Performance stability studies of GEM detector under sustained operation at the CMS experiment at LHC

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Introduction

The Large Hadron Collider (LHC) [1] with his four experiments ATLAS (A Toroidal LHC Apparatus) [2], CMS (Compact Muon Solenoid) [3], LHCb (LHC-Beauty) [4] and ALICE (A Large Ion Collider Experiment) [5] has been a very successful accelerator. The Standard Model (SM) [6] was tested in an unprecedented energy regime and with high precision. The missing key particle of the SM, the Higgs boson [7, 8] was discovered in 2012 by the ATLAS and CMS experiment. New ‘Beyond the SM’ (BSM) particles have been searched for in many channels, and stringent limits have been set, but so far no new physics was found. In order to continue the line of scientific success achieved so far, an increase of the collision data to be obtained during LHC operation until 2035 is required. A total integrated luminosity of 3000 $fb^{-1}$ is envisaged for the high-luminosity (HL) Phase, HL-LHC, exceeding the LHC design objective by one order of magnitude. The HL-LHC upgrade of the accelerators and of the LHC detectors will be implemented mainly during the Long Shutdown 3 (LS3) but some installation will take place during earlier LHC shutdowns. Successive upgrades on the LHC during the Long Shutdown 2 (LS2, 2019-2021) will increase the proton density and consequently the collision rate.

As LHC is moving to its high-luminosity, instantaneous luminosity in the experiments will increase about a factor 4 with respect to the previous running time. In parallel with the accelerator, the LHC experiments have to face several modifications in order to adapt to the increased luminosity and maintain their excellent performance at higher particle rate and detector occupancy.

The increase of the energy and luminosity during the future upgrades of the LHC machine will deeply affect the performance of the CMS Muon System due to the harsh background environment and the high pile-up. The muon chambers will be operated in an environment with significantly increased high-rate radiation, with rates up to $5 \times 10^4 \text{Hz/cm}^2$.

Muons are detected in CMS with multi-layer gas-ionization detectors positioned outside the solenoid. Gaseous detectors have proven over the last decades to be a versatile and cost effective technology for large volume Muon spectrometers. However their performance can be heavily affected by the presence of the intense background and the operation in such conditions could cause detector aging that would compromise long term performance stability. With the invention and evolution of Micro Pattern Gaseous Detectors (MPGD) during the twenty years, gaseous detectors improved significantly in timing, spatial resolution and rate capability. In order to cope with very high operation condition, high pile-up and background environment in particular in the forward region, the CMS Collaboration is going to install MPGD detectors based on the Gas Electron Multiplier (GEM) technology, instrumenting the nonredundant
high pseudorapidity region with detectors that could withstand the hostile environment and high luminosity rates at the LHC and its future upgrades. The triple-GEM technology will be installed in three main vacant stations of the muon system: first GE1/1 during the Long Shutdown 2 (LS2) and then, during subsequent shutdowns, GE2/1 and ME0.

Due to the large active detection area, the GEM will be the largest GEM based system ever utilized in an LHC experiment. Consequent R& D resulted in substantial experience in construction and operation of gaseous detectors and broad understanding on the operational parameters of these detector technologies.

This thesis takes place in the framework of the CMS GEM R& D activities related to the long term stability of those large area detectors in the operation condition in very harsh environments. I have analyzed the different sources of operation instability, that are related both to the environmental conditions (such as the radiation background) and detector configurations (such as GEM foils, electric fields, power distribution, front-end electronics). The main objective is to investigate the parameters which can affect the stability related to the occurrence of discharges, which constitute the most complex and potential serious problems which could limit, or severely impair the operation of the detector. The data collected with different electric field configurations have been modeled with empirical functions which allow to identify the most suitable configuration for stable operation.

The thesis is organized in four chapters:

- In chapter 1 a brief description of the Large Hadron Collider and CMS experiment and the foreseen Upgrade is presented.
- In chapter 2 I introduce the working principles of particle gas detectors, providing more details on processes occurring in MPGD and in particular on the GEM detector. The main aspects affecting the stability of the operation of the GEM detectors are described.
- In chapter 3 I describe the CMS GEM system. The details about background condition and the implication on the longevity and discharge occurrence according to the recent observation are provided. I investigate the mitigation strategy adopted and I present the results of the test I have performed at CERN on a new design for the GEM foil.
- In chapter 4 I present the R& D on the optimization of GEM parameters for stable operation of the detector. The tests are performed in the GEM Bari laboratory on a $10 \times 10 \, cm^2$ prototype. The first attempt to model the data collected as a function of the electric fields is presented and new field configurations are derived that would allow to reduce the primary and secondary discharge probability. The perspective for future discharge studies and implementation of the proposed strategy on large size prototypes are described.
Chapter 1

Physics at LHC and the CMS experiment

1.1 The Standard Model and the Physics beyond the SM

The Standard Model (SM) is a quantum field theory which describes all the elementary particles and their fundamental interactions, except for the gravity. It is based on the principle of gauge invariance which allows to unify the electromagnetic, the weak and the strong interactions. It was formulated in 1960s by Glashow, Weinberg and Salam and it is still subjected to further developments. Many predictions have been successfully confirmed by experimental evidences during the past years, but in the same time the theory is not able to explain many other experimental observations. Many details can be found in [6].

1.1.1 The elementary particles

According to the SM, the matter can be described in term of two families of elementary particles, divided into two groups: the leptons and the quarks. They are fermions with half-integer spin. Both the families are further divided into three generations of particles with two particles each, coupled by the same intrinsic properties. The leptons families consist of three negatively charged particles, the electron, the muon and the tau (\(e^-\), \(\mu^-\), \(\tau^-\)) with their associated neutrinos (\(\nu_e\), \(\nu_\mu\), \(\nu_\tau\)). The quark families consist of two opposite fractional charged particles, +1/3 and −2/3, organized in particle doublets: (u, d), (c, s) and (t, b) [9]. The theory also states that each elementary particle has an anti-particle, characterized by the same physical properties but with opposite charge and parity. The leptons can only interact via Electro-Magnetic force (EM) and weak forces; the quarks also feel the strong force [10].

1.1.2 The fundamental interactions

The SM describes the fundamental interactions postulating the existence of boson mediators exchanged by the interacting particles. The interaction itself is
mathematically described as a quantum field which satisfies the local gauge invariance. The direct consequence is that the interaction is mediated by the exchange of energy quanta, named gauge bosons, having spin 1. The SM includes two gauge theory: the ElectroWeak (EW) theory, that unifies the electromagnetic and the weak forces, and the Quantum ChromoDynamics (QCD), describing the strong interaction. The quanta of the EW field are the bosons $\gamma$, $W^-$, $W^+$ and $Z^0$. The gluons are the bosons mediator of the strong field and are accommodated in the QCD [10]. A prospectus summarizing the elementary particles and the boson mediators is shown in figure 1.1.

Figure 1.1: Prospectus of the elementary particles predicted by the SM. The graviton, which hypothetical mediates the gravitational interaction, is also presented outside the box [11].

A further particle is needed to fully describe the theory: the Higgs boson, mediator of the Higgs field described in the next section.

1.1.3 The Higgs mechanism and the ElectroWeak Symmetry Breaking

The SM allows to unify three of the fundamental interactions. The electromagnetic and the weak forces are unified in the gauge group $SU(2) \times U(1)$ [12]. In order to satisfy the gauge symmetry, the lagrangian of the EW theory does not contain mass term, i.e. the theory postulates that the interaction carriers are massless particles. This is in contrast with the fact that the mass of a gauge boson is inversely proportional to the associated force range. The electromagnetic interaction range is infinite and the photon is indeed massless. The weak force instead has a short range and at low energy can be described with the point-like Fermi theory [13]. This means that the bosons $(W^\pm, Z^0)$ are massive particles. The presence of mass terms in the lagrangian breaks the gauge invariance and the theory becomes not normalizable.
A mechanism to generate the masses of the weak force gauge bosons was proposed by Englert, Brout and Higgs [14, 15] and accommodated in the SM theory by Weinberg and Salam [16]. A doublet of complex scalar fields invariant under the transformations of the group $SU(2) \times U(1)$ and the lagrangian for this field are introduced. The energy ground state of this field is obtained in correspondence with an infinite set of values: the $SU(2)$ symmetry is broken and the mechanism is known as *spontaneous ElectroWeak Symmetry Breaking*. When the complex scalar field is coupled, i.e. interacts, with the gauge bosons and the fermions a mass term appears in the Lagrangian as a consequence of the interaction. This complex scalar field is a quantum field and the boson mediator is a massive neutral 0-spin particle, named Higgs boson. This is one of the most important prediction of the SM together with the fact that the coupling constants with the fermions scale with the mass of the particle, while for the gauge bosons, the coupling constants scale with the mass squared. Furthermore, the mechanism foresees a self-coupling of the Higgs boson.

### 1.1.4 Discovery of the Higgs boson

The gauge bosons $W^\pm$ and $Z^0$ were discovered at CERN in 1983 and their masses were measured. In 2012 the experiments ATLAS and CMS operating at CERN announced the discovery of a new neutral particle with invariant mass of about 125 GeV [7, 8], spin-parity $JP = 0^+$ [17] and coupling factors [18] and decay rates [19] compatible with the predicted SM Higgs boson.

### 1.1.5 Limits of the SM and the physics beyond SM

Even though many SM predictions have been successfully confirmed and the theory has been tested in a wide range of energies, there still are some open questions the SM is not able to solve. These unsolved questions inspired the construction of new theories beyond the SM and point out that the SM can only be an approximation of a wider unified theory. For example, the discovery of the Higgs particle seemed to complete the puzzle of the elementary particles but brought in the same time some other issues, such as the mass hierarchy or the *naturalness problem*. In fact, a fine tuning between the bare Higgs mass and its radiative corrections would report the Higgs mass in the range of 100 GeV. Furthermore the theory leaves 25 parameters (fermions masses and coupling constants) unpredicted. The self-consistency of the theory itself, formulated as a non-abelian gauge theory quantized through path-integral, is still not proved. The theory also predicts the existence of the antiparticles but it is not capable of explaining the lack of antimatter in the universe. The actual percentage of matter of the universe described by the SM is only 4.9%. The rest and larger fraction is shared between Dark Matter and Dark Energy. Finally, the General Relativity describing the gravitation shows incompatibilities with the SM which does not include the gravitation in its description.

Several theories have been developed and are grouped under the name *Beyond Standard Model* (BSM) theory, but nowadays none of them has been proved. All these unsolved puzzles point out that the SM has to be challenged by searching experimental evidences of new physics.
1.2 The Large Hadron Collider

The Large Hadron Collider (LHC) [1] is the biggest and more powerful particle accelerator of the world. It is a proton-proton superconducting collider installed in the existing 26.7 km tunnel. The choice for the protons lies in the fact that a wide range of energy can be explored at a fixed center of mass energy, being the protons non elementary particles. Furthermore, contrary to the electrons, they are subjected to a smaller energy loss from synchrotron radiation with respect to the electrons. In fact, the energy loss per turn in a circular collider of radius $R$ is proportional to $(E/m)^4/R$, being $E$ and $m$ the energy and the mass of the accelerated particles. The protons are accelerated up to 7 TeV and collimated through a series of steps.

- At first the protons are obtained ionizing hydrogen atoms and then they are accelerated up to 50 MeV by the linear accelerator LINAC 2 (shown in figure 1.2).
- They are injected in the Booster (PSB) and then in the Proton Synchrotron (PS) reaching the energy of 26 GeV.
- In the Super Proton Synchrotron (SPS) a further acceleration step is performed and the protons reach the nominal energy of 450 GeV.
- The value of 7 TeV is finally reached in the LHC ring.

The figure 1.2 provides an overview of the accelerator system with the main experiment at CERN.

![Overview of the accelerator system and the main experiment at CERN](image)

Figure 1.2: Overview of the accelerator system and the main experiment at CERN [11].

The beam pipe of the LHC is instrumented with a set of superconductive dipoles that provide the curvature of the proton beam around the ring and a
system of quadrupole and octupoles to guarantee the focusing of the beam. The whole system is kept at the temperature of 1.9 K in order to assure the superconductive behaviour. In the LHC ring, two proton beams are simultaneously accelerated. Each beam is composed by bunches of about $10^{11}$ protons. The bunches are collided by intersecting the two beams head to head in the interaction point of the experiments, at a frequency of the order of 40 MHz, i.e. every $\sim 25 \text{ ns}$.

### 1.2.1 LHC main characteristics

The most important parameters affecting the LHC performances are the beam energy and the luminosity.

The beam energy is the crucial aspect since it is chosen according to the physics to be investigated. The energy available is referred to the center of mass of the two beams, expressed in terms of the Mandelstam variable $s$ which is Lorentz-invariant. If $p_1 = (E_1, p_1)$ and $p_2 = (E_2, p_2)$ are the quadrupoles of the two particles of the colliding beam, the center of mass energy is given by

$$s = (p_1^0 + p_2^0) \cdot (p_1 + p_2) = m_1^2 + m_2^2 + 2 \cdot (E_1 \cdot E_2 - p_1 \cdot p_2) \quad (1.1)$$

Since LHC is a collider, to the first order approximation, the relation between the beam momenta $p_1 = -p_2$ holds. Furthermore, in the high energy limit $E >> m$ and the center of mass energy can be expressed by

$$\sqrt{s} = 2E \quad (1.2)$$

The luminosity refers to the number of particles crossing the unit area per unit time. For a synchrotron like LHC, the luminosity can be expressed by

$$L = f \frac{N_1 N_2}{4\pi \sigma_x \sigma_y} \quad (1.3)$$

where $f$ is the collision frequency, $N_1$ and $N_2$ the number of particles of the two colliding bunches and $\sigma_x$ and $\sigma_y$ the transverse beam profiles of the bunch [20]. The luminosity is clearly correlated with the number of events $N_{exp}$ produced in a certain time

$$N_{exp} = \sigma_{exp} \int Ldt \quad (1.4)$$

being $\sigma_{exp}$ the cross section of the interested event and $\int Ldt$ is called integrated luminosity $L_{int}$. The latter is often measured in $fb^{-1}$ since the cross section uses the barn ($10^{-24} \text{ cm}^2$) as unit of measurements.

The first years LHC operated at $L = 6 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ center of mass energy of $\sqrt{s} = 7 \text{ Tev}$ and integrated luminosity of $5.1 \text{ fb}^{-1}$. The actual value of the luminosity, reached by gradual upgrades, is $L = 1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ and the center of mass energy is $\sqrt{s} = 13 \text{ Tev}$ with integrated luminosity of $150 \text{ fb}^{-1}$ (see figure 1.3).
Figure 1.3: Total integrated luminosity as a function of the time for a center of mass energy $\sqrt{s} = 13$ TeV up to September 2018. The blue region corresponds to the delivered value from LHC; the yellow one corresponds to the CMS integrated luminosity recorded [21].

1.2.2 Overview of the experiment at the LHC

Four main experiments are actually active at the LHC placed in four different collision points (see figure 1.4).

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

The ATLAS and CMS experiment are general purpose experiments: they were built to search the Higgs boson, but also to perform precise measurements on the SM parameters and find new physics. The two experiments are built according to the same guidelines: a tracking system made of silicon detectors is placed close the interaction point and surrounds the beam pipe, providing precise measurements of the secondary vertex and the trajectories of charged particles; an electromagnetic calorimeter measures the energy of the electrons and photons; the hadron calorimeter measures the energy of the hadronic jets providing indications of missing energy. Both of them use a superconducting magnet in order to bend the particle trajectories of the charged particles allowing the momentum measurements. The ATLAS and the CMS experiments share the same structure but use different technologies in order to guarantee the reproducibility of the measurements.

The LHCb experiment studies the asymmetry between matter and antimatter studying the rare decays of the hadrons with beauty, focusing the afford of...
the technology on the detection of the b-quarks. The ALICE experiment studies the confinement of the quarks by colliding heavy ions at high energy thus producing the quark-gluon plasma. For this reason ALICE principally collects data when LHC operates with lead ions.

![Figure 1.4: Layout of the LHC including the four main experiments [11].](image)

**1.3 The Compact Muon Solenoid**

The Compact Muon Solenoid (CMS) [3] is one of the four main experiments operating at the LHC. It is a multi purpose experiment aiming at describing all the known particles of the SM as well as finding new physics at the TeV energy scale. The CMS detector system has a cylindrical barrel shape closed by two endcaps disks. The overall system dimensions are $\sim 21$ m of length, $\sim 15$ m of diameter and $\sim 14000$ tonnes of weight. The main characteristic of the system is the large superconductive solenoid which gives rise to an intense magnetic field of about $\sim 3.8$ T. The detectors are installed both inside the bore of the magnetic core (inner tracker, calorimeter) and outside the coil (muon detection). An overview of the CMS system is presented in figure 1.5, where the main parts of the subdetectors can be distinguished.

The CMS detectors are positioned following the traditional scheme of the subdetectors location: the layer closest to the interaction point consists of an inner tracking detector; it is followed by the Electromagnetic and Hadronic Calorimeters. On the outside, the magnet return yoke, which confines the magnetic field, is alternated with four layers of muon detectors, the Muon Spectrometer. They are briefly discussed in the next sections.

The CMS experiment uses a right-handed coordinate system, with the origin in the nominal Interaction Point (IP), the x-axis pointing radially towards the
center of the LHC ring, the y-axis pointing upwards and the z-axis following the beam line. Nonetheless, the reconstruction algorithms use a cylindrical coordinate system exploiting the geometry of the experiment. It is based on the radial distance $R = \sqrt{x^2 + y^2}$ from the origin of the system, the azimuthal angle $\phi$ with respect to the x-axis and the polar angle $\theta$ with respect to the beam line. However, a more efficient coordinate, the pseudorapidity $\eta$, is introduced for a better description of the uneven particle distribution over the angle $\theta$. The pseudorapidity is related to the polar angle $\theta$ by the expression

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

Figure 1.5: Schematic overview of the CMS experiment [3].

Figure 1.6 provides a representation of the CMS coordinate system.

1.3.1 The CMS subsystem

The first system the particles produced by the pp collisions encounter is the inner tracker [23], which surrounds the IP. The purpose of the inner tracker is the reconstruction of the high-$p_T$ charged particle (electrons and muons) tracks in the region $|\eta| < 2.5$, the precise measurements of the impact parameter and the reconstruction of secondary vertices. It entirely consists of silicon detectors exploiting their fast response, high granularity and high spatial resolution which
are necessary given the harsh radiation environment. Therefore four layers of pixel detectors and ten layers of silicon strips are installed in the barrel and additional silicon disks in the endcaps.

The CMS electromagnetic calorimeter (CMS ECAL) [24] is a hermetic homogeneous calorimeter made of 61200 lead tungstate crystals (PbWO₄) in the barrel, read out by Avalanche Photodiodes (APDs), and 7324 crystals in the endcap region, read out by Vacuum Phototriodes (VPTs). The ECAL subdetector covers the pseudorapidity range $|\eta| < 3.0$. Thanks to the use of PbWO₄ crystals, the calorimeter has a fast response, fine granularity and it is radiation resistant. The design of the calorimeter was also influenced by the necessity to detect the decay into two photons of the Higgs boson $H \rightarrow \gamma\gamma$. This capability is also reached thanks to the good energy resolution provided by the homogeneous calorimeter.

The CMS hadron calorimeter (CMS HCAL) [25] is made of scintillator layers, coupled with photodiodes, alternated by brass absorber layers. The main purpose is to provide a precise measurement of the hadron jets energy in order to detect the missing energy, carried away by neutrinos and eventually non-interacting new particles. The HCAL consists of a barrel region covering the pseudorapidity region up to $|\eta| < 1.3$ (Hadron Barrel) and of an endcap region up to $|\eta| < 3$ (Hadron Endcap). Furthermore, a Cherenkov-based calorimeter, placed outside the solenoid, increases the total hadronic absorber material covering the pseudorapidity region up to $|\eta| < 5.2$ (Hadron Forward).

The Muon system

The Muon system is the crucial apparatus in CMS, as suggested by the name of the experiment: the muon reconstruction is a powerful tool necessary to recognize interesting processes, having muons in the final states, over the very high background rate expected at HL-LHC. The Muon Spectrometer has three main functions: the muon identification, momentum measurement and triggering. A good momentum resolution and trigger capability are achieved thanks to the high field solenoidal magnet (providing the bending of the muons trajectory) and its flux return yoke, which also works as absorber for muon identification.

The Muon Spectrometer has been designed to cover the maximum pseu-
dorapidity region. It is installed in the barrel region and in the two endcaps, exploiting different gaseous detector technologies: the Drift Tubes (DTs) installed in the wheels of the barrel, for precise measurement and triggering; the Cathode Strips Chambers (CSCs), serving the same function of the DTs in the endcaps; the Resistive Plate Chambers (RPCs), installed in both the barrel and the endcaps, for coarse measurement and triggering. They are described below; a deeper dissertation can be found in [3, 26].

The barrel Muon system is divided into five wheels, to cover the full azimuthal coordinate; each wheel is further divided into 12 sectors, each consisting of four layers of DTs and six layers of RPCs. Four stations of CSCs and RPCs are used to instrument both the endcaps. All the muon detectors contribute to the Level-1 Trigger System, providing independent and complementary informations.

**Drift Tubes** The Drift Tubes (DT) are the main detection system in the barrel. They consist of rectangular wire chambers characterized by a specific design that guarantees the uniformity of the electric field, in order to maintain the electron drift velocity constant in the entire gas volume. The time resolution of the order of some nanoseconds permits a reliable measurement (with respect to the bunch crossing time of the LHC) of the drift time of the secondary electrons and to go back to the interaction point. This allows to reach an overall space resolution of $\sim 100 \, \mu m$ combining several interaction point coming from different DTs. The detectors are filled with a gas mixture of $\text{Ar}/\text{CO}_2 \ 85/15$ and operate at a gas gain of $10^5$, providing in this configuration a drift time of 380 ns for 21 mm. The DTs are installed in a number of 250 detectors organized in five wheels further divided in four concentric layers. The structure thus arranged covers a pseudorapidity region up to $|\eta| < 1.3$ and veil all the $\phi$ coordinate. DTs are used only in the barrel region, as already said, since they can only sustain particle rates up to several tens of $Hz$ and could not afford the high particle background of the endcaps ($10^2 - 10^3 \, Hz/cm^2$). Moreover the intense magnetic field in the endcaps ($\sim 3 \, T$) would bend the electron trajectory compromising the working principle of the detector.

**Cathode Strip Chambers** The Cathode Strips Chambers (CSCs) are installed in the endcaps in a number of 540 detectors, organized in four station per endcaps, providing a pseudorapidity coverage of the region $0.9 < \eta < 2.4$. They perform the same function as the DTs but are preferred in the endcaps for the higher particle rate up to few tens of $kHz/cm^2$. The CSCs consist of Multi Wire Proportional Chambers, whose cathode is divided into strips arranged perpendicularly to the wires. This design provides a space resolution up to 75 $\mu m$, combining the information from the wire and the strips. The time resolution is of the order of 6 ns, permitting the bunch crossing identification. The CSCs operate at a gain of $7 \times 10^4$ in a gas mixture of $\text{Ar}/\text{CO}_2/\text{CF}_4$: the $\text{CF}_4$ is added to slow down the aging effects of the wires and to increase the electron drift velocity limiting the diffusion effects.

**Resistive Plate Chambers** The Resistive Plate Chambers are installed in both the barrel (360 detectors divided in four stations) and the endcaps (252 detectors divided in four stations) in order to provide redundancy of the muon hit and solve tracking ambiguities. The RPCs are very fast detector providing
time resolution of the order of 1 ns. For that reason they can be used to provide independent trigger in the region $|\eta| < 1.9$. A RPC is a parallel plate chamber constructed by two plates of High Pressure Laminate (HPL), a high resistivity material. The RPCs operate in the avalanche mode with a gas mixture of $C_2H_2F_4/i - C_4H_{10} - SF_6$ (95.2 - 4.5 - 0.3). Since the RPCs employ high resistive materials, this detectors are particularly sensitive to the charging up effect, which occurs at interaction rate higher than 1 $kHz/cm^2$.

1.3.2 The Trigger System

The proton-proton collision rate at the LHC is 40 MHz, equivalent to one collision every 25 ns. Each collision produce $\sim 1$ MB of data, resulting in an overall amount of data of $\sim 40 \times 10^8$ MB. Such a huge amount of data is not only impossible to be stored but it also includes a large amount of informations related to non-interesting phenomena, such as low-energy collisions. The trigger system takes care therefore of the data selection in order to collect only the interesting events, reducing the amount of data to a few hundreds of MB/s. The CMS trigger system [27] consists of two levels of selection, the Level-1 (L1) and the High Level Trigger (HLT).

- The L1 is a preliminary and fast selection of the events carried out combining the informations coming from the calorimeters and the muon system. The tracker informations are at this step neglected since the multitude of channels composing the DAQ system of the tracker would slow down the whole process. The L1 decides in less than 3.2 $\mu$s which are the accepted events on the basis of their tranverse energy and momentum. This first step reduces the event rate from 40 MHz to less than 100 kHz. The L1 goodness of selection directly depends on the muon system performances, in terms of speed of response and quality of the reconstruction. The triggered events are then sent to the HLT.

- The HLT is a complex software algorithm executed by a computer farm. This consists in a more sophisticated screening of the events combining the information coming from all the detectors. The events are accepted on the basis of their topology defined by the physics of interest. The selection process is performed in few milliseconds and the event rate is further reduced to a few hundreds of Hz.

1.4 The upgrade of the LHC

The main scopes of LHC upgrades are the increase of the center of mass energy, in order to produce more massive particles and the increase of the luminosity, which allows the production of rare physics process. The LHC updates are scheduled periodically and runs and technical stops are carried out at pre-established intervals. During the Long Shutdown 1 in 2013 and 2014 the purpose of increasing the center of mass energy was successfully fulfilled, bringing it from the value of 7 - 8 TeV to 13 TeV. The luminosity was increased as well from the value $6 \times 10^{23}cm^{-2}s^{-1}$ to the nominal value of $1 \times 10^{24}cm^{-2}s^{-1}$. During the LS2, started from 2019, the ongoing work will double the luminosity bringing it to a value of $2 - 2.5 \times 10^{24}cm^{-2}s^{-1}$ and the following Run 3 will continue until
the integrated luminosity reaches the value of $300 \text{ fb}^{-1}$. A new shutdown is foreseen for 2025, when the High Luminosity LHC will start. This upgrade phase is called Phase-II and the luminosity will reach the value of $5 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$. The subsequent run will last until the integrated luminosity reaches the value of $3000 \text{ fb}^{-1}$. The most recent scheduled program is reported in figure 1.7.

