	3	$ \eta < 1.35$	2	$1.375 < \eta < 1.5$
	2	$1.35 < \eta < 1.475$	3	$1.5 < \eta < 2.5$
			2	$2.5 < \eta < 3.2$
Granularity $\Delta\eta \times \Delta\phi$ versus $ \eta $				
Presampler	0.025×0.1	$ \eta < 1.52$	0.025×0.1	$1.5 < \eta < 1.8$
Calorimeter 1st layer	$0.025/8 \times 0.1$	$ \eta < 1.40$	0.050×0.1	$1.375 < \eta < 1.425$
	0.025×0.025	$1.40 < \eta < 1.475$	0.025×0.1	$1.425 < \eta < 1.5$
			$0.025/8 \times 0.1$	$1.5 < \eta < 1.8$
			$0.025/6 \times 0.1$	$1.8 < \eta < 2.0$
			$0.025/4 \times 0.1$	$2.0 < \eta < 2.4$
			0.025×0.1	$2.4 < \eta < 2.5$
			0.1×0.1	$2.5 < \eta < 3.2$
Calorimeter 2nd layer	0.025×0.025	$ \eta < 1.40$	0.050×0.025	$1.375 < \eta < 1.425$
	0.075×0.025	$1.40 < \eta < 1.475$	0.025×0.025	$1.425 < \eta < 2.5$
			0.1×0.1	$2.5 < \eta < 3.2$
Calorimeter 3rd layer	0.050×0.025	$ \eta < 1.35$	0.050×0.025	$1.5 < \eta < 2.5$
Number of readout channels				
Presampler	7808		1536 (both sides)	
Calorimeter	101 760		62 208 (both sides)	
LAr hadronic endcap				
$ \eta $ coverage			$1.5 < \eta < 3.2$	
Number of layers			4	
Granularity $\Delta\eta \times \Delta\phi$			0.1×0.1	$1.5 < \eta < 2.5$
			0.2×0.2	$2.5 < \eta < 3.2$
Readout channels			5632 (both sides)	
LAr forward calorimeter				
$ \eta $ coverage			$3.1 < \eta < 4.9$	
Number of layers			3	
Granularity $\Delta x \times \Delta y$ (cm)			FCal1: 3.0×2.6	$3.15 < \eta < 4.30$
			FCal1: $\sim$ four times finer	$3.10 < \eta < 3.15,$ $4.30 < \eta < 4.83$
			FCal2: 3.3×4.2	$3.24 < \eta < 4.50$
			FCal2: $\sim$ four times finer	$3.20 < \eta < 3.24,$ $4.50 < \eta < 4.81$
			FCal3: 5.4×4.7	$3.32 < \eta < 4.60$
			FCal3: $\sim$ four times finer	$3.29 < \eta < 3.32,$ $4.60 < \eta < 4.75$
Readout channels			3524 (both sides)	
Scintillator tile calorimeter				
	Barrel		Extended barrel	
$ \eta $ coverage	$ \eta < 1.0$		$0.8 < \eta < 1.7$	
Number of layers	3		3	
Granularity $\Delta\eta \times \Delta\phi$	0.1×0.1		0.1×0.1	
	Last layer 0.2×0.1		0.2×0.1	
Readout channels	5760		4092 (both sides)	

Figure 3.2.4: The table shows the coverage of the ATLAS calorimeter and its subcomponents.[16]

3.3 ATLAS-Muon-System

3.3.1 Muon interactions

As shown in the scheme in Figure 3.0.1, ATLAS has a dedicated detector system only for the precision measurement of muons. [18][19]

Figure 3.3.1 shows that the stopping power of materials for muons in the energy regime interesting for ATLAS is very low, using copper as an example.

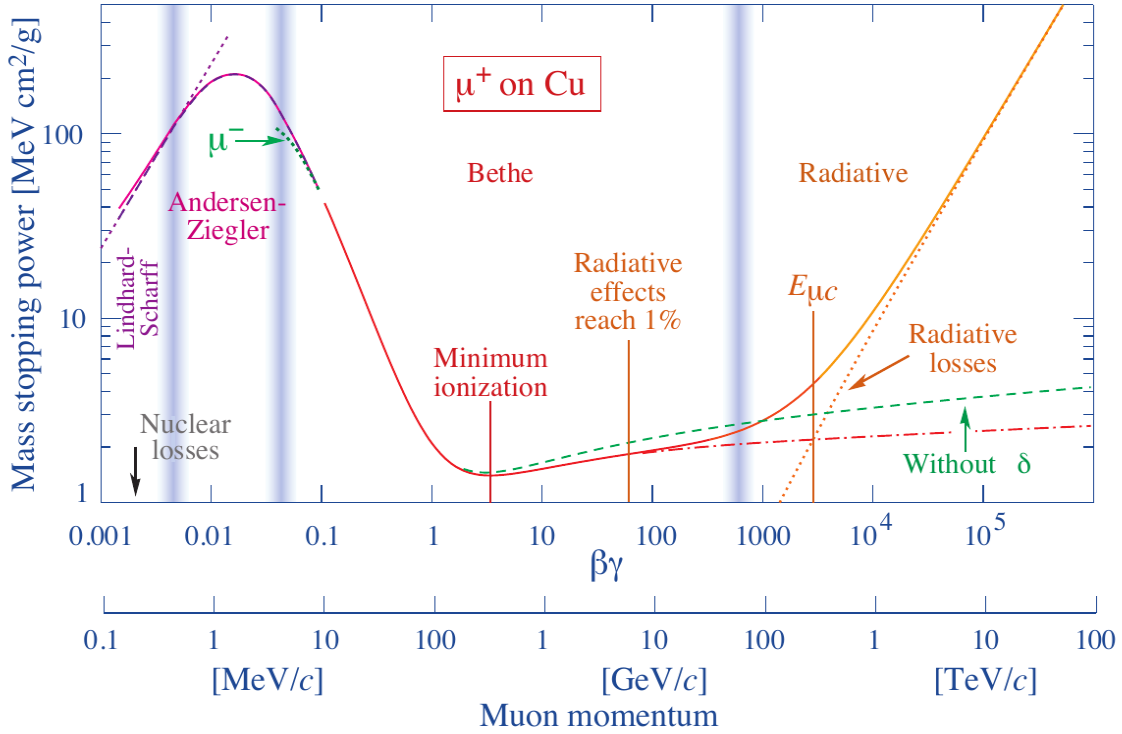


Figure 3.3.1: Mass stopping power(= $\langle \frac{-dE}{dx} \rangle$) for a positive muon flying through copper as a function of $\beta\gamma = \frac{p}{Mc}$. The vertical bands indicate boundaries between different approximations. [20]

The muons' interaction with the surrounding material in the energy regime of $20 \text{ GeV} < p_T < 1 \text{ TeV}$, can be described by the Bethe-Bloch-Equation:

$$\left\langle \frac{-dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \cdot \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (3.3.1)$$

with W_{max} being the maximum energy transfer in a single collision, Z the atomic number of the absorber, A the atomic mass of the absorber, z the charge of the incident particle, c the speed of light, I the mean excitation energy, m_e the electron mass, $\delta(\beta\gamma)$ the density effect correction to ionization energy loss and $K = 4\pi N_A^2 r_e^2 m_e c^2$ a coefficient. [20]

Additionally, for the highest momenta some radiative effects have to be considered, however for a general impression the Bethe-Bloch-Equation and Figure 3.3.1 are sufficient. As the energy lost by the muon in matter is minimal, they fly through the first layers of detectors (the tracker and calorimeter- systems) as well as through the magnets and support structures surrounding them, with negligible momentum loss. To reduce scattering, the ATLAS magnet system for the muon detectors is made out of a large air volume around the magnet coils.

Due to these characteristics, most parts of the system are placed in the outermost layers of ATLAS where mostly only muons can reach. An additional benefit of this is that the longer traveling distances increase the deflection experienced by the muons in the magnetic field, increasing the detection precision.

3.3.2 Operating goals

The Muon Spectrometer (MS) is the outermost layer of the ATLAS detector, designed to achieve a standalone transverse momentum resolution that is better than 15 % for muons with 1 TeV transverse momentum in the region $\eta < 2.7$ and to trigger on high- p_T muons in the region $\eta < 2.4$. All this requires that the muon system has to be capable to measure the sagitta of the muon trajectory with a resolution of about 75 for a sagitta of approximately 500 μm . The sagitta is determined by measuring three small sections of the tracks of particles passing an inhomogeneous magnetic field. These tracks are reconstructed from straight segments spanned by these three sections and then matched to tracks from the ID. Each section in the MS is measured by a detector made of several layers, providing a minimum of six points along the muon trajectory that can be reconstructed as a straight track with a well-measured orientation in space. The points are positioned, starting with one close to where the tracks exit the calorimeters and upstream of the torrid magnetic field, one inside or immediately downstream from the torrid magnetic field and the last well outside the magnetic field of ATLAS. [16]

3.3.3 Structure

Figure 3.3.2 shows a cut-away view of the ATLAS muon system, while Figure 3.3.3 shows two schematics of the ATLAS muon system divided into the so-called Small (S) sectors that are in line with the eight coils of the barrel toroid magnet, and the eight Large (L) sections sitting in between. The main components of the current run 3 muon system are:

The torrid magnets: Three superconducting magnets with an air-core bend the muon path, which then allows for the measurement of the sagitta. The magnetic field of the magnets is mostly orthogonal to the muon trajectory and minimizes the degradation of the resolution due to multiple scattering. The magnet system consists of three magnets with the large barrel toroid covering $|\eta| < 1.4$ and two smaller toroid magnets inserted into the endcaps on both ends of the barrel toroid

covering $1.6 < |\eta| < 2.7$. In between the regions for $1.4 < |\eta| < 1.6$ the field bending the muons is given by a superposition of the barrel and the endcap magnetic field. In total the field integral ranges between 2.0 and 6.0 Tm across most of the detector.

The Barrel muon system: It is divided into the Barrel Outer (BO), Barrel Middle (BM) and Barrel Inner (BI) sections which are designed in a concentric and approximately cylindrical. They are all comprised of Monitored Drift Tube (MDT) chambers, with additional RPCs in the BO and BM section. In addition to the original configuration, several so-called “BOE” chambers were mounted in order to improve cover gaps in the acceptance. The BOE chambers are comprised of the standard MDT and RPC detectors. A second addition are the so-called “BME” chambers that cover holes in the barrel middle layer. These utilize so-called small-diameter MDT (sMDT) and new thin-gap RPCs. The MDTs are designed for the precision measurement in the bending coordinate, while the RPCs are there for triggering and reconstructing the azimuthal coordinate of the track.

The Endcap muon system: One Endcap is positioned on each end of the barrel and is divided into three so-called “Wheels” with the Endcap Outer (EO), Middle (EM), Inner (EI) and the Extended Endcap Ring (EE) which is positioned outside the radius of each endcap toroid cryostat.

The New Small Wheels (NSWs), which are the new so-called Small wheels, comprising the EI are positioned between the calorimeters and the endcap toroid cryostats inside the barrel toroids covering $1.3 < |\eta| < 2.7$. These are composed of small-strip Thin Gap Chamber (sTGC) and micro-mesh gaseous structure (Microegas) detectors, which both can be used for precision tracking. The region $1.0 < |\eta| < 1.3$ is covered by a separate system (EIL4) of MDT and standard TGC detectors mounted between the toroid coils.

As even the EIL4 chambers have gaps for the barrel toroid coils in the Small sectors, new sMDT and thin-gap RPCs have been added as a replacement for the original BIS7 and BIS8 detectors. These chambers are called BIS78 as they replace both chambers with one.

The “Big Wheels” that comprise the EM are located on the far side of the endcap toroid cryostats and are made of MDT chambers for precision tracking sitting between TGCs for triggering and measuring the azimuthal coordinate.

The EO wheels have a size similar to the EM wheels and are mounted to the end-walls of the ATLAS cavern and contain MDTs measuring the bending coordinate. The EE rings sit in between the EI and EM wheels, providing additional measurements for tracks in the region, $1.05 < |\eta| < 1.3$, which are not covered by the EO and do not contribute to the trigger.[16]

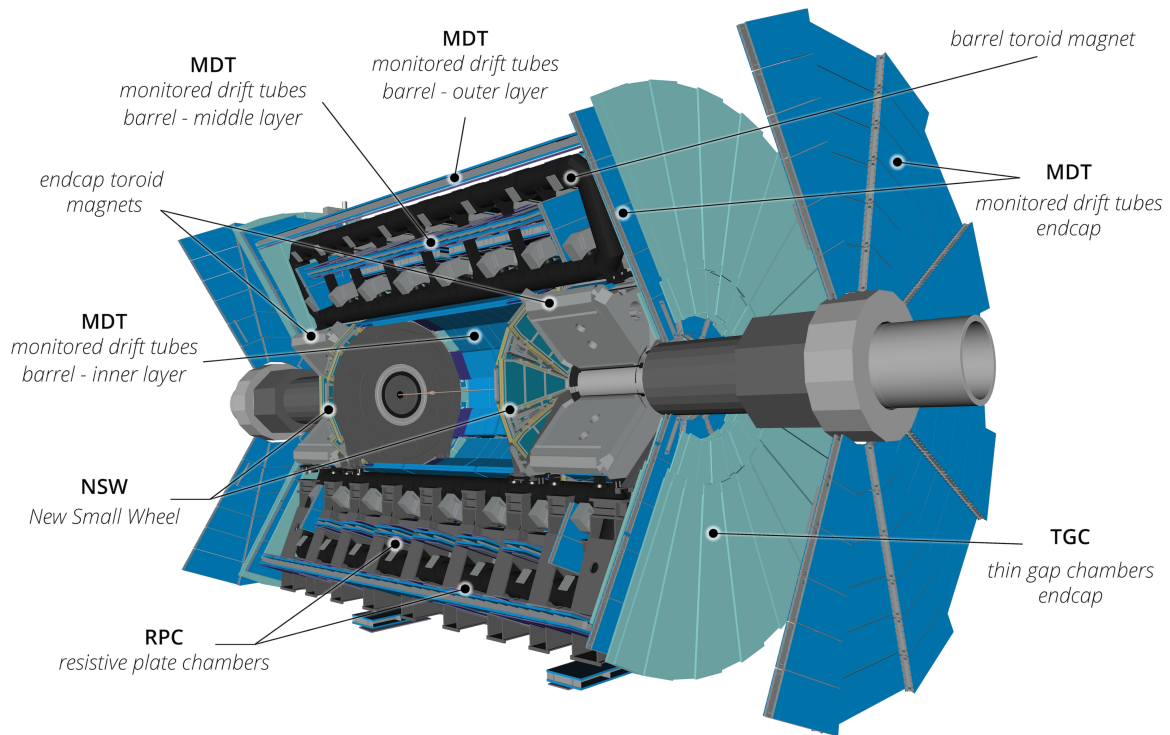
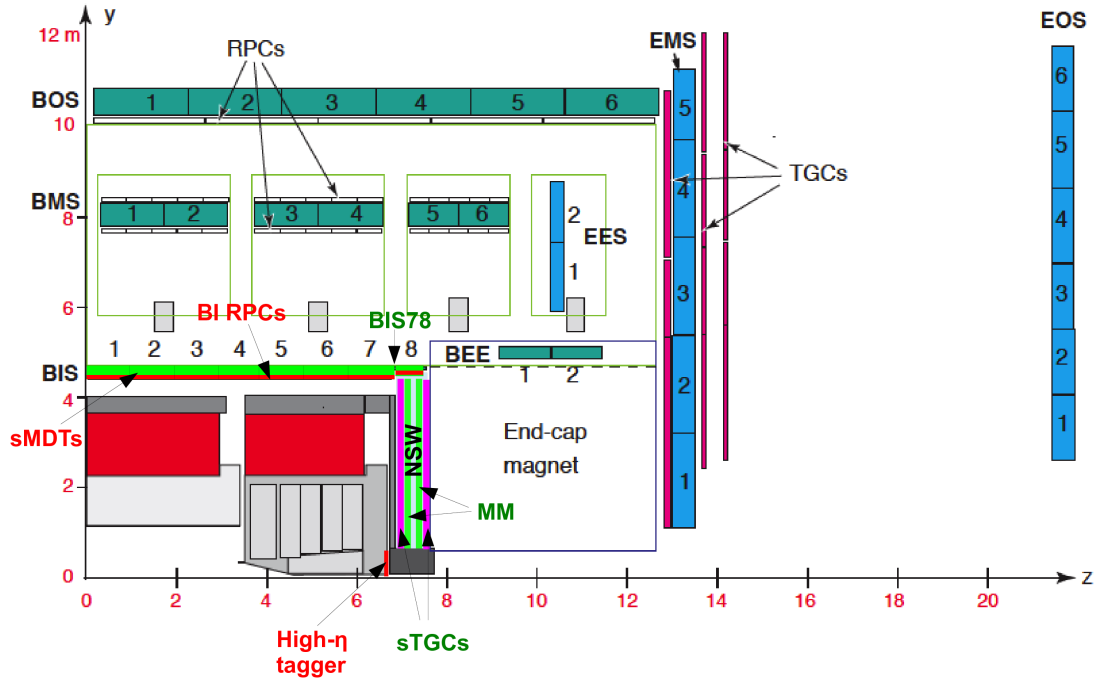
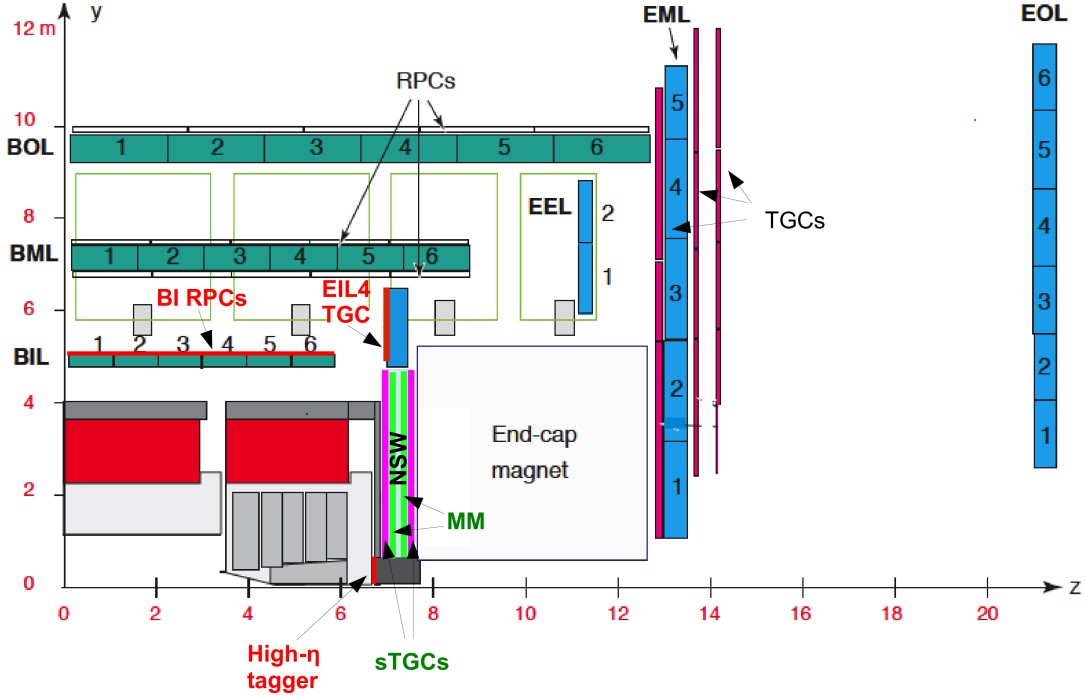


Figure 3.3.2: Cut-away view of the ATLAS muon system with all subcomponents shown. [16]



(a) The cut view shows a schematic of the small sectors of the ATLAS muon system [16]



(b) The cut view shows a schematic of the large sectors of the ATLAS muon system [16]

Figure 3.3.3: The schematics show a cut view of the main components of the ATLAS MS and their positions in the detector. The components marked with red labels are not installed yet and will be installed during LS3, while the ones marked with green have been installed in LS2 and the black ones staying unchanged. The red blocks mark the position of the Tile Calorimeter. [16]

3.3.4 The HL-LHC upgrade of the muon system

As the luminosity and particle flux in the HL-LHC will be nearly an order of magnitude higher than in the current LHC, all existing components of the MS have to be re-qualified for at least 10 years of operation at the HL-LHC with an integrated luminosity of 3000fb^{-1} while all new components that are going to be installed in the phase II upgrade during the LS3 have to be certified for a total integrated luminosity of 4000fb^{-1} . The operational target is an instantaneous luminosity of $7.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and a pile-up of $\langle\mu\rangle = 200$ without significant performance losses. In order to keep the reconstruction efficiency, fake rates, and momentum resolution similar to the current ATLAS muon system, the trigger system needs to be upgraded. The current limitation is the spatial resolution of the RPC and the TGC trigger chambers in the bending coordinate. The efficiency of the trigger is limited by its geometrical acceptance in the barrel region, due to its lower than 80% efficiency for tracks detected in three RPCs. These new detectors that are going to be installed are shown in Figure 3.3.3. Additional upgrades also include replacing parts of the front end, trigger and read-out electronics.

A big issue with the current system is that the RPCs in ATLAS have not been designed for the high rates of the HL-LHC. To be able to use them during the HL-LHC operation, the gas gain will have to be lowered in order to keep the RPC within the original design specification for a current and integrated charge. This reduction in gas gain will also significantly reduce the efficiency of the RPCs, with hit inefficiencies reaching up to 35%, which in turn reduces the trigger efficiency of the barrel below acceptable levels. To combat this, newly designed RPCs and sMDTs have to be installed in the BI, BM and BO region, which at the same time will close most of the acceptance holes in the current barrel muon trigger. The new smaller sMDTs allow the installation of a sMDT and RPC in place of a single older MDT in the BI region. A pilot for this complete replacement of BIS1-6 MDT chambers with new sMDT+RPC chamber modules was the replacement of the BIS7 and 8 MDTs with BIS78 modules, shown in Figure 3.3.4. [19]

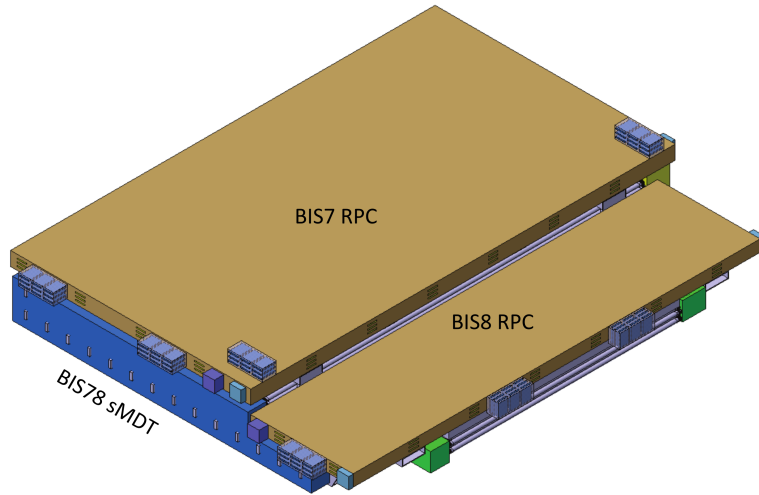


Figure 3.3.4: CAD rendering of a BIS78 station made of two multilayer sMDTs and a BIS7 and BIS8 RPC triplet; the total dimensions fit into the same space as the current BIS7 and BIS8 MDTs.
[19]

This thesis focuses on the production and testing of smaller prototypes of these new RPCs, in order to validate the Max Planck Institute for physics in Munich as an additional production site.

