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Advanced aging study on Triple GEMs for CMS GE2/1 and ME0

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To achieve great things, two things are needed:
a plan, and not quite enough time.

(Leonard Bernstein)

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Introduction

After several years of successful R&D with Gas Electron Multipliers (GEM) based detectors, the CMS GEM collaboration is going to install the innermost region of the forward muon spectrometer of the Compact Muon Solenoid (CMS) experiment with the triple-GEM technology. This region is characterized by a harsh radiation environment, primarily composed by neutrons and photons. Aging phenomena constitute one of the most complex and potential serious problems which could limit, or severely impair, the use of gaseous detectors in unprecedented harsh radiation environments. As for all gaseous detectors, the Triple-GEM technology might be subject to classical aging, i.e. the degradation of their detection performance due to the presence of contaminants in the gas volume when operating in a high-rate particle environment. Most of the contaminants usually comes from the outgassing of some materials which tend to release some of their molecules in the gas volume, triggering the polymerization processes and further inducing the performance degradation of the detector.

Although many potentially dangerous materials were removed from the detector mass production, many others can be present in the gas systems and in the detectors themselves. Furthermore, it is crucial to understand the role of the particle's specific ionization power in the aging processes. New tests on these issues are needed in order to assure a safe operation of Triple-GEM technology in such harsh environment like the CMS end-caps.

In this thesis work a new concept of aging study is proposed with the goal to better understand the aging issues in contaminated gas mixtures and in densely ionizing particles environment. To our knowledge, no such test is present in literature.

In Chapter 1 a brief description of the particles interaction theory, the Large Hadron Collider and CMS will be given. Chapter 2 analyses the particles-matter interactions together with the description of the gaseous detector technologies. In the Chapter 3, the experimental setup characterization will be illustrated and in Chapter 4 the theory behind the aging processes and the past studies on this subject will be described. Finally, Chapter 5 describes the work done in order to perform the aging test along with the obtained results.

This work will be the first of a long series of tests that will be performed in future to achieve a deeper comprehension of aging processes. The need of a substantial theory or, at least, a model that can predict and correct the detector's aging processes will be more and more important for the experiments at high luminosities machines.

Chapter 1

Standard Model, LHC and CMS

This chapter starts with a brief introduction to the Standard Model, the most precise theory of the subnuclear world we have at present time. In section 1.2, the Large Hadron Collider (LHC), the most powerful and largest particle accelerator in the world, will be presented with a description of its main experiments and future upgrades. Finally, in section 1.3, the Compact Muon Solenoid (CMS) experiment focusing on the muon spectrometer will be discussed.

1.1 The Standard Model

The *Standard Model* (SM) is a quantum field theory based on the principle of the gauge invariance which unifies electromagnetic, weak and strong interaction, but is not able to include the gravitation. It was formulated in the late 1960 by S. Glashow, S. Weinberg and A. Salam, and further developed until today. Despite producing many predictions which have been confirmed during the past years with great accuracy, several experimental observation are not accounted for in the SM.

Since this thesis is concerned with experimental works, a full and depth description of SM will not be given, however a detailed explanation can be found at [1].

1.1.1 Matter elementary particles

In the framework of the SM, matter is described using 12 elementary particles with spin $1/2$, i.e. *fermions*. These are divided in two groups, the charged leptons: electron (e^-), muon (μ^-) and tau (τ^-) with their associated neutrinos (ν_e , ν_μ and ν_τ) and the quarks of the three generations: (u, d), (c, s) and (t, b). In addition to each of these particles there are also antiparticles, which possess identical physical properties, but with an opposite charge and parity, resulting from CPT invariance.

1.1.2 Elementary Interactions

The SM define also the quanta of every interactions fields: the so called gauge bosons, with spin 1, which mediate the force between two particles. The interactions described by the SM are as follows:

- Electromagnetic interaction (EM): this applies only to charged particles. After gravity, it was the first elementary interaction discovered. Initially described

by J.C.Maxwell within a classical framework in his equations, it was later reformulated by R.Feynman through Quantum ElectroDynamics (QED), a quantum field theory. The EM interaction is of note, as this interaction forms the basis for the detection of particles in gaseous detectors.

- Strong interaction: this force only acts on quarks and the respective gauge bosons i.e. color charged particles. This is an auto-interacting force which is carried by 8 gluons and the full description is expressed by Quantum Chromo Dynamics (QCD). The phenomenon of color confinement, typical of this interaction, doesn't allow the quarks to cluster in color charged objects; therefore no free quarks can be found in nature, they can only exist within bound states composed of either 3 quarks (baryons) or a quark-antiquark pair. Also weakly bounded states formed by 4 or 5 quarks are possible.
- Weak Interaction: this applies to all particles in the SM and permits many decays of heavy particle into lighter ones. It was first proposed by E.Fermi in order to explain β decay, afterwards a more consistent theory by S. Glashow, S. Weinberg and A. Salam resulted in the unification of this interaction with the EM force, predicting the existence of 3 new gauge bosons (W^+ , W^- and Z).

Gravitation does not fit into the framework of the SM. This issue highlights one of the major problems of the SM. It appears that physics 'beyond the SM' is required to unify all of the fundamental forces.

Table 1.1 displays the different relative strengths of the fundamental forces.

Interaction	Relative Strength
Strong	1
Electromagnetic	$1/137$
Weak	$10^{-5} - 10^{-7}$
Gravitation	10^{-39}

Table 1.1: Strength of the different interactions relative to the strong interaction.

1.1.3 The Brout-Englert-Higgs mechanism

In the electro-weak theory the particles are described without using mass terms in the lagrangians. The Brout-Englert-Higgs mechanism fills the hole in the theory by generating the masses of bosons and fermions. This procedure also predicts a new scalar boson with spin parity 0^+ , the *Higgs boson*.

A new scalar boson was discovered in 2012 by CMS and ATLAS collaborations, but only after some years this was confirmed to be the SM Higgs Boson.

A brief resume of the particle's properties is given in Figure 1.1

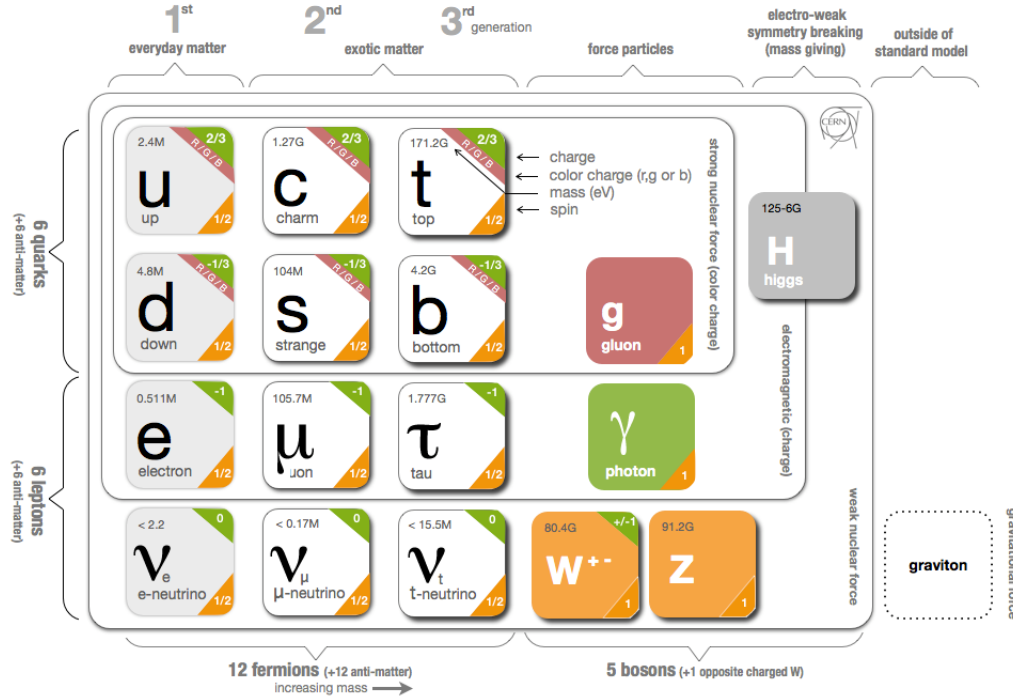


Figure 1.1: Schematic representation of the elementary particles predicted by the Standard Model with the addition of the hypothetical presence of the graviton that is the mediator of the gravitational force. Credits: CERN

1.1.4 Limitations of SM

In the last decade SM was successfully tested with great precision and on a wide range of energies. The discovery of the Higgs boson seems to complete the framework of the SM, but several considerations show that SM could not be complete as it is but only an approximation of a wider unified theory. Below are several deficiencies in the SM which support the need for physics beyond the SM:

- Gravitation is not included in the SM description. There are fundamental incompatibilities between the SM and the theory which describes gravitation: Einstein's General Relativity;
- The self-consistency of the SM, formulated as a non-abelian gauge theory quantized through path-integral, has not been proven yet, there is no justification for the choices of the gauge groups and the three generations of fermions. Furthermore SM has 19 free parameters (fermions masses and coupling constants) which are undefined by the theory and need to be determined experimentally.
- Standard model predicts the existence of the antiparticles, but does not explain why there is no presence of anti-matter in our universe.
- From cosmological studies it is evident that only a small fraction (4.9%) of our universe is made of SM matter. Indeed the rest is shared between Dark Matter and Dark Energy. SM only describe a little portion of our universe.

All those limitations seem to require a new and presently unknown theory for elementary particle physics. Several theories have been developed and are grouped under the name Beyond Standard Model (BSM) theory, but until this day none of these theories have been validated by experiments.

1.2 CERN and The Large Hadron Collider

CERN (Conseil Européen pour la Recherche Nucléaire-European Council for Nuclear Research) was founded in 1954 by 12 European countries. Each member state invests financial and human capital in order to build the most sophisticated particles accelerator complex in the world. Nowadays the collaboration numbers 22 member states plus some external observers. The main scientific goals are, among others, to measure precisely the SM predictions, to understand the mass of the fundamentals particles and to look for physics beyond SM.

1.2.1 Accelerators overview

LHC, as already mentioned, is the biggest and most powerful particles accelerator on the earth and the main asset of CERN. It accelerates protons bunches up to 7 TeV but this nominal energy is reached after 4 main acceleration steps, which can be seen in Figure 1.2:

- Protons are obtained through stripping the electrons from hydrogen atoms and then accelerated up to 50 MeV by a linear accelerator (LINAC 2);
- They are injected in the Booster (PSB) and afterwards in the *Proton Synchrotron* (PS) where they reach the energy of 26 GeV ;
- Subsequently another acceleration is made by *Super Proton Synchrotron* (SPS) with a nominal energy of 450 GeV ;
- The final acceleration is reached in the LHC where the protons acquire energies up to 7 TeV

LHC measures 27 km in circumference and it is placed 100 m underground. The beam pipes contain a set of super-conducting dipoles in order to curve the protons around the ring, also quadrupole and octupoles are present to assure the focusing of the beam. To guarantee the superconductive behaviour all the system is kept at the temperature of 1.9 K .

1.2.2 Center of mass energy and Luminosity

In LHC two proton beams are simultaneously accelerated, these beams are composed by bunches of about 10^{11} protons. Bunches are made to collide by intersecting the beams head to head in different places at frequencies of about 40 Mhz

The performance of a particles accelerator is determined, among others, by two main parameters: the center of mass energy and the luminosity:

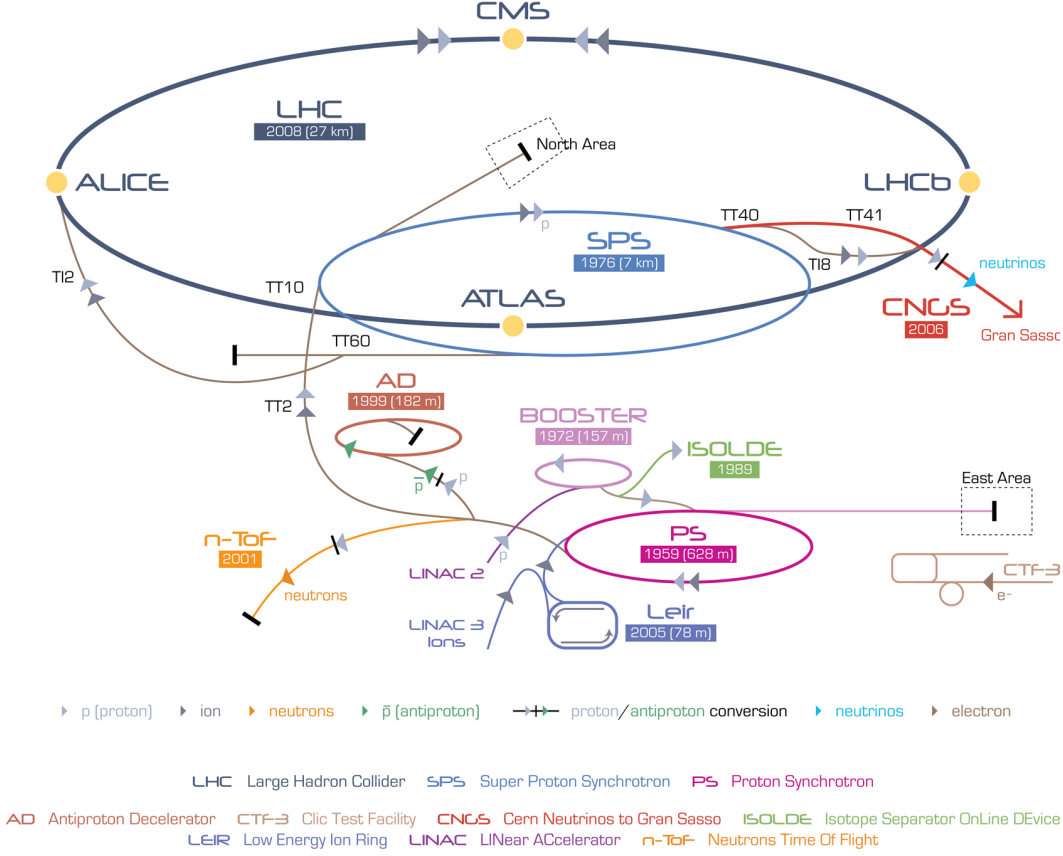


Figure 1.2: Overview of the accelerator system and the main CERN experiments. Credits: CERN

- Center of mass $\sqrt{s}$ defines the energy available in the collision. It depends on the particles beam momenta and energies and its definition comes from the Mandelstam variable s :

$$s = (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu}) = m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2),$$

where p_1^μ and p_2^μ are respectively the quadri-momenta* of the two beams, E indicates the energy and m the particle mass. [2] Since LHC is a collider, to first order approximation, the momentum of one beam $\vec{p}_1$ is opposite to the other $\vec{p}_2$ ($\vec{p}_1 = -\vec{p}_2$). In the high-energy limit ($E_{beam} \gg m_p$) the center of mass energy can be expressed as:

$$\sqrt{s} = 2E_{beam}. \quad (1.1)$$

- The luminosity $\mathcal{L}$ specifies the number of particles crossing a unit surface area

* $p^\mu = (E, \vec{p})$, where E is the energy and $\vec{p}$ the momentum

per unit time. For a synchrotron like LHC, luminosity could be expressed:

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}, \quad (1.2)$$

where f is the collisions frequency, n_1 and n_2 the numbers of grouped particles in the two colliding bunches and σ_x and σ_y the transverse beam profiles of the bunch. [2] Luminosity is clearly correlated with the number of events produced during a certain time:

$$N_{exp} = \sigma_{exp} \int \mathcal{L} dt, \quad (1.3)$$

where σ_{exp} is the cross section of interest and the quantity $\int \mathcal{L} dt$, is also called integrated luminosity $\mathcal{L}_{int}$. The latter is often measured in fb^{-1} since the cross section use the *barn* ($10^{-24} cm^2$) as unit of measurement.

1.2.3 Experiments

Though many experiments orbit around LHC there are 4 main setups placed in 4 different collision points Figure 1.3

- ATLAS (A Toroidal Lhc ApparatuS) in point 1;
- CMS (Compact Muon Solenoid) in point 5;
- ALICE (A Large Ion Collider Experiment) in point 2.
- LHCb (LHC beauty) in point 8;

ATLAS and CMS are general purpose experiments, built to discover the Higgs Boson, make precise measurements about the SM predictions and obviously search for physics beyond SM. The structure of these two experiments is pretty similar: the inner tracker is used to measure the charge and the trajectories of the charged particles and then their the momentum, an electromagnetic calorimeter measures the total energy of electrons and photons, the hadron calorimeter permits to measure the energy deposited by hadrons and jets while the muon spectrometer reconstructs the muons tracks and momentum. All the experiments have an embedded superconducting magnet in order to bend the trajectories of the charged particles and then to permit the measurement of their momentum. Although the purpose of the experiments is similar, the technology and the assembly procedures used by CMS and ATLAS is unique to each. This in order to improve the repeatability and reproducibility of the measurements.

LHCb is built to make precise measurements about the asymmetry between matter and anti-matter and it focuses on the detection of the b-quarks, its antiparticles and their bounded states.

The purpose of ALICE, the fourth experiment, is to study the the confinement of the quarks through the quark-gluon plasma produced in heavy ions collisions. For this reason ALICE principally collect data when LHC operates with lead ions.

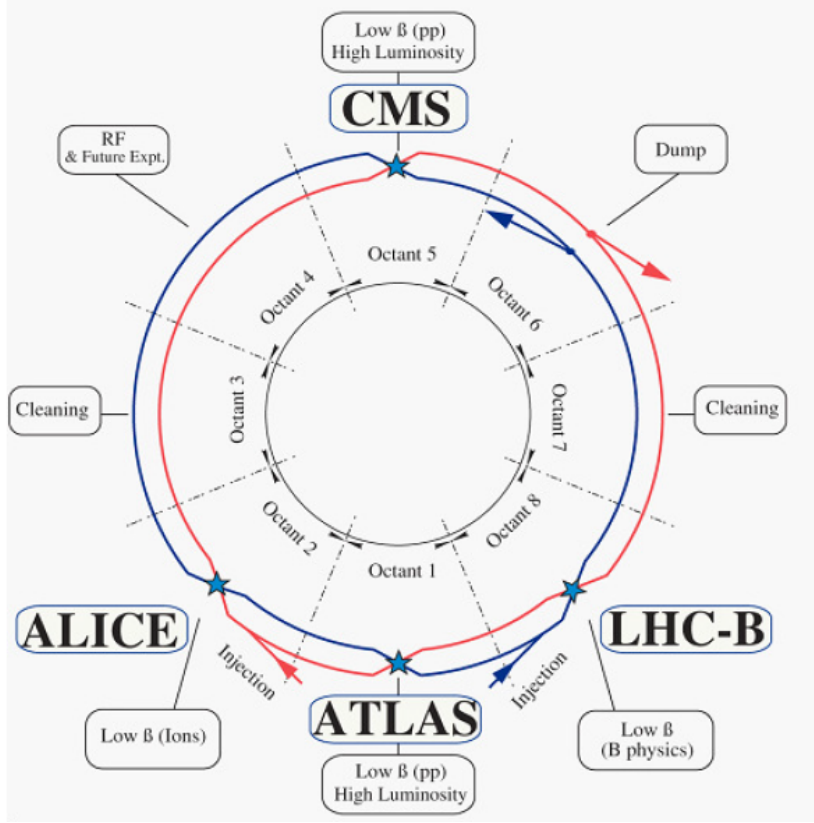


Figure 1.3: Layout of the LHC including the four main experiments. [3]

1.2.4 Upgrades

In order to stay competitive and improve year by year the discovery potential of the accelerator machine, programmed update for each system is scheduled periodically. LHC Upgrades are primarily of two different types: the increase of center of mass energy to produce more massive particles and the increase of luminosity which permits access to rare physics process. LHC schedule foresees a succession of runs and technical stop carried out at pre-established intervals, the most recent schedule can be found in Figure 1.4.

A center of mass energy upgrade was successfully fulfilled during the first long shutdown (LS1) in 2013 and 2014 when the initial center of mass energy $7 - 8 \text{ TeV}$ was increased to 13 TeV and further up to 14 TeV . Also the luminosity was increased from $7.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ up to the nominal value of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. After this period, LHC Run 2 is going on, and it will continue until the integrated luminosity will reach the value of 150 fb^{-1} . The next stop, LS2, is foreseen in 2019 where the luminosity will be increased to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and the following Run 3 will continue until the integrated luminosity will reach 300 fb^{-1} . Once again a new shutdown will happen in 2024, here the High-Luminosity LHC era begins. This new upgrade will start the so called LHC Phase 2: this big upgrade will improve the luminosity and will permit to reach $5 - 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and the following run will take place until the integrated luminosity will reach 3000 fb^{-1} .

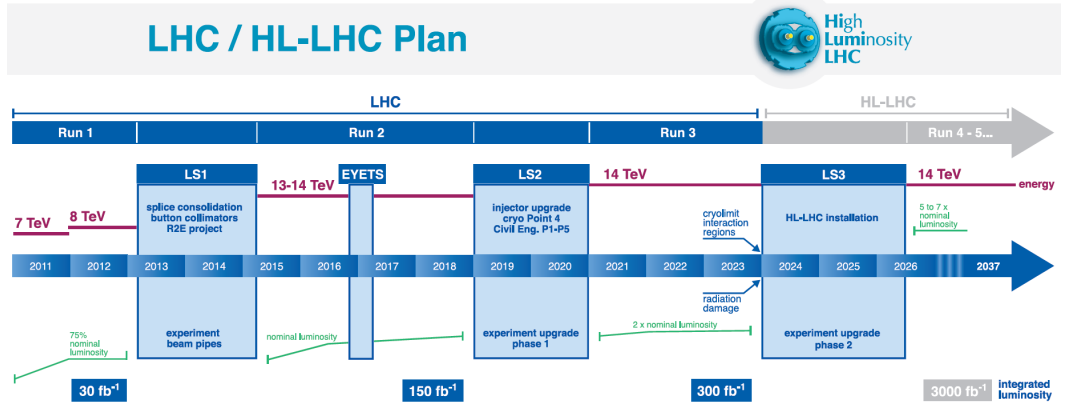


Figure 1.4: Projected LHC instantaneous and integrated luminosity as a function of the year and preliminary dates for Long Shutdowns. [4]

1.3 The Compact Muon Solenoid

As mentioned in section 1.2.3 CMS is one of the two big multi-purpose experiments on the LHC ring. The detector system, shown in Figure 1.5, is a cylinder 21 *m* long and 15 *m* in diameter which weight around 1400 *tonnes*.

The object positions are usually expressed in polar coordinates system (R, θ, ϕ) . However it is preferred to use the pseudorapidity instead of the polar angle, since this quantity carries geometrical information about the particles:

$$\eta = -\ln\left(\tan \frac{\theta}{2}\right) = \frac{1}{2} \left(\frac{|\vec{p}| + p_L}{|\vec{p}| - p_L} \right), \quad (1.4)$$

where $\vec{p}$ is the momentum of the particle and p_L its projection on the beam axis. Figure 1.6 shows how the pseudorapidity and the polar angle θ are correlated.

1.3.1 Subsystems Overview

CMS, like the others LHC experiments, is a layer organized detector composed by five main slabs. Four of these will be briefly described here while the most interesting for this thesis purpose, the muon spectrometer, will be discussed in next section.

1. The tracker system:

This is the inner part of the detector. It consists of three layers of silicon pixel detectors in the barrel near the interaction point covering a detection region up to $|\eta| = 2.5$. Furthermore, in the outer region, either in the barrel and the end-caps are placed ten layers of silicon strips detectors. The overall system is needed in order to measure the bending angle of the charged particles in magnetic field, i.e. their momenta, and the reconstruction of primaries and secondary vertices. Silicon detectors were chosen due to their radiation hardness and high spatial resolution since in this region the particle density is very high. The overall system consists of about 66 millions of pixels and 10 millions of strips.[6]

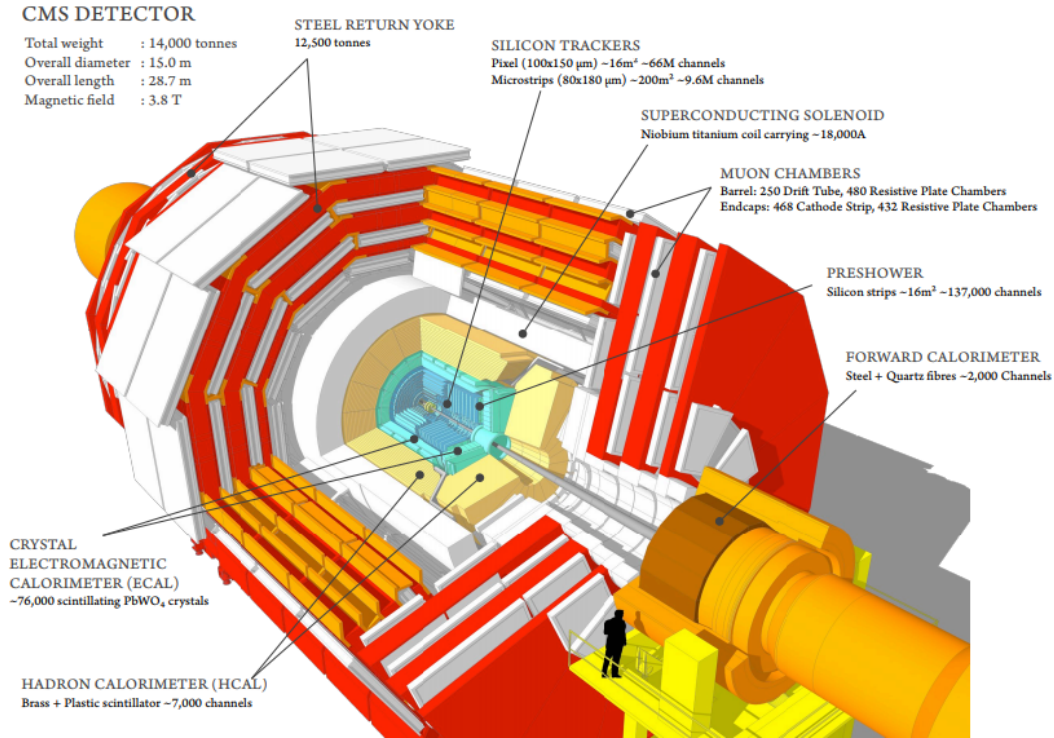


Figure 1.5: Cutaway view of the CMS detector. [5]

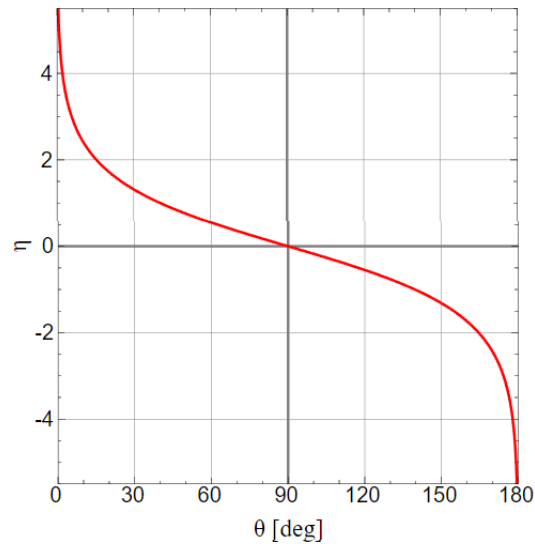


Figure 1.6: A plot of polar angle vs. pseudorapidity.

2. The electromagnetic calorimeter (ECAL):

This calorimeter consists of more than 61000 $PbWO_4$ scintillating crystals in the barrel and 15000 in the end-caps, covering a pseudorapidity region up to $|\eta| = 3$. The purpose of this detector is to induce photons and electrons to EM-shower in the crystals and then measuring their energy loss. The scintillation light is collected by photo-diodes in the barrel region while in the end-caps photo-triodes are used due to their higher radiation hardness.[7]

3. The hadronic calorimeter (HCAL):

The HCAL consists of alternating layers of brass and about 70000 scintillators tiles read by hybrid photo-detectors (HPD). The system covers a detection region $|\eta| < 3$. There is also a forward section of the hadronic calorimeter placed in the very high η region; here different materials and technologies were used due to the very different particles environment. The HCAL complex has a depth more than $10 \lambda_{int}$. [8]

4. The superconducting magnet:

CMS exploit a superconducting solenoidal magnet where a current of about 20 kA flows, generating a magnetic field up to 4 T in the tracker system. As already said the magnetic field is essential to bend charged particles.

1.3.2 Muon System

Nowadays the reconstruction of muon track is a fundamental tool to identify interesting decay modes and discover new physics, then it is not surprising that one of the major CMS sub-system is the muon spectrometer. It is placed in the outer region, outside the magnet and the calorimeters. The overall system, in order to reach the maximum detection efficiency and resolution uses three different technologies of gaseous detectors which cover the detection region up to $|\eta| = 2.4$. These technologies (briefly described later) are: Drift Tubes (DT), Cathode Strip Chambers (CSC) and Resistive Plate Chambers (RPC).

In Figure 1.7 a longitudinal cross section view of the CMS subsystem is shown. "MB" label refers to Drift Tubes, "ME" to CSC detectors while "RE" and "RB" refers to RPC respectively in the end-cap region and in the barrel one. The number next to the label of the barrel detectors increases with the radial distance from the beam line. For the end-caps detector the first number increase with the longitudinal distance from the interaction point and the second with the radial distance.

The next dissertation is adapted from [9].

1. Drift Tubes (DT):

This system represents the main detection technology in the barrel region. This consists of several rectangular wire chambers in which the electric field is maintained uniform by a specific inner geometry, this in order to make the electron drift velocity constant in all the gas volume (see Figure 1.8). The interaction point is calculated by measuring the drift time of the secondary electron produced by the muon ionization. The spatial resolution can be of the order of $100 \mu m$ if several interaction points from several DTs detectors are combined. This technology permits DTs to have a detection efficiency not less

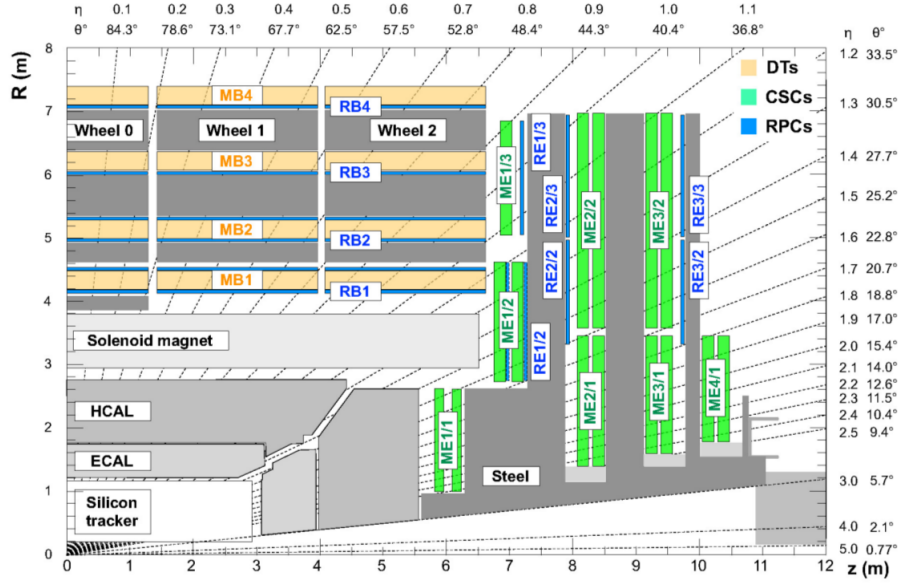


Figure 1.7: A quadrant of the CMS longitudinal cross section showing the actual muon systems.

than 95% for a time resolution of some nanoseconds, which allows the proper identification of the proton bunch crossing (BX) related to a certain muon.

250 of such detectors were mounted in the CMS barrel for about 200000 channel. They are filled with a gas mixture of Ar/CO_2 (85 : 15) and operate at a gas gain of 10^5 , this configuration provides a drift time of about 380 ns for 21 mm. Covering a pseudorapidity region up to $|\eta| = 1.3$, this subsystem is organized in five wheels each one divided in four concentric layers in order to veil all the ϕ coordinate.