<table>
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<tr>
<th>Year</th>
<th>2019</th>
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<td></td>
<td>Run 1</td>
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<td>Long Shutdown 1 (LS1)</td>
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<td>Run 3</td>
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<td>Long Shutdown 2 (LS2)</td>
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![Schedule for the upgrade of the LHC and the stepwise increase of the instantaneous and integrated luminosity as a function of the year starting from the LS2 [28].](image)

1.5 The upgrade of the CMS

The stepwise upgrade of the LHC comes as well with the need of upgrading the CMS experiment, in order to exploit the LHC performances and afford the high luminosity foreseen. The detectors will be exposed to high background environment that will challenge the efficiency of the hardware and the data acquisition system. The upgrade of CMS is divided into two phases: the Phase-I that will be completed during the LS2 (till the end of 2020) and the Phase-II, planned during the LS3 starting in 2025.

The upgrade in both Phase-I and Phase-II involves different CMS subsystems. An important aspect related to the increase of instantaneous luminosity and hit occupancy concern the trigger, for Phase-II, the overall CMS trigger architecture will remain the same, with a hardware L1 and a Higher-Level Trigger (HLT) that is implemented in software. The maximum L1 rate will be increased from the current 100 kHz to 750 kHz, and the front-end data buffers will be made sufficiently deep to capture the data with an L1 trigger latency increased from the current 3.6 ms to 12.5 ms. This implies the replacement of electronics in many detectors in order to be able to sustain the rate and to deal with high data bandwidth. A brief discussion on the upgrade of the tracking system and the calorimeters is presented here. A particular focus will be dedicated to the upgrade of the muon system.

- **Tracker**: The actual pixel detectors composing the inner tracker were designed to properly operate at a luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. Therefore, they cannot sustain the conditions of the HL-LHC program. During the present Phase-I, the pixels were replaced in order to maintain the maximum tracking efficiency. Due to the radiation damages expected after the
Run 3, the Phase-II will consist in the replacement of the entire tracking system, increasing the granularity by a factor of 4. Furthermore, one more layer of detectors is going to be installed in the endcaps, improving the redundancy and increasing the pseudorapidity coverage up to $|\eta| < 4$.

- **Calorimeters**: During the Phase-I, the HCAL photo-detectors has been substituted by silicon photomultiplier, in order to improve the light detection and the signal-to-noise ratio. They have also the advantage of not being affected by the magnetic field. During the Phase-II instead, the calorimeters of the endcaps will be replaced by a High Granularity Calorimeter (HGCal) for both the hadron and electromagnetic calorimeters. In particular, the structure will altern metallic absorber layers (made of $W/Cu$ for the EM part and $CuZn/Cu$ for the hadronic one) and silicon sensors.

### 1.5.1 The upgrade of the muon station

The Muon system is the fundamental component of the CMS experiment and its performances must be adapted in view of the upgrade of the LHC, in order to maintain the excellent muon identification capability. Therefore, the upgrade plans involves all the gaseous technologies employed. The Phase-I upgrades concerning the DTs, the CSCs and the RPCs mainly focuses on the improvements of the readout electronics, the data acquisition system and the beam monitoring. During Phase-II, new detectors using the RPC technology, the iRPC, are going to be installed increasing the detector coverage up to $|\eta| = 2.4$. Technical details on the upgrade of Phase-I and Phase-II can be found in [29, 30].

The main upgrade during Phase-I concerns the installation of the first station of Gas Electron Multiplier (GEM) detectors, called GE1/1, in the pseudorapidity region $1.6 < |\eta| < 2.15$, in order to enhance the redundancy of the muon hits and improve the L1 trigger in rejecting a fraction of soft muons with overestimated momentum. All the work done to characterize and validate this technology can be found in [31]. During Phase-II, two other stations are going to be instrumented with the GEM technology: the GE2/1 and the ME0. The addition of these detectors will bring redundancy in a region where it is needed the most, due to the high rate it is subjected to. In fact, the combination of GEM and CSC can provide a good measurement of the muon direction within a single station, increase the robustness of the track reconstruction already at the L1 trigger level. More technical details on GEM projects can be found in [32, 33]. I will also provide more details in chapter 3.
Chapter 2

Micro Pattern Gaseous Detectors

Gaseous detectors have always been used in the field of high energy physics, thanks to their performing characteristics and their relatively low cost with respect to other technologies. One of the new development of gaseous detectors finds expression in the Micro Pattern Gaseous Detectors (MPGD), which were invented to overcome the limitations brought by older structures, such as the Multi Wire Proportional Chambers (MWPC). The main advantage of MPGD is the microscopic dimensions of the amplification structures, which allows a quick and easy evacuation of the charge and to operate in high rate. Besides, the amplification region is usually separated from the collection one, making them strong and robust against discharge phenomenon. In the first part of this chapter, a brief overview of MPGD will be provided and a particular focus will be dedicated to the GEM detectors. In the second part, the process of the discharge formation in gaseous detectors will be discussed together with the main points on the current knowledge on discharge phenomenon in GEM detectors.

2.1 Introduction to gaseous detectors

When a charged particle passes through a medium, it interacts via Coulomb force with the molecules of the medium, transferring them a certain amount of energy. The acquired energy causes the excitation of the molecule, which can result in the activation of higher rotational or vibrational states of energy (if the molecule is not monoatomic), in the emission of a photon with the same energy as the acquired one or in the fragmentation of the molecule. If the energy released is higher than the ionization potential of the medium, the interaction results in the ionization of the molecule. The charged particles (electrons and ions) produced after the ionization can be collected in gaseous detectors and be related with the passage of the particle [34]. Under normal conditions, a charged particle undergoes many scattering events, in each of which it loses part of its energy. The Bethe-Bloch formula describes the average energy loss per unit path of a charged particle inside a certain medium (see figure 2.1). In particular, the energy loss inside a given medium is an increasing function of
the mass of the incoming particle [35]: heavier particles release more energy in the medium and thus resulting in a higher number of electron ion pairs for a gaseous medium.

If a photon passes through a medium, it can interact via electromagnetic field with the molecules of the medium itself. Three main phenomena occur, depending on the energy of the incoming photon, $E_\gamma$ (see figure 2.2): the photovoltaic absorption ($E_\gamma < 50$ keV), the Compton scattering ($E_\gamma > 100$ keV) and the pair production ($E_\gamma > 1.022$ MeV). In the photoelectric effect and in the pair production, the photon is destroyed and can only free one pair of charged particles; in the Compton scattering, a photon with different energy and direction is also present in the final state. The electron eventually scatters with the other molecules of the medium, losing energy and releasing clusters of charged particles.

The working principle of the gaseous detectors is based on the collection of the charge produced by the passage of the particle. This is done applying an electric field in the region where the interactions between the gaseous medium and the particle occur. In figure 2.3, the charge collected at the electrodes as a function of the applied electric field is shown.

Depending on the electric field magnitude, different working modes of gaseous detectors can be distinguished. If no electric field acts on the free charged particles, they can easily recombine by multiple collisions with the gas atoms and reach the thermal equilibrium, leaving no evidence of the passage of the ionizing particle. Recombination also prevails at very low values of the fields. In the ionization mode, the electric field is high enough to just collect the charge left in primary ionization and the signals produced are very low in amplitude. The result is the plateau in the second region of figure 2.3.

In the proportional mode, the applied electric field gives the primary electrons enough energy to ionize other molecules of the gas, in secondary ionization events. They can trigger a multiplication process, where the number of electron-
Figure 2.2: Mass attenuation coefficient $\mu/\rho$ in Ar/CO$_2$ versus the energy of the incoming photon. In the Lambert Beer law, $I(x) = I_0e^{-\mu x}$, the inverse of the mass attenuation coefficient is the absorption length and it represents the thickness of the medium crossed, for which the intensity of the monoenergetic photon beam is reduced by a factor $1/e$ [31].

ion pair created is proportional to the one coming from the primary ionization. The signal can be amplified up to a factor of $10^6$.

As the tension applied increases, the charge density can become very high. Since the electrons are faster than the ions, the ions separate from the electrons. Therefore, in the region of the avalanche an electric field is generated which adds itself to the applied one. The overall electric field is distorted and the proportionality is lost (limited proportionality region).

If the tension further increases, one enters the Geiger-Muller region: the number of pairs is very high and the Raether limit can be crossed, giving rise to discharge phenomenon in the gas. At this point, during the amplification process, every information regarding the crossing particle is lost. Therefore the Geiger Muller detectors are mostly used as event counters.

Entering the streamer region, the electric field crosses the onset of continuous discharge, bringing unrecoverable damages to the detectors.

According to their specific purpose, the gaseous detectors can be designed to properly operate in each regime, exploiting the characteristics of the multiplication process in each region.

In their motion towards the collecting electrode, the electrons and the ions induce a signal on it and it can eventually be amplified by the read out circuit. The electrons are usually very fast and reach the anode in a time of the order of ns; the ions are slower and they induce signal with long tails lasting hundreds of $\mu$s. The current induced is time dependent and can be calculated applying the Ramo-Schockley theorem [37, 38]. It states that, given a system of $N$ conductors interconnected by a network, the current induced on a grounded electrode by a point charge $q$ moving along a path defined by $x(t)$ is

$$I_{n}^{\text{ind}}(t) = -\frac{q}{V_w} \cdot E_n[x(t)] \cdot v(t)$$

(2.1)

where $E_n[x(t)]$ is the weighting field of the electrode $n$ and it is defined by remov-
Figure 2.3: Number of charge collected as a function of the electric field applied, for $\alpha$ particle and electrons [31].

ing the charge $q$, applying the voltage $V_n$ to the $n$th electrode and grounding all the others. The sign of the current depends on the sign of the point charge and on its direction with respect to the weighted field of the electrode.

Further details on gaseous detectors can be found in [34, 39, 40].

2.1.1 The Townsend amplification in the proportional mode

Once the primary charge is produced through ionization events, the electrons have to be multiplied in order to give rise to detectable signals. Indeed, the common electronics is not sensitive to the single electron. Therefore, the electrons undergo strong electric fields in order to gain sufficient energy to ionize further gas molecules. The secondary electrons are produced in a region where an intense electric field is present and, therefore, they already have the energy to free other charge. The whole process results in the formation of an avalanche. Due to the much greater electron mobility with respect to the ions, the avalanche assumes the characteristic drop-like distribution, shown in figure 2.4, in which the electrons gather in the head. The slower ions are also mostly present in the head but they are the only ones to be present in the queue.

The increase of the number of electrons $dN_e$ during the path $(x, x + dx)$ is given by

$$dN_e = \alpha \cdot N_e \cdot dx$$  \hspace{1cm} (2.2)

where $\alpha$ is the first Townsend coefficient [41] and represent the inverse of the mean free path of ionization, which is the average distance between successive ionizations. It depends on the excitation and ionization cross sections of the electrons interacting with the gas molecules. The cross section depends in turn on the electron energy and ultimately on the reduced electric field. There is no fundamental formulation for the first Townsend coefficient, though it has been described through several analytic expressions, valid in different regions of the electric field. A simple approximation, for example, is the one proposed by the Rose-Korff model [42]

$$\frac{\alpha}{P} = A \cdot e^{-\frac{P}{B}}$$  \hspace{1cm} (2.3)
where $P$ and $E$ are the pressure of the gas and the electric field in the ionization region respectively; $A$ and $B$ are phenomenological constant depending on the gas mixture.

Solving the equation 2.2, one gets the number $N_e$ of electrons produced along the path between $x_0$ and $x_1$

$$N_e = N_0 \cdot \exp \left( \int_{x_0}^{x_1} \alpha(x) \, dx \right)$$  \hspace{1cm} (2.4)

where $N_0$ is the initial number of electrons. The amplification factor, or gas gain $G$, is

$$G = \frac{N_e}{N_0} = e^{\int_{x_0}^{x_1} \alpha(x) \, dx}$$  \hspace{1cm} (2.5)

In case of a uniform electric field, $\alpha$ does not depend on the position and the multiplication factor $G$ is an exponential function of the electric field, therefore it is sensitive to any variation of the applied electric field or of the gas conditions.
2.2 Overview of the Micro Pattern Gaseous Detectors

Micro Pattern Gaseous Detector (MPGD) is a relatively young family of gaseous detectors, developed thanks to the evolution of the photolitographic techniques, which allowed the production of microscopic electrodes (of the order of about 100 µm). The aim of this new technology was to overcome the limitations related to early gaseous detectors, such as the Multi Wire Proportional Chamber. This chamber, for example, had tight geometrical conditions, necessary to guarantee the proper strength of the wire against mechanical stresses. The geometrical constraints limited the spatial resolution and the extension of the chamber itself, which therefore could not cover wide regions. Besides, when exposed to high rate of particles, the ions produced in the avalanche generate a positive space charge which distorts the amplification field. The result is a drop of the gas gain and of the overall detection efficiency. Additionally, they are particularly subjected to aging phenomena (see section 2.6.1).

MPGDs have been developed in the 1990s, in the continuity of the Micro-Strip Gas Counters. The name MPGD refers to a large number of detectors sharing patterned amplification structures and sub-millimetric sizes. The first example of a micro pattern detector is the Micro-Strip Gas Chamber (MSGC) [43, 44]. The most common MPGDs are the MICRO-MEsh GAseous Structure (Micromegas) [45] and the Gas Electron Multiplier (GEM) [46] detectors.

Micro-Strip Gas Chamber

The Micro-Strip Gas Chamber was designed by Oed in 1988 [43]. The structure of the detector and the geometry of the field lines are shown in figure 2.5a. The anode and the cathode consist of metal strips, wider for the cathode, alternately deposited on an insulating layer through photolitographic techniques. The distances between the strips is typically of the order of 100 µm. The insulating substrate supports the strips and is itself placed on a metallic layer, called back-plane, orthogonally segmented with respect to the strips, giving the second coordinate. The upper electrode, called the drift electrode, defines the drift region.

The electrons, freed in the drift region by the primary interaction between the gas and the incoming particles, move towards the anodic strips, following the field lines, where they are multiplied. The ions produced in the primary ionization and in the avalanche are collected on the drift electrode and on the cathode strips.

The small size of the gap between the cathode and the anode and the reduced dimensions of the anodic strips (0.3-0.5 µm) allow to reach high spatial resolution as well as a faster collection of the ions, with respect to the MWPCs.

The limits of this structure appear when operating in a high rate environment: indeed, the ions from the avalanche can accumulate on the insulating substrate giving rise to a distortion of the electric field. This effect is known as charging up and provokes a drop of the gain. Furthermore, this technology appears to be rather susceptible to aging and discharge phenomena: in long term studies, the accumulation of polymers on the surface of the substrate has been observed, resulting in a degradation of the performances of the detector; besides,
the short distances between the electrodes favours the outbreak of destructive events and discharges, resulting in a permanent damage of the detector.

MICROMEGAS
MICRO MEsh GAs Structure was proposed in the early 1990 [45]. Figure 2.6 shows a sketch of the structure and its working principle. The incoming particle creates electron-ion pairs along its path in the drift gap, where the electric field applied is enough to let the electrons drift towards the mesh, without triggering secondary ionizations. The micromesh is nearly transparent to the electrons, 95% of which reaches the amplification gap, where the avalanche occurs. The electrons are finally collected by the anodic strips. Typical value for the gain are between $10^3$ to $10^4$ and the spatial resolution can be better than 100 $\mu$m. The small gap size (about 100 $\mu$m) between the strips and the mesh allows to quickly collect both ions and electrons, resulting in a lower ion feedback and in a time resolution of the order of 5 − 10 $\text{ns}$.
2.3 The GEM technology

GEM (Gas Electron Multiplier) technology was invented by Sauli in 1994 [46]. It uses a thin foil of about 50 µm made of insulating polyimide (commonly, kapton) covered on both sides with a thin (5 µm) copper layer. The whole surface is chemically perforated with holes of microscopic size and biconical shape [39]. The typical external diameter of the hole is 70 µm, the internal diameter is 50 µm and the hole pitch 140 µm. Figure 2.7 shows a sketch of the structure of a GEM foil and a microscopic view of the foil.

![Figure 2.7: Structure of a GEM foil and the corresponding microscopic view](image)

One can realize a GEM based detector, like the one shown in figure 2.8, placing a GEM foil between a cathode and an anode board and flushing it with an appropriate gas mixture. In GEM detectors, the primary ionization region, the amplification and the collection one are separated. Applying a difference of potential across the electrodes of the GEM foil, an intense electric field (30 ÷ 100 kV/cm) is established inside the holes: a particle crossing the detector frees electron-ion pairs in the drift gap and the electrons are drifted towards the holes, where the multiplication occurs; the secondary electrons from the avalanche are extracted from the holes and induce the signal on the anode board.

![Figure 2.8: Section of a single GEM detector](image)

The choice for the geometry of the holes and their distribution on the foil
is the result of the optimization of the parameters, in order to reach gain of the value of $10^3$ on a single GEM layer. I will discuss further details on GEM technology and GEM based detectors in next paragraphs.

### 2.3.1 GEM production techniques

The GEM holes are realized thanks to the etching process using different chemicals for the copper and the polymide. The initial technique was called double mask. It consisted in the transfer of the defined hole pattern by means of two masks, one for the top and one for the bottom electrode. This process requires an alignment precision of $\sim 10 \, \mu m$ and allows the production of foils up to $40 \times 40 \, cm^2$. In order to overcome this limitation, the single mask technique has been developed, according to which the mask is transferred only on one side of the foil, avoiding the alignment procedure. The steps of the techniques are shown in figure 2.9.

![Figure 2.9: Steps for the production of a GEM foil with the double and the single mask techniques](image)

For the double mask technique, a 15 $\mu m$ thick photo-resistive layer is applied on both the copper layers of the foil. The mask is placed on the photo-resistive layer and the system is exposed to UV radiation. The copper layer is etched through chemicals solvents and acid baths to form the holes. After that, the copper layer acts as a mask for the kapton substrate which is dissolved by chemical etching. For the single mask technique, the kapton layer is used as a mask for the bottom copper layer. A further step is included to adjust the shape of the holes engraved in the kapton, giving them the characteristical biconical shape [49].

The two different techniques result in a different GEM hole geometry. The holes obtained with the single mask show significant differences between the top and the bottom cones: the average diameter of the bottom cone is 20% larger than the top diameter. This difference gives rise to a different amplification field with respect to the foil produced with the double mask technique and therefore
it leads to a different response of the foil when used inside the detector. I will provide more details in section 2.5.3.

2.4 Single GEM detector

The simplest GEM based detector is the single GEM detector. It consists of a GEM foil enclosed between a drift electrode and an anode board, which is in turn divided into strips for the signal collection. Referring to the figure 2.10, one can therefore distinguish three main regions:

- the drift region between the drift cathode and the top of the GEM foil, where the primary ionization occurs;
- the amplification region, inside the GEM holes, where intense electric field are established, necessary to the formation of the avalanche;
- the induction region, between the bottom of the GEM foil and the anode board, whose field has to bring the electrons towards the strips in order to induce the signal.

![Figure 2.10: Schematic view not in scale of a single GEM detector. The electric field lines (in red) are shown in the three regions; they intensifies inside the holes of the GEM foil. The equipotential lines are shown in green. The blue region represents the electrons moving from the drift gap towards the holes where they are amplified. Some of the electron (∼40%) are lost on the GEM electrodes, whereas ∼60% of the electrons reach the anode. The red region represents the ions moving in opposite direction with respect to the electrons. Some of them reach the drift electrode, the rest is collected on the top electrode of the GEM][50].

The single GEM is filled with an appropriate gas mixture (usually the Ar/CO₂ in the proportion 70/30 is preferred). At this point, if a charged particle passes through the detector, it interacts with the gas molecules, releasing clusters of electron-ion pairs in the drift volume. The positive ions travel towards the cathode and the electrons towards the GEM foil. A fraction of the electrons is lost on the top of the foil; most of them, instead, enter the GEM
holes and experience the intense electric field, starting the multiplication process. Depending on the strength of the field inside and below the GEM, a fraction of the electrons collects on the bottom electrode of the foil, while the others reach the anode, inducing the signal on it. In a similar way, the ions come out the holes and are collected on the top electrode or drift towards the cathode, leaving the GEM holes in a time of the order of $\mu s$ \cite{48, 51}.

From what explained so far, one can deduce that the only contribution to the signal comes from the motion of the electrons. Therefore, thanks to the high mobility of the electrons, the signals induced are fast and do not have the long tails due to the ions motion.

\subsection*{2.4.1 Gas gain in a single GEM detector}

If a difference of potential is applied to the electrodes of the GEM foil, an electric field builds up inside the holes. A few hundreds of Volts are sufficient to generate an electric field of the order of tens kV/cm, which is enough to start the gas amplification in the gas mixture Ar/CO$_2$ 70/30 \cite{34}. The intrinsic gain $G_{\text{intr}}$ of the GEM foil depends on the voltage $V_{\text{GEM}}$ applied:

\begin{equation}
G_{\text{intr}} = \exp \left( \int (\alpha(x) - \eta(x)) \delta x \right)
\end{equation}

where $\alpha(x)$ and $\eta(x)$ are respectively the first Townsend coefficient and the attachment coefficient for the path $\delta x$. For the typical electric field inside the holes, $\eta(x)$ can be neglected and the 2.6 becomes

\begin{equation}
G_{\text{intr}} = e^{\langle \alpha \rangle} V_{\text{GEM}}
\end{equation}

being $\langle \alpha \rangle$ the average Townsend coefficient for the whole electron path. However, the measured gain is not equal to the one expressed by the formula 2.7, because of the electron losses on the surface of the GEM foil. The effective gas gain $G_{\text{eff}}$ is given by the intrinsic gain $G_{\text{intr}}$ multiplied by a coefficient $T$, the transparency of the foil, which takes into account the electron losses

\begin{equation}
G_{\text{eff}} = G_{\text{intr}} \times T
\end{equation}

where $\epsilon_{\text{collection}}$ and $\epsilon_{\text{extraction}}$ are respectively the efficiency of collection and extraction. The former represents the fraction of electrons entering the GEM holes over the total number of electrons in the upper region; it is related with the electron diffusion phenomena and to the field line defocusing effect on the upper electrode of the GEM foil. The effect can be reduced applying an efficient value of the drift field. The latter is the fraction of electrons outgoing the GEM holes over the number of electrons produced in the avalanche. Simulation studies have found that with an induction electric field set at 5 kV/cm in order to assure a safe detector operation, a fraction of $\sim 50\%$ of multiplication electrons are lost on the lower electrode of the GEM-foil and the other 50% move towards the readout electrode \cite{52}.

\subsection*{2.4.2 Influence of the hole diameter}

The gas gain in a GEM based detector depends on the diameter of the GEM holes: generally, a reduction of the diameter leads to an intensification of the
field lines in the hole itself, resulting in an increase of the gain. This is shown in figure 2.11, where the real gain and the effective gas gain are compared as a function of the hole diameter.

![Figure 2.11: Gas gain and effective gas gain of a single GEM detector as a function of the hole diameter, in the mixture Ar/CO$_2$ 70/30 \cite{48}. The effective gas gain is lower than the gas gain of a factor, the transparency, that depends on the electron losses on the foil.](image_url)

One should notice that while the real gain could be increased as desired reducing the hole diameter, the effective gas gain reaches a saturation for diameter below $\sim 70 \text{ } \mu\text{m}$. This is an effect related to the transparency of the foil and actually has the positive effect of reducing the dependence of the gain from the precision of the GEM construction.

### 2.4.3 Influence of the hole pitch

The combination of the GEM hole pitch and diameter affects the collection efficiency of the electrons produced in the upper volume with respect to the GEM foil. The collection efficiency is strictly related to the transparency of the GEM foil, as defined in section 2.4.1, equation 2.8. It represents the fraction of electrons entering the GEM foil with respect to the total electrons in the upper region. Figure 2.12 reports the GEM transparency as a function of the drift field, for different pitch-hole diameter ratio.

From the plot, one can deduce that the maximum transparency is reached for a low GEM hole pitch.

### 2.4.4 Influence of the hole shape

The shape of the holes is related with the insurgence of the charging up effect and affect the gain stability in high rate operation. The charging up consists in the accumulation of positive charge produced in the avalanche on the surface of the resistive material of the GEM holes, modifying the amplification field and thus the overall gain. The cylindrical shape is the one minimizing the effect, as
CHAPTER 2. MICRO PATTERN GASEOUS DETECTORS

Figure 2.12: Electron transparency as a function of the drift field, in a single GEM detector, for different pitch-diameter ratio [48].

shown in the plot in figure 2.13. However, since the cylindrical holes are difficult to produce, the choice falls on the biconical shape, characterized by an easier production process.

Figure 2.13: Charging up effect as a function of the time in a single GEM detector, for different shape of the GEM holes [48].
2.4.5 Parameter of a single GEM detector

Both the gap size and the value of the electric field in each region affect the performance of the detector.

Drift region. The drift electric field has the function of drifting the primary electrons through the gap and pushing them inside the GEM holes, minimizing the losses. Figure 2.14 shows the relative amplitude of the signals induced on the read out board as a function of the drift field. At low value of the fields (< 0.5 kV/cm), the primary electrons and ions are very slow and recombination and high diffusion effects can prevail over the collection of the electrons, resulting in low amplitude signals; for values higher than 3 kV/cm, the field lines end on the upper electrode of the GEM foils instead of entering the holes. This affects the collection efficiency and, consequently, the effective gain. The value of the drift field is usually chosen in the range between 1÷3 kV/cm in order to optimize both the collection efficiency and the electron drift velocity [51].

![Figure 2.14: Collection efficiency as a function of drift electric field in a single GEM detector measured through the integral current or the amplitude pulse with two shaping time [51].](image)

The drift gap acts as a conversion gap: therefore, it has to be wide enough to guarantee a high detection efficiency. A value of 3 mm ensures that a proper number of clusters is generated by the incoming particles, so that they give rise to a detectable signal, even for minimum ionizing particles. A wider extension, otherwise, could increase the pile up of the ions without an increase of the conversion efficiency [32, 48].

Induction region. After the last stage of amplification, the electrons has to drift towards the anode and to induce the signal during their motion. The induction field has to fulfill this purpose. In figure 2.15, the evolution of the currents induced on the electrodes as function of the induction field is reported: $I_S$ is the current on the anode; $I_T$ and $I_B$ are the current on the top and on the
bottom of the GEM foil, respectively. $I_D$ is the current on the drift and $I_{TOT}$ is the sum of all the currents. Applying low value of the field, almost all the electrons are collected on the bottom of the GEM and no signal can be induced: indeed, one can see in the plot that the current $I_B$ has the maximum value in modulus, whereas $I_S$ is zero. Incrementing the induction field, the fraction of electrons reaching the anode increases as well, at the expense of $I_B$, collected on the bottom electrode of the GEM. For high value $\sim 8 \text{ kV/cm}$, one can incur in destructive phenomenon, which can result in serious damage of the front end electronics. A good compromise is between $4 \div 5 \text{ kV/cm}$, which allows about half of the electrons to reach the anode [53].