4 Resistive Plate Chambers (RPCs)

Resistive plate chambers (short RPC) are parallel plate gaseous ionization detectors that have a combined drift and ionization region. They have an excellent time resolution, making them ideal as a *trigger* inside the ATLAS muon system.

4.1 General Structure of a RPC

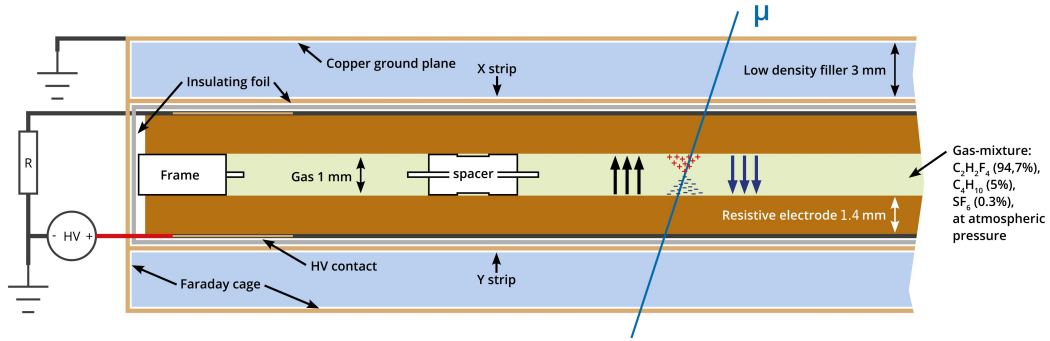


Figure 4.1.1: The scheme shows the structure of an ATLAS RPC singlet.

The three main components of a RPC are shown in Figure 4.1.1.

The gas gap, where the actual ionization and gas amplification takes place. It is made out of two highly resistive plates (the brown bulks in the figure), usually consisting of glass or high-pressure phenolic laminate (HPL), coated with a conductive layer (the thin black layer on the brown plate in the Figure) needed to create an electric field within the gap that drives the gas-amplification (as illustrated in the Figure by the blue and red charges). In the case of the ATLAS RPCs, the electrodes are made of HPL with a target volume-resistivity ρ of $(1.5 \cdot 10^{10} - 9.9 \cdot 10^{10})$ k Ω cm and coated with a graphite layer of surface resistivity 350 k Ω /□ with a tolerance of $\pm 30\%$. The inner surface of the electrodes is coated with a thin linseed oil layer meant to create a smoother inner surface, reducing electric field in-homogeneities and thereby discharges that would introduce noise in the detector. Inside and around the gap there is a support structure made out of a polycarbonate frame and spacers (marked as the gray rectangles in the Figure) that keeps the two electrodes at a constant distance of 1 mm, preventing both the expansion due to the pressure of the gas during operation and the collapse of the gap due to the attraction of the two oppositely charged plates. The shape, dimensions, and positions of the spacers are optimized to reduce the number of blind spots in the detector, improving the geometric inefficiency.

The gas that fills the gap created by the electrodes. Various gas mixtures can be used, depending on the parameters of the application. The gas used for the operation of the ATLAS RPCs and the prototypes described in this thesis is the so-called standard gas mixture, consisting of 94.7% Tetrafluoroethane (R134a; $C_2H_2F_4$), 5.0% Isobutane and 0.3% sulfur hexafluoride (SF_6).

The strip panel, which picks up the signal generated in the gas. It is made out of copper coated FR4 PCBs (indicated in orange in Figure 4.1.1) and a low-density filler (indicated in light blue in Figure 4.1.1) and is placed on the outside of the gas gap, separated from the graphite by a polyethylene terephthalate (PET) foil. Highly sensitive amplification and pulse/shaping electronics are mounted on the strip panel to read the signals picked up with it (further information is in Chapter 4.5).

4.2 Operational Principle

A RPC is a gaseous ionization detector in which the primary ionization is amplified in an avalanche process. The unique characteristic of a RPC is that the high resistivity of the electrodes confines the charge to a limited region of the detector. Additionally, the gas mixture in the RPC is designed to improve the operation of the RPC, with each gas having unique qualities, targeting specific improvements in order to operate a RPC at its best efficiency for the ATLAS detector, in the so-called *saturated avalanche mode*. Tetrafluoroethane is an electronegative gas with low charge amplification that due to its high density is used as the main gas for primary ionization.

The isobutane in the mixture acts as a *quencher* that absorbs photons generated in the electron-ion recombination process, suppressing photoionization and thereby the generation of streamers.

The last component of the mixture, the sulfur hexafluoride (SF_6) is an additional electronegative gas that absorbs excess electrons with low energy keeping the working point and plateau in the avalanche operation region and reducing the probability of streamers even further.[21][22]

4.2.1 Primary Ionization

The primary ionization charge inside the gap is generated in collisions of impinging muons ionizing the gas molecules. As the main particles of interest for this thesis are muons, the following part will focus on the ionization caused by muons in a RPC.

As discussed in Chapter 3.3.1 the muon loses energy in the gas according to the Bethe-Bloch-Formula. This loss in some cases transfers a sufficient amount of energy to an atom to ionize it, creating an electron-ion pair. As the gas has a comparably low density and the RPC is very thin, this energy loss can be considered negligible compared to the total energy of the muon, allowing the assumption that the distribution of the number of primary ionization is given by a Poisson statistic which is characterized solely through λ the mean free path for ionization.

The formula for the primary ionization is then given by:

$$I_p = e \frac{g}{\lambda} = en_p \quad (4.2.1)$$

with

4 Resistive Plate Chambers (RPCs)

e the electron charge

λ^{-1} the number of ionization per unit length also written as α the first Townsend coefficient

g the gas gap thickness

n_p the mean number of primary ionization

The probability that a muon ionizes k atoms is given by

$$P(n_p, k) = \frac{n_p^k}{k!} e^{-n_p} \quad (4.2.2)$$

[23]

Tetrafluorethane, the main gas in the RPC, has a $\lambda^{-1} \approx 75 \frac{\text{ionizations}}{\text{cm}}$ which for a 1 mm gas gap leads to a mean number of primary ionizations $n_p \approx 7.5$. [24]

4.2.2 Secondary Ionization

As the amount of charges generated by primary ionization is very low, the RPC relies on the secondary ionization generated by the gas amplification to generate the bulk of the signal inside the chamber. This happens due to the electrical field in the chamber that accelerates the electrons from the primary ionization toward one of the electrodes. When the electrons get accelerated enough, reaching a sufficiently high kinetic energy, they start ionizing atoms themselves. This secondary electron itself gets accelerated as well and can ionize atoms on its own. This process continues, forming an avalanche of drop shape where the bulk of the electrons is concentrated in the front, while the ions are gathered in the tail.

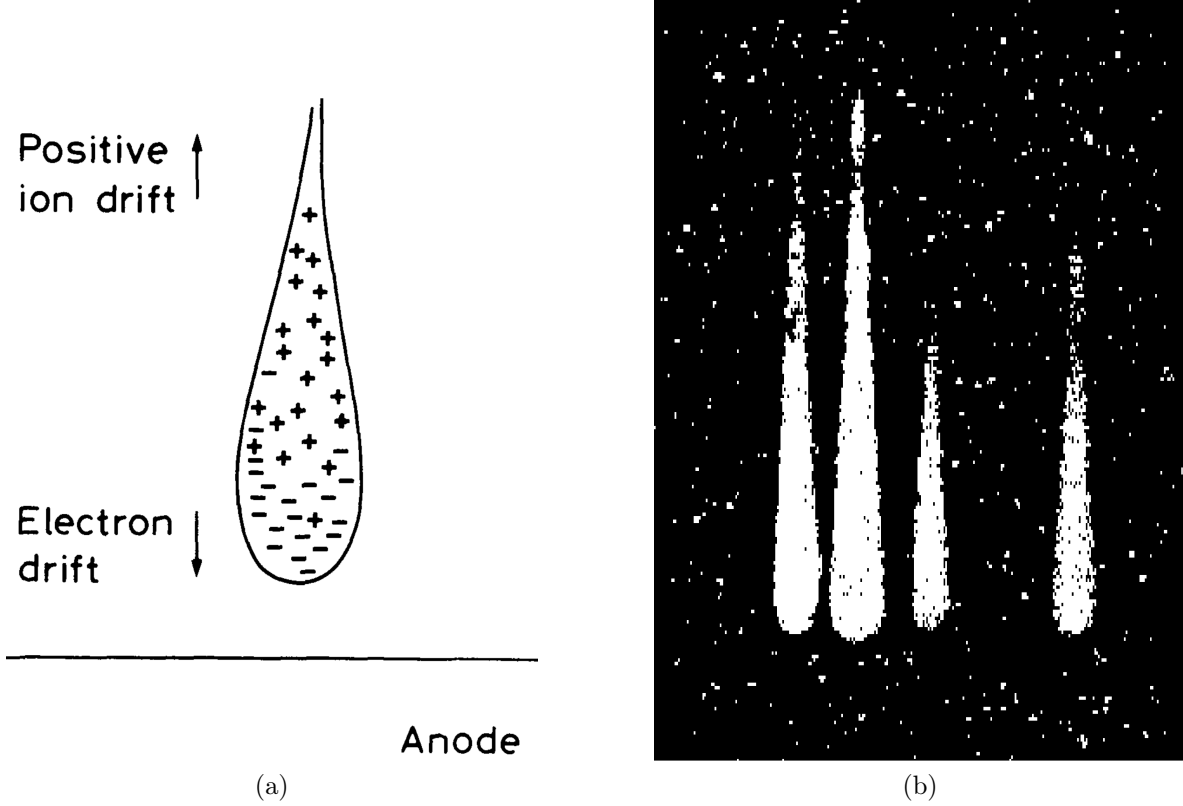


Figure 4.2.1: The illustration in (a) the shape of an avalanche, showing the Ions gathered in the tail of the drop while electrons are moving in the front part towards the Anode[25], while the picture in (b) shows a cloud chamber photograph of an electron avalanche taken in a parallel plate counter. [23]

The shape is caused by the different drift velocities of the electrons and the ions. Ions are slower and therefore stay in the tail of the drop, while the electrons move much faster and gather in the front part.

The mechanism describing the avalanche evolution is based on the Townsend Model. This can be derived by assuming that at first there are n electrons inside the avalanche moving to the anode, creating

$$dn = n\alpha dx \quad (4.2.3)$$

new electrons. Now considering that the electrons move with the drift velocity v_d we can calculate that after any time t , the electron moved a distance

$$\Delta x = v_d t \quad (4.2.4)$$

when integrating Equation 4.2.3 and inserting the expression for Δx , the result is

$$n(t) = n_0 \cdot e^{\alpha v_d t}. \quad (4.2.5)$$

4 Resistive Plate Chambers (RPCs)

Using this it is possible to build a simplified model assuming

- Λ the mean free path for primary ionization depends only on the gas mixture
- $\alpha = \lambda^{-1}$ is independent of the electrical field
- primary electrons are generated at the beginning
- all secondary electrons are generated at a distance of Λ from the origin of the electron they are generated by

[26]

Then, each primary electron has

$$S_l = g - l\Lambda \quad (4.2.6)$$

space to create a secondary ionization. This leads to the number of generated electrons being given by

$$n_l = n_s e^{\frac{S_l}{\lambda}} \quad (4.2.7)$$

Assuming that each primary electron creates its own avalanche, the total charge produced can be calculated by summing over all primary electrons n_p

$$\frac{q}{e} = N = \sum_{k=1}^{n_p} n_l + \frac{q}{e} = n e^{\frac{g-l\Lambda}{\lambda}} \quad (4.2.8)$$

with n_s being the mean number of secondary ionization. When the number of primary ionization is large, $n_p \rightarrow \infty$ we can simplify this to

$$\frac{q}{e} \approx n_s e^{\frac{g}{\lambda}} \frac{1}{1 - e^{\frac{-\Lambda}{\lambda}}} \quad (4.2.9)$$

The gain here increases with the voltage V applied on the electrodes, as α is a function of the electric field in the gap

$$\alpha = \frac{1}{\lambda} e^{-\frac{V}{E\lambda}} \quad (4.2.10)$$

This model shows good acceptance with experimental results at low voltages where additional effects limiting the avalanche do not influence the avalanche.[26]

4.3 Space Charge Effect

When the voltage and thereby the gain are increased, the number of charges that accumulate in a very small space of the gas gap create an electrical field strong enough that it reduces the overall electrical field in the small volume around the gap. As more electron pairs are added, the reduction of field strength becomes increasingly significant. Eventually, the space charge reaches a value, at which the overall electrical field is reduced to such a degree, that the electrons are no longer accelerated enough to reach an energy that allows for secondary ionization, which stops the development of the avalanche and effectively limits the total possible charge.

This effect has the additional benefit, that it becomes possible to construct a RPC with a high gain and sensitivity while having total charges low enough that the detector is capable of running for prolonged periods under high radiation.[23]

4.4 Streamer mode

Another operational mode of the RPC is the so-called streamer mode. In this mode, the voltage applied to the chamber is so high that UV photons are generated in the avalanche. These photons can move much further and faster through the gap than the electrons. When these photons reach the cathode they knock electrons out of its surface which in turn are accelerated rapidly and in turn ionize the gas even further. The avalanches generated by these electrons then merge to form a plasma pillar that locally discharges the electrodes and reduces the electrical field drastically, creating a current puls orders of magnitude larger than the one of an avalanche and considerably longer in time. Therefore, streamers often show an avalanche signal several ns before the actual streamer signal. This operational mode however has the disadvantage that it only allows the operation at lower particle rates due to its high plus charges, compared to the avalanche mode. Additionally, the high charges of streamers reduce the longevity of RPCs due. The probability of streamers occurring can be lowered by adding small amounts of SF_6 to the gas mixture. [23][27] An example of a streamer signal can be seen in Figure 4.4.1.

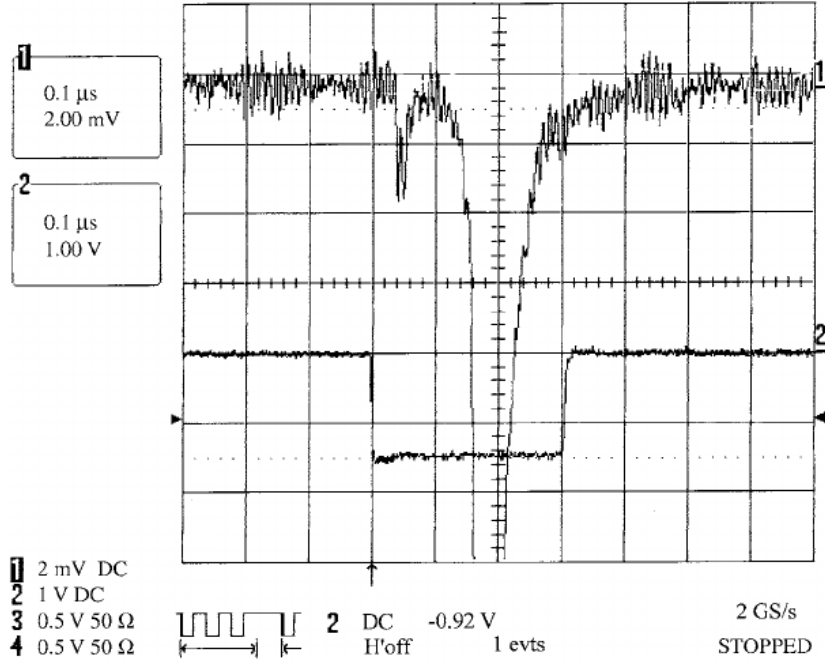


Figure 4.4.1: Avalanche (small signal) and streamer signal (large signal) taken directly from a readout strip of a RPC. [28]

4.5 Induced Signals

The ions and electrons moving in the gap induce charges in the electrodes. As the electrons/ions move in the gap the amount of charges induced changes creating a measurable current. This current is described by the equation:

$$i(t) = \vec{E}_w(\vec{x}(t)) \cdot \vec{v}_D(t) e N(t) \quad (4.5.1)$$

with

$i(t)$ the current induced at a time t ,

$\vec{E}_w$ the weighting field inside the gas gap at a position $\vec{x}(t)$,

$\vec{v}_D$ the drift speed of the particles moving,

e the unit charge of the electron,

N the number of particles moving in the gas. [23]

As the drift velocity of the electron in the gap is very high, they induce a measurable current signal on the electrodes. The signal of the ions is much smaller due to their much smaller drift speed and is usually not utilized in most experiments.

4.6 Signal propagation to the strip panel

When the charge generated in the avalanche reaches the electrode, the high resistivity prevents the dispersion and confines it to a small area, forcing the charge to move through the electrode to the conductive graphite coating on the outside. Due to this, each small volume around the avalanche can be represented as a separate cell in a matrix of several other independent cells. The size of these cells is determined by the size of the avalanche, with the surface being proportional to the charge in the avalanche and the gap width:

$$S \propto Q_g \quad (4.6.1)$$

The signal in this cell is then transmitted by capacitive coupling to the readout strips on the strip panel to which the readout electronics are mounted. Figure 4.6.1 shows an electrical model of such a cell, with the left scheme showing the cell in a state of no ionization and the right a cell with ionized gas.

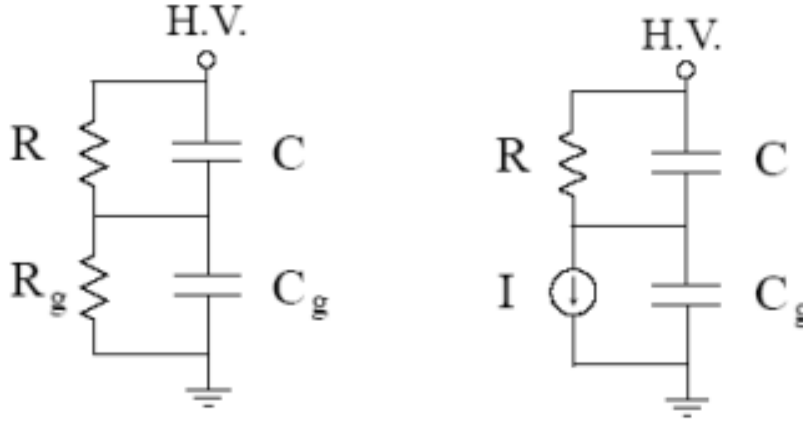


Figure 4.6.1: Schematics of an electrical model for a RPC cell.[29]

with $R = \rho_{\text{HPL}} \frac{2d}{S}$ the resistance of the HPL electrode and $C = \epsilon_r \epsilon_0 \frac{S}{2d}$ the capacity of the HPL electrode, with d being the thickness and S the surface, as well as $C_g = \epsilon_0 \frac{S}{g}$ and R_g the respective capacitance and resistance of the gas gap with thickness g .

Without any ionization the gas acts as a perfect insulator, therefore the resistance of the gas gap can be assumed to be infinite. In this state, all the voltage is applied to the capacitance of the gas gap C_g .

When the gas gets ionized (see Figure 4.6.1 on the right) R_g is replaced with a current generator that causes a local decrease in voltage, which leads to a discharge of the capacitor C_g transferring the applied voltage to the resistive electrodes which are described by C . The charging time of a cell is calculated with:

$$\frac{dq_C}{q_C} = \frac{dt}{\tau} = \frac{dt}{R(C + C_g)} \quad (4.6.2)$$

4 Resistive Plate Chambers (RPCs)

where τ is the characteristic time, or dead time:

$$\tau = R(C + C_g) = \rho\epsilon_0\left(\epsilon_r + \frac{2d}{g}\right) \quad (4.6.3)$$

For the new ATLAS 1 mm RPCs with $\rho = 10^{10} \text{ } \Omega\text{cm}$, $d = 1.4 \text{ mm}$ and $g = 1 \text{ mm}$, τ is in the order of 10 ms. This allows for the calculation of the time it takes for a cell to get back to its resting state. This minimal dead time allows for the approximate calculation of the maximum rate capability of a cell utilizing the formula:

$$f = \frac{1}{\tau} \quad (4.6.4)$$

This is also the maximum rate capability of the whole chamber, as the cells are independent of each other and when operating in saturated avalanche mode have similar charges in the avalanche. [29]

4.7 Rate capability

The main goal for the HL-LHC upgrade of the ATLAS components is to improve rate capability without losing the longevity or precision of the detector systems. As the currently installed generation of RPCs is not able to provide these qualities, changes have been made to the design of the ATLAS RPCs.

The RPCs are limited in their counting rate mainly by the voltage drop over the resistive electrodes. The voltage drop over the electrode V_e is given by

$$V_e = V - V_{gas} = RI \quad (4.7.1)$$

with V being the voltage applied to the detector, V_{gas} the voltage drop over the gas, R the resistance of the electrodes and I the average current flowing in the RPC during uniform irradiation. To keep the rate capability high V_e must be negligible compared to V_{gas} . Another way to calculate V_e is to look at it as a function of the basic detector parameters. Then it is possible to calculate V_e as a function of ρ the bulk resistivity of the HPL, d the thickness of the two electrodes, $\langle Q \rangle$ the average charge per hit in the chamber, and Φ the counting rate per unit surface using the equation:

$$V_e = \rho d \langle Q \rangle \Phi \quad (4.7.2)$$

this can then be solved for Φ giving

$$\Phi = \frac{V_e}{\rho d \langle Q \rangle}. \quad (4.7.3)$$

4 *Resistive Plate Chambers (RPCs)*

This equation presents four ways to increase the rate capability:

1. increasing the voltage V that would combat the voltage drop over the electrodes
2. reducing the resistivity of the electrodes
3. decreasing the electrode thickness
4. reducing the average charge per hit in the chamber

the first solution is not feasible, as any increase in applied voltage leads to an exponential increase of charge in the chamber in turn reducing the rate capability.

A reduction of the electrode resistivity would lead to an increase in current, which would lead to increased noise and possible issues with the aging of the electrodes as the number of discharges in the gap increases.

The reduction of the electrode thickness would also lead to a reduction of the electrode resistivity, and even though the lower distance to the strip panel improves the signal-to-noise ratio, the overall effect is not desirable.

The last option of decreasing the charge inside the gap is the most efficient one, due to the lack of penalties to the gas gap itself. The reduced charge allows for a high rate capability while still providing good aging behavior. The significant drawback of this approach is the reduction of the total signal, which necessitates new, more sensitive, electronics. [30][29]

5 Production of prototype gas-gaps

In order to produce the RPCs for the HL-LHC upgrade, the Max Planck Institute for Physics had to determine the best procedures and materials for the production of gas gaps for the ATLAS upgrade. For this reason, several materials and techniques were tested at MPI and then transferred to three companies which, in order to be accepted as a possible manufacturer, had to produce several prototypes, that were tested for performance. For this purpose, a smaller gas gap design has been used that allows for faster manufacturing. Figure 5.0.1 shows the CAD scheme for the small-sized test sample.