The major limit of the DT technology is the sustainable particle rate, indeed an interaction rate higher than several tens of Hz will create too much spatial charge inside the gas volume distorting the uniformity of the electric field. Moreover the high intensity magnetic fields will ruin the space-time relationship since the electron will start to bend. DTs can be used then only in the barrel region because in the end-caps the particle rate is of the order of $10^2 - 10^3 Hz/cm^2$ and the magnetic field about 3 T.

2. Cathode Strip Chambers (CSC):

This technology serves the same aim of DTs but in the end-caps region. As shown in Figure 1.9, the design is the same as a multi-wire proportional chamber where the cathode is segmented into strips perpendicular to the wires direction. This configuration permits to exploit the cathode as a further detection layer. A single chamber provides the ionization position with a spatial resolution of about $75 \mu m$ with all the information from the wires and the strips. Time resolution of 6 ns permits the bunch crossing identification with a probability of 92%.

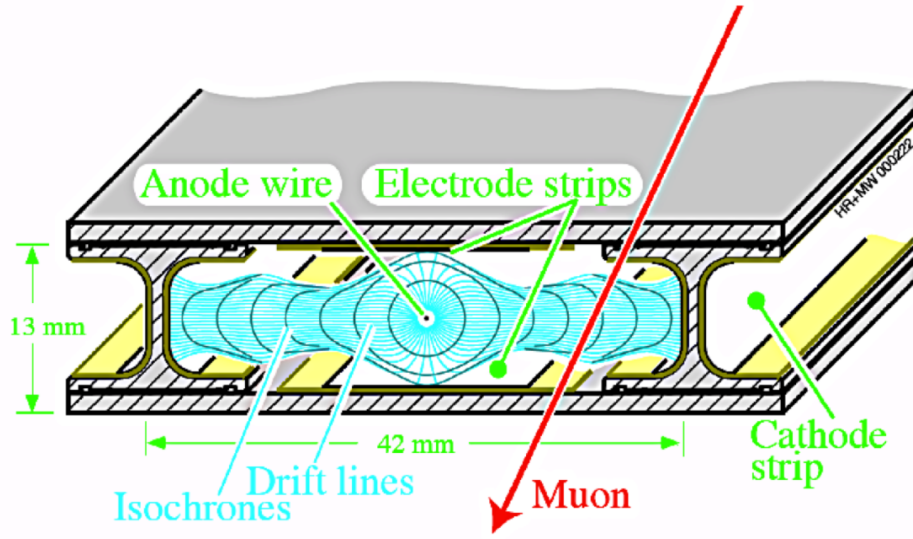


Figure 1.8: Schematic view of a CMS Drift Tube detection cell.

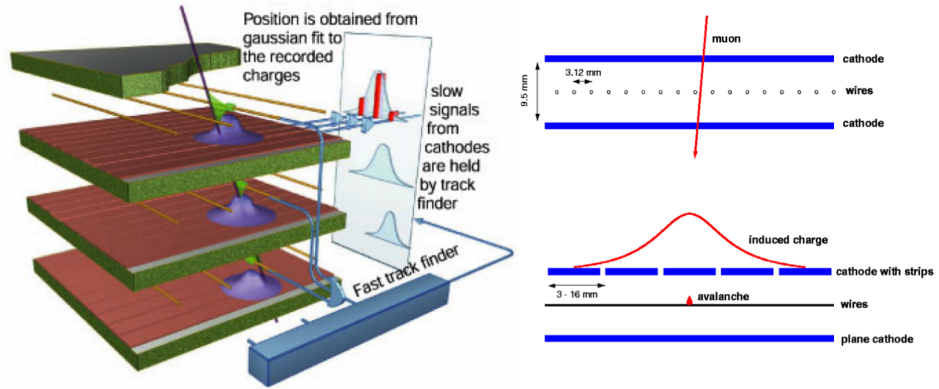


Figure 1.9: Schematic view of a CMS Cathode Strip Chamber. The signals from both electrodes are combined to recover the exact position of the muon hit.

The CSC system is made of 540 detectors organized in four stations per end-cap covering a detection range of $0.9 < \eta < 2.4$. CSCs operate at a gas gain of 7×10^4 in $Ar/CO_2/CF_4$ (50 : 40 : 10). CF_4 is added in order to reduce the aging of the wires and also to increase the drift velocity of the electrons since it will cause less diffusion of the latter and then a better spatial resolution.

3. Resistive Plate Chambers (RPC):

RPCs are present both in barrel and end-caps in order to ensure the redundancy of the muon hit and solve tracking ambiguities. A resistive plate chamber is constructed of two parallel plates of High Pressure Laminate (HPL), a material with high bulk resistivity. RPCs are very fast detectors with a time resolution of 1 ns , which make them very suitable for triggering issues. CMS mounts 360 RPCs detectors divided in four stations in the barrel and 252 detectors in four

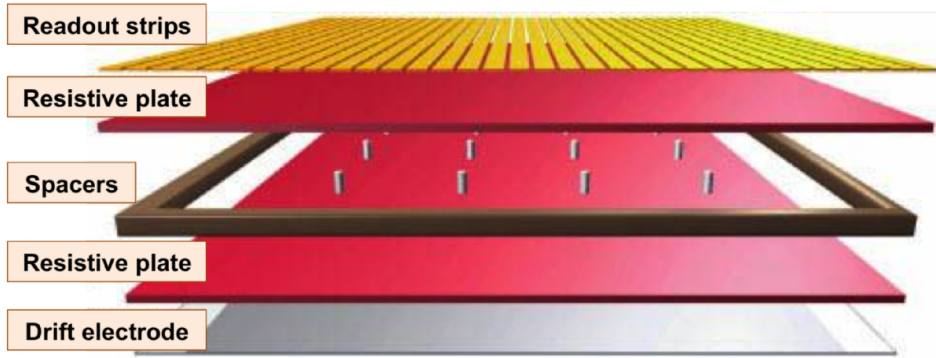


Figure 1.10: Schematic view of a CMS RPC detector.

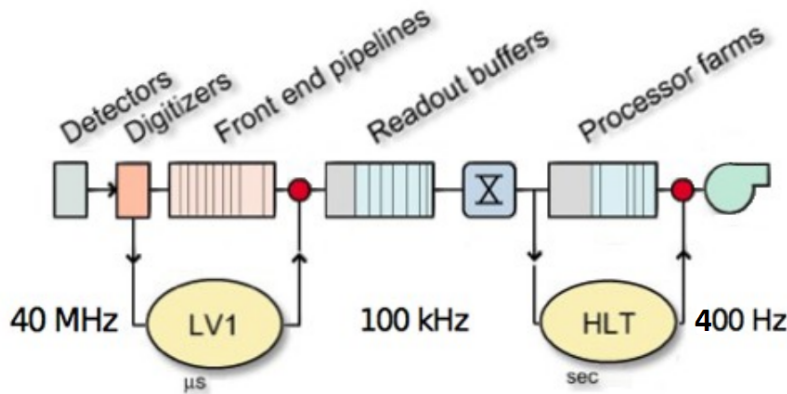


Figure 1.11: Structure of the trigger system of the CMS experiment.

station in each end-caps. These detectors work in avalanche mode with a gas mixture of $C_2H_2F_4/i - C_4H_{10} - SF_6$ (95.2 : 4.5 : 0.3).

Due to the high resistivity of the HPL, charging up effect will occur if the interaction rate is higher than 1 kHz/cm^2 . RPCs are then not suitable for high particle flow environments like the high η region of the end-cap; for this reason the RPCs extend their coverage only up to $|\eta| < 1.6$.

1.3.3 Trigger System

LHC provides a bunch crossing rate of 40 MHz , i.e. a collision each 25 ns . Since each collision produce about 1 Mb of data it is impossible to store all the events [10]. To solve this, a trigger system selects only the interesting event reducing the output rate. This structure is based on a two level trigger (as shown in Figure 1.11):

- **Level 1 (L1):**

This is a detectors level trigger which combines the informations from the calorimeters and the muon system (see Figure 1.12). Best candidates are compared to p_T and E_T threshold and then accepted or rejected. Tracker informations are not included because of the too many channels which will slow down the triggering process.

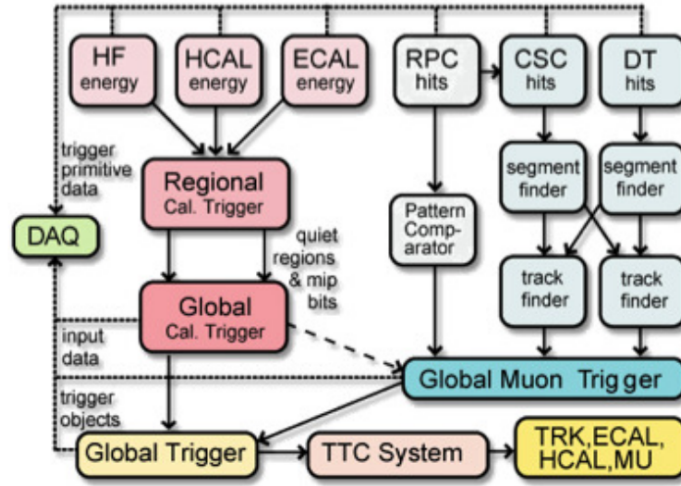


Figure 1.12: Overview of the current architecture of the L1 trigger system [11].

The aim of L1 is to reduce the event rate from 40 MHz to 100 kHz and it has not more than $3.2\text{ }\mu\text{s}$ to make a decision.

- **High Level Trigger (HLT):**

This trigger is a complex software algorithm which select events candidates on the base of the event topology defined by the interested physics. It runs on a processor farm and reduces the event rate to an average of 400 Hz [12].

After these two selection procedures data are stored on magnetic tape and subsequently shared with the entire CMS community which will perform a fine analysis of the raw data.

1.4 CMS Upgrades

As LHC will improve itself, the CMS experiment has to perform detector upgrades to better exploit the LHC performance and sustain the higher luminosity foreseen for the next years.

1.4.1 Phase 1 Upgrades

Most of the following upgrades are already completed or will be finished during LS2:

- *Tracker:* Pixel detectors will be replaced and the front-end electronics will be improved in order to maintain the maximum tracking efficiency.
- *Calorimeters:* In HCAL the photo-detectors will be substituted with silicon photo-multiplier. These will improve the light detection by increasing the efficiency, the signal-to-noise ratio. They are also immune to magnetic fields.
- *Muon systems:* The CSC system was arranged with a fourth layer of detectors and an extension of the RPC system. During LS1 The ME4/2 station was mounted and the RPC detection coverage was extended up to $|\eta| = 1.6$.

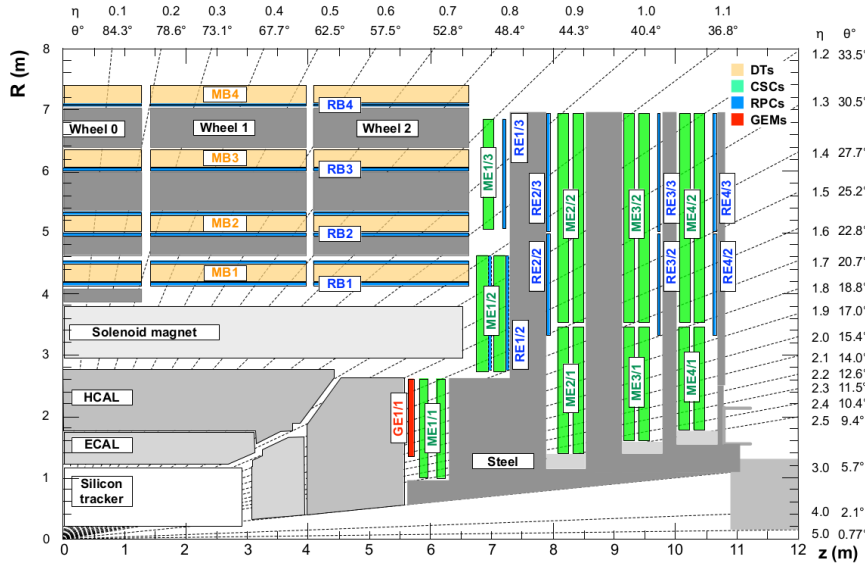


Figure 1.13: A quadrant of the CMS longitudinal cross section showing the foreseen system for Phase 1.

The main upgrade will be the installation of the first station of GEM-based detectors named GE1/1; this will take place during LS2. It consists of positioning 36 GEM based detectors in each of CMS end-caps covering the pseudorapidity region $1.6 < |\eta| < 2.15$, enhancing the redundancy of the muon hits in this region. Also it will permit to largely reduce the fraction of soft muons with overestimated momentum and the trigger rate for a given p_T threshold, while maintaining a high trigger efficiency. All the work done to characterize and validate this technology can be found in [13].

The detector system foreseen for Phase 1 is shown in Figure 1.13.

Not only the detectors system are improved, for example in the field of data acquisition a lot of work is done to increase the bandwidth for the data collection and transfer. Also the upgrades in the beam monitoring system permits to better measures the beam background and the luminosity.

A detailed explanation of the phase 1 upgrade can be found in [14]

1.4.2 Phase 2 Upgrades

In a similar way many upgrades are foreseen for LHC Phase 2:

- *Tracker*: The entire tracking system will be replaced in order to overcome the radiation damages, furthermore the granularity of the detector will increase by a factor ~ 4 . One more layer of detectors in the end-caps will improve the redundancy and the total coverage increases up to $|\eta| = 4$. During all Phase 2 tracker will participate to L1 trigger in order to ensure the required rate reduction.

- *Calorimeters:* A High Granularity Calorimeter (HGCAL) will replace the end-caps system and will include both EM and hadronic components, in particular it will alternate metallic absorber (W/Cu for EM part and $CuZn/Cu$ for the hadronic one) and silicon sensors.
- *Muon systems:* New detectors based on the RPC technology called iRPC will be installed, increasing the detection coverage up to $|\eta| = 2.4$, the projects names are RE3/1 and RE4/1. Other two GEM-based projects will be installed during LS2: GE2/1 and ME0, they will be discussed in the next two sections.

As the previous upgrades, a big effort will be done to improve or replace the readout electronics, the data acquisition systems and the beam monitoring. Technical details can be found at [16]

1.5 GEM Based Upgrades

GEM (Gas Electron Multiplier) detectors are Micro Pattern Gaseous Detectors (MPGD) based on electron avalanche multiplication which occurs in gases when an electric field is applied. In particular, the structure of triple-GEM detectors is composed of three overlapping polymer foils ($50 \mu m$ thick) with $5 \mu m$ copper clad on both surfaces. The GEM foils present a regular pattern of holes, chemically etched along the surface in a controlled and uniform way obtaining about $5000 \text{ holes}/cm^2$. The inner space (holes and gaps between foils) is filled with an appropriate gas mixture (typically Ar/CO_2 70/30) that is ionized when radiation passes through it, producing primary electrons. If a voltage is applied between the foils, the electric field causes electrons to drift downwards in the gaps between foils and avalanche multiplication in the holes. Gains of the order of some 10^4 can be reached. The multiplied charge induces a signal on some electrodes that are usually shaped into strips or pads to make the detector position-sensitive and is finally read out by sensitive electronics [28]. Such detectors are sensitive to ionizing particles that can enter the detector and cause a reasonable amount of primary electrons in the gas and with the use of strips or pads readout, they are capable to identify where primary ionization happened in the 2-D plane.

1.5.1 GE2/1 Project

This new detector system consists of positioning 18 "super-chamber" per end-caps in the region $1.6 < |\eta| < 2.4$. Each super-chamber is composed of two triple-GEM layer of trapezoidal shape, covering 20° in ϕ , as shown in Figure 1.15.

Each GE2/1 chamber covers an area of $1.45 m^2$ for a total active area of $105 m^2$. Every chamber is segmented in four modules in R each containing 12 sectors and each sector is read by 128 radial strips. This means that each chamber has about six thousand strips, their pitch can vary from $0.5 mm$ to $1.2 mm$. The nominal voltage is around $3200 V$ that means an effective gas gain of $1 - 2 \times 10^4$. The expected spatial resolution varies, from inner to outer radius, from $200 \mu m$ to $410 \mu m$.

Each sector of every chamber is read out by the front-end ASIC chip. This chip consists of 128 channel each containing a charge sensitive preamplifier, a shaper and a constant fraction discriminator; resulting in a time resolution, with the detector,

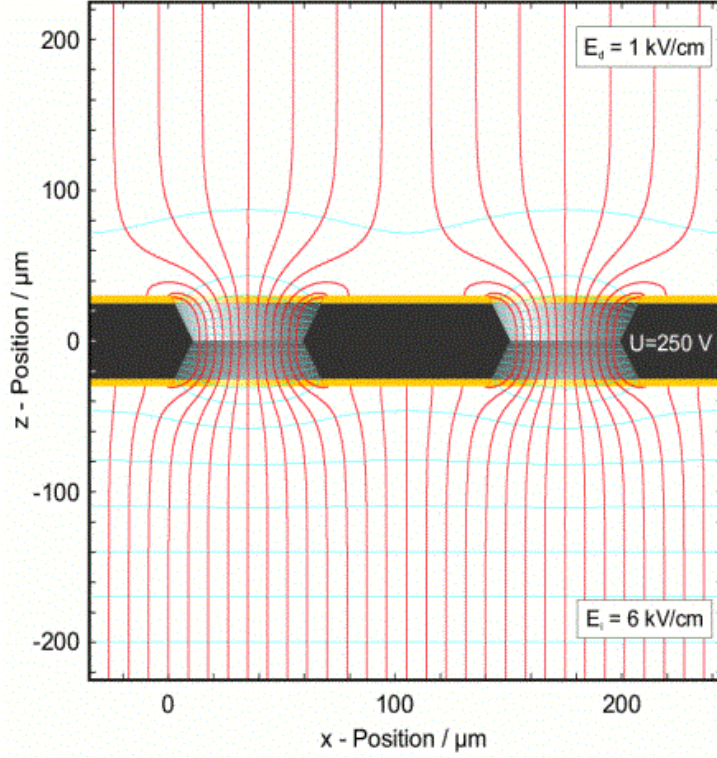


Figure 1.14: Traversal view of a GEM foil. Lines represent the equipotential surfaces.

of 7.5 ns . The connection with the off-detector electronics is provided by an Opto-Hybrid board (OH), which contains a Transceiver (GBT), an FPGA and the optical receiver and transmitter.

Motivation

GE2/1 will add an additional detection layer which covers the pseudorapidity region up to $|\eta| = 2.4$, previously only covered by CSC chambers. In the region covered also by GE1/1 the number of hit for a traversing muon will increase at eight.

The main advantages provided by GE2/1 project are:

- In order to estimate the momentum of a muon at L1 trigger level, a precise measurement of the the position of the track segments in the CSCs are required. Adding a layer of GEM chamber will increase the local lever arm for the segment reconstruction by more than a factor two with respect to the CSC system only. Furthermore, due to the lack of iron yoke between GE2/1 and ME2/1, multiple scattering is negligible. This combination of GEM and CSC can give a good measurement of the muon direction within a single station. This better estimation will provide a less fraction of soft muons with overestimated momentum, resulting in a trigger rate reducing for a fixed p_T threshold.
- The enhanced redundancy provided by GE2/1 will increase the robustness of the track reconstruction already at the L1 trigger level.

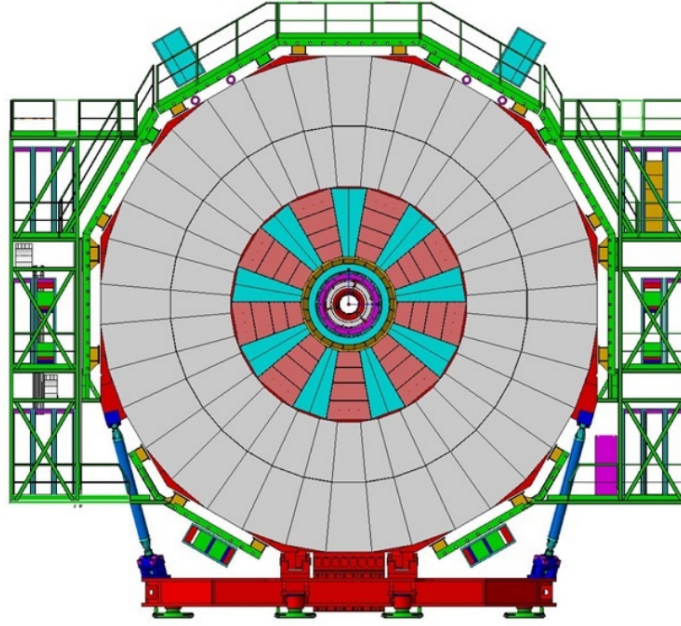


Figure 1.15: Location of the 18 GE2/1 detectors (blue and red) on the back of the yoke disks $YE\pm 1$. The two chambers of neighbouring super chambers overlap in ϕ , to avoid acceptance holes. [15]

- Also in the case of displaced vertices for which the vertex constrain cannot be exploit, an additional lever arm can be useful. The muon stations in the end-caps can provide a standalone muon momentum reconstruction already at L1 trigger level.

1.5.2 ME0 Project

This detector system consists of positioning 18 modules per end-caps, each of them made of 6 layers of triple-GEM detectors of trapezoidal shape, thus a total of 216 chambers are needed. The station will be installed behind the new HGCAL calorimeter exploiting the space freed by this upgrade.

The covered region extends from $|\eta| = 2$ to $|\eta| = 2.8$, which is the maximum possible range due to mechanical constrain. This increases the total acceptance of the muon spectrometer. The system will overlap with the exiting CSCs systems and with the new RPCs stations (up to $|\eta| = 2.4$).

The total active area of ME0 upgrade is 105 m^2 . The segmentation of a single chamber layer is 8 rings in η and 3 sectors in ϕ , each of the latter subdivided into 128 radial strips. The construction details are the same of the GE2/1 chambers, while the spatial resolution is more accurate: $160 \text{ }\mu\text{m}$ in the inner radius and $390 \text{ }\mu\text{m}$ in the outer one.

The electronics readout and the data transfer and communication systems will be the same as the GE2/1 station.

Muon subsystem	GE1/1	GE2/1	ME0
$ \eta $ range	1.6-2.15	1.6-2.4	2.0-2.8
Number of chambers	144	72	216
Number of channels	442368	442368	663552
Numbers of layers	2	2	6
Total surface area	54 m^2	105 m^2	64 m^2
Spatial resolution	$200\text{-}340 \text{ }\mu\text{m}$	$200\text{-}410 \text{ }\mu\text{m}$	$160\text{-}390 \text{ }\mu\text{m}$
Time resolution	8 ns	8 ns	8 ns

Table 1.2: Resume of the main parameters for the GEM-based detectors upgrades foreseen in the next years.

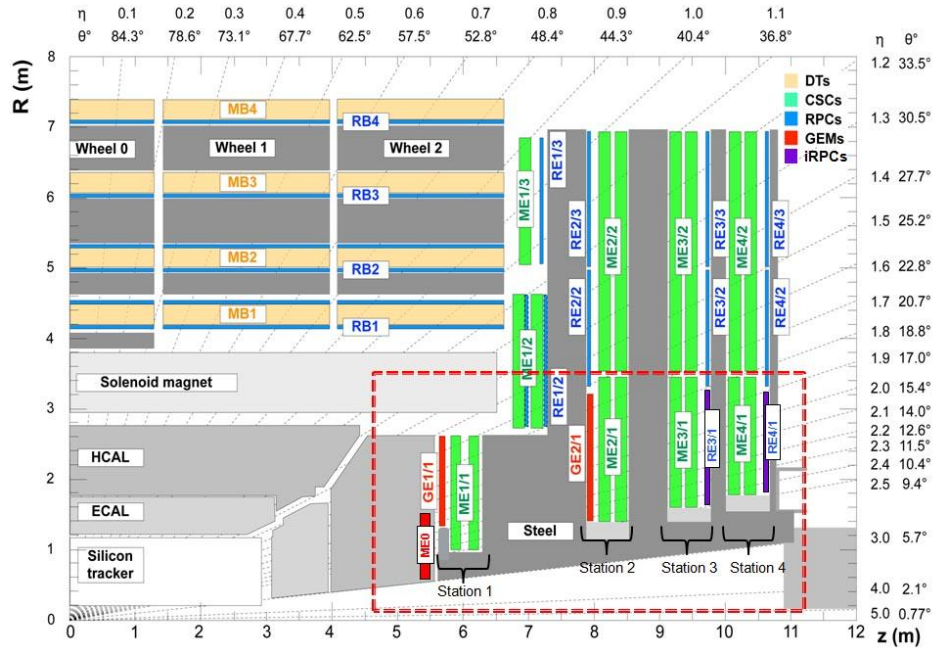


Figure 1.17: A quadrant of the CMS longitudinal cross section showing the foreseen system for Phase 2.

Chapter 2

Overview on gaseous detectors

In this chapter the basic information about particles detection with specific interest in gaseous detectors are presented. Since the aim of this thesis is to study the triple-GEM technology for the CMS muon end-caps upgrade, the focus is on the physical processes at work in CMS end-caps or during the R&D activities in laboratory. In the second part of the chapter, a brief historical review about gaseous detectors and their operating principles will be given, with a particular attention to the Triple-GEM technology.

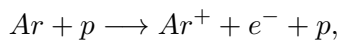
2.1 Particles interaction with matter

All the informations and the Figures presented here are adapted from [2], [13], [17], [18], [22] and [23].

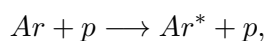
2.1.1 Charged particles

When passing through the matter a charged particle can interact via EM, strong or weak force. Weak interaction is negligible for most of the particles (except for neutrinos which it is the only possible interaction); while strong interaction has a very low cross section since the nucleus sections are a factor 10^{10} lower the the atomic ones. The electromagnetic interaction is the most probable process that occurs when a charged particle pass through any materials.

An heavy charged particle (with mass much greater than the electron mass) crossing a material layer, interacts with electrons transferring to them part of its energy. One energy releasing mechanism is the *ionization*:



an impinging particle p will yield a sufficient energy to an atomic electron (Argon atom in this example) in order to create a couple ion-electron. The typical cross section of this interaction in gaseous mediums is of the order of 10^{-16} cm^2 [19]. Also *excitation* of the target atoms could occur:



this happens only if the correct energy amount is released. The atom will de-excite

after some time releasing a photon. Since these are resonance processes their cross section is negligible if the deposited energy is not very similar to the excitation energy. In resonant case the cross section can reach 10^{-17} cm^2 in noble gases [19]. However, since the ionization processes have an energy threshold relatively high and low energy deposit are more probable, the excitations processes will dominate in gaseous medium [18].

The average energy deposited per unit length by a heavy charged particle is well approximated by the Bethe-Block formula:

$$-\left\langle \frac{dE}{\rho dx} \right\rangle = \frac{2\pi e^4 z^2}{m_e c^2 \beta^2} N Z \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_m}{I^2} \right) - 2\beta^2 - \delta(\beta\gamma) \right], \quad (2.1)$$

where m_e is the electron mass, ze the particle charge and N and Z the atomic density and the atomic number respectively. I refers to the mean ionization and excitation potential of the medium while T_m stands for the maximum transferable energy for a single interaction:

$$T_m = \frac{2m_e c^2 \beta^2}{1 - \beta^2}.$$

Equation 2.1 is valid approximately in the range $0.1 < \beta\gamma < 1000$. For $\beta\gamma > 4$ a relativistic rise of the stopping power can be observed. However, since the particle polarize the atoms along its path, the electrons far from the path are shielded. Here the Fermi density correction $\delta(\beta\gamma)$ arises in order to take care of this effect. Bethe-Block formula is not valid under $\beta\gamma = 0.1$ because the assumption of electrons at rest is no longer valid; indeed the electron speed become comparable to the classical orbital speed allowing the electron capture processes. Other corrections are needed in order to describe the low energy range such as shell correction, Barkas correction and Bloch correction.

At very high energy (approximately $\beta\gamma = 10^4$ for muons) radiative losses become the major energy loss factor: processes as Bremsstrahlung and Cherenkov effect contribute to the rise of the mass stopping power at high energies.

Typical muons to be detected in CMS end-caps has a average energy loss close to the minimum and then constant for the major part of their paths. Particles with such of this behaviour are called *Minimum Ionizing Particles (MIP)*. The typical behaviour of the mass stopping power of a positive muon in copper is shown in Figure 2.1.

Triple GEM detectors operating in the CMS end-caps will use Ar/CO_2 (70/30) mixture. It is possible to estimate the mean energy per unit path released by a muon (MIP case) in this mixture and the average energy released in the 3 mm conversion gap typical of the GEM detectors. A good estimation for the gas mixture stopping power can be found using the *Bragg's Rule*:

$$\left\langle \frac{dE}{dx} \right\rangle_{Ar/CO_2} = \rho_{mix} \left[0.7 \left\langle \frac{dE}{\rho dx} \right\rangle_{Ar} + 0.3 \left\langle \frac{dE}{\rho dx} \right\rangle_{CO_2} \right] = 2.76 \text{ keV/cm}, \quad (2.2)$$

where:

$$\rho_{mix} = 0.7\rho_{Ar} + 0.3\rho_{CO_2} = 1.716 \times 10^{-3} \text{ g/cm}^3.$$

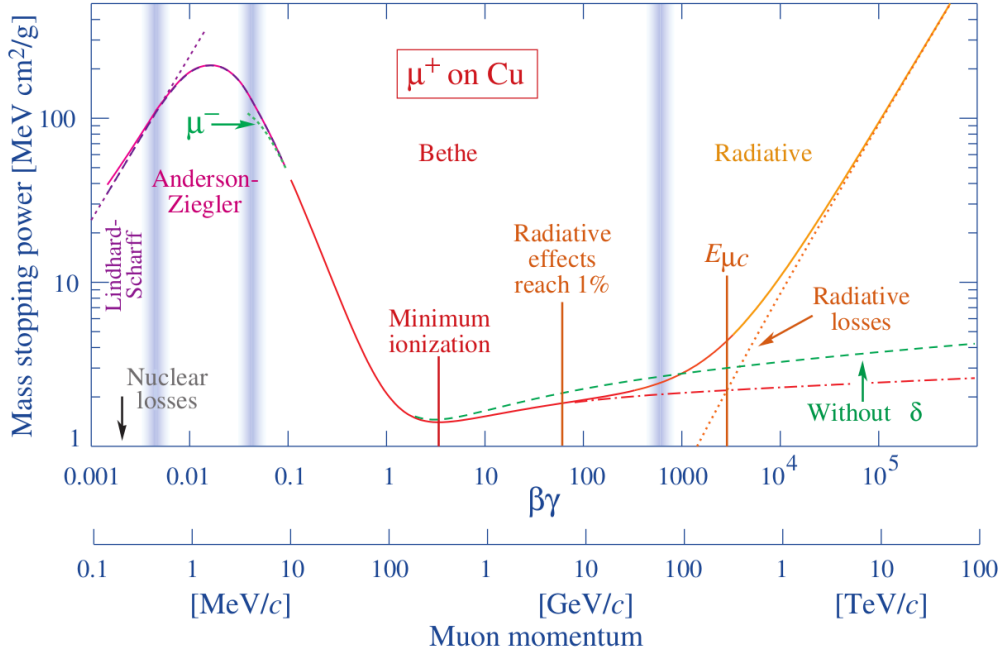


Figure 2.1: Stopping power for positive muons in *Cu* as a function of $\beta\gamma$. Solid lines represents the total stopping power. [2]

Element	ρ [g/cm^3]	$\left\langle \frac{dE}{\rho dx} \right\rangle$ [$MeV cm^2/g$]
Argon <i>Ar</i>	1.662×10^{-3}	1.519
Carbon Dioxide <i>CO</i> ₂	1.842×10^{-3}	1.819

Table 2.1: Density and minimum stopping power used for calculations. Gases are evaluated at one atmosphere and 20°C [20].

Using Equation 2.2, the average energy deposited by a muon in the 3 mm drift gap of a GEM detector is:

$$\langle E \rangle = \left\langle \frac{dE}{dx} \right\rangle_{Ar/CO_2} 0.3 \text{ cm} = 828 \text{ eV}. \quad (2.3)$$

Summary on the used data is show in 2.1.