Figure 2.15: Currents measured on the electrodes of a single GEM detector as a function of the induction field. $I_S$ is the current on the anode; $I_T$ and $I_B$ are the current on the top and on the bottom of the GEM foil, respectively; $I_D$ is the current on the drift and $I_{TOT}$ is the sum of all the currents [51].

As for the induction gap dimension, for the Ramo theorem, it should be sufficiently small, in order to allow an efficient signal formation: the amplitude of the signal is indeed proportional to the ratio between the drift velocity and the induction gap. However, the gap can not be as small as desired, because of the consequently increase of the discharge probability. It is usually of the order of mm [32, 48].

2.5 Multi GEM detectors

In the applications, GEM detectors with at least two stages of amplifications are usually preferred. In single GEM, reasonable gains are obtained only with large voltage applied and the detector operates very close to the breakdown voltage of the gas, making it more sensitive to discharges. Instead, the use of several layers of amplifications allows to reach the same gain applying less voltage. This is possible with GEMs because they are transparent to electrons.

For the double GEM detectors, besides the drift, the induction and the
amplification gaps, another region is created between the two GEM foils, named transfer region.

The most used GEM based detector is the triple GEM detector, which consists in three GEM foils in cascade, embedded between a drift cathode and a readout board. Figure 2.16 gives a schematic view of the detector. Besides the amplification gaps between each GEM foil, four main regions can be distinguished: the drift gap, between the drift plane and the top of the first GEM foil; the transfer gaps, between the bottom of the first GEM and the top of the second one and between the bottom of the second and the top of the third; finally, the induction gap, between the bottom of the last GEM foil and the anode.

![Schematic view of a triple GEM detector](image)

Figure 2.16: Schematic view of a triple GEM detector [46].

### 2.5.1 Parameter of a multi GEM detector

For what concerns the drift and the induction gap, the considerations already done for the case of the single GEM detector (in section 2.4.5) are also valid in a double and in a triple GEM detector. The transfer regions are discussed below.

**Transfer regions.** The transfer field extracts the electrons from the holes of the upper GEM foil and focus them in the holes of the next. Therefore, the value of the transfer field deeply affects the transparency of the detector. Figure 2.17 reports the evolution of the currents on the electrodes as a function of the transfer field in a double GEM detector. The same considerations are valid for the case of a triple GEM detector for both the first and the second transfer fields.

At low value of the transfer field \(< 2 \text{ kV/cm}\), the extraction efficiency is too low to allow an efficient transfer of the electrons towards the next amplification step: a large fraction of the field lines outgoing the holes close themselves on the bottom of the foil, without reaching the following GEM. This reflects on the measured currents: \(I_{B1}\) is maximum, while \(I_{B2}\) and \(I_S\) are minimum. Increasing the field, an increasing fraction of electrons coming out the first GEM holes reaches the second amplification stage. In the range of field between \(3 \div 5 \text{ kV/cm}\), the \(I_S\) current increases to the detriment of the current on the bottom electrode.
Figure 2.17: Currents measured on the electrodes of a double GEM detector as a function of the transfer field. $I_S$ is the current on the anode; $I_{T1}$ and $I_{B1}$ are the current on the top and on the bottom of the first GEM foil, respectively; $I_{T2}$ and $I_{B2}$ are the current on the top and on the bottom of the second GEM foil, respectively; $I_D$ is the current on the drift [51].

of the GEMs, $I_{B1}$ and $I_{B2}$. At very high electric fields $> 6 \text{kV/cm}$, the detector is characterized by a reduced collection efficiency: the field lines end on the top electrode of the second GEM instead of entering the holes and $I_S$ decreases again because the electrons are mostly collected on the top electrode. Optimum values for the electric fields in the Ar/CO$_2$ 70/30 mixture are in the range of $3 \div 5 \text{kV/cm}$.

For a triple GEM detector, the thickness of the first transfer gap has to be chosen in order to minimize the bigem effect, a phenomenon correlated with the number of multiplication stages primary electrons undergo. Primary ionization can indeed occur in each region of the detector and the difference between electrons freed in different regions is the number of GEM foils they pass through. Contrary to the pairs generated in the second transfer gap and in the induction gap, the one from the first transfer region are subjected to two stages of amplification and they can eventually induce signals whose amplitude passes the discriminating threshold. Furthermore, if $v_{drift}$ is the electron drift velocity inside the gas mixture and $h_1$ is the first transfer thickness, the signal will anticipate of a quantity $\delta t = h_1/v_{drift}$ the real signal. Several studies found that a good value for the first transfer gap thickness is 1 mm [54].

The gap size of the second transfer gap, instead, is strongly correlated with the arising of discharge phenomenon, since the charge density in this region starts to be very high. Increasing the thickness of the gap to 2 mm, electrons are more spread among the holes reducing the charge density in each of them [54].
CHAPTER 2. MICRO PATTERN GASEOUS DETECTORS

2.5.2 Gas gain in a triple GEM detector

The intrinsic gain $G_{\text{intr}}$ in a triple GEM detector is proportional to the product of the intrinsic gain of each single foil:

$$G_{\text{intr}} \propto \prod_{i=1}^{3} \, e^{\langle \alpha \rangle} V_{\text{GEM}i} \, e^{\langle \alpha \rangle} \sum_{i=1}^{3} V_{\text{GEM}i} \, e^{\langle \alpha \rangle} V_{\text{tot}}^{\text{GEM}}$$

(2.9)

The effective gas gain is instead given by the product of the intrinsic gain and of the total transparency

$$G_{\text{eff}} = G_{\text{intr}} \cdot T_{\text{tot}} = e^{\langle \alpha \rangle} V_{\text{tot}}^{\text{GEM}} \cdot \prod_{i=1}^{3} T_{i}$$

(2.10)

The formula 2.10 states that the effective gas gain in a triple GEM detector only depends on the sum of the voltage applied on the GEM foil, $V_{\text{tot}}^{\text{GEM}}$. This allows to choose an efficient configuration for the fields in order to minimize the discharge probability inside the holes of the third GEM, where the discharges are more likely to happen due to the high charge density. The voltages are therefore applied in a descending order: the highest on the first GEM, the lowest on the third one. This configuration has also the positive effect of reducing the bi-gem effect: the primary ionization produced in the first transfer gap does not produce detectable signals since the electrons undergo a lower amplification stages with a lower amplification factor.

Finally, the study on the gain developed in [51] for a single, a double and a triple GEM detector shows that the triple GEM detector reaches higher gain with respect to the single GEM detector, already in correspondence with a low voltage applied on the foils (see figure 2.18). This is achieved thanks to the fact that the amplification is shared among three different stages, avoiding the charge to reach the Raether limit in each foil ensuring operational stability.

2.5.3 Comparison between the single and the double mask technique

As already said in section 2.3.1, the GEM foils produced with the two different techniques, the double and the single mask, have unavoidable geometrical differences arising during the production phase. In particular, the top and the bottom cones of the holes produced with the single mask are asymmetric, with a ratio of the 20% between the top and the bottom hole diameter. The gain of triple GEM detectors employing single mask foils is found to be different if the orientation of the foils is changed. This differences are quantified in [31, 55]. In these works, a detector with three single mask GEM foils is used, with the purpose of testing the two orientations (see figure 2.19) without opening the chamber, the three foils being always oriented in the same way.

As indicated in figure 2.19, in the orientation "A", the larger holes are facing the drift board (i.e. the radioactive source) while in the orientation "B", they are facing the readout board. The effective gain for both the orientations is measured irradiating the detector by a 55Fe source, which produces 5.9 keV photons fully converted in the drift gap. The results are shown in figure 2.20, where the gain of the double mask GEM detector is compared with the one for single mask in the two orientations.
The effective gain of the double mask GEM detector is identical to the single mask in the orientation A. Both of them are lower with respect to the single mask configuration in the orientation B by a factor $\sim 3.6$. In the three cases, the potential applied on the electrodes of the detectors are identical, therefore all the fields are identical. Nonetheless, the amplification factor and the transparency of the GEM foils are different and this reflects on the difference of effective gains: in the orientation A, the exit holes are identical with respect to the double mask technique, thus the extraction efficiency is identical in the two cases; in the orientation B, the exit holes are larger and so it is the extraction efficiency. This results in a higher effective gain with respect to the double mask configuration. The CMS collaboration selected the configuration B for the GE1/1 application, since the detector gain is higher than the one reached with the orientation A, with the same configuration of fields.

### 2.5.4 Time performances in GEM detectors

The time resolution in a GEM detector depends on the statistical nature of the cluster’s formation inside the drift gap. In general, the number of clusters produced in the drift region is correlated to the type of incident particle ($\alpha$, $\gamma$, $\pi$, proton), to its energy and the gas mixture used as converter. The general expression for the space-distribution of the cluster $j$ created at distance $x$ from the first GEM is given by the Poisson statistic [56]

$$A_j \pi(x) = \frac{x^{j-1}}{(j-1)!} \cdot \pi^j \cdot e^{-\pi x}$$

(2.11)

where $\pi$ is the average number of electron clusters per unit length $x$. For a given drift velocity in the drift gap, $v_d$, the probability distribution for the arrival time on the first GEM for the cluster $j$ is given by
Figure 2.19: (a) Orientations of the single mask GEM foil in the configuration A and B: in the orientation A, the larger holes are directed towards the drift; in the orientation B, they are directed towards the readout board [31]. (b) Sketch of the triple GEM detector used for the measurements [55].

$$P_j(t_d) = A_j \pi(v_d t_d)$$  \hspace{1cm} (2.12)

For the first cluster produced closest to the first GEM $j = 1$, one gets

$$P_1(t_d) = \pi \cdot e^{-\pi v_d t_d} , \Rightarrow \sigma_1(t_d) = \frac{1}{v_d t_d}$$  \hspace{1cm} (2.13)

The latter gives the expression for the time resolution of the detector if the first electron cluster is always detected. Therefore, in order to reach high time resolutions, a high primary ionization $\pi$ and a fast gas mixture $v_d$ should be chosen. The electron drift velocity represents the average velocity of electrons moving in a region where an electric field is applied. It is directly proportional to the electric field applied $E$ through the formula (Townsend, 1947)

$$v_d = \frac{k e E \tau}{m}$$  \hspace{1cm} (2.14)

being $k$ the Boltzmann constant, $\tau$ the mean time between successive interactions and $m$ the electron mass. Therefore, in a triple GEM detector, fixed the gas mixture a proper choice of the value of the electric applied (especially in the drift and in the transfers gaps) should take into account this dependence in order to minimize the diffusion phenomena and improving the time performances.
Moreover, the intrinsic time resolution represents actually a lower limit: infact, due to the limited collection efficiency of the first GEM foil, the statistical fluctuations on the gas gain and the finite threshold of the frontend electronics, the signal induced by the first cluster is often not discriminated. Therefore, in order to generate a detectable signal, it is necessary that the clusters of electrons accumulate reaching a signal amplitude above the electronic threshold. The latter effect is the major limitation of the time resolution of the triple GEM detector. Therefore, the use of gas mixture characterized by a high drift velocity at a relative low value of drift electric field is preferred.

2.5.5 The signal formation in GEM detectors

The current induced on the strips of the read out board can be calculated through the Ramo’s theorem. Detailed simulations in [52] have been performed on the triple GEM detector behaviour, up to the formation of the signals on the read out strips. Since the weighted electric field has been found to be practically uniform in the induction region, the velocity of the electrons is also uniform. Therefore, these studies suggest that the single electron coming out the holes of the third GEM induces a rectangular current signal on the nearest strip given by

\[
    i = \frac{q}{l} = \frac{q \cdot v_d}{x} \quad (2.15)
\]
where \( v_d \) is the drift velocity of the electron inside the induction gap and \( x \) is the gap thickness. In order to have high induced signals, the induction gap should be kept as thin as possible and a fast gas mixture should be preferred.

### 2.6 Operational stability of gaseous detector

The operational stability of a gaseous detector has to be evaluated according to two different perspectives: the stability during long term operations, which is referred to as *longevity*, that can be affected by aging phenomena deteriorating the detector performances, and the stability in short term operations, that can be compromised by destructive phenomena, such as the uprising of gaseous breakdowns arising in response to the passage of Highly Ionizing Particles (HIPs). Both of them are aggravated when the detector operates in a high background environment. I will discuss the detector longevity in the next section, whereas the discussion on discharge phenomena is postponed in section 3.5.2.

#### 2.6.1 Detector longevity

When operating a gaseous detector for long time and exposing it to continue radiation, aging phenomenon can arise and start to affect the detector performances. The effect of deterioration is related to complex chemical processes, which mainly take place inside the hot plasma of the multiplication channels: the energy produced inside the avalanche can create gas molecule fragments that sediment on the electrodes, giving rise to polymers distorting the electric field and consequently altering the gas gain. For detectors using wire electrodes, the aging effects result in a polymerization of the wire, which becomes thicker and lowers the gain. Figure 2.21 shows the SEM analysis of wire deposits of a MWPC after being subjected to intense radiation.

![SEM micrographs of the gold plated tungsten wire in a MWPC](image)

Figure 2.21: SEM micrographs of the gold plated tungsten wire in a MWPC: a) shows a clean wire and b), c), d) polymers deposited on the wire surface after being exposed to sustained radiation [57].
For example, for the wire chambers such as CSCs and DTs in the CMS experiment, the non conductive polymers deposited on the surface of the cathode can become charged if exposed to intense radiation. The resulting strong electric field can favor the emission of the electrons from the cathode: these electrons start their own avalanche processes, producing ions which in turn hit the same non conductive spot on the cathode and feeding the whole process. Eventually, at a certain point, a self sustained local discharge can be triggered. This is the so called Malter effect and its mechanism is schematized in figure 2.22.

Figure 2.22: Schematic mechanism of the Malter effect [31].

The conductive polymers can cause, instead, a distortion in the electric field lines and, as a consequence, a reduction in the gas gain.

GEM detectors are also interested by aging phenomena: the non conductive deposits on the resistive kapton inside the holes can distort the electric field, lowering the overall gas gain and the general stability of the detector [33]. The longevity study of CMS GEM chambers is described in 3.5.1.

2.7 Discharge formation in gaseous detectors

As it can be seen from figure 2.3, the collected charge increases with the voltage applied in the multiplication region. Depending on the geometry of the detector, a threshold for the voltage exists, after which the detector operates under unstable conditions entering the discharge regime. Unless specifically designed to work in this regime (i.e. the Geiger counter), the detectors and their electronics can be seriously and permanently damaged by the discharges. Even when working at proper conditions of the gas gain, discharges can anyway be triggered by the passage of the HIPs (High Ionizing Particles), since they leave very high charge density in the gas that during the avalanche the Raether limit can be easily overcome.

The phenomenon of discharge in a gas between two electrodes is related to the breakdown of the insulating gas which turns into a conductive medium, allowing the passage of a high current that shortcircuits the electrodes. Discharges can be triggered by the presence of micro defects on the electrodes and dust spots (which are semiconductive); for good quality detectors, the break-
down can anyway occur when the total charge in the avalanche reaches a certain threshold:

\[ Q_{\text{crit}} = G_{\text{max}} \cdot n_0 \simeq 10^6 \div 10^7 \text{electrons} \]  

(2.16)

where \( G_{\text{max}} \) is the maximum achievable gas gain and \( n_0 \) is the number of primary electrons. If \( n_0 = 1 \), the gain can be as high as \( 10^6 \div 10^7 \); if an \( \alpha \) particle causes the primary ionization then \( n_0 = 10^5 \) and the gain can only reach the value of \( 10^2 \) to avoid discharges. \( Q_{\text{crit}} \) depends anyway on several other factors, which include the geometry of the detector, the diffusion phenomenon of the electron-ion cloud (which in turn depends on the gas composition and the electric field); one can therefore try to optimize all these factors in order to increase the maximum achievable gain.

The following paragraphs provide a discussion on the mechanism of formation of discharges inside the gaseous detectors, with particular attention dedicated to the GEM detectors. For further details, the consultation of [41] is proposed.

### 2.7.1 Electron avalanche

Consider two plane electrodes, a cathode and an anode, in a region of space filled with gas. Let \( E_0 \) be the uniform electric field in the region between the electrodes and the cathode correspond with the position \( x = 0 \) of the x axis, orthogonally directed towards the anode; \( r \) is the distance from the x axis in the transverse direction. Consider an electron leaving the cathode at the time \( t = 0 \) and that the interaction between the electron and the gas only results in the ionization of the gas (producing electron-ion pairs) and the electron attachment (producing negative ions as the electrons are absorbed from the gas molecules). These processes affect the number \( N_e \) of free electrons in the gas. The situation can therefore be described with the following equations:

\[ \frac{dN_+}{dx} = (\alpha + a)N_e; \quad \frac{dN_+}{dx} = \alpha N_e; \quad \frac{dN_-}{dx} = aN_e; \]  

(2.17)

where \( N_+ \) and \( N_- \) are the number of positive and negative ions respectively, \( \alpha \) and \( a \) are the ionization and attachment coefficient. During the motion of the electrons, the ions can be considered as static, since they are 2-3 order of magnitude slower than the electrons. According to the model, the equations 2.17 approximately describes the charge density of the electrons, neglecting the diffusion, of the positive and the negative ions. An approximated solution for the positive ion density for \( t \to \infty \) is given by

\[ n_+(x, r, t = \infty) = \frac{\alpha}{\pi r_D^2(x)} \exp\left(\alpha x - \frac{r^2}{r_D^2(x)}\right), \quad r_D(x) = \sqrt{\frac{4D_e x}{\mu_e E_0}} \]  

(2.18)

being \( D_e \) the diffusion coefficient for the electron, \( \mu_e \) the electron mobility; \( r_D \) is the distance from the x axis at which the charge density decays of a factor 1/e. According to this expression, the ion density increases exponentially along the direction of development of the avalanche, whereas it spreads with a Gaussian law on the transverse direction. Figure 2.23 shows a sketch of the shape of the avalanche and of the charge distribution.
The space charge produced creates an electric field $E'$ that adds itself with the original one $E_0$. As the electrons proceed in their motion, ionizing further gas molecules, a dipole is formed: the faster electrons gather on the head of the avalanche, leaving the ions on the tail. The distortion in the original electric field increases as the contribution $E'$ becomes more relevant. In figure 2.24 a sketch of the process is represented.

The dipole electric field $E'$ has opposite direction with respect to the applied one, in the region inside the dipole where the total field is lowered; in the region external to the dipole, $E'$ has the same direction as $E_0$, enhancing the total electric field.

### 2.7.2 Raether theory of streamer

If the external field is strong enough, either if it is the applied one $E_0$ or the dipole one $E'$, the primary avalanche can develop into a streamer, between the anode and the cathode.

Townsend proposed an argument to explain the breakdown inside the gas. Assuming both the electrons and the ions as responsible for the mechanism, he evaluated the number of electrons reaching the anode in a parallel plate chamber:
\[ n = n_0 \frac{(\alpha - \beta)\exp[(\alpha - \beta)l]}{\alpha - \beta\exp[(\alpha - \beta)l]} \] (2.19)

where \( l \) is the distance between the electrodes and \( \alpha \) and \( \beta \) are the ionization coefficients for the electrons and the ions respectively and depend on the field. For \( l \) approaching the value \( l_c = 1/(\alpha - \beta) \times \ln(\alpha/\beta) \), \( n \) diverges, meaning that electrons reach the anode even if they are not produced in primary ionization. The model failed in the explanation of the time scale of the phenomenon, which is about 2 or 3 order of magnitude faster than predicted.

Thanks to the development of experimental techniques, new experimental evidences helped in the interpretation of the phenomenon. Rather founded a limit for the charge \( \sim 10^7 \), above which the avalanche becomes unstable. He measured the velocity of formation of the streamer towards the anode, founding a value of \( 8 \times 10^7 \text{ cm/s} \) in correspondence with \( E/p = 40 \), and he compared it with the electron drift velocity in similar conditions, which is \( 1.3 \times 10^7 \text{ cm/s} \). He also observed that after a while the streamer develops also towards the cathode, short circuiting the electrodes and producing an intense flash of light, a spark followed by a clack sound.

Relying on this evidences, Raether proposed that an important role in the development of the streamer towards the cathode is played by photoelectrons: the effects of recombination of the gas, the bremsstrahlung emission and the de-excitation of the gas molecules produce energetic photons that can release electrons in photoelectric effects with the gas. The photoelectrons produced in the proximity of the streamer, in the region facing the avalanche, experience a very intense electric field, adding avalanches to the streamer and initiating the one towards the cathode. Figure 2.25 shows a representation of the development of a streamer in a parallel plate counter.

Figure 2.25: Two successive moments of the development of a streamer [41].

To simplify the approach, we can consider that at the beginning of the avalanche, both the negative and the positive charge density can be described through a spherical density of radius \( \rho \). At a certain time \( t_0 \), a photoelectron is released at a distance \( 2\rho \) from the positive spherical distribution, in the region close to the cathode, where the electric field is supposed to be 10 times higher than \( E_0 \). According to the model, after migrating for a tract of \( \delta x = 0.3\rho \), the multiplication has produced enough charge to reproduce the same electric field generated in proximity of the spherical distribution of positive charge.
the same time, therefore, the surface of the ion distribution has advanced for a
tract of $(2\rho - \delta x) - \rho$. The ratio between the velocity of the development of
the streamer and the velocity of the electrons is given by:

$$\frac{v_{aval}}{v_e} = \frac{(2\rho - \delta x) - \rho}{\delta x} = 2.3$$

Therefore, the avalanche is faster than the electrons, considering the contri-
bution of the radiation. The streamer towards the anode develops through a
similar mechanism, which is strengthened by the fact the electrons travel in the
same direction of the field.

### 2.7.3 Spark development

The growth of the streamer channel can lead to the formation of a spark inside
the gap. A qualitative explanation of the phenomenon can be found in [41].

When the anode directed streamer enters in contact with the anode itself, the
front of the streamer directed towards the cathode is at the same potential
as the anode. In the gap between the cathode and the front of the streamer
directed towards the cathode, an intense electric field is therefore present and
it speeds up the whole process. The photoelectrons feeling the electric field are
multiplicated and the avalanches propagate towards the anode passing through
the streamer channel. The result is the formation of a reverse streamer channel,
made of a high ionized plasma. When the anode and the cathode are connected,
the spark channel is created, allowing the passage of the current up to 1 A or
even higher. The Joule effect increases the temperature of the channel (reaching
$2 \times 10^4$ K) and of the gas in the neighbourhood, enhancing the ionization. Due
to the highly conductive channel a flash in the gas can be produced followed by
the shock wave sound. The conductive channel shortcircuits the electrodes and
nullifies the $\Delta V$ across them, extinguishing the process.

The large amount of current released during the process can lead to serious
damages on the micro structure of the MPGD and even burn the front end
electronics.
2.8 Discharge studies on GEM detectors

Several studies have been performed on the breakdown phenomenon inside the GEM detector. In this section, I will present a review of the main results achieved in [58–60].

It has to be said at first that the triple GEM detector are usually preferred in the applications, thanks to the possibility to reach high gain at relative low fields with respect to GEM detectors employing a lower number of amplification stages. Furthermore, the use of three steps of amplification allows to operate in safe conditions even at gain as high as $10^5$: figure 2.26 taken from [58] shows the discharge probability as a function of the gas gain for a single, a double and a triple GEM detector. The onset of breakdowns appears at higher gain in a triple GEM: fixing the gain, in fact, one needs to apply a higher field in a single or a double GEM to reach the same value of the gain, favouring the crossing of the threshold voltage for the breakdown.

Figure 2.26: Discharge probability as a function of the effective gas gain, for a single, a double and a triple GEM detectors. For the triple GEM detectors, the onset gain for the discharge occurrence is higher with respect to the other GEM based detector, with a lower number of amplification stages [58].

2.8.1 Discharge inside the GEM holes

A discharge inside a GEM foil corresponds to a breakdown between the top and the bottom foil through one of the holes, where the electric field is high enough to reach the gas amplification. Due to the exponential nature of the amplification process, the largest amount of charge is produced at the bottom of the foil: the electrons in this region do not feel the multiplication field and are just transferred towards the next amplification step; the ions can instead be considered as static because of their much slower velocity with respect to the electrons. Therefore, the ion space charge at the bottom of the foil can be considered as the only responsible for the distortion of the electric field.

To achieve the formation of the streamer inside the hole, the sum of electric field generated by the ion space charge $E_Q$ and the applied one $E_0$ has to be
high enough to activate gas amplification in the proximity of the avalanche, the \textit{streamer condition}. This condition is satisfied in correspondence with a certain value of the number of charge produced \( N_e \). An evaluation for this number is calculated in \cite{61}; for the mixture of \( \text{Ar}/\text{CO}_2 \) 90/10 the gas amplification starts for an electric field equal to \( \sim 10 \text{ kV/cm} \); the ion space charge can be considered as a sphere with radius \( R = 20 \mu \text{m} \); the external field \( E_0 \) can be neglected since the ion space charge mostly concentrates at the bottom of the foil and outside of it, where the field is not enough to induce amplification. According to this hypothesis we have:

\[
E_Q + E_0 = E_Q = \frac{eN_e}{4\pi\varepsilon_0 R^2} = 10 \frac{\text{kV}}{\text{cm}}
\]  

finding for \( N_e = 3 \times 10^6 \). Even if this result suffers from many approximations, the order of magnitude matches with the experimental measurements.

A discharge inside a GEM detector is recognized electronically as a fast and large pulse on the involved electrodes and the charge released roughly corresponds to the product of voltage and source capacitance. Large induced signals are also seen in all other electrodes. In most cases, a discharge is detected also as an overload of the power supply, usually set to a limiting value of maximum current.

An example of discharge event in a single GEM detector, recorded with a four-track digital oscilloscope, is reported in figure 2.27. It represents the potentials of all the electrodes of a single GEM detector as a function of time: top to bottom, the anode strips, the GEM side facing the anodes, the opposite side of the same and the drift electrode. In this particular event, the breakdown interested only the GEM foil and one can see the voltage difference across the GEM drops symmetrically to zero (since no protection resistors are applied on the electrodes). A negative signal on the anode and a positive one on the drift electrode are also induced, due to the capacitive coupling of the electrodes. The recovery time of the pulses in the plots (around 10 \( \mu \text{s} \)) is determined by the circuit used for readout, a 10 nF capacitor on 50 \( \Omega \), and does not correspond to the real response of the HV circuit (several ms).

![Figure 2.27: Non-propagating discharge in a single GEM detector [58].](image-url)
2.8.2 Propagation of the discharges inside the gap

It has been observed that a discharge in a GEM hole (which is going to be referred to as primary discharge) can trigger a second breakdown (secondary discharge): after the first rupture of the gas rigidity inside the GEM foil, normally in the last stage of amplification where the charge density is larger, the discharge can also propagate forward and backward to the other electrodes, even for a reverse transfer field. The secondary discharges can occur in the gap between GEM foils and eventually propagate in the induction gap, reaching the anode board. The secondary discharge usually appears a few tens of µs after the primary event. This observation is compatible with a photon-mediated breeding of charge by ionization of the gas or of the metal electrodes.