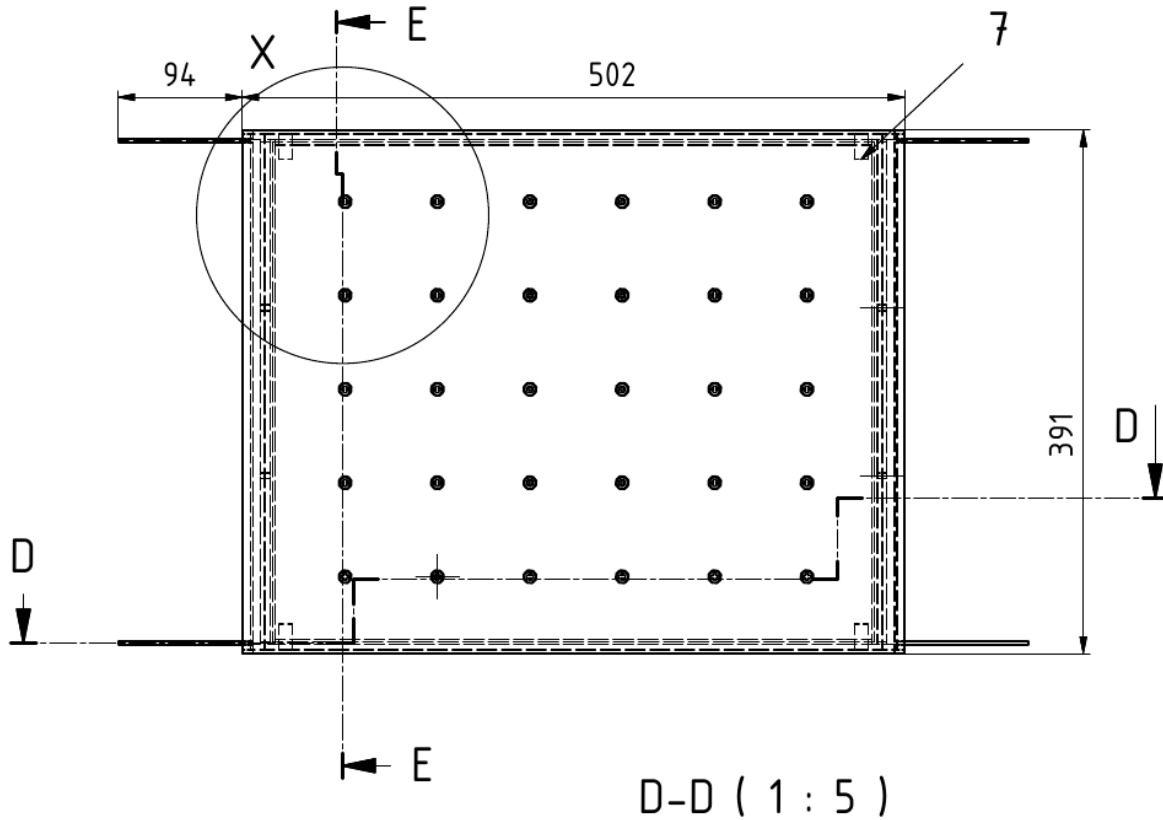


Figure 5.0.1: Technical sceth of a test sample.

During the testing and material evaluation of the test samples, care was taken to ensure that all materials and procedures are also applicable to the gas gaps in full size. A constant exchange with the companies also ensured that their production was able to scale to the required dimensions.

5.1 Production of a gas gap singlet

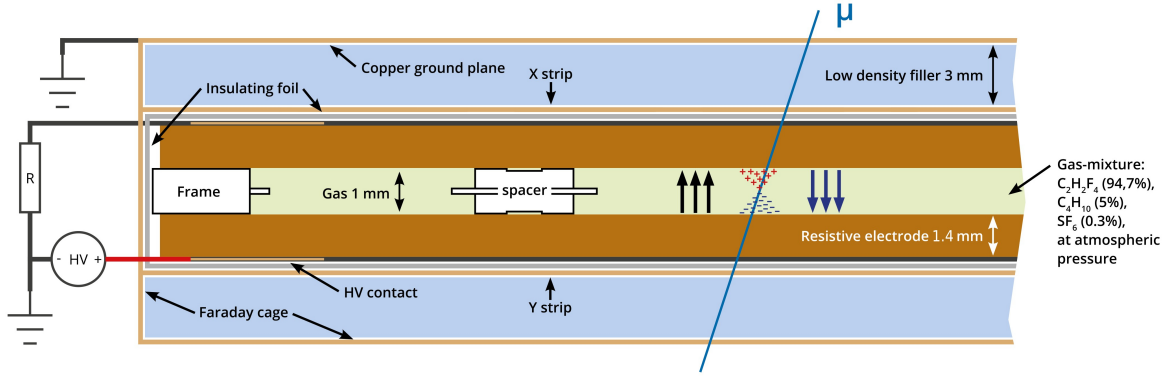


Figure 5.1.1: The scheme shows the structure of an ATLAS RPC singlet.

The production steps for a gas gap like the one shown in 5.1.1 are:

Step one: The inspection of HPL plates, which must meet certain requirements. These requirements include having a target volume resistivity between $1.5 \cdot 10^{10}$ and $1.0 \cdot 10^{11}$ kΩcm and having at least one side that is free of scratches or other structural damages. This is important because any surface roughness can lead to a non-uniform electrical field if a plate is placed with the rough side facing inside the gas gap.

Step two: After the HPL plates have been inspected and approved, one side of the plate is coated with a layer of graphite varnish. This layer must then be allowed to cure before being tested to ensure that the target surface resistivity has been achieved. Any surface damage on one side of the plate can be ignored during the inspection process, as it will be covered by the graphite varnish layer.

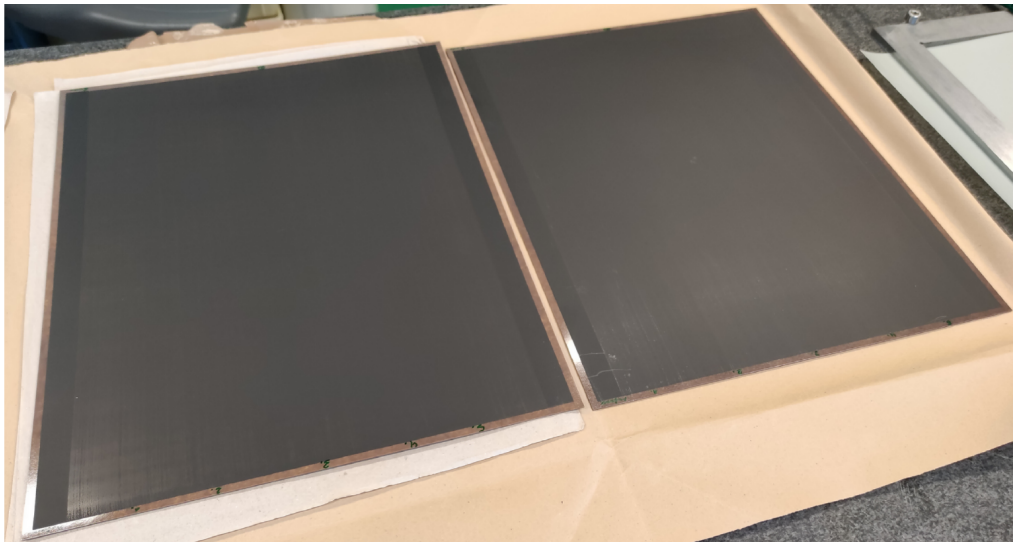


Figure 5.1.2: Two electrodes with graphite coating applied.

Step three: When the electrodes have passed the inspection, a small brass strip, with a wire soldered to it, is fixed on the graphite layer (for the final production there will be only one such connection, while for the prototypes there were two per plate for redundancy in case the contacting procedure shows problems in reproduction). This brass contact is used to connect the graphite to the high voltage.

Step four: Now the electrodes are finished by applying an insulating foil to the outer part of the electrode where the graphite is. This is done by pre-heating the HPL to 85 °C, then the PET foil with a factory-applied EVA hot melt glue is put on the electrode and a heating mat is put on the foil and electrode heating the hot melt to a temperature of 105 °C for 1h. After this, the glue is left to slowly cool down in order to prevent microcracks due to rapid cooldown.

Step five: The spacers, and the frame structure, are glued to one of the electrodes using the 3M DP460 glue (also known GößlPaff GP46). To make this process easier, a fixture has been designed to hold the spacers and frames in place. The fixture additionally allows a pump to be connected to it, in order to utilize a system of channels and holes to draw the spacers and frames down, securing them in place. The fixture designed for the small prototypes is shown in Figure 5.1.3. When the spacers and frames have been positioned and secured in the fixture, the glue is applied to them using a glue dispenser (shown in picture 5.1.4). Then, the HPL plate is pressed onto them using a vacuum bag, ensuring that the plate is pressed down on all the supporting elements.

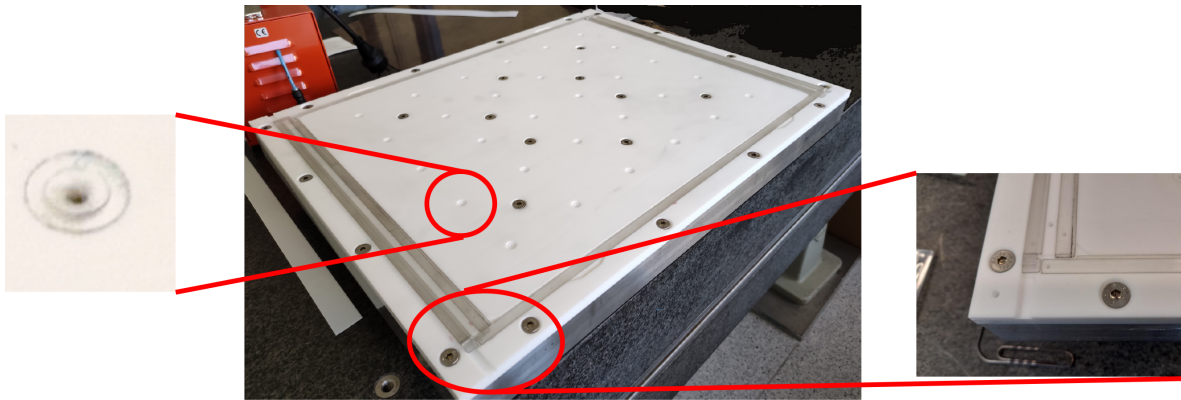


Figure 5.1.3: Picture of the gluing fixture with zoom on the spacer and the frames.

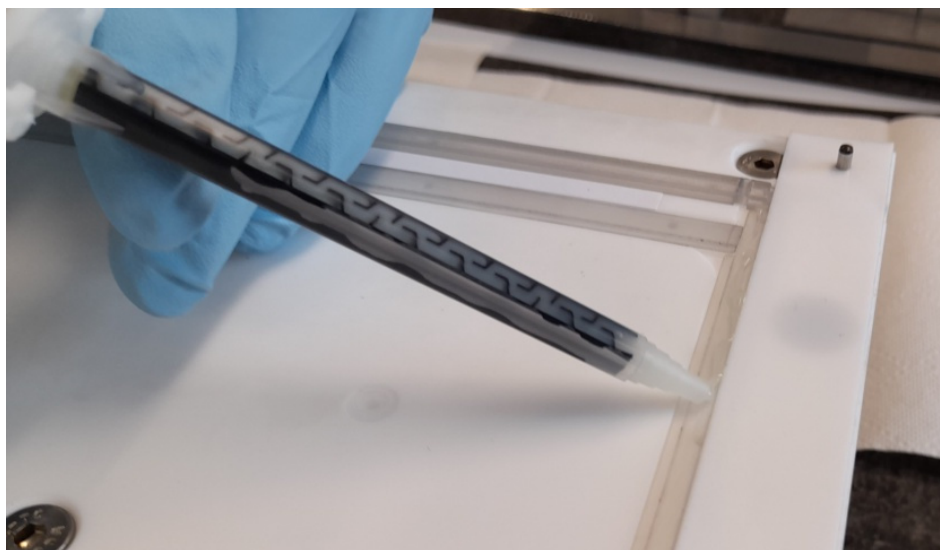


Figure 5.1.4: Epoxy is applied to the frame of the gas gap.

Step six: Closing the gas gap. This is done by applying glue to the frame structure and the spacers attached to the first electrode. The second electrode is then carefully positioned on top, with a vacuum bag used to ensure a firm and even application.

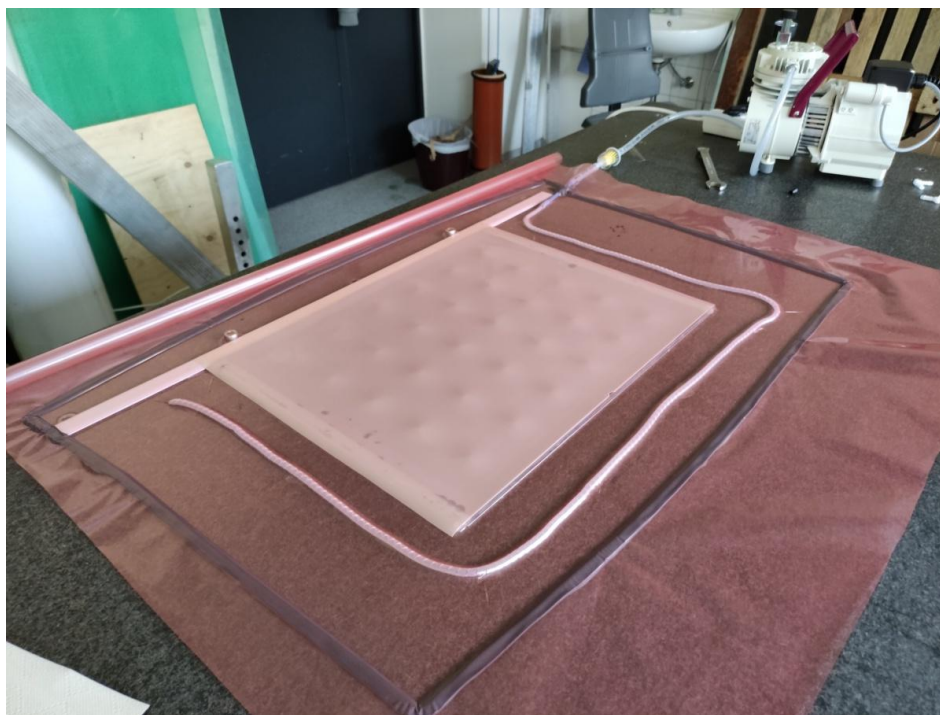


Figure 5.1.5: Gas gap is closed under pressure in a vacuum bag.

Step seven: Now that the gap is closed, the gas pipes are inserted into their corresponding holes in the frame structure, and the structure is sealed by applying some

hot melt glue on the edges. When the glue has cured, the gap is clamped between two plates in order to prevent the glue bonds on the spacers and the frame structure from breaking when a slight over pressure is applied to check the gap for leaks. If any leaks are found, additional glue is applied to seal them.



Figure 5.1.6: Gas pipe inserted into the gas gap frame structure.

Step eighth: After the gap has been sealed and leak tested, it is filled with a mixture of linseed oil and heptane, which is then slowly drained so that it leaves a smooth inner layer without streaks and drops. Once this layer has cured it is not only smoothing the surface even more, but it is also protecting the inner surface of the RPC.

5.2 Study of glues and foils

An important part of a RPC gas gap is the glue used to bind the outer foil to the graphite coated HPL electrodes and the frame structure on the edges. The foil and glue serve a dual purpose of sealing the gas gap in order to prevent the gas from leaking from the gas gap and electrically insulating the electrodes. In order to be used in the ATLAS experiment at CERN, the glue has to satisfy several regulations concerning fire safety. Another criterion is that the glue has to have good out-gassing properties, meaning that there are no components in the glue that can harm the detector while evaporating over time. For this, the glue must either be certified for use in CERN detectors, or it has to undergo a certification process. Additionally, it was decided to use a glue that retains elastic properties after curing, which makes handling of the final gas gap easier due to the glue not cracking during handling as easily as a rigid one would. Several types of glue were tested by gluing a PET foil to other PET, HPL, and graphite-coated HPL surfaces and measuring the adhesive strength using a Newton meter fixed to the foil and pulling it off the surface in a vertical direction (see Figure 5.2.1).

5 Production of prototype gas-gaps

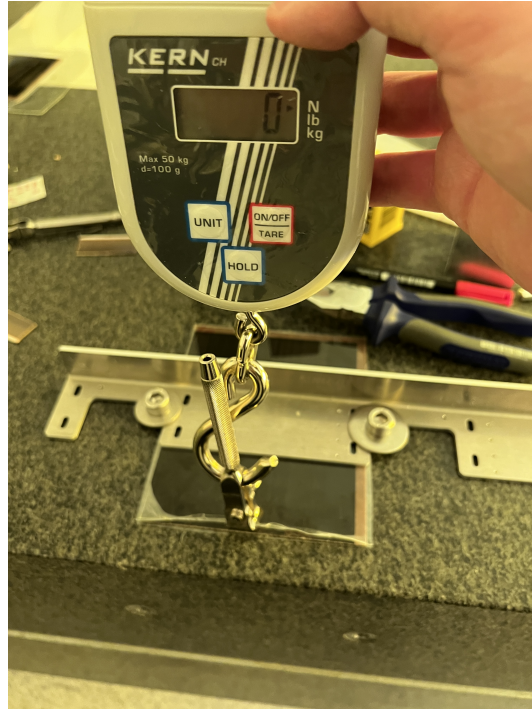


Figure 5.2.1: Test procedure for adhesive strength.

The results were normalized to the width of the edge that was pulled on and compared to a sample of a gas gap provided by a certified CERN supplier. As can be seen in Figure 5.2.2, two types of glue satisfy the strength requirements.

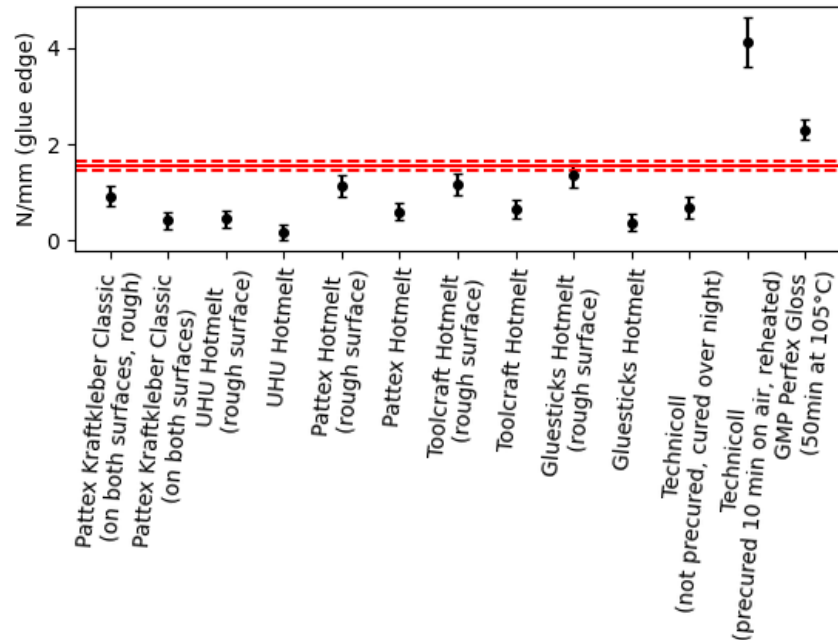


Figure 5.2.2: Tested glues and target glue strength (red line)

The two glues that fulfill the requirements are the Technicoll cured in air and the GMP Perfex Gloss. Even though the Technicoll does fulfill the requirements of strength, it is not based on a certified glue and has the issue that it is only curing properly when in contact with sufficient amounts of air (see data points 11 and 12 in 5.2.2). As the glue is meant to be but between a PET foil and the HPL electrodes, the air supply is very limited and thereby the curing process is slow.

The GMP Perfex Gloss is a lamination foil with pre-applied EVA hot melt glue. This foil has sufficient strength for bonding with the graphite-coated HPL electrode and is easy to apply in mass production, while also being based on EVA and PET which both are approved for the use in CERN detectors. Therefore the GMP Perfex Gloss has been chosen for use in the mass production of the ALTAS RPCs at MPI.

5.3 Graphite coating study

Another factor that influences the quality of the gas gap is the resistivity of the graphite coating on the electrodes. To get the most even and easily reproducible coating, it was decided to use a silk screen printing procedure, comparable to the one used for the production of CMS RPCs.[31] In order to help determine the parameters for the graphite coating process, a small manual silkscreen printer was set up and tested with different screens and graphite varnishes. However, after first tries with one of the varnishes failed to produce a coating that reliably covered the whole sample without leaving holes, the focus was shifted to the second one, provided by the Heysung trading company from South Korea and used for CMS RPC production.[32] This varnish was easier to apply and reliably produced an even coating layer.

It was applied using a T90 nylon mesh and a manual spatula. The setup can be seen in the picture in Figure 5.3.1.



Figure 5.3.1: The silkscreen printer with the T90 mesh.

The picture in Figures 5.3.2 shows the samples after the application of the graphite.

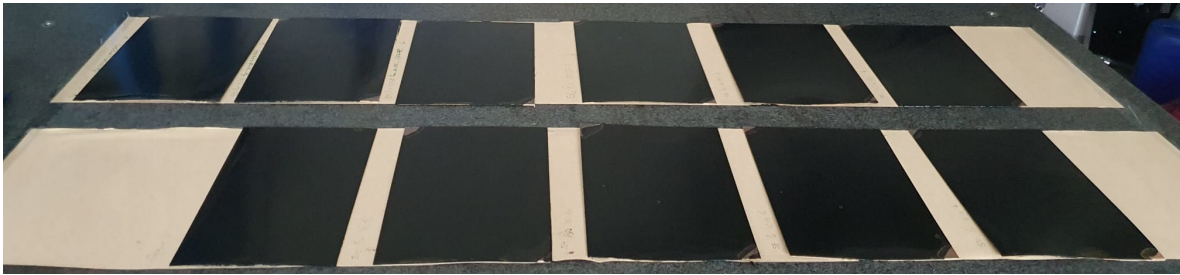


Figure 5.3.2: Samples drying in air directly after coating.

Each sample produced was cured under monitored conditions, as the curing process can have an additional influence on the resistivity of the graphite coating. Different curing procedures were tested to see which give the best result. In addition to the regular curing, a second step was introduced in which each sample was heated to a temperature of 105 °C for 1 hour in order to simulate the application of the insulating foil on the electrode.

