Studies on Gas Mixture and Gas Recirculation Effects on GEM Detectors Operation at the CERN GIF++ Facility

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Abstract
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The future Physics Program established for the Large Hadron Collider (LHC), with the upgrade of the accelerator, sets important challenges for all detector systems. Several upgrades will affect Muon Systems, including the ones on the gas mixture in use, since their stability and correct composition are at the basis of safe long-term operation. The aim is to lower operational costs and gas emission, while maintaining high performance levels. Gas systems are therefore operated in recirculation mode. The purpose of this thesis is a detailed study of the performances of Gas Electron Multiplier detectors (GEM), commonly operated with Ar/CO\textsubscript{2} gas mixtures, but also the addition of CF\textsubscript{4}, to obtain an improved time resolution. The use of CF\textsubscript{4}, that is considered a greenhouse gas, force the operation in recirculated gas systems, that makes fundamental to guarantee optimal detector operation in such condition.

A Triple-GEM detector characterization was realized in different gas mixture conditions. Studies on GEM performance when operated in a gas recirculation system and under high irradiation rate were realized at the CERN Gamma Irradiation Facility (GIF++), that provides irradiation with gamma emission (662 keV photons) from a $^{137}$Cs source (activity 14 TBq). Two Triple-GEM detectors are installed inside the GIF++ facility with R&D purposes. The aim of the measurement campaign at GIF++ is to progress with the validation of their operation in a system as close as possible to the ones in LHC experiments.
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Chapter 1

High Energy Physics at the Large Hadron Collider

1.1 CERN and the LHC

The Large Hadron Collider (LHC) is a two-ring superconducting hadron accelerator and collider at the European Organization for Nuclear Research (CERN). Made of 27 km of superconducting magnets, laying 100 m underground, it allows the confinement and acceleration of two proton beams, running in opposite directions. It has been designed to provide enough statistics to fulfill the requirements of the CERN physics program, oriented to studies on the Standard Model as well as to the search of new physics.

The LHC can nominally provide a center of mass energy of 14 TeV for proton-proton collisions, created by 2808 bunches containing \(1.15 \times 10^{11}\) particles each, with a bunch spacing of 25 ns. The design luminosity of the collider is of \(10^{34}\) cm\(^{-2}\) s\(^{-1}\). Primary protons are obtained from Helium, and they are accelerated in a first linear collider (Linac), to be then injected in the chain of circular accelerators that allows the achievement of their maximum energy (6.5 TeV). Protons pass through the Proton Synchrotron (PS, 25 GeV), the Super Proton Synchrotron (SPS, 450 GeV) and finally are injected in the LHC (Figure 1.1).

The LHC is also capable of providing heavy ions beams. When not in the \(pp\) mode, PbPb and \(pPb\) collisions can be supplied, reaching a center of mass energy of 2.76 TeV and 5.02 TeV respectively.

Figure 1.1: LHC Accelerator Complex layout. [1]
Chapter 1. High Energy Physics
at the Large Hadron Collider

Four experiments were designed and built to completely exploit the physics program for proton collisions. They are located at four interaction points of the LHC, in which the actual collisions happen. Two general purpose experiments, ATLAS (A Toroidal Lhc ApparatuS) and CMS (Compact Muon Solenoid), were designed to explore all the possible aspects of the LHC physics, from heavy-ions collisions and forward physics, to Higgs boson physics and direct search of new particles. Specially dedicated to heavy-ions physics is the ALICE experiment (A Large Ion Collider Experiment), while the LHCb has the aim to maximize the LHC potential in beauty and charm physics.

Though the final purpose is specific for each experiment, the requirements on the detectors of which they are composed are quite the same. Their capability of identifying charged particles and measuring particles momentum with high resolution is of fundamental importance. In addition, they all need high granularity, to reduce the influence of overlapping events, and a fast and radiation-tolerant electronics for proper data acquisition.

LHC experiments can be described dividing their structure into three different categories (in Figure 1.2 the CMS experiment is reported as an example):

- **Inner Detectors:**
  They are located close to the collision points, allowing tracking and momentum measurement of charged particles, as well as vertices reconstruction;

- **Hadronic and Electromagnetic Calorimeters:**
  They measure the energy of hadrons, photons and electrons, based on the energy loss of emerging particles;

- **Muon systems:**
  Since muons escape the electromagnetic calorimeter, a dedicated muon system is used to detect them. Placed at the outermost layers of the experiments, it allows to unambiguously detect the signature of many relevant events.

The design and layout of Muon Systems will be widely discussed in the following, since gaseous detectors the key focus of this thesis. Although the four experiments have significantly different goals, they all indeed rely on gaseous detectors for muon detection and tracking as well as for event triggering.

![Figure 1.2: CMS Experiment, showed in a transversal section.](image)
1.2 Physics at the LHC

1.2.1 Standard Model Physics

The Standard Model (SM) theory finds its roots in the early Sixties, when the Quark Model was finally put beside the already known leptonic side of the elementary particles picture. In its complete formulation, the SM combines special relativity and quantum mechanics, through a gauge theory based on symmetry groups. Fundamental constituents of matter are spin-1/2 particles, the so-called fermions. They are divided into quarks and leptons, each composed of three different families (Figure 1.3). For each fermion, a correspondent anti-particle exists, with opposite quantum numbers.

Fermions interact among them through the exchange of spin-1 particles, the gauge bosons, which are elementary particles themselves. Their presence arises from the invariance of the SM theory under gauge symmetries. Each of the fundamental interactions is described with a different gauge group and different mediators:

- **Electromagnetic Interaction:**
  It is described by the Quantum Electro-Dynamics (QED), and it is mediated by the photon, a massless boson. It is associated with a U(1) symmetry, as there is a single gauge boson and one quantum number, the electromagnetic charge Q;

- **Weak Interaction:**
  It is mediated by the massive $W^\pm$ and $Z^0$ bosons, and it is described with the symmetry group SU(2). It involves all the elementary particles and it is the only interaction capable of changing quarks flavour;

- **Strong Interaction:**
  Mediated by gluons, it is described with the SU(3) symmetry group, which describes the color symmetry. In Quantum Chromo-Dynamics (QCD) only quarks are involved, since leptons are colorless;

In 1963, the Weak and Electromagnetic Interactions were unified with the ElectroWeak theory, accomplished under a SU(2)$\times$U(1) gauge group. Corresponding gauge bosons were the three W bosons (from SU(2)) and the B boson (from U(1)).

Nonetheless, all the mediators foreseen by the first ElectroWeak model were massless. Being this far from the already proved physics at the time, in 1964 a new mechanism was developed to introduce in the theory the bosons masses. It was called the Higgs mechanism, and it was worth the Physics Nobel Prize in 2013 for F. Englert and P. Higgs. The theory foresees an extra fundamental particle, the Higgs boson,
whose interaction with ordinary particles generates their own masses. The fact that $W^\pm$ and $Z^0$ bosons are massive particles, while the photon is massless, invariably requires the Higgs-mechanism to break the ElectroWeak symmetry, with the direct consequence of the existence of a new spin-0 boson. The mass of such boson is however an open parameter of the theory.

### 1.2.2 The Higgs Boson at the LHC

In the first three-years physics run of the LHC (2010-2013) results were highly remarkable. The LHC has been operated at up to 8 TeV of center of mass energy, delivering about 25 fb$^{-1}$ with a peak luminosity of $7.7 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (in ATLAS and CMS).

Within several physics results, the major achievement was undoubtedly the observation of a new particle, with a mass of 126 GeV and Higgs-like properties. The discovery came from both ATLAS and CMS experiments, which identified the new particle as the Standard Model Higgs boson.

The channels with the strongest Higgs sensitivity at the LHC are the vector-boson fusion and gluon-fusion, while the most significant decay processes are the di-photon, the ZZ to four leptons and the leptonic WW channels. For both experiments, the most relevant results were obtained in the ZZ and di-photon channels, which allowed the measurement of the Higgs boson mass with a very high precision (0.43% and 0.34% for ATLAS and CMS respectively). The discovery was determined by the 5-standard-deviation significance of the deviation from the background-only hypothesis in the cited channels. As it can be seen in Figure 1.4a, looking at the invariant mass distribution of di-photon events from CMS events analysis, an excess can clearly be seen at the mass value of 126 GeV. Similarly, the signal excess can be seen in the invariant mass distribution of four lepton events from the double Z decay, measured by the ATLAS experiment (Figure 1.4b).

![Figure 1.4: a) Invariant mass distribution of a di-photon event and b) of a four lepton event, detected from CMS and ATLAS experiment respectively. Excess of signal over background can be seen in both distribution (data from Run1).](image-url)
Being this discovery of fundamental importance for the Standard Model, part of the future LHC program will be focused on measurements of the properties of the Higgs boson. This implies studies to test the Standard Model pattern of its coupling to elementary particles, as well as searches for additional Higgs bosons. As a matter of facts, the capability of the LHC to reach a center of mass energy of 14 TeV, delivering an integrated luminosity of 3000 fb$^{-1}$ by 2030, will lead to the possibility of pushing further the studies on the Higgs boson itself, as well as a variety of other matters in which the new particle is involved. Besides, off-shell and high transverse momentum Higgs production will allow access to new physics near the TeV scale that may otherwise be hidden. Finally, the Higgs self-coupling process will possibly be investigated, leading to the crucial test on whether its potential is the one associated with the actual vacuum, as its field properties seem to suggest.

1.2.3 Physics Beyond the Standard Model

Notwithstanding the Standard Model having been successfully tested in the last decades, it presents numerous lacks on fundamental questions in particle physics. As an example, forces unification, hierarchy problem of the Fermi scale as well as dark matter and antimatter issues are still unresolved. This leads to the thinking that the Standard Model may only be a low energy effective theory.

Several theories have been proposed, such as the extension of the SM in the Super Symmetry (SUSY) theory, which foresees a symmetry between fermions and bosons. It potentially offers elegant solutions to many of the SM shortcomings, but as of today, there are not evidences of SUSY particles. Beyond Standard Model theories are an open scenario, for which the future LHC period at higher luminosity will be invariably essential.

1.2.4 Other Physics at the LHC

In parallel to Higgs and new physics searches, flavour and heavy ions physics is of fundamental importance in the LHC physics program.

Flavor physics studies are lead by the dedicated LHCb experiment, which accomplished notable results during the first run. The very rare decay $B^0_s \rightarrow \mu^+\mu^-$ was observed, with a branching ratio extremely consistent with the one calculated with the SM theory. Moreover, the first experimental evidence of direct CP violation was observed in $B^0$ decays. LHCb will then be the leading experiment for a wide range of important observables concerning rare decays and CP violation in charm and beauty hadrons.

Furthermore, very successful PbPb and $p$Pb runs brought unprecedented results in heavy-ion physics, such as the detailed studies of jet quenching in PbPb collisions and di-jet production in $p$Pb collisions. Involved experiments are ATLAS, ALICE and CMS, that will have in the future a significant role in the studies of heavy-flavour particles, quarkonium states and many others.
1.3 Muon Detector Systems at the LHC Experiments

As previously mentioned in Section 1.1, each LHC experiment is equipped with a Muon Detector System. Muon detection is fundamental for a complete identification and characterization of collisions, since muons represent a very clean probe for many events of interest. In addition, they can provide trigger and veto for event selection. With a mass of 105.6 GeV, muons can quite easily penetrate matter and therefore they escape electromagnetic calorimeters. Muon systems are then made of dedicated detectors, capable of identifying and tracking these particles. A brief summary of the Muon System of each LHC experiment is here reported, followed by the description of how their infrastructure is sustained.

**LHCb**

LHCb is a single-arm spectrometer with a forward angular coverage from 10 mrad to 300 mrad in the bending plane, to best exploit the statistics of the $b$ and $\bar{b}$ production, which predominantly happens in the same forward or backward region. The muon detection system is fundamental in the LHCb since muons are present in the final states of many CP-sensitive B decays. They provide a tag of the initial state flavor of the accompanying neutral B mesons for semi-leptonic decays. The system provides fast information for high pT muon trigger at the earliest level of online event selection, as well as muon identification for the high-level trigger and offline analysis. The muon system is here mainly composed of Multi Wire Proportional Chambers (MWPC), except for the high rate region, where Gas Electron Multipliers (GEM) are used. It is divided into five rectangular stations, along the beam axis, with a total of 1380 chambers covering an area of $435 \text{ m}^2$ (Figure 1.5a). GEMs are located in the inner region, where the expected particle rate would not be sustained by MWPCs due to ageing safety limits. Lastly, the outmost layer hosts the Outer Tracker, a gaseous detector that covers approximately a $30 \text{ m}^2$ area with twelve double layers of straw tubes.

**CMS**

The CMS experiment structure is based on a super-conducting solenoid, that produces a 3.8 T magnetic field: the tracker, the electromagnetic and hadronic calorimeters are located within the field volume. The iron yoke is equipped with a muon spectrometer for identification, triggering and momentum measurement. The system is divided into five separate wheels in the barrel, with four concentric layers of detectors (Figure 1.5b). Both the positive and negative end-caps are instead instrumented with four independent disks. Three different gaseous detector technologies are employed. In the barrel region, Drift Tubes (DT) are used to detect muons up to pseudo-rapidity $|\eta| < 1.2$. Cathode Strip Chambers (CSC) located in the endcap region ($0.9 < |\eta| < 2.4$) allow the handling of higher rates and non-uniform magnetic field. Lastly, Resistive Plate Chambers (RPC) are employed in both barrel and endcap region ($|\eta| < 1.6$).

**ATLAS**

The physics program of the ATLAS experiment requires high performance over the large range in transverse momentum. Its muon system includes three large superconducting air-core toroids, precision tracking chambers for accurate momentum...
resolution, and an effective trigger system. The latter is realized with two different detector technologies: RPCs are used in the barrel, with two layers of chambers installed in the middle station and a third layer on the outer chamber station. The end-cap trigger system is instead composed of Thin Gap Chambers (TGC), multi-wire chambers operated in saturated mode. Three multi layers are located in the middle tracking station, while some others are part of the inner station (Figure 1.5c). Precise $p_T$ measurements are instead made possible by Monitored Drift Tubes (MDT). They can in fact sustain high rates without aging with little sensitivity to space charge. Their surface can reach $10 \text{ m}^2$, requesting an extremely accurate mechanical construction to best exploit their tracking accuracy. Moreover, the use of CSCs in the inner station of the end-cap allows to have optimal performances regardless the high background rate in this region.

**ALICE**

Being ALICE experiment fully dedicated to heavy ion physics, its muon spectrometer needs to measure very low $p_T$ in a large rapidity range ($-4 < \eta < -2.5$). Its tracking system (MCH, Muon Chambers) is made of five stations with two detector planes each, consisting of cathode pad chambers. These detectors are multi-wire proportional chambers with a segmented cathode plane. Different pad densities are present, depending on the station position with regard to the pseudo-rapidity. The system is also capable of high efficient triggering (MTR, Muon Trigger), with four planes of 18 RPCs, operating in streamer mode. They are located at approximately 20 m from the Interaction Point, and deliver online information to the central trigger processor (Figure 1.5d).
1.3.1 Gas Systems for Muon Detectors

Regardless the location and scope of each gas detector inside LHC experiments, the most critical of the infrastructures is their gas distribution system. Indeed, the gas mixture is a fundamental parameter for detector operation and safety for both short and long term periods. A total of 30 dedicated gas systems deliver the proper gas mixture to corresponding detectors. Their extension can reach several hundreds of meters and they are subject to severe requirements on design and components quality to guarantee good and safe long-term detector operation. High reliability is needed in terms of both stability and quality of the gas mixture, since it is the primary element influencing detector performance.

The LHC gas system has been implemented following a modular design, in way that it can be adapted to each gaseous detector requirements, but still remaining based on a common structure. The function-oriented design allows an effective construction, as well as an easier maintenance and intervention in case of any failure. Each module is also associated with a Programmable Logic Controller (PLC), an industrial PC with basic functionalities for managing and monitoring the unit.

Building blocks are located over three different levels: the surface room (SG), the underground service room (US) and the experimental cavern (UX). All the units that need an immediate access are located in the SG, while the US provides the first pre-distribution of gas into several channels. The effective detailed distribution to each detector is instead done in the UX.