The secondary discharge probability, defined as the ratio between the number of secondary discharges and the total discharge events, increases with the energy of the primary discharge and with the value of the electric field in the gaps, but it does not depend on its direction. In fact, the measurements performed in [58] on a double GEM detector show that if a discharge arises in one of the GEM it can propagate towards the other, even for a reverse transfer field.

In the work [59], the propagation probability inside the gap between the GEM foils and in the induction gap is measured. The experimental setup and the high voltage powering scheme used in [59] are shown in figure 2.28. The detector under test can contain one or two $10 \times 10 \text{ cm}^2$ GEM foil of standard design. The gap size are of the order of mm, comparable with the CMS configuration. Potentials are applied to the electrode via independent channel power supplies with the use of loading resistor $R_{load}^{top}$ for the top and $R_{load}^{bot}$ for the bottom. The readout anode is connected to ground through $R_{anode}$ resistor; for dedicated measurements, its value is changed or the anode is polarized with positive potential.

![Experimental setup used in [59] to perform discharge studies. For the study the setup was also extended by another GEM, which is not shown here.](image)

The top of the figure 2.29 shows, for different values of $R_{load}^{top}$, the probability of the secondary discharge in the gap between the two GEMs measured as a function of the transfer field, raised of the quantity $\Delta V_{GEM2}/d_t$ in order to take into account the drop of the GEM2 top potential as a consequence of the primary discharge. On the x axis therefore the quantity $E_t + \Delta V_{GEM2}/d_t$ is
reported, being \( d_t \) the size of the transfer gap. On the bottom of figure 2.29, the propagation probability towards the anode is plotted as a function of the induction field. The different curves are obtained for a standard induction field (in blue) and for a reverse one (orange).

![Figure 2.29: On the top: discharge propagation probability inside the transfer gap as a function of the transfer field increased of the quantity \( \Delta V_{\text{GEM}}^2/d_t \), in correspondence of four different values of \( R_{\text{load}} \). On the bottom: discharge propagation probability inside the transfer gap as a function for normal and inverted direction of the induction field [59].](image)

For the propagation inside the transfer gap, the plots follow the typical trend of a threshold dominated phenomenon with the probability rising over a narrow field range from 0 to 1. The onset field increases from \(~5 \text{ kV/cm}\) to \(~7 \text{ kV/cm}\) when the resistor \( R_{\text{load}} \) is changed from 0 to 100 k\( \Omega \). For the propagation inside the induction field, the onset field appears in correspondence with a value of ~4 kV/cm. Furthermore, the propagation probability does not change when the induction field is reversed. This fact points out that the modulus of the fields...
inside the gap is the driving factor for the propagation, whereas its direction does not seem to play an important role. The onset field for both the cases is lower than the electric field needed for Townsend amplification and therefore the mechanism cannot be explained through the streamer theory discussed in paragraph 2.8.1.

### 2.8.3 Features of the propagation inside the induction gap

The propagation inside the induction gap is the most concerning phenomenon for the potentially destructive effects and the permanent damages it can cause to the front end electronics. The discharge propagation probability inside the induction gap depends on the modulus of the induction field and on the energy of the primary discharge. Furthermore, in [58] it is found that it increases if a capacitor is added in parallel to the induction gap. Figure 2.30 shows the discharge propagation probability inside the induction gap as a function of the induction field, for different values of the capacitance in parallel to the gap.

![Figure 2.30: Discharge propagation probability as a function of the induction field, for a 100 pF, 50 pF and 0 pF capacitances added in parallel to the induction gap [58].](image)

As the capacitance increases, the onset of the induction field for the appearance of the propagated discharge decreases. Even if not fully understood, an interpretation of this evidence relies on the fact that a larger amount of energy is available to the discharge, inside the capacitors. The same consideration can also explain the different behaviour between the large GE1/1 detector and the $10 \times 10$ cm$^2$ prototype, presented in the next chapter.

In the work [59], a further interesting feature of the propagating discharges inside the induction gap is recorded. The current in the induction gap is measured through a resistance connecting the anode to the ground potential. Figure 2.31a shows the recorded signals on the anode during a primary discharge event, for two different values of the resistance $R_{\text{anode}}$. 

![Figure 2.31a: Recorded signals on the anode during a primary discharge event.](image)
Figure 2.31: Anodic signals recorded in discharge events, in a single GEM detector. (a) Primary discharge in GEM foil, for two different values of $R_{\text{anode}}$. (b) Propagating discharge in the induction gap, triggered by a primary breakdown in the GEM, for $R_{\text{anode}} = 5k\Omega$. After about 15µs from the primary discharge, the current in the gap starts increasing until it develops in a discharge, giving rise to a high voltage pulse. [59].

For the value corresponding to 25 Ω, a fast oscillating signal amplitude can be seen; in the case of 5 kΩ, the oscillation sits on top of a unipolar signal. This is a strong evidence that a current is passing inside the induction gap as a consequence of the initial discharge which decays on a time scale longer than 10 µs. If a secondary discharge occurs, as one can see in figure 2.31b, about 1 µs before it is visible through a large voltage breakdown of the induction gap, the current stops decreasing and develops again resulting in the huge signal ~ 16 µs after the primary event. The slight drop between 15 µs and 16 µs is a preparatory mechanism of the secondary discharge and it can be referred to as precursor current.

In [60] a further study on the discharge propagation toward the anode is realized. In this work, a single GEM detector is used. The foil is characterized by a large hole pitch and the induction gap is 2 mm thick. The mixture used is Ne/CO$_2$/N$_2$ (85/10/5). A high speed camera is used, with the aim of correlate the signals monitored on the electrodes and the optical view of what happens.
inside the detector. In figure 2.32 the time evolution of the potentials applied to the GEM electrodes with the simultaneously photograph by the high speed camera triggered on the GEM hole discharge are shown.

![Oscilloscope data and photograph](image)

**Figure 2.32:** Recorded oscilloscope data and the simultaneously high speed photograph of a propagated discharge. The induction field is 6.8 kV/cm, the decoupling resistor $R_{dc} = 50$ kΩ. The camera is triggered on the primary discharge [60].

On the top, the event corresponds to a primary discharge in the GEM hole, with the visible spark on the right side; on the bottom, the primary discharge is followed after $\sim 80$ µs by a secondary discharge. In the photograph it is visible the formation of the streamer in the induction gap. Besides, observing the pattern of the potential of the bottom electrode, one can see the re-ignition of the secondary discharge in the induction gap, each time that the bottom potential hits the ground. During this phenomenon, a large amount of current is induced on the anode.

Based on all these evidences, in [59] a mechanism for the formation of the secondary discharges inside the induction gap is proposed. It relies on the thermoionic emission, that could explain the delay of the order of tens µs between the primary and the secondary discharge. As a consequence of the primary discharge, the bottom of the GEM is heated up. The energy required to extract the electrons is reduced and the induction field is enough to enhance the emission. A self-sustained mechanism is activate and the current develop into a streamer.
In figure 2.33 and 2.34, the microscopic view of the GEM holes after the discharges shows the droplets of the melted copper around the rim, supporting the hypothesis of the thermoionic emission. Studies conducted by the CMS GEM group on $30 \times 30 \, cm^2$ and GE1/1 detector, confirming the proposed mechanism are presented in section 3.7.1.

**Figure 2.33:** Microscopic view of a single hole GEM foil after a certain amount of discharges [62].

**Figure 2.34:** Microscopic view of the bottom of the three foils damaged by 450 discharges accumulated [31].
2.8.4 HV settings and influence of the external circuits on the discharge probability

A work performed in [63] studies the effects that the high voltage scheme and the RC circuit have on the propagation probability, on a single GEM detector. The experimental setup is shown in figure 2.35. A single $10 \times 10 \text{ cm}^2$ GEM foil is mounted on a frame with a 2 mm thick induction gap. The potentials on the GEM electrodes are applied through protection resistors, $R_{\text{top}}$ and $R_{\text{bot}}$ on the top and the bottom respectively. Resistors to ground, $R_{\text{top}}^{\text{sink}}$ and $R_{\text{bot}}^{\text{sink}}$, are also installed, in order to ensure a safe recovery in case of a power supply trip. The HV cables used for the connections are coaxial and shielded cables with a capacitance of 100 pF/m. Therefore, they introduce parasitic capacitances, whose effects are also tested. The symbols $C_{\text{ps}}^{\text{top}}$ and $C_{\text{ps}}^{\text{bot}}$ are used to indicate the capacitances between the protection resistors and the power supply, and $C_{\text{gem}}^{\text{top}}$ and $C_{\text{gem}}^{\text{bot}}$ are used for the capacitances between the protection resistors and the GEM electrodes.

![Experimental setup](image)

Figure 2.35: Experimental setup in the studies performed by Lautner et al. and described in [63]. The prototype under test is a single GEM detector. On the electrode of the GEM the protection resistors (on the top) and the decoupling resistors (on the bottom) are soldered. Resistors to ground ($R_{\text{top}}^{\text{sink}}$ and $R_{\text{bot}}^{\text{sink}}$) are installed to ensure a safe and fast discharge in case of a power supply trip. The parasitic capacitance introduced by the HV cables are also shown in the circuit. An $\alpha$-emitter is used to induce discharges and it is mounted on a hole drilled on the cathode.

**Influence of the protection and decoupling resistance on GEM electrodes**

Protection resistances are usually applied on the top of the electrodes to suppress the primary discharge and protect the foils from the related damages. The value of the resistor is chosen to ensure that, in case of a discharge, most of the potential drop occurs on the upper side of the sector. Whilst obviously the best protection is obtained with very high value resistors, the experimental requirements (particle rate and gain) determine the maximum values that can be used in order to maintain the potential drops under high particle fluxes within acceptable limits. Typical values used in the applications are in the range between 1 M$\Omega$ and 10 M$\Omega$. As shown in figure 2.36, the $R_{\text{top}}$ does not
affect the propagation probability, but for high value, such as 10 MΩ, it shifts the onset of the induction field towards higher values.

What can be relevant for the discharge propagation probability is the ratio between $R_{\text{top}}$ and $R_{\text{bot}}$: one should keep $R_{\text{top}}$ higher than $R_{\text{bot}}$, in such a way that the field below the discharging GEM does not increase significantly during the primary discharge, reducing the secondary discharge probability.

The use of resistors, $R_{\text{bot}}$, on the bottom electrode is also advantageous in order to lower the propagation probability: in fact, the primary discharge is followed by the flow of the precursor current in the gap below; the presence of a resistor absorbing the current causes a drop in the potential that reduces the field in the gap, on which the occurrence of the propagation depends. The relevance of the choice of the resistors in the stability of the operation of GEM detector for CMS experiments is presented in details in section 3.7.2.

Influence of the parasitic capacitance on GEM electrodes

If the connection between the electrodes of the GEM foil and the protection resistor is made through a coaxial and shielded HV cable, parasitic capacitances
to ground, $C_{top}^{GEM}$ and $C_{bot}^{GEM}$, are introduced in the circuit (see figure 2.35).

The presence of the capacitance on the top electrode, $C_{top}^{GEM}$, affects the position of the onset of the induction field, beyond which discharge propagation occurs (see the top of figure 2.37). The onset induction field is shifted towards lower values, with respect to the configuration in which the protection resistor is directly connected to the electrode (no HV cable in between). Once again, this is explained by the fact that the energy stored in the parasitic capacitance can be released during the primary discharge (the discharge propagation probability increases with the energy of the primary event).

The capacitance $C_{bot}^{GEM}$ is added in parallel to the one of the induction gap, increasing the energy stored inside the region: again, more energy is stored in the system and can be released during the propagation (see the bottom of figure 2.37). One should observe that the capacitance of the induction gap depends on the extension of the electrodes: particular care has to be used for the design of large size detectors.

The capacitance $C_{ps}^{top}$, introduced between the power supply and the resistor, instead does not affect the measurements when the protection resistors $R_{top}^{ps}$ of the value of MΩ are present. This means that the MΩ protection resistors are efficient in decoupling the electrodes from the rest of the circuit minimizing the

![Figure 2.37: Secondary discharge probability as a function of the induction field, for different values of the parasitic capacitance on the top electrode (a) and on the bottom electrode (b) [63].](image)
effects of extra capacitances eventually present in the circuit. Similar conclusions can be drawn for the case of $C_{\text{bot}}$: the presence of the resistor $R_{\text{bot}}$ has the effect of decoupling the bottom electrode from the parasitic capacitances placed beyond the resistor.

2.9 Operational stability of electronics

Frontend electronic can also be very sensitive to the damages wreaked by destructive phenomena or high flux rate. The most vulnerable components are the semiconductive chips, which are subjected to two main problems: ionization, caused by incoming particles and photons, and the displacements of the atoms, due to neutrons. The ionization brings to the increase of the conductivity in the bulk of the semiconductor material; the neutrons can activate nuclear reactions or displacements of the nuclei and create imperfections inside the bulk that can act as charge trap centers affecting the overall electrical properties of the materials.

These phenomena contributes to the aging of the electronics, which manifests itself as an increase of the noise, a loss of linearity in the response characteristics, a growth in the leakage currents. The caused damages can be permanent and unrecoverable [33].

It is very important to point out once again that the occasional occurrence of heavily ionizing trails may trigger a local breakdown which can propagate to the anode plane with possible harmful consequences on the readout electronics. The first operational experience of GEM detectors in CMS experiment demonstrates the paramount impact of those discharges on the front end electronics. The observation, the results and mitigation strategy are presented in chapter 3.
Chapter 3

The CMS triple GEM detector: long term operation stability studies

3.1 The new stations in the innermost region of the CMS forward Muon Spectrometer

As a consequence of the upgrade of the LHC, the instantaneous luminosity is going to increase to a value of $5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. This will lead to an increase in the amount of the particle flux, especially in the high pseudorapidity region of the Muon Spectrometer, where the major source of background mainly consists of neutrons interacting with the material of the return yoke of the magnetic field.

One of the main characteristics of the CMS muon system is the redundancy that allows to reach high efficiency. Nonetheless, the high pseudorapidity region lacks of redundancy in the muon trigger even though the high luminosity and the hostile environment make the region particularly challenging for muons reconstruction in terms of background and momentum resolution. In fact, the lack of redundancy and the high background, in addition to the low value of the magnetic field, which does not allow a proper bending of the muon tracks, lead to a muon momentum mismeasurements in the level 1 of the trigger (L1) whose rate can reach very high values. A qualitative indication [30] that additional chambers are needed in the forward region to overcome performance issues at high luminosity is presented in figure 3.1. The black histogram on the left represents the average number of $\phi$-measuring muon hits associated with a global muon track, as a function of $\eta$ for the Phase-I muon detector: in the barrel muon detector, where $\eta < 0.8$, muon tracks are associated with an average of 25 hits; in the forward region with $\eta > 1.6$ instead, this number decreases to only 18. On the right scale of the same figure, the blue curves illustrates the rate of one of the major backgrounds, the neutron flux through the first station of the muon system. It drastically increases (note the logarithmic scale on the right) with increasing $|\eta|$, and other backgrounds such as the flux of low-$p_T$ muons also exhibit a similar trend. The muon detector redundancy is therefore currently
the least in the region where the backgrounds are the largest.

Figure 3.1: On the top, the black histogram shows the average number of $\phi$-measuring muon layers with reconstructed hits that are attached to a standalone muon track, for simulated muons from $Z \rightarrow \mu\mu$ as a function of $\eta$. It is compared to the flux of neutrons in $Hz/cm^2$ shown as colored curves (note the log scale on the right), which are the dominant cause of background hits, for the muon station first crossed by a muon with a given $\eta$. On the bottom, standalone muon trigger rate as a function of pseudorapidity for the current Phase-I muon detector under loose (red) and tight (green) trigger conditions [30].

Therefore, the CMS collaboration is going to install gaseous detectors based on GEM technology in the region defined by $1.5 < |\eta| < 2.4$ of the Muon Spectrometer. In figure 3.2, a quadrant of the Muon Spectrometer indicating the position of the new detectors.

The choice for the GEM technology is preferred not only because it can fulﬁl the geometrical constraints imposed, but also thanks to its excellent performances at high rate of particles: in fact, triple GEM detectors are characterized by a detection efficiency of 98%, even at rate higher than $MHz/cm^2$; the gain stability is granted for rate as high as several $MHz/cm^2$; they have good spatial ($\sim 100 \mu m$) and time resolution ($\sim 8-10$ ns).
CHAPTER 3. THE CMS TRIPLE GEM: STABILITY STUDIES

Figure 3.2: Sketch of a quadrant of the CMS Muon Spectrometer, showing the gaseous detectors used. In particular, the positions for the new detectors are shown: red for the GEM technology, GE1/1 and GE2/1 stations (orange for ME0), violet for the updated RPCs [33].

Triple GEM detectors are going to be installed in GE1/1 and in GE2/1 stations, where "G" stands for GEM, "E" for End-cap, the first number "1" or "2" refers to the first and second muon station, while the second "1" stands for the first ring of the station.

GE1/1 consists of 144 large trapezoidal chambers coupled to form superchambers covering the full $\phi$ coordinate and the pseudorapidity region in the range $1.55 < \eta < 2.18$, in both positive (GE+1/1) and negative (GE-1/1) endcaps of the CMS muon system. The detectors will be inserted in front of the ME1/1 station in the slots originally foreseen for RPC detectors. Due to geometrical constraints, the GE1/1 project includes two types of triple GEM detectors, the long and the short one, with a length of 120.9 cm and 106.1 cm, respectively. Two identical detectors are going to compose the superchambers and each of them covers around 10°C. Therefore 36 superchambers are needed to achieve full azimuthal coverage of one disk (72 for the entire system), alternating long and short chambers (see figure 3.3).

GE2/1 consists of 36 superchambers (18 for each End-Cap) of trapezoidal shape covering the full $\phi$ coordinate and the pseudorapidity region in the range $1.6 < \eta < 2.4$, partially overlapping with the GE1/1 region. The superchambers are made of two superimposed triple GEM detectors. Each of them covers 20°C and therefore 18 of them are needed to complete the ring, in order to guarantee full azimuthal coverage and redundancy, enhancing the triggering and tracking capabilities in the region.

Besides the two stations, the ME0 regions are also going to be instrumented with triple GEM detectors, exploiting the spatial extension of the inner tracking
CHAPTER 3. THE CMS TRIPLE GEM: STABILITY STUDIES

Figure 3.3: (Top left) Exploded view of a long GE1/1 triple GEM detector, showing all the internal components. (Bottom left) Assembled super chamber. (Right) Mechanical overview of the GE1/1 detector inside the Muon Spectrometer showing the alternance of long (cyan) and short (pink) modules. [32].

capabilities. It consists in 36 superchambers made of 6 layers of triple GEM detectors, covering the pseudorapidity region between $2 < \eta < 2.8$ and they will allow a better rejection of neutron background and increase the efficiency in muon identification and triggering capabilities.

The GE1/1 station is currently being instrumented and the installation of the negative endcap has been completed during October 2019, while the positive endcap is planned for installation in summer 2020. The GE2/1 station is planned for installation during one of the next Year-End Technical Stop (YETS) before LS3. The ME0 installation is planned for the LS3.

An earlier installation of GE1/1, called Slice Test, has been successfully operated during 2017-2018 and has provided a first functional experience of triple GEM detectors under the CMS conditions. I will discuss in detail the results and the lessons learnt during the slice test in section 3.6.

3.2 GE1/1 technical design

The CMS GE1/1 detectors consists in a triple GEM detector trapezoidal shaped. The gas volume is enclosed by the drift electrode and a readout board and by an external frame on the side. Two O-ring are placed in the groove of the frame to ensure the gas tightness. Figure 3.4 offers an exploded view of the components of the detectors.

The inner structure includes a stack of the three GEM foils, separated through the help of specific plastic spacers giving the needed gap size: 3 mm between the drift electrode and the GEM 1 top, 1 mm between the GEM 1 bottom and GEM 2 top, 2 mm between GEM 2 bottom and GEM 3 top, 1 mm
between the GEM 3 bottom and the readout board.

The surfaces of the GEM foils oriented towards the anode are made of a single continuous conductor, while the ones facing the drift board are divided into 40 sectors for the short chamber and 48 for the long one. The sectors have all approximately the same area of $100 \text{ cm}^2$, so their width narrows when going from the short end to the large one of the trapezoid. The aim of the segmentation is to reduce the amount of current that can be drawn in a discharge; furthermore in the extreme case of a destructive discharge occurring in one sector, the damage is limited to the sector only, instead of compromising the whole GEM foil. The sectors are powered separately (and are indicated as HV sectors) by fixing a common connection point connected to the external power supply and routing the HV trace along the border of the GEM foils. The traces end on each sector through a $10 \text{ M}\Omega$ protection resistor.

The readout board is a Printed Circuit Board (PCB) containing 3072 strips running radially along the long side of the detector. The strips are connected to the external side of the board on which they are collected in $8 \times 3$ partitions in $(i_\eta, i_\phi)$. Each partition contains 128 strips which end on the termination of a Panasonic connector.

Figure 3.5 shows the block diagram of the electronic readout system, divided in two parts: the On-detector and the Off-detector. On the On-Detector side the 24 divisions of the readout board are visible. The strips belonging to each partition are connected to the input of the front-end ASIC (the hybrid version 3 of the VFAT3, with $470 \ \Omega$ as the input resistor). The control and the power of the VFAT is delivered through a PCB, known as GEM Electronic Board (GEB). An opto-hybrid board plugged in the GEB contains the GigaBit Transceiver (GBT) chip set and the Field Programmable Gate Array (FPGA) and provides links to the Off-Detector region. The front-end VFAT3 ASIC converts analog signals coming from the readout board into digital signals containing tracking and trigger information that are delivered to the Optohybrid board, which concentrates and sends the data to the backend electronics.

A deeper description of the technical design of the detector, of the frontend electronics and of the Off-Detector system can be found in [32].
3.2.1 Requirements for CMS GE1/1 triple GEM detectors

Due to the conditions they have to work within and the necessary trigger performances, there is a series of requirements GE1/1 detectors have to fulfill [32]:

- The GE1/1 detectors have to cover the largest possible area in order to achieve the maximum geometric acceptance. The maximum geometric acceptance means indeed the maximum physics yield, in terms of acquiring data. This is achieved alternating long and short superchambers.
- The rate capability has to be of the order of 4.5 kHz/cm$^2$.
  In fact, in the scenario of HL-LHC, the expected rate that will hit the region is estimated to be of the order of 1.5 kHz/cm$^2$, as shown in table 3.1; this value is multiplied by 3 as a safety measure.
- A single chamber efficiency has to be of 97% for MIP.
  With this efficiency on an individual detector, the combination of two of them in a superchamber has an efficiency of 99.9%, since the signals coming from the two chambers are OR-ed.
- The angular resolution in $\Delta \phi = \phi_{GE1/1} - \phi_{ME1/1}$ has to be of the order of 300 $\mu$rad or lower between the angular position of the hits in GE1/1 and ME1/1: in this way the trigger becomes more reliable in discriminating the high-$p_T$ muons from the low-$p_T$ muons.
- A single chamber time resolution has to be of the order of 10 ns or better; the timing information provided by the GE1/1 station is combined with the one coming from the CSCs and the matching of the two is reliable enough with respect to the 25 ns bunch crossing time at the LHC.

Figure 3.5: The GEM electronic readout system, divided into the On-Detector and the Off-Detector [32].
• The uniformity gain has to be of 15\% on the whole chamber.
Each GEM foil has an intrinsic variation in the gain across the surface by 5-8\% and this is caused by unavoidable defects in the production phase. In a triple GEM detector, the variation is increased by a factor of \(\sqrt{3}\), bringing the overall variation to 10-15\%. No other causes for the changing in the gain can be accepted in order to avoid geometrical trigger or reconstruction biases.

• The chamber must be able to integrate a charge of \(\sim 18 \text{ mC/cm}^2\) during its lifetime without affecting the performances due to aging effects.
The total charge expected in the GE1/1 sector in 10 years of activity is estimated to be 6 mC/cm\(^2\). A factor of 3 multiplies the estimation as a safety measure.

### 3.3 GE2/1 and ME0 technical design

The GE2/1 stations are going to be instrumented with two layers of triple GEM detectors, in the geometrical shape shown in figure 3.6. Each layer is made of four modules of different dimensions, M1-M4. The modules consist of triple GEM detectors. The full system consists of 72 GE2/1 chambers, for a total of 288 single modules. The modules differ from each other only with respect to their dimension. Putting together the modules to form a whole GE2/1 chamber introduces unavoidable non active gap: in order to avoid that the non active gap of the two chambers overlaps creating a region of low acceptance, the front and back chambers have different dimensions.

![Figure 3.6: A GE2/1 back chamber, made of 4 different modules [33].](image)

The ME0 station will be instrumented with 36 module (18 per endcap). Each of them consists of 6 modules mounted on an aluminium structure for mechanical support. The module will be mounted upside down with respect to the two neighbours module to allow maximum coverage.

The modules for both the GE2/1 and ME0 are divided into partitions in the \(\eta\)–direction and strips in the \(\phi\)–direction. Strips belonging to the same \(\eta\)
partition are further collected in groups of 128 strips to match the granularity of the front-end electronics.

Each group of 128 strips is read out by the ASIC VFAT3 chip, which has to be optimized for the requirements of each region in order to improve the signal to noise ratio. Except for the geometric shape, the electronic system employs the same or updated versions of existing elements, already designed for the GE1/1 system.

Further details on the GE2/1 and ME0 projects can be found in [33].

3.3.1 Requirements for CMS GE2/1 and ME0 triple GEM detectors

The physics performances for the GE2/1 and ME0 stations impose some technical requirements they have to respect [33]:

- Maximum geometric acceptance, which will allow to acquire a higher amount of data.
- Efficiency of 97% for MIPs on a single chamber.
  This is mandatory for the GE2/1 modules which are made of just two layers of detectors, in order to achieve a reliable muon detection efficiency; for ME0 modules, the efficiency of 97% on a single chamber will give an efficiency of 98.8% for at least five hits for stub reconstruction based on combinatorics.
- Rate capability of at least 2.1 kHz/cm$^2$ for GE2/1 and 150 kHz/cm$^2$ for ME0: in fact, the estimated rate for the GE2/1 region is 0.7 kHz/cm$^2$, for the ME0 region is 50 kHz/cm$^2$, as reported in table 3.1; this values are multiplied by a safety factor of 3.
- Angular resolution of the order of 500 $\mu$rad or better, which is required in order to get a reliable track reconstruction between the information coming from the CSCs and the GEMs module.
- The timing resolution has to be of about 8-10 ns on a single chamber, in order to match with the correct bunch crossing (each every 25 ns).
- For the same reason said before (see section 3.2) the gain uniformity has to be of 15% on the whole chamber and only imputable to intrinsic variation of the gain on the foils.
- No gain loss after 9 mC/cm$^2$ for GE2/1, 840 mC/cm$^2$ for ME0 over 20 years of operation, according to the expected overall integrated charge, multiplied by a safety factor of 3.
- A discharge rate that does not impede performance or operation

Since the design of the triple GEM for the new detectors will follow the one of the GE1/1 chambers, many of the results already achieved for GE1/1 can be directly applied to the new modules.
3.4 Background condition at HL-LHC

The new extreme radiation environment due to the high luminosity regime at the LHC establishes new challenges on the signal identifications and on the performances of the detector, especially in the high pseudorapidity region. Indeed, the background particle rates is particularly high in the most forward region ($|\eta| > 1.6$) of CMS. The estimation of the background hit rate in this region is therefore a matter of primary importance, in order to set up a proper hardware system capable of operating efficiently in this harsh environment.