The target is an average surface resistivity of $350 \Omega/\square$ with a maximum deviation of $\pm 30\%$. After each step of curing/heating, the surface resistivity was measured using

5 Production of prototype gas-gaps

the METRISO 3000 Resistance Tester, based on the EC 61340-2-3 norm, guaranteeing systematic error of at most 5% for every single measurement. During each measurement, the temperature, and the humidity of the surroundings were measured in order to check if there are large changes that would influence the measurement, which were not observed. The picture in Figure 5.3.3 shows the measurement setup.



Figure 5.3.3: Measurement with of the surface resistivity of the graphite.

The surface resistivity of the samples was measured in a grid of 4×3 points. Each point was measured 5 times in short succession, and from these single measurements, a weighted average was calculated. An example for the measured resistivity of a sample at each measured position is shown in Figure 5.3.4. As can be seen, the procedure of silk screen printing gives a very uniform coating over the whole sample.

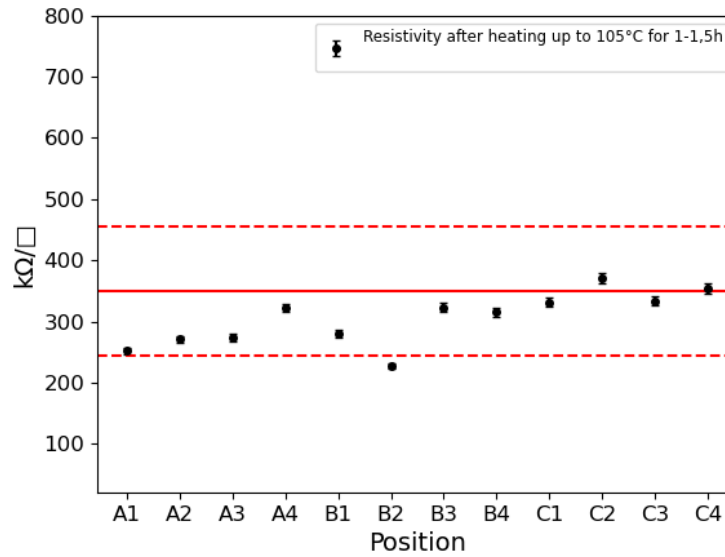


Figure 5.3.4: The resistivity across a single plate, depending on the measurement location.

Figure 5.3.5 shows the measured average resistivity of all samples.

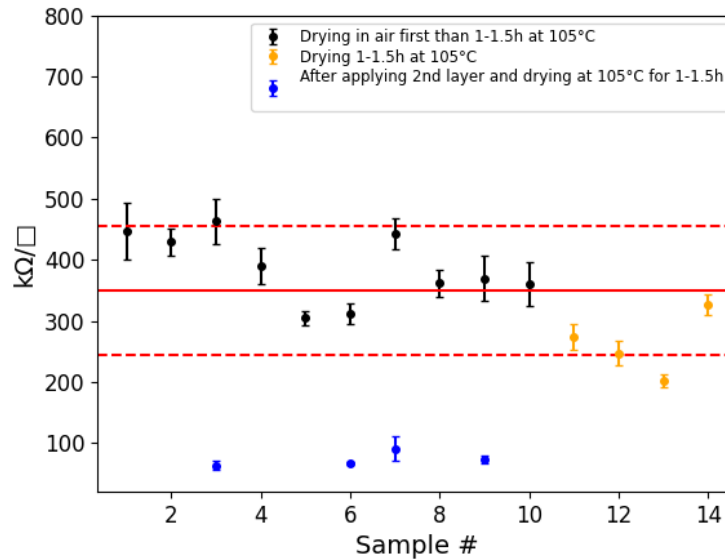


Figure 5.3.5: Average surface resistivity of the tested graphite samples; target resistivity (bold red line); acceptable range of resistivity (dotted red lines); black samples: first dried in air then heated to 105°; orange: directly heated to 105 °C for 1-1.5h; blue: coated with a second layer after the first one has cured.

The second heating process that simulates the application of the insulating foil produced

5 Production of prototype gas-gaps

the results shown in Figure 5.3.6. This data set shows that the changes in resistivity after the second heating process are small and that their influence on the production is negligible.

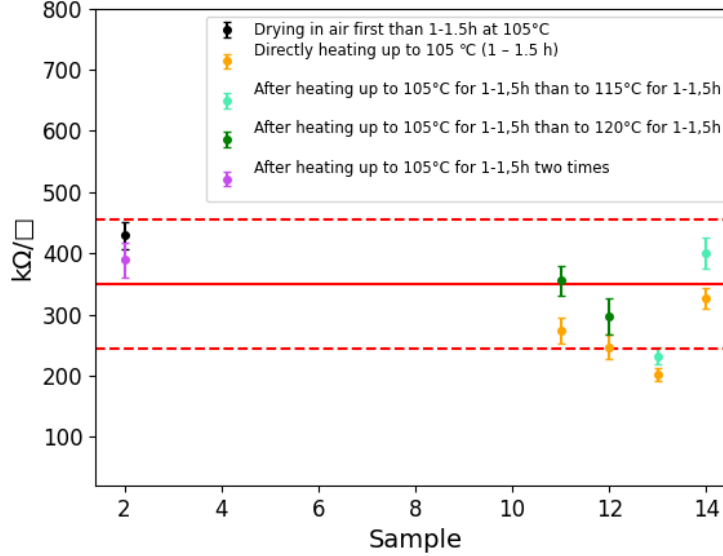


Figure 5.3.6: Resistivity of graphite coating before and after the second heating run.

These results show that the carbon paste provided by the Heysung trading company applied using a T90 silk screen and cured at 105 °C for 1.5h provides a surface that matches the parameters of the ATLAS RPCs.

5.4 Transfer of Production to Companies

These production steps and materials were then transferred to three companies for the production of their sample RPCs. These were then tested by the MPI, in order to determine their characteristics.

5.5 Voltage-Current curve

For each gas gap, the first thing done after they arrived at MPI, was measuring the Voltage-Current curve. This curve shows the current in the gas gap plotted against the voltage applied to the electrodes. This is done by soldering a resistor with known resistivity (100kΩ) into the ground connection of the high voltage cable of the gas gap and measuring the voltage drop over the resistor using a multimeter. To do so, the gap is connected to the gas pipe, and flushed with the standard gas mixture until there is no more air inside. Then, a BNC connector is soldered to the HV-contacts on the electrodes that was connected to a CAEN R1470ETD power supply. The curve can be

separated into two part. The first one is the linear part that follows a strictly ohmic trend. In this region, the currents are governed by the pure ohmic resistivity of the materials the gap is made of. The second part of the curve is the exponential. In a 1 mm gas gap flushed with the standard gas mixture, gas amplification starts from around 5000 V and soon the current in the gas becomes so high that it dominates the current of the whole gas gap. Therefore, after reaching this voltage, the whole curve starts showing an exponential shape as shown in Figure 5.5.1.

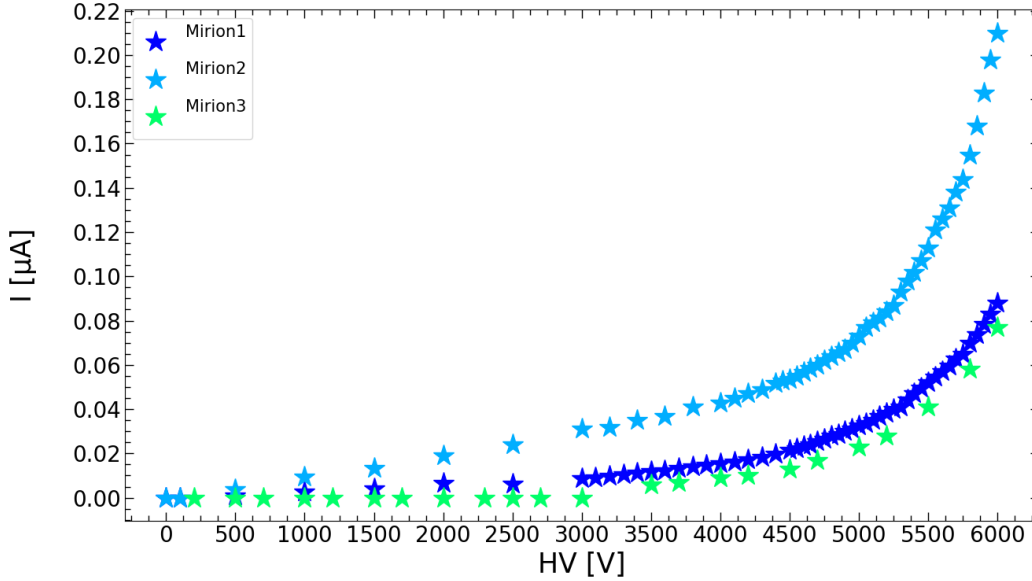


Figure 5.5.1: Currents of all gaps produced by Mirion plotted against the applied voltage. Measurements were done with a PeakTech 3444 multimeter with an accuracy of $\pm 0.5\%$ for DC voltage.

Due to its characteristics, it is possible to use these curves as an indicator for the quality of the gas gap. Depending on the size of the gap, the avalanche region starts at a specific voltage, which can be read from the curve by looking at which voltage at which the exponential rise of the curve starts. Additionally, one can also determine possible issues like unglued sectors in the gas gap by looking at the uniformity of the curve. If the gap is partially unglued, the curve can show a form that deviates from the optimal shape. The resulting voltage current curves of the tested RPC prototypes made by Mirion are shown in Fig. 5.5.1. These are yet uncorrected for the influence of temperature and pressure, however the test parameters in between runs were comparable. As can be seen, the current in the region around 6100 V is below $0.2 \mu\text{A}$ after subtracting the linear ohmic part, which is in line with the requirements for the ATLAS RPCs. The same measurements were done for all gaps made by all manufacturers.

5.6 The Strip-panel

The strip-panels used for the tests are made of standard FR4 PCB material with a layer of copper on one side. The copper layer has been removed using a CNC-mill in order to cut the structure of the strip panel. Due to size limitations given by the CNC mill, the front part of the panel with the strips cut into it had to be produced in two pieces. To assemble the final strip panel, two PCBs with cut out strips are glued to one side of a paper honeycomb sheet using GP12 glue, and a second uncut PCB is glued to the other side of the sheet in order to act as ground plane. The ground strips and the ground plane are then connected using copper tape. The layout of the strips is based on the layout of the readout panel for the full size ATLAS RPCs, with 28 mm thick strips and a 0.2 mm thick ground strip in between for better noise and crosstalk reduction. After the panel itself is finished, the electronics and the grounding resistors are mounted. In order to terminate the strips, several resistors were tested based on the signal shape and resistors with $18\ \Omega$ were chosen as best fitting. Both ends of the strips were terminated with resistors. Then, on one end of the strip panel, a preamplifier[33] designed for the use with RPCs was connected to the strips. A picture of the strip panel in production can be seen in Figure 5.6.1, while figure 5.6.2 shows a finished strip panel with the pre-amplifiers connected and a gas gap test fitted.

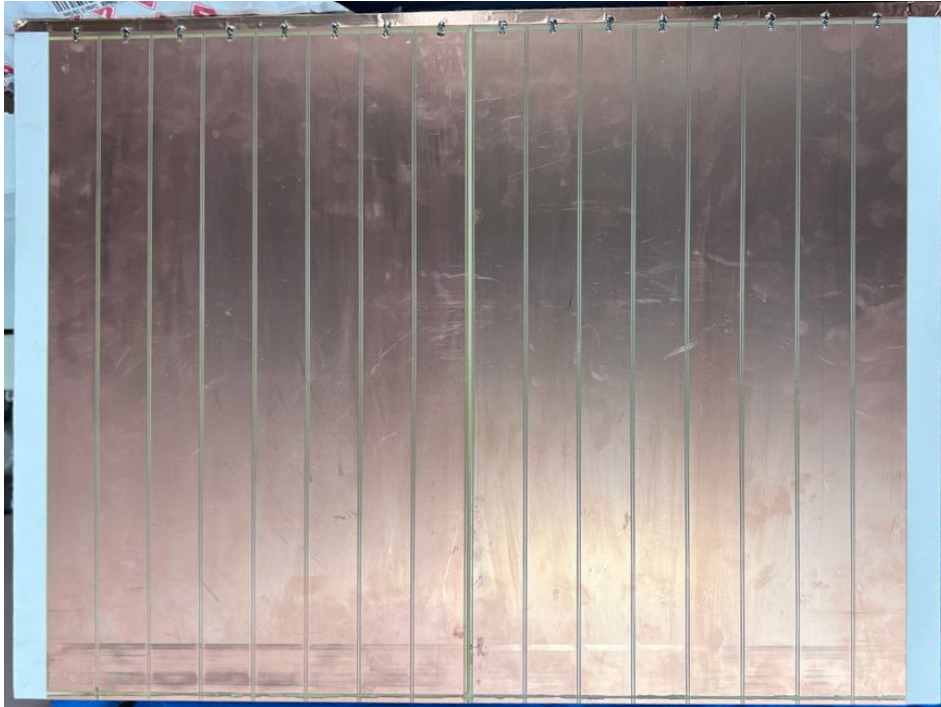


Figure 5.6.1: Strip panel with one row of resistors soldered to it.

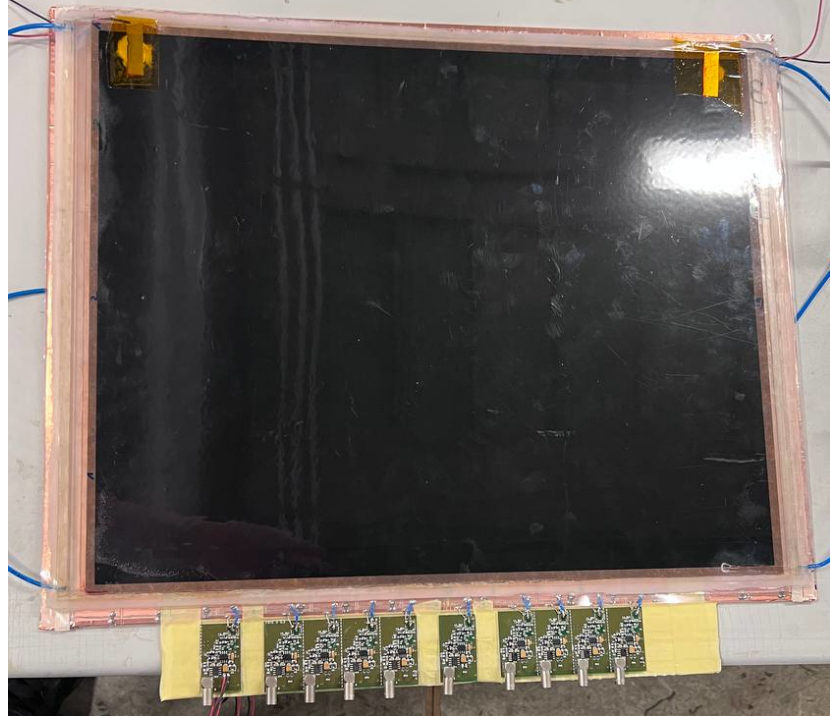


Figure 5.6.2: Strip panel with all electronics mounted to it and a gas gap test fitted.

5.7 Assembly of a singlet for the test beam

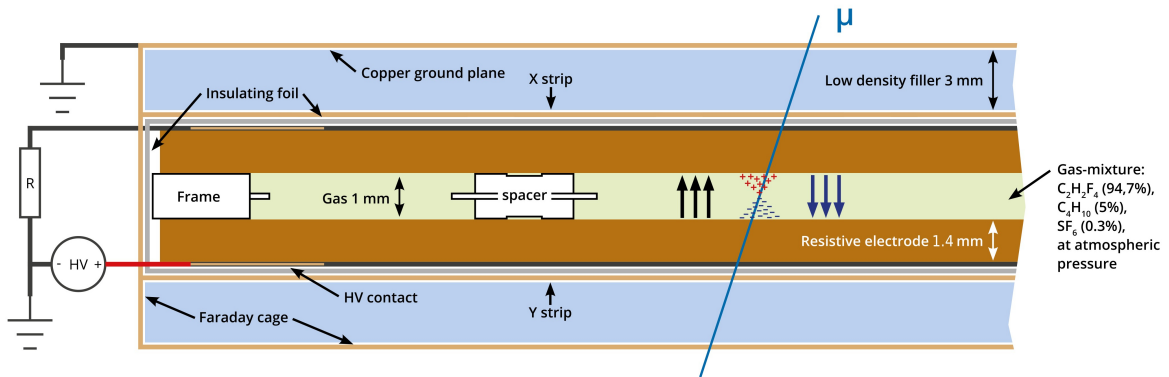


Figure 5.7.1: The scheme shows the structure of an ATLAS RPC singlet

As shown in the scheme in Figure 5.7.1 The RPC singlet consists of a gas gap and a strip panel with mounted frontend electronics. As it is always possible that there is an unnoticed hole in the insulating foil on the outside of the gas gap or that a deep scratch damaged it during transport, an additional layer of PET-foil is fixed on the outside of the gas gap. After this, the singlet is closed by fixing a strip panel or one strip panel and a continuous ground plane, on either side of the gas gap and sealing the edges with a conductive copper or aluminium tape. The two strip panels and the

5 *Production of prototype gas-gaps*

conductive tape create a Faraday cage that helps to reduce the noise on the singlet. In order to improve the grounding of the frontend, an additional connection between the frontend electronics and the second strip panel is created using a wire. This is done to improve the quality of the signal.

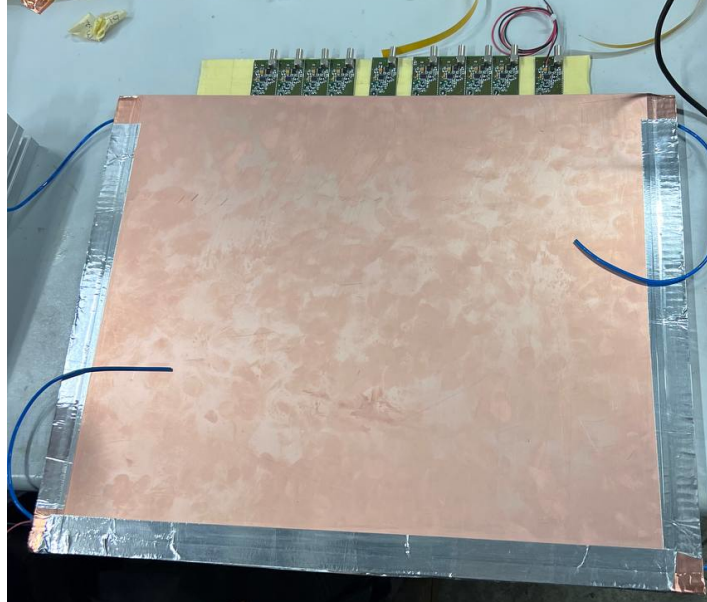


Figure 5.7.2: Picture of a fully closed singlet with one equipped strip panel.

The scheme in Figure 5.7.1 shows a fully closed singlet like the one in Figure 5.7.2

6 Setup at the gamma irradiation facility

Due to limitations with the supply of material for the strip panels and the amount of usable readout channels only three gaps could be equipped for a full functional test at the Gamma Irradiation Facility (GIF++) at CERN. The gaps chosen are Mirion3, Metron3 and PTS3 (From here on just called Mirion, Metron and PTS). Upon arrival, it was discovered that PTS may be damaged (some spacers are unglued), which was later confirmed. For the tests, Mirion and PTS were each equipped with a single strip panel containing ten fully operational strips, whereas Metron was tested using two strip panels, each of which had five functional strips. The GIF++ allows for the utilization of a gamma source to study the behavior of the gas gap under high irradiation, as well as the use of a high-energy muon beam, provided by a fixed target at an SPS beam line.

6.1 The GIF++

The GIF++ has been designed and built as a successor to the original GIF, which ceased operation in 2014. Like the original GIF, which was built to study and test particle detectors and components including those meant for the LHC, the new GIF++ has been built to test the detectors and components for the HL-LHC upgrade. The GIF++ began operation in spring of 2015. The facility has a 100 m² area with a roughly 5 m high ceiling, leaving enough space to test several full size prototypes of detectors. Figure 6.1.1 shows a top-down view of the GIF++ facility with a schematic representation of the radiation cones.

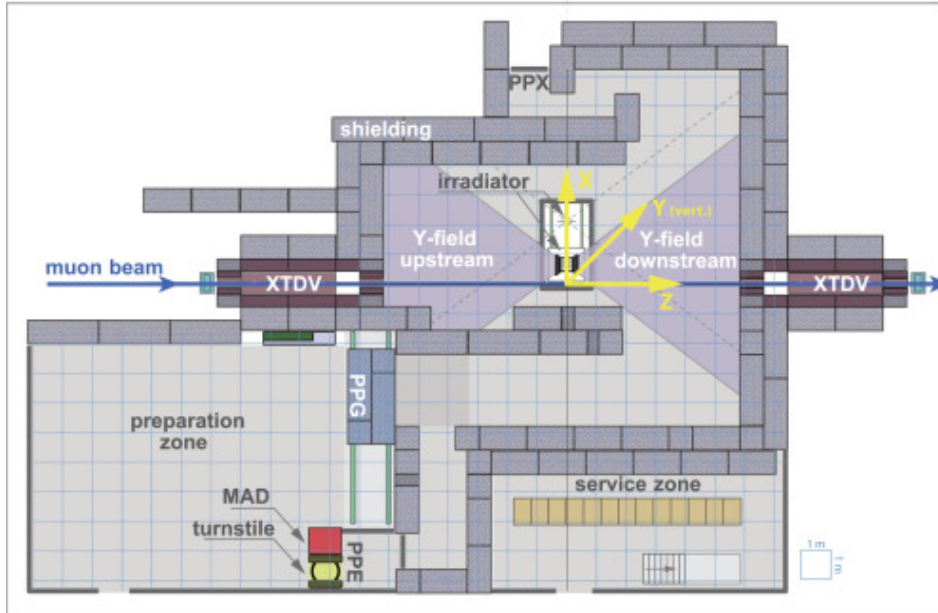


Figure 6.1.1: Schematics of the GIF++ facility.

6.1.1 The GIF++ irradiator

The irradiator of the GIF++ is made of a ^{137}Cs with separate filters on either side, allowing for a mostly independent radiation field on either side of the irradiator. The ^{137}Cs was chosen due to its long half-life of 30.08 years, which is important as the decrease of the gamma rate over the operation time of the GIF++ is supposed to be as minimal as possible. Also, the γ -background radiation in the experiments at the LHC has a typical energy that is close to the energy spectrum of the source, being composed of primary 662 keV photons and lower energy scattered photons. The Figures in 6.1.3 show the setup of the irradiator. The source itself moves from the shielded storage position on the bottom of the support tube inside the shielded receptacle to the top irradiation position, where panoramic collimators with a cone of $\pm 37^\circ$ are located. These allow the irradiation zone to cover most of the bunker as can be seen in Figure 6.1.1 while the Figure 6.1.3b shows the cone at the source in a side view of the source and the bunker. Additionally, the irradiator has a lens shaped angular correction filter, which can be seen in Figure 6.1.3a. It ensures the uniform photon distribution over the xy-plane that is necessary to test detectors with larger area by attenuating the photons differently depending on the angle of the photon, changing the natural $\frac{1}{r^2}$ dependence of the photon current. Figure 6.1.2 shows the photon flux in the GIF++ with the angular correction filters in place.