The energy loss estimated is an average value, indeed the ionization of gas atoms is a stochastic process subjected to fluctuations. The distribution of the deposited energy is Gaussian if the absorber is thick, i.e. if the number of single interactions is sufficiently high to satisfy the *Central Limit Theorem (CLT)*. In GEM detectors case the active layer is very thin (3 mm), for this reason the hypothesis of the CLT are not satisfied. The energy loss distribution is described by the Landau-Vavilov distribution:

$$f_{L-V}(\Delta, \beta\gamma, x) = \phi(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}, \quad (2.4)$$

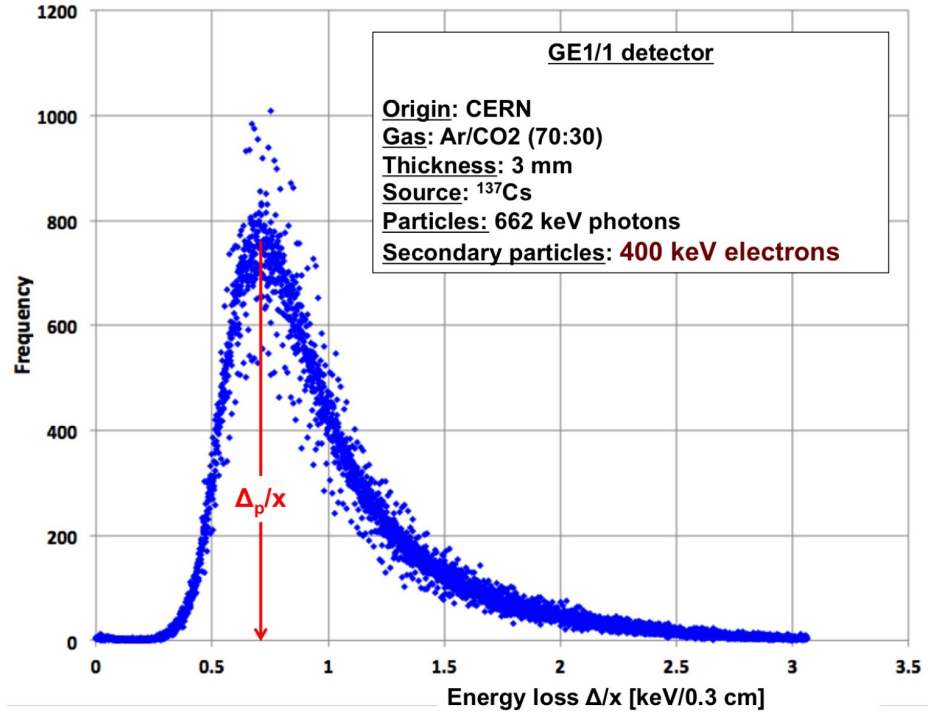


Figure 2.2: Energy distribution of 400 keV electrons in a GEM detector. The electrons are produced from Compton scattering of 662 keV photons with copper in front of the gas volume.^[13]

where x is the tightness of the medium. The variable λ indicates the difference between the energy loss Δ and the most probable energy loss Δ_p :

$$\lambda = \frac{\Delta - \Delta_p}{\xi},$$

where:

$$\xi = \frac{2\pi e^4 z^2}{m_e c^2 \beta^2} N Z x.$$

The most probable energy can be written:

$$\Delta_p/x = \xi \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} + \ln \frac{\xi}{I} + 0.2 - \beta^2 - \delta(\beta\gamma) \right]. \quad (2.5)$$

A practical example of this distribution can be found in Figure 2.2.

Is is also possible to estimate the average number of electrons-ions pair generated n_p by an incoming particle:

$$n_p = \frac{\langle E \rangle}{W},$$

where $\langle E \rangle$ is the mean deposited energy and W is the average energy needed in order to produce a pair. W is greater than the average ionization and excitation potential I , because some of the deposited energy in the gas volume can be lost in energy transfer or can be absorbed in non radiative process such as excitation of

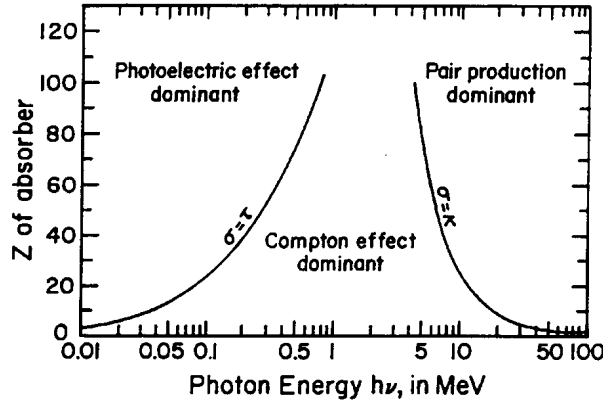


Figure 2.3: Relative importance of the three main photons interaction processes with matter, solid curves show the point for which the interactions have the same cross section [22].

vibrational or rotational energy levels. Following a process similar to the one used in 2.2 it is possible to estimate the mean electron-ion pairs produced by a MIP in the active layer of a typical GEM detector:

$$n_p = \langle E \rangle \left[\frac{0.7}{W_{Ar}} + \frac{0.3}{W_{CO_2}} \right] \simeq 30 \text{ pairs.} \quad (2.6)$$

$\langle E \rangle$ comes from Equation 2.3 while $W_{Ar} = 25.5 \text{ eV}$ and $W_{CO_2} = 32.6 \text{ eV}$ from [21].

2.1.2 Photons

Photons don't have any intrinsic charge, for this reason the previous discussion can not be applied to them. Considering photons with energy higher than some tens of keV their interactions with the matter are:

- Photoelectric effect,
- Compton or incoherent scattering,
- Pair production,
- Rayleigh or coherent scattering,
- Photo-nuclear interaction,

and will be discussed in the next sections except for Rayleigh and photo-nuclear interaction since there is no interest for this treatment. It is important to notice that the interaction type strongly depends on the energy of the photon and on the material (its atomic number Z). A brief resume is shown in Figure 2.3.

Let's suppose to treat with a mono-energetic beam composed by N_p number of photons incidents on an infinitesimal layer dx of material with section Σ . Let's also assume that, when a photon interact, it will disappear from the initial beam. In this configuration the number of lost photons dN_p is :

$$dN_p = -N_i, \quad (2.7)$$

where N_i is the number of photon interactions in the layer dx . This quantity can be expressed:

$$N_i = pN_pN_b, \quad (2.8)$$

where p is the interaction probability of a photon on a single target atom, while N_b is the number of target atoms. They can be respectively written as:

$$p = \frac{\sigma_a}{\Sigma}; \quad N_b = ndV = \rho \frac{N_A}{A} \Sigma dx \quad (2.9)$$

where σ_a is the atomic cross section, n the atomic density of the target material, $dV = \Sigma dx$, N_A the Avogadro number, A the mass number of the target and ρ its density.

Concluding, using Equations 2.7, 2.8 and 2.9, that:

$$dN_p = -N_p \sigma \rho \frac{N_A}{A} dx,$$

and:

$$N_p(x) = N_p e^{-\frac{\mu}{\rho} \rho x}. \quad (2.10)$$

Where $\frac{\mu}{\rho}$ is the *mass attenuation coefficient* defined as:

$$\frac{\mu}{\rho} := \sigma \frac{N_A}{A},$$

Finally, since the beam intensity I is proportional to the number of photons N contained in it, using 2.10:

$$I(x) = I_0 e^{-\frac{\mu}{\rho} \rho x}. \quad (2.11)$$

It is important to notice that this description is valid if the number of photons (a discrete quantity) can be approximated to a continuous quantity, i.e. if this number is very large. This is a well satisfied hypothesis in almost all the cases.

The total mass attenuation coefficient (proportional to the total atomic cross section) can be written as sum of the single interactions ones:

$$\left. \frac{\mu}{\rho} \right|_{tot} = \left. \frac{\mu}{\rho} \right|_{photoelectric} + \left. \frac{\mu}{\rho} \right|_{Compton} + \left. \frac{\mu}{\rho} \right|_{pair},$$

the other processes have been neglected because they are not of interest. Figure 2.4 shows the main contributions to the total mass attenuation coefficient in the gas mixture $Ar/CO_2(70/30)$.

Photoelectric effect

In the photoelectric interaction the whole energy of a photon is spent to remove an electron from an atomic shell. This can happen only if the electron has energy E_γ

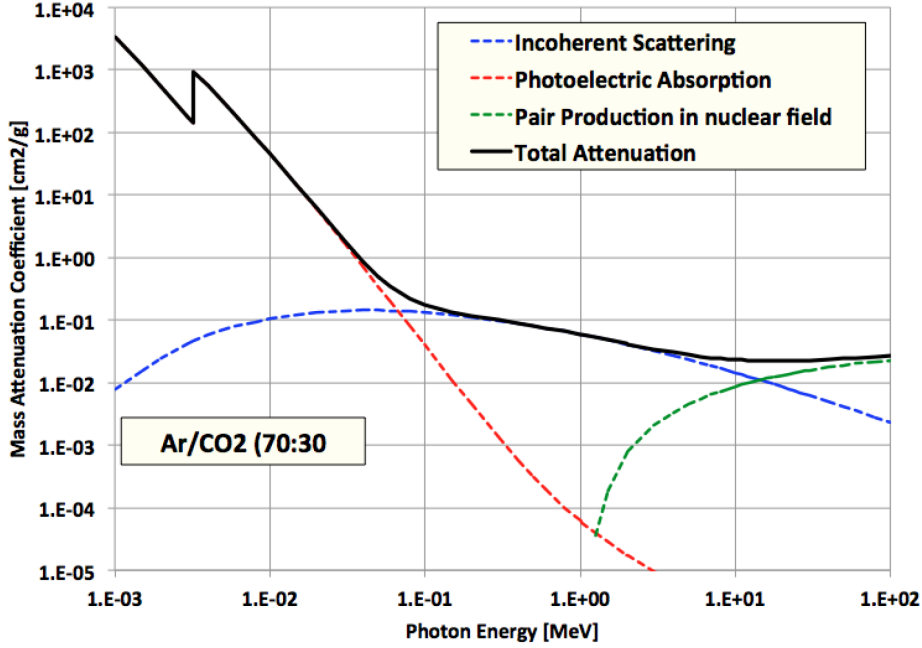


Figure 2.4: Total and partial mass attenuation coefficient in $Ar/CO_2(70/30)$ [24]

higher than the electron binding energy E_i . This effect is more probable when the incident photon has the same energy of the shell and it decreases when the photon energy increases.

The outgoing photoelectron has energy $E_e = E_\gamma - E_i$; this because the recoil of the atom can be always neglected due to its bigger mass. After the emission of a photoelectron the atom is in an excited state and it can return to its ground state by filling the shell vacant seat. This can happen in two different ways:

- By Auger process. The shell vacancy will be filled by an electron from the upper shell and the energy difference is transferred to the even upper electronic shell, releasing one of its electron. For example a vacancy in the K-shell may be filled by a L-shell electron transferring its energy to a M-shell electron, ejecting it. This electron is called Auger electron and its energy will be:

$$E_{Auger} = E_K - E_L - E_M.$$

- By fluorescence. The vacancy of a shell is filled by an electron from the outer shell. This result in an emission of a photon with an energy equal to the difference of the binding energies of the two atomic shells.

Argon based gas mixtures can release this secondary radiation if irradiated with photons. Table 2.2 shows the most important characteristic X-ray line energies for Argon; the weighted average of these transition energies is $\langle E \rangle_{esc} = 2.997 \text{ keV}$

Other Argon transition lines and carbon dioxide ones are not of interest since they all have energy below 300 eV [25] [27].

Shell Transition	KM_{III}	KM_{II}	KL_{III}	KL_{II}
Relative Intensity	~ 0.2	~ 0.1	1	0.5
Energy(KeV)	3.190	3.190	2.958	2.956

Table 2.2: Most energetic characteristic X-ray line energies for Argon. The intensity is normalized to the higher emitting transition [25].

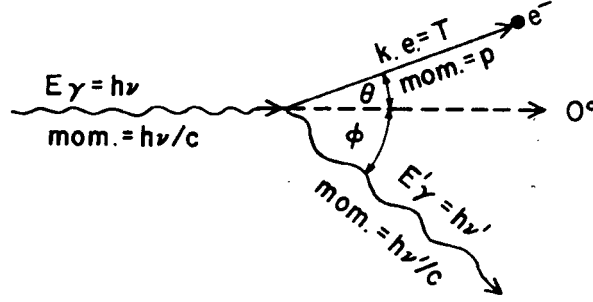


Figure 2.5: Compton effect kinematics [22].

Compton effect

Compton effect is a photon-electron interaction. In this case the photon gives only a certain amount of its energy $h\nu$ to the electron, which recoils with a certain kinetic energy T_e at an angle θ . The outgoing photon has now a lower energy $h\nu'$ and its new direction forms an angle ϕ within the incident direction.

$$h\nu = T_e + h\nu',$$

By supposing the momentum conservation two relations are obtained in order to calculate the energy and the direction of the outgoing photon:

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_e c^2}(1 - \cos\phi)}, \quad (2.12)$$

$$\tan\theta = \frac{1}{(1 + \frac{h\nu}{m_e c^2})\tan\frac{\phi}{2}}. \quad (2.13)$$

Klein and Nishina have used the relativist theory of Dirac to evaluate the differential cross section of the Compton interaction [26]:

$$\frac{d\sigma}{d\Omega} = Zr_e^2 \left(\frac{1}{1 + \alpha(1 - \cos\phi)} \right) \left(\frac{1 + \cos^2\phi}{2} \right) \left(1 + \frac{\alpha(1 - \cos\phi)^2}{(1 + \cos^2\phi)[1 + \alpha(1 - \cos\phi)]} \right), \quad (2.14)$$

where $\alpha = \frac{h\nu}{m_e c^2}$.

A graphics example of the angular distribution of the outgoing photon is shown in Figure 2.6.

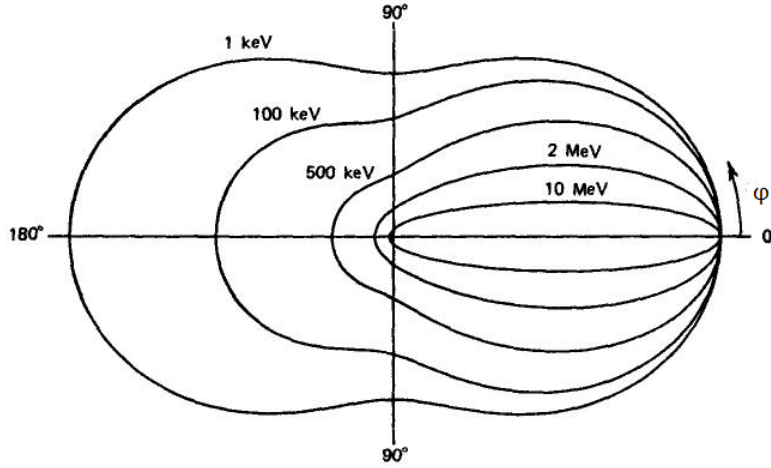


Figure 2.6: A polar plot of the number of photons (incident from the left) Compton scattered into a unit solid angle at the scattering angle ϕ . The curves are shown for the indicated initial energies [17].

Pair production

Pair production is a quantistic effect that happens when an incident photon interacts with a virtual photon. This interaction can lead to the creation of a particle-antiparticle pair; in particular the most probable and less energy expensive is the electron-positron couple. For this reason, in order to produce a pair, the incident photon must have at least the same energy as the rest energy of the two particles (1.022 MeV in e^+e^- case) * The average energy of a pair element is:

$$\langle T \rangle = \frac{h\nu - 1.022 \text{ MeV}}{2}.$$

The exact analytic form for the cross section of pair production must be calculated through quantum electrodynamics in the form of Feynman diagrams. The cross section can be written as:

$$\kappa_a = \alpha r_e^2 Z^2 P(E, Z), \quad (2.15)$$

where α is the fine structure constant, r_e is the classical electron radius, Z is the atomic number of the material and $P(E, Z)$ is some complex function that depends on the energy and atomic number.

2.1.3 Neutrons

Like photons, neutrons are uncharged particles and they are not susceptible to Coulombian force. They can interact only via strong force, i.e. only interacting with nuclei. Therefore it is very difficult to detect a neutron, in particular with a gas detector. However, it is possible to detect the secondary emission due to a previous neutron interaction; this is eased by inserting in the gas volume a neutron sensitive

*This is valid only in nuclear fields pair productions; when they are created in the electron field the threshold is higher due to the electron recoil.

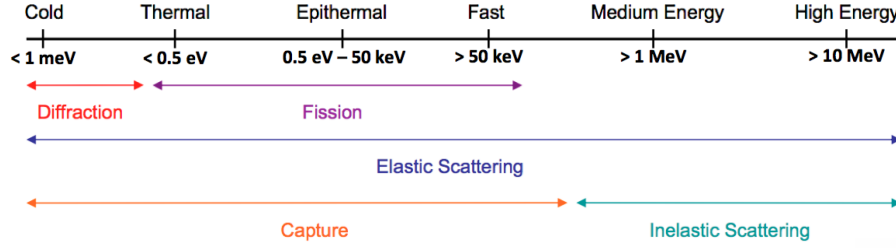


Figure 2.7: Classification of free neutrons with the most probable type of interaction with matter.

material (like ${}^3\text{He}$). There are five main interactions between neutron and the matter depending on their energy, as shown in Figure 2.7.

- Neutron-induced fission occurs mostly at relatively low energies and only with some types of target elements. The target nucleus is split into two, or more, smaller nuclei and releases a lot of energy in the form of neutrons, photons and other particles.
- The elastic scattering between neutrons and nuclei is mainly responsible of the slowing down of neutrons. This interaction leads the neutron to change their trajectories and lose energy, while the nucleus recoils remains in the ground state. The elastic scattering is also called neutron moderation and it is the dominant process for intermediate and high energy neutrons.
- Some elements are susceptible to capture a neutron in their nuclei. When this happens a prompt photon is emitted and afterwards the unstable nucleus will eject a proton (n, p) or an alpha particle (n, α) in order to return in its ground state.
- At high energies the main interaction is the inelastic scattering with the medium $A(n, n')A^*$. The neutron loses a sizeable fraction of its energy leaving the target nucleus in an excited state. Secondary radiation will then be emitted.

2.2 Gaseous Detectors Operating Principles

2.2.1 Avalanche Multiplication

A simple gaseous detector can be imagined as a cathode and an anode plates immersed in a gas volume, then applying a certain voltage on the plates, an electric field will form. In gaseous medium, when the electric field is higher than few kV/cm , the primary electrons can acquire sufficient kinetic energy between two collisions to provoke the further excitation or ionization of the medium. The resulting secondary electrons will produce tertiary ionization and so on. This chain reaction, called avalanche, is responsible of the electron amplification in gaseous medium. The electrons *mean free path* λ in gases indicates the average distance that an electron can travel before being involved in an ionizing process. The inverse of this quantity is

called *First Townsend Coefficient* $\alpha = 1/\lambda$ and it is proportional to the probability to emit secondary electrons.

If there are n electrons in a certain point x , the number of secondary electrons produced in an avalanche in an infinitesimal path dx will be:

$$dn = n\alpha dx.$$

Integrating, the total number of electrons after an avalanche path x is obtained:

$$n(x) = n_0 e^{\alpha x},$$

where n_0 is the number of primary electrons. Now the multiplication factor, i.e. the gain G , can be written:

$$G := \frac{n(x)}{n_0} = e^{\alpha x}. \quad (2.16)$$

If the electric field in the avalanche is not uniform, the Townsend coefficient will be function of the distance x . In this case the gain between x_1 and x_2 will be:

$$G = \exp\left(\int_{x_1}^{x_2} \alpha(x) dx\right).$$

An expression of the Townsend coefficient is given by the Rose-Korff approximation [29]:

$$\alpha = C_1 P e^{-C_2/S},$$

where P is the gas pressure, $S = \frac{E}{P}$ the reduced electric field and C_1, C_2 two parameters to be evaluated experimentally.

Since the Townsend coefficient can be supposed to be proportional to the inverse of the gas density ρ [30] ; it is possible to write:

$$\alpha \propto \frac{1}{\rho} \propto \frac{T}{P}.$$

Then the gas gain as a function of the gas temperature and pressure is:

$$G\left(\frac{T}{P}\right) \simeq A e^{B \frac{T}{P}}, \quad (2.17)$$

where A and B are to be experimentally evaluated.

2.2.2 Operating Regimes

In order to understand the basic working principle of a gaseous detector, it is possible to think to a parallel plate detector. The physical processes and the signals produced by an incoming particle which ionizes the gas can be very different according to the different electric field applied to the electrodes. Four main operating modes can be distinguished. Figure 2.8 shows the relation between applied electric field and the collected charge on the electrode in the different regions of operation.

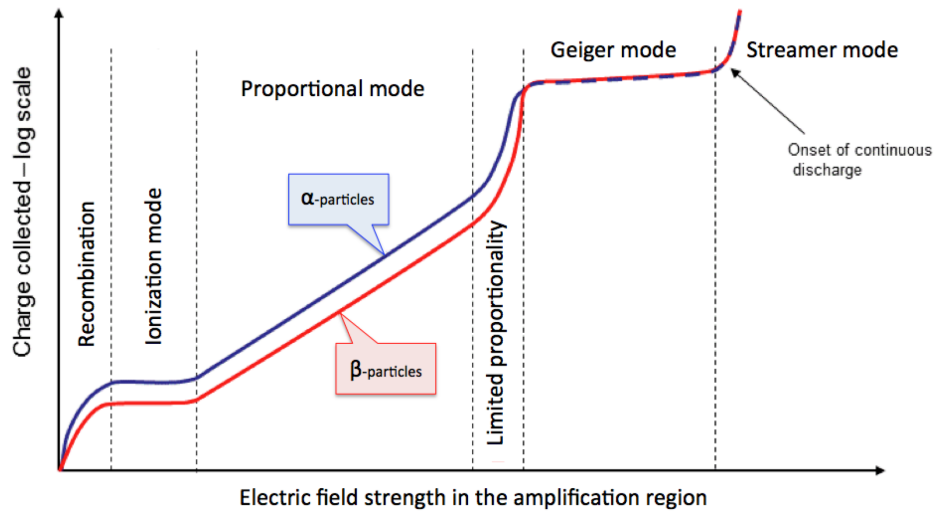


Figure 2.8: Gain-Voltage characteristic for gaseous detectors showing the different operating modes. The y axis refers to the collected charge in logarithmic scale.

Ionization Mode

The amount of electron-ion couples freed by an incoming particle depend on its energy, type and detecting medium. With a relatively low electric field the primary charge starts to drift following the field lines and the electrodes inducing an electronic signal; then it will be collected. Since in this operating mode there is no amplification of the charge, the signals will be relatively small and the particle are detectable only if they release a conspicuous amount of electrons-ions pairs. Also, part of the charge will be lost in ion-electron recombination and further by electron attachment of neutral molecules of the medium.

Proportional Mode

If the particles to be detected generate a too low signals to be detectable, there is the need to amplify the freed charge. At a certain threshold voltage, the average energy of the primary electrons become sufficient to ionize again the medium and then producing the avalanche. From the previous section it is clear that the multiplication factor, i.e. the gain, is constant for fixed medium, voltage and detector geometry (see Equation 2.16). This means that a linear proportionality between the deposited energy and the signal amplitude exists.

When the applied voltage increases, the amplification factor will increase too and more secondary charges are produced. At a certain field value the space charge, due to the heavy positive ions drifting through the electrode, will reduce the effective electric field resulting in a loss of proportionality.

Geiger-Muller Mode

When the amplification field is very high, the primary avalanche will provoke many secondary avalanches. Most of them are triggered by UV photons created by the excitation of electronic levels of the gas molecules or by the ions recombinations

on the electrodes surfaces. This chain reaction will affect all the gas volume until the process is stopped by the too much space charge or by a voltage drop. This operation regime is called Geiger-Muller mode. It is clear that, when a detector is working in this way, the signals are not carrying anymore informations about the particle deposited energy.

Streamer Mode

With even higher fields, the space charge produced in the avalanche become comparable with the charge density on the electrodes. This causes the focusing of the field lines against the avalanche region. The secondary avalanches are then forced to propagate on the same direction; this creates a thin plasma filament (also called streamer) in the gas volume. Like in the Geiger mode signals don't carry any information about the primary charge. In most of the gases this regime is reached when $\alpha x \sim 20$, this is called Reather limit.

2.2.3 Gas Mixtures

One of the most important decision when building a gaseous detector is to chose the correct gas mixture. Each experiment require different physical performances from the detector; they can be: high rate capability, high detector longevity, low discharge probability, good time or space resolution etc. This thesis will focus on the Ar/CO_2 mixture.

Noble gases are usually preferred to the polyatomic molecules in particle detection; this because they don't show too many de-excitation channels. Furthermore Argon is often used because of its acceptable number of electron-ion pairs per unit length for MIP and moreover because it is relatively cheap compared to heavier noble gas such as xenon or krypton. However, when excited, argon atoms return to their ground state by emitting a photon of about 11.6 eV which can induce secondary avalanches. Then, it appears necessary to add a "quenching" gas, i.e. a gas which could absorb the Argon de-excitation photons and then could dissipate the energy in non-radiate ways. CO_2 represents a good choice for this purpose: its photon cross section is relatively high in the argon emitting region and dissipates the energy through vibrational and rotational transitions.

Sometimes another type of gas, called "cold", is added to the mixture; these gases permit the electrons to have a bigger drift velocity and then causing lower diffusion. This will assure a better time and/or space resolution. One of this gases is CF_4 .

2.3 Historical Overview on Gaseous Detectors

At the beginning of the twentieth century, first concept of gaseous detector were introduces under the form of cylindrical tubes. However one of the major improvement was achieved by G.Charpak and his collaborators [32], developing one of the first electronically-readout detectors of the modern era: the Multi Wire Proportional Chamber (MWPC).

A MWPC consists of an anode wires plane between two cathode planes, see Figure 2.9. The typical distance between the wires is 2 mm while the spacing

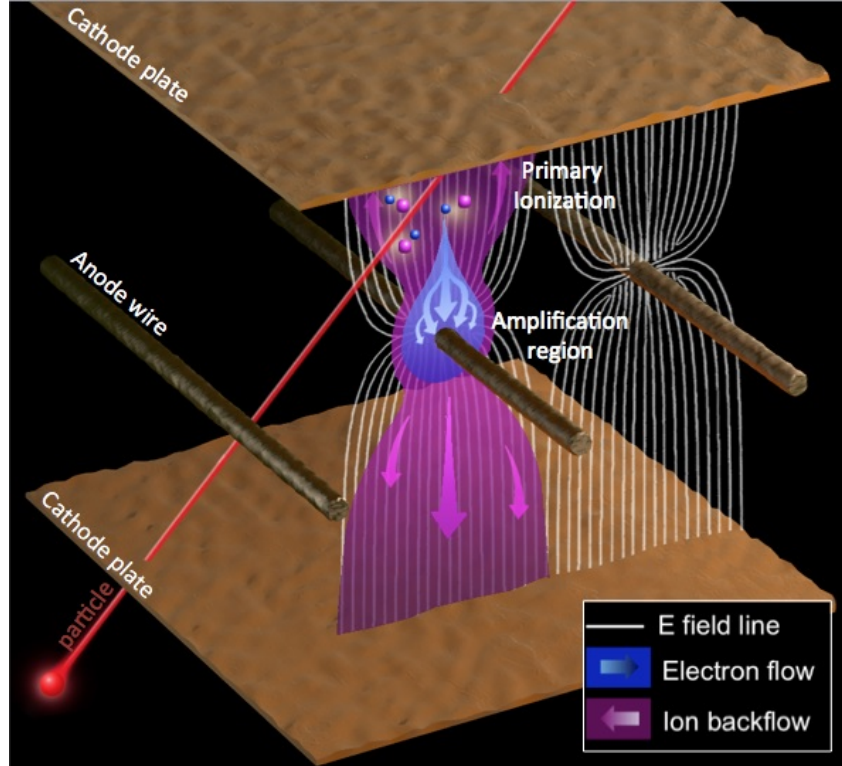


Figure 2.9: Schematic view of a MWPC.

between anode and cathode is about 3 – 4 times larger. When a sufficiently strong voltage is applied, an electric field is developed that amplify the primary charge in the region near to the wire. [32]

The spatial resolution of a MWPC is:

$$\sigma = \frac{pitch}{\sqrt{12}},$$

where *pitch* is the distance between two near wires. However the resolution can be improved by adding more detection layer and/or segmenting the cathode. The time resolution is of the order of 10 ns in Ar/CO_2 (70 : 30) mixtures [13].

The main disadvantages of these detector is the long ions drift path (about 100 μs): this provoke a build-up of the positive charge in the gas volume limiting the rate capability of the detector. Furthermore the wire technology is very sensitive to classical aging effect (described later in this thesis) and requires particular conditions to be able to operate for a long time.

2.3.1 Micro Strip Gaseous Chambers (MSGC)

After the various progress achieved in the semiconductor industry, it was possible to build electrodes thickness of about 100 μm with a very good position accuracy. With this new knowledges, A. Oed in 1988 firstly proposed the Micro Strip Gaseous Detector [34]. This detector consisted in various metal strips engraved on a resistive substrate; when alternately connected to cathodes and anodes an electric field

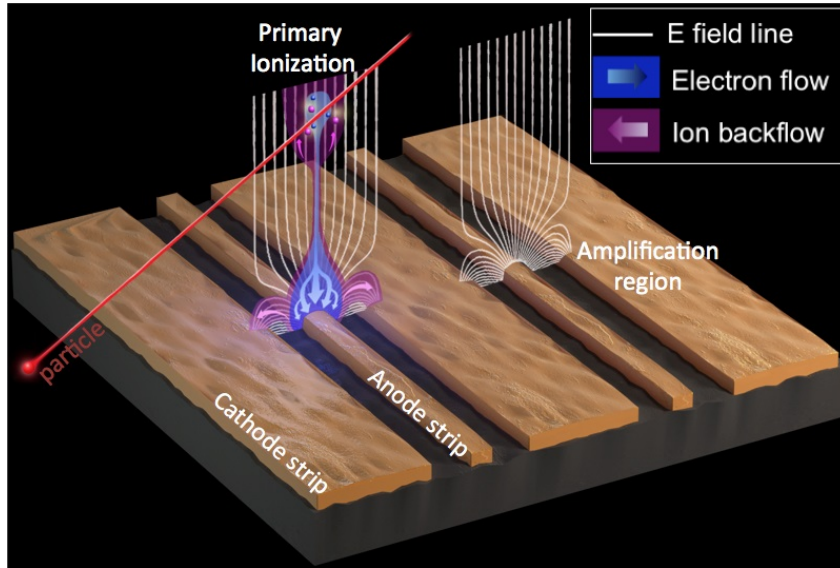


Figure 2.10: Schematic view of a MSGC.

allowed to multiply the primary charge (see Figure 2.10).

Many studies were performed in the 90's showing that these detectors can reach gains over 10^4 [35]; space resolution down to $30 \mu m$ rms [36] and rate capabilities over $10^6 Hz/mm^2$ [37] were achieved.

Although, with this detector design, many of the problems related to the MWPC were overcome, a major problem was the discharges. Indeed in cases of big energy releases or high rates the number of electrons released in the avalanche could overcome the Raether limits and then induce a streamer; due to the little distance between the electrodes a streamer could damage permanently one or more strips. This obviously affected the possibility to use this technology in long-term experiment and in harsh environments.

2.3.2 Micro Pattern Gaseous Detectors (MPGD): the Triple-GEM Technology Case

In order to overcome the MSGC limitations MPGD were developed since the end of the previous century; today they represent the last generation of gaseous detectors used in particle physics.

One of the most common MPGD is the Gas Electron Multiplier (GEM), already briefly described in section 1.5. This technology was invented by F. Sauli in 1996 [38] to pre-amplify signals in MSGC detectors; nowadays this technology is usually used as standalone amplification method. In Figure 2.11 a detail of one GEM hole.

The amplification of one single GEM foil can reach 5×10^3 but, at this regime, the foil is very near to its electric breakdown and the discharge probability is about some percent [39]. The main advantage of the GEM technology is the possibility to concatenate the foils and then reach gains up to 10^5 without approaching the electrical breakdown of the single layer.