The major source of backgrounds, which determines the hit rate and the occupancy inside the detectors, is due to neutrons and to the secondary particles arising from neutron interactions with matter. This background has a long lifetime as neutrons can propagate for seconds without interacting. Neutrons are generated by the interactions of hadrons produced in primary pp collisions with the material of the beam pipe and the structures positioned in the very forward region (very forward calorimeter (HF), beam collimator and shielding). The energy spectrum of these long-lived neutrons ranges between the thermal region and a few GeV (see figure 3.7).

![Figure 3.7: Energy spectra for different background particles extracted with FLUKA simulation considering CMS-FLUKA Phase-2 geometry and an instantaneous luminosity of $5 \times 10^{34}cm^{-2}\cdot s^{-1}$ for the upgrade GEM detector in the GE1/1 (a) and ME0 (b) regions [64].](image)

The slow neutrons capture by nuclei with subsequent photon emission in the detector material produces photons and, consequently, electrons and positrons capable of giving rise to detectable amounts of ionization in gas detectors. When neutrons or photons enter a GEM chamber, they interact with the material of the detector producing secondary particles which can reach the gas gaps and generate signal. Electrons and positrons can directly generate signals by penetrating the chamber and ionizing the gas; otherwise, they can interact with the walls or the inner structures of the chamber and cause electromagnetic showers producing secondary particles that can generate signals inside the detector.

In order to evaluate the rate of the hits generated in the chambers by the backgrounds induced by the long-lived neutrons, the knowledge of the flux for each particle type has to be known, together with the probability for a given...
type of particle to generate a spurious signal in the detector. The latter probability, referred to as the detector sensitivity, depends on the particle energy and the direction along which it crosses the outer surface of the chamber. The convolution of the particle fluxes and the detector sensitivity gives the hit rates.

The flux of long-lived neutrons and of the secondary particles produced by the interactions of the neutrons with the material of the detector has been computed using the CMS-FLUKA simulation tool [65]. The sensitivity of triple GEM detectors to the different background contributions and energies has been modelled with the GEANT4 framework [66]. The results of the simulations are shown in figure 3.8a for GE1/1, 3.8b for GE2/1 and 3.8c for ME0 and they are summarised in table 3.1.

![Figure 3.8](image.png)

**Figure 3.8**: Estimated Background Hit Rate extracted with a combination of FLUKA+GEANT4 simulations considering CMS-FLUKA Phase-2 geometry and an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$ for the upgrade GE1/1 (a) GE2/1 (b) and ME0 (c) station. The plots shows the contribution of the different neutron induced background particles (neutrons, photons, $e^+ e^-$) weighted according to detector sensitivity and the total contribution as a function of the R coordinate [64].
Table 3.1: Expected background components and the corresponding maximum hit rate for the three different stations of Muon Spectrometer instrumented with triple GEM technology, GE1/1, GE2/1 and ME0. The total accumulated charge corresponding to 10 HL-LHC years of activity is calculated from the total hit rate in correspondence with a detector gain of $2 \times 10^4$ [33].

<table>
<thead>
<tr>
<th>GEM station</th>
<th>Max. neutron flux [MHz/cm²]</th>
<th>Max. neutron induced hit rate [Hz/cm²]</th>
<th>Total acc. charge after 10 HL-LHC years [mC/cm² - no safety factor]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE1/1</td>
<td>0.277</td>
<td>499</td>
<td>6</td>
</tr>
<tr>
<td>GE2/1</td>
<td>0.191</td>
<td>343</td>
<td>3</td>
</tr>
<tr>
<td>ME0</td>
<td>3.28</td>
<td>5910</td>
<td>283</td>
</tr>
</tbody>
</table>

The total accumulated charge is calculated from the total hit rate in correspondence with a detector gain of $2 \times 10^4$ [33].
3.5 Radiation effect in the CMS GEM system

The background hits have a double effect on the detector performance and operation: long-term radiation damage effects after long sustained operation in a high rate environment, that represents the longevity of the detector, and the discharge events when the avalanche size exceeds the so-called Raether limit. Extensive studies on this effect have been carried on in order to evaluate the response of the GEM technology. They are summarized in the sections 3.5.1 and 3.5.2.

3.5.1 Detector longevity

The increase of the luminosity after the upgrade of the LHC (HL-LHC) is going to increase as well the background and the particle flux that hits the detectors. The hardware is therefore going to be subjected to faster aging deterioration and the detectors need to be updated in order to sustain the harsher conditions.

Aging represents one of the most serious limitations to the performances of gaseous detectors, due to the degradation it can cause especially in high rate conditions. It affects both the gaseous detectors and electronic components. For example, deposits on the anode wires can result in a decrease of gas gain and hit-efficiency losses. Background hit rates can rise as well, eventually leading to a high voltage breakdown inside the detector. Radiation damage of the silicon substrate in electronic chips can lead to noisier electronics performance and even fatal failures of entire electronics boards. The phenomena are complex, but in general the performance of gaseous detectors deteriorates with an increase of the integrated charge released in the gas volume, expressed in either $C/cm$ or $C/cm^2$ for wires or surfaces. For the electronics longevity, the relevant quantities are the integrated neutron flux, or fluence, measured by the number of neutrons per $cm^2$, and the total ionization dose (TID), measured in Gray (Gy) or Rad units.

To evaluate the response of the GEM detectors to a high flux of particles and to establish if the technology can afford it, the detector under test is exposed to an intense radiation in order to accumulate a sufficient amount of charge that is comparable with the expected values of integrated charge accumulated during the lifetime of the HL-LHC.

The estimation of the integrated charge is evaluated considering the maximum interaction rate $R_{\text{max}}$, the primary charge deposited by the particles $n_{\text{TOT}}$, the gas gain $G$ of the detector and the time of exposure to irradiation $t_{\text{LHC}}$.

The average energy loss per unit path in Ar/CO$_2$ (70/30) mixture by a MIP is given by the Bragg additivity law:

\[
\langle \frac{dE}{dx} \rangle_{\text{TOT}} = \langle \frac{dE}{dx} \rangle_{\text{Ar}} \times f_{\text{Ar}} + \langle \frac{dE}{dx} \rangle_{\text{CO}_2} \times f_{\text{CO}_2} \approx 2.61 \text{ keV/cm} \quad (3.1)
\]

where $\langle dE/dx \rangle_{\text{Ar}}$, $\langle dE/dx \rangle_{\text{CO}_2}$, $f_{\text{Ar}}$ and $f_{\text{CO}_2}$ are respectively the average energy loss per unit path in argon and carbon dioxide for a MIP and the gas percentage of argon and carbon dioxide in the mixture.

Considering a conversion gap of 0.3 cm, as the standard CMS triple GEM detector, the energy lost by a MIP is $E_{\text{MIP}} = 0.78 \text{ keV}$. The corresponding charge $Q_{\text{MIP}}$ is therefore given by:

\[
Q_{\text{MIP}} = \frac{E_{\text{MIP}}}{\langle \frac{dE}{dx} \rangle_{\text{Ar}}} \times f_{\text{Ar}} + \frac{E_{\text{MIP}}}{\langle \frac{dE}{dx} \rangle_{\text{CO}_2}} \times f_{\text{CO}_2}
\]
\[ Q_{MIP} = \frac{E_{MIP}}{W_i} \times e \times G \]  
(3.2)

where \( W_i \) is the average energy required to create an electron-ion pair in the mixture and \( e \) is the electron charge; assuming for \( G \) the nominal value of \( 2 \times 10^4 \), then \( Q_{MIP} \approx 98.26 \, \text{fC} \).

The total integrated charge over 10 years of HL-LHC is given by

\[ Q_{TOT} = Q_{MIP} \times R_{\text{max}} \times t_{\text{LHC}} \]  
(3.3)

using for \( R_{\text{max}} \) the maximum hit rate for GE1/1, GE2/1 and ME0 reported in table 3.1 and for \( t_{\text{LHC}} \) the effective exposure time which is estimated to be \( 6 \times 10^7 \) s.

The purpose of the longevity tests is to reproduce in the laboratory the irradiation conditions shown in table 3.1 with a safety factor of 3, accumulating a charge of 18 mC/cm\(^2\), 9 mC/cm\(^2\) and 850 mC/cm\(^2\) for the GE1/1, GE2/1 and ME0 stations respectively. The tests are performed at CERN Gamma Irradiation Facility (GIF++), using an intense 14 TBq (2015) 137Cs source, emitting 662 keV \( \gamma \) rays and through a 22 keV x ray source, on detectors flushed in Ar/CO\(_2\) (70/30) mixture and operated at a gas gain of \( 2 \times 10^4 \). The 662 keV photons have low probability of interacting with the gas molecules in the drift gap of the GEM detectors (\( \sim 10^{-5} \), estimated with the Lambert Beer law). The interaction is instead more likely to happen with the 35 \( \mu \)m thick copper layer of the drift electrode, through Compton scattering. The probability for this event is of the order of \( 10^{-3} \). The most of the Compton electrons are released in the drift gap with a peak energy around 400 - 500 keV, close to the minimum ionization energy. Therefore, the 662 keV photons at a flux of \( 10^7 \, \text{Hz/cm}^2 \) can be considered as MIPs with a flux of \( 10^4 \, \text{Hz/cm}^2 \).

The results of the tests are shown in figure 3.9 and 3.10. Figure 3.9 shows the results for the aging tests for a GE1/1 chamber irradiated with \( \gamma \) ray. In twelve months of irradiation, the accumulated charge is 125 mC/cm\(^2\), which corresponds to 10 years of operation at GE1/1 with a safety factor of 21, 10 years of operation at GE2/1 with a safety factor of 42 and the 44% of the total ME0 operation.

Figure 3.10 shows the results for the aging tests for a GE1/1 chamber irradiated with x ray. The total accumulated charge is 875 mC/cm\(^2\) which corresponds to ten years of ME0 operation with a safety factor of more than 3.

No drop of the gas gain is recorded. These tests confirm therefore the robustness of GEM detectors against the accumulation of charge and aging effects [67].
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Figure 3.9: Result of the aging test at GIF++ facility on a GE1/1 chamber, showing the normalized gas gain as a function of the accumulated charge [67].

Figure 3.10: Result of the aging test using the 22 keV x-ray source on a GE1/1 chamber, showing the normalized gas gain as a function of the accumulated charge [67].
3.5.2 Discharge probability

In gaseous detectors, the occurrence of discharges strongly depends on the gas gain and on the number of charges created by primary ionization. Usually, they happen when the number of charges in the amplification region passes the Raether limit. Discharges are dangerous because of their potentially destructive effects, especially on the front end electronics, causing a loss of efficiency and in general compromising the overall performance.

In any case, the probability to actually have a discharge in triple GEM detector is much lower comparing to other gaseous detectors, thanks to two main reasons: the multiplication stage is split in three separated regions, avoiding the charge to reach the Raether limit in each foil, even at gain of the order of $10^5$; in the same time, the electrons coming from the avalanche are spread over adjacent holes of the next foil, lowering the number of charges for each hole. Furthermore, the amplification region is completely separated from the readout board: the absence of a strong electric field in proximity of the collecting circuit lowers the damage probability. These two characteristics give the triple GEM detectors stability and resistance at high rate operations.

Detailed studies on discharges in GEM detectors have been performed since 2000, providing the precautions to prevent or lower the discharge probability [58]. They are adopted in CMS triple GEM detector and consist in:

- a segmentation of the top electrode of each GEM foil in sectors of area of 100 cm$^2$, in order to reduce the energy available to the discharge;
- the addition of a 10 MΩ protection resistance on each top electrode, in order to absorb any eventual current flowing through it and to decouple the energy stored in the HV cables and power supply;
- the asymmetric distribution of the electric field among the three steps of amplification.

The CMS GEM group conducted a series of tests using different types of radiation, in order to measure the discharge probability in triple GEM detector and to evaluate their effects on long term operations. For example, in 2014 a triple GEM detector in the CMS configuration was irradiated with 5.5 MeV α particles in order to reproduce the Highly Ionizing Particles (HIPs) produced by the neutrons background in CMS. The discharges are recognized through the fast fluctuations of the high voltages and of the anode current. At nominal gain, the expected discharge probability is of the order of $10^{-9} - 10^{-10}$, therefore the gain is pushed to a higher value of $5 - 6 \times 10^5$, in order to collect a sufficient number of discharges in a reasonable time. The discharge probability at lower gain is then obtained through extrapolation from the measured data. The results show that the discharge probability for a triple GEM detector in the CMS configuration is of the order of $10^{-10}$/HIPs [32].

Further studies at the CHARM facility [68] allowed to reproduce more realistic background conditions: a triple GEM detector in the CMS configuration was irradiated in order to reach a neutron fluence of the order of $2.5 \times 10^8$/cm$^2$ and it was operated at a gas gain of $3.5 \times 10^4$ in Ar/CO$_2$ 70/30. A multi-channel power supply was used to power independently the GEM foils in order to monitor the current flowing on each electrode and easily recognize discharge.
events. A picoammeter connected to the anode board allowed to measure the total charge generated inside the detector. As a result, a preliminary upper limit to the discharge probability has been found to be $2.85 \times 10^{-9}$/neutron at 95% CL, compatible with the results obtained with the tests performed with the $\alpha$ source.

During these tests a total of 450, with the $\alpha$ source, and 24, at the CHARM facility, discharges were recorded. Any performance degradation or unstable operations were observed: in figure 3.11 the gain measured before and after the two discharge studies are compared and no gain loss was recorded.

![Figure 3.11: Comparison between the gas gain measured before and after the discharge studies with the $\alpha$ source (a) and at the CHARM facility (b) [33].](image)

An estimation of the total number of discharges per detector expected in 10 HL-LHC years of operation can be calculated. They are shown in table 3.2. The estimations are done taking into account the discharge probability measured at CHARM facility and with the $\alpha$ source and that about the 20% of the total neutron spectrum, corresponding to neutrons with energy above 1 MeV, can produce HIPs and trigger discharges in the detector. The highest number, about $225/cm^2$, is obtained for the ME0 station, where indeed the rate is the highest.

### 3.6 Discharge study at CMS: the GE1/1 slice test experience

In order to gather operational experience on the acquisition and analysis of the data and to demonstrate the integration of GE1/1 chambers within the system the CMS collaboration allowed the preliminary installation, known as *slice test*, of five GE1/1 superchambers into the muon endcaps, during the Year-End Technical Stop in 2016-2017. Four of them were powered with a ceramic voltage divider and instrumented with VFAT2 electronic chain; the other one was powered with a multichannel power supply and instrumented with VFAT3 electronics.
Table 3.2: Expected number of discharges inside the GE1/1, GE2/1 and ME0 detectors after 10 HL-LHC years of operation. The number are estimated using the maximum neutron fluence in the hottest region of the detectors, assuming that only the neutrons with energy higher than 1 MeV are able to trigger discharges[33].

<table>
<thead>
<tr>
<th>GEM station</th>
<th>Expected number of discharge (using $P = 10^{-10}$ from tests with $\alpha$) [1/cm²]</th>
<th>Expected number of discharge (using the preliminary upper limit $2.85 \times 10^{-9}$ measured at CHARM [1/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE1/1</td>
<td>0.6</td>
<td>17.0</td>
</tr>
<tr>
<td>GE2/1</td>
<td>0.4</td>
<td>11.7</td>
</tr>
<tr>
<td>ME0</td>
<td>7.9</td>
<td>224.8</td>
</tr>
</tbody>
</table>

During the slice test, irreversible channel loss in the test version of the front-end electronics has been observed. In order to understand the origin of such channel loss a measurement campaign has been launched in June 2018. The channel loss has been correlated to discharges triggered by highly ionizing particles and propagating to the anode plane of the detector. The observations on discharges have shed new light on the understanding process of discharge propagation in GEM detectors. In the following sections I will present the observation, the procedures established to detect the discharges and the mitigation strategy adopted by the CMS.

### 3.6.1 Channel loss data

During the slice test, a certain fraction of the readout channels of VFAT2 instrumented superchambers was lost. No channel loss was observed for the VFAT3 instrumented chambers. VFAT3 electronics chip is an improved version of the VFAT2, specifically optimized for triple GEM detectors and for the CMS trigger. The VFAT3 chip is made of 128 analog channels each provided with a low noise and a low power charge sensitive amplifier, followed by a shaper and a Constant Fraction Discriminator (CFD). The output of the discriminator, which is synchronized with the LHC clock, splits in two signals: one is sent through a fixed latency path for the trigger generation and the other to the storage and data acquisition. Each channel is also equipped with an input protection circuit, made of a 8 Ω resistor followed by an ElectroStatic Diode (ESD), designed to provide robustness and to absorb high current flowing in case of a discharge.

The channel loss on VFAT2 were discovered through the daily s-curve, a routine that allows to monitor and calibrate the readout channels. It consists in a scan of all the readout channels, by sending N pulses to each channel at a fixed discriminator threshold. The number of events over the threshold is stored and then the amplitude of the signal is increased by 1 DAC unit. The scan is continued until the amplitude of the pulses reaches the last value of the 8-bit DAC. The s-curve for a given channel is then obtained plotting the number of pulses over the threshold as a function of the amplitude of the pulses itself: theoretically, an Heaviside function centered in the threshold value is expected; as a consequence of the noise of the discriminator output, an s shaped curve is
obtained.

The s-curve are fitted with the error function, whose mean value represents the threshold of the discriminator and the width corresponds with the channel Equivalent to Noise Charge (ENC). Disconnected channels present a low noise value compatible with a zero added capacitance.

During the slice test, a rapid drop in the noise showed that the concerning channel was not connected to the readout strips anymore. From visual inspections on a dismounted VFAT, it was seen that the soldering of some of the input channels were broken, probably because of the flowing of a high current through the input resistor, which was not able to dissipate it in time [69]. In order to discover the cause of the channel loss, a measurement campaign was launched, called the GEM Sustained Operation.

3.6.2 The GEM Sustained Operation campaign

Different hypothesis have been proposed as the cause of the channel loss and they have been tested in the laboratory. Even though the channel loss was observed only for the chamber instrumented with the VFAT2, the tests were performed on a GE1/1 detector equipped with VFAT3, which will constitute the final front-end electronics. The detector was flushed with the Ar/CO₂ (70/30) mixture and operated at a gas gain of 10⁴. The sectors of the detector were gathered into three groups, with the aim of testing three different hypothesis: the first group includes VFAT with no power, in order to evaluate if the channel loss could be related with a failure of the LV; VFAT in the second group were operated at normal condition, to exclude that normal avalanches could have resulted in the burning of the channels; two VFAT, componing the third group, were irradiated with Cd109 x rays, in order to understand if background particles could have caused any damage. The channels of all the VFAT were daily monitored through the s-curve scan and no channel loss was recorded. However, the high voltage power supply registered three different discharge events, after which the s-curve showed that some of the channels had been damaged. In figure 3.12, the s-curve before and after the test revealed that the very intense discharges, which were able to trigger propagation towards the other electrodes and, in particular, towards the readout, were responsible for the channel loss. The high current brought by the discharge in fact burns the input resistor, resulting in the disconnection of the concerned channel. Further details on the discovery of the propagating discharges as the cause of the channel loss can be found in [69, 70].
Figure 3.12: 2-D view of the s-curves measured using the VFAT3 front end chips. The red points are the mean value from the fit, the errors correspond to the ENC. The left s-curve measurement refers to operation in normal condition, while the right plot was taken after a discharge occurred in the detector. Empty regions in the s-curves indicate that the channel is no longer responding, narrow sigma s-curve indicate that the channel is disconnected from the strip [69].

Figure 3.13: 2-D view of s-curves measured using the VFAT3 front end chips. The left s-curve measurement was taken in normal operation, while the right plot was taken after a discharge occurred in the detector [69].
3.7 Propagation probability in GE1/1 detectors

The cause of the gradual channel loss in GE1/1 detectors during the slice test has been identified in a specific type of discharge propagating to the read out board. An R&D campaign started with the aim to understand the discharge propagation phenomenon and the mitigation techniques to reduce the damage caused or even their occurrence.

3.7.1 Mechanism of the propagation

When a primary discharge occurs in one of the GEM foil, the energy released can be high enough to melt the copper near the hole; this can lead to create a hot spot (> 2500°C) on the copper. Through thermoionic emission, electrons (coming from electrodes, the HV cables etc.) are released in the gas; the effect is also enhanced by the high electric field in that region. A precursor current starts to flow through the induction gap (in a time of about tens µs) and develops into a streamer, triggering a secondary discharge, which can be eventually followed by discharge re-ignition. The process is shown in figure 3.14.

![Discharge propagation mechanism](image)

(a) A primary discharge occurs in one of the holes of the GEM foil.
(b) A hot spot is created on the copper.
(c) A precursor current develops in the induction region.
(d) Electrons extracted from the hot spot feed the current which turns into a streamer.

Figure 3.14: Discharge propagation mechanism [71].

Measurements are performed on both GE1/1 detectors, which are characterized by large trapezoidal foils, and small 10×10 cm$^2$ prototype in the CMS configuration, in order to compare the results. The detectors are powered through multichannel power supply in order to monitor the electrodes separately. HV filters are used to kill the high frequency noise carried by the HV modules. The
detectors are irradiated with α particles of 5.5 MeV and the voltage on GEM 3 is set to higher value (395 V for GE1/1, 400 for the $10 \times 10 \text{cm}^2$) with respect to the standard CMS configuration, in order to induce discharges at a reasonable rate. The discharges are recognized through an antenna placed close the HV pads: the antenna catches the fast fluctuations of the potentials applied on the electrodes in case of a breakdown inside the gas. The potentials of the GEM 3 top and bottom are monitored through HV probes directly connected to the electrodes: abrupt jumps in the potentials reveal short circuits between the electrodes as a consequence of a discharge. In figure 3.15 the time evolution of the potentials applied on GEM 3 top and bottom together with the signal coming from the antenna are shown for the GE1/1 chamber and the smaller prototype.

The mechanism of propagation is clearly different: in the $10 \times 10 \text{cm}^2$ triple GEM detector, the discharge only involves GEM 3 and the read out board; for a GE1/1, the process is more complicated. The discharge starts in GEM3 but it also involves GEM 2, traveling backward and forward accumulating more energy.

Furthermore, the discharge propagation probability, defined as the ratio between the number of propagated discharge over the number of total primary discharge, also shows different behaviour between the small detector and the large one. The plots shown in figure 3.16 reports the discharge propagation probability as a function of the induction field on the top, as a function of the HV filter resistance on the bottom. It can be seen that for the GE1/1 detector, the propagation probability does not change with the induction field nor with the HV filter resistance and it always is around 0.7, even at the standard CMS operation induction field, $\sim 4.4 \text{ kV/cm}$. In the case of the small detector, the propagation probability appears to be different from zero at an induction field of $\sim 7 \text{ kV/cm}$. Indeed, for the small prototype, the plot of the propagation probability as a function of the HV filter resistance is obtained fixing the induction field to a value, 8 $\text{kV/cm}$, above the onset of the occurrence of the propagation. The propagation probability drops to zero at a resistance of the $\sim 20 \text{ k}\Omega$. 

**Figure 3.15:** (a) Propagation in a 10x10 triple GEM detector. 1. Primary discharge in GEM3. 2. Propagation from GEM3 to RO. 3. Re-ignition of the propagation. (b) Propagation in a GE1/1 detector. 1. Primary discharge in GEM3. 2. Propagation backward GEM2. 3. Propagation forward in GEM3. 4. Propagation from GEM3 to RO. 5. Re-ignition of the propagation.
In order to understand the differences between the small and the large detectors, further tests are carried out on the $10 \times 10 \text{ cm}^2$ prototype varying the capacitance of the third GEM foil (in figure 3.17) and of the induction gap (in figure 3.18) by adding capacitors in parallel to the concerning gap.

Clearly, the propagation probability depends on the capacitance of the induction gap, indicating that the propagation is more likely to happen when a higher energy is stored in the system, since $E = \frac{1}{2} C V^2$, and it is available to feed the discharge. Indeed, since the induction gap can be treated as a parallel plate capacitor, the capacitance is proportional to the area of the foil, $A_{\text{ind}}$: for a GE1/1 $A_{\text{ind}} \sim 4000 \text{ cm}^2$ and it is $\sim 40$ times larger than the $10 \times 10 \text{ cm}^2$ prototype. Therefore, the energy stored in the induction gap is $40$ times higher for a GE1/1 with respect to the small prototype.

The capacitance of the induction gap for a GE1/1 detector is about 2.8 nF. Therefore, the energy released during a discharge at the standard CMS induction field (4.4 kV/cm) is $\sim 0.271 \text{ mJ}$. For a $10 \times 10 \text{ cm}^2$ operating at the same induction field, the energy is $\sim 7 \mu\text{J}$. 

Figure 3.16: Propagation probability toward the readout as a function of the induction field (top left) and of the HV filter resistance (bottom left) on a small prototype. Propagation probability toward the readout as a function of the induction field (top right) and of the HV filter resistance (bottom right) on a GE1/1 detector [71].
Figure 3.17: Discharge propagation probability as a function of the capacitance of the third foil for a $10 \times 10$ cm$^2$ triple GEM detector [71].

Figure 3.18: Discharge propagation probability as a function of the induction capacitance for a $10 \times 10$ cm$^2$ triple GEM detector [71].
3.7.2 Propagation mitigation strategies

The channel loss rate $R_{ch}$ is given by

$$R_{ch} = R_{BKG} \times P_{dis} \times P_p \times P_{dam}$$  \hspace{1cm} (3.4)

where $R_{BKG}$ is the background rate (reported for each GEM stations in table 3.1), $P_{dis}$ is the discharge probability, $P_p$ is the discharge propagation probability and $P_{dam}$ is the damage probability. The discharge probability is an intrinsic feature of every gaseous detector and it is, in any case, already low for triple GEM detector, as discussed in section 3.5.2. Therefore, to lower the channel loss rate, we have to work on reduce either the propagation probability or the damage probability.

When the problem of the channel loss via propagating discharges was discovered, the GE1/1 modules had already been produced, so the focus had to be on reducing the damage probability. The methods implemented consist in the use of higher HV filter resistance, so that a higher onset electric field is needed to trigger the discharge, and in the use of a resistor in series in front of the inputs of the VFAT3 hybrid chips.