The main building blocks are common to all the systems. A brief description is here given for the most significant ones.

- **Gas Supply Monitoring System:**
  Each gas is provided by two independent supply sources, one in use and one in stand-by, that can compensate when there is a failure in the main one.

- **Mixer Module:**
  Primary gases are used to prepare the suitable gas mixture for each detector. Mixer modules have up to four input lines, equipped with Mass Flow Controllers (MFCs), managed via software. Gas mixture are prepared with high precision, better than 1% on the concentration of each gas component.

- **Gas Distribution:**
  Several steps are needed to distribute the gas mixture to each detector, choosing gas flow and pressure. Pre-distribution modules (located in US) are related to different detector sectors of the experiments, and they still allow some parameter tuning during LHC runs. The gas is then sent in the UX, where the final distribution modules are located. Each pre-line is split into several smaller lines, to distribute the gas with the required granularity.

- **Pump Module:**
  Once the gas has flown inside detectors, it is sent back to the pre-distribution rack. Its outlet leads to the pump module, that compressing the gas to an higher pressure sends it to the circulation module at the surface.

In addition to these fundamental components, other blocks are generally present in the gas systems, more related to the gas management and quality monitoring.
1.3. Muon Detector Systems at the LHC Experiments

- **Gas Analysis Module:**
  Gas analysis modules allow continuous monitoring of some critical mixture components, as well as the presence of impurities (O₂ and H₂O). Normally O₂, H₂O and Infra-Red analysers are present, but also Gas Chromatograph (GCs) can be used. In particular, CMS and LHCb are equipped with GC modules to allow more specific studies, i.e. monitor the presence of more complex impurities.

- **Gas Recuperation Module:**
  Expensive or greenhouse gases can be recuperated during the emptying of detector volumes, mainly to contain operational costs. The returning mixture is cooled down, until the liquefaction point of the gas, that can then be stored and reused. Typical recuperated gases are Xe, C₄F₁₀, CF₄ and nC₅H₁₂.

As it will be widely discussed in this work, another key element of Gas Systems is the infrastructure for recirculation. The gas mixture can in fact be collected after being used, and re-injected into the supply lines. While this could allow a reduction in operational costs by 90% or more, it could favour the accumulation of impurities, such as N₂, O₂ and H₂O. It is then fundamental to filter them as much as possible for a safe operation condition. A purifier system is installed along the gas line, with cartridges filled with suitable cleaning agents (molecular sieves for water removal and metalic catalysts for oxygen removal). In this way only a small percentage of gas (0% - 10%) is sent to the exhaust line, while the most fraction can be re-injected in the system after purification. The fraction sent to the exhaust is automatically replaced with fresh gas mixture from the mixer module.

![Figure 1.6: Example of gas system structure, in particular for the CMS Muon System.](image-url)
1.4 Detector Upgrades for HL-LHC

With the LHC Upgrade during the LS2 and the future High-Luminosity phase, intense consolidation and upgrade for all experiments are invariably needed. It is in fact fundamental to reach the highest possible performance to make the most out of the extremely improved running conditions of the LHC. While integration of new features and replacement of several machine components will be the basis of the future collider performance, experiments are as well in need of a complete renewal and reinforcement.

The increasing rates and pile-up effects will make more and more challenging the experiments operation. A staged upgrade program during the long shutdowns has been established. It has started during the LS1 (2013/2014) and it will continue in two other LS periods: the LS2 (2018/2019) and the future LS3 (2023/2025), as visible in Figure 1.7.

![Figure 1.7: LHC long term schedule, including performances and upgrades. [11]](image)

Major upgrades of ALICE and LHCb will take place during the LS2, with the improvements of some sub-systems and the re-design of read-out electronics. Detector constraints set in fact limits, which need to be overcome to face the increased luminosity, already during Run 3. Moreover, the HL-LHC phase will require a significant upgrade with regard to the detector performance degradation caused by the extremely high integrated radiation dose. In this view, a substantial improvement for both CMS and ATLAS will be of primary importance. These operations are foreseen for the LS3, during which many systems will be replaced due to their radiation damage or inability to proper read-out at very high data rates. At the same time, it will be fundamental to maintain an appropriate performance for the high pile-up environment physics, which requires then innovative components to be integrated in the already existing systems.

Being this work mainly focused on gaseous detectors, main upgrades of the Muon Detector Systems will be illustrated in the following paragraphs.
1.4. Detector Upgrades for HL-LHC

1.4.1 Motivations for Muon Detector Systems Upgrade

As previously illustrated, gaseous detectors are widely used in the LHC experiments for tracking, trigger and particle identification. In particular, the Muon Systems are fundamental for muon identification and momentum measurement. In the general picture of experiments upgrades, this is the system that will probably experience the least issues due to increased radiation dose. Nevertheless, a continuous performance monitoring is fundamental to keep under control their response under high particle flux. Weaknesses and failures has to be preventively spotted, to minimize the issues that will invariably be faced during future operations. Performance degradation due to aging and HL, read-out electronics limitations and generation of fake hits are the major aspects which need to be addressed for the future operation of gaseous detectors.

The extremely elevate luminosity that will be delivered by the LHC sets the main goals of muon systems upgrades, that include improved timing resolution, greater trigger sharpness and higher efficiency in the background rejection. These elements will mainly affect the systems in ATLAS and CMS. In particular, their forward region ($|\eta| \geq 1.0$) already experiences particle rates around 10 kHz/cm$^2$, which causes a very high pile-up of events that can compromise the accuracy of $p_T$ measurements. It has been demonstrated that nowadays in the ATLAS experiment about 90% of the the muon triggers in the end-caps are fake or background dominated by low energy particles (mainly protons), which can be confused with high $p_T$ muons (analysis of 2012 data, Figure 1.8).

![Figure 1.8: $\eta$ distribution of the Level-1 muon signal compared to subsets with matched muon candidate and with offline reconstructed muon with $p_T > 10$ GeV in the ATLAS experiment. [12]](image)

Together with the upgrade of the detectors themselves, common topics for the four LHC experiments are related to the gas mixtures used in such large systems and to the use of expensive and greenhouse gases. The aim is to reduce operational costs and gas emission, while maintaining high performance levels.
Regarding gas emission, it has to be taken into account that some of the gases commonly used in the Muon System detectors are recognised as greenhouse gases (Figure 1.9). In particular, gases such as C$_2$H$_2$F$_4$, SF$_6$ and CF$_4$ are nowadays fundamental for the operation of Resistive Plate Chambers (RPCs), CSCs and GEMs, but they have a remarkable global warming potential. Therefore, their impact on climate changes is significant and with this in mind measures will be taken to restrict their consumption in the near future.

To reduce gas emissions, gas systems are operated in recirculated mode, remembering however to maintain the high standard on detector performance. The quality of gas mixture can in fact deteriorate in closed loop systems, mainly due to impurities accumulation. The contamination can either come from the gas system or from detectors themselves, and they could significantly affect their performance.

![Figure 1.9: Distribution of greenhouse gases emission in LHC experiment during Run1.](image)

1.4.2 Examples of Muon Systems Optimization

In this paragraph are shortly illustrated some examples of the upgrades (related to both detectors and infrastructures) that Muon Systems are facing, to fulfill the requirements for the future collider upgrade.

**GEMs in LHCb Experiment**

The LHCb Muon System hosts GEM detectors in the region where high particle rates are present, with a total of 20 chambers, each made of two triple-GEM detectors. The gas mixture used is Ar/CO$_2$/CF$_4$ (45%/15%/40%), with a gas flow around 100 l/h. The presence of CF$_4$ makes the exhaust a greenhouse gas mixture. For this reason, already in 2016 the gas system was upgraded from open mode to recirculated. For the first time, GEM detectors were operated in a closed loop system after intense R&D to validate the detector performance in such configuration. With this improvement, the reduction of greenhouse gases reached 90% with respect to previous operation.

**Micro-Megas in ATLAS Experiment**

The forward section of ATLAS muon spectrometer, the Small Wheel, will exceed its design rate capabilities, since rates up to 15 kHz/cm$^2$ are expected after the LS2. The system upgrade foresees the installation of MicroMegas, that will cover the full New Small Wheel. Intense R&D studies allowed to reach an efficient configuration
for these detectors, for which the presence of sparks is generally a key issue. Resistive strips laying on the ordinary read-out strips make MicroMegas spark resistant, while maintaining their ability to measure minimum-ionizing particles with an excellent precision in high-rate environments. A total of eight planes of MicroMegas will be installed during LS2, for a total detector area of 1200 m$^2$. In addition, to make the NSW a fully redundant system, it will be equipped with eight planes of Thin Gap Chambers (TGC).

**GEMs and iRPCs in CMS Experiment**

CMS experiment will be in need of increasing redundancy in tracking and reconstruction capabilities in the forward regions, since by now it only relies on the CSCs. Here the high background rates ($\approx 100$ kHz/cm$^2$) in the High Luminosity phase) can heavily compromise the momentum resolution, leading to a significantly higher trigger rate. Proposals to minimize this effect have found their convergence on the installation of two new stations in the end-cap region, with Gas Electron Multipliers (GEMs). In particular, triple-GEM chambers will be in-stalled in a double-layer configuration, during the LS3. As shown in the preliminary simulation of Figure 1.10, this will reduce the trigger rate in this region thanks to improved momentum resolution. Moreover, an extension of the Muon System acceptance is foreseen (to $|\eta| < 3$), with a new GEM-based station that will be installed in the space left by the new compact end-cap calorimeter. Also improved RPC (iRPC) chambers are proposed for some end-cap stations, in order to extend the present RPC system. The new configuration could offer excellent time resolution and at the same time it would allow a significant reduction in the neutron background and pile-up effects.

**FIGURE 1.10:** Trigger rate distribution for high $p_T$ muon candidates as a function of $\eta$, in the scenario with and without GEM detectors in the end-caps of CMS experiment. [15]
Chapter 2

Gas Electron Multiplier Detectors (GEM)

This Chapter describes the working principles of gaseous detectors and then, in particular, the Gas Electron Multiplier Detector. The assembling and testing procedure for a small GEM detector will be described, as it was carried out to build the detectors used to perform the studies described in Chapter 4 and 5. A brief overview of where GEM detectors are employed at CERN will follow, as well as an introduction on their operation in gas recirculation systems.

2.1 Gaseous detectors operation principles

One of the primary way of interaction of charged particles passing through gases is the direct ionization. It sits at the origin of gas-filled detectors operation, together with the phenomenon of gas multiplication. Both processes will be described, to give a complete overview on the pulse generation process of gaseous detectors.

2.1.1 Gas Ionization

As a fast charged particle passes through a gas, it can create ionized molecules along its path. When a neutral molecule is ionized, it results in an ion pair, i.e. a positive ion plus a free electron. Ion pairs serve as the basic constituent of the electrical signal developed in gaseous detectors. The incoming particle must transfer a minimum amount of energy equal to the ionization energy of the gas molecule to allow the ionization process to occur. Nonetheless, other mechanisms by which the incident particle may lose energy exists, such as excitation processes, in which an electron may be elevated to a higher bound state without being completely removed. This leads to the definition of the W-value, the average energy lost by the incident particle per ion pair formed, which is always greater than the simple ionization energy. The W-value generally depends on the gas involved, the type of radiation and its energy. Typical values are between 25 eV and 35 eV per ion pair (Table 2.1). Assuming W to be constant for a given type of radiation, the energy deposit will be proportional to the number of ion pairs formed in the gas.

Positive ions or free electrons created within the gas also take part in the random thermal motion, with the tendency of moving away from regions of high density. The process is much more pronounced for electrons, being their thermal velocity much higher. Of the many collision processes that normally take place between free electrons, ions and neutral gas molecules, the most significant ones for gaseous detector operation are charge transfer and recombination. Charge transfer can occur when a positive ion encounters a neutral molecule, that transfers an electron to the
Table 2.1: Values for $W$ from ICRU Report 31, for different gases and different types of radiation. [16]

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Ar</td>
<td>15.7</td>
<td>26.4</td>
<td>26.3</td>
</tr>
<tr>
<td>He</td>
<td>24.5</td>
<td>41.3</td>
<td>42.7</td>
</tr>
<tr>
<td>N$_2$</td>
<td>15.5</td>
<td>34.4</td>
<td>36.7</td>
</tr>
<tr>
<td>O$_2$</td>
<td>12.5</td>
<td>30.8</td>
<td>32.2</td>
</tr>
<tr>
<td>H$_2$</td>
<td>15.6</td>
<td>36.5</td>
<td>36.4</td>
</tr>
<tr>
<td>Air</td>
<td>-</td>
<td>33.8</td>
<td>35.1</td>
</tr>
</tbody>
</table>

ion, reversing the role of each. Free electrons can instead attach to a neutral gas molecule during collisions, creating an ion with similar properties to the original positive ions, but with opposite electric charge. Recombination processes happen instead when positive ions collide with free electrons, capturing them and returning to a neutral charge state. When the irradiation rate is significantly high, many tracks are formed in a short time, and it is possible for ions and electrons from independent tracks to collide and recombine.

The influence of both phenomena is significantly mitigated by the application of an external electric field, used to favour charge mobility and subsequent collection. Electrostatic forces tend to move the charges away from their point of origin, in a motion that consists in the superposition of random thermal velocity with drift velocity in a given direction. Positive ions will move in the direction of the conventional electric field, whereas free electrons will drift in the opposite direction. In both cases, their velocity is defined by

$$v = \frac{\mu E}{p}$$

where $E$ is the electrical field strength and $p$ is the gas pressure. The mobility coefficient $\mu$ tends to remain fairly constant over wide ranges of electric field and pressure. Nevertheless, while its typical value for ions is around $1.5 \cdot 10^{-4}$ m$^2$ atm/V, mobility for free electrons has a value which is generally 1000 times greater than that for ions. This leads to very different collection times, approximately milliseconds for ions and microseconds for electrons. As electrons drift through the gas, they will to first approximation follow the path of the electric field line that passes through their origin point, but in reverse direction.

### 2.1.2 Gas Multiplication

When a low electric field is applied in a gas volume, electrons and ions created by incident radiation simply drift to their collecting electrodes. Nonetheless, when the field is properly increased, gas multiplication process becomes of significant importance. Free electrons are easily accelerated by the applied field, gaining kinetic energy. When this energy is greater than the ionization energy of the gas molecules, secondary ionization can occur in the collision between the free electron and neutral gas molecules, generating an additional ion pair. Typically the average energy gained by free electrons increases with increasing electric field, imposing then a threshold value of the field above which secondary ionization can take place (around $10^6$ V/m).
2.1. Gaseous detectors operation principles

The electron from secondary ionization will in turn be accelerated by the field, undergoing collisions during its subsequent drift and thus creating additional ionization. The gas multiplication process takes the form of a cascade, the so called Townsend avalanche. Each free electron created can potentially create more free electrons, and the whole process can be described by the Townsend equation:

\[
\frac{dn}{n} = \alpha \, dx
\]

where \( \alpha \) is the first Townsend coefficient. It is zero for electric field values below the threshold, and increases with increasing field strength. Assuming a spatially constant field, the equation gives as a solution the exponential growth of the electron density for increasing distance, as the avalanche progresses:

\[
n(x) = n(0) \cdot e^{\alpha x}
\]

Under proper conditions, the number of secondary ionization events can be kept proportional to the number of primary ion pairs formed, but the total number of ions can be multiplied by a factor of many thousands. Since the charge amplification happens within the detector itself, the signal-to-noise ratio is significantly improved and the demand of external amplifiers is reduced.

As it can be seen in Figure 2.1, it exists a region of the applied voltage, thus of the electric field inside the gas volume, for which the collected charge begins to multiply, and the observed pulse amplitude increases (Proportional Region). Over most of this region, the gas multiplication is linear, and the collected charge is then proportional to the number of original ion pairs created by the incident radiation. This region of true proportionality represents the usual operation mode of gas-filled proportional counters. If the applied voltage is further increased, non linear effects can be introduced, falling in a limited-proportionality region.