The most used GEM configuration is the triple-GEM technology, Figure 5.27:

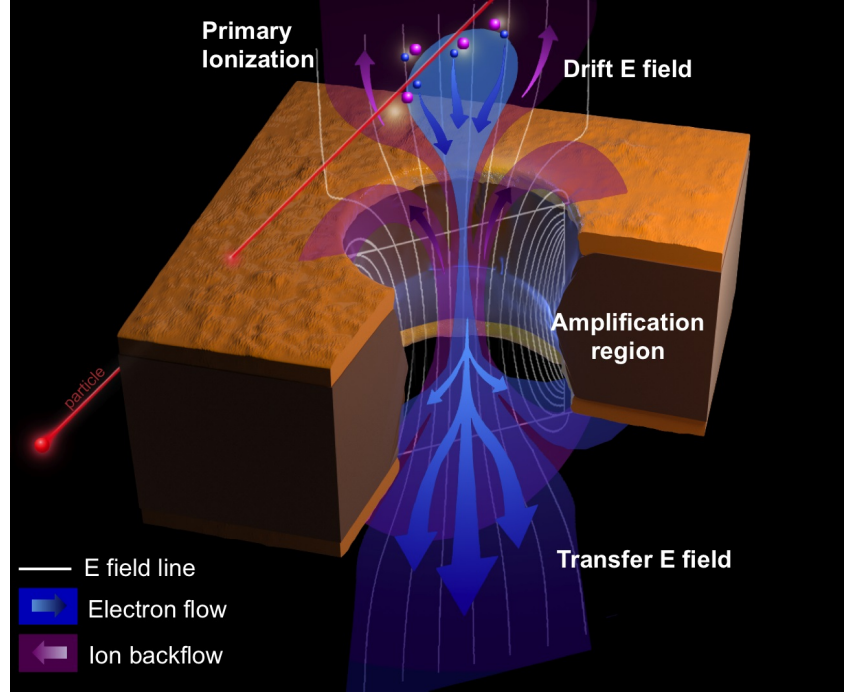


Figure 2.11: Schematic view of a GEM hole.

three GEM foils are piled up between a cathode (drift plane) and a segmented anode (readout board). In this arrangement is possible to individuate: the drift region (3 mm) between the drift gap and the first GEM foils, the two transfer gaps between the foils and finally the induction gap where the charge generates the signal. The chosen layout for the CMS end-caps upgrade is "3/1/2/1", (these numbers refers to the gaps dimension in mm starting from the drift gap) which revealed to be a good compromise between the mechanical constrains and the magnitude of the electric field either for multiplication and drift. As can be seen in Table 2.3: the voltage across GEM1 is 3% higher than across GEM2, which in turn is 5% higher than that of GEM3; this in order to prevent the discharges productions, following the recommendations given from past studies [39].

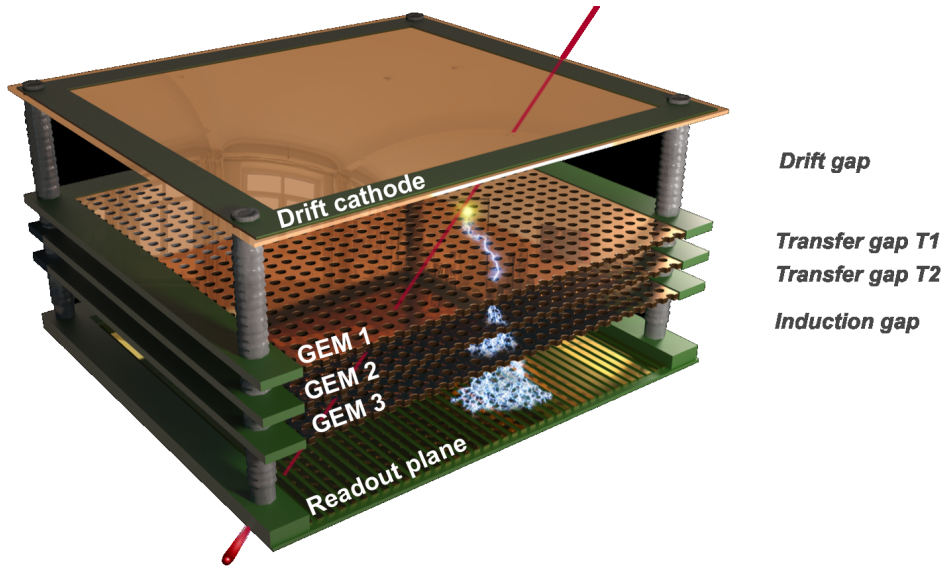


Figure 2.12: Schematic view of a triple-GEM detector.

Region	Voltage(V)	Average Electric Field(kV/cm)
Drift	810	2.7
Δ_{GEM1}	410	81
Transfer1	320	3.2
Δ_{GEM2}	400	80
Transfer2	630	3.2
Δ_{GEM3}	380	76
Induction	450	4.5

Table 2.3: Voltages and electric fields configuration of a triple-GEM detector in "3/1/2/1" gap configuration at the nominal voltage of 3400 V. The parameters Δ_{GEM1} , Δ_{GEM2} and Δ_{GEM3} stand for the regions between the copper layers of each foil.

Chapter 3

Triple-GEM Prototype Characterization

In the following chapters a triple-GEM prototype detector will be used to perform an advanced aging study on this technology. It is therefore mandatory to fully understand and characterize the prototype performance before starting the test. The present chapter is devoted to the prototype description and its characterization.

3.1 Prototype Description

The CMS muon GEM group has provided a fully assembled $10 \times 10 \text{ cm}^2$ prototype (see Figure 3.1). The gap configuration is the same as the CMS detectors “3/1/2/1”, but the power supply system is different. In the CMS standard GEM chambers each electrode is powered by a single HV channel for a total of 7 different electronic channels; otherwise in R&D measurement is useful to use only one electronic channel supplying the nominal voltage, while the correct voltages are provided by a ceramic divider. Additionally several $10 \text{ M}\Omega$ resistance are applied between the divider and the top of the GEM foils and the drift plane in order to restrict the current flowing over the foils when a discharge occurs and to stop their propagation. The readout board of the prototype is made of two perpendicular set of 256 strips, each set is divided into two group of 128 strips, each group connected to a Panasonic connector (see Figure 3.1). Furthermore a capacitor decouples the bottom side of the third GEM foil (GEM 3 Bottom ‘G3B’) from the HV allowing to read the pulse signals.

The aging measurement presented in this thesis requires to irradiate the prototype also with 5.6 MeV α -particles. Since the Kapton window plus the Drift electrode are too thick to allow these particles enter the drift volume, a special 30 mm^2 opening in either the surfaces was manufactured. The gas tightness is provided by a $10 \text{ }\mu\text{m}$ thick Polyethylene terephthalate window.

All these informations are schematically shown in Figure 3.2

In order to reduce the electromagnetic noise, the whole detector is covered with a Kapton foil copper clad on one side in order to EM insulate the detector, leaving holes to permit particles to enter the Kapton window (see Figure 3.3). For the same purpose, an RC filter (see Figure 3.4) is placed between the HV power supply and the divider in order to eliminate the low frequency noise. With this precautions the

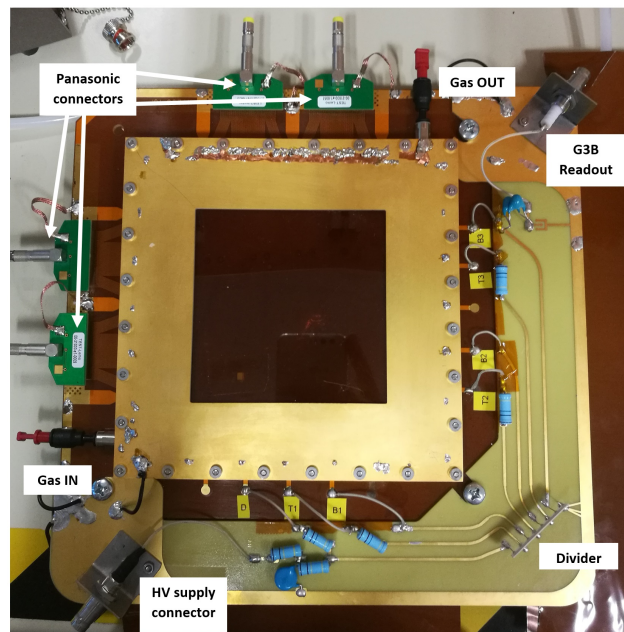


Figure 3.1: The working detector prototype.

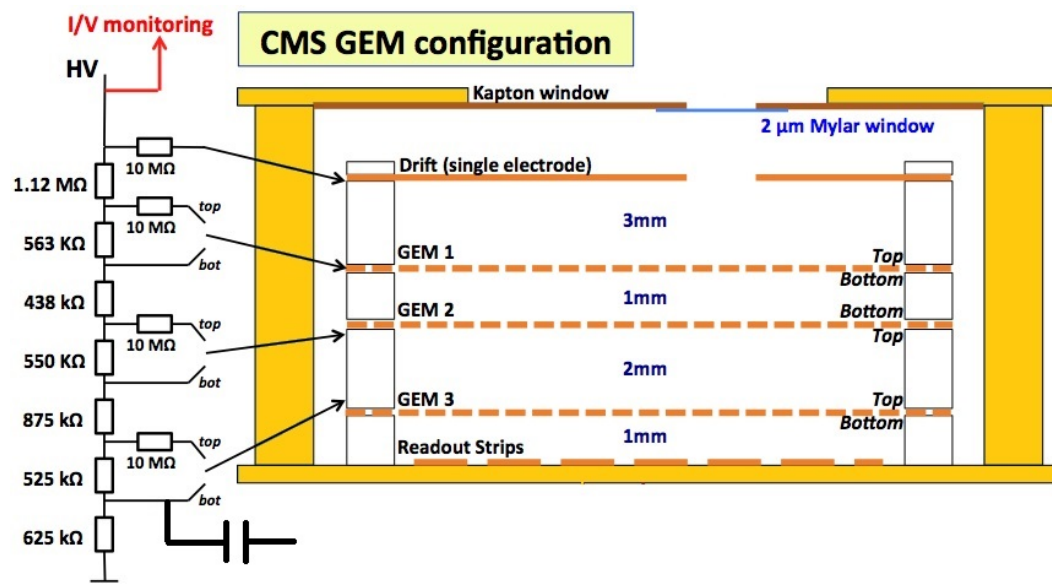


Figure 3.2: Schematic view of the triple-GEM prototype used in this thesis showing the divider and the gap configuration.

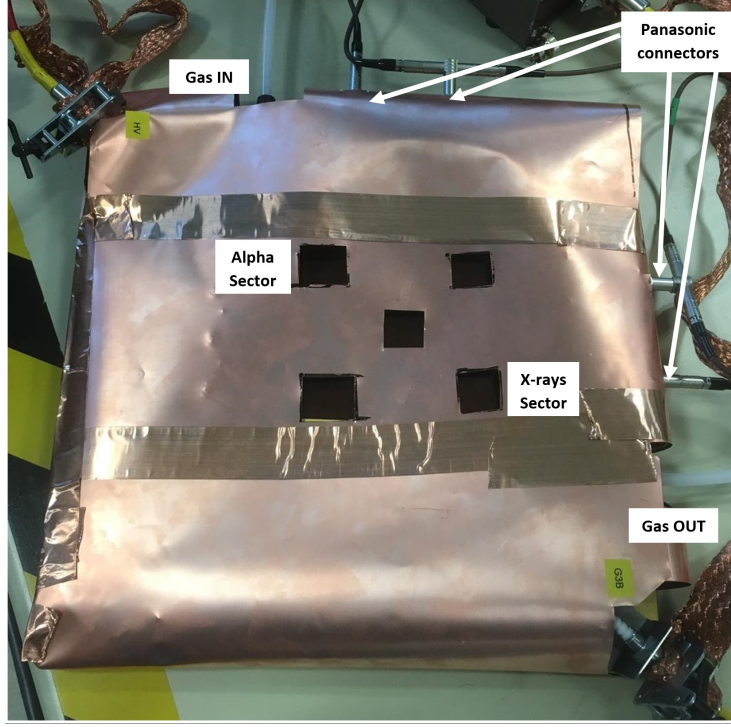


Figure 3.3: GEM prototype with the EM shielding.

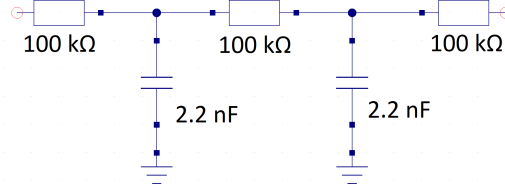


Figure 3.4: Scheme of the HV filter.

electromagnetic noise has been reduced to 60 mV peak-to-peak.

All the test and measurement in this thesis were performed out the CERN CMS GEM laboratory.

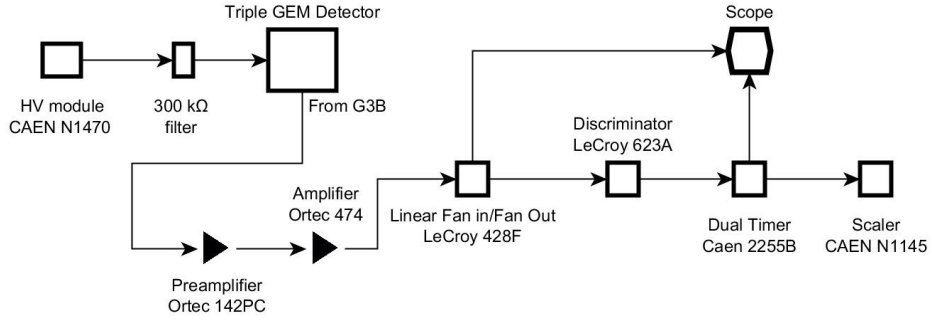
3.2 High Voltage Tests

Two high voltage tests have been done in order to assure the correct operation and stability of the foils and the divider when working at the nominal voltages.

The first test qualitatively measures the impedance between the two sides of each GEM foil when a certain high voltage is applied. Also, the rapidity to reach the nominal impedance value has to be comparable between all the foils, in order to assure the good quality of the solders and the foils. Indeed, if an impedance reaches too slowly its nominal value, it means that some sort of leakage current is flowing between the two layers. This privileged flowing channel can stimulate streamers through the foils or shortcuts in the electrical connections, damaging the detector.

Amplifier Ortec 474	
Coarse Gain	1
Fine Gain	2
Diff. Time(ns)	100
Int. Time(ns)	100

Table 3.1: Ortec 474 Amplifier settings

Figure 3.5: Data acquisition and power supply chain for the measurement of the IV characteristic.

A Megger Mit420 was used to directly apply 500 V between the sides of the foils: all the foils reached the nominal value in about the same time. Since the full scale of the instrument was $100\text{ G}\Omega$, an indicated value of " $> 100\text{ G}\Omega$ " was considered as a good electrical behaviour of the GEM foil as an insulator, as expected.

The second test consists in measuring the IV characteristic (divider current vs. applied voltage) and the spurious signal rate due to the internal leakage current and defects in the electrical circuits. The aim of this test is to verify the linear behaviour and possible defect in the power supply circuit. The entire test is performed flushing the detector with pure CO_2 (5 l/h) to avoid real signals from cosmic rays or environmental background and then detect only electronic induced signals. High voltage was applied through a CAEN N1470 module, which also provide the measurements of both the divider voltage and current with an error of $\pm 0.02\% + 2\text{ V}$ on the voltage and $\pm 2\% + 2\text{ }\mu\text{A}$ on the current [40]. The signals are read from the G3B shaped and amplified (amplification setting are shown in Table 3.1); then they are sent to a LeCroy 623A Octal Discriminator with a setted threshold of -142 mV . The logical output signal is transferred to a Dual Timer module with the purpose to increase its width until is comparable with the analogical signal width; this is made to prevent a pulse from producing more than one logical signal caused by electrical fluctuation around the threshold value. Finally, the signals are counted by a scaler for each value of supplied voltage. The complete acquisition chain is shown in Figure 3.5

The result plot is shown in Figure 3.6 where also a linear fit of the IV data

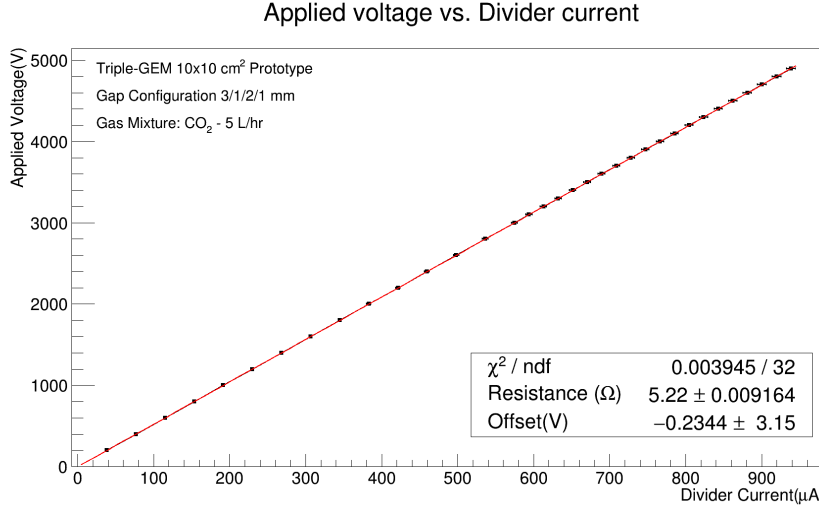


Figure 3.6: IV characteristic curve with the spurious signal rate .

appears which permits to well measure the total resistance of the divider and the HV filter. The percentage deviation between the measured resistance at a certain voltage and the fit value is shown in Figure 3.7. There is a decreasing trend of the resistance with the applied voltage, but since the difference between the lowest and the highest value is less than 0.5% assuming it to be constant in the working range. Moreover, the spurious rate count revealed to be up to 6.1 Hz , much less than the expected interaction rate in the next aging test (see Table 5.1).

From now on, when referring to the HV power supply system is indicated the combination of the CAEN N1470 module and the 300 $k\Omega$ filter; furthermore when the signals are discriminated it is implied the use of both the discriminator and the dual timer module.

3.3 Gain Measurements

As defined in the first part of Equation 2.16, the gain is the electron multiplication factor, i.e. the ratio between the collected charge and the primary ionization charge. Measuring the gain for certain values of applied voltages it is possible to verify the exponential behaviour, furthermore precise gain measurements are required in order to know the detector performance before starting the main aging study.

In order to measure the gain, a 34.18 MBq ^{55}Fe x-rays source was used to irradiate the detector. This source emits well detectable 5.9 keV photons; these x-rays interact mostly with the copper clad of the drift electrode via photoelectric effect releasing electrons which will deposit their energy in the gas volume. The average number of primary charge n_0 released in the detector can be estimated with a procedure similar to the one used in Equation 2.6:

$$n_0 = 5900 \text{ eV} \times \left[\frac{0.7}{W_{Ar}} + \frac{0.3}{W_{CO_2}} \right] \simeq 214 \text{ pairs.} \quad (3.1)$$

This estimation is valid if the photoelectrons release all their energy in the gas. A

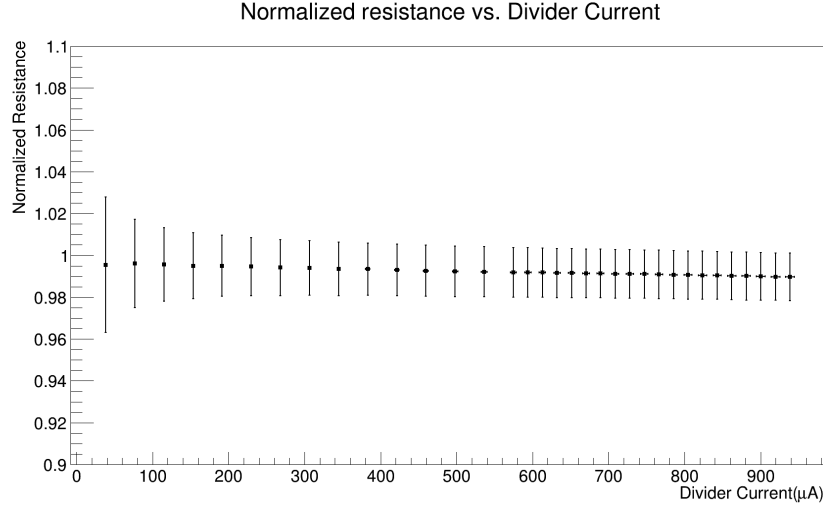


Figure 3.7: Resistance values measured at various voltages, normalized to the value obtained from the linear fit.

qualitative electron range estimation is made by using the NIST's ESTAR database [43]; supposing that a photon converts in the copper layer, it is possible to estimate the average range of the photoelectron in Ar/CO_2 (70/30). This range results to be $\simeq 2.1$ mm for 10 keV electrons (the lowest energy present in the database), for this reason it is possible to suppose that all the energy carried by a 5.9 keV photoelectron is deposited in the 3 mm drift gap.

There are two main methods to measure the gas gain: the first one consists in measuring the charge collected by the readout strips when a 5.9 keV photon interact in the drift volume. This is possible by measuring the charge spectrum of the source using a ADC and computing the charge relative to the photo-peak Q_{Fe} by a Gaussian fit. The gain will be:

$$G = \frac{Q_{Fe}}{n_0 e}, \quad (3.2)$$

where e is the electron charge. A typical ^{55}Fe spectrum is shown in Figure 3.8, the main peak is relative to 5.9 keV photoelectrons while the other peak is the so called *escape peak*: as discussed in section 2.1.2, when an internal electron shell of an Argon atom is freed by an incoming photon, the rearranging of the atom will cause an emission of a photon with energy of 3 keV. If this photon leave the detector, only a part of the original photon energy is deposited in the gas volume:

$$E_{esc} = E_{Fe} - E_K,$$

where $E_K = 3.2$ keV is the binding energy of the K shell [25], $E_{Fe} = 5.9$ keV and then $E_{esc} = 2.7$ keV is the energy relative to the escape peak. This procedure permits to measure the absolute gas gain only if the acquisition chain is charge calibrated.

The previous procedure was not used in the prototype characterization, but

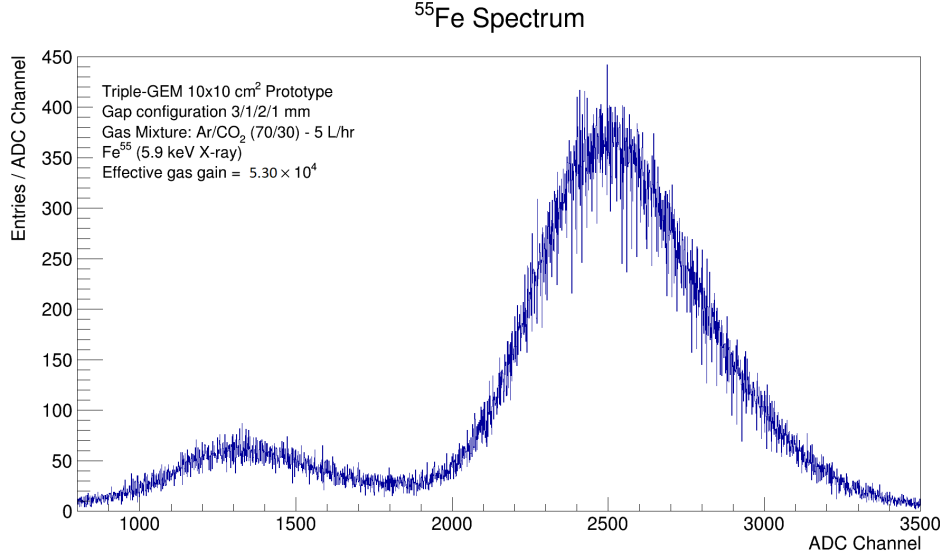


Figure 3.8: Typical ^{55}Fe spectrum, the main peak refers to 5.9 keV photoelectrons while the lower one is the escape peak.

a variant of this will be illustrated and used in the next chapter for the aging measurements. The second method to estimate the gas gain consists in measuring the current from the readout strips I_{an} and the interaction rate at the maximum detection efficiency R when a ^{55}Fe source is placed on the top of the detector, then the gain can be computed as:

$$G = \frac{I_{an}}{n_{Fe}eR}. \quad (3.3)$$

It is important to notice that n_{Fe} is different from n_0 since the latter is the average number of electron-ions pair produced by a 5.9 keV photoelectron, while n_{Fe} is the average pairs released by a 5.9 keV photon. Indeed in this case we have to take into account the events under the escape peak: these are due to the original photons but they contribute less to the total created electron-ion pairs.

In order to estimate the difference between these two parameters, the ratio r_e between the escape peak events N_e and the total photoelectric events is supposed to be the same as the probability to have an escape event when a 5.9 keV photon interact p_{esc} , i.e.:

$$r_e := \frac{N_e}{N_e + N_p} = p_{esc}.$$

To measure r_e 100 spectra were acquired by the GEM detector, then the integrals of the two peaks are computed and the r_e values are obtained, the distribution of the measured values is shown in Figure 3.9. The setup and the procedure used for acquire the spectra is illustrated in the next chapter.

With the measured value $r_e = 0.116 \pm 0.001$ is possible to estimate the difference between n_{Fe} and n_0 :

$$n_0 - n_{Fe} = p_{esc} \times 2700 \text{ eV} \times \left[\frac{0.7}{W_{Ar}} + \frac{0.3}{W_{CO_2}} \right] \simeq 12 \text{ pair}.$$

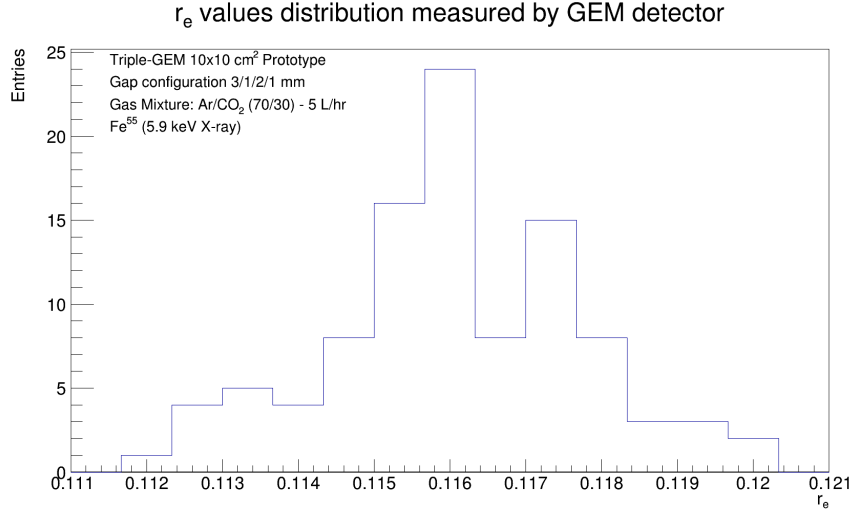


Figure 3.9: Distribution of the r_e measured values from the spectra acquired from the GEM prototype.

	Value(pairs)
n_0	214
n_{Fe}	202

Table 3.2: Average value of the electron-ion pairs produced by a 5.9 keV photoelectron n_0 and average pairs released by a 5.9 keV photon.

The values used in this thesis are shown in Table 3.2

Since the constant n_{Fe} is now fixed, it is possible to proceed to measure the prototype gain. In order to measure the current, all the four Panasonic connectors were connected to collect all the strip current and then read by a Keithely 6485 picoammeter. The rate is monitored by the same setup as the IV test (see Figure 3.10).

A complete gain measurement was performed either in the corner with the 3.14 mm^2 windows and in the opposite corner by placing the ^{55}Fe source on the relative opening in the copper shielding. The gain values was investigated in the divider current range of $620 \div 730 \mu\text{A}$ with $10 \mu\text{A}$ steps. For reasons that will be clear in the next chapter, the corner with the window will be labelled *Alpha Sector* while the opposite one *X-rays Sector*. A photo of a typical gain setup is shown in Figure 3.11

The test results are shown in Figure 3.12 . It is possible to see that the Alpha sector's gain is systematically lower than the X-ray sector one ($\simeq 16\%$ on average). This happens because of the electric field distortion inducted by the tiny window in the drift plane, which causes the decrease of the transparency of the first GEM foil. Furthermore the rate in Alpha sector is always lower than the other, once again because of the window in drift plane; indeed, in this position, the attenuation coefficient is lower because the lack of one of the copper layer, resulting in less

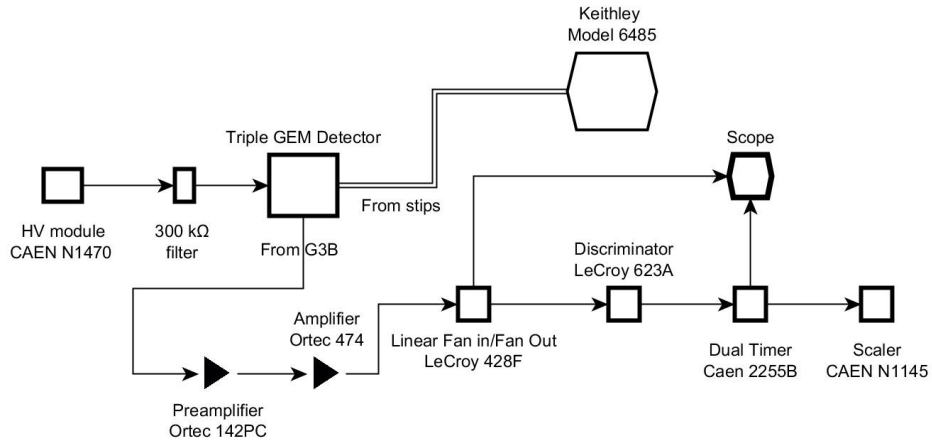


Figure 3.10: Schematic setup arranged for the gain measurement.