A further strategy, which is the purpose of the thesis, is to look for a new configuration of the applied fields that allows to reduce the propagation probability and in the same time does not affect the detector performances.

Since there is still development for GE2/1 and ME0, three other strategies are adopted to affect the propagation probability itself:

- increase the HV filter resistance, so that a higher induction field is needed for the discharge to happen;
- use of a drain resistance between the read out and the ground, which can act as a quencher of the precursor current;
- double segmentation of the foils, to reduce the capacitance and the energy stored in the system.

All these strategies are going to be detailed in the next paragraphs.

Effect of the HV filter

The low pass RC filters are used to filter the ripple of the power supply, reducing the electronic noise. In figure 3.19 two configurations of HV filters applied to a GE1/1 are compared, on the left the standard configuration with 10 $k\Omega$ resistor, on the right using 1 $M\Omega$ resistor. The measurement was performed using $\alpha$ particles from a source of AM and a very high induction field in order to increase the discharge probability. The discharges are monitored through antenna coupled to the HV pads delivering the potentials on the electrodes and through HV probes on GEM 3 top and bottom. In the standard configuration of the filter, several reignitions are recorded potentially destructive for the front end electronics. Using a resistor of the order of 1 $M\Omega$ instead, no reignitions are observed.

Furthermore, the plot already shown in figure 3.16 shows that for high value of the filter resistance, the propagation probability gradually drops to 0.
Figure 3.19: Temporal evolution of the antenna signal (in black) and of the potentials of the GEM 3 electrodes (green for the top, red for the bottom) monitored through HV probes. On the top, the filter configuration is the original adopted for GE1/1. After a short circuit involving GEM3 and the readout, the potential of GEM3 bottom hits several times the ground potential, in reignition phenomenon. On the bottom, the resistor on the GEM side is increased to 1 MΩ and, after a propagating to the readout discharge, the potential of GEM 3 bottom slowly recovers to its initial value [71].
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Figure 3.20: Relative effective gas gain as a function of the normalized interaction rate for a GE1/1 detector, measured in correspondence with three different values of the filter resistance: 10 kΩ, 100 kΩ and 1 MΩ. [71]

However, the choice of the value of the decoupling resistors has to be evaluated taking also into account the side effects it can have on the detector operation, in particular for what concerns the rate capability. When operating at high flux of particles, the large amount of charge induced on the electrodes can provoke a drop of the potential if the resistances on the electrodes are too high. The result is a drop of the gain as well. In order to choose the most suitable decoupling resistor, the rate capability with the original value of 10 kΩ and with two other values, 100 kΩ and 1 MΩ are compared. The results are shown in figure 3.20.

The best compromise is reached for the value 100 kΩ.

Hybrid VFAT input protection circuit

In order to provide protection to the front-end electronics from the destructive events, the robustness of two new different electronics configurations were tested on a GE1/1 chamber. They were designed in order to provide additional input protection and to be implemented on the hybrid plugin board on which the VFAT is mounted. They are named hybrid HV3b_v3 and HV3b_v4. The hybrid version HV3b_v3 consists in the addition of an external input protection to absorb the high current flowing during the discharge. However, the employment of a further resistor on the electronic chain could increase the ENC of the channel and worsen the cross-talk between adjacent channels. Therefore, the values for the input resistors had to be a compromise between the two needs: two values were tested corresponding to 330 Ω and 470 Ω. The version HV3b_v4 includes an ESD on the channel input. The circuitual scheme of the two hybrid version are shown in figure 3.21.

The GE1/1 detector is operated at high value of the induction field in order
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Figure 3.21: On the left, the circuital scheme of the input of one channel of the hybrid v3 chip. On the right, the input circuit for the hybrid v4 chip [72].

Figure 3.22: Damage probability in a GE1/1 detector for different hardware configurations of the VFAT3 electronics with the energy discharge fixed to 1 mJ. The hybrid version v4, which appears the best solution for the small prototype, shows a damage probability of 1 for the large detector. The damage probability is minimized instead for the hybrid v3 with the value of 470 Ω for the input resistor [71].

to trigger the discharge propagation towards the readout. The test consisted in irradiating the detectors with α particles for a certain time; then stopping the irradiation and performing a control on the VFAT channels through the s-curve scan. The damage probability is obtained through the ratio between the number of damaged channels over the total number of channels. The results are shown in figure 3.22.

The solution minimizing the damage probability corresponds to the hybrid HV3b_v3, with input protection resistors of 470 Ω, while the tests on the HV3b_v4 destroyed all the input channels showing a damage probability of 100%. The hybrid version HV3b_v3 is therefore the choice adopted in the final version of the front-end. Further details on the tests on the hybrid VFAT can be found in [70].

The final configuration for the GE1/1 consists in the employment of the VFAT3 hybrid v3, with input resistance of 470 Ω and of a modified version of the HV filter, replacing the 10 kΩ resistances on the electrode with the higher
The minimum for the damage probability is found in correspondence with the VFAT3 hybrid v3, with the input resistor of 470 Ω, using the HV filter resistance of 100 kΩ [71].

value of 100 kΩ. A summary of all the studies and the final configuration adopted in GE1/1 are shown in figure 3.23.

Drain resistors

The presence of a precursor current before a propagating discharge lead to consider the addition of a drain resistance between the anode and the ground, as shown in figure 3.24.

Its role consists in dissipating the current and quenching the discharge: the induction field would then be reduced and the carriers slowed down with mitigation effects in the discharge propagation. The result is a shift in the onset field at which the propagation is triggered and it is shown in figure 3.25.

Tests to improve the efficiency are still ongoing, especially because the employment of a resistance to ground can cause a loss in the signal, that might affect the overall detection efficiency.
Mitigation in GE2/1 and ME0: double segmentation and protection resistors

From the measurements performed on the GE1/1 detectors, it appeared clear that the size of the electrodes, especially the bottom one, plays a special role when it comes to discharges and the related damages. With the perspective of finding better mitigation strategies for the GE2/1 and ME0, a new design of the foil has been proposed: not only the top foil of the GEM but also the bottom ones are divided in sectors of 100 cm². Reducing the area of the electrodes in fact means reducing the capacitance of the induction gap and therefore, the energy available for the discharge.

Measurements on the first prototype produced, operated at nominal CMS configuration of the fields, show promising results, with a propagation probability < 4%, with a confidence level of 68% and no damage was recorded at all. The propagation probability was also measured as a function of the induction field. The results are shown in figure 3.26. The measurements on the double segmented GE1/1 reproduce and actually improve the results obtained for the 10×10 cm² prototype.

For the detectors of the GE2/1 and ME0 stations, there is also the possibility to equipe the electrodes with protection $R_P$ (for the top) and decoupling $R_D$ (for the bottom) resistors, after the HV filter step and directly soldered on the PCB, in order to minimize the parasitic capacitance of the HV cables. Several values has to be tested for both $R_P$ and $R_D$, performing in parallel discharge probability measurements and rate capabilities in order to find a good compromise. Typical values for $R_P$ are 10 MΩ, 5 MΩ and 1 MΩ, lower values are preferred for ME0, because of the intense flux of particles; for $R_D$ are of the order of 100 kΩ: it is important to keep a large ratio between $R_P$ and $R_D$, otherwise the bottom potential would jump toward the top and ignite the propagation.
CHAPTER 3. THE CMS TRIPLE GEM: STABILITY STUDIES

3.8 Discharge study with double segmented foils

We already know that the double segmented detectors have a much better behaviour against discharge phenomena with respect to the GE1/1 configuration and this is shown in figure 3.26. To prove once again the validity of a double segmented chamber and improve the upper limit to the discharge propagation probability, I have performed a test at CERN on a double segmented detector with a GE1/1 geometry. In order to force discharges at a rate which is convenient to measure, an $\alpha$ radiation source is used. The source is put on a hole drilled on the drift board of the detector and covered with a thin plastic layer, in order to avoid to introduce interaction material along the path of the $\alpha$ particles. The detector is powered with a multichannel power supply, giving the configuration of voltages shown in table 3.3, chosen to favour the occurrence of the discharges inside GEM 3.

Table 3.3: Differences of voltage applied on the double segmented GE1/1 prototype.

<table>
<thead>
<tr>
<th>Gap</th>
<th>(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>787.50</td>
</tr>
<tr>
<td>GEM 1</td>
<td>397.00</td>
</tr>
<tr>
<td>Transfer 1</td>
<td>306.60</td>
</tr>
<tr>
<td>GEM 2</td>
<td>385.00</td>
</tr>
<tr>
<td>Transfer 2</td>
<td>612.50</td>
</tr>
<tr>
<td>GEM 3</td>
<td>410.00</td>
</tr>
<tr>
<td>Induction</td>
<td>437.50</td>
</tr>
</tbody>
</table>
In order to monitor and count the discharge events, an antenna is placed near the pads which the electrodes are connected to, as shown in figure 3.27, in order to catch signals, coming from a rapid variation of the potentials of the electrodes interested by the discharge. The antenna signal is used to trigger the oscilloscope and the acquisition chain. An HV probe is connected to the GEM 3 bottom and it monitors the time evolution of the potential on the electrode. Monitoring both the signals on the oscilloscope, one can see if a primary discharge is followed by a propagation towards the readout. The oscilloscope communicate with the computer and data are stored on it at every triggered acquisition (see figure 3.28).

![Figure 3.27: Antenna and HV probe connected to GEM 3 bottom.](image)

The signal coming from the antenna is manipulated as follow (see figure 3.29): it is first sent to a fan in fan out, to get more copies of it without distortion. One of the copies of the signal, triggered by the primary discharge, is sent to a discriminator, with the threshold set to -15 mV. The output digital signal is fed to a dual timer, in order to give it a proper temporal width (in blue in figure 3.30a) and delay ($\sim 3\mu s$) to only temporally cover secondary discharges, due to propagation (in pink in figure 3.30a). The other copy of the antenna signal is sent to another discriminator and the output is fed to the dual timer in order to adjust the width of the signal to cover a single discharge peak (green signal in figure 3.30b). The green signal and the pink one are sent to a coincidence module, getting a signal that produces a pulse only for secondary discharges (in yellow in figure 3.30c). In order to have the scaler counting only once for a
secondary discharge event, the yellow signal is made longer in time through a single timer module. This operation produces the purple pulse in figure 3.30c, which is finally sent to the scaler unit. In this way, we count the signals related to the primary discharges (the blue one in figure 3.30a) and the one related to secondary discharges (the purple one in figure 3.30c). The propagation probability is calculated as the ratio between the secondary discharges and the primary ones.

During the data acquisition, a total of 10353 primary discharge events are collected. No propagation is observed. This change the upper limit for the propagation probability $P_p$ in a double segmented GE1/1 detector to $P_p < 1/10353 \sim 10^{-4}$ with confidence level of 68%.
(a) The blue signal corresponds to the stretched pulse coming from the discriminator; the pink one is a delayed copy of the previous.

(b) A signal (the green one) for every discharge, both primary and secondary, is produced.

(c) The pink signal and the green one are put in coincidence, obtaining a signal (in yellow above) that produces a pulse for secondary discharges only if a primary one happened before. The purple signal is generated to let the scaler adds one for a single secondary discharge event.

Figure 3.30
Chapter 4

Optimization studies of the GEM electric field configuration

In the previous chapters, the problematic of the discharge formation and propagation inside the GEM detector has been treated. One of the main factors contributing to the phenomenon of the propagation is the energy stored in the system. The gaps of the triple GEM detectors can be reasonably approximated as parallel plate capacitors, therefore the energy stored in one gap is given by $E \sim \frac{1}{2} \cdot C \cdot \Delta V^2$, being $C$ the capacitance of the gap and $\Delta V$ the voltage applied on the electrodes. One of the way of reducing the available energy and, consequently, the probability of propagation in the gaps is to reduce the capacity of the gap itself. To achieve this, the geometry of the detector should be changed, reducing the area of the GEM foil or increasing the thickness of the gaps. In both cases, it is necessary to change the detector design. The second option is obviously discarded, as the thickness of the gaps is already optimized to improve the detector’s performances. In the GE2/1 modules indeed the double segmentation of the GEM foils has been proposed, in order to reduce the area of the gaps. The same cannot be done for the GE1/1 modules, which have already been produced. Therefore other solutions have been implemented in order to mitigate the discharge propagation and prevent the damages caused for the GE1/1 modules: the use of protection resistors after the HV filters together with the use of a more robust electronic front end. They are already discussed in chapter 3.

However, the safest and most efficient way to reduce the discharge propagation probability is to lower the $\Delta V$ in the gaps, given the square dependency. A change in the field configuration could lead to a loss of the detector’s performances, as the value of the fields are strictly related to the transparency and, therefore, to the gain. The purpose of this thesis is to propose a configuration of electric fields that reduces the propagation probability and, at the same time, preserves the detector working parameters (in particular, the gain).

In the following chapter, the measurements with a $10 \times 10 \text{ cm}^2$ triple GEM detector prototype are reported. In the first section, the reported measures aim at validating the detector (the gas leak test, the validation of the single foils).
In the second part, the measures aim at characterizing the performances of the detector. In particular, the role of the transfer field and of the induction field are investigated, because of their special role in the mechanism of the discharge propagation.

4.1 Prototype under test and quality controls

The prototype under test is a triple GEM detector with an active area of 100 cm². A sketch representing the prototype is shown in figure 4.1.

Figure 4.1: A sketch of the prototype tested. The drift electrode is a GEM foil with the copper layer covering only the side facing the first GEM foil. The gap sizes are the ones indicated in the sketch [32].

The amplification foils are the standard GEM foils: they consist in a kapton layer of thickness 50 μm, covered on both sides with a copper layer of thickness of 5 μm. The holes have biconical shape and are obtained with the double-mask etching technique; the inner diameter is 50 μm, the external diameter is 70 μm, the pitch of the holes is 140 μm. The gaps between the foils are realized through plastic spacers that are ~0.55 mm thick inserted in such a way to reach dimensions as close as possible to those of GE1/1, taking also into account half of the frame of the GEM foil (~0.65 mm). For the drift gap, three spacers have been used (~1.65 mm); considering also the frame of the GEM foil (~0.65 × 2 mm) the thickness is ~3 mm. For the first transfer gap, the frame of the foil would have been sufficient to define the thickness of the gap (~1.3 mm); nonetheless a plastic spacer was added during the validation of the prototype as a safety measure to allow the passage of the gas. The first transfer gap thickness is therefore ~1.8 mm. The dimensions of the second transfer gap was obtained adding two spacers, reaching the value of 2.3 mm. The value of 1.2 mm for the induction gap was obtained considering half of the frame of the third foil and adding one spacer between GEM 3 and the PCB.

The drift electrode is characterized by a GEM like structure: it is a perforated kapton layer covered in copper only on one side, the one facing the first amplification foil.
The readout anode consists of two planes of strips arranged perpendicularly to each other and mounted on a PCB. The top plane of strips is insulated from the bottom one through 50 $\mu$m ridges of kapton, as shown in figure 4.2. The strips width is 80 $\mu$m for the top, 350 $\mu$m for the bottom which is partially covered by the top strips. The strips pitch is 400 $\mu$m for both layers [73]. A microscopic view of the readout board is shown in figure 4.3. A picture of the readout board is shown in figure 4.4. The strips are connected through the PCB to four Panasonic connectors placed outside the gas volume.

Figure 4.2: Schematic view of the two planes of strips componing the readout anode, separated by a insulating ridges [73].

Figure 4.3: Microscopic view of the readout structure. The width and the pitch of the strips are indicated [73].

On the PCB, tracks to deliver the high voltage to the electrodes inside the gas volume are also present. Two different high voltage connection schema are typically adopted. One consists in distributing the voltages between the electrodes with the help of a ceramic divider, installed as shown in figure 4.5: the voltage is applied to the drift electrode and the current through the divider chain produces voltage drops on the divider resistors, connected in parallel to the gaps. The resulting electric field in the gaps is given by $E_{\text{gap}} = I_{\text{div}} \cdot R_{\text{gap}}/t_{\text{gap}}$, where $I_{\text{div}}$ is the divider current, $R_{\text{gap}}$ is the resistance across the gap and $t_{\text{gap}}$ is the gap thickness. The simplicity of this configuration is one of its main advantages: only one HV channel is needed to supply the whole detector. On the other hand, the possible development of short circuits in one of the GEMs (due to discharges, for example) would affect the corresponding resistor in the supply chain and, consequently, the whole detector would be unusable.

The other configuration consists in the use of a multichannel power supply, to polarize each electrode indipendently. Contrary to the divider chain, this
configuration allows continued operations of the detector even if a short circuit is present in one of the sectors. Besides, this solution is the ideal for systematic studies on the detector. Nonetheless, it requires high stability of the HV supply system, in order to allow safe operations.

For my study, I used the multichannel configuration and each electrode is powered independently. This configuration allows the voltages and the drawn currents on each electrode to be monitored independently.

The gas volume is enclosed sideways by an epoxy frame. It is designed in order to allow to fix two elastomer O-rings, which ensure the gas tightness, on the top and on the bottom of the frame. Two connectors for the gas pipe are fixed on the frame. The detector is closed on the top by a mylar window and a plastic frame, fixed by a series of screws.

4.1.1 Assembly in the clean room

The assembly has to be held in the clean room (of class 10000 or better), since the GEM technology heavily depends on the integrity of the GEM foils and its precision-etched micron level holes. Even the smallest of particulate contaminant could become a source for irregular operation or could even cause unrepairable damage to the detector. The GEM foils are at first cleaned with an anti-static adhesive roller that can remove dust of microscopic dimension. Then, they are tested with a MEGGER MIT420 insulation test (figure 4.6): a difference of potentials of about 550 V is applied across each foil, so that an intense electric field is generated inside the holes. This value for the voltage difference is higher than the real operational value but it is just below the threshold for the breakdown inside the air, given by the Paschen curves [74]. Some sparks can possibly be observed and heard, due to dust trapped inside the holes: the sparks burn the dust inside the holes and the test works as a further cleaning step of the foils. The resistance of each foil is measured and it is > 100 GΩ.

The foils are placed one by one in the stack (see figure 4.7a), alternating by
CHAPTER 4. OPTIMIZATION OF GEM ELECTRIC FIELDS

The plastic spacers, in a number corresponding to the gap width that one wants to get and that are indicated in figure 4.1.

Finally, the gas volume is closed on the top by a plastic frame, with a mylar window in correspondence of the active volume, and fixed on the anode board by a series of screws.

4.1.2 Gas Leak Test

Once the detector has been assembled, it can be brought outside the clean room. The first test to be performed is the gas leak test, in order to verify the good tightness of the gas and to quantify the leakage rate. The gas may in fact come out the detector through a not proper tightness of the screws that fix the drift board, a presence of a gap between the frame and the drift board or the readout, an incompatibility of the O-ring and the groove of the frame.
emission of the gas is dangerous because the source of leakage can become as well source of pollution or unknown gas molecules from the outside that can affect the properties of the gas mixture and therefore they have to be reduced to the minimum.

The test consists in the measurement of the gas leak rate through the measurement of the drop of the pressure inside the detector. The leak rate will depends on the initial over pressure and on the size of the leakage surface. The mass flow rate can be determined as follow:

\[
\frac{dm(t)}{dt} = -S \times v \times \rho(t) \tag{4.1}
\]

where \( S \) is the area of the leak, \( \rho(t) = m(t)/V_{det} \) is the density of the gas, the minus sign indicates a loss of mass; \( v \) is the velocity of the gas emitted from the hole and it can be calculated through the help of the fluid dynamic theory. In fact, the velocity of a fluid coming out a very small orifice approaches the sound velocity and it is equal to

\[
v = \sqrt{\gamma \times R \times T_{det}}/M \tag{4.2}
\]

where \( \gamma \) is the adiabatic coefficient, \( R \) the Boltzmann constant, \( T_{det} \) the temperature of the gas and \( M \) is the molar mass of the gas. Substituting the 4.2 into the 4.1, one gets

\[
\frac{d\rho(t)}{dt} = \frac{S \times \sqrt{\gamma \times R \times T_{det}}/M}{V_{det}} \times \rho(t). \tag{4.3}
\]

Considering the gas inside the detector as ideal, the ideal gas law can be applied:

\[
P(t) \times V_{det} = n(t) \times R \times T_{det} \tag{4.4}
\]

where \( n(t) = m(t)/M \) and \( V_{det} = m(t)/\rho(t) \). The density of the gas can be expressed in terms of the internal pressure:

\[
\rho(t) = \frac{P(t) \times M}{RT_{det}} \tag{4.5}
\]
and so the drop in the pressure is expressed by the differential equation:

\[
\frac{dP(t)}{dt} = -\frac{S \times \sqrt{\gamma \times R \times T_{det}}}{V_{det}} \times P(t) \quad (4.6)
\]

Solving the equation, the pressure as a function of the time is obtained:

\[
P(t) = P_0 \times \exp\left(\frac{S \times \sqrt{\gamma \times R \times T_{det}}}{V_{det}} \times t\right) = P_0 \times \exp(-t/\tau) \quad (4.7)
\]

where \(P_0\) is the initial over pressure of the system and \(\tau\) is the gas leak rate constant. The \(\tau\) parameter depends on the gas composition and describes how fast the drop in the pressure occurs. It can be evaluated through the fit with a decreasing exponential function of the experimental data. For the GE1/1 the \(\tau\) parameter has to be of the order of several hours.

**Experimental setup and results**

The experimental setup is sketched in figure 4.8. The input of the gas system is connected with a \(\text{CO}_2\) bottle. The input flow meter allows to control the gas flow rate at the entrance of the detector; the output flow meter controls the output gas flow and identifies possible large leaks. The input and the output valves allow to isolate the detector while the ongoing test.

Figure 4.8: Gas leak test setup including the detector (up) and without detector for calibration purpose [75].

The pressure inside the detector is monitored through a digital pressure transducer, connected between the input and the output values. An atmospheric and temperature sensors are also present and placed nearby the detector. The sensors are connected to a ARDUINO Mega 2560 microcontroller [76], which takes care of the data acquisition.

For this test I have adopted the same configuration and validation criteria established by the CMS GEM group to qualify the GE1/1 detectors [75].
According to that, the test is passed if the pressure drop inside the detector does not exceed the 7 mbar/h.

The gas leak test consists in two phases: the measurements of the gas leak rate of the system and the measurements of the gas leak rate of the system and of the detector.

For the first phase, the input and the output lines are connected together as shown in figure 4.8 (bottom) and the CO$_2$ is flushed inside the system at a flux of 2.5 L/h. The output valve is closed and the pressure in the system ramps up until it reaches the value of about 25 mbar. The input valve is also closed and the data acquisition is started.

The second phase has the same procedure, but it also includes the detector in the setup, as shown in figure 4.8 (top). The detector is flushed with CO$_2$ through the gas system. The output valve is closed and the detector is brought to an over-pressure of 24.32 ± 0.01 mbar. The input valve is closed too and the acquisition software is started. The result is shown in figure 4.9.

![Gas Leak Test](image)

Figure 4.9: Result of the gas leak test in CO$_2$. Beside the internal pressure drop (in red), the temperature (in blue) is also monitored in time, since the environmental conditions can affect the results of the test.

The pressure drop is fitted with the function 4.7 and the fit gives $\tau \sim 8$ hours, compatible with the acceptance limit to pass the test for CMS triple GEMs, which requires $\tau$ to be of the order of several hours. After one hour, the drop of the internal pressure is of $\Delta P = 2.61 \pm 0.46$ mbar. The equivalent drop in volume $\Delta V(t) \approx 112$ cm$^3$ is given by the Boyle law

$$\frac{\Delta p(t)}{p_0} = \frac{\Delta V(t)}{V_{det}}$$

(4.8)

where $V_{det}$ is the volume of the detector and it is equal to $\sim 400$ cm$^3$. 
4.2 Experimental setup for the measurements with the x ray source

Once the gas tightness is verified, the detector is flushed in the mixture of Ar/CO\(_2\) (70/30) for few hours at a flux of 2.5 L/h, in order to allow the replacement of the gas volume. The detector is installed in the x ray box and connected to the HV system. The detector and the anodic strips are grounded; in particular, the Panasonic-to-lemo adapter are connected to the four sectors of the strips and they are grounded through the 50 Ω resistors. A sheet of copper is arranged around the detector in order to shield it from the environmental noise. The block diagram of the experimental setup is drawn in figure 4.10.

![Block diagram of the experimental setup](image)

Figure 4.10: The block diagram of the experimental setup during the measurements with the x ray source.

**HV system**

Each electrode of the detector is powered independently, using two HV module, the power supply N1471 [77] and the N1471H [78], produced by CAEN. Each of them provides four high voltage independent channels. The N1471 4-channels can supply up to 5.5 kV/300 μA with a resolution of 5 nA on the monitored current; the N1471H 4-channels is a high resolution version of the N1471: it can supply up to 5.5 kV/20 μA with a precision of 1 nA in the monitored current. In high accuracy mode, the maximum supported current is 2 μA and the resolution is of 50 pA. The N1471H is used to measure the currents on the electrodes, since it has a better resolution on the monitored current and it can appreciate the variations induced by the source. Both the modules have the possibility to set the ramp-up (ramp-down), i.e. velocity of the powering on (off) the channel, expressed in Volts per second. For my test, I setted them at 10 V/s. A safety feature warns if one of the channels draws a current higher than the setted limit, entering in a TRIP status for a setted time, the TRIP-time, and then turning off the channel. For my test, the TRIP-time was setted to 0.5 s.
The power modules have been controlled remotely via USB, through the software GECO 2020 [79], which allows to change the settings on the voltages and the currents applied. A LabView [80] program is also used to monitor the voltages and the currents drawn, with the help of graphics reporting the two physical quantities as a function of the time. The voltage and the current values can eventually be stored and analyzed later.

The HV outputs are delivered with SHV connectors and distributed on the electrodes through a system of high voltage filters, as sketched in figure 4.11. The circuit shown is modified as described in section 4.3, to measure the variations in the currents drawn by the electrodes.

Besides the filters, protection and decoupling (depending on which electrode they are connected to) resistors are put in series in the circuit, with the purpose of quenching the currents and reducing the propagation probability in case of a primary discharge event.

![Circuit diagram of the high voltage filters and the resistors soldered on each electrode.](image)

Figure 4.11: Circuit diagram of the high voltage filters and the resistors soldered on each electrode. Besides the protection and the decoupling resistors, the circuit represents low-pass filters, which cut the high frequency noise coming from the HV modules.