![Figure 2.1: Different regions of operation of gaseous detectors, given by the plot of observed pulse amplitude as a function of the applied voltage. [16]](image-url)
Chapter 2. Gas Electron Multiplier Detectors (GEM)

The total gas multiplication factor can be calculated from the Townsend equation:

\[ M = \frac{n}{n_0} = e^{\alpha x} \]

When the condition of field uniformity is lost, for example for cylindrical geometries, the multiplication can be defined with the more general expression, in which \( \alpha \) depends on the position in the avalanche. The gas gain is however physically limited to values around \( 10^8 \), after which breakdown occurs.

\[ M = \exp\left[ \int_{r_1}^{r_2} \alpha(x)dx \right] \]

Moreover, it has to be considered that the Townsend coefficient does also depend on many other parameters, the main ones being the nature of the gas, field and gas pressure (a more detailed description will follow in Section 4.2).

2.1.3 Single Wire Proportional Chambers

The most simple gaseous detector is a Single Wire Proportional Chamber (SWPC), and it will be used in the following to describe the principle of pulse formation.

The cylindrical configuration consists of a sealed container, with conducting walls and a thin end window. The tube is the cathode, while the wire positioned along its axis acts as anode (Figure 2.2a). Fundamental in this layout is the polarity of the applied voltage, as electrons must be attracted towards the central axial wire. The electric field at a radius \( r \) in such geometry is indeed given by:

\[ E(r) = \frac{V}{r \cdot \ln(b/a)} \]

where \( V \) is the applied voltage, \( a \) is the anode wire radius and \( b \) is the cathode inner radius. Being electrons attracted to the anode, with such field they will be drawn towards the high field region, which happens to be in the immediate vicinity of the anode wire, where \( r \) is very small. In Figure 2.2b, the electric field is plotted against the distance from the anode. It can be seen from the plot that the multiplication region begins only when the field becomes large enough to support avalanche formation. Considering a minimum field value of \( 10^6 \) V/m, the avalanche can only happen for radii less than 0.04 cm.

The signal generation rises from the induced charge on the electrodes by the movement of ions and electrons. Assuming to have a charge \( q \) moving a distance \( dr \) towards the anode wire, the change in its potential energy is expressed as:

\[ dW = q \cdot \frac{d\phi(r)}{dr} \cdot dr \]

Given the electrostatic energy in the cylindrical capacitor to be \( W = lCV_0^2/2 \) and the total energy to be conserved, it can be written that:

\[ dW = lCV_0dV = q \cdot \frac{d\phi(r)}{dr} \cdot dr \Rightarrow dV = \frac{q}{lCV_0} \cdot \frac{d\phi(r)}{dr} \cdot dr \]
The voltage change \( dV \) is then induced across the electrodes by the displacement of the charge. Taking into account that the multiplication charge is much smaller for electrons than for ions, one can see that the main contribution to the induced signal comes from the motion of positive charges. The time development can then be determined with the potential and capacitance typical for the single wire cylindrical configuration:

\[
V(t) = \int_{r(0)}^{r(t)} \frac{dV}{dr} \cdot dr = \int_{r(0)}^{r(t)} \left( \frac{q}{lCV_0} \cdot \frac{d\phi(r)}{dr} \cdot dr \right) \frac{1}{dr} \cdot dr
\]

with \( \phi(r) = \frac{CV_0}{2\pi \varepsilon} \cdot \ln \left( \frac{r}{a} \right) \)

It is now useful to express \( r(t) \) as a function of the mobility and the electric field:

\[
\frac{dr}{dt} = \mu E(r) = \frac{\mu CV_0}{2\pi \varepsilon} \cdot \frac{1}{r} \Rightarrow r \cdot dr = \frac{\mu CV_0}{2\pi \varepsilon} dt
\]
Since all the positive ions come from close to the anode, it can be set $r(0) = a$ and the integration gives:

$$r(t) = \left(a^2 + \frac{\mu CV_0}{\pi \varepsilon} t\right)^{1/2}$$

This can now be substituted in the expression of the signal time development:

$$V(t) = -\frac{q}{4\pi \varepsilon l} \cdot \ln\left(1 + \frac{t}{t_0}\right)$$

where $t_0 = a^2 \pi \varepsilon / \mu CV_0$.

### 2.1.4 Fill Gases

The most widely used gas to fill gaseous detectors is Argon, due to the optimal combination of its properties with a generally limited cost. It has in fact a very low electron attachment coefficient, that guarantees most of the free electrons to reach the multiplication region without interference. It should however be taken into account that, beside simple ionization, the collision between electrons and neutral gas molecules may give rise to excitation, without the creation of a secondary electron. The excited molecules decay to their ground state, through the emission of a visible or ultraviolet photon, that may create additional ionization elsewhere in the gas. These events are normally undesirable, since they may cause a loss of proportionality or the presence of spurious pulses. Moreover, they cause the avalanche to spread.

It has been found that the addition of a certain amount of polyatomic gas, such as Carbon Dioxide (CO$_2$), can suppress the photon-induced effects by absorbing the photons in a mode that does not lead to further ionization (vibrational modes). The polyatomic component is then usually present in some percentage, together with the monatomic one, as a stabilizing additive (also called quencher).

Another point in adding a quencher gas into the gas mixture is its influence on the free electrons motion. Being Argon a purely inelastic gas, electrons tend to collide with gas molecules and scatter in every direction, making the drift quite inefficient. A polyatomic gas as CO$_2$ is instead an inelastic gas, with many degrees of freedom (linear, rotational, roto-vibrational modes), which allow electrons to be much faster in reaching the anode. Their drift path is in fact quite straight and less spread around. This phenomenon can be studied with simulations of the electron path, as the ones reported in Figure 2.3. It can be clearly seen that in pure Argon (0% CO$_2$), the transport along the field direction is very inefficient, while the electron path becomes more and more straight with the addition of more CO$_2$ in the mixture.

Another fundamental point is to maintain the purity of the chosen gas, that can be obtained with a continuous flow through the chamber. It can be a once-through type, in which the gas simply exits into the atmosphere, or a recirculation type, with the purification of the gas after re-injection. Traces of oxygen or other electronegative impurities must be removed, since they can cause significant losses of free electron.
2.1. Gaseous detectors operation principles

Figure 2.3: Drift path of free electrons in Ar/CO$_2$ gas mixture, simulated with Magboltz software for different CO$_2$ percentages in the mixture. [18]
2.2 Triple Gas Electron Multiplier Detectors

Gas Electron Multipliers (GEMs) belong to the wider class of Micro-Pattern Gaseous Detectors (MPDGs), mainly developed in the late Nineties to surmount the limits of Multi Wire Proportional Chambers (MWPCs), in term of efficiency at high particle rates and limited operating life span. The first GEM layout was proposed by F. Sauli in 1997, and it was widely studied and improved since then. GEM detectors are nowadays an affirmed technology, employed in many experiments worldwide.

2.2.1 GEMs Operating Principle

The GEM electrode is a thin polymer foil, metal-coated on both sides, perforated with a high density of holes. The typical foil is based on a 50 μm thick Kapton foil, with two 5 μm layers of Copper as coating on the opposite sides. Holes have normally a diameter of 70 μm, with 140 μm pitch (Figure 2.4a).

The foil manufacturing is based on a double-mask process: the pattern of holes is engraved by conventional photo-litography on the metal of both sides of the foil, and holes are then opened with a Kapton-specific solvent. Dissolving the unprotected polymer on both sides creates holes with a double-conical shape with the diameter in the centre of the insulator slightly smaller than that at the metal surface (Figure 2.4b).

![Figure 2.4: a) Electron microscope picture of a typical GEM electrode [19], and b) schematic representation of GEM holes geometry. [20]](image)

The basic GEM detector is formed by a GEM foil, inserted in a gas volume containing a drift foil and a patterned read-out electronics. Working in the regime of proportional gaseous detector, each hole works as an individual proportional amplifier (Figure 2.5b). Ionization is produced by incoming radiation in the upper drift region.

The usual gas mixture used for GEM detectors is Ar/CO₂, in the proportion 70/30. To accomplish requirements on a better time resolution, carbon tetrafluoride can be added to the standard gas mixture, that becomes than Ar/CO₂/CF₄ in the proportion 45/15/40.

Applying a potential difference between the top and the bottom GEM electrodes, a
dipole field develops in the holes, focusing there the electrons. Electric field equipotential lines can be seen in Figure 2.5a, obtained with GARFIELD simulations. If the field intensity is high enough (around 50 kV/cm), the multiplication process will occur inside the holes. Electrons produced in the upper region will drift towards the holes and they will acquire sufficient energy to cause ionizing collisions with the molecules of the gas. A fraction of the electrons in the avalanche will leave the multiplication region and transfer into the lower section of the structure, when they can be collected by an electrode.

![Figure 2.5: a) Structure of a basic GEM detector [20] and b) graphic representation of the electric field equipotential lines in the vicinity of GEM holes. [19]](image)

Unlike other gaseous detectors, the negative signal on the anode is generated only by the collection of electrons, without a contribution from the slow positive ions. This makes the device potentially very fast and minimize space charge problems. The purely electronic signal is generated by the movement of the negative charges in the induction gap, as previously illustrated in Section 2.1.3. The size and shape of the signal depend on the induction field, that creates faster and narrower signals when it has an higher value. As already mentioned, ions do not participate to the signal induction: they slowly drift back towards the top GEM electrode and the drift. The signal generated by the movement of positive charges is totally shielded by the GEM foil, therefore no ion tail is contained in the typical GEM signal.

### 2.2.2 Triple-Foil Structure

A unique feature of GEM devices is that the fraction of amplified electrons transferring to the gas gap following the first electrode can be injected and multiplied in a second foil. The advantage of a multiple structure is that the overall gain can be obtained with each foil operated at a lower voltage, therefore with less probability of discharges. In particular, single foil GEM are normally operated at about 500 V, with a final gain reaching $10^3$. Combining instead three GEM foils, in the common Triple-GEM structure, each foil can be operated at less than 400 V, obtaining a final gain factor up to $10^5$.

Triple-GEMs detectors are composed by three identical GEM electrodes, separated
by gas-filled gaps. Typical spacing between foils is 3-2-2-1 mm or 3-1-2-1 mm, referring to the drift space, two transfer gap and induction gap respectively (Figure 2.6).

Foils can either be supplied with a dedicated voltage line each, or with a single voltage source and a resistive distribution chain. In the latter case, the resistive circuit can be either realized with a series of resistors or with a single ceramic voltage divider. For the GEM used in this work, the second solution is the chosen one. In particular, resistor values are properly selected to optimize the voltage sharing between the foils. A schematic representation of the resistive circuit is showed in Figure 2.7, as well as the picture of the one commonly used for triple-GEMs at CERN.
2.3 Characterization of a GEM detector

In this Section the assembling and testing procedure for a standard 10x10 cm$^2$ GEM detector will be described, since it is the type of GEM that was used to carry on the studies described in the following Chapters.

2.3.1 Standard 10x10 cm$^2$ GEM Assembling

It is fundamental to carry on the whole GEM assembling procedure in a certified clean room, to avoid any possible contamination of the parts that will be in direct contact with the filling gas. The basic components of the GEM detector can be seen in the scheme of Figure 2.8. The bottom board on which the whole structure is mounted is itself the readout device for the detector. Three GEM foils and one drift foil are then piled on top of it, paying attention to interpose between them the proper spacers, to obtain the desired gaps between the foils. The last foil is the drift one, always placed with a 3 mm gap with respect to the last foil. In this case, the 3-1-2-1 mm configuration was chosen.

The structure is then sealed with the use of a top cover plate and a box frame. The cover plate is generally made of a plastic frame, under which a thin plastic foil and an aluminium foil are placed. The aluminium would be a good solution to avoid possible permeability of the structure, but if it was in direct contact with the gas it could possibly enhance sparks formation. The addition of the second foil underneath prevent this to happen. The box frame is instead made with Teflon, to limit the box air-permeability, and two Viton O-rings on the top and bottom allow the gas tightness of the detector. The frame also hosts the gas inlet and outlet connectors. Board, frame and top cover are kept together with 28 screws, placed on the edge of the top cover. The foils stack is instead kept in position by four nylon screws at the corners, which are then sealed from the outside with Araldite-2011 glue, to prevent any gas leak.
Different steps of the assembling operation are reported in Figure 2.9. It can be seen from the pictures that the bottom board also hosts the resistive circuit for voltage supplying to GEM foils, as well as the readout strips, grouped in four pads. Though GEM detectors are capable of measuring space resolution, this feature is not really relevant for gas-related studies of this thesis. For this reason, Panasonic Strip-to-Lemo readers were applied on the readout pads to merge together the strips. During operation, three of them will be closed with 50 Ω terminations, while the fourth will be properly adapted to allow current reading (see details in Section 2.3.2).

![Figure 2.9: GEM detector assembling phases: foil integrity check, electrodes and drift stacking, frame positioning. The last two pictures show instead the Strip-to-Lemo connectors for the read-out pads.](image)

### 2.3.2 Laboratory Characterization

Once the GEM detector is assembled, a simple set-up can be arranged for testing purposes. The gas inlet of the detector frame is connected to a pre-mixed gas bottle, with the standard mixture for GEMs: 70% Argon and 30% CO₂. The flow can be regulated with a rotameter to values between 0 l/h and 5 l/h. Taking into account that the gas-filled volume is approximately 0.25 l, the detector is generally flushed with 10 to 20 volumes per hour.
The high voltage is supplied with a CAEN Programmable HV module (NIM N570), with a low pass filter on the line. The HV module is capable of measuring the current flowing in the divider that supplies voltage to each GEM foil. This can be exploited to evaluate the behaviour of the resistive circuit. The expected current can be calculated knowing the total applied voltage and values of the various resistors as \( I_{\text{div}} = \frac{HV_{\text{tot}}}{\sum R} \).

In Figure 2.10 the trend of calculated and measured values of the divider current are shown. It can be seen that the higher is the voltage, the wider is the difference between the two. The measured current is always slightly higher than the expected value, probably due to a non-exact estimation of the total resistance value of the circuit.

Detector performance can be probed through two different measurements:

**Current:**
One of the Panasonic strip readers can be used to measure the current induced on the read-out layer, modifying it in way that clip connectors can be pinned. A PicoAmmeter (Keithley 6400) is used to directly read current values. It should however be noticed that since it is read from only one of the connectors, the measured value will be the one collected only from half of the GEM foils.

**Pulse Signal:**
The pulse signal can be read from the bottom of the third foil. using a lemo connector added in the resistive circuit that supplies voltage the foils. After a proper electronic chain (PreAmplifier and Amplifier CAEN N474), the signal is then sent to a desktop digitizer (CAEN DT5724), that acts as an analogue to digital converter (ADC). Digitized signal can then be read with the PC, to be registered and analysed offline.

The experimental set-up is schematically represented in Figure 2.11. Signal and current are independently collected with two electronic lines, and they are both read with the PC. The experimental set-up is schematically represented in Figure 2.11.
Measurements are realized with the use of a $^{55}$Fe source. Its activity is 35 MBq, that can eventually be reduced of a factor of about 3.5 or 5, rotating the source case to shield more the out-coming radiation. Though the source irradiates at $4\pi$, the radiation only comes out of the case from one side. For this reason, in the following it will be considered only half of its activity, 17.5 MBq.

The $^{55}$Fe source emits photons, in the form of X-rays, that extract primary electrons from the gas molecules. If the energy of the incoming X-ray is greater than the absorption edge of the gas, it can produce characteristics X-rays from the gas itself, that generate what is termed an escape peak. It in fact decreases the apparent energy of the incident X-ray and yields a separate peak offset towards lower energy by 3.2 keV. In this case, the main peak sits at 5.9 keV, while the escape peak at 2.7 keV. The typical pulse shape read from this set-up is shown in Figure 2.12. The acquired spectrum is showed in Figure 2.13, where both the main peak and the Argon escape peak are visible. Being the emission mono-energetic, events follow a Gaussian distribution, that can be fitted to obtain precise estimation of the mean and width values of the spectrum.
2.3. Characterization of a GEM detector

The basis of detector characterization consists in an high voltage (HV) scan, in which relevant parameters are measured for increasing values of the voltage. The aim is to evaluate the efficiency of the GEM, in particular finding its optimum working point. The total HV is increased by 50 V or 25 V steps, starting from about 3300 V \(^1\), until the complete efficiency is reached. Looking at the voltage divider circuit (Figure 2.7 in previous paragraph), it can be seen that the resistor values for the three GEM foils are different from each other. This means that for a specific value of total HV, each foil is supplied with a slightly different voltage:

\[
V_{foil} = \frac{HV_{total}}{\sum R_i} \cdot R_{foil}^i \quad \text{with} \quad R_{foil}^1 \neq R_{foil}^2 \neq R_{foil}^3
\]

It should then be noticed that in the following it will be indicated as \(V_{foil}\) the average value of the effective voltage on each foil.