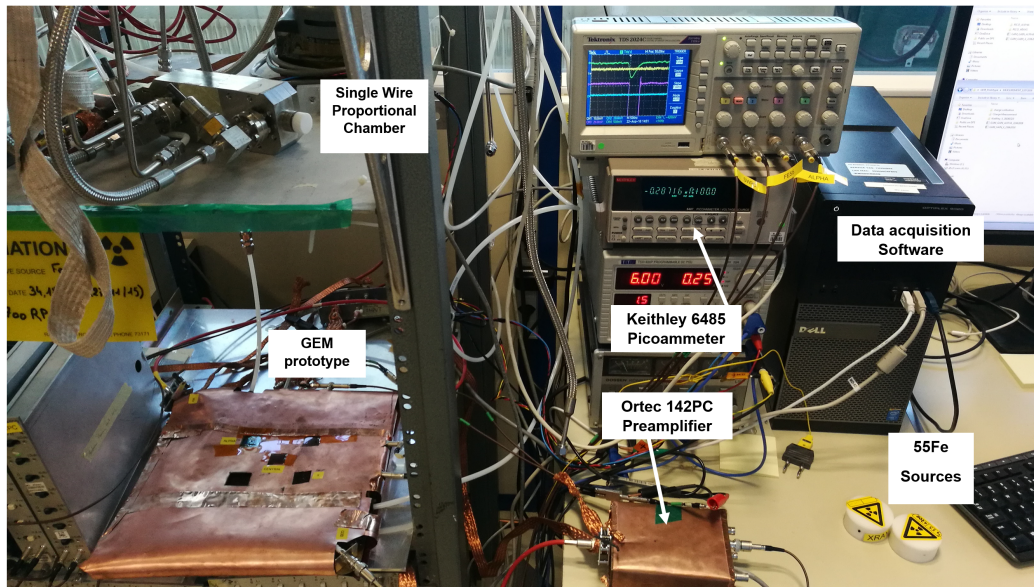
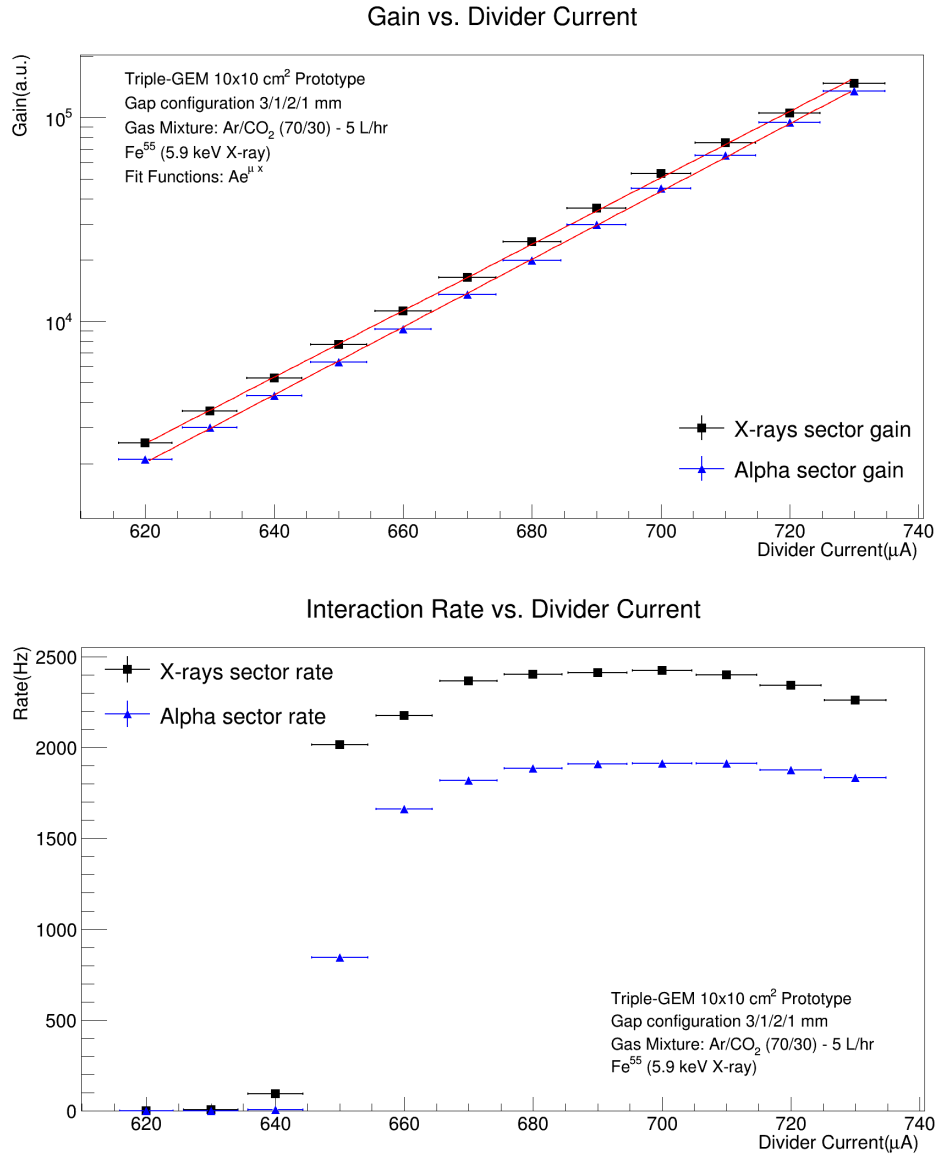


Figure 3.11: Typical setup for a gain measurement, also the SWPC is shown.



	Gas Gain
Alpha Sector	$5.05 \pm 0.06 \times 10^4$
X-rays Sector	$5.96 \pm 0.07 \times 10^4$

Table 3.3: Measured gain values for both the sectors at the working divider current of 700 μA

photon converted. It can be seen that the rate decreases in both the sectors after the plateau (current higher than 710 μA). For this reason it was decided to perform all the experiments supplying the detector with no more than 3623 V equivalent to 700 μA flowing in the divider; the gains relative to this working point are written in Table 3.3.

In order to avoid too much current flowing on GEM foils, a trip current of 705 μA was set on the high voltage module. If this value is overcome the module turns off automatically. This is made in order to avoid unwanted damages on the detector and, indirectly, to identify the occurrence of a discharge. The value of 705 μA was set in order to exclude a possible statistical fluctuation (current varies within the interval [668.75, 700.75] μA) and recognize an undesired event.

It is important to notice that all the gain measurements were performed only after several hours of preparatives. Indeed the detector was turned ON several hours before placing the source on its top and, once again, before starting the current and rate measurement some time is waited. This in order to avoid the charging up effect due to the polarization and the radiation effects. These effects have been widely studied and explained in [13], [44] and [45].

3.4 Single Wire Proportional Chamber (SWPC)

In the next chapter it will be required to monitor the pollutants and their effects during the electron multiplication, in order to do this a SWPC was connected to the same gas line of the GEM detector.

This detector was initially designed by the GEM group within the RD10 collaboration. This detector consists in a stainless steel outer box, working as a cathode, and a 30 μm diameter gold-plated tungsten wire serving as anode. In order to permit the particles to enter in the gas volume a rectangular window is made on the cylinder, while the gas tightness is assured by a stainless steel window sandwiched between two stainless steel plates, one of which is soldered to the cylinder (see Figure 3.13). To permit to read the pulse signals from the wire a de-coupling capacitor is placed, with a resistance through ground to avoid the charging up of the capacitance (see Figure 5.32).

For this detector it was not required the same calibration measurement done for the GEM detector, because only relative variations on the gain are of interest. Nevertheless previous measurements on the same detector revealed that the gain was 4×10^4 at a supply voltage of 2200 V (see [13]).

However, a rate measurement with a constant ^{55}Fe source with various values of HV supply was made in order to measure the working tension of the SWPC; the setup is the same as other rate measurement. The results are shown in Figure 3.15

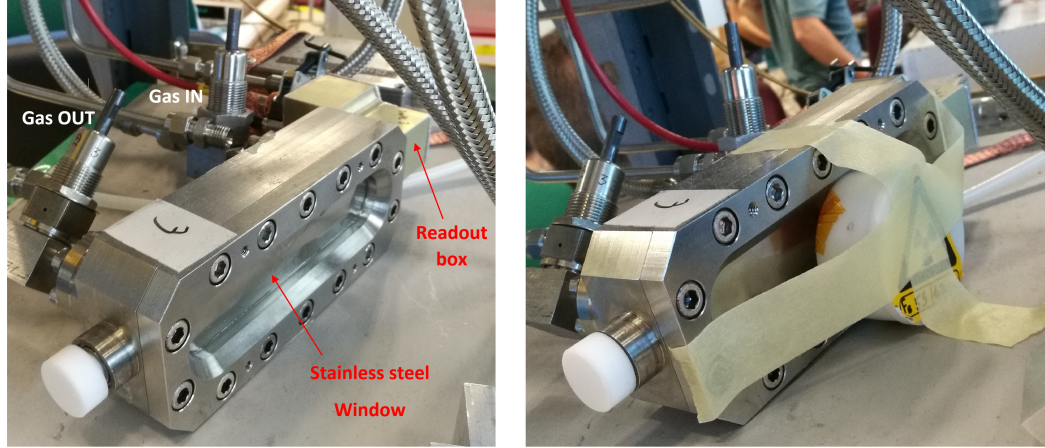


Figure 3.13: On the left the SWPC box. On the right the SWPC with the ^{55}Fe source placed in front of the stainless steel window, the position of the source is maintained constant by some masking tape.

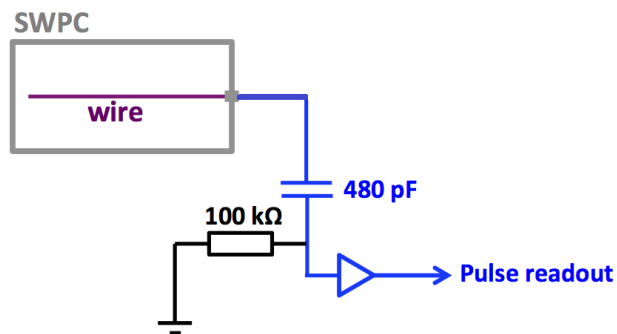


Figure 3.14: Scheme of the pulse signals readout.

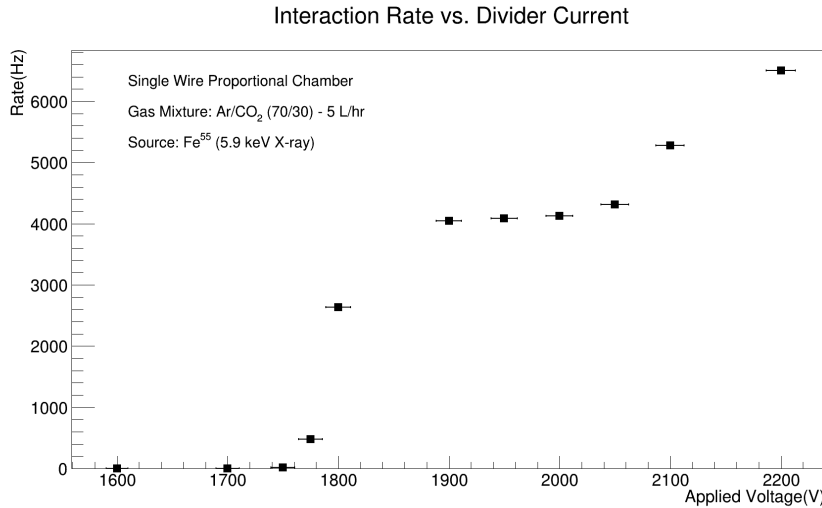


Figure 3.15: Measured rate in function of the voltage applied.

where it is possible to see that the nominal rate is reached at 2000 V; after this value the rate increase rapidly because of the noise, indeed the electric field became so high to extract electron from the stainless steel of the outer surface inducing signals that are not from the 5.9 keV photons.

3.5 Conclusion

This chapter was dedicated to understand the detectors behaviour and chose their working points. After this preliminary test the correct operation of the detectors was demonstrated. Furthermore the detectors working points were chosen in order to get the best performances. The working voltage of the GEM chamber was chosen to be 3623 V (divider current of 700 μA) while the SWPC was operated at 2000 V.

Chapter 4

Aging of Gaseous Detectors

4.1 Introduction

Aging is referred to every type of deterioration in performance of a gaseous detector: loss of gas gain, loss of efficiency, worsening of energy resolution, excessive currents, self-sustained discharges, sparks, loss of wires, changes of surface quality etc. The main contribution to aging in gaseous detector is given by chemical processes at work inside the gas volume during the electron amplification. Aging phenomena have not been fully understood yet; indeed, since the variables are too many, it is impossible to think to use simple variables to describe this issue. Moreover, nowadays, the relation between the microscopic variables and the macroscopic ones (the controllable ones) is not known.

In this chapter a brief description of the physical and chemical processes which lead to the aging of gaseous detectors is proposed; afterwards, typical effects on different detector technologies will be illustrated. Finally some motivation will be given to the need for the developing of new types of experiments to better understand the aging issue.

All the elements, notions and concepts are adapted from [13], [46], [47], [48], [49], [50], [51], [52] and [55].

4.2 Aging Mechanisms and their effects

The aging of a detector is strictly related to the chemical processes which happen inside the gas volume during the electron amplification. Since the dissociation energy of molecules is 2-5 times lower than their minimum ionization energy, it is clear that every avalanche is surrounded by the production of a very large amount and variety of free radical molecules (with unsatisfied covalent bonds); such a molecule has no net electrical charge, but it has typically a large dipole moment, because it is frequently distorted. Furthermore these radical molecules are very chemically active and they can either recombine or react with other active species to form monomers; the latter can associate in chain reaction until the bonds of the chain radicals are satisfied by a complementary fragment. Figure 4.1 shows the structure of a polymer

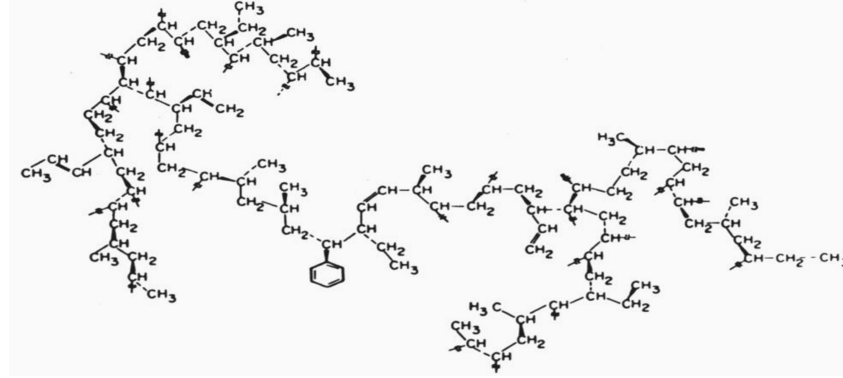


Figure 4.1: A predicted structure of polyethylene produced in the plasma environment. [52]

created after the ionization of CH_4 molecules:



and the subsequently rearrangement of the CH_2 radicals.

It is now possible to analyze the effect of these polymers when they deposit themselves on the cathode or anode surface in a gaseous detector. In Figure 4.2 it is schematically shown that the polymer formation is caused by a large amount of free radicals. At the beginning of its formation the polymer is lightly bound to the anodic surface unless other reactions take place; this means that the gas flow can relatively easily remove the polymer from the anode and release it in the gas volume, if the chain reaction is not so extended. Otherwise, if the polymer is freed from the anode and it is positively charged, it can slowly migrate through the cathode and then deposit on the latter.

4.2.1 Anode Aging

Polymer deposits on the anode behave in different ways whether they are conductive or resistive. If they are conductive, there is a direct effect: the electric field weakening due to thicker wire and also a distortion of the field lines. Otherwise if the polymer is insulating, there will be an accumulation of electrons on the top surface of the pollutant with the subsequently decreasing of the effective electric field acting on the ionization charge and thus a loss of gas gain. In Figure 4.3 it is possible to see the silicon based polymer deposited on an anode wire.

4.2.2 Cathode Aging

Polymer deposition on the cathode surface can lead to even more dramatic effects. If the ions cannot reach the cathode surface due to this deposit, they cannot evacuate from the gas volume and they will accumulate on the top of this layer. This can produce a large dipole field between the cathode and the trapped ions and if this field overcomes the threshold for field emission ($\sim 10^7$ V/cm); electrons will be extracted from the cathode. These electrons can penetrate the polymer layer and further stimulate avalanches. This effect is also called *Malter* effect from the name of

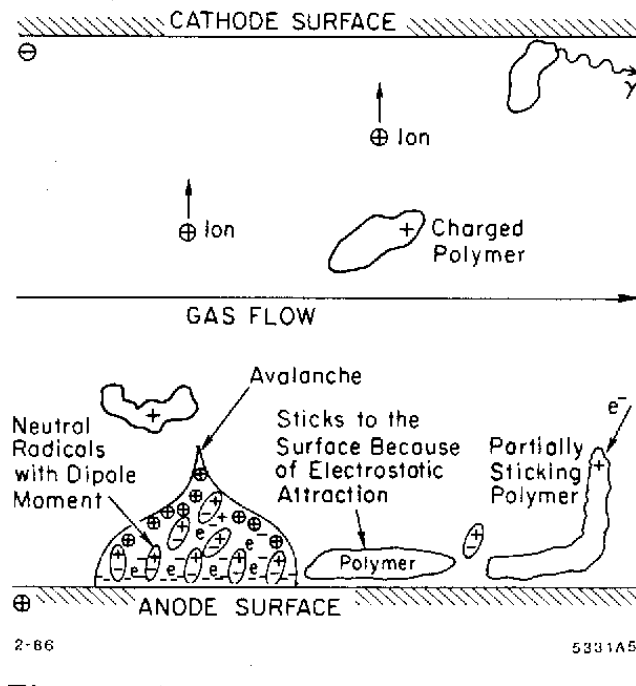


Figure 4.2: A naive model of formation of polymers out of free radicals on the anode surface and an effect of gas flow on heavy positively charged species slowly drifting towards the cathode. [52]

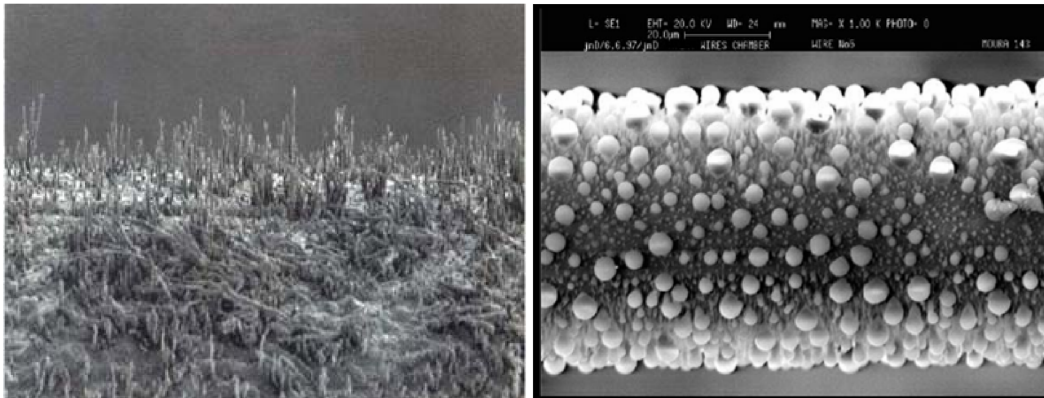


Figure 4.3: Examples of Si-deposits on the anode wires. (Left) picture from [53]. (Right) from [54]

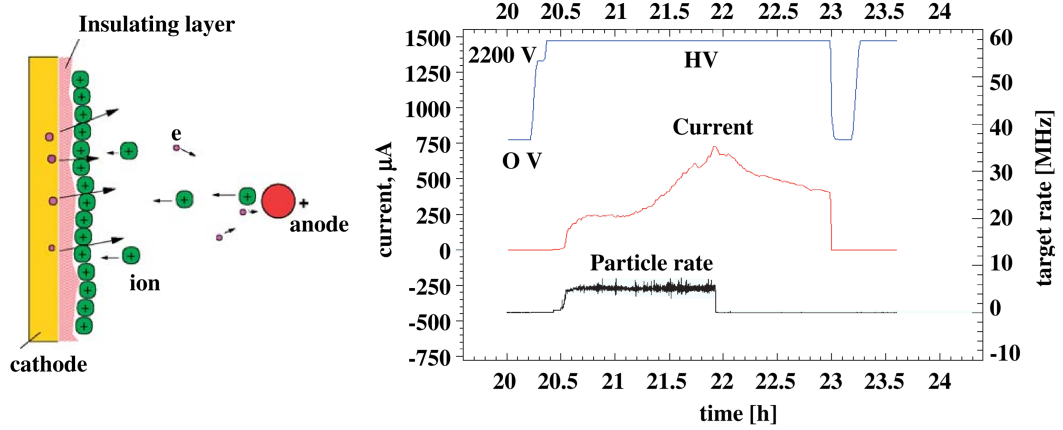


Figure 4.4: Schematic of the mechanism leading to the Malter effect (left). Example of a spontaneous increase of chamber current which persists even after the incident radiation has been switched off (right). The current only goes back to zero once the high voltage has been switched off [56].

its first observer in 1936 [57]. This type of deposition will increase the dark current of a detector and rise the probability to have self-sustained discharges. In Figure 4.4 the schematic mechanism leading to the Malter effect and also the effect on the dark current after some time of operation is shown.

4.3 Aging in Different Gaseous technologies

The effect of aging on gaseous detectors was initially identified in Geiger counters around the 40's [58], [59] and [60] as a reduction of the working plateau after a sustained irradiation (see Figure 4.5) or as an increase of the spurious counts. However, at those days, it was very difficult to understand the processes behind this performance deterioration and also most of the tubes were built to remain sealed. The fault was given to the degradation of the amplification structure or to some changes in chemical proprieties of the gas.

With the introduction of proportional counters and, later, MWPCs, aging was observed as a gain loss, energy degradation and self-sustained discharges. This issue had more visibility when MWPC started to be more used in the HEP experiments. A commonly used gas mixture was Ar/CH_4 ; first analysis with optical microscopes discovered the presence of hydrocarbon structures on the anode wires; Figure 4.6 shows the aging of a wire chamber. Then it became clear that the aging of a gaseous detector is proportional to the dose rate on the detector; a typical unit of measurement of the aging is the collected charge per centimetre of wire (C/cm).

MSGCs raised great interest in the HEP experiments because of their very promising high-rate and high-accuracy performances, thus starting first characterizations and aging studies on this technology. Obviously, in this case, the old typical aging unit of measurement had to be changed, because of the different nature of the detectors: the new units were C/cm^2 or $C/(cm \text{ strip})$. For reasons which are not fully understood, but probably related to the small area of the anode strips, these types of detectors are much more sensitive than traditional MWPCs to aging, for

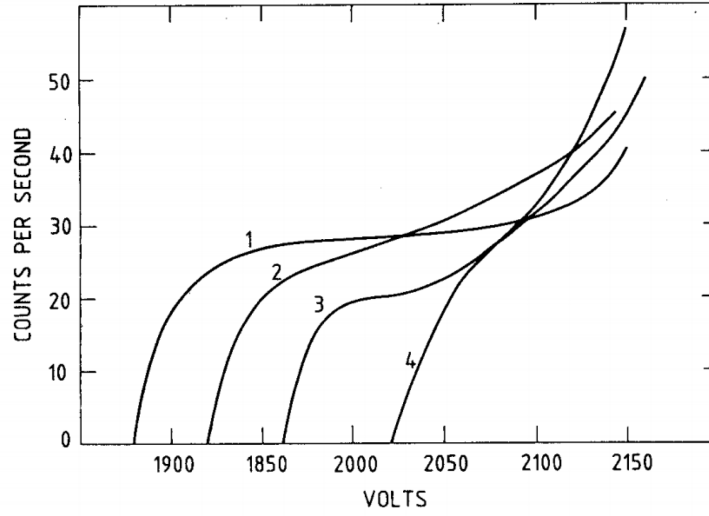


Figure 4.5: Count rate plateau of a Geiger tube filled with methane [60]. The curves were taken at different ages (curve 1 after 10^7 counts, curve 4 after 10^8 counts).

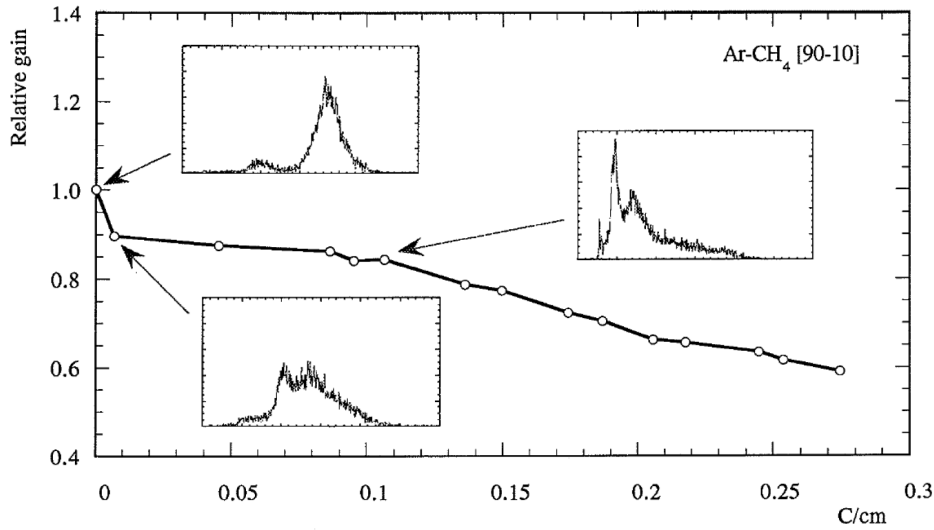


Figure 4.6: Aging of a wire chamber operating in $Ar/CH_4(90/10)$ at a gain of 2×10^4 [55]. The curve represents the evolution of the gas gain normalized with the initial value as a function of the accumulated dose, expressed as the total charge accumulated per centimetre of wire. The energy response to an X-ray source was also measured at different times to illustrate the degradation of the energy resolution.

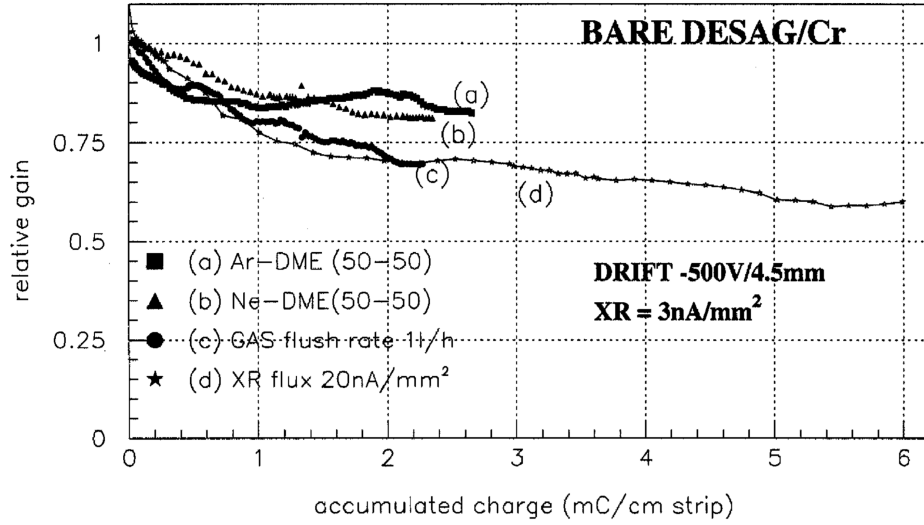


Figure 4.7: Aging of a MSGC operating in Ar/DME and Ne/DME at a gain of about 10^3 , the curves represent different operation conditions. Changing the rare gas nature (from Ar to Ne) hasn't changed so much the detector response (comparison between (a) and (b)), otherwise a net effect appears when decreasing the flow rate from 4 *renewals/h* to 1 *renewals/h* (comparison between (a) and (c)). Also a clear dependence from the interaction rate is observed when increasing the incoming X-ray intensity from a read current density of 3 nA/mm^2 to 20 nA/mm^2 (comparison between (a) and (d)). [63]

this reason they require more attention as far as the purity of gases and materials used for their construction is concerned [61]. An example of an aging study on the MSGC technology can be found in Figure 4.7.

All past studies suggest to eliminate hydrocarbon molecules from the gas mixtures in order to avoid the formation of radical which can easily form polymers. Furthermore it was clear that some oxygen based molecules can reduce the polymerization rate by absorbing the hydrocarbon radicals and they are also relatively chemically inactive. This because oxygen-based radicals, which can be released for example from CO_2 dissociation, are known to have the freedom to make double bonds, which are stronger and allow to make more stable volatile molecules, which can be removed by gas flow. Most of the gas mixtures in HEP experiments are composed of Ar/CO_2 for the previous reasons.

Although a clean mixture as Ar/CO_2 can prevent many aging processes, the presence of pollutants in the gas system can provide molecules and very active radicals, which can trigger the polymerization processes. In all the practical cases pollution is always present in gas systems: from tubes contamination, gas leakages, residuals in the gas cylinders or, most probably, from materials which releases some of theirs molecules in the gas system; the latter effect is also called *outgassing*. Many materials were banned during the years because found to stimulate the polymer formation; in particular silicon based materials revealed themselves to release, during the avalanche, a lot of free radicals which can propagate through the detector. Silicon is found in many industrial glues, greases and adhesives, but more dangerous are the silicon residual found in some type of production processes not always mentioned by

the manufacturer. Halogens are another type of elements to avoid in gas systems: since their low dissociation energy they will produce a big quantity of free radical during the avalanche. Halogens can be imported into gas systems by certain types of cleaning processes and also by the outgassing of some kind of rubbers and plastic materials.

4.4 GEM technology aging

Triple-GEM technology is very promising from the aging point of view, particularly for its geometrical features:

- First of all GEM detectors have a significant separation between the amplification planes and the cathodic and anodic ones. The absence of high electric field, which permits the electron multiplication, near the readout board strongly reduces the probability to directly create polymers on the strips. This will avoid the aging issues found in the MSGC case. In a similar way a possible deposit on the cathode surface is strongly suppressed, preventing Malter effect.
- Secondly, sharing the gain over three stages helps to reduce the energy available to release radicals. Indeed the avalanche in the single foils are smaller and with less available energy with respect to a single stage detector.

Another factor which helps to reduce the aging processes is the choice of the gas mixture: Ar/CO_2 is a clean mixture from the aging point of view, as already mentioned in the previous section, and it is used in many experiments for this reason.

Many risk factors are removed in the Triple-GEM case. However, they are not immune to aging processes, indeed, since many electric field lines terminate on the hole rims, unpleasant effects may happen. A polymer accumulation on this tiny region can lead to electric field distortion, i.e. losses in the amplification processes and a decrease in the foil transparency. Furthermore deposit on the top of the rims can prevent the ions to correctly flow over the foil, causing Malter effect. At last, although the gas mixture is clean and the materials are chosen to not present outgassing behaviour, the presence of contaminants in the gas systems is not completely avoidable.

4.4.1 Past studies on aging of GEM-based detectors

During the years many studies were performed in order to demonstrate the long term stability of Triple-GEM technology for its application in many experiments. Below are briefly reported some of the aging test performed during these years:

- Double-GEM technology was tested with Ar/CO_2 (70/30) working at a gas gain of 2.2×10^3 . The detector was irradiated with a X-rays source for about 900 *hours* at an average interaction rate of 4.75 MHz/cm^2 . After an accumulated charge of about 1.2 C/cm^2 no aging was observed.[\[67\]](#)
- In 2001 an aging study on a Triple-GEM was performed in Ar/CO_2 (70/30) at a gas gain of 8.5×10^3 with a gap configuration $3/2/2/2 \text{ mm}$. After 240

hours of X-ray irradiation at 630 kHz/cm^2 and 240 hours at 2.5 MHz/cm^2 , the chamber accumulated a total charge of 700 mC/cm^2 without showing any sign of aging or resolution loss [68]. One similar test was performed with a Triple-GEM operating in the same gas mixture at a gas gain of 6×10^3 and with a gap configuration $5.5/1.5/3/3.5 \text{ mm}$. Once again the detector was irradiated by an X-rays source with an interaction rate of about 6 MHz/cm^2 for a total of 750 hours; the collected charge reaches 2.7 C/cm^2 and no aging effect or polymer deposit were found. [69]

- Other aging studies on Triple-GEM were performed by the LHCb collaboration with detectors operating in $\text{Ar}/\text{CO}_2/\text{CF}_4$ (45/15/40) at gas gain of 6×10^3 and with a gap configuration $3/1/2/1 \text{ mm}$ (same as the CMS GEM detectors). Several detectors were exposed to 1.25 MeV photons at a rate of $1 \div 20 \text{ MHz/cm}^2$ and to a X-rays source at 50 MHz/cm^2 . In this case an high decreasing of the GEM performance was reported: a gas gain drop of about 80% at 2 C/cm^2 . After chemical analysis, the aging was attributed to the HF-acid corrosion of the GEM foils, this acid was produced during the avalanche plasma after the fragmentation of CF_4 . The problem was solved by increasing gas flow rate in order to remove the fluorine radical before they can react with the GEM foils. [70] [71].
- A test on Triple-GEM+CsI was performed in pure CF_4 at a gas gain of 10^4 and a gap configuration of $1.5/1.5/1.5/2 \text{ mm}$. The chamber was exposed to a UV source with a rate of 1 GHz/cm^2 . No drop in performance was observed up to a integrated charge of 10 mC/cm^2 . [72]
- In order to test the Triple-GEM technology for the GE1/1 project, the CMS collaboration performed an aging study on a GE1/1 chamber working in Ar/CO_2 (70/30) at a gas gain of 2×10^4 with a gap configuration $3/1/2/1 \text{ mm}$. The chamber was irradiated at the GIF++ facility [74] with an intense source of 622 keV γ -rays at an interaction rate of the order of 10^4 Hz/cm^2 . The chamber accumulated a total charge of 55 mC/cm^2 after 6 months of continuous irradiation, i.e. the equivalent of 10 years of real operation of a GE1/1 chamber in its respective position in the CMS end-cap with a safety factor 9. A similar test was made in the same way with a same detector but working in $\text{Ar}/\text{CO}_2/\text{CF}_4$ (45/15/40). Here the total integrated charge was 53 mC/cm^2 . In each of these experiments no gain or resolution losses were reported [13].
- Also the Triple-GEM technology for the ME0 project are being tested by the CMS collaboration in the same way as the GE1/1 chambers at the GIF++ facility. During the writing of this thesis the integrated charge reached the value of 182 mC/cm^2 with no performance losses. In order to accelerate the aging test and the validation of the technology for its use in the ME0 project, one entire sector of a brand new chamber was irradiated with an X-ray gun (emitting 22 keV photons) resulting in an interaction rate of about $1.4 \times 10^5 \text{ Hz/cm}^2$. In this case the integrated charge is, until now, 875 mC/cm^2 i.e. 10 years of real operation of a ME0 chamber in its respective position in the CMS end-cap with a safety factor 3.1. All these tests were performed in Ar/CO_2 (70/30) [73].