**X ray source**

The source used is the *Amptek Mini-X X ray generator* [81], which uses an electron gun incident on a silver target. The device can communicate with the computer via USB and it is controlled through the mini-X software. The power of the beam can be set by changing the voltage (between 10 kV and 50 kV) and the current (between 5 µA and 200 µA). The maximum allowed power is 4 W. The nominal output flux is \( \sim 10^6 \text{s}^{-1}\text{mm}^{-2} \) at a distance of 30 cm at the maximum power. The X ray beam exit in a 120 degree cone; when the 2 mm collimator is used, the aperture of the cone is 5 degree. The spectrum of
the source is shown in figure 4.12a: the higher peak corresponds to the K\(\alpha\) transitions at 22 keV, the other peak to the K\(\beta\) transition at 24.9 keV, over a bremsstrahlung continuum background. When the photons reach the detector, they interact with the copper of the drift electrode, converting in fluorescence photons of 8 keV and 8.9 keV. The photons entering the gas volume interact with the Argon atoms via photoelectric effect: each photon can free one electron of energy of \(\sim 8\) keV (the ionization potential of the Argon is 15.8 eV), which have, in turn, enough energy to produce clusters of electron-ion pairs in the drift volume. In some cases, the photon extracts an electron from the inner K-shell of the argon and the vacancy is filled with an outer electron. The process results in the emission of a further x ray photon, seen by the detector and a second peak can be seen in the x ray spectrum, called escape peak. The spectrum of the x ray gun with the silver target interacting with the molecules of the \(Ar/CO_2\) 70/30 mixture is shown in figure 4.12b. It is measured in [82] through a multichannel analyzer acquiring signals from the readout of a \(10 \times 10\) cm\(^2\) triple GEM detector, irradiated with three different sources: the x ray gun with the silver target, setted at a potential of 40 kV and a current of 25 \(\mu\)A, a Fe55 x ray source and a Cd109 x ray source.

The x ray source and the detector are both put inside a box, whose walls are covered with a copper thickness of 0.5 mm and an aluminium thickness of 2.5 mm. The whole structure shields the laboratory from the x ray and works as a Faraday cage, preventing the detector from interfering with the environmental noise. The x ray gun position inside the box can be controlled via three handle that can move it in the three direction of the space. In figure 4.13 a picture of the x ray box used during the tests is shown.

Unless otherwise stated, the measurements are performed with the x ray pointing towards the sector of the strips from which the current (or the rate) is measured, using the 2 mm collimator. In this conditions, the area of the detector interested by the radiation is \(\sim 540\) mm\(^2\).
Figure 4.12: On the top, the output spectrum of the x ray gun with the silver target. The peak corresponds to the silver transitions, K-\(\alpha\) and K-\(\beta\), centered on 22 keV and 24.9 keV, over a bremsstrahlung continuum [81]. On the bottom, x ray spectrum measured in Ar/CO\(_2\) 70/30 in a triple GEM detector, for different x ray sources [82].
Figure 4.13: Picture of the x ray box used during the measurements. The detector and the x ray gun are closed inside the box.
4.3 Validations of single foils

In order to be sure of the proper operation of each foil, the GEM foils are tested separately, measuring the current on the electrodes involved as a function of the voltage applied on the GEM electrodes.

Since the HV modules used can only measure positive currents, the electrodes are connected to ground through resistors of the order of magnitude of GΩ, as it can be seen in the circuit in figure 4.14: the currents flowing towards the ground constitutes a positive offset that allows to measure also the negative variations in the current drawn by the electrodes, when the source is turned on and off. The order of magnitude of the resistors is chosen in order to obtain measurable currents of the order of µA.

The x ray tube powering voltage and current are set to 40 kV and 40 µA, respectively. The distance between the source and the detector is 30 cm. The detector is flushed in Ar/CO₂ 70/30 mixture.

The offset currents have been measured at first, thanks to the LabView software mentioned in the paragraph 4.2. A file containing the stored values is generated for each $V_{GEM}$ point; the average current $I_{off}$ and its error are calculated. The same procedure is followed to measure the currents in the presence of the source and $I_{on}$ is calculated. The currents induced by the source is thus given by $I_{xray} = I_{on} - I_{off}$, for each electrode.

These tests have been fundamental during the setting up of the detector, since they allowed to discover a bad soldering on GEM 3 bottom and proceed to the quick reparation.

![Figure 4.14: A GΩ resistor connects the monitored electrodes to ground, for the measure of the current during the validation tests.](image)

In the next sections, I will refer to the current induced on the electrodes as $I_{drift}$, for the drift electrode, $I_{GiT}$, with $i = 1, 2, 3$, for the GEM top, $I_{GiB}$, with $i = 1, 2, 3$, for the GEM bottom.

Validation of GEM 1

The monitored electrodes are the drift, the GEM 1 top and bottom and the GEM 2 top. Each electrode is connected to ground as shown in figure 4.14. The drift field is constant at the efficient value of 3 kV/cm [51] and the field in the first transfer gap is at a value of 0.5 kV/cm, in order to ensure the extraction of the electrons from the holes of the first GEM and their collection on its bottom electrode. The difference of potentials between the electrodes of the first foils, $\Delta V_{GEM1}$, varies in the range of 100 V to 450 V. The other electrodes are kept at the same potential as the GEM 2 top, thus the electric field in the other regions is null.

Figure 4.15 shows the results of the test: $I_{GiB}$ grows exponentially with the field inside the holes, as shown by the fit. In particular, for low values of the
applied voltages, both $I_{G1T}$ and $I_{G1B}$ are negative: in fact, since the collection efficiency is low, electrons coming from primary ionization are collected on the top electrode, whose current is higher in absolute value than the current on the bottom electrode. As the applied voltage increases, a higher amount of ions coming out from the holes starts to be collected on GEM 1 top, whose current has now two contributions of opposite sign: the primary electrons, lost on GEM 1 top, and the ions of the avalanches. For $\Delta V_{GEM1} \approx 300$ V, the ions contribution becomes more relevant and the sign of the current changes. The value of $I_{G2T}$ remains constantly low varying $\Delta V_{GEM1}$, due to the low value of the first transfer field which prevent the electrons extracted from GEM 1 to drift towards the GEM 2. The current on the drift electrode, instead, slowly increases with the field inside the holes, as an increasing fraction of the secondary ions moves towards the drift.

**Validation of GEM 2**

The same procedure is followed to test the GEM 2: the involved electrodes are the GEM 1 bottom, the GEM 2 top and bottom and the GEM 3 top. They are connected to ground as shown in figure 4.14. The configuration of the fields is chosen in order to allow the primary electrons in the first trasfer gap to drift toward the GEM 2: it is 3 kV/cm in the drift and in the first transfer gap, 4 kV/cm in the GEM 1. The electric field in the second transfer gap is 0.5 kV/cm; it is null between the GEM 3 electrodes and in the induction gap.

Figure 4.16 shows the results of the test. GEM 2 is also proved to work properly and similar considerations already done for GEM 1 are also valid in this case: the electrons and the ions from the avalanche induce a negative current
and a positive current on the bottom and on the top of GEM 2, respectively, and, since the gain grows exponentially with $\Delta V_\text{GEM 2}$, so does $I_{G2B}$.

For what concerns $I_{G1B}$, it does not depend strongly on the $\Delta V_\text{GEM 2}$, except at higher voltage where we observe a slightly increase, when it weakly begins to increase. One should note that the current involved in the test of GEM 2 are not as high as the ones obtained for the GEM 1. In fact the upper foil, GEM 1, prevents the full transparency to the electrons produced in the drift gap, where the primary interaction is more likely to happen.

**Validation of GEM 3**

The measured currents are the ones induced on the GEM 2 bottom, the GEM 3 top and bottom and the anode. The last one can not be compared with the currents on the electrodes, since it has been collected only from one sector of the readout, whereas the others flow on the whole surface of the electrodes.

For the validation of the third foil, all the fields have been set in order to guarantee the maximum transparency in the upper amplification stage. They are 2.6 kV/cm for the drift field, 3 kV/cm for the first and the second transfer field, 4.3 kV/cm for the induction field. The differences of potentials applied on GEM 1 and GEM 2 are 380 V and 370 V, respectively.

The validation method allowed to spot immediately some issues during the assembly of the chamber. In figure 4.17, it is reported the first attempt of test on GEM 3. The plot shows a clear problem with GEM 3: $I_{G3T}$ is negative and does not change with $\Delta V_{\text{GEM 3}}$; $I_{G3B}$ is even compatible with zero, meaning that the electrons are not entering the foil at all.
The problem was due to a bad soldering which caused the GEM 3 not to be reached by the HV. The problem has been properly fixed as reported in figure 4.18.

For very low value of the amplification field, corresponding to $\Delta V_{GEM3} < 250$ V, $I_{G3B}$ is compatible with zero: the exponential function fits the data starting from $\Delta V_{GEM3} = 250$ V. $I_{G2B}$ does not change with the amplification field: one can therefore state that the third GEM is reached by the same amount of charge for each value of $\Delta V_{GEM3}$ and thus the increase of $I_{G3T}$ and $I_{G3B}$ is a consequence of the amplification in GEM 3.
Figure 4.18: Currents on the electrodes as a function of the voltages applied on the third GEM foil. The currents on the bottom (green) of the GEM grow exponentially with the voltage applied.
4.4 Effective gas gain

The measured gain is referred to as effective gas gain: in fact, it depends on the intrinsic gain, given by the product of the gain of each step of amplification, but it takes into account the electron losses, due to the ion recombination and the attachment phenomena inside the gas mixture, and the collection and extraction efficiencies, related with the electron transparency of the foils.

The measure of the effective gas gain is performed in Ar/CO$_2$ (70/30) mixture, using the x ray source. The gain $G_{eff}$ is calculated comparing the current induced on the readout board $I_a$, which is the result of the amplification through each GEM foil, and the primary current $I_i$, due to the primary interaction between the gas molecules and the incoming photons. It is given by

$$G_{eff} = \frac{I_a}{I_i} = \frac{I_a}{R \times n_0 \times e^{-}}$$ (4.9)

where $R$ is the interaction rate, defined as the number of primary events per unit time; $n_0$ is the number of primary electrons produced in each interaction, $e^{-}$ is the charge of the electron. In fact, it is not possible to directly measure the primary current $I_i$, either because in the drift region it does not exceed the several tens of fA, either because the primary interaction does not occur only in the drift gap and the photons can convert in each gap of the detector. The primary current $I_i$ is, therefore, calculated through the measurement of the interaction rate $R$ and the estimate of the number of the primary electrons $n_0$.

This is done as follow. Considering that the photoelectron produced after the interaction has an average energy of $\Delta E \sim 8$ keV, which can be lost through the collision with the other molecules of the gas; given the gas composition and the average ionization energy of the gas mixture, the average number of primary electrons is given by

$$n_0 = \Delta E \times \left( \frac{0.7}{W_i(Ar)} + \frac{0.3}{W_i(CO_2)} \right)$$ (4.10)

where $W_i(Ar)$, equal to 26 eV, and $W_i(CO_2)$, equal to 33 eV, are the average energies needed to produce a electron-ion pair in the argon and in the carbon dioxide, respectively. In this way, $n_0 \approx 289$. However, the value of $\Delta E \approx 8$ keV is an approximation that does not take into account the interaction of the escape peak and the continuum background. A measurement of the number of the primary electrons is performed in [82]. In this study, the response of a $10 \times 10$ cm$^2$ triple GEM detector, filled with the mixture Ar/CO$_2$ 70/30, has been evaluated for three different sources, the Fe55, the Cd109 and the x ray source with the silver target setted at a value of the potential and current of 40 kV and 25 $\mu$A. The spectra of the three sources are measured through a multichannel analizer: the measurement of the well known spectrum of the Fe55 source allows a fine calibration of the ADC channels which is converted into eV scale. The measurement of the position of the peaks for the spectrum of the x ray with the silver target allows to calculate the weighted average of the energy distribution. As a final step, the value of the number of the primary electrons is calculated with formula 4.10, obtaining $n_0 = 346.0 \pm 2.9$.

The primary current is finally given by $I_i = \frac{R \times n_0 \times e^{-}}{\overline{e}}$.

For what concerns, the anodic current, it is of the order of $10^{-10} \div 10^{-8}$ A, so it can be easily measured with a picoammeter.
4.4.1 Experimental setup for the gas gain measurement

The setup for the effective gas gain measurement is shown in figure 4.19. The measurement is performed on one of the four sectors of the strips, through a Panasonic-to-lemo adapter, that produces in output the OR of the signals induced on the strips connected. The unused connectors are grounded through the 50 Ω resistors. For measuring the anodic current, the adapter is directly connected to the picoammeter, through a shielded cable in order to minimize the electronic noise; for measuring the rate, the readout of the detector is done through a charge sensitive preamplifier connected to an amplifier+shaper unit. The shaped and amplified signal is split in order to be monitored through an oscilloscope and sent to a discriminator and a scaler unit, that counts the number of events over the threshold in a fixed temporal window. All the precautions are adopted to minimize the electronic noise: the use of a grounded copper sheet around the detector, shielding it from the external electromagnetic waves; the anode board, the SHV connectors, the preamplifier and the HV filters are grounded; short lemo cables are preferred, when possible. In this configuration, the level noise is lower than 70 mV.

![Block diagram of the acquisition setup for the measure of the effective gas gain.](image)

The detector is powered on as described in the paragraph 4.2, in the same configuration sketched in figure 4.11. The gain is measured as a function of the equivalent divider current; even if there is not an actual ceramic divider distributing the voltages between the electrodes, the differences of potentials to be applied are the same as the one in the divider configuration. This allows us to be able to compare the performance of the prototype chambers with respect to the results obtained with GE1/1 detector built and fully tested in Bari.

For each acquired data, the temperature and the atmospheric pressure are recorded and corrections given by the formula 4.11 are made on the applied electric fields $E$

$$E_{corr} = E \times \frac{P_0}{P} \cdot \frac{T}{T_0}$$  \hspace{1cm} (4.11)

where $P_0 = 1013 \text{ mbar}$ and $T_0 = 300 \text{ K}$ are the atmospheric pressure and the environmental temperature.
4.4.2 Procedure of the gain measurement and results

The amplifier parameters are set in such a way that the signals are shaped (integrated and differentiated) in a time of 100 ns; the discriminator threshold is -100 mV and the scaler clock is set to 60 s. The x ray tube powering voltage and current are set to 30 kV and 5 \( \mu \)A, respectively. The distance between the source and the detector is 30 cm and it points towards the readout sector. The detector is powered on at the maximum reachable value of the tension, that provides a corresponding value of the equivalent divider current of 725 \( \mu \)A (712 \( \mu \)A, when T/P correction applied to the voltage). The plot in figure 4.20 shows the hit rate per unit area as a function of the divider current. The area of the detector interested by the radiation is estimated according to geometrical considerations knowing the aperture cone of the x ray source (\( \sim \) 5 degree, with the 2 mm collimator) and the distance between the x ray gun and the detector (30 cm); it is found to be \( \sim 5.4 \text{ cm}^2 \).

![Figure 4.20: Measure of the hit rate per unit area as a function of the equivalent divider current.](image)

The interaction rate increases with the divider current, reaching a saturation for a value of 697 \( \mu \)A, in correspondence with the configuration of the fields shown in table 4.1. At these value in fact the detector enters full efficiency regime: the increase of the divider current is not followed by an increase in the rate. The value of the rate at 697 \( \mu \)A will be used to calculate the gain (using the formula 4.9). The uncertainty on the voltages applied corresponds to the resolution of the HV modules, 1 V [77, 78]. The uncertainty on the measured fields, taking in account the uncertainty on the HV board and the gap spacers, has been estimated to be 0.1 kV/cm.

As a second step, the anodic current coming from the same sector is measured through the Keithley 6487 picoammeter [83]. The instrument is controlled via
Table 4.1: Configuration of differences of voltage and electric field applied, in correspondence with a value of 697 µA.

<table>
<thead>
<tr>
<th>Gap</th>
<th>(V) (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>782 ± 1 2.7 ± 0.1</td>
</tr>
<tr>
<td>GEM 1</td>
<td>399 ± 1</td>
</tr>
<tr>
<td>Transfer 1</td>
<td>558 ± 1 3.1 ± 0.1</td>
</tr>
<tr>
<td>GEM 2</td>
<td>384 ± 1</td>
</tr>
<tr>
<td>Transfer 2</td>
<td>710 ± 1 3.1 ± 0.1</td>
</tr>
<tr>
<td>GEM 3</td>
<td>366 ± 1</td>
</tr>
<tr>
<td>Induction</td>
<td>524 ± 1 4.4 ± 0.1</td>
</tr>
</tbody>
</table>

4.4.3 Measure of the spectrum of the signals

The pulse height spectra for different values of the gain is measured. The acquisition chain is shown in figure 4.23. The signals coming from the anodic sector are amplified and shaped. Their polarity is inverted and they are sent to the Amptek MCA8000D [84], a digital Multi Channel Analyzer. The device is controlled via USB by the Amptek DPPMCA display and acquisition software, which allows to set the number of the ADC channels and the acquisition time. A first acquisition without the source is started to measure the ADC pedestal and set the threshold. Then, the source is turned on and the real acquisition is started.

The pulse height spectra are shown in figure 4.24. As the divider current and the gain increase, the peak position of the MCA shifts towards the right, showing that the electron avalanches increases with the gain. The distributions are fitted with Gaussian functions. The peak positions of all the spectra obtained from the fit as a function of the divider current are plotted in figure 4.25. The plot shows an exponential behaviour (note the log scale).
Figure 4.21: Measure of the current as a function of the equivalent divider current. The trend of the current is an exponential increasing function.

Figure 4.22: Measure of the gain as a function of the equivalent divider current.
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Figure 4.23: Experimental setup for measuring the pulse height spectra.

Figure 4.24: Pulse height spectra of the signals picked up from the anode, for different value of the gain. The peak position shifts towards the right as the gain increases.
Figure 4.25: Peak position of the MCA as a function of the equivalent divider current. The red dots correspond to the mean obtained from the Gaussian fit, the error bars are the sigma of the Gaussian curve.
4.5 Rate capability

One of the most successful characteristics of the GEM detectors is their ability to sustain high fluxes of interaction rate without affecting the performances. The small size of the amplification structure (~ 50 µm) indeed allows the ions produced in the avalanche to quickly evacuate the holes, reducing the space charge effects. For the triple GEM detector, three main regions of operation can be distinguished according to the interaction flux they are subjected to [85]:

- for fluxes up to $10^4 \, Hz/mm^2$, the gas gain remains constant, since the space charge does not affect the electric field;
- for fluxes in the range between $10^4 - 10^5 \, Hz/mm^2$, an increase of the gas gain is observed: the space charge distorts the electric field in such a way that it is lower near the top electrodes and higher near the bottom one, resulting in an increase of the collection and the extraction efficiencies;
- for higher fluxes in the range between $10^5 - 10^6 \, Hz/mm^2$, a drop in the gain is caused by the accumulation of ions inside the holes.

The stability of the gas gain of the prototype is tested for a certain range of the interaction rate. The gain is kept fixed at the value of the equivalent divider current of 697 µA, corresponding with a value of $(5.50 \pm 0.24) \times 10^3$. The x-ray source is placed at a distance of 30 cm from the detector. The x-ray tube powering voltage is set to 30 kV, while the current is changed in the range between 5 µA and 80 µA. The interaction rates and the currents from the anodic sector are measured as described in section 4.4. The gas gain is calculated using the formula 4.9.

In figure 4.26, the plot of the effective gas gain as a function of the hit rate per unit area is plotted. The hit rate per unit area is obtained as described in section 4.4.2. The plot shows a weak increasing trend. This may be caused by a systematic underestimation of the interaction rate due to the charging up effect during the rate measurements. The charging up effect is a short term stability effect occurring for a certain time after the detector is submitted to the radiation. It is due to the accumulation of the ions on the high resistive surfaces of the kapton inside the holes, distorting the amplification field and resulting into a lower amplification. Comparing the results with the maximum expected total hit rate per unit area of GE1/1 (1469 Hz/cm²), GE2/1 (672 Hz/cm²) and ME0 (47510 Hz/cm²) [33], the performance of the prototype under test are expected to be stable in a range that exceed the expected hit rate of GE1/1 and GE2/1.
Figure 4.26: Effective gas gain as a function of the hit rate per unit area. The measurement is performed in correspondence with an equivalent divider current of 697 $\mu$A.
4.6 Study on the transfer fields

The role of the transfer field \(^1\) in a triple GEM detector is to pick up the electrons from the previous GEM foil and focus them inside the holes of the next amplification stage, minimizing the losses of the electrons. Its value has to optimize both the extraction and the collection efficiencies, on which the effective gas gain depends. Studies on the transfer fields are performed on the prototype, since their magnitude participate in the propagation of the discharges between the GEM foils.

In the following, I will use the expression \(G_iT\) and \(G_iB\), where \(i = 1, 2, 3\), to refer to the top and the bottom electrodes; I will refer to the currents induced on the top electrodes as \(I_{G_iT}\) and on the bottom \(I_{G_iB}\), where \(i = 1, 2, 3\); \(\Delta V_{GEM_i}\) are the voltages applied across the GEM foils.

In figures 4.27 and 4.28, the currents on the electrodes as a function of the first transfer field, \(E_{\text{transf}_1}\), and the second transfer field, \(E_{\text{transf}_2}\), respectively, are shown for the prototype under test. The measurements are performed in the same configuration as the one described in section 4.3: the currents are measured through resistors to ground on the concerned electrodes, following the scheme sketched in figure 4.14. The x ray tube powering voltage and current are set to 30 kV and 5 \(\mu\)A, respectively, corresponding to an interaction rate of 4.7 \(kHz/cm^2\). The readout current is also plotted. Even though it is not comparable with the other currents, since it only refers to a quarter of the whole anode board, as described in paragraph 4.7, it helps anyway giving an idea of the value of the efficiency of the transfer fields.

\[\text{Figure 4.27: Currents on the electrodes as a function of the first transfer field.}\]

\(^1\)The transfer field also affects the time resolution of the detector, since it takes part into the diffusion phenomena of the electron cloud. This is described in chapter 2.
In figure 4.27 the currents induced on the electrodes are shown as a function of the first transfer field, the one in the gap between G1B and G2T. For low values of the transfer field $E_{\text{transf}1} < 3 \text{ kV/cm}$, the extraction efficiency is low and the electrons, that still go out from the holes thanks to the intense multiplication field, are collected on G1B and the current $I_{G1B}$ should be negative. Nevertheless the current is compensated by some of the ions generated in the avalanches of GEM2 and by the primary interaction in the first transfer gap.

For increasing values of the first transfer field, $E_{\text{transf}1} > 3 \text{ kV/cm}$, a larger amount of electrons are extracted and injected in the holes of the second foil: $I_{G1B}$ becomes positive since it is induced by the motion of the ions. One can see that for $3 \text{ kV/cm} < E_{\text{transf}1} < 4.5 \text{ kV/cm}$, the readout current does not change with the transfer fields, meaning that the extraction and collection efficiencies are optimized for this range of fields. For higher values, the collection efficiency starts to be affected: the field lines end on the G2T rather then being focused inside the holes, leading to a loss of electrons. This effect can be seen from the decreasing in the readout current when $E_{\text{transf}1} > 5 \text{ kV/cm}$, whereas the current on the other electrodes (on G2T, in particular) seem not to be affected. The triple GEM detector has a complex structure and a monitoring on all the electrodes would have allowed a better understanding of the phenomena involved.

Figure 4.28: Currents on the electrodes as a function of the second transfer field.

For what concerns the second transfer field, similar considerations can be drawn. The plot is shown in 4.28. First of all, it can be noticed that $I_{G3T}$ and $I_{G3B}$ are the highest in the plot, because the density of charge produced in the third amplification foil is very high. For low fields $E_{\text{transf}2} < 2.5 \text{ kV/cm}$, the extraction efficiency is low and the electrons remain on G2B; good values for the second transfer fields are between $3 \text{ kV/cm} < E_{\text{transf}2} < 5 \text{ kV/cm}$: $I_{G3T}$...
begins to grow, because a large number of ions are coming out the foils; so it does $I_{G2B}$, since an increasing amount of electrons is capable to reach the third foil; $I_{G3B}$ decreases as a result of the outgoing of the electrons from the avalanches. For higher fields, the collection efficiency is compromised and the electrons are mainly collected on the G3T.

Finally, the effective gas gain is measured as a function of each transfer fields, $E_{\text{transf}1}$ and $E_{\text{transf}2}$. The measurement is performed as described in section 2.5.2. The results are reported in figure 4.29.

![Figure 4.29: Effective gas gain as a function of the first transfer field (in red) and of the second transfer field (in blue).](image)

As already expected from the plots shown before, there is a plateau for the gain in the range between $3 \text{ kV/cm} < E_{\text{transf}1,2} < 5 \text{ kV/cm}$, while for higher or lower values the gain drops, because the transparency of the foils is reduced by the decrease in the collection and extraction efficiencies. The aim for further studies is to measure the gain and the rate capability for lower values of the second transfer field, maybe trying to compensate the possible losses, setting higher values for the first transfer field. The gain curves as a function of the two fields $E_{\text{transf}1}$ and $E_{\text{transf}2}$ have been fitted with a second grade polynomial functions

$$y = p_0 \cdot x^2 + p_1 \cdot x + p_2$$  \hspace{1cm} (4.12)

where $y$ stands for the effective gas gain, the $x$ for $E_{\text{transf}1}$ and $p_0$, $p_1$ and $p_2$ are the parameters of the fit. The results are shown in figure 4.30 and 4.31.
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Figure 4.30: Effective gas gain as a function of the first transfer field. The red points are the experimental data, the black line is the fitting function.

\[
\begin{array}{|c|}
\hline
\chi^2 / \text{ndf} & 2.352 / 16 \\
p0 & -401.1 \pm 59.43 \\
p1 & 3441 \pm 455.9 \\
p2 & -799.8 \pm 812.3 \\
\hline
\end{array}
\]

Figure 4.31: Effective gas gain as a function of the second transfer field. The red points are the experimental data, the black line is the fitting function.

\[
\begin{array}{|c|}
\hline
\chi^2 / \text{ndf} & 3.713 / 15 \\
p0 & -643.6 \pm 54.7 \\
p1 & 5353 \pm 418.6 \\
p2 & -4388 \pm 733.3 \\
\hline
\end{array}
\]
4.7 Study on the induction field

The effect of the induction field is also studied for the prototype. In particular, its role is to pick up a sufficient amount of electrons in order to induce detectable signals on the readout board. In the same time it can not be too high to trigger the discharge propagation.

In the prototype under test, given the geometry of the readout board described in section 4.1, made of 2D planes of strips (which it will be referred to as x and y strips), it is necessary to measure a correction factor, in order to get the current from the whole anode and compare it to the currents on the other electrodes. For this purpose, the two sectors of the x strips are ORed and the current $I_{ROx}$ is measured; the same is done with the sectors of the y strips, measuring the $I_{ROy}$. The readout current is therefore given by $I_{ROtot} = I_{ROx} + I_{ROy} = I_{ROx} + c \times I_{ROx} = (1 + c) \times I_{ROx}$, where $(1 + c)$ is the correction factor.