The main peak and its width are recorded, collecting a complete spectrum for each set voltage, as well as the event rate, from the desktop digitizer. The latter is used as a reference to establish the working point of the detector. Both values are shown in the example plot of Figure 2.14.

For foil voltage values lower than about 335 V, no signal is seen in the detector. Increasing the voltage, event rate starts increasing, and reaches efficiency with fast slope. The peak position follows instead a proper exponential increase, as the fit line shows in the Figure. The first very low values are caused by the auto-trigger threshold set on the desktop digitizer, necessary to avoid noise spurious signals.

Looking at the efficiency curve (Rate trend), a peculiarity of Triple-GEM detectors can be noticed. To evaluate the working point of detectors, one would normally fit the efficiency curve with a Sigmoid Function (or Error Function), that tracks the

\(^1\)The value is referred to the specific case, in term of set-up configuration and gas mixture.
Figure 2.14: Event rate and peak position are plotted against the total HV (top X axis) and the average foil voltage (bottom X axis). Peak mean trend is fitted with an exponential function.

rapid slope (symmetrical with respect to the turning point), and the subsequent achievement of the efficiency plateau. Nonetheless, it is clear how this fit would not work for the measured trend for Triple-GEMs. The plateau is in fact reached in small steps, after the main jump in the rate value.

This can be explained taking into account the design of the voltage divider. As already pointed out, each foil is indeed supplied with a different voltage. Assuming that each foil reaches its maximum efficiency for the same voltage, this particular value will be reached at different total HV for each of them. For example, considering the plot in Figure 2.14, at a total HV equal to 3450 V, the first foil might have already reached efficiency, while the others do not. This makes the working point choice a bit more arbitrary than a precise fit. It is normally set about 50 V after the first stable rate value. However, as mentioned in Section 2.2.2, the working voltage for each foil is found to be lower than 380 V, coherently with what expected for the Triple-GEM structure.

The detector current measurement is instead useful to evaluate the multiplication gain of the detector. Measured current is indeed proportional to the final number of negative charges that reach the anode. Taking into account the number of pairs generated for each incoming photon ($N_{pairs}$ ≈ 4), the total gain can be estimated as follows:

$$Gain = \frac{2 \cdot |I_{GEM}|}{N_{pairs} \cdot Flux \cdot Area \cdot \varepsilon \cdot e}$$

where $e$ is the electron charge ($1.6 \cdot 10^{-19}$ C), $Flux \cdot Area$ is the source activity and $\varepsilon$ is the detecting efficiency (normally around $10^{-3}$). The factor 2 that doubles the current value is present to take into account the fact that it is only measured from half of the GEM foils.
Figure 2.15 shows the gain trend, as well as the current one. Gain exponentially increases up to more than $10^5$, when the detector reaches its efficiency. The measured value of GEM current is negative, as it is induced by negative charges approaching the anode.

Another useful test to be done on foil-based detectors is a uniformity scan. In this case it was performed moving the $^{55}$Fe source on the GEM surface, measuring for each point relevant parameters (peak mean, rate and current). The measurement here reported as example was realized moving the source on a 7x7 grid, with 2x2 cm$^2$ squares, covering the actual foil surface for the internal 5x5 grid (10x10 cm$^2$).

The first two plots of Figure 2.16 show the 2D map of the rate and peak mean values obtained during the scan. A relative deviation of 4% and 5% respectively is found for the internal square, which covers the actual GEM foils surface. Edges values for the rate are not taken into account, as the simply show that only part of the radiation was reaching the foils (only photons emitted at the limit of the radiation cone).

The measurement of current (third plot of Figure 2.16) shows instead a relative deviation of about 10%, but its realization also had less accuracy. Only half of the foil can actually be measured, and the values read on the PicoAmmeter are quite unstable. The current order of magnitude is in fact of the nanoAmpere, with oscillations of about 0.1 nA.
Figure 2.16: Example of a uniformity scan realized on a 10x10 cm$^2$ GEM. The 7x7 grid covers 14x14 cm$^2$, with the actual GEM surface in the 5x5 internal grid. While the rate and peak mean were recorded on the entire surface, the current value was only measured on the lower half of the area.
2.3. Single Foil Test

As illustrated in the previous paragraph, the basis of Triple-GEM detectors is the multiple amplification generated by consequent single GEM foils. The complete and optimal operation is then guaranteed by the correct behaviour of the three foils. If one of them is not properly working, the overall performance is compromised. This makes therefore necessary to have a procedure to verify the correct operation of a single foil.

Defective foils can mainly be spotted from a significant gain decrease in the detector. When a foil is damaged, it contributes to the total gas amplification with a lower or null factor. It is here reported the specific case of a damaged foil in one of the Triple-GEMs used for this work studies.

After some time of operation, the $^{55}$Fe spectrum resulting from normal acquisition was found to be shifted on the left, with the Argon escape peak completely disappeared (Figure 2.17). The main peak position was way reduced with respect to the last good spectrum acquired, at the usual working voltage, and its shape is no longer Gaussian. Moreover, increasing the total HV to possibly reach again full efficiency, the spectrum resulted to be strongly distorted, though the main peak and the escape peak structure could still be seen (Figure 2.18). In this case, the distortion of the spectrum structure came from the fact that, as later found out, the defective foil was the third one, from which the pulse signal is read.

A direct test on GEM foils can be performed with the use of a Source-Measurement Unit (SMU). In the ideal case, a GEM foil can be seen as an RC circuit with infinite resistance, avoiding current flows towards the foil. Supplying the single foil with 500 V, a total resistance higher than 10 GΩ should be measured (a good approximation of an infinite value). Were the resistance to be lower, it would mean that a leak current is flowing in the foil which is then not working correctly.
Nonetheless, it has to be taken into account that this operation cannot be done simply leaving the foil in air. It would indeed imply to generate strong discharges, mainly due to high humidity in air, that would surely damage the foil. A proper set-up was built to allow flushing the foil while performing the test (Figure 2.19). In particular, simple Nitrogen was used to minimize possible discharges. A sealed box was equipped with gas inlet and outlet, and with holes to let in the two pins attached to the foil conductive termination.

In the case reported as example, the third foil was found to be damaged. With 500 V supplied, a total resistance of only 7.3 MΩ was measured, with a correspondent leak current of 0.6 µA. Acceptable values for well performing foil are around 0.05 nA of leak current. Looking at the foil, a small defect was found, that was not present
when the new foil was mounted in the assembling phase (Figure 2.20). It could be
the source of the malfunctioning, possibly generated by a strong discharge during
operation.

![Figure 2.20](image1)

**Figure 2.20**: In the first picture testing operation are shown, with the foils still in the detector structure. The second picture shows instead the foil that was found to be damaged.

A first analysis was done observing at the microscope the damaged foil. A little white spot was barely visible to the naked eye, but it could very clearly be identified when magnifying the foil surface. From the picture reported in Figure 2.21 it can be well identified the damaged part of the foil (pictures on the right), when comparing it to the clean part (pictures on the left). Further investigations will be carried on in the future to better understand the origin of the problem, in particular with the use of a Scanning Electron Microscope (SEM), with which it could be understood whether the damage is caused by the deposit of some material on the foil or by an eventual erosion of the surface.

![Figure 2.21](image2)

**Figure 2.21**: Pictures of GEM electrode holes taken with an electronic microscope. On the left the pictures are taken in a clean area of the foil, while the one on the right are centred on the damaged area.
Chapter 2. Gas Electron Multiplier Detectors (GEM)

2.4 GEM Detectors at CERN

Being GEM detectors a fairly new and promising technology, they are more and more employed outside and inside CERN, in the latter case for both LHC and non-LHC experiments.

As previously illustrated in Section 1.4, the Muon System in LHCb has already profited of GEM technology to obtain better performances, while CMS experiment is already on its way to exploit it in view of the future LHC upgrade. Nonetheless, not only these systems are interested by this new technology.

In the ALICE experiment, the main device for particle tracking and identification in the central barrel is a Time Projection Chamber (TPC). It consists in a cylindrical barrel with a field cage (the drift volume), a central cathode and two electrodes on the side (Figure 2.22). It was designed to sustain extremely high particle multiplicity, but its maximum operating rate is significantly reduced by the readout gating grid, for which MWPCs are currently employed. The readout rate is indeed of approximately 3 kHz, while the TPC would be capable of sustaining up to 50 kHz. For this reason, GEM detectors will take the place of MWPCs as readout chambers. This will allow to work in continuous and trigger-less readout mode, also thanks to their intrinsic suppression of ion back-flow, significantly increasing the rate capability of the system.

![Figure 2.22: Schematic structure of the ALICE TPC tracker. [22]](image)

For what concerns instead non-LHC experiments, two examples of GEM Detector application are the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) and the TOTal cross section, Elastic scattering and diffraction dissociation Measurement (TOTEM).

COMPASS is a multi-purpose experiment, and its major aim is to investigate the gluon and quark structure of hadrons. It employs high intensity muon and hadron beams from the Super Proton Synchrotron. To achieve high mass resolution for charmed mesons the set-up comprises a two-stage magnetic spectrometer. The first aims at detecting secondary particles with low momenta (down to 0.5 GeV/c), while the second is optimized for momenta above 5 GeV/c. The tracking area in between the two spectrometers is made of 10 tracking stations, to measure the central area near the beam. This tracking system is totally made of GEM detectors. Each station is made of two GEMs, rotated of 45 degrees one with respect to the other. The
employment of Triple-GEM detectors allows a high precision in space and time measurements, as well as the capability of sustaining rates from 30 kHz up to 150 kHz for regions very close to the beam axis. Moreover, the central section of the RICH (Ring-Imaging Cherenkov detector) is facing an upgrade that involves the substitution of the central MWPC-based detectors with a combination of MPGDs. In particular, double ThickGEMs and bulk MicroMegas were installed and commissioned in 2017, making the RICH Hybrid fully operational and ready to deal with the COMPASS phase II physics program. A sketch of the COMPASS spectrometer is showed in Figure 2.23.

Figure 2.23: The COMPASS complete structure, located at the SPS accelerator. [23]

The physics program of TOTEM is instead mainly dedicated to precise measurements of the \(pp\) interaction cross section, as well as to the in-depth study of the proton structure. This require simultaneous measurements of both elastic and inelastic \(pp\) scattering interaction, with a good rapidity coverage up to the very forward region. Inelastic events are measured with two telescopes, placed in the forward region of the CMS experiments, on both sides of the interaction point. Lower rapidity \((3.1 < |\eta| < 4.7)\) is covered by CSCs (T1), while the extended tracking to the rapidity range \(5.3 < |\eta| < 6.5\) is realized with GEM detectors (T2). Triple-GEMs are built with a semi-circular shape, with an inner radius matching the beam pipe. Each arm of the telescope has a set of twenty GEM detectors, combined into two aligned semi-planes mounted on each side of the vacuum pipe (Figure 2.24). GEMs were chosen to accomplish requirements on good position and time resolution, as well as high rate capability and radiation hardness.

Figure 2.24: One arm of the TOTEM T2 Telescope. [24]
2.5 GEM Detectors and Gas Recirculation

As already pointed out in Section 1.4.1, one of the most important upgrade for Gaseous Detectors and Gas Systems in the LHC is the transition to recirculated gas operation. For GEM detectors in particular, large GEM Systems are planned to be installed in the next future, implying an increase in operational costs and gas emission. Though the most common gas mixture is Ar/CO\(_2\) (70/30), GEM performance is enhanced by the addition of CF\(_4\), that improves the time resolution of the detector (Ar/CO\(_2\)/CF\(_4\) 45/15/40). CF\(_4\) is nevertheless a greenhouse gas, which emission in the atmosphere has to be strictly controlled when the gas flow is very high (20-30 l/h for large area GEMs).

A viable solution to cut down the gas consumption is to operate the detector in a Closed Loop System. Nonetheless, this type of system has different drawbacks which should be kept under control. The quality of the gas mixture can deteriorate, due to the accumulation of impurities such as O\(_2\), N\(_2\) and H\(_2\)O. In Figure 2.25 it is showed the Gas-Chromatograph of a gas recirculated system with a mixture similar to the one in use for GEMs (CMS DT), in which O\(_2\) and N\(_2\) are clearly visible. Then only Closed Loop System for GEM Detectors currently in use is the one implemented for the Muon System of the LHCb experiment, already described in Section 1.4.2. In this case, the best possible operations are guaranteed by the use of purifiers in the closed loop.

Even if it has been demonstrated that Triple-GEM detectors can still work well with gas recirculation, it is fundamental to progress with the R&D studies that will allow the reduction of impurities accumulation inside the gas system. Moreover, behaviour of these detectors in such conditions need to be very well known, in way to guarantee high quality and safe operation for the systems that will be installed in LHC experiments in the future.

With this in mind, the guidelines of the studies that will be presented in this work were established. While the next Chapter will deal with ordinary GEM operation, focusing on detector response under gas mixture properties variation, the entire Chapter 5 will be dedicated to an extended study of its performance in a recirculated gas system.
Chapter 3

Gamma Irradiation Facility (GIF++)

3.1 Outlook on GIF++ facility

Between 2000 and 2014, the Gamma Irradiation Facility (GIF, SPS West Area) was widely used at CERN, as dedicated test zone for large area muon chambers, for both performance characterization and aging test. It is in fact essential to test and characterize particle detectors before their installation into LHC experiments. Relying on a $^{137}\text{Cs}$ source, the facility was capable of providing a gamma irradiation rate of the order of kHz/cm$^2$ (source activity around 700 GBq), sided by an high-energy particle beam from X5 beam line.

Nonetheless, during the Long Shutdown 1 (LS1, 2013-2014), a new Gamma Irradiation Facility (GIF++) was built in the CERN SPS North Area. This kind of facility is indeed in the eyes of many users, whose requests could not be handled by the previous one. With the use of a stronger source it gives nowadays the possibility of a parallel utilization of the irradiator, together with a gamma emission rate way more suitable to mimic the foreseen High Luminosity phase of the LHC. With the increase of collider luminosity, also the particle background will indeed significantly increase, and it is estimated that gas-based muon detectors will experience a background rate one order of magnitude higher than the one in present condition. The facility has been operating since spring 2015, and is expected to be in use for approximately ten years.

![GIF++ Facility CAD 3D Plan, view from the main entrance side.](image-url)
The GIF++ area is mainly composed by the actual irradiation area, a preparation zone and a two-floor area that hosts the gas systems and the electronic services. The bunker is delimited by 1.6 m thick concrete blocks, creating a shielded area that is accessible from two sides. The roof of the bunker, made as well of concrete blocks, can be removed when necessary, for example for the installation of very large setups. Just outside the main bunker entrance, a preparation area is available for preliminary test on detectors before moving them into the irradiation area (Figure 3.1, Figure 3.2).

Currently more than ten setups are under test in the facility (Figure 3.3), covering different gaseous detector technologies: Drift Tubes (DT), Cathode Strip Chambers (CSC), Micro-Megas (MM), Resistive Plate Chambers (RPC) and Gas Electron Multipliers (GEM). The different setups come from the four LHC experiments, which make use of the GIF++ facility for both R&D studies as well as for validation purposes.
3.2 Gamma irradiation field and $^{137}$Cs source

The GIF++ facility makes gamma irradiation available throughout the entire year. Thanks to the bunker structure, two independent irradiation zones are present, named *upstream* and *downstream*, referring to their position with respect to the gamma source. The complete planimetry of the facility can be seen in Figure 3.4, which shows the actual bunker area (around 100 $m^2$) as well as the external preparation area and service zone.