Parameter	Plasma Chemistry[64]	Wire Chamber
Average electron energy	$1 - 10 \text{ eV}$	$5 - 10 \text{ eV (Ar)}$
Effective volume	$100 - 1000 \text{ cm}^3$	$10^{-10} - 10^{-8} \text{ cm}^3$
Typical electron density	$10^9 - 10^{12} \text{ e/cm}^3$	$10^{14} - 10^{17} \text{ e/cm}^3$
Typical power density	$0.01 - 10 \text{ W/cm}^3$	$10^8 - 10^{12} \text{ W/cm}^3$
Gas pressure	$0.01 - 10 \text{ Torr}$	$> 760 \text{ Torr}$
E/p	$10 - 50 \text{ V/(cm Torr)}$	$100 - 400 \text{ V/(cm Torr)}$
Type of electrical field	RF	DC
Typical gas flow	$\sim 1 \text{ gas volume/1 - 10 min}$	$\sim 1 \text{ gas volume/1 - 8 h}$

Table 4.1: Comparison between the plasma chemistry conditions and the typical ones in a wire chamber [52]

All this set of experiments confirm the radiation hardness of the Triple-GEM technology. It is important to notice that these tests were performed in many different geometry configurations and using different construction methods and materials. Moreover the interaction rate were very different between the experiments. Then, it is not possible to completely compare these tests since their differences can lead to different aging processes triggered by different construction materials or different polymer deposit geometries. Although the tests were performed with the same type of particles, i.e. photons, can not be compared to each other. This is because the interaction rates and the energies involved are extremely disparate.

4.5 Motivation for further studies on aging

Although studies on aging of gaseous detectors were performed since the born of this technology, a lot of work has to be done in order to fully understand these processes. Plasma chemistry is the science branch which studies the chemical processes happening during the electrons multiplication. Unfortunately typical operating conditions of plasma chemistry experiments are very different compared to the typical ones present in the gaseous detectors environments (see Table 4.1). These large differences in the operation environments is why many predictions from the plasma chemistry are not suitable for describing aging processes; however this subject can give many guidelines to produce clean detectors with clean gas mixtures from the aging point of view.

As already said many aging studies on the Triple-GEM technology were performed in the past, however the particle environment foreseen in the CMS muon end-caps (in particular in the region where the ME0 detectors will be placed) will be very challenging from the aging point of view. This because of two different factors: the particle environment made of radiation with high ionization power and the high background rate.

The expected energy spectra of the particle background (neutron, photon and electrons) in the ME0 position is shown in Figure 4.8. In spite of the GEM detector's

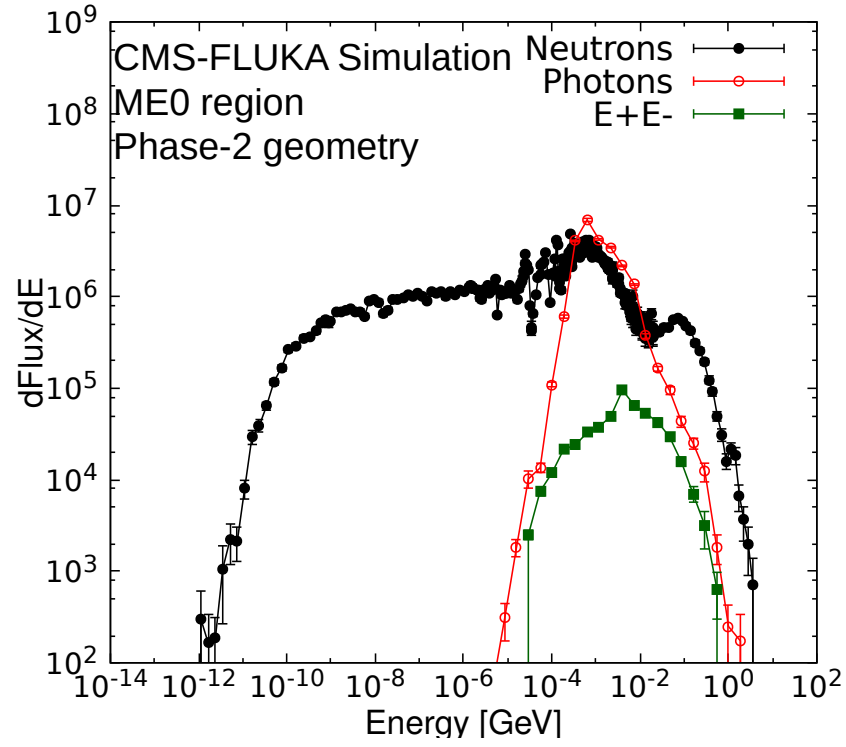


Figure 4.8: Energy spectra for different background particles extracted with FLUKA simulation considering an instantaneous luminosity of $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ for the upenergygrade ME0 detector. [65]

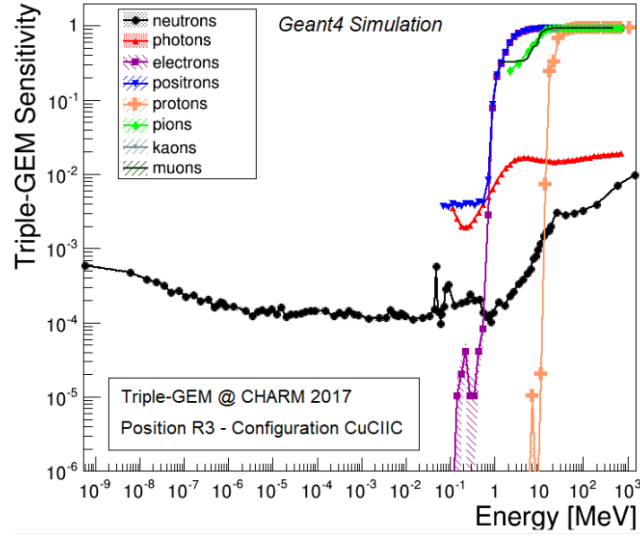


Figure 4.9: Sensitivity of the Triple-GEM detector exposed to the CHARM flux as a function of the energy of the incident particle, for the different particle species present. [66]

low neutrons sensitivity (less than 1% on all the energy spectrum, see Figure 4.9), the flux of these particles is very high and it extends over a wider energy range [65]. The intrinsic nature of neutrons will make them interact punctually in the detector provoking a big amount of released energy (in particular when they interact via inelastic scattering). This means that the density of the primary electrons will be higher with respect to the primary charge released by a particle with a lower specific ionization power. For this reason an interacting neutron will lead to an higher charge density during the electron multiplication, i.e. more events which can exceed the Raether limit. Then the probability of creating a discharge become higher and each of them is a potential danger from the aging point of view since they can prepare the electrode surface for subsequent buildup of deposits. Furthermore, any defect left from sparks on electrodes create imperfection on the electric field lines with all the disadvantages that it implies. Moreover, higher electron density during the avalanche processes can lead the formation of different polymers at different speeds since they can trigger different chemical reactions and change their kinematics.

The second risk factor is the high interaction rate of the ME0 (shown in Figure 4.10); this will cause an increase of the number of tracks, i.e. more polymer creation triggers and the possibility to overlap the energy deposit with the result of higher charge density and all the problems related. Another issue about the rate is the increasing of the detector gain when the rate overcome the value of $\sim 10^6 \text{ Hz/cm}^2$ (see Figure 4.11). Fortunately this issue will not affect the ME0 project since the maximum rate is expected to be one order of magnitude less: $\sim 10^5 \text{ Hz/cm}^2$. However, future experiments, which will exploit the Triple-GEM technology for very high rate environments, have to take into account the effect of the gain increasing caused by the ion space-charge in the transfer regions which tends to decrease the electric field near the top of the GEM foils and increase it near the bottom holes. As a result, the electron collection and extraction efficiencies increase, as well as the effective gain. An increase of the effective gas gain will lead to an higher charge

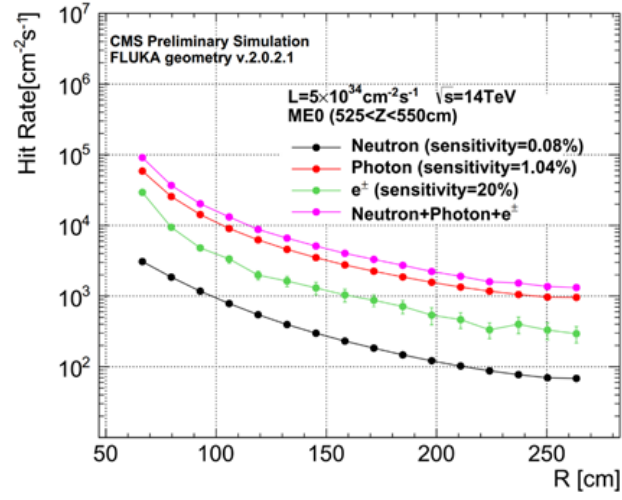


Figure 4.10: Simulated particle rate for a Triple-GEM detector in the ME0 position. [15]

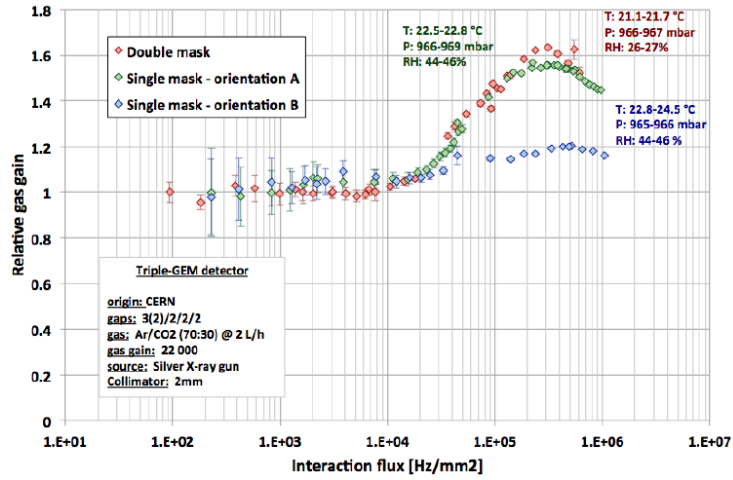


Figure 4.11: Rate capability of a Triple-GEM detector. For each point, the gain is normalized with the absolute value 2.2×10^4 . Single mask and double mask refer to different production method of the GEM foils. [13]

density during the electrons multiplication, i.e. more events which can exceed the Raether limit, with all the problems already described.

Chapter 5

Aging Study

The importance of performing new kind of experiments was clear in the previous chapter. In this chapter a new concept of aging test is presented; first of all a description of the experimental setup will be given. After this, the data analysis procedure and the environmental corrections will be illustrated and, finally, the obtained results and hints for following tests will be given.

5.1 Introduction

All the past studies on aging, illustrated in the previous chapter, exploited an higher interaction rate than the one foreseen for the experiment they were evaluating. This was an obliged choice in order to collect, in a reasonable time, the same charge expected in the real experimental environment; the photons were always chosen because easy to produce and to contain in a typical R&D laboratory. This was the usual way to accelerate an aging test; another one consists in increasing the gas gain of the detector to enlarge the total number of collected electrons. These accelerating methods have their pros and cons but, as already said, it is very difficult, if not impossible, to compare these experiments.

The new idea of accelerated aging test is to accelerate the outgassing of the materials. As already said, it is impossible to have a completely clean gas environment in a real situation; then an interesting idea for a new aging test is to pollute the gas volume much more than expected in a “clean” situation.

In this work an outgassing accelerated aging test is presented as well as some interesting outcomes. It is also possible to carry out more information about different polymerization rates and deposit geometries by irradiating the detector under test with two kind of particles with very different specific ionization powers. In this case it is important to collect the same charge per unit surface to compare the effects.

5.2 Experimental setup

The Triple-GEM prototype and the SWPC, exploited for the aging test, have already been described in chapter 3.

In order to perform such test it is important to pollute the gas volume and monitor the amount of occurred polymerization. This is made with a gas system

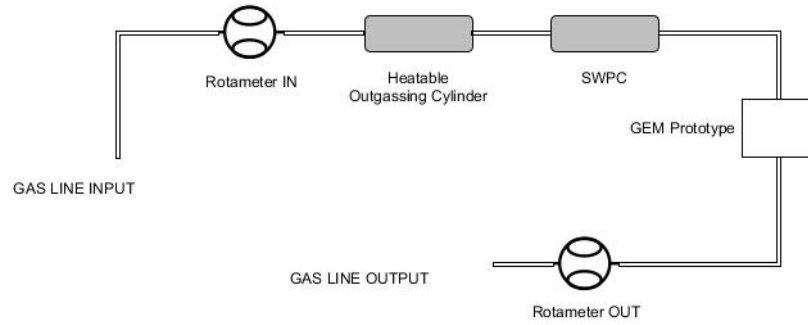


Figure 5.1: Schematic view of the gas system used in this work.

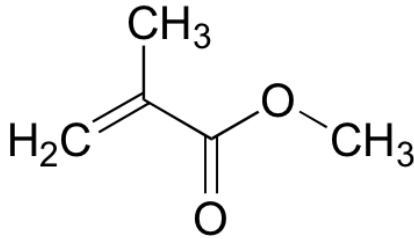


Figure 5.2: Methyl Methacrylate.

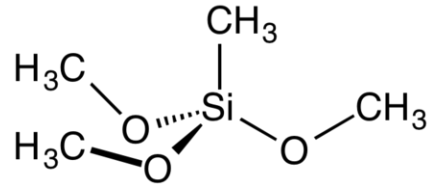


Figure 5.3: Methyltrimethoxysilane.

like the one shown in Figure 5.1 where the gas mixture Ar/CO_2 (70/30) is flushed and all the pipes are made of stainless steel. The rotameters put at the beginning and at the end of the piping system monitor the flux, which has to be maintained at the average value of 5 l/h. Before the detectors a stainless steel cylinder (called outgassing tube) is placed and inside it the contaminants are present. The chosen pollutants are (see Figures 5.2 and 5.3):

- Methyl Methacrylate;
- Methyltrimethoxysilane.

These come from 3140 RTV Coating[®] and Acrifix 1R 0192[®] respectively, which are glues used in the past for gaseous detectors construction. These contaminants are known for their outgassing properties and in particular for the induced damage to the gaseous detector performance. The contaminants were chosen to simulate a range of pollutants as wide as possible, given that one is a pure hydrocarbon while the other one is a silicon based molecule; the dissociation of these molecules create both hydrocarbon and Si-based radicals, which affect the detectors performances in different ways. The outgassing tube can be heated up with a resistive tape wound around. In particular, during the first run of data taking, the tube will be left at room temperature while, during the second run, the temperature will be raised up to about 50 °C. After being contaminated in the outgassing tube the gas mixture is flushed inside the SWPC and then inside the Triple-GEM prototype.

For this work's purposes it is important to read the pulse signals from the wire chamber and from the GEM prototype for a total of 3 electronics channels, as

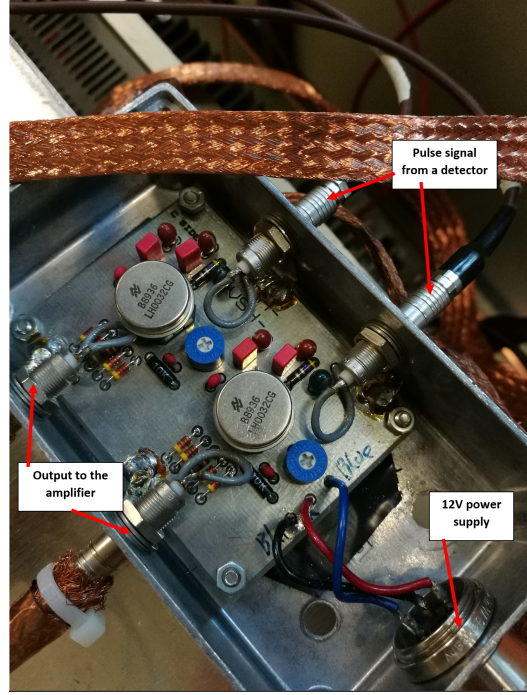


Figure 5.4: Top view of the charge amplifier used in this work, inputs-outputs and power supply are indicated.

described in 3, indeed the strip structure of the GEM prototype permit to read signal from either the Xrays and the Alpha sectors. The idea is to measure the pulse height spectra from these channels. In order to do so pulses from the detectors are preamplified by a custom made charge amplifier (see Figure 5.4). Signals are then sent to a linear amplifier: the amplitude of the outputs is now proportional to the charge collected by the detector, that is the energy of the revealed particle. These signals are sent to a ADC which acquires a pulse height spectrum every 30 minutes for each of the three channel. In order to generate the correct ADC gate, i.e. the reading window, pulse signals are split and discriminated and the logical signals from all the channels are input to an OR logic port. The OR of all the three channels is the gate needed. In this way is possible to sample, for each channel, either a particle signal and the zero value. The gate created in this way permits to have spectra within additional peak on the left which refers to the zero charge, or energy position. With this kind of setup there is no need to calibrate the ADC channels; in fact the information about the detector gain is contained in the difference between the signal peak position and the zero peak position. In Figure 5.5 an example of a 5.9 keV photon source spectrum is shown. A schematic of the setup is illustrated in Figure 5.6, while a photograph is shown in Figure 5.7.

This experiment is performed by taking a spectrum from each of the channel every 30 minutes. The SWPC and the GEM Xrays sector are irradiated with a ^{55}Fe source, while the GEM Alpha sector is irradiated with an ^{241}Am source which emits, between others, alpha particles of about 5.6 MeV . An example of spectrum is shown in Figure 5.8; it is possible to observe that there are two different signals peaks: the main one is the signal from the 5.6 MeV alpha particles while the lower

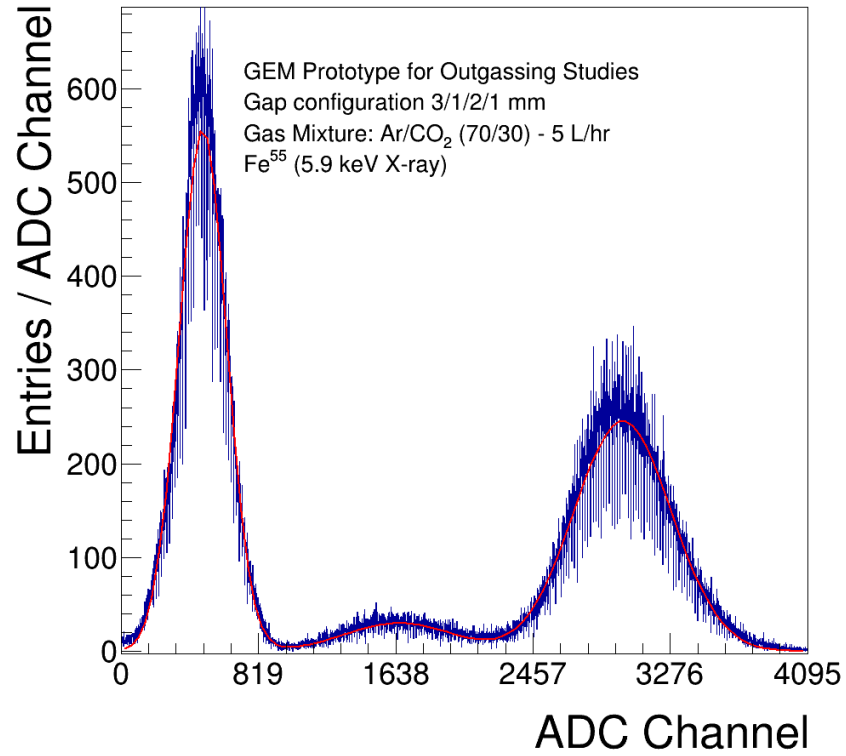


Figure 5.5: A ^{55}Fe charge spectrum taken by the GEM prototype. The main peak refers to the zero position. The red line is from the best fit of the spectra with 3 Gaussian functions.

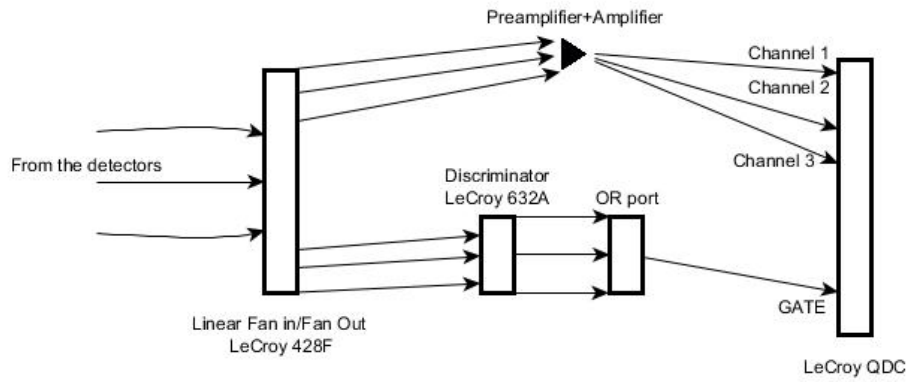


Figure 5.6: A schematic of the setup used in this work.

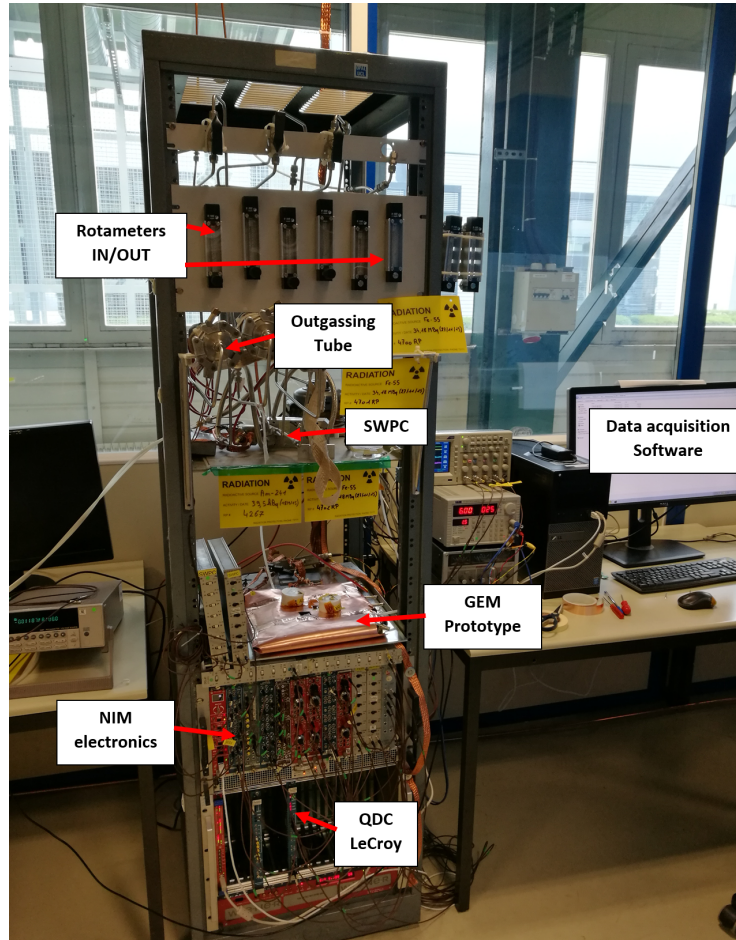


Figure 5.7: A front view of the experimental setup.

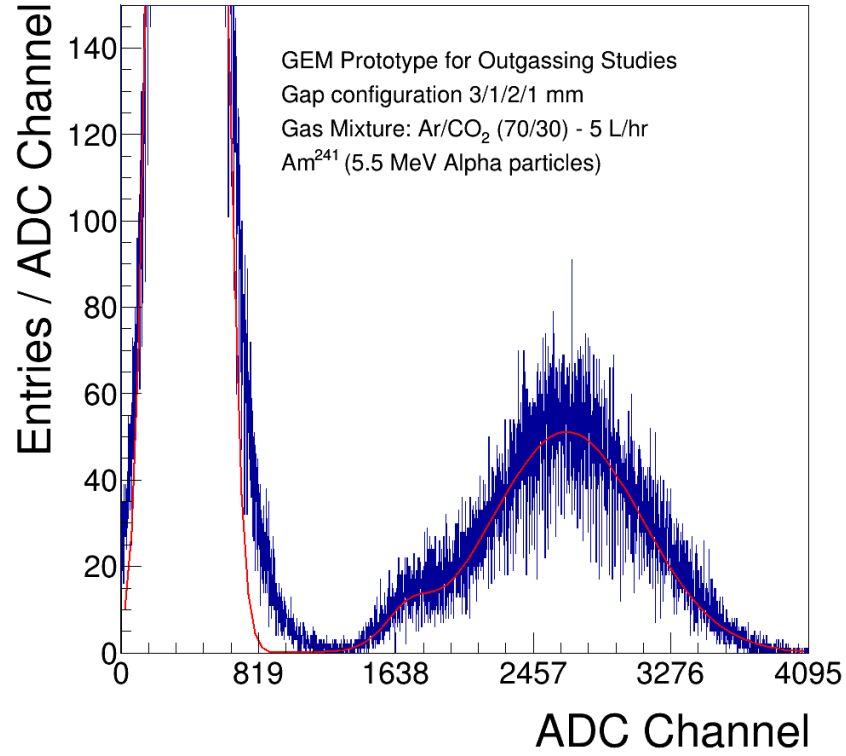


Figure 5.8: A ^{241}Am charge spectrum taken by the GEM prototype. The red line is the best fit to the spectra with 3 Gaussian functions.

Channel	Run 1	Run 1 bis	Run 2	Run 2 bis
SWPC	$\sim 800 \text{ Hz}$	$\sim 7.5 \text{ kHz}$	$\sim 800 \text{ Hz}$	$\sim 8.5 \text{ Hz}$
Xrays sector R_X	$\sim 900 \text{ Hz}$	$\sim 20.5 \text{ kHz}$	$\sim 900 \text{ Hz}$	$\sim 22 \text{ kHz}$
Alpha sector R_α	$\sim 600 \text{ Hz}$	OFF	$\sim 600 \text{ Hz}$	OFF

Table 5.1: Average interaction rate during the data taking runs

one came from other alpha particles with lower energies $\sim 5.4 \text{ MeV}$ [42].

The ^{55}Fe sources, placed on the SWPC and on the Xrays sector, have to be attenuated in order to obtain the same interaction rate as the Alpha sector $\sim 600 \text{ Hz}$. This was done at the beginning of each of the two runs. When the first run stopped, a run which involves only the SWPC and the Xrays sector is performed at higher interaction rate, in order to match the integrated charge in the Xrays sector with the Alpha one; the same procedure was made after the second run. This is necessary because of the extremely different energy of the irradiating particles: 5.9 keV photon versus 5.6 MeV alphas, which makes Alpha sector gain integrated charge more rapidly than the Xrays sector at the same integration rate. The different interaction rate during the various runs are shown in Table 5.1 The method used to estimate the integrated charge will be described in the next section.

An Arduino-based weather station was placed near the detectors in order to

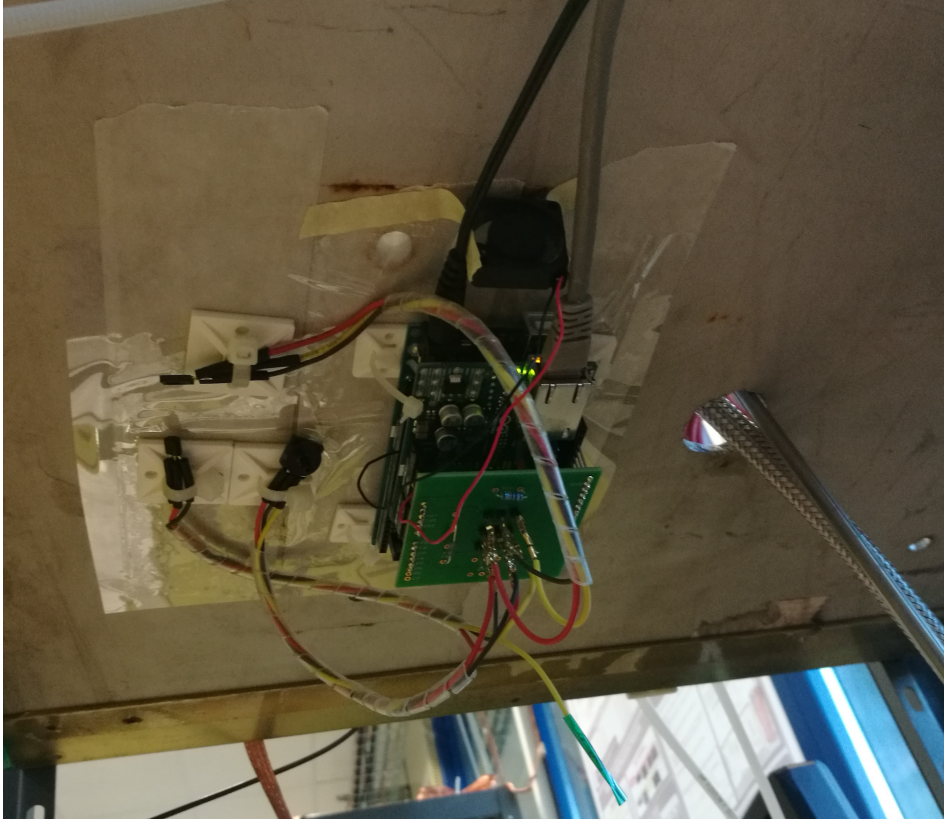


Figure 5.9: Bottom view of the Arduino station.

monitor the environmental parameter of interest: temperature and pressure in particular. The setup is shown in Figure 5.9. The station is placed outside the gas volume because it was demonstrated in past studies [13] that there is no difference between sampling the temperature and pressure inside the gas or outside, as long as the station is not so far from the detector.

5.3 Data analysis

5.3.1 Integrated Charge estimation

It is fundamental to integrate a similar charge per unit surface in each of the GEM sectors to compare the final results. Since the QCD calibration changes during time and this work requires several weeks of data taking without interruptions, it is not possible to make an absolute calibration of the spectra from the ADC. The idea is to measure the calibration charge Q : the charge collected by each sector of the GEM for 30 minutes before beginning the run; this is made by measuring the strips current and multiplying it for the time. Then a 30 minutes spectrum is taken in order to measure the calibration quantity I defined as:

$$I = \sum_{i=0}^{4095} (i \times h_i), \quad (5.1)$$

where the index i spans over the 4096 ADC channels, while h_i is the number of entries in the i -th channel. Since it is clear that I is proportional to the charge, it is possible to assume that the ratio Q/I is constant during the data acquisition period. During the run it is then possible to estimate the charge associated to the j -th spectrum Q_j by measuring the value I_j for this particular spectrum, then:

$$Q_j = \frac{I_j}{I} Q. \quad (5.2)$$

This method was validated by directly measuring Q_j at different gains and with different radioactive sources and comparing the results with the estimated values obtained using Equation 5.2. The ratios Q_j/I_j matched within 5%, then the method is assumed as valid.

5.3.2 Spectra Analysis

As already mentioned the detector gain is proportional to peaks positions. In this particular experimental setup the information about the gain is obtained from the difference between the signal peak and the zero peak. In order to obtain them, since all the three channels produce spectra with three characteristic peaks, the spectra are fitted with a function which is a sum of 3 Gaussian functions:

$$f(x) = A_1 e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} + A_3 e^{-\frac{(x-\mu_3)^2}{2\sigma_3^2}}. \quad (5.3)$$

Where the indexes 1, 2 and 3 refer respectively to peak at zero, middle peak (escape or lower energy alphas) and signal peak (photopeak or higher energy alphas).

The quantity of interest is then the difference $\mu_3 - \mu_1$ since:

$$Gain \propto (\mu_3 - \mu_1).$$

Also the quantity $\mu_2 - \mu_1$ carries information about the gain, but in this work it is neglected since the middle peak has, typically, a lower amplitude and then less statistical relevance.