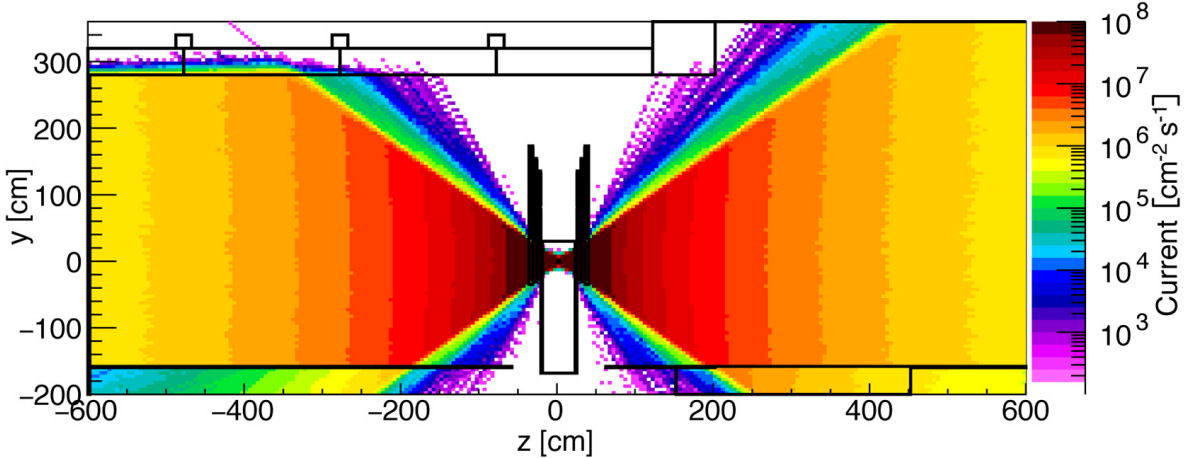


Figure 6.1.2: Photon current in the vertical plane through the source(yz plane) at $x = 0.65$ m with filters at 1. Due to the angular correction filters, the current of 662 keV photons is uniform in xy planes.

The attenuation filters have no dependence on the incidence angle and are formed in such a way that each photon no matter which angle of incidence it has is attenuated the same amount. On each side, the filters are made of 3x4 convex lead attenuation filters and are meant to give a more granular control of the photon flux. The three planes of filters (A,B,C) are each made of three filters allowing for the nominal attenuation factors 1 (A1, B1, C1), 1.5 (B2), 2.2(C2), 4.6 (C3), 10 (A2) and 100 (A3, B3), which

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gives 24 different attenuation factors between 1 and 46415 shown in Figure 6.1.3c. The nominal attenuation factor is defined as the attenuation of 662 keV photons. The photons with lower energy are attenuated more than the nominal value.

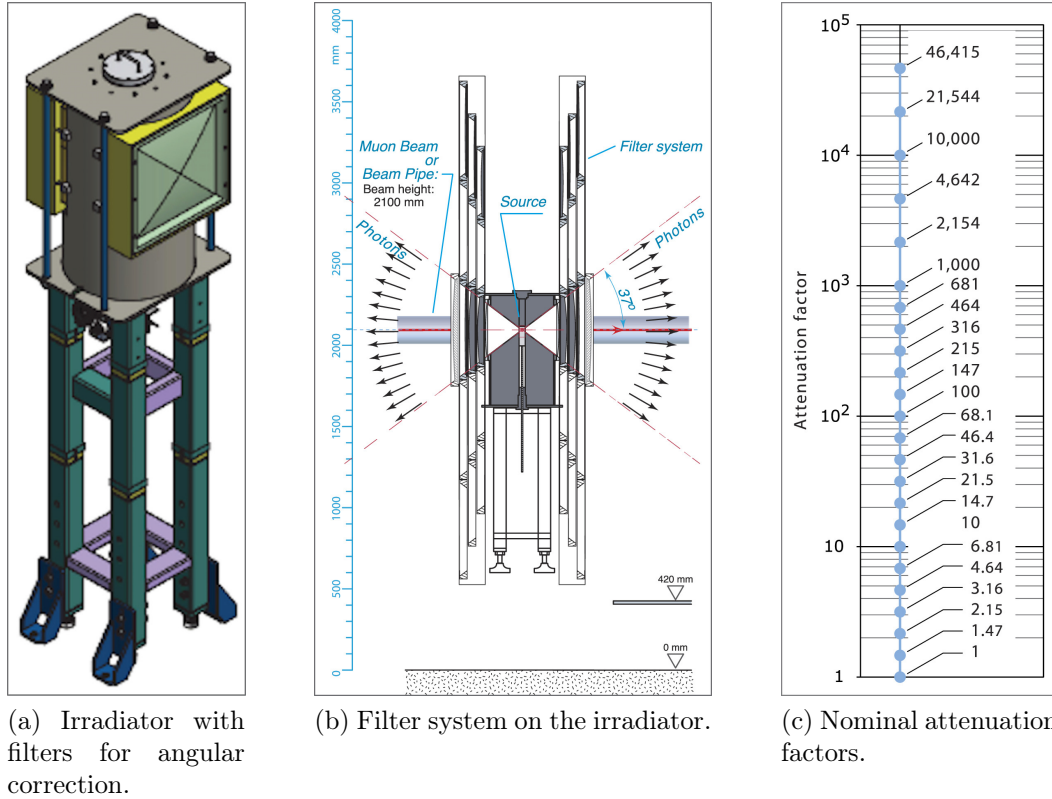


Figure 6.1.3: (a) Schematic of the irradiator with angular correction filters and independent filters on both sides. (b) Independently movable remotely controlled attenuation filters and collimators permit the variation of emitted photons. (c) All combinations of attenuation factor achievable with the 3x3 filters. [34]

Even though the most significant portions of the flux on both sides of the irradiator are independent of each other, a minimal amount of radiation is scattered from one side to the other. Figure 6.1.4 shows the flux of scattered photons when only one of the sides of the irradiator is open. [34]

6 Setup at the gamma irradiation facility

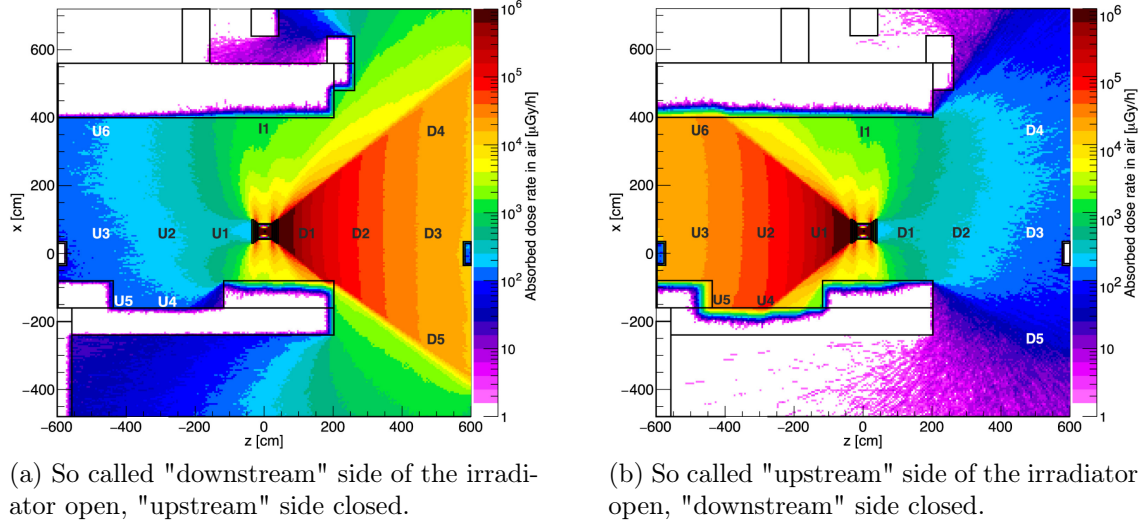


Figure 6.1.4: Picture of the simulated absorbed dose rate in air in the xy plane of the GIF++. (a) shows the flux with the downstream irradiator opened and the upstream one fully closed, and (b) showing the flux of the upstream irradiator opened and the downstream one fully closed. [34]

6.1.2 The muon beam

The muon beam for the GIF++ is supplied by the H4 SPS beam line in EHN1. This beam line provides a proton beam of 10 GeV up to 450 GeV in momentum, covering the full range of the SPS. To convert the proton beam to a muon beam, the proton beam is shot onto a production target, where pions and kaons are produced which decay into muons. The users of the beam line can choose the muon beam energy between 57%-100% of the nominal proton beam energy and which part of the energy bandwidth is transported to the GIF++. The spills follow the SPS with a nearly flat distribution that lasts 4.8 seconds on average, coming every 30 seconds depending on the needs of other users. The lateral distribution also allows for a large range of variation, depending on several settings like the final focusing, with a rough average of 10 cm x 10 cm containing 50% of the muon beam with the rest, the so-called beam halo, being spread over an area of about 1 m². With the maximum acceptance of the beam line, the muon beam can reach an intensity of up to $10^4 \frac{\text{muons}}{\text{spill}}$. [34]

6.2 Setup description

6.2.1 Integration of three singlets

The full test setup consists of three singlets that are packaged together in a mechanical structure designed to accommodate the three singlets as well as the gas pipes, the high

6 Setup at the gamma irradiation facility

voltage and the low voltage wiring. Pictures of the CAD design are shown in Figures 6.2.1, 6.2.2 and 6.2.3.

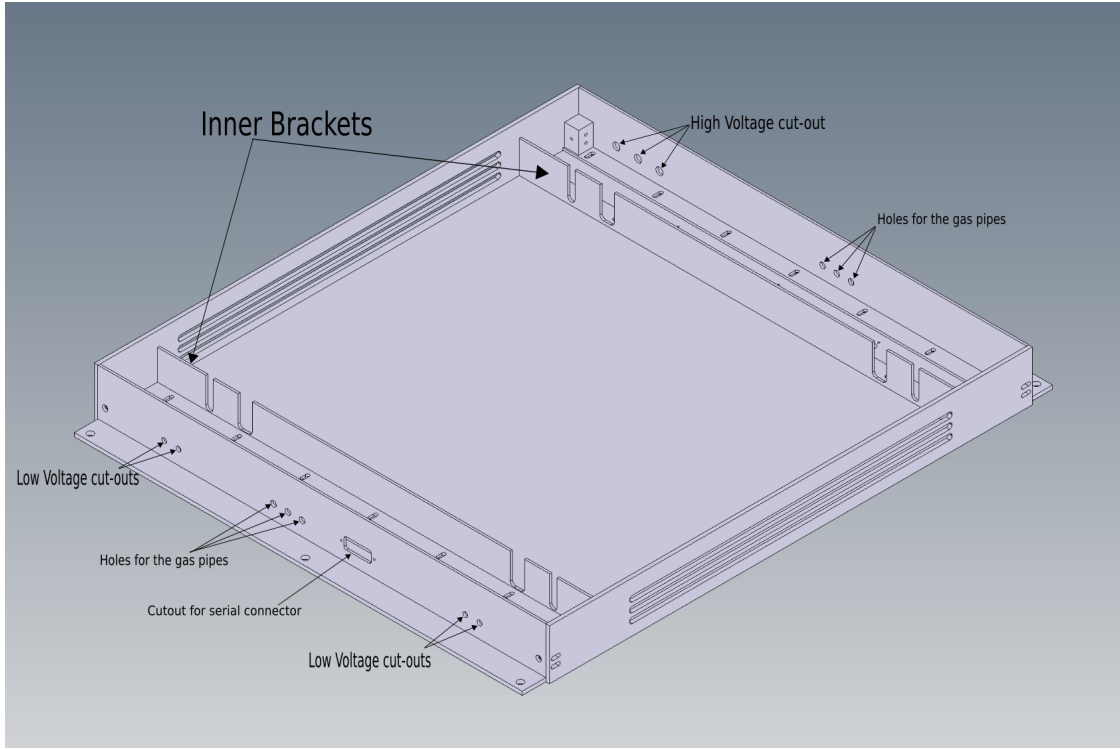


Figure 6.2.1: Iso top view of the mechanical box in without the top cover

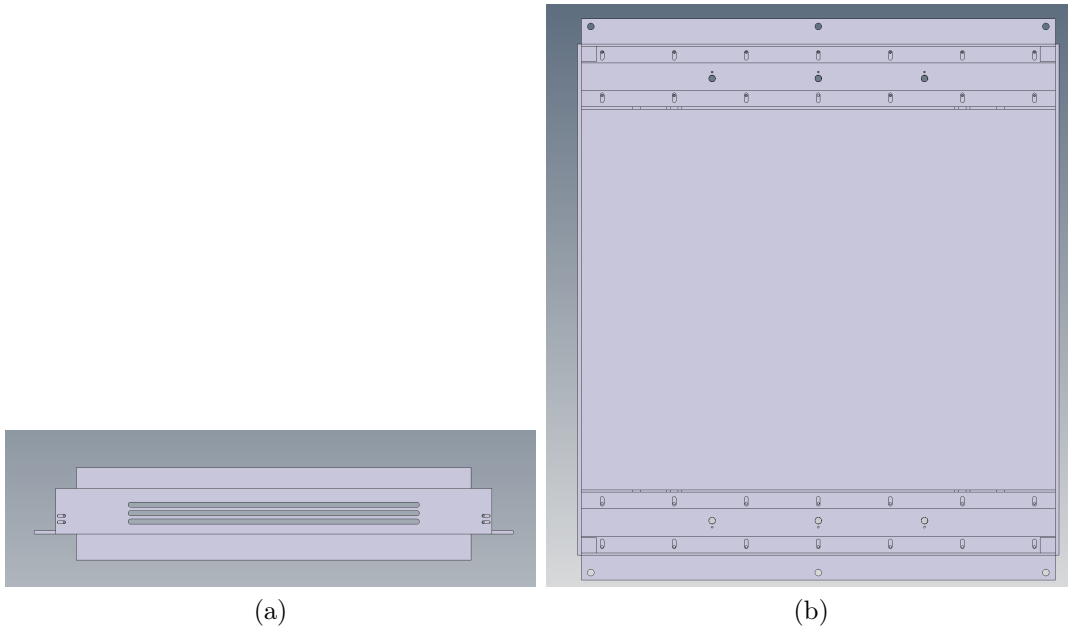


Figure 6.2.3: (a) is a front view of the mechanical box, showing the slits for the cables. (b) shows a top view of the box with the cover off.

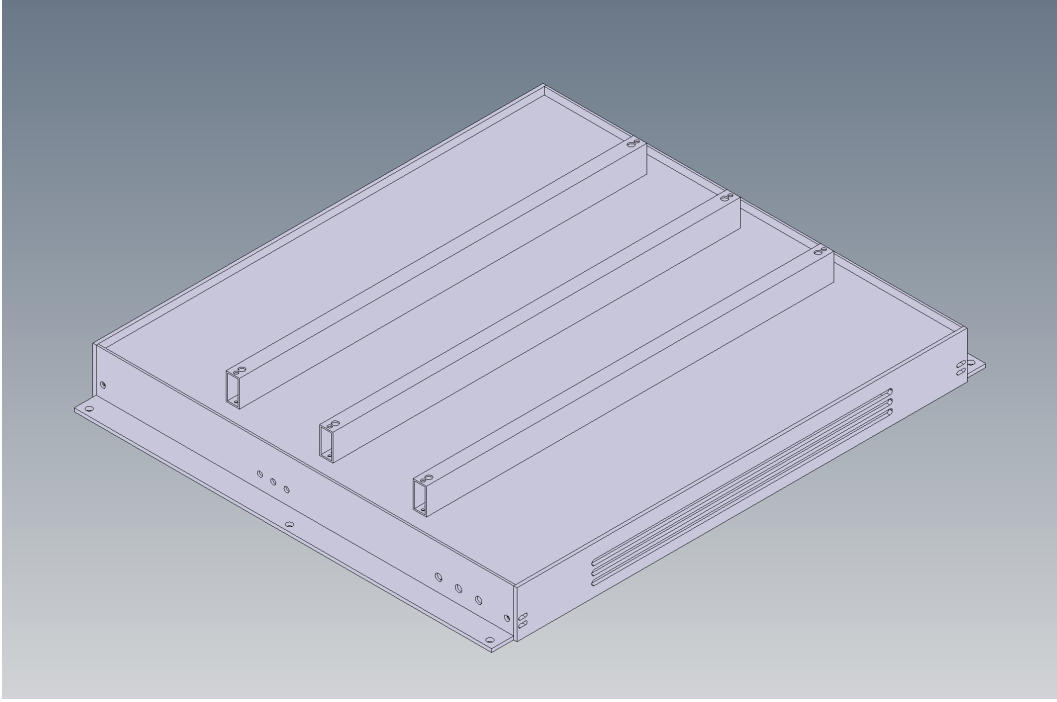


Figure 6.2.2: Iso top view of the mechanical box in with the top cover

The inner brackets (visible in Figure 6.2.1) allow for easier alignment of the singlets in one direction, while the outer walls allow closing an additional Faraday cage around the triplet. The inner brackets also have u-shaped cut-outs for the cables and pipes to pass through to the connectors and holes in the outer walls where they can be connected to the main gas pipes and cables. An additional benefit of the design is that the lid is freely suspended on the screws, which allows us to compress potentially broken gas gaps and recuperate some lost performance. All gaps are grounded to the frame, and the ground planes of all the strip panels are in direct contact with each other and the mechanical box. Pictures of the final assembly with all services and cables connected can be seen in Figure 6.2.4.

Two of the three singlets (Mirion and PTS) have 10 consecutive strips in the middle of the strip panel connected to the readout. For Metron the decision was made to equip the chamber with two strip panels, one on either side, and read 5 strips on both of the strip panels, with the frontend electronics facing opposite directions. This is done in order to be able to measure the time difference between a signal being detected on the two sides of the RPC. This information then can be used to determine the coordinate along the strips at which the muon crossed the chamber.

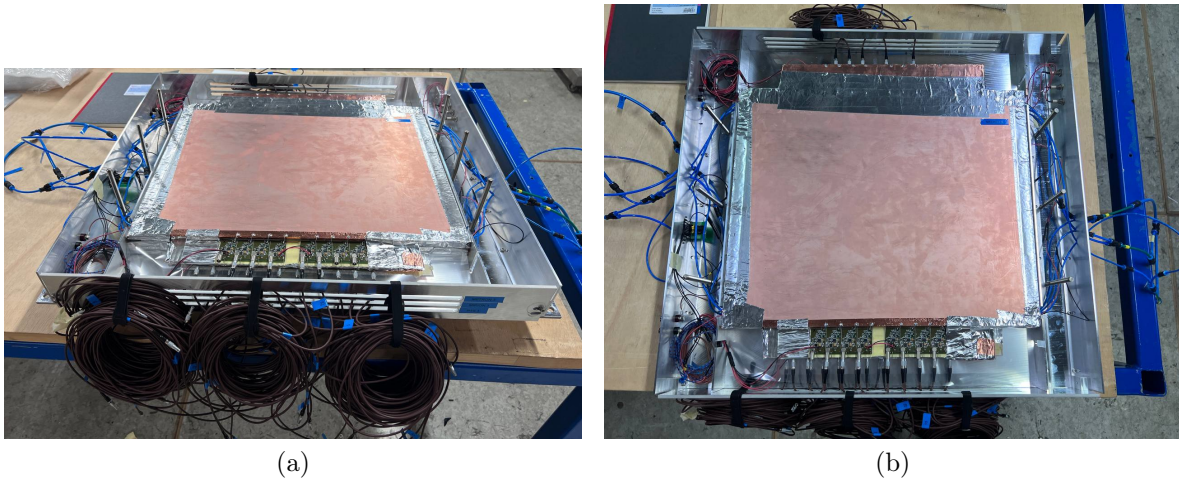


Figure 6.2.4: Picture (a) and (b) show the three RPCs placed in the mechanical box shown from the front and top respectively

6.2.2 Mechanical setup

The RPC setup was installed using MPIs' existing sMDT setup with a distance of approximately 1.5 m from the source. Figure 6.2.5 shows the location of the setup inside the GIF++ facility.

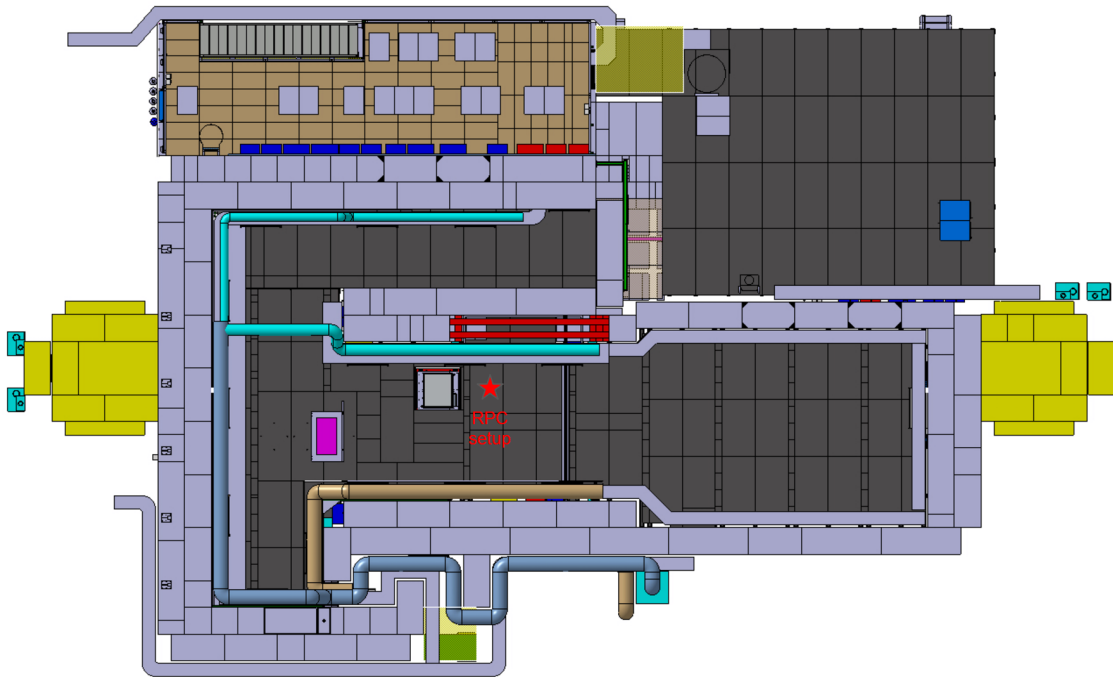


Figure 6.2.5: Layout of the GIF++ facility with the position of the RPC setup

The box was mounted in such a way that the muon beam, positioned on an axis roughly

160 cm from the raised floor of the GIF++ bunker, hit approximately the middle of the active area. A scheme showing this configuration is shown in Figure 6.2.6.