![Figure 3.4: Planimetry of the GIF++ area. [26]](image)

The gamma source is the $^{137}$Cs isotope, whose spectrum is composed by primary 662 keV photons and scattered photons with lower energy. This isotope was chosen, over for example $^{60}$Co, for its long half-life (approximately 30 years) which can give a more uniform photon rate over time. Moreover, its spectrum very well resembles the typical neutron-induced background present in LHC experiments. The activity of the source is 13.5 TBq (measured in March 2016), making it capable of delivering approximately 1 Gy/h at a distance of 1 meter.

The irradiator has been developed in cooperation with the Czech company VF a.s., and it is showed in details in Figure 3.5. It is equipped with two $\pm 37$ degree panoramic collimators, which allow to cover with irradiation a large part of the bunker area. The source itself is embedded between two Tungsten blocks, which assure the source OFF status when it is in the so called garage position, at the bottom of the support tube. The source can be moved on the top of the tube to bring the irradiator in the source ON status.

In addition, angular correction filters are present to guarantee a uniform photon distribution of the whole irradiated zone, mainly in favor of large area detectors. Without this correction, the source would be approximately a point source, for which the photon current would be dependent on $x$, $y$ and $z$ coordinates. It is instead made possible that the current intensity only depends on the $z$-coordinate, i.e. on the distance from the irradiator, as it is shown in the simulated current plot in Figure 3.6.
A useful tool is the attenuation system, which makes the upstream and downstream areas independent from each other. The system is in fact equipped with two independent $3 \times 3$ arrays of absorption filters, convex filters made out of paint coated lead.

The filters can be arranged to fine tune the photon flux according to 24 nominal attenuation factors that can be selected with the different combinations of single filters. The nominal reduction factor of each filter is given in Table 3.1. A total attenuation between 1 and 46415 can be selected, with nearly equidistant steps on a logarithmic scale.

<table>
<thead>
<tr>
<th>Plane/Pos</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>1.47</td>
<td>2.15</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>100</td>
<td>4.64</td>
</tr>
</tbody>
</table>

Table 3.1: Nominal attenuation factors for the different filters. [26]
It has however to be taken into account that the nominal attenuation factor of the filters is the attenuation of the 662 keV photons, and that the effective attenuation for photons of lower energy can differ from these values. As it can be seen in Table 3.2, for factors greater than 10 the dose attenuation is significantly lower than the nominal one, as lower energy photons give a substantial contribution to the effective dose. The reported measurements were taken with the Automess Gamma Probe 6150AD-15, available at GIF++ for dose measurements.

<table>
<thead>
<tr>
<th>Nom. Attenuation</th>
<th>Filter Combination</th>
<th>Dose Rate [mGy/h]</th>
<th>Dose Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A1 B1 C1</td>
<td>470</td>
<td>–</td>
</tr>
<tr>
<td>1.5</td>
<td>A1 B2 C1</td>
<td>400</td>
<td>1.2</td>
</tr>
<tr>
<td>2.2</td>
<td>A1 B1 C2</td>
<td>211</td>
<td>2.2</td>
</tr>
<tr>
<td>4.6</td>
<td>A1 B1 C3</td>
<td>105</td>
<td>4.5</td>
</tr>
<tr>
<td>10</td>
<td>A2 B1 C1</td>
<td>55</td>
<td>8.8</td>
</tr>
<tr>
<td>100</td>
<td>A1 B1 C1</td>
<td>6.5</td>
<td>72.3</td>
</tr>
<tr>
<td>100</td>
<td>A1 B3 C1</td>
<td>6.2</td>
<td>75.8</td>
</tr>
<tr>
<td>464</td>
<td>A1 B3 C3</td>
<td>1.59</td>
<td>295.6</td>
</tr>
<tr>
<td>4642</td>
<td>A2 B3 C3</td>
<td>0.22</td>
<td>2156</td>
</tr>
<tr>
<td>46415</td>
<td>A3 B3 C3</td>
<td>0.05</td>
<td>9400</td>
</tr>
</tbody>
</table>

Table 3.2: Nominal attenuation factors (for 662 keV photons) and measured effective attenuation in position D1. [25]

Also the simulation realized for the spectra of photon current in location D1 (x=0.65m, y=0.00m, z=1.10m) shows that a broad low energy component is present. The narrow 662 keV peak can be seen at the far right of the spectrum (Figure 3.7). The simulation takes into account all the possible scattering events in the path of the photons between the source itself and the detector. Already before the angular correction filters, photons scatter with the source capsule and the irradiator collimator, as well as with the bunker walls, floor and roof after they leave the irradiator.

![Figure 3.7: Simulated spectrum in location D1, with downstream attenuation factors 1, 10 and 100, with upstream side fully closed. [25]](image-url)
Directly related to the photon current inside the GIF++ bunker is the absorbed dose rate. The fundamental parameter for aging studies is indeed the dose equivalent rate that detectors receive during their operation. Dose rates experienced by detectors at GIF++ will allow the efficient testing of muon systems against the expected HL-LHC background, which is estimated to be around 0.1 Gy/year (Table 3.3).

<table>
<thead>
<tr>
<th>Max. HL-LHC expected dose</th>
<th>GIF++ equivalent time (50 cm from source)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-Trackers ≈ MGy/y</td>
<td>≫ years</td>
</tr>
<tr>
<td>Calorimeters ≈ 20 kGy/y</td>
<td>&lt; 1 year</td>
</tr>
<tr>
<td>Muon Systems ≈ 0.1 Gy/y</td>
<td>≈ minutes</td>
</tr>
</tbody>
</table>

**TABLE 3.3:** Comparison between the expected dose at the HL-LHC and the required time at the GIF++ for different detector systems [26].

As demonstrated by the simulations results shown in Figure 3.8, as well as from the measurement of the Radiation Monitoring campaign, GIF++ is capable of delivering the same dose that a detector would yearly experience in the HL-LHC in a shorter time, allowing efficient aging tests. Moreover, it is deduced from the simulation that most of the bunker area is subject to sufficiently high irradiation and that, as expected, the downstream and upstream zones are independent from each other. It can also be noticed that the angular correction filters do not only create a uniform photons current, but also lead to a dose distribution that depends almost exclusively on the z coordinate.

![Figure 3.8: Absorbed dose rate in air [µGy/h] in the xy plane at y=0.00m inside bunker.][25]
3.3 GIF++ Services

3.3.1 Control System

In a facility such as GIF++, a Control System is of fundamental importance to monitor and archive all relevant parameters. It is based on a WinCC Open Architecture project, hosted in the CERN Control Centre (CCC). Irradiator source state, access status, beam characteristics and environmental conditions are some examples of the variety of values that are acquired and stored in a central CERN database. Some of them can also be used as monitoring tool, to provide interlocks to user equipments. The design of the Control System is displayed in Figure 3.9.

![Figure 3.9: GIF++ Control System design, with hardwired connections (red) and software connections (green). [26]](image)

3.3.2 DIP Service

All the relevant information regarding GIF++ is made accessible to the users through the DIP, an information distribution service that allows real-time data sharing, commonly used also in LHC experiments.

The contents of DIP are given by publishers, who own the data and make them public through this communication protocol. The subscribers (or DIP Clients) are the users of the platform, having the possibility to read and download all the required data. Access can be sometimes restricted for sensitive information: the network is divided into Technical (TN) and General Purpose (GPN). The first is only accessible under special permission, and it is usually reserved to experiments. More general and non-sensitive information is instead published on the GPN, as most of the GIF++ relevant parameters.

In particular, available values for GIF++ concern bunker access status, source status, absorption filters, environmental parameters and some information about the composition of gas mixtures and flammable gases level (Figure 3.10).
3.3.3 Gas Service System

In order to allow the operation of many gaseous detector setups, the GIF++ is equipped with a powerful gas service system. Primary supply panels make available all the commonly needed gases, such as Ar, CO₂, N₂, He, SF₆, C₂H₂F₄, iC₄H₁₀, nC₅H₁₂ and CF₄. Gas racks are installed in the service area to allow the preparation of gas mixture, different for each type of detector.

The monitoring of gas lines is guaranteed by the gas analysis system, which measures the flammability level of mixture components, as well as Oxygen and water vapour. Both supply and return lines are checked with dedicated sensors. More specific analyses on components concentration are allowed by a gas chromatograph that is permanently available in the facility.

A total of 48 gas lines can be used to bring the gas mixtures from the service area to the irradiation bunker, through a piping path of about 20-30 m.

3.3.4 Radiation Monitoring System

As mentioned at the end of Section 4.2, dose equivalent can be measured inside the GIF++ bunker with the use of RADiation MONitoring sensors. These are part of the so called RAdiation Monitoring System for Environmental Safety (RAMSES), that
monitors radiation levels continuously inside the facility. The sensors are air-filled plastic ionization chambers, which are capable of measuring gamma radiation in the $^{137}$Cs energy range.

Besides safety purposes, RAMSES sensors are used to evaluate the duty cycle of the irradiator, defined as the fraction of time for which the source is in the irradiation position. Taking into account the weekly access to the bunker (on Wednesdays) and the more frequent accesses asked during beam time, the duty cycle is on average around 70%.

### 3.3.5 High-Energy Muon Beam

The GIF++ facility can profit of approximately six to eight weeks of beam time as main user every year, being located on the H4 beam line (Figure 3.12),

![Figure 3.12: CERN North Area beam lines, with GIF++ located on the H4 site.](image)

Muon beam is generated as a secondary beam from the primary SPS proton beam, on a production target. The decay of pions and kaons produced in the primary target generates the muon beam, with an energy range of 57% to 100% of the nominal energy. Beam line users are allowed to choose the nominal momentum of beam particles, from a minimum of 10 GeV/c to a maximum of 400 GeV/c.

The spill structure follows the one of the SPS, with normally a spill every 30 seconds. The intensity of the beam can reach $10^4$ muons per spill, but it is limited by radiation protection aspects.

The lateral distribution of the muon beam (Figure 3.13) depends on several factors, but mainly on the final focusing, that can be varied within a large range. Generally the core of the beam covers a surface of $10 \text{ cm} \times 10 \text{ cm}$, where about half of the particles are contained. The other half is spread over a footprint of about $1 \text{ m}^2$.

![Figure 3.13: $xy$ plane distribution of muon beam particles at centre of GIF++ bunker.](image)
Chapter 4

Gas-Related Studies On GEM Performance

This Chapter describes the studies realized with a GEM detector operated in a laboratory set-up. After the experimental layout description, the results of three test are reported: the study of GEM performance with variations of the gas flow, the analysis of the consequences of changes in standard mixture concentrations (Ar/CO₂) and finally a test on detector response under the introduction of different Oxygen concentrations in the standard gas mixture.

Though the main aim of this thesis is to analyse GEMs behaviour in a gas recirculation system, the study of its response in different gas conditions helps understanding which are the consequences of specific changes in the gas mixture. In a complex system like the one recreated for the Closed Loop test (Chapter 5), or the LHC experiments one, many variables can affect detectors response and it is then fundamental to know what is their individual effect. A simple system like the one realized for these tests is a good option to individually study each effect, to better understand the outcome of their combination when operating in a real system.

4.1 Experimental Setup

The set-up realized for these studies consists in an extended version of the one used for the basic detector characterization (as described in Section 2.3.2). A schematics of the system is reported in Figure 4.1. As in the basic characterization, pulse signal and detector current are collected and recorded with the desktop digitizer and PicoAmmeter respectively.

The main difference sits in the input gas, that comes from a custom-made system that allows to control the percentage of the gas mixture and different gas flows before they are injected in the detector line. Two Mass Flow Controllers (MFCs, Bronkhorst F210CM) are respectively connected to the supply lines of Argon and CO₂. MFCs are capable of adjusting the proportion of each component and the total flow injected into the detector. MFCs are usually made with a turbulent filter, a laminar flow element, a thermal mass flow sensor and a control valve. The incoming gas is converted into a laminar flow by a series of thin layers alternated to small openings, and their impedance allows the gas to pass through the mass flow sensor. The latter consists of a capillary tube with a heater placed between two temperature sensors, that measures the temperature difference as it is proportional to the mass flow of the gas. Given the mass flow, the exit valve can then be opened or closed based on the desired gas output.
Figure 4.1: Graphic representation of the laboratory set-up (gas lines, electronics, sensors) used for open mode operation tests.

MFCs are remotely controlled with the PC, to which they are plugged with a BUS connector. Dedicated software (FlowDDE, FlowView, FlowPlot from Bronkhorst) allows the communication, and it makes possible to set for each MFC the desired flow values. To create the standard gas mixture Ar/CO\textsubscript{2} in proportion 70/30, the system is set in a way that one channel (Ar) is dependent on the other (CO\textsubscript{2}). Fixed the CO\textsubscript{2} flow, the Argon one will be adjusted in consequence to create the right proportion. For the case of two components, the proportion flow factor in the Slave (Argon) is simply set knowing the total capacity of each channel and the desired percentage of each gas as:

\[
\text{Factor(Ar)} = \frac{\%\text{Ar}}{\%\text{CO}_2} \cdot \frac{\text{Capacity}_{\text{Ar}}}{\text{Capacity}_{\text{CO}_2}} \cdot 100
\]

Each component flows then into a volume, in which the two gases properly mix, to be then injected into the line. The gas flow is controlled with a rotameter, with which it can be set from 0 l/h to 6 l/h. After the rotameter, a MEMS Flow Sensor (Micro ElectroMechanical System, OMRON D6FP0001A1, 0-0.1 LPM) measures the actual gas flow passing through the line. Its voltage output is sent to a PicoLog ADC-24.

The PicoLog unit also collects information from the two other key elements in the set-up. Two sensors are installed on the exhaust line of the GEM detector, to measure Oxygen and Humidity concentration in the gas. The O\textsubscript{2} sensor (O2X1 by GE Infrastructure Sensing) is capable of measuring O\textsubscript{2} concentration from 0 ppm to 25%, while the Water sensor (Vaisala Dewpoint Transmitter DMT242) can measure H\textsubscript{2}O concentration in the range ± 60 degrees. Finally, temperature and atmospheric pressure are measured with dedicated sensors (Electrotherm with Pt100), and their output is collected with the PicoLog board as well.
4.1. Experimental Setup

The correct operation of the mixer system was tested with a Gas-Chromatograph, a 3000 Micro GC Gas Analyzer by Agilent Technologies. The instrument was provided with two analysis columns, one PPlotU (Porous Layer Open Tubular) and one MolSieve (5Å zeolite molecular sieve). The first is suitable for the separation of hydrocarbons, CO$_2$, CH$_4$, H$_2$O, while the second can well separate permanent and noble gases (Ne, H$_2$, O$_2$, N$_2$).

In this case, the main components of interest are Argon and CO$_2$, both well detected by the PPU column. Nonetheless, analysis are carried out at the same time also with the MolSieve column, to eventually detect the presence of Air, that in this case would be separated in O$_2$ and N$_2$ in the column.

A pre-mixed bottle with 70% of Argon and 30% of CO$_2$ was used as a reference, since its accuracy is of the 0.5%. After the calibration, the GC was connected to the analysis point after the mixer volume, to measure the concentrations of the two gases in the injected gas mixture (Mixer), as well as after GEM (Exhaust).

The PPU column result is reported in Figure 4.2. The column is capable of separating Argon (first peak, 16 sec) and CO$_2$ (second peak, 25 sec). As it can be seen from the plot, the three chromatograms are almost superposed, but a slight difference can be seen in the CO$_2$ peak. Comparing the values of the peak areas, it was calculated a positive offset of 1% for the mixture prepared with the MFCs, so in both the Mixer and Exhaust analysis.

The reason why this difference is only tangible in the CO$_2$ peak comes from the GC limitation of not being capable of detecting quantities higher than about 60%. Being the Argon present for the 70% of the mixture, the area measurement would be inaccurate since it would not comprehend all the gas in the mixture. The Argon percentage is then calculated by difference from the CO$_2$ value.