5.3.3 Environmental Corrections

As mentioned in chapter 2 gain can fluctuate because of changes in the environmental parameters. A model predicts an exponential behaviour of the gain versus T/P variable [30]. However in this work a different method, used widely in literature [13] [55] [73], will be exploited in order to have more degree of freedom in the correction.

This method supposes that the gain environmental fluctuations are parametrizable with a power law function where pressure and temperature are not correlated:

$$G_{uncorr}(T, P) = G_{corr} \left(\frac{T}{\langle T \rangle} \right)^a \left(\frac{\langle P \rangle}{P} \right)^b, \quad (5.4)$$

where $\langle T \rangle$ and $\langle P \rangle$ are the average values of temperature and pressure, while a and b are parameters, greater than zero, to be evaluated experimentally. Note that in this section gain and peak positions are written with the same letter G . The

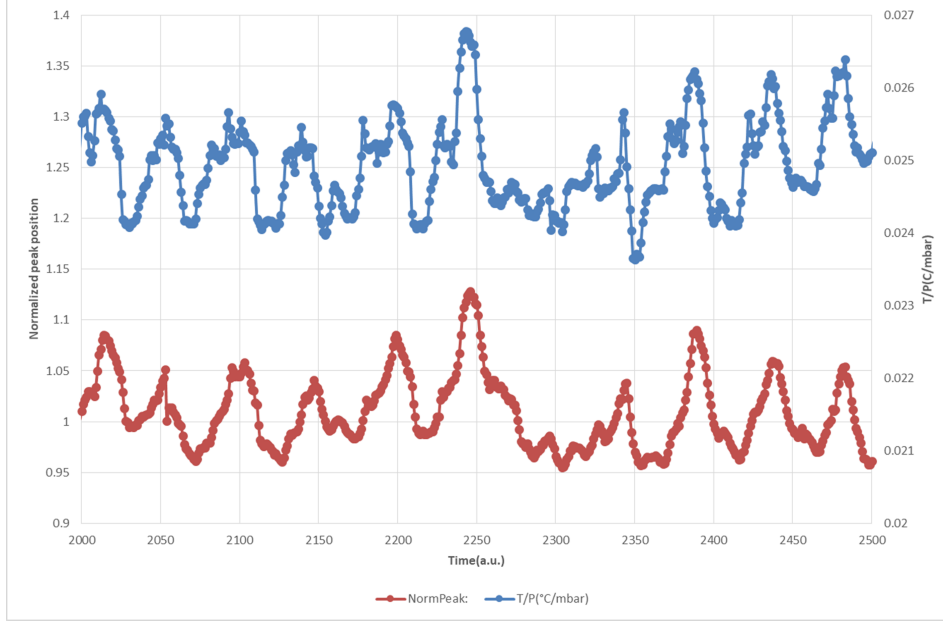


Figure 5.10: Peak position (*NormPeak*) and T/P fluctuation in time. The correlation is easy to notice.

qualitative behaviour of the gain compared to T/P is shown in Figure 5.26, where data from the GEM Xrays sector are illustrated.

The procedure to find the accurate parameters to correct fluctuations consists in two steps: first correction of the pressure dependence and, after, the correction of the temperature dependence. In Figure 5.11 and 5.12 the dependences of the peak positions on the gas pressure of the SWPC and the GEM Xrays sector are shown.

The fit function used is:

$$f(x) = \left(\frac{B}{P}\right)^b,$$

where B revealed to be very near to the value of $\langle P \rangle$. After this, peak positions were corrected:

$$G_{Pcorr}(T) = \frac{G_{uncorr}}{\left(\frac{B}{P}\right)^b}.$$

These new values of the peak positions depend only on the temperature variable as Figure 5.13 and 5.14 show.

This time the fit function is:

$$f(x) = (AT)^a,$$

and the value of A is very close to $\langle 1/T \rangle$ one more time. The peak position can be now corrected completely:

$$G_{corr} = \frac{G_{Pcorr}}{(AT)^a}.$$

In Figure 5.15 and 5.16 the distribution of the peak positions is shown before and

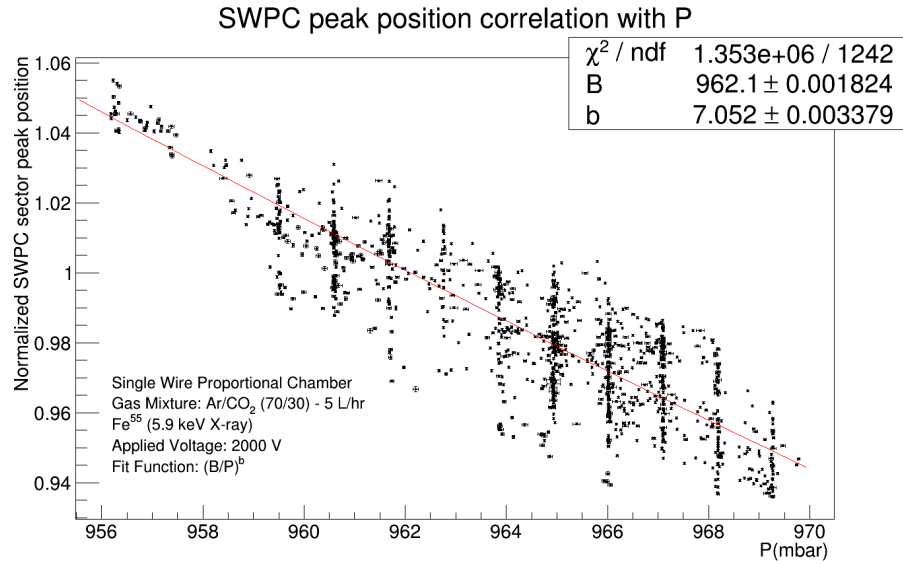


Figure 5.11: SWPC Peak position as function of the gas pressure.

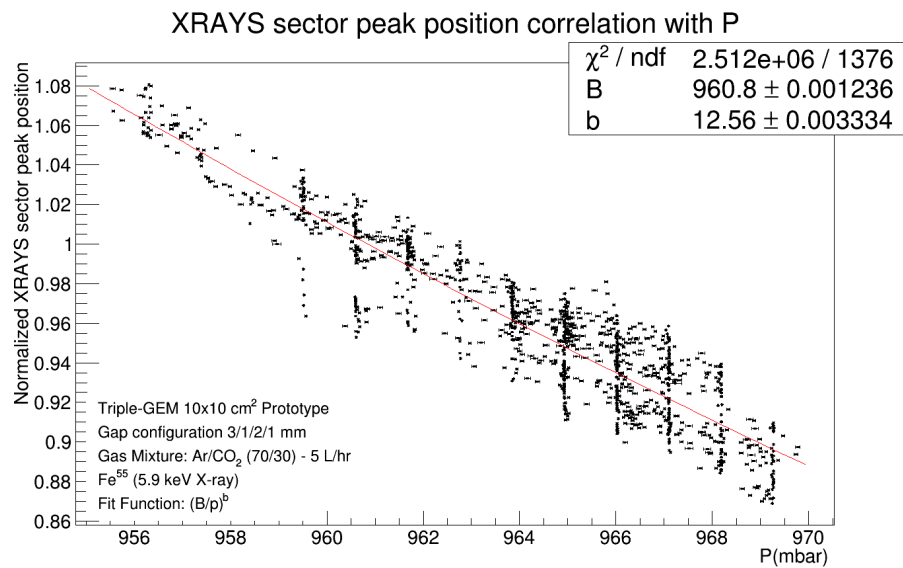


Figure 5.12: Xrays sector Peak position as function of the gas pressure.

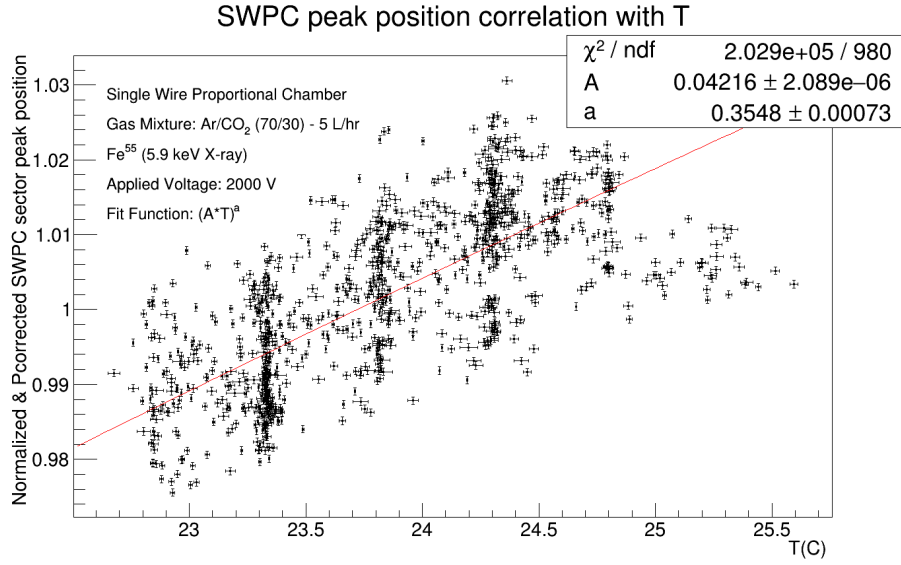


Figure 5.13: SWPC Pressure corrected Peak position as function of the gas temperature.

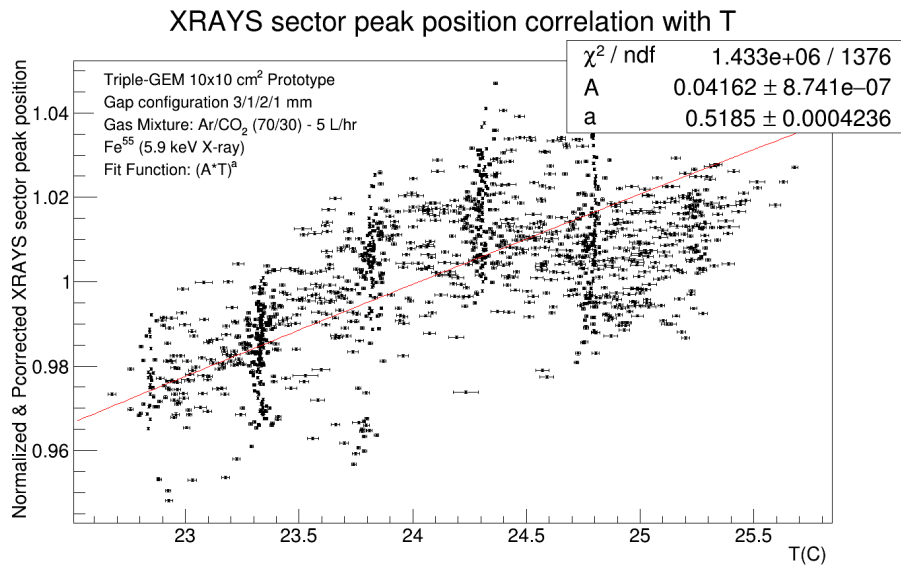


Figure 5.14: Xrays Pressure corrected sector Peak position as function of the gas pressure.

after the correction.

It is important to say that the correction parameters were evaluated fitting a certain sample of all the data collected. The sample has to be chosen from data where we know there are no absolute gain fluctuations in order to correct only the environmental ones. Once found the parameters, all the data can be corrected.

As far as Alpha sector is concerned, no such a good sample can be found and therefore it is not possible to correct Alpha peak positions. More information about this issue may be found in the following section.

5.4 Results

During this experiment, two runs were realized: the first one lasted 30 days, for a total of 1391 spectra acquired in the Alpha sector irradiated with the ^{241}Am source; regarding the SWPC and the Xrays sector, 1626 spectra were acquired. The charges integrated by the two GEM areas were 91 mC/cm^2 for the Xrays sector and 73 mC/cm^2 for the Alpha one. During the second run the outgassing tube was heated up to about $50\text{ }^\circ\text{C}$. This run lasted 35 days and a total of 1759 spectra were acquired, 1522 of which from the Alpha sector. The collected charge on the Alpha sector was 99 mC/cm^2 while in Xrays one was 88 mC/cm^2 . The history of the irradiation of the two GEM areas is shown in Figure 5.17 and 5.18 respectively. The total charge collected on the Alpha sector was 172 mC/cm^2 while in Xrays one was 179 mC/cm^2 ; it is important to notice that this aging study cannot be compared to a traditional one where the gas mixture is clean. The integrated charge collected in this experiment is equivalent to much more charge than a classical aging test.

During the acquisition time, the peak positions of the 3 channels were monitored. Peak position development of the SWPC is shown in Figure 5.19, while in Figure 5.20 the same values corrected by the environmental fluctuations are shown. It is possible to notice that the SWPC peak position, at the end of the test, decreased by about 20% of the initial value. The degradation of the peaks can be seen in Figure 5.21. The loss of performances of the SWPC means that the pollutants inside the gas volume, during the electron multiplication, released a lot of radicals and the latter created polymers structures which damaged the multiplication region near the wire. It is now sure that the quantity of created polymer was sufficient to damage a traditional gaseous technology as the SWPC.

As regards the GEM detector, the history of the Xrays sector peak position is shown in Figure 5.22 while the corrected one in Figure 5.23. As it is possible to see, no degradation in the GEM Xrays Sector performance occurred. As far as Alpha sector is concerned, the history of the peak position is shown in Figure 5.24. Also in this sector no degradation in the GEM performances is shown. It is noticeable that the peak position rose during the acquisition run and only after a certain period it stabilized to its nominal value. This situation is due to the charging up effect of the foils, which take more time to stabilize the gain, since the high charge deposited by the alphas and the defects in the electric field lines due to the window on the drift plane. This behaviour is the reason why it was not possible to have a good sample to make the environmental correction; since the peak position is not constant during a sufficient amount of time, it is not possible to isolate the pure environmental fluctuations.

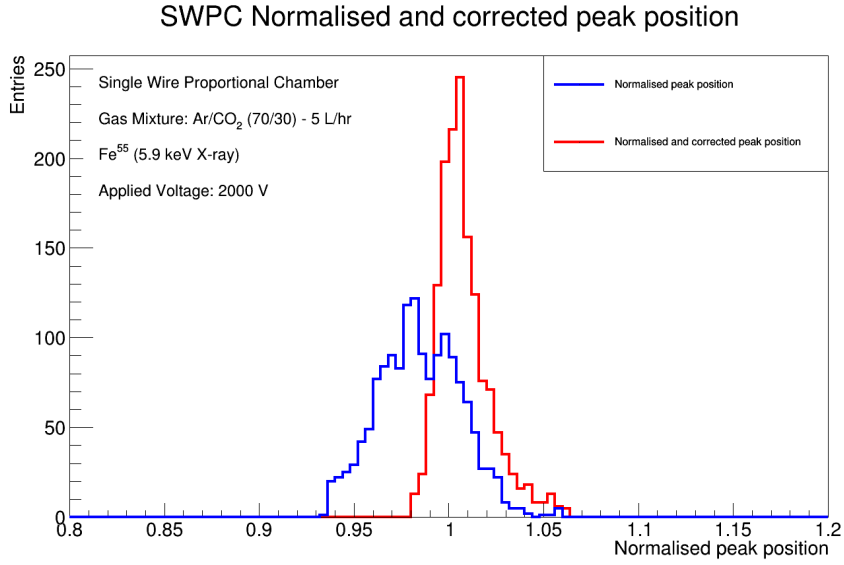


Figure 5.15: Distribution of the SWPC corrected Peak position and the uncorrected one.

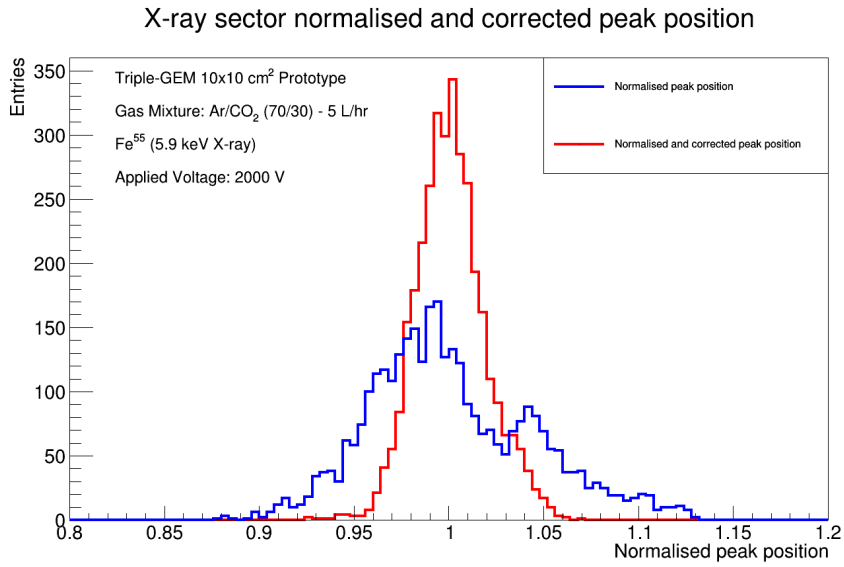


Figure 5.16: Distribution of the Xrays sector corrected Peak position and the uncorrected one.

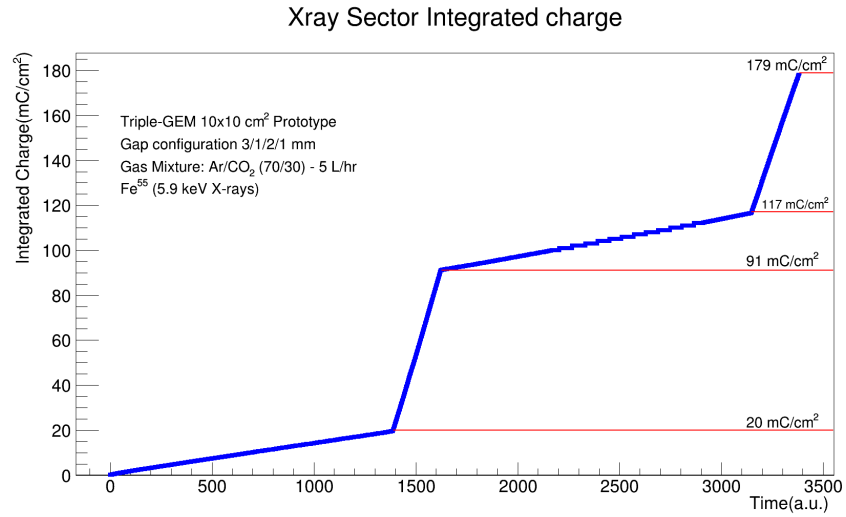


Figure 5.17: History of the integrated charge by the Xrays sector.

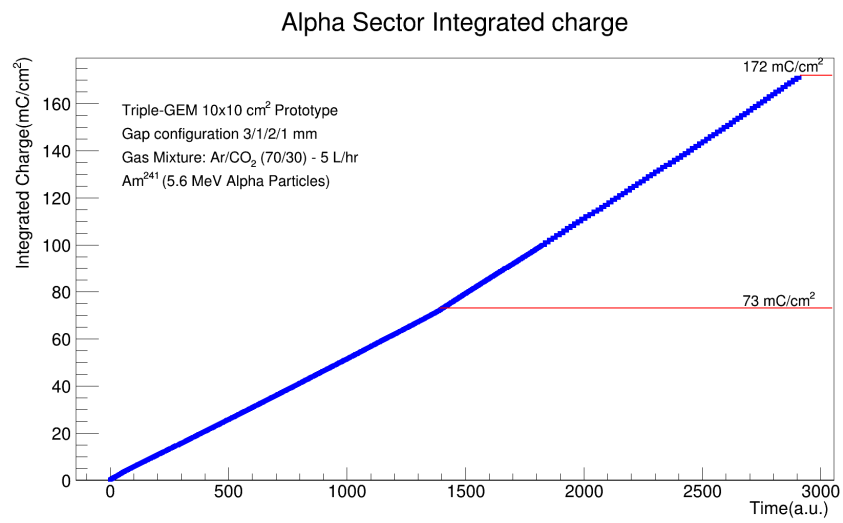


Figure 5.18: History of the integrated charge by the Alpha sector.

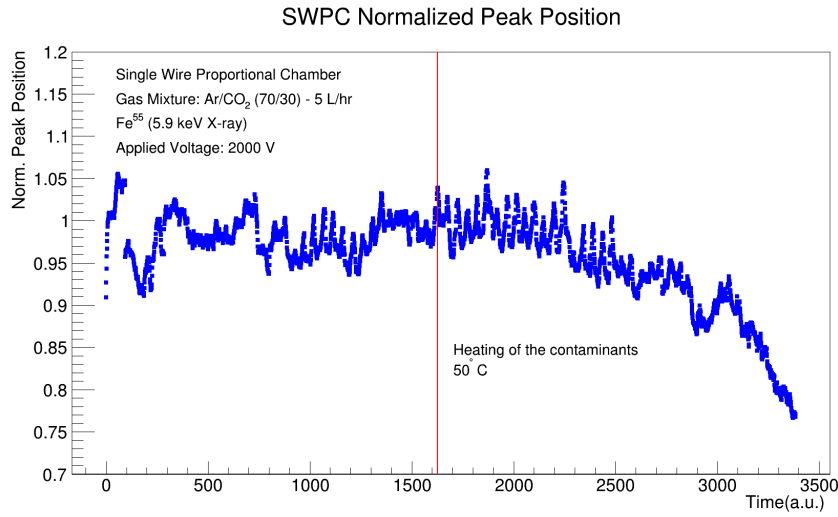


Figure 5.19: History of the peak position of the SWPC sector.

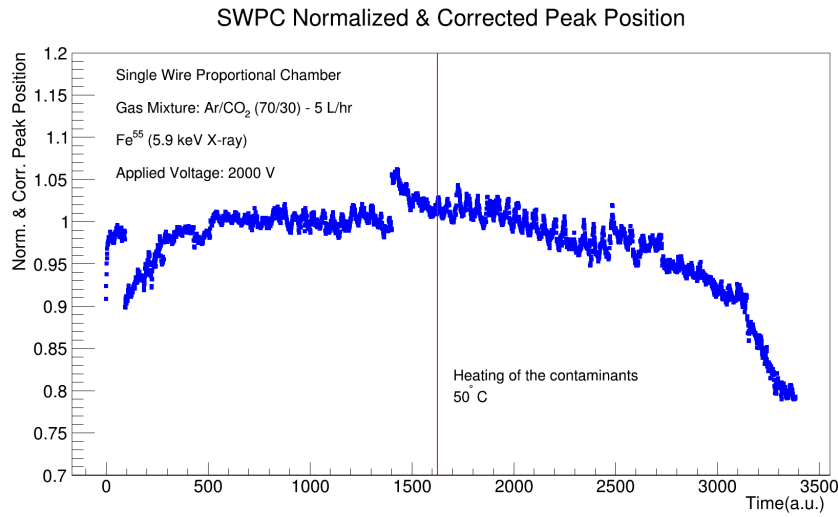
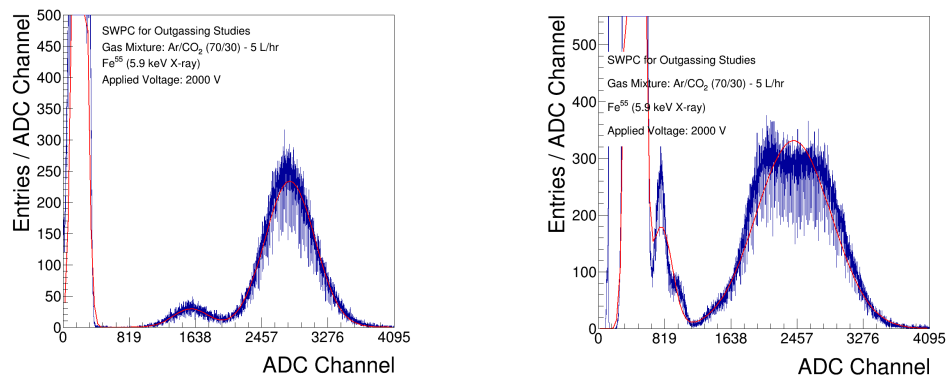


Figure 5.20: History of the peak position of the SWPC sector, corrected for the environmental fluctuations.

Figure 5.21: ⁵⁵Fe source spectrum comparison: on the left spectrum acquired at the beginning of the test, on the right after the entire test.

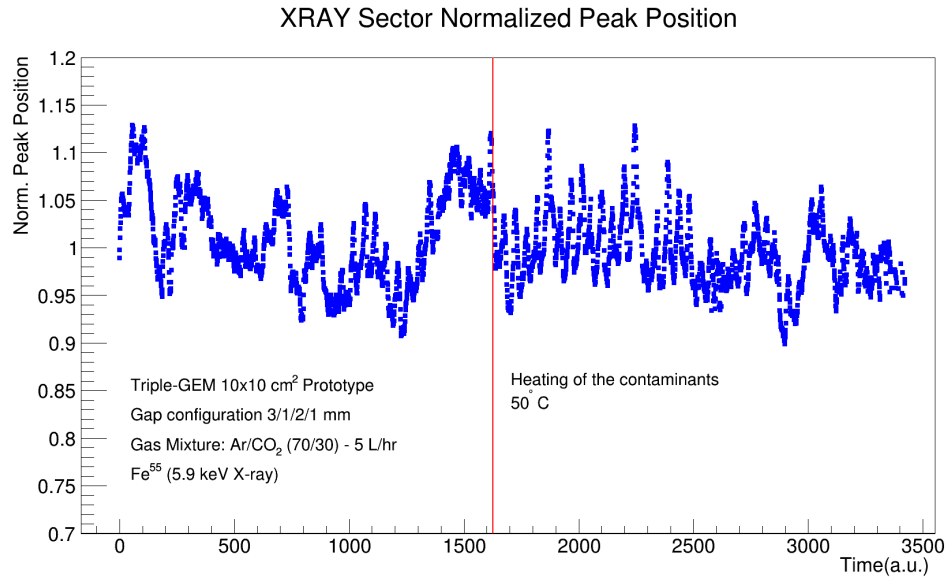


Figure 5.22: History of the peak position of the Xrays sector.

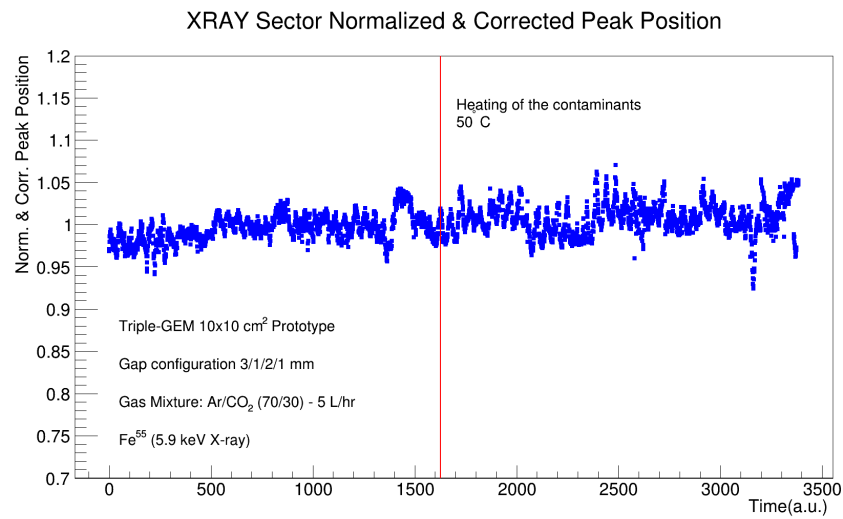


Figure 5.23: History of the peak position of the Xrays sector, corrected for the environmental fluctuations.

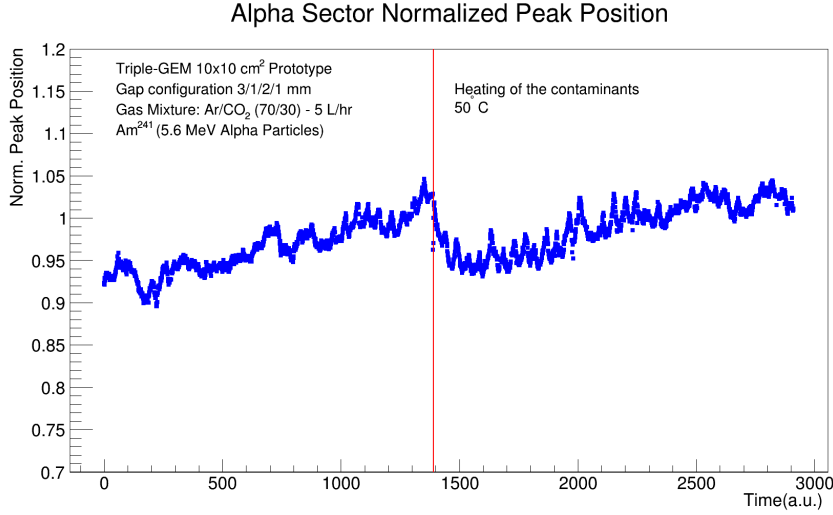


Figure 5.24: Alpha sector gain during the acquisition time.

In order to make reference measurements of the peak position, during every stop of the data taking, an absolute gain measurement was performed with a rate and strips current measurement, as described in section 3.3. The results, at different times, are shown in Figure 5.25. Within environmental fluctuations, the GEM sectors absolute gas gain remains constant during all the data acquisition time. This confirms the thesis of no aging observed on the GEM detector in both the sectors.

The acquired spectra permit also to monitor the energy resolution of the peaks. The data analysis was performed only using peak position because these data fluctuate less and it is less sensible to the EM noise present in laboratory. However it is clear the anti-correlation between these two variables: the energy resolution is defined as:

$$R(E) := \frac{FWHM}{E}, \quad (5.5)$$

where $FWHM$ is the Full Width Half Maximum, which is related to the σ of the Gaussian distribution ($FWHM = 2.355 \times \sigma$), while E is the energy related to the peak, i.e. the peak position. The latter is obviously proportional to the number of electron collected by the readout strips N . Since the ionization process and then the multiplication one are Poisson processes, the error on the number of electrons produced during these processes is $\sqrt{N}$. The resolution is then:

$$R \propto \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{Peak Pos.}}.$$

It is then sufficient to use only one of this observable in order to monitor the GEM performance. The anti-correlation is clearly visible in Figure 5.26, where a sample of the SWPC data where analysed.

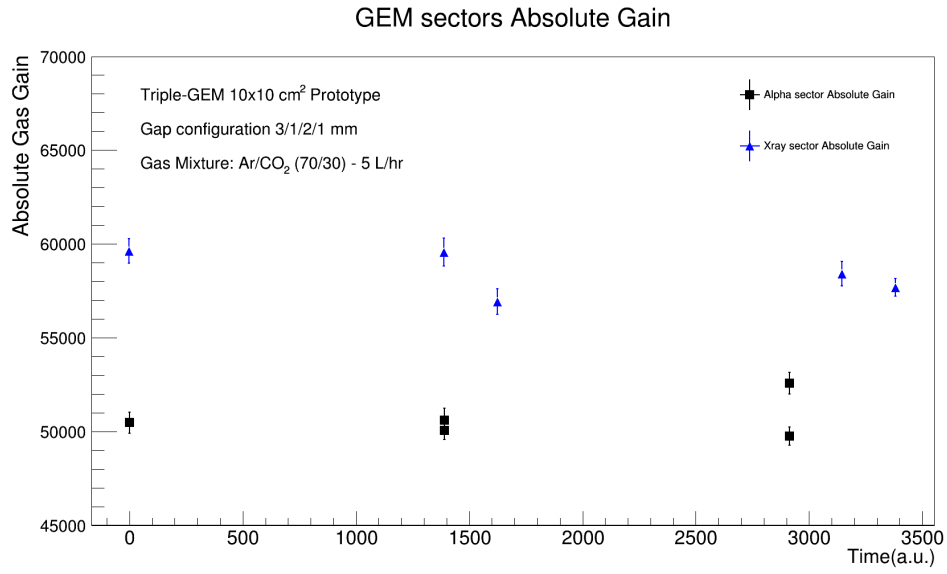


Figure 5.25: Alpha sector gain during the acquisition time.