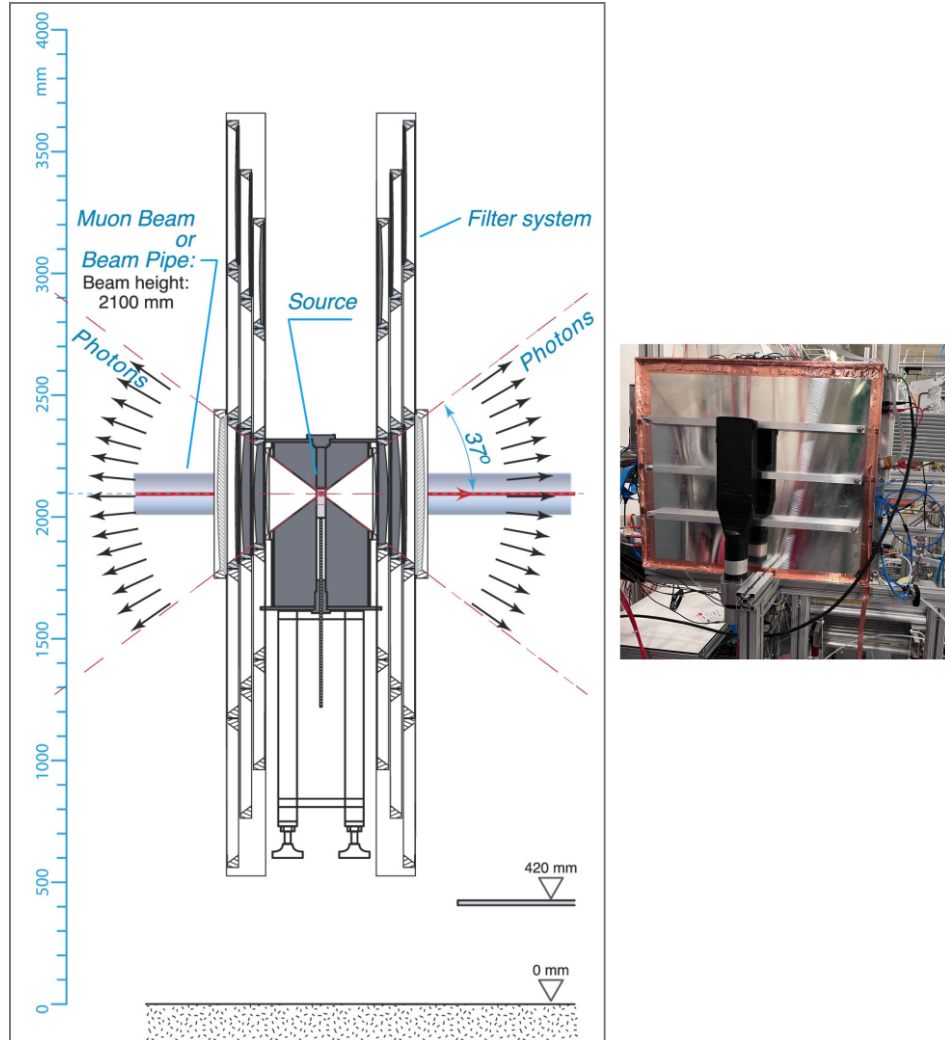


Figure 6.2.6: The scheme shows the position of the mechanical box with the three singlets, compared to the irradiator and the beam trajectory.

A picture of the final setup can be seen in Figure 6.2.7. A scintillator with an active area of $10 \times 25 \text{ cm}^2$ was positioned in such a way that it is in the center of the active strips, and the whole setup was then moved so that the beam hits the center of the active detector area.

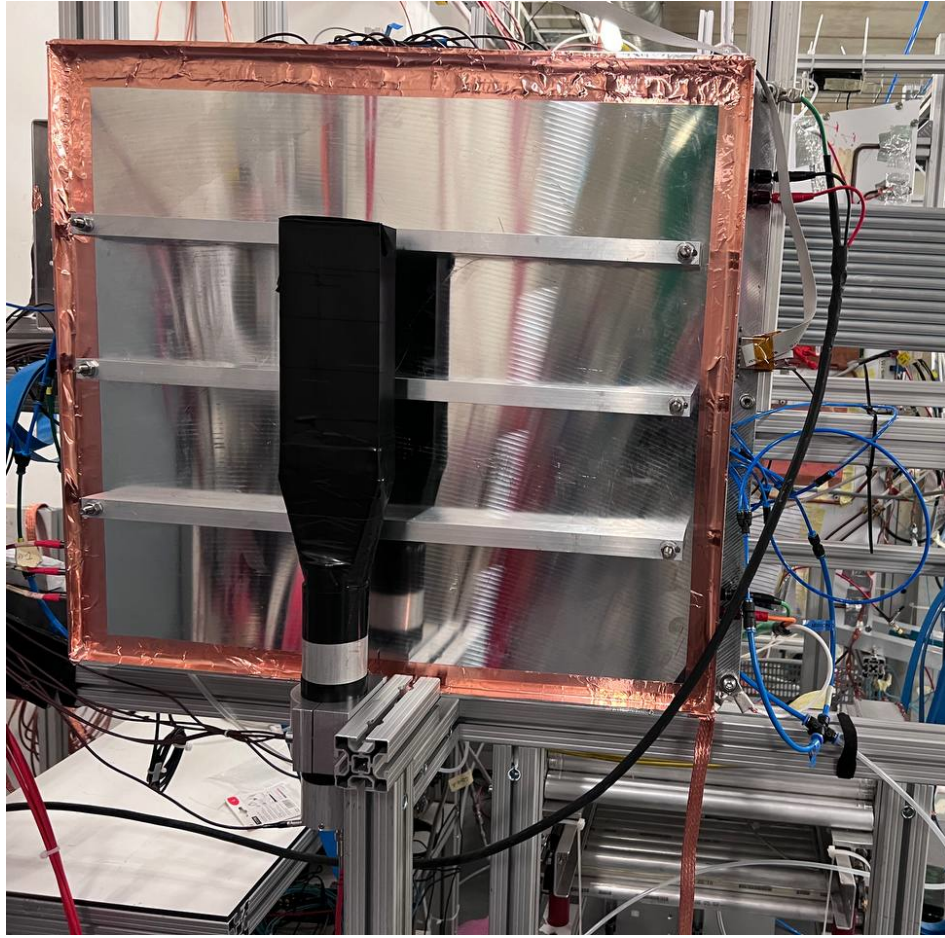


Figure 6.2.7: Picture of the Mechanical box and reference scintillator mounted to the GIF test rig.

This was first done by measuring the position of the detector. Then a first data run was taken, which showed an asymmetric distribution of the clusters per channel for the raw counts, as can be seen in Figure 6.2.8. This cut, which can be seen when looking at channels 101 and 102 where the count rate does not drop, shows that the alignment of the chamber with respect to the beam and the reference scintillator was not perfect. After realigning the chamber, a new run was taken, which showed the expected Gaussian distribution. The data for this run can be seen in Figure 6.2.9.

6 Setup at the gamma irradiation facility

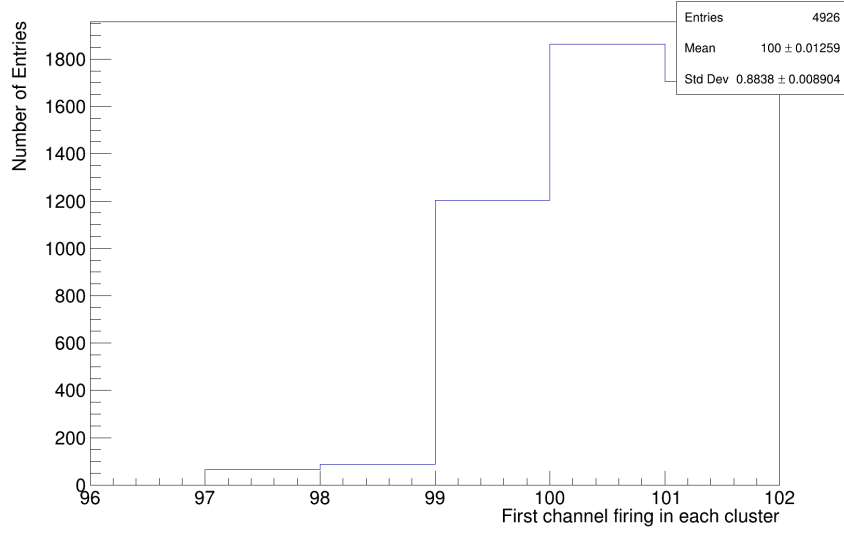


Figure 6.2.8: Signal distribution for Metron on the negative side for an unaligned setup at 6kV and a threshold of 30mV; the cut-off at channel 102 is visible.

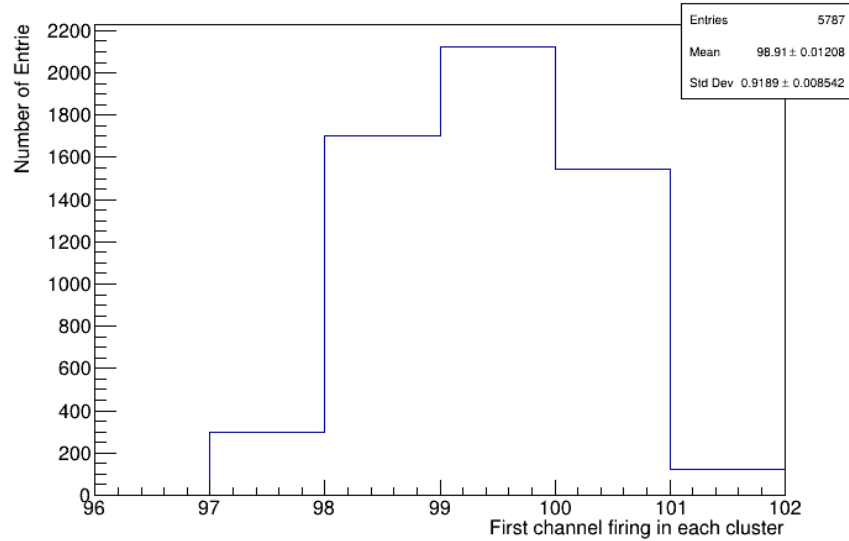


Figure 6.2.9: Signal distribution for Metron on the negative side for an unaligned setup at 6kV and a threshold of 30mV after repositioning.

6.2.3 The DAQ-System

The raw signal from the amplifier boards was injected into 3 CAEN Mod. V258B VME discriminators, with fixed output signal width, that were connected to a CAEN Mod. V1190A TDC. The discriminators and the TDC communicate using the ECL standard. The external trigger consisted of the GIF++ external Scintillators positioned

6 Setup at the gamma irradiation facility

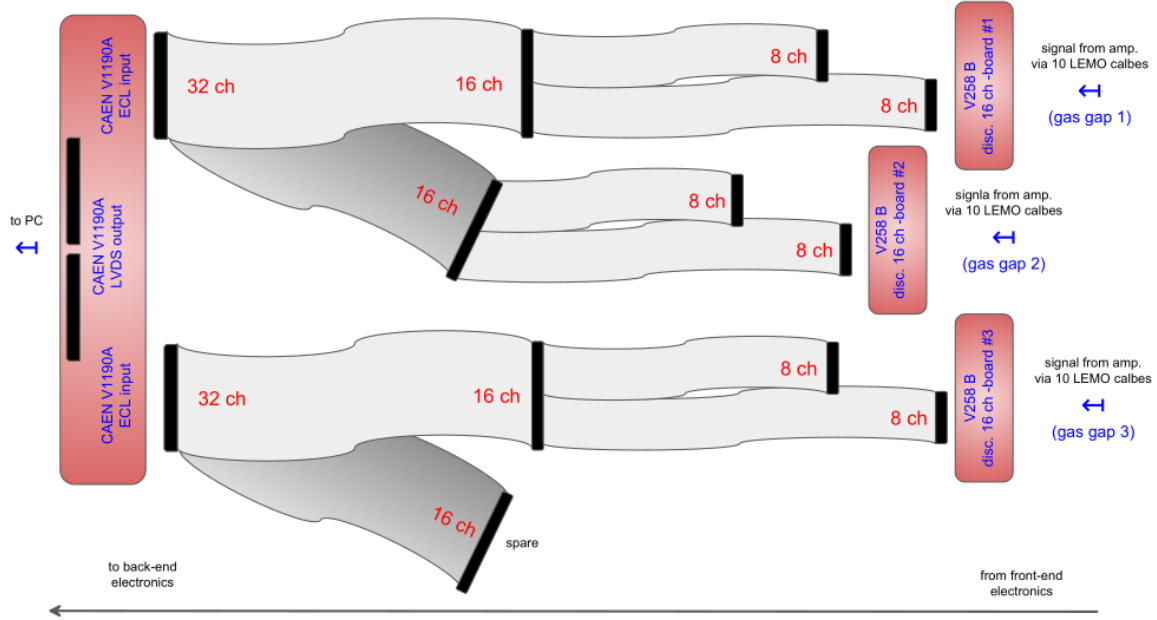


Figure 6.2.10: The scheme shows the final DAQ system for the test beam.

on the outside walls of the GIF++ bunker and the small reference Scintillator positioned directly in front of the chamber. These two inputs were put into a hardware AND which was connected to the NIM input of the TDC. The TDC then was read out using a custom readout script running on an PC outside the GIF++ bunker, that was connected over a USB over Ethernet adapter. A scheme of the setup is shown in Figure 6.2.10 and Figure 6.2.11 shows a picture of the final setup.



Figure 6.2.11: The Picture shows the VME-crate with the three discriminator on the left connected to the CAEN TDC on the right.

7 Data analysis

To check if the chambers fulfill all requirements for the ATLAS muon system, the data taken at the testbeam was analyzed to determine the efficiency, the cluster size and the time resolution for all the three prototypes.

7.1 Voltage-Current curves at GIF++

To test if the finished setup is in working condition, the voltage-current curves were measured to check if the setup works properly. All the voltage-current curves in the GIF++ were measured using a 104 SMD resistor of 100 k Ω with a tolerance of $\pm 0.1\%$ and a Tenma 72-13440 multimeter with an accuracy of $(0.5\% + 2)$.

7.1.1 No γ irradiation of the RPC

After the integration and the installation of the gas gap triplet, the first voltage-current curves were taken without γ irradiation in order to set a baseline for the final setup and to check if the chambers weren't damaged during the integration and installation process. As can be seen in Figure 7.1.1 the gaps Mirion and Metron show the expected behavior of a 1 mm ATLAS gas gap with an exponential increase of currents around 5000 V, while PTS shows a different voltage-current curve with a linear dependence of the current on the voltage, whereas the others show an exponential current. The reason for this behavior is that the glue joints of the spacers of PTS are broken due to mishandling. Therefore the gap thickness is greater than 1 mm and can change due to the forces of the electric attraction of the plates and the pressure of the gas inside.

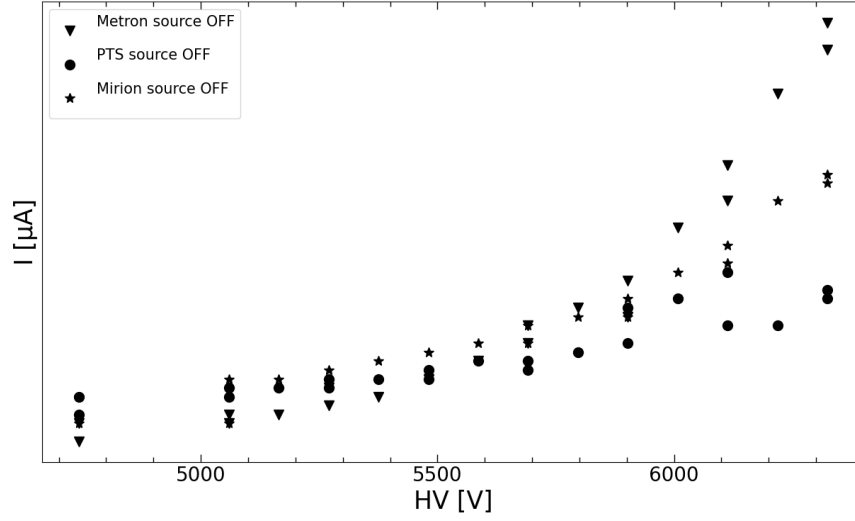


Figure 7.1.1: Current measured with a multimeter as voltage drop over a 100k resistor plotted against voltage without the γ irradiation.

In order to get the most comparable results, the high voltage applied on the gas gap was corrected for the influence of temperature and pressure. This is necessary as the density of the gas varies with these two parameters.

In order to apply this correction, the following formula was used:

$$HV_{correctd} = HV \frac{P_0}{P} \frac{T}{T_0} \quad (7.1.1)$$

with $P_0 = 1010$ mBar and $T_0 = 293$ K. [27]

7.1.2 Performance under γ irradiation

After the initial tests without the γ radiation had shown the chambers were operational, the the voltage-current curves were measured for different amounts of γ irradiation. The measurements were done starting with a filter of attenuation factor 220, which corresponds to an irradiation of $215 \frac{\text{Hz}}{\text{cm}^2}$. The radiation dose was then increased gradually. Figure 7.1.2 shows the currents of prototype Mirion under different irradiation.

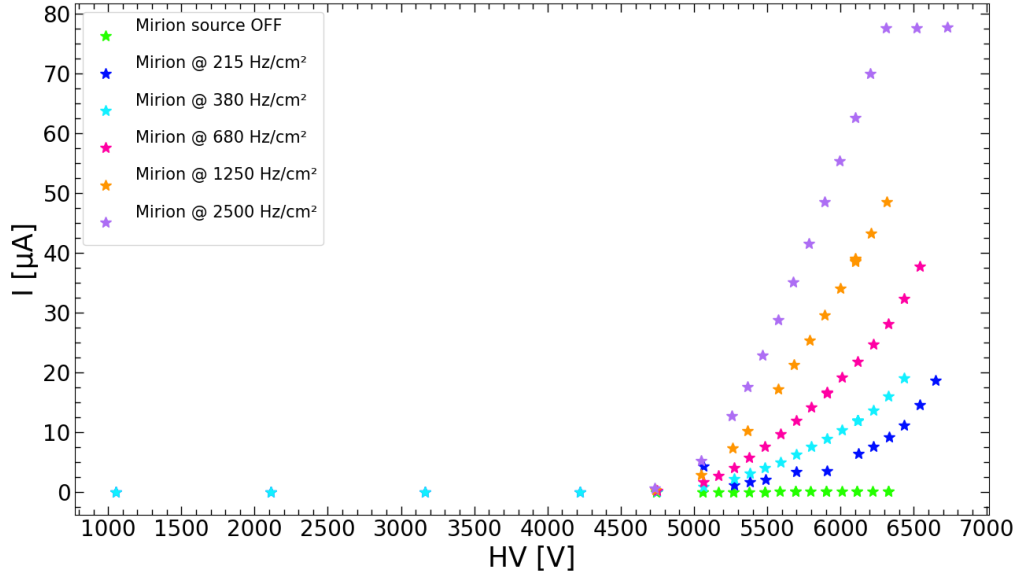


Figure 7.1.2: Voltage-current curves for the Mirion gas gap for different γ irradiation levels measured as a voltage drop over a 100k resistor.

The figure shows the increase in overall current with decreasing attenuation of the source. As can be seen, due to the high number of ionizing photons the exponential part of the curve gets steeper and at a certain point, here with a filter as low as 10, corresponding to an irradiation of 2500 Hz/cm², at around 6000 V, the gas reaches a point of total ionization which, if the filter would be reduced further, would also start at lower voltages. Figure 7.1.3 shows the HV-I curves for all the tested prototypes under irradiation with two different filters and with the source OFF.

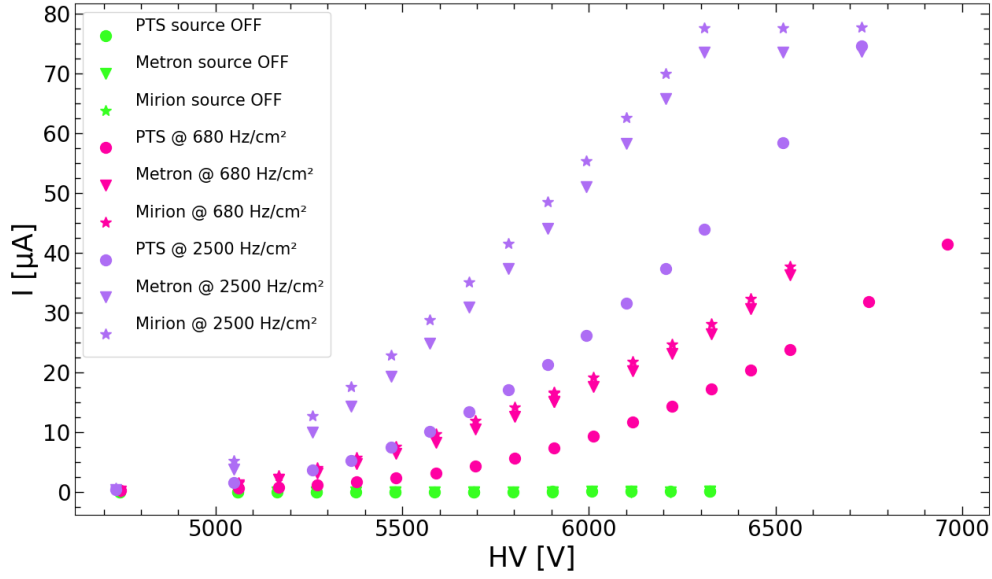


Figure 7.1.3: Current of all prototypes, measured with a multimeter as voltage drop over a $100\text{k}\Omega$ resistor, plotted against voltage under irradiation with three different radiation doses.

As can be seen, Mirion and PTS show a similar behavior, while Metron shows a much flatter curve at the same voltages due to its unglued state and wider gas gap.

7.2 Determining the time window for muon hits

The first step in the data analysis is determining the delay between the RPC and the reference trigger. This is done by plotting the timestamps for the leading edge of the signals in the chambers while the beam is operating. Figures 7.2.1 and 7.2.2 show the distributions of these timestamps.

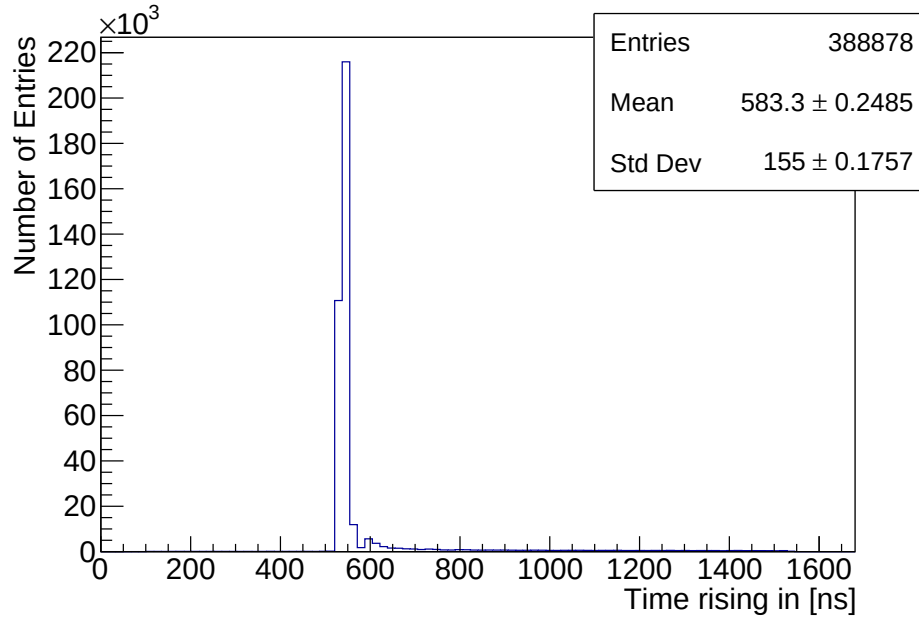


Figure 7.2.1: The distribution of the leading edge of the raw data signals in relation to the trigger for Mirion at full efficiency and no irradiation.