![GEM - GC Analysis - PPU Column](image.png)

**Figure 4.2:** PPU Column Gas-chromatogram of the Ar/CO$_2$ 70/30 pre-mixed bottle (Yellow) and for the same mixture reproduced with the MFCs after Mixer (Orange) and at GEM Exhaust (Blue).
4.2 Effects of Environmental Parameters

As already pointed out in Section 2.1.2, the gain of a gaseous detector is determined by the Townsend equation \( n = n_0 e^{\alpha x} \), that gives the number of electrons after a distance \( x \) in the multiplication avalanche. Nonetheless, the main parameter that characterizes the avalanche development, the Townsend coefficient \( \alpha \), is considered to be constant only under strict and hardly realistic condition.

Defined as the inverse of the mean free path \( \lambda \), \( \alpha \) expresses the number of ionizing collisions per centimetre. Depending the ionization process upon many parameters, this leads to a dependence of \( \alpha \) on the same variables. The nature of the gas, the applied field \( E \) and the gas pressure and temperature are the main ones that one should take into account. In particular, considering the definition of \( \alpha \) as \( 1/\lambda \), it is deduced that \( \alpha = \nu_i/D \), where \( \nu_i \) is the average ionization frequency and \( D \) is the drift velocity. Given this, it has been demonstrated that the ratio \( \alpha/E \) of a given gas only depends on \( E/\rho \), where \( \rho \) is the mass density ([28], [29]). Therefore, the Townsend coefficient is found to be explicitly dependent on the gas temperature and pressure:

\[
\alpha \propto 1/\rho \propto T/p
\]

Considering now that the multiplication gain of a gaseous detector is defined as \( M = n/n_0 \), the dependence of detector gain on environmental parameters is obtained as:

\[
Gain = M \propto e^{\alpha} \propto e^{T/p}
\]

This dependence has been experimentally observed, looking at the correlation plot relating the measured gain versus the ratio \( T/p \). As an example, such plot is here reported for an acquisition campaign carried out for the studies presented in this Chapter. As it can be seen in Figure 4.3, it does exist a correlation between the two variables, and it is well modelled by the exponential fit curve

\[
Gain(T/p) = A \cdot e^{B T/p}
\]

where \( A \) and \( B \) are the fit parameters, \textit{Constant} and \textit{Slope} respectively.

**FIGURE 4.3:** Correlation plot of the GEM multiplication gain with the ratio Temp/Press.
The dependence of the gain on these parameters is such that for a difference of the 1% in the ratio $T/p$, variations in the gain can reach the 20%. Single dependencies on Temperature and Pressure are showed in Figure 4.4.

![GEM - Gain:Temperature Correlation](image)

![GEM - Gain:Pressure Correlation](image)

Figure 4.4: Correlation plot of the GEM multiplication gain with respect to A) the temperature and B) the atmospheric pressure.

As observed during prolonged acquisition, such influence of temperature and atmospheric pressure on the gain can make its trend in time significantly fluctuating. Figure 4.5 reports the measured gain and $T/p$ trend in time, clearly showing that the two have synchronized oscillations.

![GEM - Gain and T/p Trend](image)

Figure 4.5: Superposed trends of the GEM multiplication gain and the ratio $T/p$, in the same time interval.

This effect is not negligible since it obviously influences the measurements result: a corrected gain is computed from the effective gain exploiting its correlation curve with regard to $T/p$. The corrected gain is given by:

$$Gain_{corr} = \frac{Gain}{A \cdot e^{B \cdot T/p}}$$
where $A$ and $B$ are the fit parameters previously obtained from the correlation plot. Figure 4.7 shows the corrected gain trend for the same time period of Figure 4.5, clearly evincing how the oscillations caused by temperature and pressure are now removed, with a trend stable in time.

Looking at the distribution of the raw and corrected measured gain, it is clearly evident that the correction eliminates the oscillations that caused the raw gain distribution to be spread and irregular. The corrected gain has now a very slight and intrinsic fluctuation, but the dependence on temperature and pressure was totally eliminated and the real gain value could be obtained.

This gain correction procedure was carried out for all the data acquired for the studies showed in this Chapter, since for prolonged acquisition the temperature and atmospheric pressure in the laboratory are subject to natural fluctuations.
4.3 Triple-GEM Performance with Different Flows

One of the parameters that can influence the performance of a gaseous detector is the injected gas flow rate. It normally depends on the detector volume, that needs to be properly flushed for optimal operation. Concerning the GEM detector used for this study, the actual volume filled with gas is approximately 150 cm$^3$, then 0.15 litres. Usually for GEM detectors a flow rate around 10 volumes per hour is set. In this case, flow rates from 0.5 l/h up to 5 l/h were scouted, so from a minimum of about 3 volumes/h. As already mentioned, the gas mixture flow can be set using the rotameter, and subsequently measured with more precision with the flowmeter. Nominal flow values chosen for the test are 0.5 l/h, 1 l/h, 1.5 l/h, 2 l/h, 3 l/h, 4 l/h, 5 l/h.

Detector performance was probed using an $^{55}$Fe source, with an activity of 35 MBq, the same that was used for the basic characterization reported in Section 2.3.2. The spectrum is acquired and analysed to obtain significant parameters from the main peak, and detector current is recorded as well. After each gas flow is set, the detector is left under flow for some hours before starting the acquisition, in way to allow the flow to stabilize.

4.3.1 Gas Line Analysis

In parallel to the test progression, after each flow was set, an analysis of the GEM exhaust line was realized with the Gas-Chromatograph. The GEM frame is indeed partly permeable to air, and the quantity of $O_2$ and $N_2$ that is absorbed may vary with the gas flow. A lower flow means a more steady dynamic inside the gas filled volume, that can favour the intake of air from the environment. Reference measurements were performed at the input of GEM detector, and they showed that no impurities were present at this level.

Figure 4.8 shows the Gas-Chromatogram of the same analysis point, after the GEM, for the different gas flows used during the test. As it can be clearly see from the

![Gas-Chromatogram of the GEM Exhaust flow, from the MolSiev column, with the Oxygen peak on the left and Nitrogen peak on the right. The area of the peaks is proportional to the component concentration.](image)
plot, both peaks are subject to a significant increase with the decrease of the flow. Figure 4.9a and 4.9b report the concentration values of the two elements calculated from peak areas. Nonetheless, looking at the proportion between the two peaks, it is evident that they do not respect what would be expected from pure air. Assuming that air is composed by $O_2$ and $N_2$ in proportion 1/4, it is found that the quantity of absorbed $O_2$ is much higher than only a quarter of the quantity of $N_2$. It is then concluded that the two compounds are absorbed in different ways by the GEM structure, with $O_2$ being absorbed more easily than $N_2$.

As a conclusion, it can be deduced that flows higher than 2 l/h (10 volumes/hour) guarantee that low quantities of $N_2$ and $O_2$ are accumulated.

\[ \text{Gas Flow [l/h]} \]
\[ \begin{array}{cccccc}
1 & 2 & 3 & 4 & 5 \\
\end{array} \]
\[ \text{O}_2 \text{ Concentration [ppm]} \]
\[ \begin{array}{cccccc}
0 & 50 & 100 & 150 & 200 \\
\end{array} \]

\[ \text{Gas Flow Test - O}_2 \text{ Concentration} \]

\[ \text{Gas Flow [l/h]} \]
\[ \begin{array}{cccccc}
1 & 2 & 3 & 4 & 5 \\
\end{array} \]
\[ \text{N}_2 \text{ Concentration [ppm]} \]
\[ \begin{array}{cccccc}
0 & 200 & 400 & 600 & 800 \\
\end{array} \]

\[ \text{GEM - Flow Test - N}_2 \text{ Concentration} \]

\[ \text{H}_2\text{O} \text{ concentration in the gas line was also measured for the different flows, using the Humidity sensor placed at the exhaust of GEM line. As for the $O_2$ and $N_2$ concentration, it was found to be decreasing with the increase of the flow (Figure 4.10), meaning that lower flows also favour the intake of humidity in the gas line. As measured in previous laboratory tests, the humidity accumulation in the gas is mainly caused by the absorption of $H_2O$ when plastic pipes are used, therefore their use should be avoided or limited. Nonetheless, as it can be seen from the plot values, the range of $H_2O$ concentration is around 10-30 ppm, which is widely acceptable for gaseous detectors operation.} \]

\[ \text{Gas Flow [l/h]} \]
\[ \begin{array}{cccccc}
1 & 2 & 3 & 4 & 5 \\
\end{array} \]
\[ \text{H}_2\text{O} \text{ Concentration [ppm]} \]
\[ \begin{array}{cccccc}
10 & 15 & 20 & 25 & 30 \\
\end{array} \]

\[ \text{GEM - Flow Test - H}_2\text{O} \text{ Concentration} \]

\[ \text{Figure 4.9: A) Oxygen and B) Nitrogen concentration as a function of the gas flow.} \]

\[ \text{Figure 4.10: H}_2\text{O concentration against the gas flow, reported in degrees on the left axis (the sensor measures the water dew point), while the ppm value is showed on the right axis.} \]
4.3.2 Results

The main noticeable effect on GEM performance of the gas flow change is found in the variation of the multiplication gas gain. Though the deviation is quite limited, a decrease is registered in both gain measurements (Peak Mean and GEM current) for low flows. Figure 4.11 shows the trend of Peak Mean position and GEM current as a function of the input gas flow.

![Figure 4.11: Peak mean and GEM current values from 55Fe spectrum plotted against the gas flow in volumes per hour.](image)

The difference between the highest and the lowest point is nonetheless lower than 5% in the Peak Mean measurement and lower than 10% in the current measurement. Assuming a greater uncertainty in the latter case, due to the instability in the PicoAmmeter measurement, the Peak Mean measurement is taken as the most reliable result. This allows to conclude that even if the gas flow rate seems to slightly affect detector performance, it is enough to maintain it at a fairly high value to avoid a loss of multiplication gain. Flows higher than 2-3 l/h (10-15 volumes/hour) should guarantee a stable performance.

Taking into account the O₂, N₂ and H₂O measurements illustrated in the previous Section, it is also concluded that the actual cause of performance worsening is most probably the increase of impurities in the gas flowing through the detector, more than the decrease in the flow itself.
4.4 Triple-GEM Performance Varying the CO₂ Concentration

The gas mixture composition is a key element in determining detector performance. The GEM standard and most widely used mixture is, as already mentioned, the one composed by 70% of Argon and 30% of Carbon Dioxide.

The reported test was carried out to better understand what is the response of GEM detectors under variations of the percentage of the two gases. Being the CO₂ the quencher gas added to Argon, reference to gas mixture variations will here be made in term of CO₂ percentage in the mixture composition.

4.4.1 Gas Mixture Variations

As already mentioned in Section 2.1.4, it is fundamental to have a certain quantity of quencher gas in the injected mixture to reach the optimum in gaseous detector operation. This also applies to GEMs, that are sensitive to the quencher presence in term of discharges reduction and performance stability. Since CO₂ is more prone to absorb photons without further ionization, it suppresses the excessive electron extraction, making the detector response more stable.

Though an optimum value of the quantity of quencher gas is not absolutely determined, it remains interesting to investigate which are the tangible effects of its variations on typically measured variables, such as the amplification gain or the particle rate of the detector.

In first place, given that the CO₂ inhibits primary ionization, one would expect the number of detected photons at detector efficiency to decrease with the increase of CO₂, for a given voltage supplied to the chamber. Assuming this, it leads to the consequence of reaching the efficiency plateau in the rate trend at a higher value of the supplied voltage for higher values of CO₂ percentage in the mixture. Moreover, even once the detector reaches efficiency, the total measured rate should be lower for increasing CO₂ percentage, since it means less Argon in the mixture, then less enhanced primary ionization.

Regarding the detector amplification gain, if the gas mixture contains a higher quantity of quencher gas, this should mean a decrease in the number of electrons produced in the electronic shower, which leads to a lower number of collected electrons. The effect should then reflect on both collected current and height of pulse signal.

As to probe the mentioned effects, acquisitions were performed with the $^{55}$Fe source. Using the MFCs, the percentage of CO₂ in the gas mixture was progressively varied from 17.5% to 35%. Lower values were avoided due to the risk of having too much Argon in the chamber, that would have meant a serious risk of damaging it for the high voltages applied.

For each step, high voltage scans were performed, as well as a prolonged acquisition of at least 36 hours, on which the $T/p$-correction was performed.
4.4.2 Results

The first probed effect is the difference in the detector working point for different gas mixture concentrations. Figure 4.12 reports the trend of the working voltage against the CO\(_2\) percentage, as well as the trend of the high voltage at which the chamber produces the first signals. As expected, more CO\(_2\) in the mixture means a higher working point, and the test shows that this increase follows a linear trend. For both plots a first order polynomial fit was performed, which results give an estimation of a voltage increase of 25 V each 2.5% of CO\(_2\) added in the gas mixture. Extrapolating this trend, it is concluded that for each unit of CO\(_2\) percentage, the supplied voltage needs to be increased of about 10 V to maintain the detector efficiency.

![GEM - CO2 Test - Working Point](image)

**Figure 4.12:** Detector working point (Blue) and high voltage for first registered signal (Red) as a function of the CO\(_2\) percentage in the gas mixture.

The effect of the CO\(_2\) on the detector efficiency can also be seen from the maximum rate capability. As summarized in Figure 4.13a, plotting the maximum rate reached by the GEM (the plateau value of efficiency curves), a decrease can be seen for CO\(_2\) percentages larger than 25%. As already pointed out, the less Argon is present in the mixture, the lower is the probability of primary ionization even when the efficiency is reached, thus at higher voltages.

Another way to compare GEM performance in presence of different CO\(_2\) concentrations is the value of its amplification gain, here realized in term of both detector current and signal pulse. For a fixed voltage \(^1\), the values of measured current and mean peak position of the \(^{55}\)Fe spectrum are collected, and plotted against the CO\(_2\) percentage, as reported in Figure 4.13b. As expected, a higher quantity of CO\(_2\) leads to a reduction in the amplification gain for a given field in the detector. In particular, it is found that both current and peak mean trend as a function of CO\(_2\) percentage have an exponential decrease. This also confirms that they are different means of measuring the same quantity, i.e. the gain.

\(^1\)The chosen fixed voltage is here 4000 V, since it is the working point that was fixed for the detector in operation with the standard gas mixture.
A qualitative overview of the test result can be observed in Figure 4.14, where the $^{55}$Fe spectrum is reported for the different CO$_2$ percentages, acquired at the detector working point. It should here be taken into account that the spectrum counts were normalized before comparing them, since during each acquisition a different number of events is recorded. It is clear from the plot that the more CO$_2$ is present, the more the spectrum is moved to lower ADC values, and it also become less spread.

A more detailed spectrum analysis was carried out to understand the possible differences in the energy distribution of detected photons when changing the mixture composition. On each acquired spectrum two Gaussian fit were performed, one on the main peak and on the escape peak. Relevant parameters were collected, as the mean position of the peak $M$, its width (Gaussian sigma $\sigma$), and the constant term $C$.

The most evident feature of the spectrum series in Figure 4.14 is the progressive decrease of the peak position and the tightening of the distribution. Looking at the
plots in Figure 4.15, it is evident the trend of both peak mean and peak width follows the expectation. The main peak and escape peak show a decreasing trend for their mean position, meaning that the spectrum is more shifted to low values the more CO$_2$ is added to the mixture, but also their width is progressively diminishing, leading to a narrower spectrum. The interesting detail of the reported plots is that in all of them the descendent trend show more or less the same shape: for central values of CO$_2$ a flat region is present, while a more steep trend characterize the extreme values.

Nonetheless, though the spectrum looks to be stretched for low CO$_2$ concentration, this does not mean a loss in the peak resolution. As reported in Figure 4.16, peak resolution was calculated for each tested concentration, following the resolution definition for a Gaussian peak:

$$ Res = \frac{FWHM}{H_0} = \frac{2.34 \cdot \sigma}{M} $$

**Figure 4.15**: A) Peak mean and B) Sigma trend against CO$_2$ percentage for the Main peak (Red) and for the Escape peak (Blue).

**Figure 4.16**: Peak resolution for the Main Peak and Escape Peak as a function of the CO$_2$ percentage.
Even if fluctuations are present, especially the main peak resolution shows values coherent with each other, whose oscillation is limited within the error bars.