In order to have a uniform and symmetrical irradiation of the strips, the x ray source is moved away from the detector, at a distance of 60 cm and its position with respect to the detector is changed in such a way that it points towards the center of the active area. In figure 4.32, the ratio between $I_{ROy}$ and $I_{ROx}$ is plotted for different values of the induction field.

$$\frac{I_{ROy}}{I_{ROx}}$$

![Figure 4.32: Ratio between the current induced on the strips on the y-coordinate $I_{ROy}$ and on the x-coordinate $I_{ROx}$, as a function of the induction field.](image)

The factor $c$, which is equal to $I_{ROy}/I_{ROx}$, is constant with the induction field and it is equal to $c = 1.24 \pm 0.01$, in agreement with results reported in [86] for a similar readout geometry. Finally, in figure 4.33, the currents on the electrodes as a function of the induction field are plotted.

From the plot, one can see that $I_{G2B}$ and on $I_{G3T}$ are not affected by the
induction field; $I_{G3B}$, instead, decreases in absolute value in favor of the readout current, sign of the fact that an increasing amount of electrons are transferred towards the anode. At very high value of the field, discharge propagation can eventually be triggered; for that reason values of $\sim 4 \div 5$ kV/cm are preferred. In correspondence with the value $E_{ind} = 4.4$ kV/cm at which the detector operates, the current is still higher in absolute value than the one on G3B.

The effective gas gain as a function of the induction field has been estimated through the measurements of the currents collected on the readout board, exploiting the direct proportionality between the anodic current and the gas gain, as expressed in formula 4.9. Referring to the plot in figure 4.33, the value of the readout current measured in correspondence with the induction field of $E_{ind} = 4.4$ kV/cm is obtained in the field configuration indicated in table 4.1 and it is assumed as the reference current, $I_{ref}$. The gas gain in this configuration is known and it is $G_{ref} \sim 6 \times 10^3$. Therefore, the currents in correspondence with the other values of $E_{ind}$ have been divided by $I_{ref}$ and the ratio is multiplied by the value of the gain $G_{ref}$. The results are plotted in the figure 4.34.

The trend of the gas gain follows the one shown by the $I_{ROtot}$ in figure 4.33, as expected being the two quantities directly proportional, weakly increasing with the induction field.
4.8 Towards an empirical model of the detector operation

In order to operate the detector at a safer working point in terms of destructive phenomena (primary and secondary discharges) ensuring at the same time the same performances required for this technology, it is very important to understand the performance of the detector under different fields condition. However having a full set of data for different fields and different conditions can be extremely difficult and time-consuming. In previous paragraphs the effective gain as a function of transfer fields and induction field have been presented. In section 2.5.2 the effective gain is expressed as the product of the intrinsic gain and the transparency of each GEM in the stack. The trasparency of each foil is strictly related to the trasfer field inside the gaps, that implies that it is possible to express the gain as a function of $E_{transf_1}$ and $E_{transf_2}$. During this thesis work, I have carried out the first attempt of deriving empirical functions to describe the behavior of the detector. The main strategy consists in:

- direct measurement of the gain at vary of each field while keeping the other parameters constant. In particular, I have measured the gain as a function of first transfer field and second transfer field, and as a function of induction field (see paragraph 4.6 and 4.7).

- producing three-dimensional plots obtained using all data from the measurements in set of triplets. In particular, for the measurements I carried out, the triplets are $(E_{transf_1}, E_{transf_2}, \text{gain})$, $(E_{transf_1}, E_{ind}, \text{gain})$ or $(E_{transf_2}, E_{ind}, \text{gain})$, keeping constant $E_{ind}$, $E_{transf_2}$, $E_{transf_1}$ respectively.
• fitting each triplet to empirical equations: \(F(G, E_{\text{transf}1}, E_{\text{transf}2}, E_{\text{ind}} = \text{const}) = 0,\) \(H(G, E_{\text{transf}1}, E_{\text{ind}}, E_{\text{transf}2} = \text{const}) = 0,\) \(R(G, E_{\text{transf}2}, E_{\text{ind}}, E_{\text{transf}1} = \text{const}) = 0.\)

• deriving, from the equations, at a fixed gain, the values of the other fields.

• identifying the most suitable field configurations for CMS experiment stability, that minimize the primary and secondary discharge probability.

In particular, assuming the standard field configuration as starting point (see table 4.1) the following scenarios have been considered:

• Optimization of the second transfer field at fixed gain

• Optimization of the induction field at fixed gain

• Optimization of induction and first transfer field at fixed gain.

It is important to underline that, as already explained in chapter 2, the fields inside the gaps are deeply related to the GEM transparency and discharges probability, which both determine the performance of the detector in term of particle detection efficiency and operation stability. So it is very important to verify that the solutions proposed by the empirical functions are viable in term of the overall performance of the detector. The study is focused mainly on the behavior of the induction field and the two transfer fields. The main experiment observations, reported in the previous section, are that for each of this field there is a range of values for which the anodic current (and this means the collection and extraction efficiency) and gain are optimized. Raising the induction field beyond the range (typically 5 kV/cm) results in an increased current at the anode, in a contact between the GEM foil and the readout anode due to the electrical force of attraction and in an enhancement of the probability to produce a propagating discharge. An increase of transfer fields may result in a decrease of transparency with a reduction anodic current and of readout signal. The main optimization strategy adopted in the following is to allow to each fields to vary inside the defined ranges in order to maintain the gain performance, but minimizing the induction and second transfer fields, in order to prevent primary and secondary discharges.

4.8.1 Optimization of the second transfer field

For this study I started with the measurement of the effective gas gain as a function of the two transfer fields \(E_{\text{transf}1,2},\) shown in figure 4.29. The three-dimensional plot obtained using all data from the measurements in a set of triplets \((E_{\text{transf}1}, E_{\text{transf}2}, G),\) keeping constant all other fields \((E_{\text{ind}}\) and \(E_{\text{drift}})\) and voltage (see table 4.1) is shown in figure 4.35.

Due to the shape of the effective gas gain in the plot of figure 4.29 suggesting a parabolic dependence, an elliptical paraboloid of equation 4.13 has been chosen as a fitting function:

\[p_0 \cdot x^2 + p_1 \cdot y^2 + p_2 \cdot x + p_3 \cdot y + p_4\]  (4.13)

where \(x = E_{\text{transf}1}, y = E_{\text{transf}2}\) and \(p_i,\) where \(i = 0, ..., 4\) are the fit parameters, shown in table 4.2. The values of \(E_{\text{transf}1}\) and \(E_{\text{transf}2}\) in correspondence
Figure 4.35: 3D plot of the effective gas gain on the z-axis as a function of the first transfer field $E_{\text{transf}1}$ on the x-axis and of the second transfer field $E_{\text{transf}2}$ on the y-axis. The white points correspond to the experimental measurements, the surface is obtained fitting the function 4.13 to the experimental data. The errore bars are within the markers.

to the null gain, obtained from the fitting functions shown in figure 4.30 and 4.31, have been added to the data set as a constraint to the fit.

At this point the empirical model describing the gas gain as a function of $E_{\text{transf}1}$ and $E_{\text{transf}2}$ is available. A projection at the constant values of the gain on the plane $(E_{\text{transf}1}, E_{\text{transf}2})$ is shown in figure 4.36.

With the purpose of minimizing the second transfer field working at the same value of the gain, the coordinates of the point corresponding to the minimum $E_{\text{transf}2}$ on the black line at the gain of $6 \times 10^3$ of figure 4.36 have been derived. The results are $E_{\text{transf}1} = 4.8 \text{ kV/cm}$ and $E_{\text{transf}2} = 2.7 \text{ kV/cm}$. Therefore, a new configuration for the fields that could minimize the discharge propagation probability inside the second transfer gap is proposed in table 4.3. The large uncertainties on the fields are due to the fact that the value has

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$</td>
<td>-2.07e+02 ± 5.58e+01</td>
</tr>
<tr>
<td>$p_1$</td>
<td>-4.97e+02 ± 1.00e+01</td>
</tr>
<tr>
<td>$p_2$</td>
<td>1.98e+03 ± 4.86e+02</td>
</tr>
<tr>
<td>$p_3$</td>
<td>4.27e+03 ± 8.53e+02</td>
</tr>
<tr>
<td>$p_4$</td>
<td>-6.71e+03 ± 1.61e+03</td>
</tr>
</tbody>
</table>

Table 4.2: Parameters of the fit with the equation 4.13 on the experimental data.
Figure 4.36: Projection on the xy plane of the effective gas gain. On the x-axis, the first transfer field $E_{\text{transf}_1}$, on the y-axis, the second transfer field $E_{\text{transf}_2}$. The line between the red and the orange regions corresponds to a value of the gain of $6 \times 10^3$. The coordinates of the point corresponding to the minimum $E_{\text{transf}_2}$ are derived to obtain the new field configuration.
Table 4.3: Configuration of the applied differences of voltage and electric fields, in correspondence with a value of the gain of $6 \times 10^3$, with the minimum value of $E_{transf2}$.

<table>
<thead>
<tr>
<th>Gap</th>
<th>(V)</th>
<th>(kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td></td>
<td>2.7 ± 0.1</td>
</tr>
<tr>
<td>GEM 1</td>
<td>399 ± 1</td>
<td></td>
</tr>
<tr>
<td>Transfer 1</td>
<td>4.8 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>GEM 2</td>
<td>384 ± 1</td>
<td></td>
</tr>
<tr>
<td>Transfer 2</td>
<td>2.7 ± 1.9</td>
<td></td>
</tr>
<tr>
<td>GEM 3</td>
<td>366 ± 1</td>
<td></td>
</tr>
<tr>
<td>Induction</td>
<td>4.4 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>

been derived from the fit whose parameters are affected by large uncertainties. The uncertainty on the measured field has been estimated to be 0.1 kV/cm as reported in paragraph 4.4.2.

4.8.2 Optimization of the induction field

A similar strategy has been implemented in order to minimize the value of the field in the induction gap, $E_{ind}$, modifying the $E_{transf1}$ in order to keep the gain unchanged. The gain is plotted in three-dimensions as a function of the induction field and of the first transfer field. It is fitted with the function 4.14, assuming a logarithmic dependence between the gas gain and the induction field:

$$p_0 \cdot x^2 + p_1 \cdot x + p_2 \cdot \log(y)$$ (4.14)

where $x = E_{transf1}$, $y = E_{ind}$ and $p_i$, where $i = 0, ..., 2$ are the fit parameters, shown in table 4.4. The results are shown in figure 4.37.

Table 4.4: Parameters of the fit with the equation 4.14 on the experimental data.

<table>
<thead>
<tr>
<th>$\chi^2/ndf$</th>
<th>16.7/29</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$</td>
<td>-1.11e+002 ± 4.75e+001</td>
</tr>
<tr>
<td>$p_1$</td>
<td>1.05e+003 ± 3.49e+002</td>
</tr>
<tr>
<td>$p_2$</td>
<td>2.57e+003 ± 3.81e+002</td>
</tr>
</tbody>
</table>

Figure 4.38 shows a projection at the constant value of the gas gain $6 \times 10^3$ on the plane $(E_{transf1}, E_{ind})$. The point of coordinate (3.1, 4.4) kV/cm belongs to the red curve, as expected by construction.

The coordinates of the point corresponding to the minimum $E_{ind}$ on the curve at a gain of $6 \times 10^3$ of figure 4.38 have been derived. The results are $E_{transf1} = 4.3$ kV/cm and $E_{ind} = 3.6$ kV/cm. Therefore, another configuration for the fields that could minimize the discharge propagation probability inside the induction gap is proposed in table 4.5. The large uncertainties on the fields are due to the fact that the value has been derived from the fit whose parameters are affected by large uncertainties. The uncertainty on the measured field has been estimated to be 0.1 kV/cm as reported in paragraph 4.4.2.
CHAPTER 4. OPTIMIZATION OF GEM ELECTRIC FIELDS

Figure 4.37: 3D plot of the effective gas gain on the z-axis as a function of the first transfer field $E_{\text{transf}1}$ on the x-axis and of the induction field $E_{\text{ind}}$ on the y-axis. The white points correspond to the experimental measurements, the surface is obtained fitting the function 4.14 to the experimental data. The error bars are within the markers.

Table 4.5: Configuration of the applied differences of voltage and electric fields, in correspondence with a value of the gain of $6 \times 10^3$, with the minimum value of $E_{\text{ind}}$.

<table>
<thead>
<tr>
<th>Gap</th>
<th>(V)</th>
<th>(kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>2.7</td>
<td>± 0.1</td>
</tr>
<tr>
<td>GEM 1</td>
<td>399</td>
<td>± 1</td>
</tr>
<tr>
<td>Transfer 1</td>
<td>4.3</td>
<td>± 1.8</td>
</tr>
<tr>
<td>GEM 2</td>
<td>384</td>
<td>± 1</td>
</tr>
<tr>
<td>Transfer 2</td>
<td>3.1</td>
<td>± 0.1</td>
</tr>
<tr>
<td>GEM 3</td>
<td>366</td>
<td>± 1</td>
</tr>
<tr>
<td>Induction</td>
<td>3.6</td>
<td>± 2.9</td>
</tr>
</tbody>
</table>
Figure 4.38: Projection on the xy plane of the effective gas gain. On the x-axis, the first transfer field $E_{\text{transf}}$, on the y-axis, the second transfer field $E_{\text{ind}}$. The line between the red and the orange regions corresponds to a value of the gain of $6 \times 10^3$. The coordinates of the point corresponding to the minimum $E_{\text{ind}}$ are derived to obtain the new field configuration.
Figure 4.39: 3D plot of the effective gas gain on the z-axis as a function of \( E_{\text{transf}2} \) on the x-axis and \( E_{\text{ind}} \) on the y-axis. The white points correspond to the experimental measurements, the surface is obtained fitting the function 4.14 to the experimental data. The error bars are within the markers.

Table 4.6: Parameters of the fit with the equation 4.15 on the experimental data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi^2/ndf )</td>
<td>6.4/27</td>
</tr>
<tr>
<td>( p_0 )</td>
<td>-7.44e+02 ± 2.06e+02</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>5.84e+03 ± 1.44e+03</td>
</tr>
<tr>
<td>( p_2 )</td>
<td>3.64e+03 ± 5.56e+02</td>
</tr>
</tbody>
</table>

With same procedure it is possible to derive an empirical function to fit the data of \( G(E_{\text{transf}2}, E_{\text{ind}}) \). The three-dimensional plot is shown in figure 4.39. The fitting function is expressed by the equation 4.15,

\[
p_0 \cdot x^2 + p_1 \cdot x + p_2 \cdot \log(y)
\]  

(4.15)

where \( x = E_{\text{transf}2} \), \( y = E_{\text{ind}} \) and \( p_i \), where \( i = 0, ..., 2 \) are the fit parameters, reported in table 4.6.

The functions 4.13, 4.14 and 4.15 allow to derive the gain as a function of each field at vary of the other fields.

### 4.8.3 Optimization of the first transfer field and induction field

In section 4.8.1, at a fixed value of the gain \( G = 6 \times 10^3 \) and of the induction field \( E_{\text{ind}} = 4.4 \text{ kV/cm} \), a minimum value of the second transfer field has been
Figure 4.40: 3D plot of the effective gas gain on the z-axis as a function of $E_{\text{transf}_1}$ on the x-axis and $E_{\text{ind}}$ on the y-axis. The white points correspond to the experimental measurements, the surface is obtained fitting the function 4.16 to the experimental data.

Proposed $E_{\text{transf}_2} = 2.7 \text{ kV/cm}$, by an adjustment of the first transfer field $E_{\text{transf}_1} = 4.8 \text{ kV/cm}$.

In the following I combine the empirical functions obtained in sections 4.8.1 and 4.8.2, to optimize at the same time both $E_{\text{transf}_1}$ and $E_{\text{ind}}$, while keeping the second transfer field at the next value $E_{\text{transf}_2} = 2.7 \text{ kV/cm}$. For this purpose a new function of gain as a function of $E_{\text{transf}_1}$, $E_{\text{ind}}$ for $E_{\text{transf}_2} = 2.7 \text{ kV/cm}$ has been built, following the strategy described in section 4.8.1. To obtain the new set of triplets $(G, E_{\text{transf}_1}, E_{\text{ind}})$, the gain as a function of $E_{\text{transf}_1}$, for $E_{\text{transf}_2} = 2.7 \text{ kV/cm}$ has been derived by equation 4.13; the gain as a function of $E_{\text{ind}}$, for $E_{\text{transf}_2} = 2.7 \text{ kV/cm}$ has been derived by equation 4.14. Data have been fitted with the function:

$$p_0 \cdot x^2 + p_1 \cdot x + p_2 + p_3 \cdot \log(p_4 \cdot y)$$  \hspace{1cm} (4.16)

where $x = E_{\text{transf}_1}$, $y = E_{\text{ind}}$ and $p_i$, where $i = 0,...,3$ are the fit parameters, shown in table 4.7. The three-dimensional plot is shown in figure 4.40.

Figure 4.41 shows the projection of the gain on the plane $(E_{\text{transf}_1}, E_{\text{ind}})$, for the fixed second transfer field $E_{\text{transf}_2} = 2.7 \text{ kV/cm}$.

The coordinates of the point corresponding to the minimum $E_{\text{ind}}$ on the curve at a value of the gain of $6 \times 10^3$ of figure 4.41 have been derived. The results are $E_{\text{transf}_1} = 4.9 \text{ kV/cm}$ and $E_{\text{ind}} = 4.5 \text{ kV/cm}$. Therefore, a further configuration for the fields has been derived from the model and it is proposed in table 4.8. The large uncertainties on the fields are due to the fact that the value has been derived from the fit whose parameters are affected by large...
Table 4.7: Parameters of the fit with the equation 4.16 on the experimental data.

<table>
<thead>
<tr>
<th>( \chi^2/ndf )</th>
<th>1.5/29</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_0 )</td>
<td>(-1.98e+002 \pm 9.13e+001)</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>(1.95e+003 \pm 7.24e+002)</td>
</tr>
<tr>
<td>( p_2 )</td>
<td>(-1.14e+004 \pm 1.83e+004)</td>
</tr>
<tr>
<td>( p_3 )</td>
<td>(3.23e+003 \pm 4.90e+002)</td>
</tr>
<tr>
<td>( p_4 )</td>
<td>(1.11e+001 \pm 2.27e+001)</td>
</tr>
</tbody>
</table>

Figure 4.41: Projection on the \( xy \) plane of the effective gas gain. On the \( x \)-axis, the first transfer field \( E_{\text{transf1}} \), on the \( y \)-axis, the second transfer field \( E_{\text{ind}} \). The line between the red and the orange regions corresponds to a value of the gain of \( 6 \times 10^3 \). The coordinates of the point corresponding to the minimum \( E_{\text{ind}} \) are derived to obtain the new field configuration.
Table 4.8: Configuration of the applied differences of voltage and electric fields, in correspondence with a value of the gain of $6 \times 10^3$, derived from the model fixing $E_{\text{transf}2} = 2.7 \text{ kV/cm}$.

<table>
<thead>
<tr>
<th>Gap</th>
<th>(V)</th>
<th>(kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>2.7 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>GEM 1</td>
<td>399 ± 1</td>
<td></td>
</tr>
<tr>
<td>Transfer 1</td>
<td>4.9 ± 1.8</td>
<td></td>
</tr>
<tr>
<td>GEM 2</td>
<td>384 ± 1</td>
<td></td>
</tr>
<tr>
<td>Transfer 2</td>
<td>2.7 ± 1.9</td>
<td></td>
</tr>
<tr>
<td>GEM 3</td>
<td>366 ± 1</td>
<td></td>
</tr>
<tr>
<td>Induction</td>
<td>4.5 ± 2.1</td>
<td></td>
</tr>
</tbody>
</table>

Uncertainties. The uncertainty on the measured field has been estimated to be 0.1 kV/cm as reported in paragraph 4.4.2.
4.9 Results and future perspective

The effect of the proposed electric field configurations have to be tested on two sides: the transparency of the detector and the response to the discharge phenomena. The detector transparency depends indeed on the ratio between the electric fields applied inside the gaps and their values have been carefully chosen in order to optimize the collection and the extraction efficiencies. This is especially true for the transfer fields, whose values have to guarantee the drift of the electrons in the gaps between the amplification stages and their entrance inside the GEM holes. The mean value of the first transfer field proposed in the first configuration, $E_{\text{transf1}} \sim 4.8 \text{ kV/cm}$, still belongs to the plateau range, $3 \text{ kV/cm} < E_{\text{transf}} < 5 \text{ kV/cm}$, of the figure 4.29; the mean value for the second transfer field, $E_{\text{transf2}} \sim 2.7 \text{ kV/cm}$, is just below the threshold of the plateau, $E_{\text{transf}} \sim 3 \text{ kV/cm}$. Therefore, it is reasonable to assume that the gas gain for the first configuration should not be affected. For what concerns the second configuration, the mean value of the first transfer field $E_{\text{transf1}} \sim 4.3 \text{ kV/cm}$ still falls on the plateau range of the gas gain and should not affect the gain.

The evaluation for the induction field is instead more complex. From the plot of figure 4.34 it can be seen that the gas gain weakly increases with the induction field (a logarithmic dependence has been assumed for the fit). The mean value of the gain in correspondence with the induction field $E_{\text{ind}} \sim 3.6 \text{ kV/cm}$ has been extrapolated from the fit and it results to be $\sim 5.5 \times 10^3$. However, the value of the induction fields affects the motion of the electrons towards the anode board and, therefore, the process of formation of the signals. From simulation studies [52], it has been found that in correspondence with a value of $E_{\text{ind}} \sim 5 \text{ kV/cm}$ half of the electrons are collected on the bottom of GEM 3; a lower value of the fields would therefore decrease the fraction of the electrons reaching the anode and the overall amplitude of the signals induced. Besides, other performances could be affected operating at a lower value of the fields, such as the time and space resolutions, which are not taken into account in this work.

The model allows to find a further configuration of the fields through the empirical functions used to describe the gain. The resulting fields are $E_{\text{transf1}} \sim 4.9 \text{ kV/cm}$ and $E_{\text{ind}} \sim 4.5 \text{ kV/cm}$ at a fixed second transfer field $E_{\text{transf2}} \sim 2.7 \text{ kV/cm}$. The mean value of the first transfer field belongs to the plateau range of the plot in figure 4.29 and no gain loss is expected. The mean value of the induction field is still sufficiently low to allow safe operations.

The performance of the detector working in these new configurations has to be experimentally tested by a direct measurement of the gas gain. Moreover, the proposed model offers for each fixed gain a whole set of pairs of fields (see figure 4.36 and 4.38).

As a next step, the configurations have to be tested in short term stability studies, by irradiating the detector with HIPs, in order to evaluate the detector behaviour with the new applied fields against the discharge propagation, comparing the results with the ones achieved in discharge studies on the standard configuration of the fields.

If successful, the new configurations have to be adapted to the GE1/1 detectors and the same tests have to be repeated to confirm the efficacy of the method.
Conclusions

The LHC upgrade will bring the instantaneous luminosity up to a value of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. As a consequence all the employed technologies has to be adapted in order to provide the same efficiency in the reconstruction and rejections of events in the new high rate environment. The CMS Muon Spectrometer region will especially be interested by the harsh background. Therefore, new gaseous detectors based on the GEM technology are going to instrument the Muon spectrometer.

The work of thesis is carried out within the context of the R\&D CMS GEM activities aiming at testing the long and short term operational stability of those gaseous detectors, in view of the upgrade of the CMS Muon Spectrometer for the HL-LHC regime.

I focused the work in particular on the problematic of the short term stability of triple GEM detectors, especially compromised by the arising of destructive phenomena such as gaseous breakdowns, with the aim of testing mitigation strategies already proposed and finding possible new ones.

The leading factors of a discharge formation and its propagation inside the gaps of the GEM detectors has been identified with the energy stored in the system and available to the discharge. The key to control the phenomenon and prevent its dangerous effects is to reduce the available energy inside the gaps. The gaps of a triple GEM detector can approximately be modeled as a parallel plate capacitors, able to store electrostatic energy of $E \sim \frac{1}{2} \cdot C \cdot \Delta V^2$, being $C$ the gap capacitance and $\Delta V$ the voltage applied to the electrodes. Therefore, one can consider two strategies: lowering the voltage applied, i.e. the electric field inside the gap, or lowering the capacitance of the gaps, modifying the design of the detector.

The second strategy has been pursued by proposing a new design for the GEM foils that consists in a sectorization of the bottom of the GEM foils. The sectors are then decoupled from each other using protection resistors. This solution allows to reduce the area of the GEM foils and as a consequence the gap capacitances. This solution cannot be deployed at GE1/1 project being currently installed, but will be implemented in the GE2/1 and ME0 projects. During my work of thesis, I took part to the validation process of this new design by performing measurements of the propagation probability of discharges $P_p$ induced by $\alpha$ particles on a double segmented GE1/1 chamber. After collecting a total of 10353 primary discharges without recording any propagation, the upper limit for the propagation probability has been set to $P_p < 10^{-4}$ with confidence level of 68% (the previous one was $10^{-4}$), confirming once again the validity of the strategy.

In order to investigate the first strategy, a series of preliminary tests aiming...
at optimizing the electric configuration inside the gaps had also been performed on a $10 \times 10 \text{cm}^2$ triple GEM prototype. Solutions towards this direction could also be implemented in the triple GEM detector of the GE1/1 project. The detector effective gas gain was measured as a function of the transfer fields and of the induction field and a very preliminary empirical function, with available data, has been implemented in order to find new configurations of the fields which allows the detector to be operated at a safer but equally efficient working point. The model describes the gain as a function of couples of parameters, such as $E_{\text{transf}1}$, $E_{\text{transf}2}$ and $E_{\text{ind}}$, and allows to derive the minimum value of one of the field by adjusting the other in order to get the same gain.

The results of the study should be considered as a proof of concept since more data points at different configurations are needed to validate the empirical function and improve the fit.

Once the optimized fields configuration are derived by the model, the performances of the detector has to be experimentally tested by a direct measurement of the gas gain and discharge probability by irradiating the prototype with HIPS. The optimization procedure needs to be validate on large size detectors, such as CMS GE1/1 and GE2/1 detectors, in term of performance and confirm the robustness against discharges.
Bibliography


[21] URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Multi_year_plots.


[37] W. Schockley. “Currents to Conductors Induced by a Moving Point Charge”. In: Journal of Applied Physics 9, 635 (1938).
[38] S. Ramo. “Currents Induced by Electron Motion”. In: Proceeding of the IRE 9, 584-585 (1939).


[64] URL: https://twiki.cern.ch/twiki/bin/view/MPGD/Phase2BkgFLUKA#Neutron_flux.


[76] URL: https://www.arduino.cc/.


[80] URL: https://www.ams-soft.de/de/leistungen/labview/#c2774.