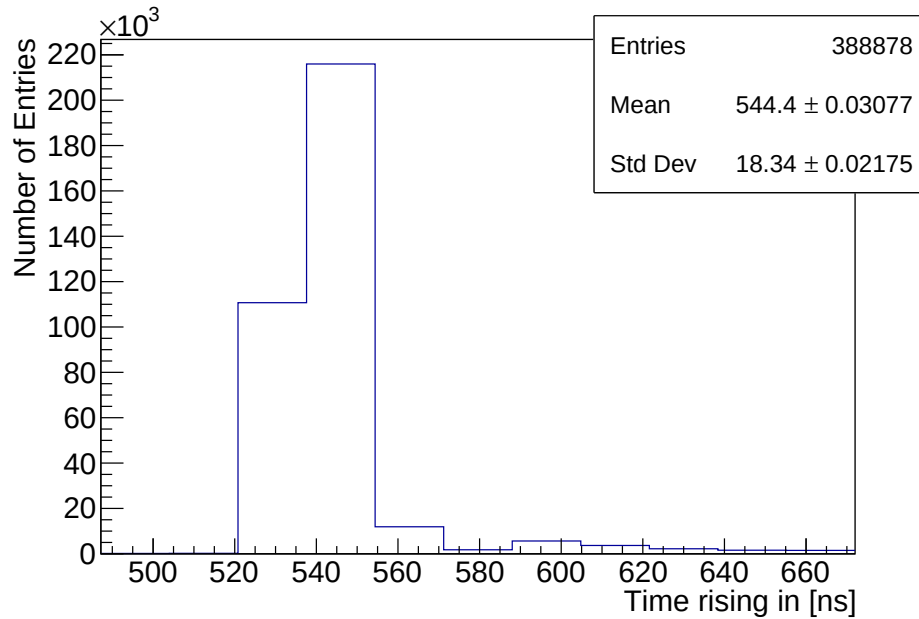


Figure 7.2.2: The distribution of the leading edge of the signal in relation to the trigger for Mirion zoomed into the peak created by the muons.

Based on the data, the cut on the time between 510 ns and 580 ns was chosen.

7.3 Clusterization algorithm

As it is possible for a particle in a RPC to create an avalanche that induces a signal on more than one strip, it is necessary to group all signals that belong to the same avalanches into clusters, in order to prevent hits from being counted multiple times. In order for signals to be counted as belonging to the same cluster, two requirements must be fulfilled:

1. all signals belonging to a cluster must come from neighboring strips.
2. all signals belonging to a cluster must start in the time window set by the duration of an avalanche moving in the gas.

In order to determine the time window of the avalanche moving, the signals were clustered using a large time matching window. Then, for a fully efficient run without irradiation, all clusters with exactly two hits were singled out and the time difference between the signals was calculated. Figure 7.3.1 shows the time difference and its negative, for a muon beam run, plotted and fitted with a Gaussian-distribution.

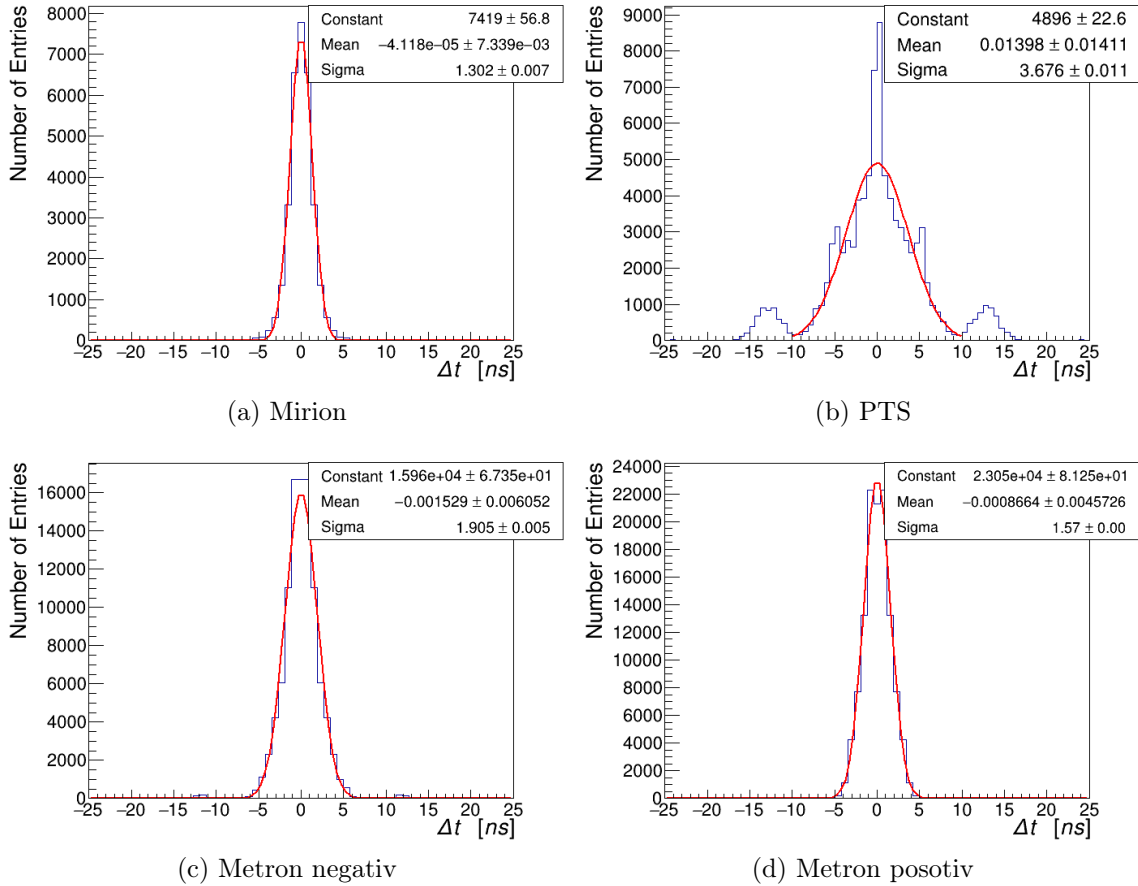


Figure 7.3.1: Δt of muon clusters plotted and fitted for (a) Mirion, (b) PTS, (c) Metron negative side and (d) Metron positive side.

The distribution in Figure 7.3.2b shows some not fully understood peaks above 10 ns, which for the analysis were not regarded in the fit. The time window for clustering was chosen as 5σ for each chamber separately to ensure that all hits for the muons that belong together are grouped together. With this and the condition of continuity, the hits were grouped to the so-called clusters for further analysis. The same analysis has been done for the photons as well, and is shown in Figure 7.3.2.

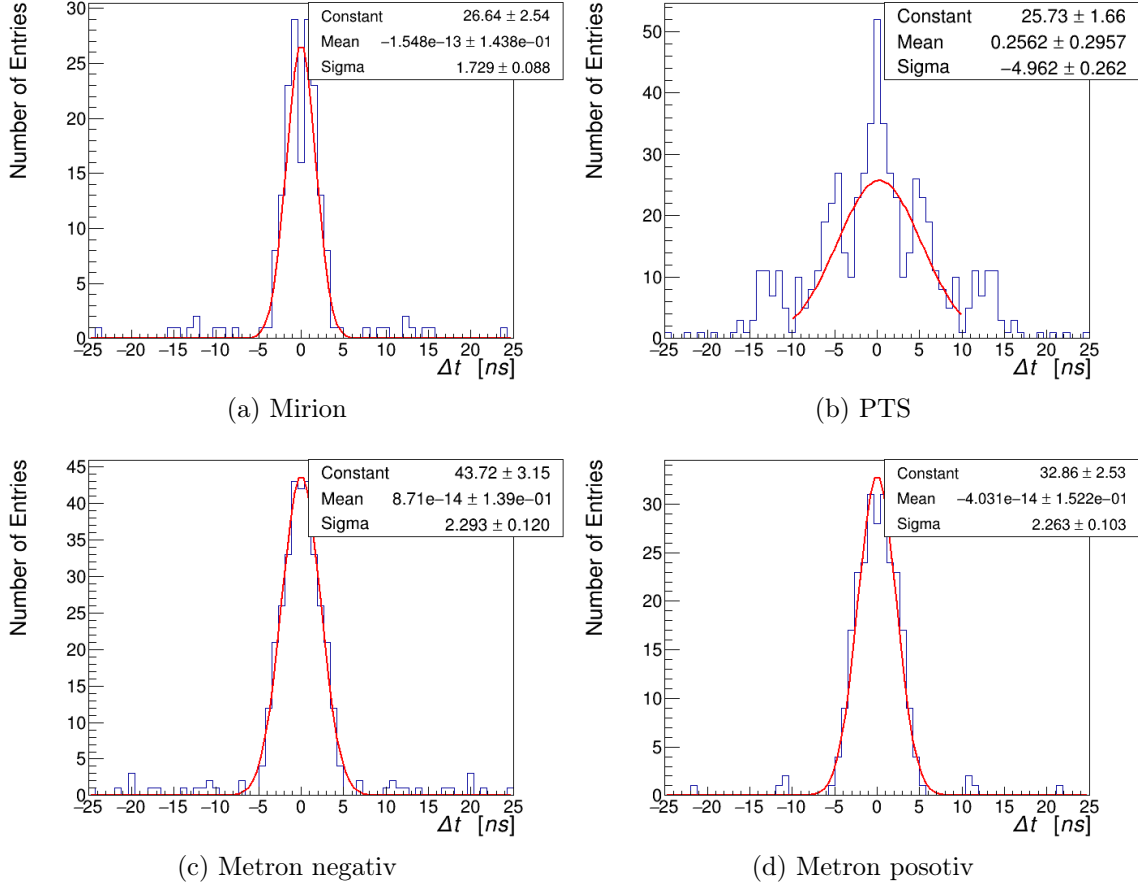


Figure 7.3.2: Δt of gamma clusters plotted and fitted for (a) Mirion, (b) PTS, (c) Metron negative side and (d) Metron positive side, for a irradiation of 680 Hz/cm^2 .

To ensure that only photons were chosen, only hits outside the muon time window were considered. In this case, only hits in the time window between 700 ns and 1500 ns after the trigger were chosen for matching.

7.3.1 Determining the cluster size

Another interesting characteristic of the gas gaps is the cluster size. This is the measure of how many strips see a signal when a muon starts an avalanche. The optimal cluster size is one strip per cluster, since the ATLAS readout scheme will only record the signal

times.[35] A larger cluster size could improve the spatial resolution beyond the strip width if paired with a readout for the signal shape, however this is not required for the ATLAS setup. Figure 7.3.3 shows the cluster size for Mirion at 6000 V while 7.3.4 shows the cluster size with a irradiation of 2500 Hz/cm². As can be seen, the cluster size average is 1 strip per cluster for both irradiation levels.

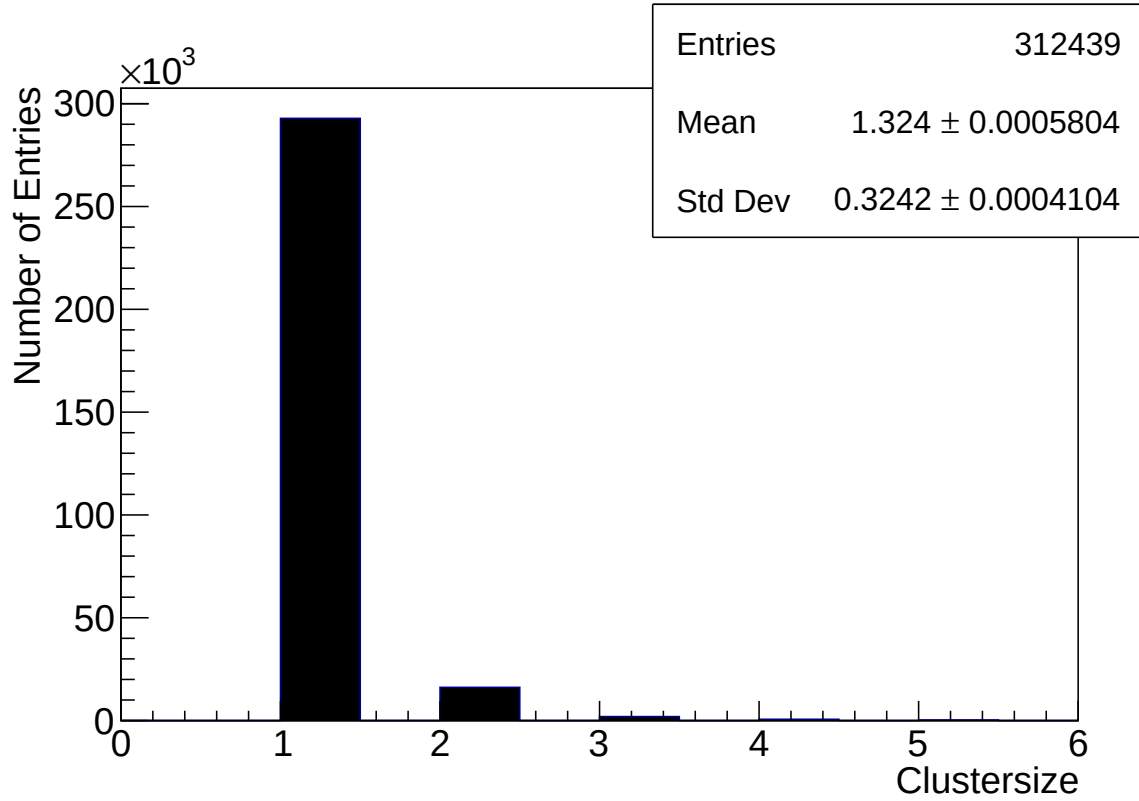


Figure 7.3.3: The Figure shows the cluster size distribution for Mirion at a set voltage of 6000V and the source OFF.

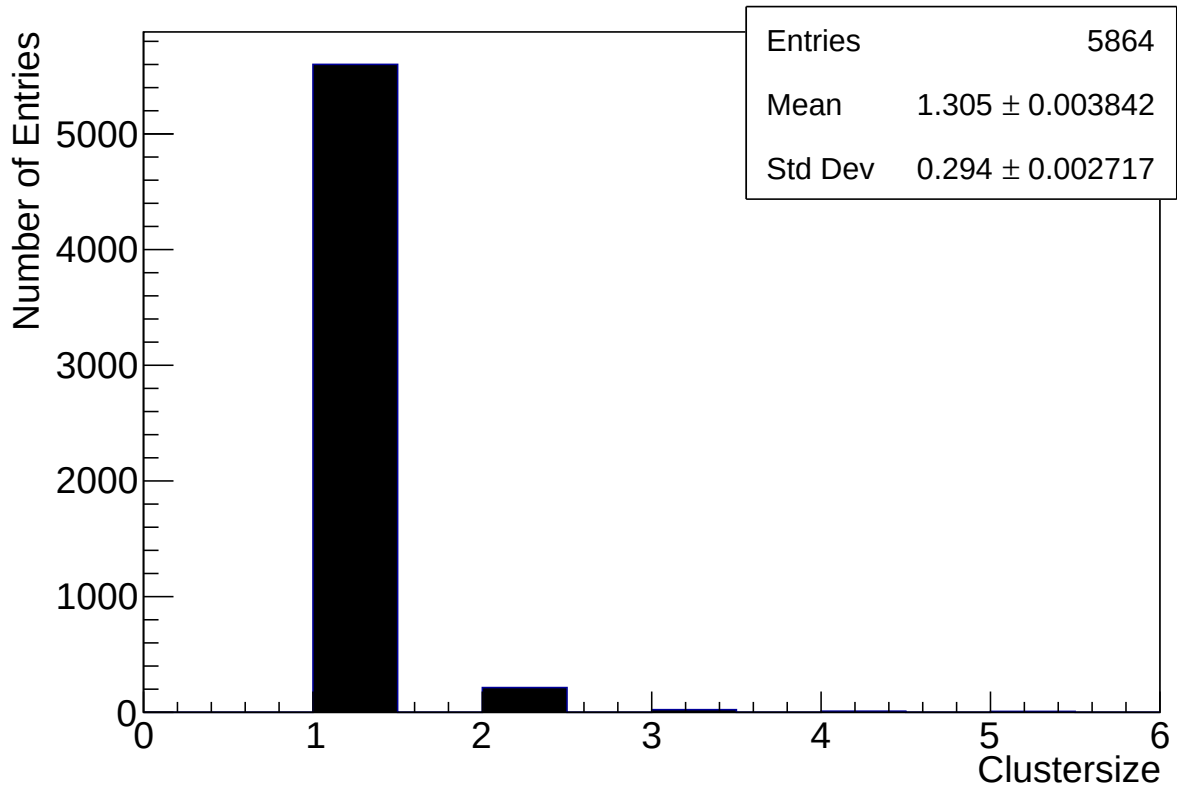


Figure 7.3.4: The Figure shows the cluster size distribution for Mirion at a set voltage of 6000V and a irradiation of 2500Hz/cm².

This shows that the chamber operates with the performance expected of a 1 mm gas gap.

7.4 Determination of the discriminator threshold

With the time window set, the next step was to choose the best operating threshold for the discriminators. For this, several runs with different thresholds and the beam on were measured. Figure 7.4.1 shows the different efficiency curves measured for Mirion with different discriminator thresholds.

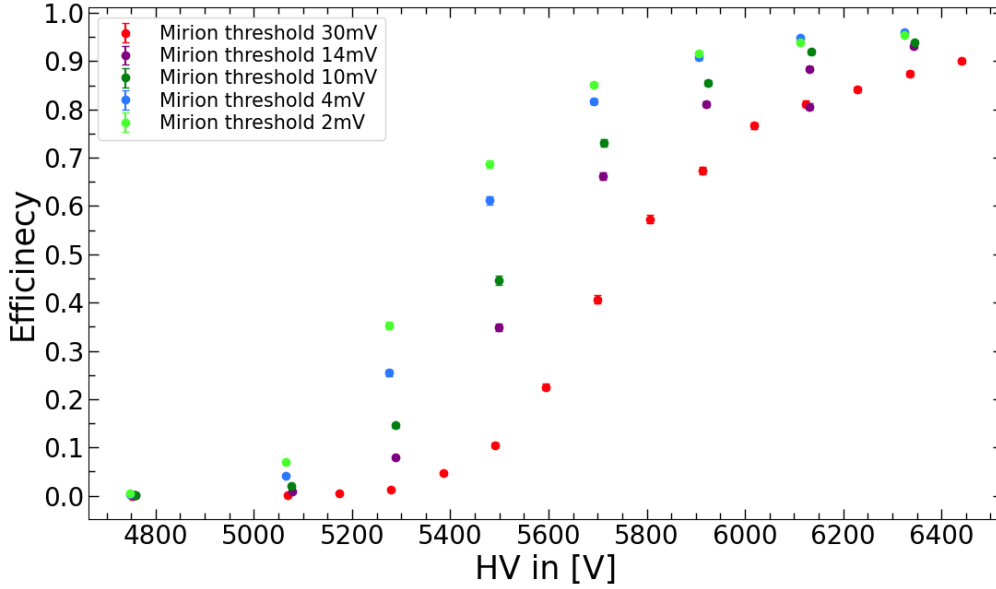


Figure 7.4.1: Efficiency for Mirion scans with different thresholds and the source OFF

The plot shows that the best efficiencies are reached with thresholds of 2mV and 4mV. However, the total amount of noise for 2mV is higher than for 4mV. As an example the noise rate of raw hits for Mirion at a threshold of 2mV is (11.12 ± 9.02) Hz/cm² while for 4 mV the rate is only (1.11 ± 0.99) Hz/cm². For reconstructed fake clusters from these measurements at 2mV we get rates (9.043 ± 7.71) Hz/cm², while for 4mV the rate is only (1.09 ± 0.99) Hz/cm². The values are all normalized on the readout area of Mirion.

Therefore, an operating threshold of 4mV was chosen for the main data taking.

7.5 Rate calculation

The rate can be calculated using either the number of clusters reconstructed using a random trigger run or using the number of clusters that have to be registered during muon trigger runs but are far outside the time window of the beam, while the chambers operated at full efficiency and no irradiation.

$$Rate = \frac{Number\ of\ clusters}{Number\ of\ Triggers \times Time\ window\ of\ the\ aquired\ data \times Area\ measured} \quad (7.5.1)$$

The rates calculated from the data using this equation are:

ABS	10	22	46	100	220
Rate in Hz/cm ²	2507	1251	685	377	214
Error in Hz/cm ²	25	10	9	7	3

The Curve for Metr

7.6 Efficiency

To determine the overall efficiency of the gaps, the total number of events with at least one cluster in them was divided by the reference value given by the total number of triggers from the external scintillators:

$$Efficiency = \frac{Events\ with\ at\ least\ one\ cluster\ reconstructed}{Total\ number\ of\ triggers} \quad (7.6.1)$$

The results for each chamber at source OFF are shown in Figure 7.6.1. The curve for Metron and Mirion reaches its full efficiency of more than 95% at around 5800 kV, which matches the geometrical efficiency and is in agreement with what is expected of a 1 mm gas gap.

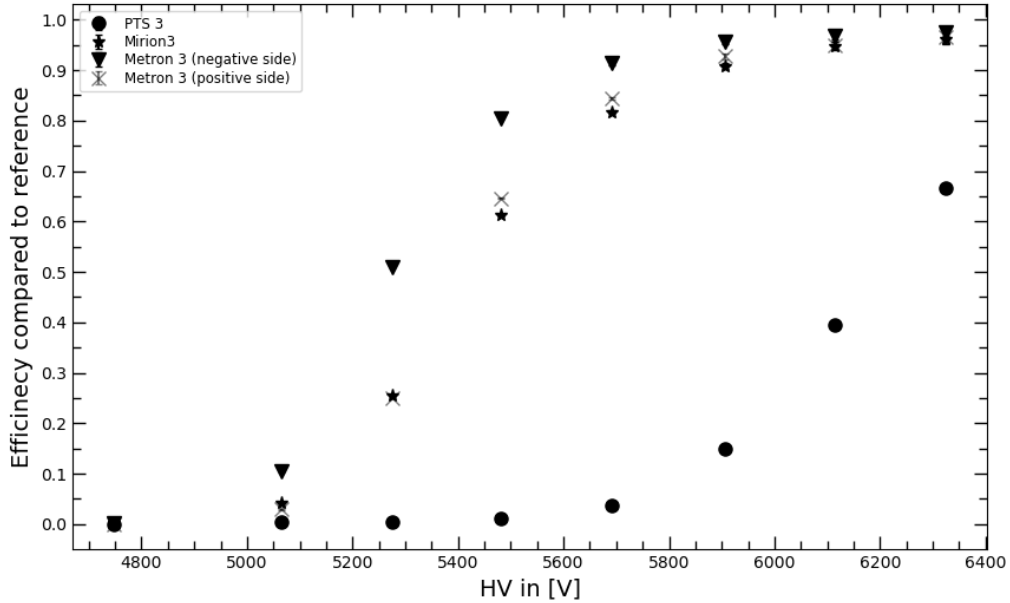


Figure 7.6.1: Efficiency plotted against the corrected voltage for all three gaps, measured without any gamma radiation and with a discriminator threshold of 4 mV.