A further analysis was done considering the area of the two peaks. For their Gaussian shape, the value of the area can be determined from fit parameters as:

\[
Area = C \cdot \sigma \cdot \sqrt{2\pi}
\]

As the spectrum tightens (with the increase of CO\textsubscript{2} concentration), the area of both main and escape peak decreases, following a trend similar to the one of mean position and sigma. In Figure 4.17, it can be seen that the descending trend presents a slight plateau in the central region, and that it is the same for the two peaks. Having normalized the distributions, the decreasing trend means that the total number of recorded events, ideally calculated as the sum of the two areas, is decreasing with the increase of CO\textsubscript{2}. This further confirms its effect as a quencher gas, that reduces the primary ionization.

Finally, a comparison between the calculated peak areas allowed to probe the difference in the physical phenomenon that give rise to the main peak and the Argon escape peak in the \textsuperscript{55}Fe spectrum. As described in Section 2.3.2, the presence of the escape peak in the spectrum is related to the relaxation of the K-shell (with binding energy of 3.206 keV) and emission of a photo-electron with an energy equal to the transferred energy minus the binding energy before the collision. In this case, the vacancy in the K-shell is filled by an electron from the upper shells, which is accompanied by the emission of the fluorescent photon out of the atom (Figure 4.18).

---

**Figure 4.17:** Peak area trend against CO\textsubscript{2} percentage for Main (Red) and Escape peak (Blue), obtained from the Gaussian fit of the two peaks.

**Figure 4.18:** Graphic representation of the Argon escape electron phenomenon.
The ratio of the peaks area was calculated as \( \frac{\text{Area}_{\text{Main}}}{\text{Area}_{\text{Escape}}} \), and the obtained values are reported in Figure 4.19 as a function of the CO\(_2\) mixture content. The trend of the area ratio is found to be decreasing, meaning that the escape peak is in proportion larger than the main one for increasing quantity of CO\(_2\) in the mixture.

The explanation can be found in the different nature of the events represented by the two peaks. While the escape peak is formed by Argon escape events, the main peak is composed of X-ray absorption events from both Argon and CO\(_2\). The decreased quantity of Argon has influence on both peaks, diminishing the contribution of typically enhanced ionization of noble gases, but the increase of CO\(_2\) has only effect on the main peak. Increasing its quantity, the quencher action is increased and make the X-ray absorption less efficient, leading to a faster decrease of the main peak.

![GEM - CO2 Test - AreaMain/AreaEscape](image)

**Figure 4.19:** Variation of the ratio between the areas of the Main and Escape peak, as a function of the increase of CO\(_2\) percentage

The overall results of this test are found to be coherent with what expected from previous literature [30], in which similar analysis were proposed, but in this case based on simulations realized with Garfield++ and Heed. Secondary electrons distribution in a GEM detector was simulated for \(^{55}\)Fe X-rays, for different compositions of the filling gas mixture, including Ar/CO\(_2\) in different percentages. The results show how for increasing quantity of CO\(_2\), the electron distribution is shifted to lower values and its width is tightened.
4.5 Triple-GEM Performance Adding Small O₂ Concentration in the Ar/CO₂ Gas Mixture

The test reported in this section was realized to probe the performance variations of GEM detectors in presence of different concentrations of O₂ in the standard gas mixture. Indeed O₂ is a common impurity present in the LHC gas systems and further studies on its effects on detector performance are fundamental to understand its impact.

4.5.1 Oxygen Effect in Gaseous Detectors

The addition to inert gas mixtures of even small quantities of electronegative gases can sensibly modify the drift properties of the gas, therefore also the overall detector performance. Oxygen is one of them, due to its high electro-negativity, which means that it has a high tendency to attract electrons to itself in a covalent bond. This can be quantified through its attachment coefficient, which expresses the attachment probability for each electron collision. Its value is essentially zero for all noble gases, then for Argon as well, while it assume finite values for other gases. Carbon Dioxide has an attachment coefficient $h$ of $6.2 \times 10^{-9}$, that is however totally negligible in comparison to the Oxygen one, that is about four orders of magnitude larger ($h = 2.5 \times 10^{-5}$) [31].

Based on these consideration, it is reasonable to expect to see tangible effects of the addition of O₂ to the standard Ar/CO₂ gas mixture in GEM detectors. The high probability of capturing electrons has a direct consequence on the collected pulse height, since it means that the total multiplication factor of primary electrons is reduced. One can then assume that the higher quantity of Oxygen is present in the gas mixture, the lower will be the GEM amplification gain. It has been calculated [31] that the presence of 1% of Air ($h = 2 \times 10^{-5}$) in pure Argon has the effect of removing about 30% of the migrating electrons per cm of drift. Considering then the similar attachment coefficient of Oxygen, the total drift space in GEMs being approximately 0.7 cm and that the standard GEM gas mixture is mainly Argon, one can expect a similar reduction of the total number of electrons collected at the anode.

Nonetheless, it has been observed that despite the gain reduction a small quantity of O₂ can in some occasions be useful to limit aging effects [32], [33]. For example, in the LHCb Outer Tracker, a few percent of O₂ is injected in the standard Ar/CO₂ gas mixture to reduce possible aging effects. In fact, the presence of O₂ leads to the formation of Ozone (O₃) in the avalanche process. Ozone is a strong ultraviolet photons absorber and can effectively quench discharges. Discharge suppression is also the reason why other systems, such as the envelop of ALICE TPC, add O₂ to their gas mixture to avoid damages for the high number of sparks.

4.5.2 Oxygen Concentration Measurements

Starting from the standard GEM gas mixture (Ar/CO₂, 70/30) controlled quantities of O₂ were added to the fresh gas injected into the detector. To achieve this, gas bottles of Argon and CO₂ were used, each of them containing in addition a precise quantity of O₂. Combining these bottles with the pure gases from the supply lines, different concentration values were obtained, as showed in Table 4.1. In this way, a quite large range of O₂ concentrations were tested.
4.5. Triple-GEM Performance Adding Small $O_2$ Concentration in the $Ar/CO_2$ Gas Mixture

<table>
<thead>
<tr>
<th>Main Gas</th>
<th>$O_2$ Bottle</th>
<th>Main Gas %</th>
<th>$O_2$ Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ar$</td>
<td>1%</td>
<td>70</td>
<td>7000 ppm</td>
</tr>
<tr>
<td>$Ar$</td>
<td>500 ppm</td>
<td>70</td>
<td>350 ppm</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>500 ppm</td>
<td>30</td>
<td>150 ppm</td>
</tr>
<tr>
<td>$Ar$</td>
<td>100 ppm</td>
<td>70</td>
<td>70 ppm</td>
</tr>
<tr>
<td>$Ar$</td>
<td>50 ppm</td>
<td>70</td>
<td>35 ppm</td>
</tr>
</tbody>
</table>

**TABLE 4.1:** Nominal $O_2$ concentrations in the standard $Ar/CO_2$ gas mixture used in the test.

Though the $O_2$ concentration in the gas bottles used to create the GEM gas mixture is highly precise (accuracy of ± 1%), the one obtained in the final mixture was checked with both the $O_2$ sensor and a Gas-Chromatograph analysis, being subject to MFCs inaccuracy.

Gas-Chromatograph analysis were performed at first taking the gas directly from the bottles, then from both Mixer and Exhaust analysis points. The continuous flow mode is selected in the GC software in way to avoid the GC pump to take in Air from the environment during the analysis. The detected $O_2$ peak from the bottle mixture was analysed to calculate the concentration in ppm of the component, and it was always found to be in the expected quantity, within the declared accuracy. Considering instead the GEM gas line, doing the same calculation to obtain the $O_2$ concentration, it is seen how the MFCs proportion is compatible with the calculated quantity (70% of the original concentration for $Ar$ bottles and 30% for $CO_2$ bottles). The input flow for this test was indeed kept at 4.5 l/h to avoid non-controlled contamination of the mixture.

4.5.3 Results

The most significant result obtained from this test was observed by studying the changes in the amplification gain of the detector with the different $O_2$ concentrations. GEM current and Peak Mean position from $^{55}Fe$ spectrum were collected for each $O_2$ concentration for some days, and their corrected and averaged values are reported in Figure 4.20. The two measurements show to have approximately the same trend, which is overall decreasing with the increase of $O_2$ quantity. This can be explained taking into account the electronegative properties of $O_2$, as already illustrated in Section 4.5.1. Its presence favours electron attachment, leading to a suppression of the electronic avalanche development. This results in a lower amplification gain, since less electrons from the avalanche are collected at the anode. The more $O_2$ is present in the mixture, the more the multiplication process is limited.

Nonetheless, an interesting feature of the descending trend can be observed: though the total variation between having no $O_2$ in the mixture and the highest concentration (7000 ppm) is of about 60%, the greatest fraction of this variation is found to be between 35 ppm and 350 ppm (about 40%). This could mean that the detector is more sensitive to $O_2$ variations when its concentration is within that range. Therefore, if the GEM detector is in use in a gas system in which the $O_2$ concentration is difficult to be kept at a very stable value, this would mean that instabilities in its performance are likely to appear. Though the range of tested $O_2$ concentrations was quite wide, given the obtained results, it would be opportune to have some more measurements for values between...
Chapter 4. Gas-Related Studies On GEM Performance

Figure 4.20: GEM current and Peak Mean values with different O$_2$ concentrations.

350 ppm and 7000 ppm. In that case, better conclusions could be drawn regarding the range of high sensitivity to O$_2$ variations of the detector. Further measurements will be carried out in the future, with the opportunity of having more concentration values in the high range.

The results from prolonged acquisitions are coherent with the ones obtained with the High Voltage scans, realized at the beginning and at the end of each data acquisition period. Figure 4.21 and 4.22 respectively show the values for the Peak Mean position and GEM current, collected during the various scans. It is evident from the plots that the gain trend is progressively decreasing for increasing values of O$_2$ concentrations. Mean values start to be measurable from about 3800 V, since before that voltage no signal is detected from the GEM. It can be nonetheless noticed how, for high O$_2$ concentrations, a higher voltage is necessary to collect the first spectrum. Current values are instead measurable from the beginning of the scan, and in all cases their trend shows the expected exponential increase.

Figure 4.21: Peak Mean position from the HV Scans with different O$_2$ concentrations.

Another relevant result can be seen from the efficiency curves of the various HV
4.5. Triple-GEM Performance Adding Small O₂ Concentration in the Ar/CO₂ Gas Mixture

Figure 4.22: Detector current registered for the HV Scans with different O₂ concentrations.

Scans. They are reported in Figure 4.23, one for each O₂ concentration value. A first feature that can be individuated is that for higher O₂ concentrations, the curve is more and more shifted to the right, then to higher values of the voltage.

Due to safety limits set on the HV Supply module, it was not possible to go beyond 4050 V, but it is still clear how for the last two curves (350 ppm and 7000 ppm) the efficiency plateau is not completely reached as it is for the others. This means that the O₂ presence not only limits the development of the avalanche, but that it also has an effect (always through electron attachment) on the primary ionization. Higher voltages would be necessary to reach the complete efficiency of the chamber, i.e. to reach its maximum rate capability.

Figure 4.23: Efficiency curve of GEM detector registered during the HV Scans done with different O₂ concentrations.
Chapter 5

Studies on GEM Detectors operated with a Recirculation Gas System

This Chapter illustrates the studies realized on GEM performance when operated in a gas recirculation system and under high irradiation rate. They were realized at the CERN Gamma Irradiation Facility (GIF++). The facility provides irradiation with gamma emission \((^{137}\text{Cs} \text{ source})\), allowing to deliver approximately 1 Gy/h at a distance of 1 meter, a dose rate suitable to mimic the foreseen High Luminosity phase of the LHC. The aim of the measurement campaign at GIF++ is to progress with the validation of the gas recirculation system for GEM detectors.

5.1 R&D Setup at GIF++

It will be here described the experimental set-up at GIF++ that allows to test detectors in a condition that is as similar as possible to their effective operation in LHC experiments. The supporting infrastructure is mainly divided into the gas system, that allows operation under gas recirculation and the use of purifier modules, and the electronic chain that makes possible data acquisition from detectors.

5.1.1 Detectors Layout

Four detectors are installed inside the GIF++ facility with Gas R&D purposes: two Triple-GEMs \(^1\), placed in the downstream area of the bunker (irradiated with the \(^{137}\text{Cs} \text{ source})\), and two SWPCs, placed outside the irradiation field. Figure 5.1 shows the detector positions inside the bunker.

\(^1\)Triple-GEMs will simply be called GEMs in the following.
Chapter 5. Studies on GEM Detectors operated with a Recirculation Gas System

The two GEM detectors, similar to the ones described in the studies of the previous Chapter, are placed at 2 m from the irradiation point. When the downstream irradiator is set at its higher intensity (attenuation 1), the $^{137}$Cs source is capable of providing a dose rate of about 0.5 Gy/h at this distance. Looking at Table 3.3, one can clearly see that this totally corresponds to the requirements for testing gaseous detectors for future application in the High Luminosity phase of the LHC.

GEM detectors are placed inside sealed aluminium boxes. On one side, they act as Faraday cages, while on the other hand they allow to flush the detectors in Nitrogen. In fact, GEM structure is made of a material that is permeable to air, and the presence of N$_2$ allows to avoid to have the detector exposed to Oxygen, so to prevent possible contamination. Nitrogen also reduces the humidity around the set-up, especially the voltage divider, and significantly diminish the probability of sparks in the resistive circuit. Nonetheless, the boxes are structured with dedicated holes to let all the necessary cables to be connected to the detectors. As it can be seen in Figure 5.2, GEMs are placed vertically with respect to the gamma field, in way to be uniformly irradiated.

![Figure 5.2: A view of the GEMs set-up inside GIF++ bunker on the left picture, and the displacement of a GEM inside its box on the right one.](image)

SWPCs are instead both contained in a shielding box, made with Lead panels, around one of the corners in the downstream area (Figure 5.3). They are introduced in the set-up as monitoring tools, and they are excluded from the $^{137}$Cs irradiation.

![Figure 5.3: Layout of the SWPCs set-up inside the Lead box (left) and a SWPC display with its connections (right).](image)
As it will be illustrated in more details in the following, the two GEMs and one SWPC are operated in Closed Loop, with recirculating gas, while the second SWPC is operated in open mode. The first SWPC allows to permanently check the recirculated gas mixture, while with the second the fresh mixture can be monitored. For doing so, two $^{55}$Fe sources are laying at the centre of the aluminium cover of the chambers. As already shown in the previous Chapters, $^{55}$Fe has a spectrum with a well defined peak that permits to monitor detectors performance, mainly in terms of amplification gain stability.

Also the two GEMs are irradiated by $^{55}$Fe sources, placed on the boxes cover. They hosts the structure that permits to place source in front of the GEM surface, with the possibility of sliding it as needed. $^{137}$Cs emission is characterized by a broadly spread spectrum, as it can be seen from the example distribution reported in Figure 5.4. Therefore, it does not allow to continuously monitor GEMs performance through their amplification gain, as the spectrum does not have any characteristic feature that can be measured and followed in time. The presence of $^{55}$Fe sources permits than to have a reference point for the amplification gain, even if its contribution can only be detected when the main source is not operational or significantly attenuated.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectrum_gem_137cs.png}
\caption{Pulse height distribution of GEM signals coming from $^{137}$Cs irradiation.}
\end{figure}

In Table 5.1 the emission and activity of all the sources used in the set-up are summarized. Activities of $^{55}$Fe sources are not given by a specific choice, but by the availability of sources at the time of the test.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Source} & \textbf{Activity} & \textbf{Emission} & \textbf{Lifetime} \\
\hline
$^{137}$Cs (GEM1/2) & 14 TBq & 622 keV $\gamma$ & 30 years \\
\hline
$^{55}$Fe (GEM1) & 800 KBq & 5.9 keV $\gamma$ & 2.7 years \\
\hline
$^{55}$Fe (GEM2) & 31 MBq & 5.9 keV $\gamma$ & 2.7 years \\
\hline
$^{55}$Fe (SWPC1) & 1.5 MBq & 5.9 keV $\gamma$ & 2.7 years \\
\hline
$^{55}$Fe (SWPC1) & 1.5 MBq & 5.9 keV $\gamma$ & 2.7 years \\
\hline
\end{tabular}
\caption{Characteristics of the sources in use for the Gas R&D set-up at GIF++.}
\end{table}
5.1.2 Gas System

The scheme showed in Figure 5.5 illustrates the development of the gas lines that supply the Gas R&D set-up at GIF++.