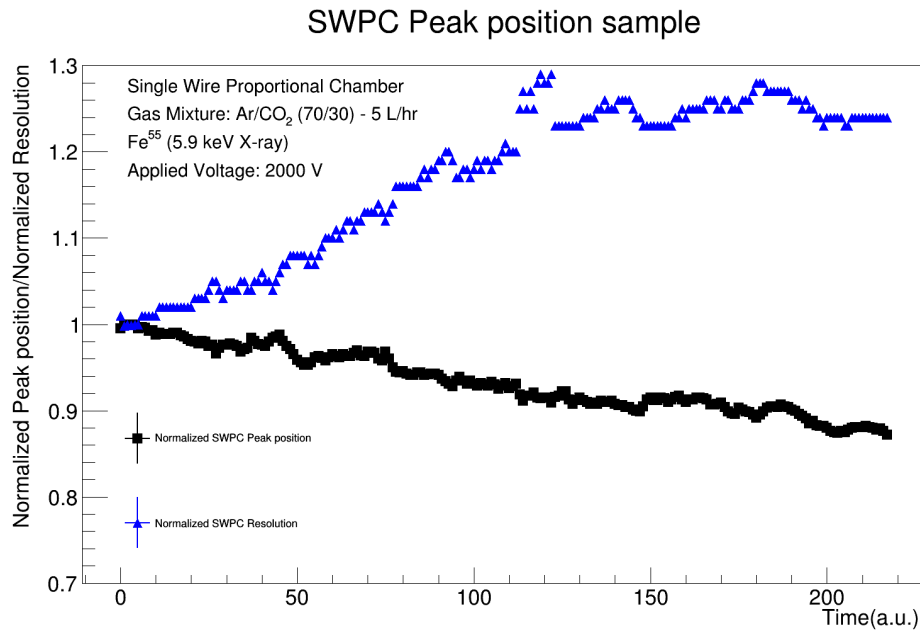


Figure 5.26: SWPC peak position and resolution which clarifies the anti-correlation between these two observables.

5.4.1 Scanning Electron Microscope (SEM) Analysis

In order to understand the different geometry of the polymer deposits in the two different sectors, the GEM prototype was dismantled after the whole data taking, in order to collect samples to be analysed. For each GEM foil 3 samples were collected: one from the area irradiated by alpha particles, one from the area irradiated by X-rays and one from a non-irradiated area as reference. the location of the considered samples is shown in Figure 5.27. It is interesting to note that the third GEM foil presents dark marks in the region where it was irradiated by alphas (Figure 5.28). This phenomenon was already observed and it is attributed to the electrochemical corrosion of the copper triggered by the current collected by the GEM electrodes and the presence of oxygen-based radicals produced in avalanche plasma. However, the oxide is conductive so it doesn't induce any degradation in performance.

In Figures 5.29, 5.30 and 5.31 pictures taken with the Scanning Electron Microscope are shown, respectively for a hole in the non irradiated area, a hole in the Xray sector and a hole in the Alpha sector. Both the irradiated holes present sort of damages to the rim and the inner part of the holes corroded. This is clearly an effect due to electron avalanches which causes the wearing out of the holes; this effect seems not to cause any loss of performance of the detector. Furthermore, it is possible to note a shadow rim around the hole irradiated with alpha particles. With a X-rays spectroscopy it was discovered that this shadow is composed by Si-based compounds. This polymer deposit wasn't found in the holes irradiated with the ^{55}Fe source; it is then possible to suppose that this deposit formation is more likely if the electron avalanches are more dense as in the Alpha sector.

As discussed in Section 4.4 the damaging of the holes edges could lead to loss of performances and an increase of the discharge probability. Moreover polymer deposit in this very sensitive region could induce loss of transparency of foils, Malter effect and other effects already illustrated before.

5.4.2 Discharge Probability

As described in chapter 3, the experimental setup permits to indirectly identify the occurrence of a discharge in the detector. Two trips were observed in the whole data acquisition time. It is possible to estimate the discharge probability if a trip is interpreted as a discharge event. This probability is easily estimated as:

$$P_{dis} = \frac{N_{trips}}{N_{tot}}, \quad (5.6)$$

where N_{trips} is the number of occurred trips events and N_{tot} is the total number of particles interactions. The latter is calculated as:

$$N_{tot} = (R_{X_1} + R_{\alpha_1})t_1 + (R_{X_2} + R_{\alpha_2})t_2,$$

where t_1 and t_2 are the acquisition times during run 1 and run 2, while the R_i ($i = X_1, X_2, \alpha_1, \alpha_2$) terms refers to the rate values of Xray and Alpha sectors respectively during run 1 and run 2 as illustrated in Table 5.1. Events during the only SWPC and Xray sector irradiation are not taken into account since it is expected that the discharge probability in this runs is much lower than the one when

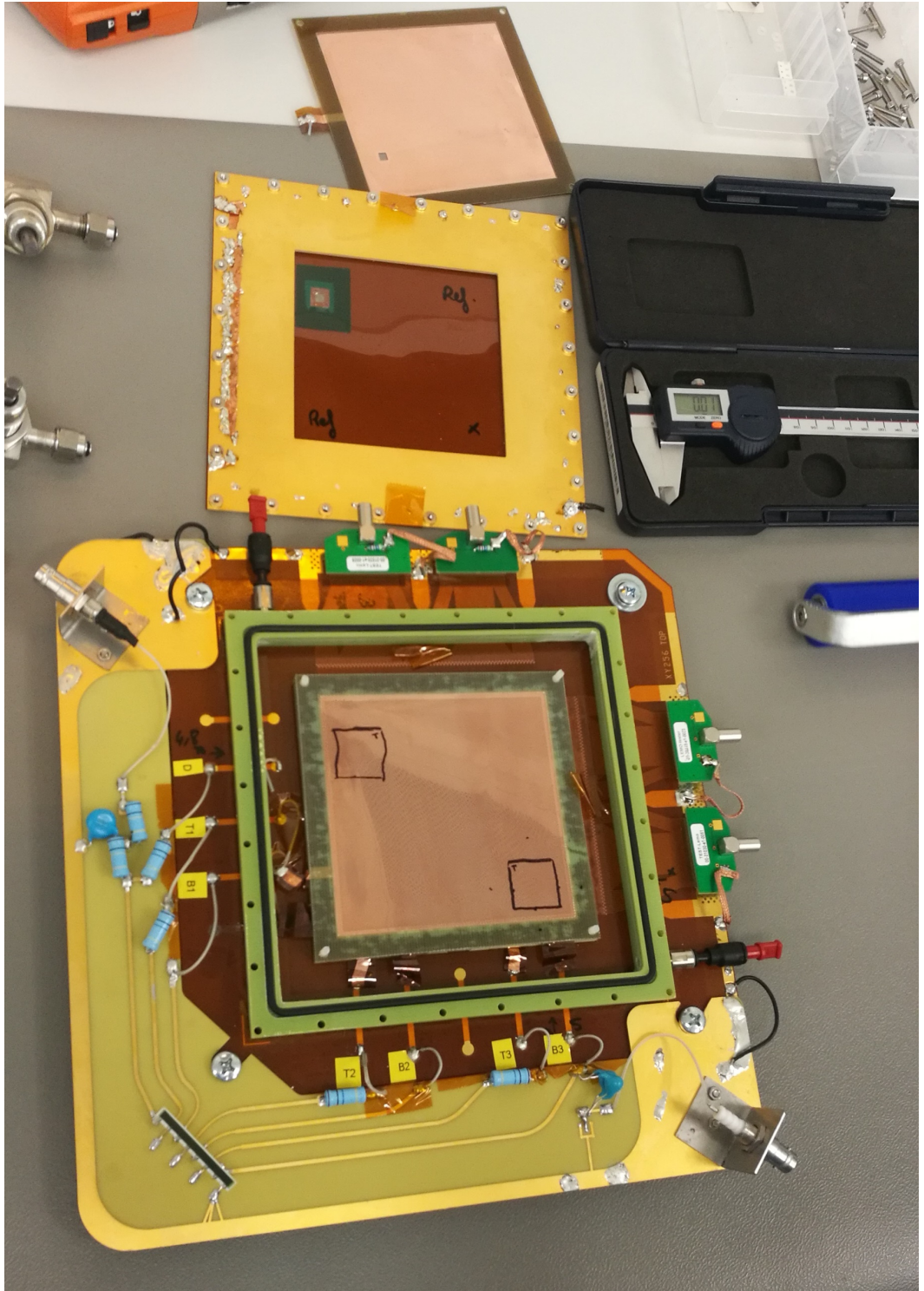


Figure 5.27: Top view of the dismantled GEM; black squares delimit the region where the samples were taken.

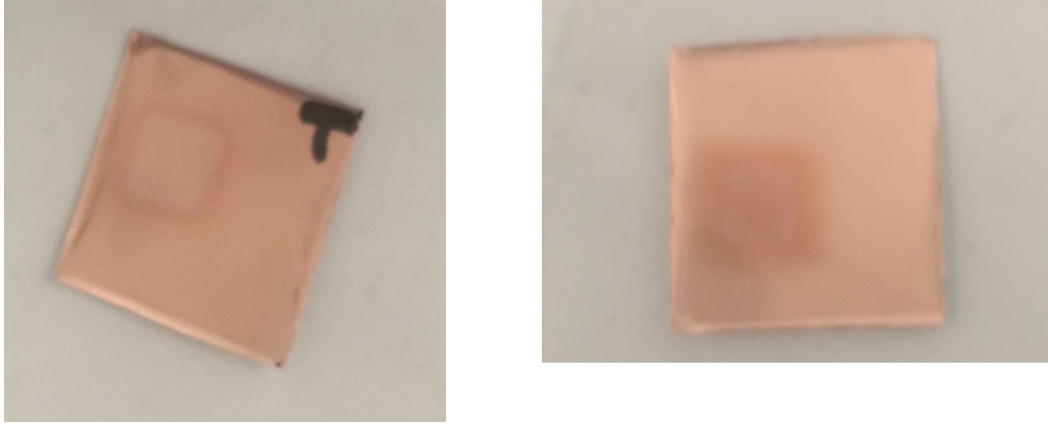


Figure 5.28: View of the Top side (left) and the Bottom side (right) of the third GEM foil irradiated by alphas. It is possible to notice the oxidized copper, this is present only in this sector.

irradiating also with alphas. The value measured during this experiment was:

$$P_{dis} = 2.5 \times 10^{-10}.$$

This value must be interpreted as a measurement of the discharge probability valid only in this experimental particular case, i.e. at this working voltage, with these particular irradiation sources, with this gas mixture contamination situation and with this particular method of discharges detection. This value results to be of the same order of magnitude of the discharge probability measured [13] at the same gain value of 9.5×10^{-10} .

5.5 ^{241}Am Number of Primaries Simulation

In order to quantify the difference in specific ionization between X-rays and alpha particles used in this experiment a simulation is needed. As discussed in Section 3.3 it is possible to assume that a 5.9 keV photoelectron, released by an incoming photon of the same energy, deposits all its energy in the 3 mm gap. The same assumption is not valid for alpha particles; as illustrated in Section 2.1.1, a charged particle has a continuous loss of energy while it passes through the matter, in particular 5.6 MeV alphas don't stop in the 3 mm drift gap but they release only a certain part of their initial energy. Then it is important to have an estimate of the ^{241}Am alpha particles energy when they enter the drift gap and, moreover, an estimation of the deposited energy within this gap. The simulation tool used was TRIM, which is contained in the SRIM software [75]. It allows to simulate the energy loss, the range and the exit energy of ions when they cross a layer of matter.

5.6 MeV alpha particles were simulated to pass through a slab composed by materials shown in Table 5.2, while a scheme of the layers is shown in Figure 5.32.

The exit energy from this layer is the entry energy of the drift gap E_{entr} , these values for various impinging angles are shown in Figure 5.33. For impinging angles greater than 60° the simulation foresees no particles coming out from this layer.

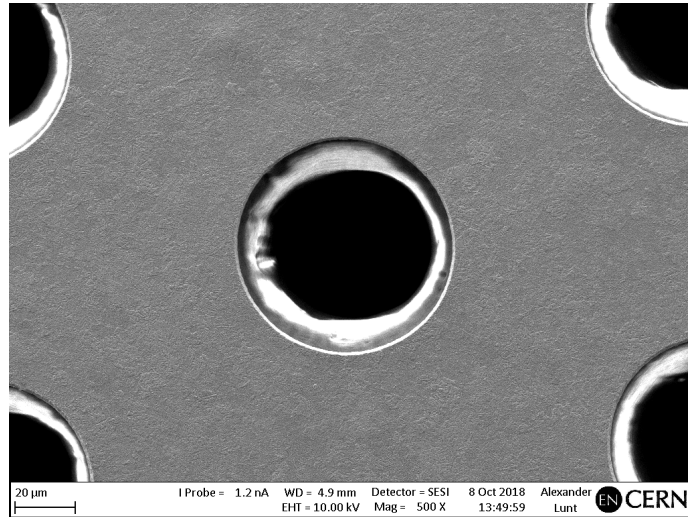


Figure 5.29: SEM picture of a hole on the third GEM foil in the not irradiated sector.

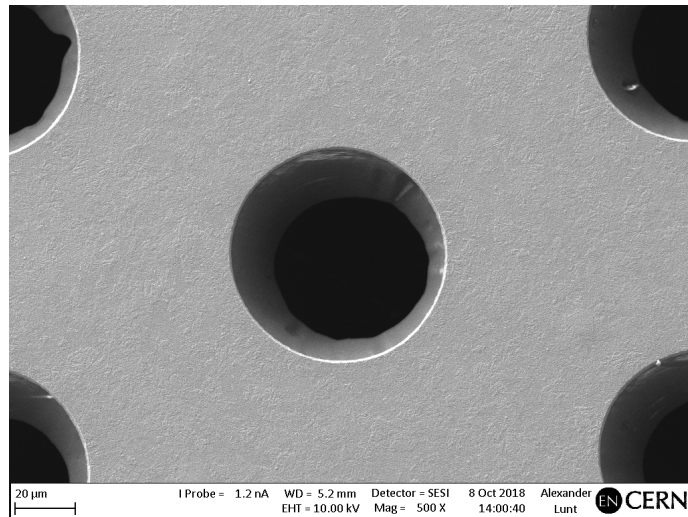


Figure 5.30: SEM picture of a hole on the third GEM foil in the Xray sector. The edge of the hole is degraded and the inner part looks corroded.

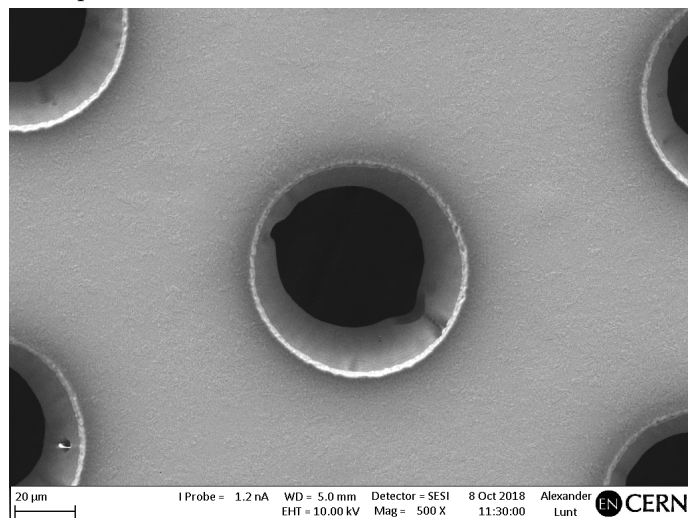


Figure 5.31: SEM picture of a hole on the third GEM foil in the Xray sector. The edge of the hole is degraded and the inner part looks corroded. Moreover a tiny shadow ring is present here, it resulted to be composed of Si-based compounds

Layer Number	Layer Composition	Layer Density (g/cm^3)	Layer Thickness
1	Air, Dry (ICRU-104)	1.205×10^{-3}	1 mm
2	Polyethylene terephthalate (ICRU-222)	1.397	10 μm
3	Ar/ CO_2 (70/30)	1.716×10^{-3}	3 mm

Table 5.2: Layers composition used in the SRIM simulation

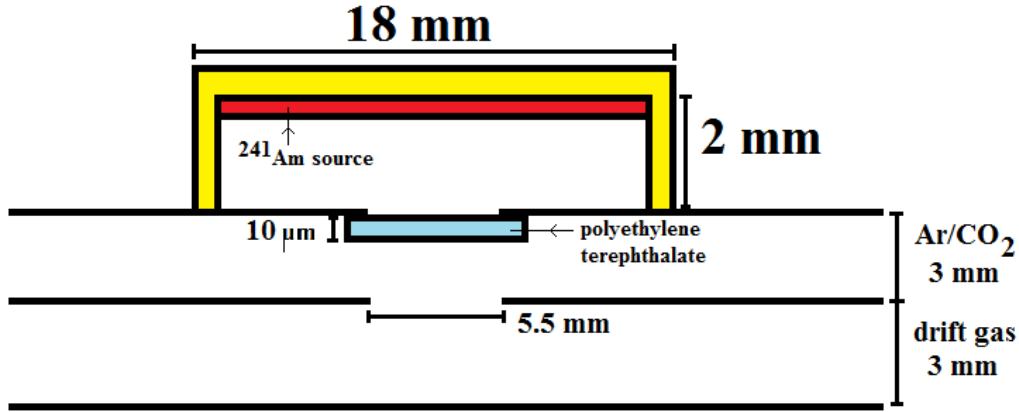
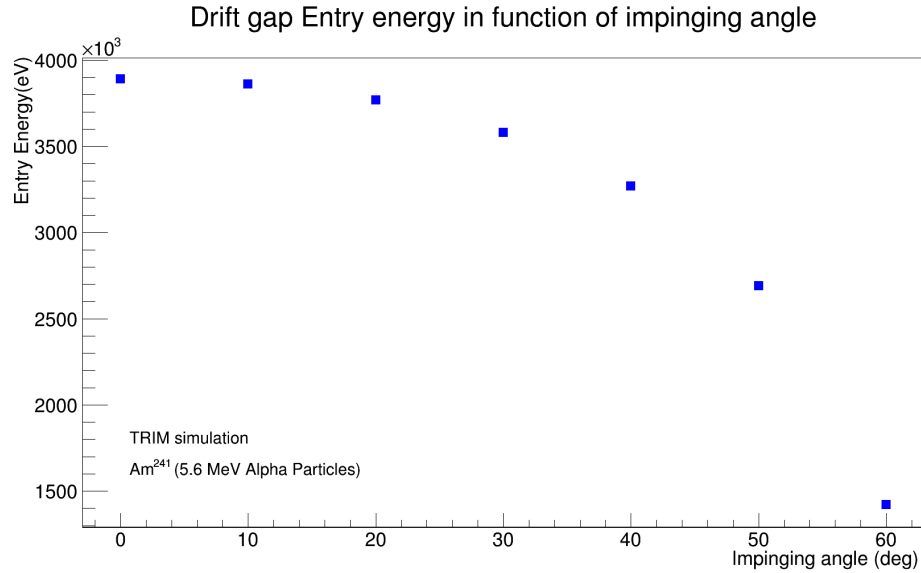


Figure 5.32: Schematic of the layers simulated in this section.

Figure 5.33: Entry energy E_{entr} of the alpha particles in the drift gap simulated at various angles.

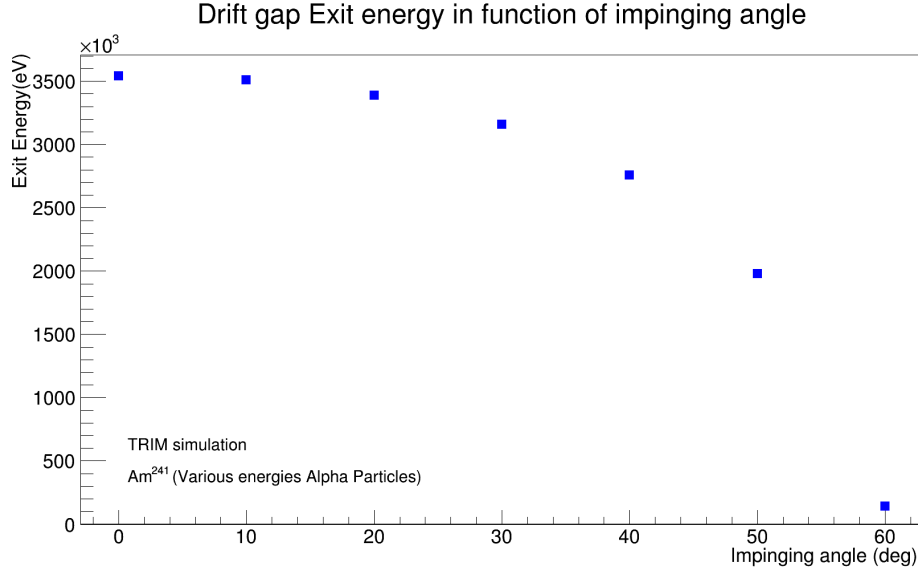


Figure 5.34: Exit energy E_{ext} of the alpha particles in the drift gap simulated at various angles, the initial energies are the one previously simulated.

The next step consists in simulating alpha particles trespassing the 3 mm drift gap with the same impinging angles and with an initial energy equal to the simulated energy E_{entr} calculated for this angle. The exit energies E_{ext} for various angles are shown in Figure 5.34.

It is now possible to calculate the energy deposit $\Delta E(\theta)$ for different impinging angles:

$$\Delta E(\theta) = E_{entr} - E_{exit},$$

these values are shown in Figure 5.35.

In order to make a raw estimate of the average number of primaries generated by a 5.6 MeV in the drift gap, the values ΔE at various angles are averaged to obtain the mean deposit energy $\langle \Delta E \rangle = 571 \text{ keV}$. The number of primaries n_α is then calculated as:

$$n_\alpha = \langle \Delta E \rangle \left[\frac{0.7}{W_{Ar}} + \frac{0.3}{W_{CO_2}} \right] \simeq 2.1 \times 10^4 \text{ pairs},$$

where the parameters are the same described in Section 2.1.1.

This calculation results to be about 100 times more greater than the value of primaries estimated for a 5.9 keV photon ($n_0 = 214 \text{ pairs}$ see Section 3.3).

5.6 Conclusion

As discussed in the Results section, there is no evidence of a loss in performance of the GEM prototype after this test. It means that Triple-GEM technology is radiation hard until an integrated charge of 172 mC/cm² for particles with both low and high specific ionization power in a very outgassing-accelerated gas environment. This result is not comparable with previous study which used clean gas mixtures

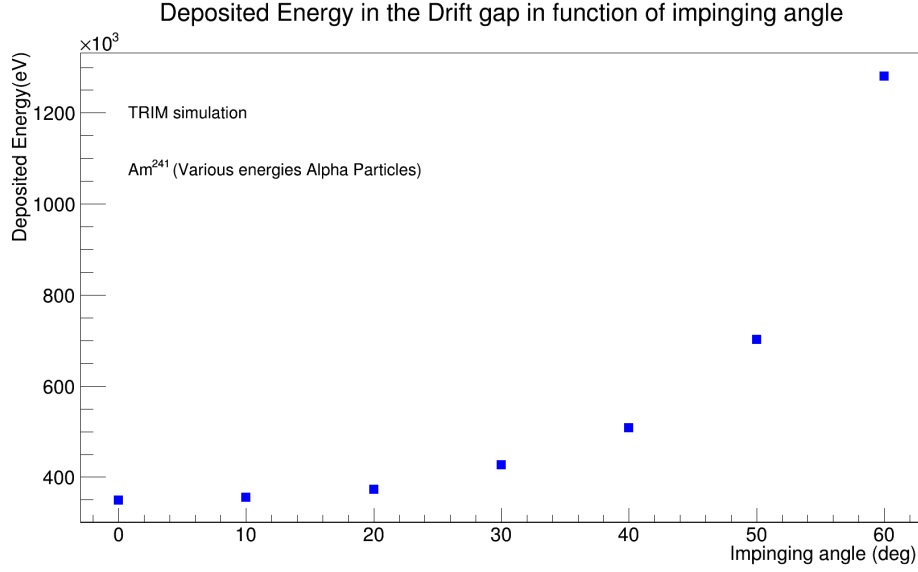


Figure 5.35: Deposited energy by alpha particle in the drift gap $\Delta E(\theta)$ at various impinging angles.

and irradiate the detectors with photons only. In principle the charge integrated by this prototype is comparable with a classic aging study collecting much more charge.

The most interesting result comes from the SEM analysis: particles with high ionization power create polymer deposit with higher rate with respect to low ionizing particles. Since most of the aging issues regards polymer deposits it is important to take care of the particles environment when an aging test is performed to validate a gaseous detector technology.

A measurement of the discharge probability of a Triple-GEM detector, in this experiment conditions, was also performed; the measured value results to be compatible with other tests. However, this measurement remains to be validated with other experiments with better accuracy and where the reproducibility is guaranteed.

Conclusion

In this thesis work a new concept of aging test was performed. The acceleration of the materials outgassing by contaminating the gas with two different kind of contaminants, allowed to simulate the pollutants released in the gas volume during many years of detectors operation. Moreover irradiating the detector with two kind of particles with very different specific ionization powers allowed to better understand how the primary charge density can affect the detector performances and trigger different aging processes.

After a total collected charge of about 172 mC/cm^2 on two regions of the Triple-GEM prototype no degradation in performance has been observed. This result is in agreement with past studies, but it is not comparable with them since the outgassing-accelerated environment reproduces a gas volume typical of many years of normal operation in a "clean" conventional gas system. Therefore, the charge collected in this work is equivalent to an extremely higher integrated charge than in a traditional aging test which exploits clean gas mixtures and irradiate the detector with photons only.

The Scanning Electron Microscope analysis showed how 5.6 MeV alpha particles, which have a ionization power ~ 100 times higher than ^{55}Fe X-rays, create Si-based polymer deposits more rapidly than 5.9 keV photons. This result is in agreement with the assumption which predicts that denser electron avalanches produce more chemical active radicals.

This test is the first of a long series of new longevity tests which will exploit new types of aging acceleration methods as the ones proposed in this thesis. This will be needed since new experiments are coming exploiting high luminosity machines that will increase, in the next decades, particles rates and high ionizing density events inside the detectors during many years of operation.

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Appendix A

Radioactive Sources Decay Schemes

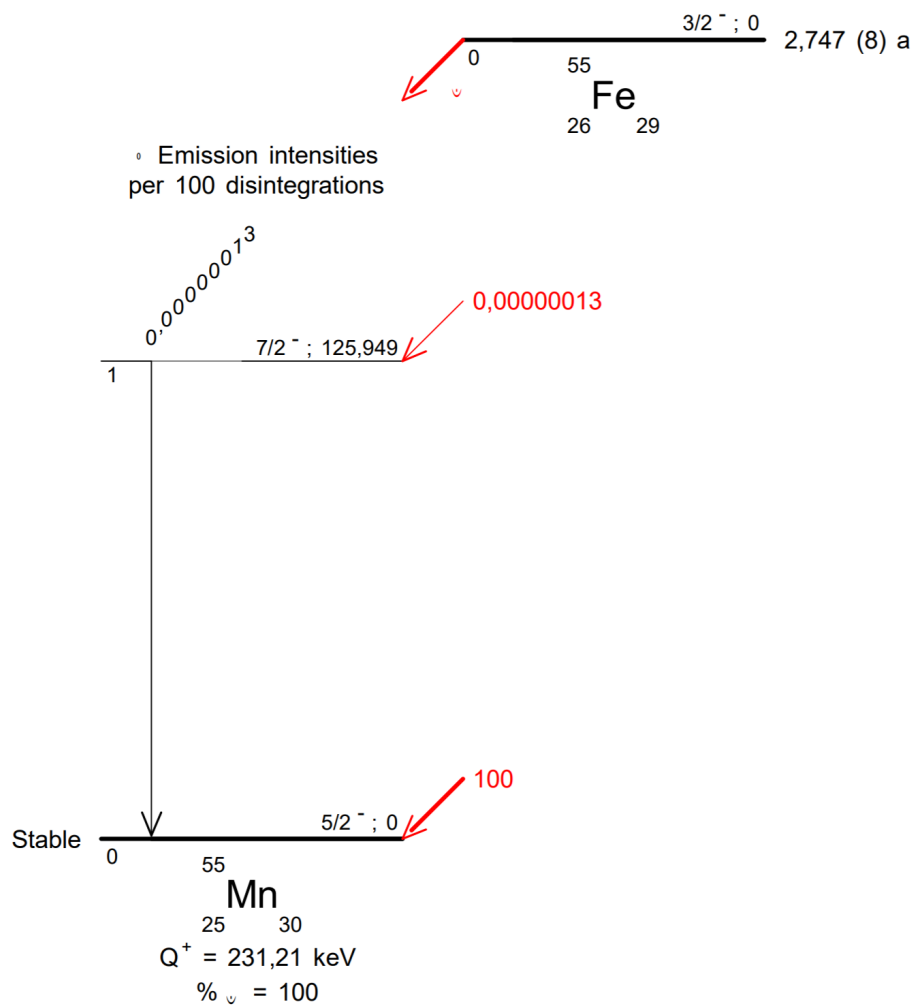


Figure A.1: ^{55}Fe decay scheme [41].

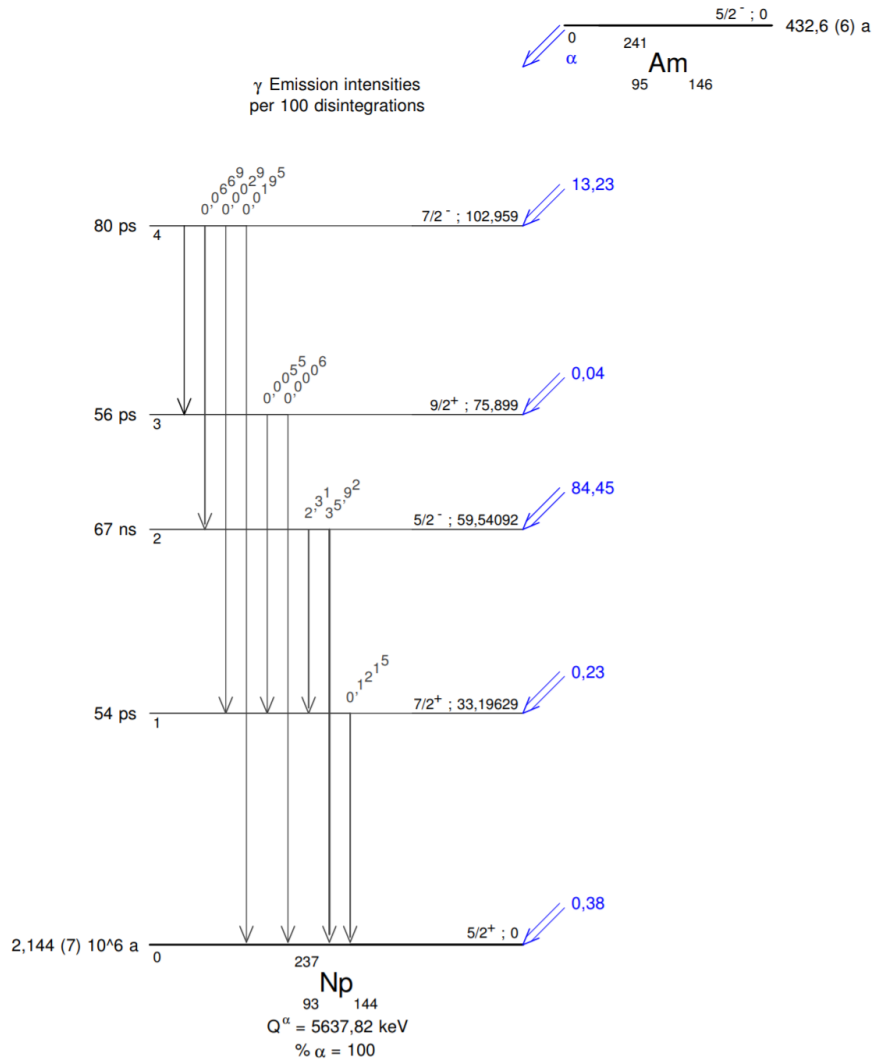


Figure A.2: A part of the ^{241}Am decay scheme, complete scheme can be found at [\[42\]](#).