As PTS is damaged, it needs a higher voltage to reach full efficiency. Figure 7.6.2 shows that the full efficiency of PTS is reached around 7000 V.

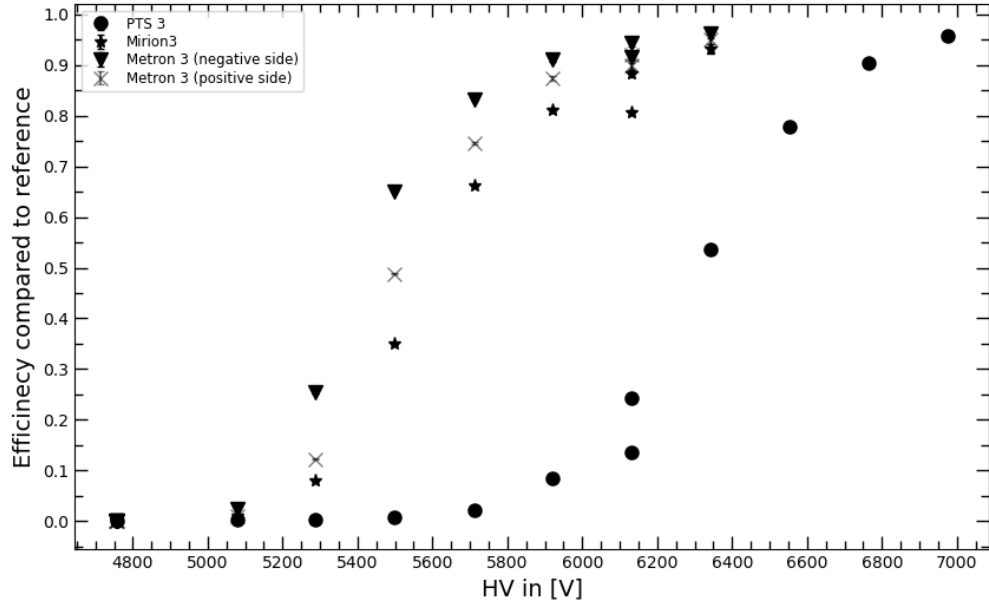


Figure 7.6.2: Efficiency plotted against the corrected voltage for all three gaps, measured without any gamma radiation and with a discriminator threshold of 10 mV.

To test for the rate capability of the prototype, a full efficiency curve was measured for each chamber with different absorption filters. The results of this scan are shown in Figures 7.6.3.

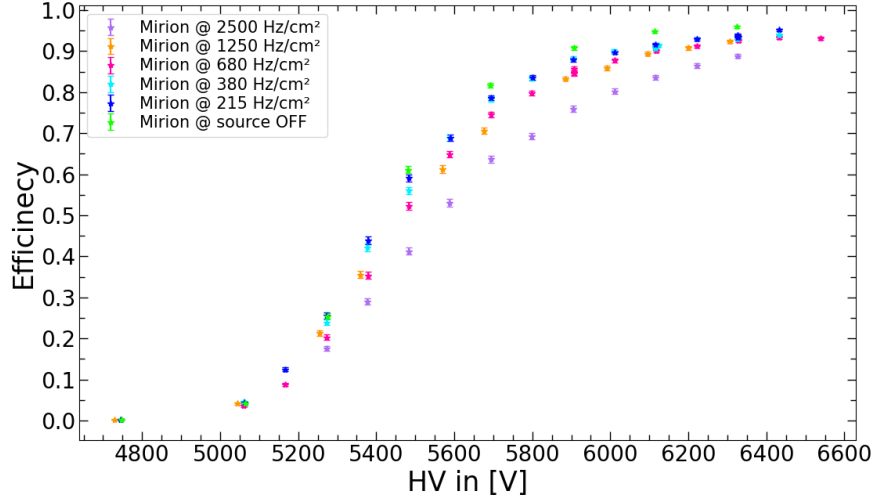


Figure 7.6.3: Efficiency plotted against the corrected voltage for Mirion measured at different abortion filters, with a discriminator threshold of 4 mV.

As can be seen, the curve for Mirion in Figure 7.6.3 shows a shift of the working point towards higher voltages, while the total max efficiency stays the same. This matches the behavior expected of a 1 mm RPC designed for ATLAS.

Figure 7.6.4 shows the efficiency scans for Metron.

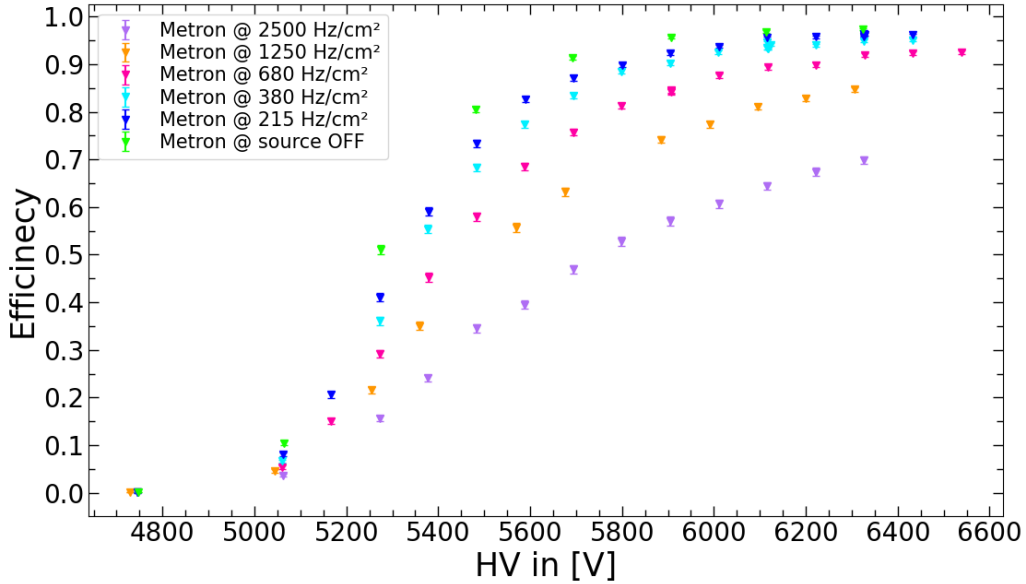


Figure 7.6.4: Efficiency plotted against the corrected voltage for Metron negative side measured at different abortion filters, measured with a discriminator threshold of 4 mV.

These show that with higher irradiation, the efficiency goes down. The reason for this is that the resistivity of the electrodes in Metron is higher than the one of Mirion, which leads to an increase in dead time of the RPC as the charges in the gap cannot escape the gap before the next muon hits the RPC.

7.6.1 Calculation of the HPL Volume resistivity of the Prototypes

Taking the voltage-current curve from chapter 7.1 and the efficiency curves at different source filters allows for measuring the shift in voltage and current at the point of 50% efficiency (any point can be chosen, however, the point of 50% efficiency is the most sensitive to changes). By doing that, it is possible to calculate the actual resistivity of the HPL plates used for the singlet. This is possible because the efficiency of the RPC, when everything else is kept the same, only depends on the voltage applied to the gas. When the irradiation is increased, more current flows through the gas, making it more conductive and reducing the voltage drop over the gas itself. Therefore, it is necessary to increase the total applied voltage in order to increase the voltage on the gas that is necessary to gain the same efficiency. As a result, the voltage dropping over the gas gap can be assumed to be the same for both source intensities. This leads to the formula:

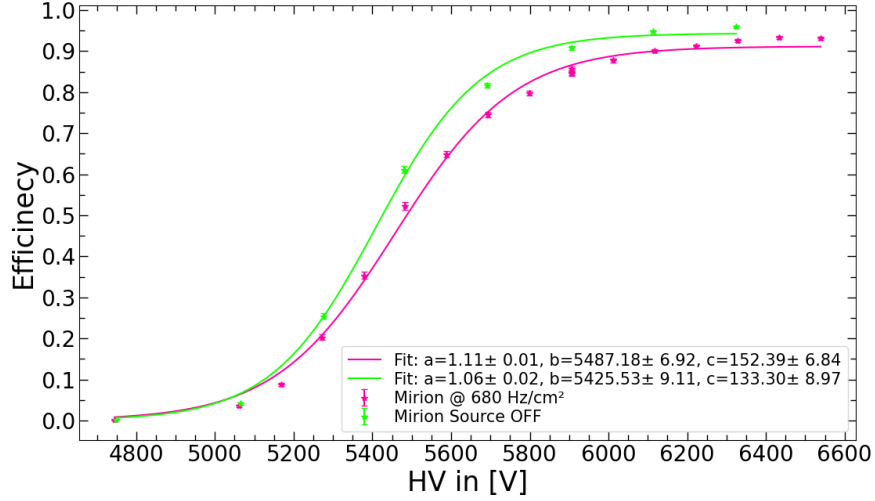
$$R_{HPL} = \frac{U_{Irradiation} - U_{Source\ OFF}}{I_{Irradiation} - I_{Source\ OFF}} \quad (7.6.2)$$

[36]

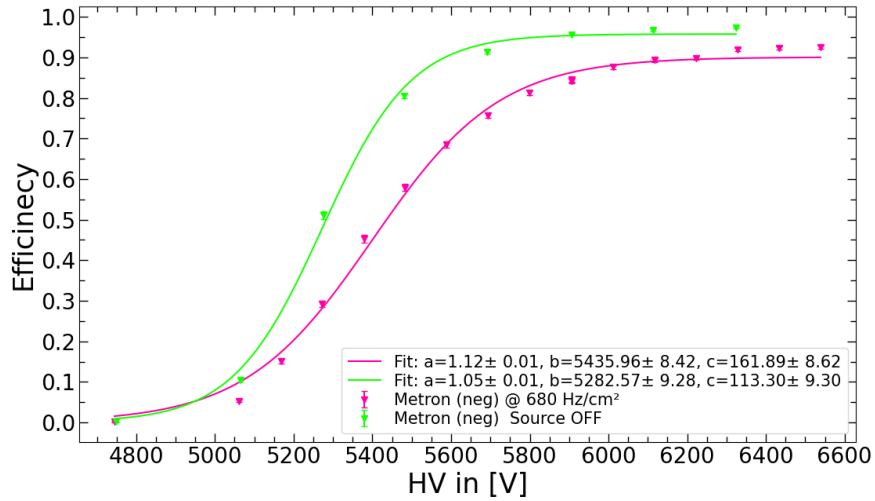
Fitting now two of the efficiency curves for Mirion and PTS with a modified Fermi statistic

$$Efficiency = \frac{a}{(2a - 1) + e^{\frac{b-HV}{c}}} \quad (7.6.3)$$

one can find the approximate voltage at which the efficiency reaches 50%. However it has to be noted that this function is only a numerical approximation, chosen due to its shape and characteristics, and there is no connection to the physics of the detector. Figure 7.6.5 shows the fitted efficiency curves for Mirion and Metron.



(a) Mirion



(b) Metron

Figure 7.6.5: Efficiency curves for two different filters, fitted with the Fermi statistics function (fit results shown in the legend).

The b value of the fit gives the voltage at 50% of the full efficiency and is used for the calculation of the resistivity. The current was read from voltage-current curves by interpolating the measured curves, shown in 7.1.1. The calculated voltage and current shifts are:

Irradiation in Hz/cm ²	Mirion		Metron	
	680	OFF	680	OFF
HV @ 0.5 in V	5487.18	5425.25	5435.96	5282.57
I in μ A	7.69	0.015	5.60	0.013

For the calculation a size of 48x38 cm² was used for the irradiated active area of the electrodes as well as a thickness of 1.5 mm per electrode. The average resistivity calculated from all irradiation intensities is $(5.91 \pm 1.23) \cdot 10^{10} \text{ } \Omega\text{cm}$ for Mirion and $(16.45 \pm 3.28) \cdot 10^{10} \text{ } \Omega\text{cm}$ for Metron.

7.7 Time resolution

In order to determine the time resolution, the time measurement of the chambers Mirion and Metron were compared. Several long runs at full efficiency were taken and the times of muons detected by both Metron and Mirion were calculated. To do so, all hits that were detected by Mirion and both sides of Metron were chosen and the time difference (Δt_{raw}) between the time of the hit on the negative Metron side and in Mirion was calculated for each muon. Additionally, the difference in time $\Delta t_{\text{neg-pos}}$ between the hit being measured by Metrons positive and negative side was calculated. This time difference is a measure for a position along the strip of Metron as the positive and negative side of Metron are read out on opposite sides of the chamber.

This is necessary as the muon hit times depend on their distances from the read-out electrodes.

To correct for this dependence of Δt_{raw} , Δt_{raw} was plotted against $\Delta t_{\text{neg-pos}}$ and the mean value of Δt_{raw} in each bin was calculated. This mean was then subtracted from the Δt_{raw} to get the time of flight Δt that is plotted in Figure 7.7.1. If we assume that Mirion and Metron have similar characteristics with respect to the time resolution, the time resolution of the gas gap doublet can be calculated with

$$\delta(\Delta t) = \sqrt{(\delta t_{\text{Mirion}})^2 + (\delta t_{\text{Metron}})^2} = \sqrt{2} \cdot \delta t = \sigma \quad (7.7.1)$$

δt being the error of the time measurement of Mirion and Metron and the deviation from the mean. Thereby, the time resolution of the chambers is given by:

$$\delta t = \frac{\sigma}{\sqrt{2}} \quad (7.7.2)$$

With this, the time resolution can be determined by retrieving the σ from Figure 7.7.1.

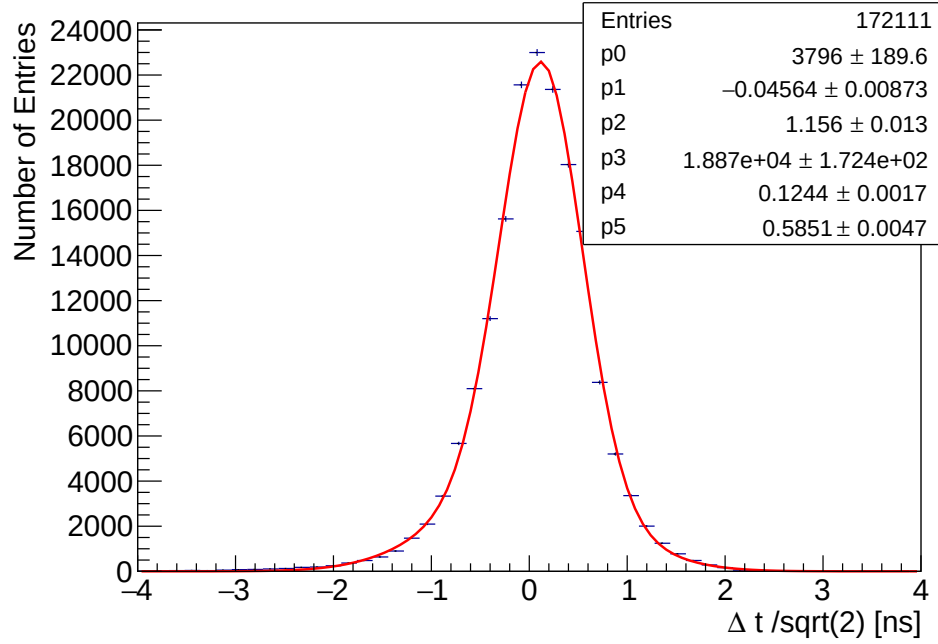


Figure 7.7.1: The distribution of the corrected time of flight for the two chambers, Metron and Mirion, divided by $\sqrt{2}$.

To do so, the distribution was fitted with the following function:

$$p_0 \cdot \exp \left[\frac{-(x - p_1)^2}{p_2^2} \right] + p_3 \cdot \exp \left[\frac{-(x - p_4)^2}{p_5^2} \right] \quad (7.7.3)$$

as 1σ is equal to the integral over 34.1% of the total distribution, the value on each side of the maximum of the distribution at which the integral reaches this percentage was found numerically and σ was determined as the average of these two values.

This gives a time resolution of $\delta t = (501 \pm 1)$ ps for Mirion and Metron.

As PTS is not similar to the chambers Mirion and Metron, the formula changes to:

$$\delta(\Delta t_{PTS \text{ Metron}}) = \sqrt{(\delta t_{PTS})^2 + (\delta t_{Metron})^2} = \sigma \quad (7.7.4)$$

$$\delta t_{PTS} = \sqrt{\sigma^2 - (\delta t)^2} \quad (7.7.5)$$

with $\Delta t_{PTS \text{ Metron}}$ being calculated the same way as the Δt for Mirion and Metron. When now retrieving the sigma from Figure 7.7.2

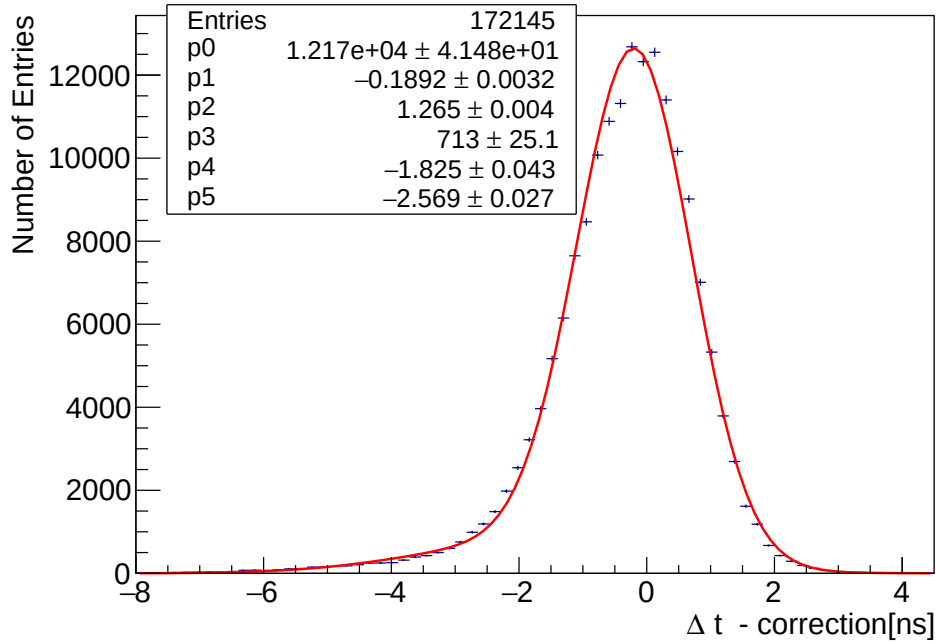


Figure 7.7.2: The distribution of the corrected time of flight for the two chambers, Metron and PTS.

the time resolution of PTS is determined to be $\delta t_{\text{PTS}} = (855.1 \pm 2.3)$ ps.

Both these results are better than the ALTAS requirements of 1 ns. Additionally both Metron and Mirion show that they meet the parameters of a operational 1 mm ATLAS RPC.

8 Conclusions

The goal of the thesis was to determine materials and production techniques for RPCs, designed for the ATLAS phase 2 upgrade, that enable mass production of these detectors by companies in Munich, supervised by the Max Planck Institute for Physics. Therefore, materials and production techniques were developed, and smaller-sized prototypes were produced by three companies, which were then tested at MPI and the GIF++ facility at CERN.

The production procedures are based on the production followed by the ATLAS and CMS experiments. The production procedures optimized in this thesis were tested by producing prototypes in the lab and then transferred to the three companies, which used and adapted them for their in-house production of test samples. It was also necessary to find a suitable PET foil, glue, and graphite coating as well as methods to apply them reliably and easily during mass production. For this reason, several types of glue and graphite varnishes were tested. The results show, that the most suitable foil and glue combination is the GMP Perfex Gloss composite foil, which has a EVA hot melt already bonded to the foil. It reached an adhesive strength of more than 2 N/mm measured with the method described, while being easy to handle and apply during mass production. It is also based on glue and a foil material that is already certified and fulfills all CERN regulations and requirements for the use in a gas detector.

The best results for the graphite coating were achieved with a varnish, provided by the Heysung Trade company (used in the production of CMS RPCs) and applied using a T90 nylon silk screen. The varnish with the silk screen printing procedure created a consistent and reproducible layer with a resistivity in the range of $350 \text{ k}\Omega/\square \pm 30\%$ as required for the ATLAS RPCs.

After initial tests at MPI, three gaps produced with these methods and materials were equipped with self-produced strip panels and electronics provided by INFN and tested in the GIF++ facility at CERN. There it was possible to test the gas gaps with a high energy muon beam and a high-intensity γ -source to simulate the conditions the gaps will face at the LH-LHC. At the beginning of the tests, it was discovered that the PTS gas gap was damaged, but it was decided to try to recuperate some functionality by compressing it in the test setup mechanics. The results show that the Mirion and Metron gaps tested had voltage-current curves that were in line with expectations for the ATLAS RPCs, while the curves for PTS were shifted due to the larger gap size caused by the broken spacers. During data analysis, the cluster size for all the curves was determined to be close to one, which is the goal for the ATLAS readout system. The efficiency of the Mirion and Metron gaps reaches over 95% without irradiation at an operating voltage of 5800 V, which is the target for the new 1 mm RPCs, while the full efficiency of PTS is reached at a higher voltage of 7000 V due to its damaged state. While testing, it was also found that the efficiency of Metron under high irradiation was significantly more degraded than the efficiency of the properly functioning gap Mirion, which showed only small changes in overall performance under higher irradiation. This behaviour could be attributed to the electrodes in Metron having a higher volume resistivity of $(16.45 \pm 3.28) \cdot 10^{10} \text{ }\Omega\text{cm}$ compared to the ones in Mirion, which have a

volume resistivity of only $(5.91 \pm 1.23) \cdot 10^{10} \Omega\text{cm}$. The time resolution calculated from the data of the test beam is $\delta t = (501 \pm 1) \text{ ps}$ for Mirion and Metron, which is even lower than the 1 ns required for the operation at ATLAS. For PTS the average time resolution was found to be only $\delta t_{\text{PTS}} = (855.1 \pm 2.3) \text{ ps}$ due to its damaged state. The prototypes show that the production methods and materials provided by the Max-Planck-Institute are suitable for the production of gas gaps for the ATLAS RPCs, and that the technology transfer to industry was successful.

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