![Figure 5.5: Drawing of the gas recirculation system at GIF++.

The first step to allow the correct operation of the system is the creation of the proper gas mixture. For this purpose, three Mass Flow Controllers (MFCs, Bronkhorst F-210CM) are respectively connected to the three supply lines of Ar, CO$_2$, and CF$_4$. GEMs are indeed commonly operated with the addition of CF$_4$ in their gas mixture, to improve performances and long-term duration. The system has then already be predisposed to operate the set-up with the gas mixture Ar/CO$_2$/CF$_4$ in proportion 45/15/40, in a second phase that follow the tests described in this work, in which only Ar/CO$_2$ mixture was used. An interlock system, based on the Siemens LOGO! logic unit, has been developed to switch off detectors in case one of the gas supply becomes equal to zero, to avoid a possible damage to the chambers.

The gas mixture prepared by the MFCs is then split into two lines: one to add the fresh gas in the Closed Loop (CL), and the other to flush one of the two SWPCs, that is operated in open mode (from here on, it will be indicated with SWPC1). The latter is normally flushed with about 2 l/h, while the remaining fresh gas (about 3 l/h) is sent to the recirculated line. The two GEMs and the second SWPC (SWPC2) are flushed with recirculated gas, with a flow of 2.5 l/h and 1.5 l/h respectively. Each detector gas flow can be manually set with rotameters, placed in the gas rack, as well as the fresh input. Fundamental is the setting of the quantity of fresh gas sent to the recirculated lines: from that it depends the percentage of recirculated gas in
5.1. R&D Setup at GIF++

the circuit, a key parameter when studying CL systems.

\[
\text{%Recirculated} = 1 - \frac{\text{Fresh}[l/h]}{\text{GEM1}[l/h] + \text{GEM2}[l/h] + \text{SWPC2}[l/h]}
\]

On the return line from the three detectors, key elements for optimal operation are installed: \(O_2\) and \(H_2O\) sensors provide a measurement of the two concentrations in the exhaust gas flow. To allow gas recirculation it is necessary to pump the gas back at the input point of the line. To do so, a pump module is installed inside the gas rack, that can be managed thanks to the logic module Siemens LOGO!. The pump speed can be read and the set points of the pressure values measured along the line can be given as input parameters. The pump will adapt its speed in way to maintain the system stable at those pressures.

Before being re-injected in the loop, the gas is sent to the purifier module. As already pointed out, it is fundamental to keep the gas mixture as clean as possible, removing impurities that can accumulate along the gas path. In this case, the purifier module is made of three different cartridges, as showed in Figure 5.6b.

![FlowView software with Ar/CO\(_2\) 70/30 settings](image1)

![View on the Purifier system inside the gas rack](image2)

**Figure 5.6:** a) FlowView software with Ar/CO\(_2\) 70/30 settings and b) view on the Purifier system inside the gas rack.

The first one is filled with Molecular Sieve, the second with Nickel (Ni) onto a substrate of Aluminium Oxide (Al\(_2\)O\(_3\)), while the third one contains both elements. MolSiev is a zeolite with pores of uniform size (here with 4 Å diameter), and it is capable of absorbing H\(_2\)O vapour molecules from the gas mixture. The Nickel acts instead through a chemical reaction with Oxygen molecules, removing them from the gas.

\[
2Ni(s) + O_2(g) \rightarrow 2NiO_2(g)
\]

A system of valves allows to decide which purifier to use, making each line independent from the others. The system is normally operated with both cartridges open,
Chapter 5. Studies on GEM Detectors operated with a Recirculation Gas System

in way to absorb both $O_2$ and $H_2O$. The cartridge filled with mixed elements in normally excluded from the gas path and kept as a spare. Since cartridges need to be regenerated when they are no longer efficient (i.e. the material is saturated), the spare one can temporarily hold the system without interrupting operation. A filter is placed at the end of the purifier module, to avoid possible contamination of the gas line with the dust released from the cartridges.

5.1.3 Electronic Chain and Data Acquisition System

The complete electronic chain realized to allow set-up operation and data acquisition is schematically illustrated in Figure 5.7.

![Figure 5.7: Drawing of the GIF++ electronic chain and data acquisition system [34].](image)

All four detectors are supplied with High Voltage through a single power supply. A CAEN Power Supply (R1470ET), located outside the irradiation bunker, allows to provide negative voltage to GEM detectors, and positive voltage to SWPCs. Each line has a low pass filter to attenuate high frequency ripples in the transmitted High Voltage. The supply unit can be remotely controlled through IP address connection thanks to its Ethernet port.

A dedicated data acquisition system was designed to allow the characterization of detectors under irradiation at GIF++. As for the simple laboratory set-up described in the previous Chapters, both pulse signal and current are collected for GEMs, while from SWPCs is only acquired the pulse shape.

Custom-made pre-amplifiers allow the first amplification step for all detectors, producing a voltage pulse that is proportional in amplitude to the integrated charge of the input signal. The main amplification stage of the signal is realized with ORTEC 474 Timing Amplifiers, that also allow an optimization of the signal-to-noise ratio. Amplified signals are then collected and digitized with a four-channels CAEN Desktop Digitizer (DT5724), that is connected via USB to the PC outside the bunker.
5.1. R&D Setup at GIF++

Nonetheless, to avoid signal losses along the line, most of the path is covered with Ethernet cables, than converted to USB to allow the connection. The digitizer has a 14 bits resolution, with an acquisition rate of 100 MSample/s. The full input dynamic range of the digitizer is 2.25 $V_{pp}$, converted on a scale 0 - 16000 of ADC channels. For each channel, a trigger threshold can be set, to only accept signals above a selected height, in way to only acquire and save effective source signals.

If the time span of the acquisition is set to 10 $\mu$s (the maximum for the digitizer), it is possible to record $1/10\mu s = 10^5$ time intervals. The 10 $\mu$s interval corresponds then to a record length of 1024 bit. The maximum possible rate that can be read by the digitizer is then calculated as Speed/RecordLength, that gives approximately 100 kHz. Knowing that the expected rate from the $^{137}$Cs is around $6 \cdot 10^6$ Hz, it follows that the system is not capable of measuring it. For this reason, a portable dosimeter has been installed next to the GEM boxes. It is a Mirion RDS-31iTx, based on a Silicon Detector, and it is capable of measuring dose and dose rate of the $^{137}$Cs source up to 200 Gy of cumulative dose. Considering the source activity when it is not attenuated, it then has to be reset about every three weeks. With this device it is possible to monitor the dose rate received by the detectors, estimating then the $\gamma$ rate coming from the source. Variations due to the application of filters or caused by the shielding of any set-up in between GEMs and the source can hence be detected and registered, thanks to the storage memory of the device.

GEM current is recorded with a PicoAmmeter (RDB 9103 Autoranging), connected to the anode read-out strip, through the Panasonic lemo connector properly modified. This device is capable of measuring DC currents from picoamps to milliamps, and it is connected via USB to the PC to read and store collected data. The dedicated software (by RDB Instruments) allows to save in text format the measured current values with the relative timestamp (Figure 5.8a).

![Figure 5.8: a) Picoameters placed close to GEM boxes with Lead shielding and b) flow-meters installed on detectors return lines inside the gas rack.](image)

All the other relevant parameters are collected from the gas system and environmental sensors through a PicoLog ADC-24. Concerning the gas system, the PicoLog receives signals from the $O_2$ and $H_2O$ sensors, as well as from the three pressure sensors (Sensor Techniques piezoelectric) installed before the pump, before and after the purifiers in the closed loop (respectively named PT01, PT02 and PT03, see Figure 5.5). Moreover, four MEMS Flow Sensors (OMRON D6F-P0001A1, 0-0.1 LPM) are installed on the return gas line of each detector, and their output signal is sent to the PicoLog board (Figure 5.8b). In this way, the output flow of each detector is
Chapter 5. Studies on GEM Detectors operated with a Recirculation Gas System

recorded. Regarding instead environmental parameters, the temperature and atmospheric pressure are measured with sensors located inside the gas rack, and recorded with the PicoLog. The unit also has four Output channels, that can be set to send a voltage signal under well-defined conditions, that can be set in the relative software. In this case, two of these channels are connected to the GEM1 and GEM2 channels on the High Voltage supplier, to send kill signals when needed (see next section on Monitoring Software).

5.1.4 Analysis and Monitoring Software

All the measuring and monitoring devices are connected to the PC placed outside the irradiation bunker, in the gas rack area. A set of custom-made software, based on C, allows to manage all the information collected and to properly analyse and store them. A key part of the software is the online monitoring of the systems, that in different ways makes possible to evaluate certain variables and take action in case of problems.

HV Module Monitoring

A first safety measure is contained in the High Voltage module software, supplied by CAEN. While the standard version of the remote control software (GECO 2020) only permits to communicate with the module and set the desired parameters, the company also makes available a C-based application, the CAEN Wrapper, that can be modified accordingly to the user necessity. In this case, two main extra features were implemented. A first control is done on the values of the measured current of GEMs, read by the software from the PicoAmmeter output files: if it overcomes a well-defined value (normally 100 nA without source attenuation) for more than 5 seconds, the software sends a kill signal to the module that instantaneously set to 0 V the line of the concerned detector. In fact, in case of a discharge problem of any nature, this prevents to damage the detector with further electric spark. A second check is done on the Source status (read from the DIP client). In case during normal acquisition the Source is found to be OFF for more than 30 seconds, GEMs voltages are lowered at a safe value (3300 V, lower than the operational value). An email is sent from the software to inform of the voltage decrease, so that it can be manually brought back to the original value after the situation has been checked. The last check is done on the voltage divider current, which upper limit is normally set a couple of μA higher than the value reached at the detectors working point. If the value recorded by the module is found to be higher, the correspondent voltage is instantaneously set to 0 V. Finally, the software was also modified in way to save every minute the values of set and monitored High Voltage, as well as of the voltage divider current.

PicoLog Monitoring and Acquisition

The software linked to the PicoLog unit is supplied in a C-based version that can be modified by the user. Firstly, it is used to monitor the values of GEMs current, sending a kill output signal from the PicoLog board to the HV module in case of over-current. Moreover, it checks every minute the values read from pressure sensors in the gas system, putting off all the HV module channels if pressures are found to be lower than a certain pre-set value. When pressure values are low it in fact means that the system is probably emptying, and it can happen that the gas does not reach any more the detectors, which can be damaged in case they are still supplied with high voltage. Nonetheless, the PicoLog software is also at the basis of the
collection of parameters complementary to the actual data acquisition from detectors. It reads and stores in text format all the values from the sensors connected to its board, that are previously converted from voltage values to the unit of measure of each particular measured quantity. The file contains a timestamp, values from flow meters (in l/h), O\textsubscript{2} and H\textsubscript{2}O concentrations (respectively in ppm and degrees), temperature and atmospheric pressure from the gas rack sensors, GEM currents and an additional temperature value collected from a sensor located inside the bunker.

Pulse height collection and analysis are done combining the desktop digitizer software with ROOT scripts, running one after the other to allows continuous acquisition and automated analysis.

**Digitizer Acquisition**

As already said, the detectors signal is acquired with the Desktop Digitizer located inside the GIF++ bunker. CAEN supplies a C-based software to read and register signals (WaveDump), that can be customized accordingly to the user needs. A set of variables can be set in the Configuration file, such as the Trigger Threshold or the record length. The executable file, once it is launched, records the signal received from each channel for a given interval of time, storing the collected waveform in text format files. The application was also modified in way that within the same session, after each acquisition, it calls automatically the ROOT macros for the data analysis. A waiting time is then set before the following acquisition: one hour during \textsuperscript{137}Cs acquisition, and 20 minutes during \textsuperscript{55}Fe acquisition. The latter is in fact performed only during the weekly access day, when the \textsuperscript{137}Cs source is set to OFF to allow detector maintenance, and given the shorter time of acquisition it is done more frequently.

**ROOT Macros**

The main analysis script is the one that scans each waveform to obtain its peak height, after analysing the background noise that precedes the signal itself. Signal height values are then stored in an histogram, which gives the pulse height distribution of the acquisition in units of ADC channels. The same script also produces a text format file in which all the relevant information are stored: the spectrum characteristics (peak mean, sigma, number of events), GEM currents from the PicoAmmeter, information from High Voltage module, as well as all the environmental and gas collection of parameters complementary to the actual data acquisition from detectors. It reads and stores in text format all the values from the sensors connected to its board, that are previously converted from voltage values to the unit of measure of each particular measured quantity. The file contains a timestamp, values from flow meters (in l/h), O\textsubscript{2} and H\textsubscript{2}O concentrations (respectively in ppm and degrees), temperature and atmospheric pressure from the gas rack sensors, GEM currents and an additional temperature value collected from a sensor located inside the bunker.

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system parameters read from the PicoLog software output. In addition, a second bunker temperature and atmospheric pressure values are read from the DIP Client, together with the attenuation factor of the downstream irradiation. One summary file is done for each of the four detectors.

Further online analysis macros read the summary files, and produce plots with the trend in time of each variable, to allow a fast overview on the state of the ongoing acquisition. To make this task even easier, all the relevant plots are published on a website that allows live monitoring without remotely accessing the GIf++ computer (Figure 5.10, https://service-gas-system-status.web.cern.ch/service-gas-system-status/Default.html).

![Example of part of the online monitoring webpage for the GIf++ set-up of GEM detectors, with acquisition data and environmental parameters.](https://service-gas-system-status.web.cern.ch/service-gas-system-status/Default.html)

**Figure 5.10:** Example of part of the online monitoring webpage for the GIf++ set-up of GEM detectors, with acquisition data and environmental parameters.

A complete scheme of the software and data analysis scripts is illustrated in Figure 5.11. It can be seen that the various software are independent one from the others, so that each of them can be controlled separately and eventually used independently of the standard acquisition.
Figure 5.11: Example of part of the online monitoring web page for the GIF++ set-up of GEM detectors, with acquisition data and environmental parameters.
5.2 Measurement Campaign

The results presented in this chapter come from the continuous monitoring of detectors operation over a time range of about nine months (June 2017 - February 2018). Nonetheless, even if the GIF++ facility is operational all over the year, some periods of measurements interruption were given by the weeks of Test Beam. During these periods, set-ups participating to the Test Beam have priority over the others, and in this case it was decided to switch off the set-up to avoid any problems with the continuous setting ON and OFF the Cesium source. Five weeks were occupied by Test Beams, plus the End-Of-Year shut-down of CERN lead to a total of seven weeks of measurement interruption.

During the period of normal operation, data are acquired from detectors six days per week, from \(^{137}\text{Cs}\) irradiation for the GEMs and from \(^{55}\text{Fe}\) irradiation for SWPCs. While for SWPCs the characteristic shape of \(^{55}\text{Fe}\) spectrum allows to monitor the detectors gain through the peak mean value, the Cesium spectrum recorded for GEMs does not have specific peaks that could be fitted and analysed, but it is shaped as a spread background over a wide energy range. This complies with the necessity of testing gaseous detectors under conditions that are the most similar possible to the actual operation in LHC experiments.

Once a week the source is put OFF for detector maintenance for a whole day, during which the acquisition is switched to \(^{55}\text{Fe}\) for the four chambers. In these days high voltage scans are performed, to keep checked efficiency and correct operation. Operational voltages are 3600 V and 3700 V respectively for GEM1 and GEM2, and 1975 V and 2025 V for SWPC1 and SWPC2. These values were set at the moment of installation of each chamber, with a precise HV scan in which efficiency is evaluated and the working point is set to remain the same for all the operation. For the HV scan procedure see Section 2.3.2.

5.2.1 Attenuated Source

GEMs performance is monitored through filter scans, possibly performed every week. As already illustrated in Section 3.2, the GIF++ irradiator is equipped with a set of filters that allow to obtain different source intensities. Progressively varying the attenuation factor, relevant parameters are recorded.

The effect on the \(^{137}\text{Cs}\) source of attenuation filters has been probed using the RDS-31iTx Dosimeter placed next to GEMs. Dose rate from the source has been recorded during a filter scan and, as it can be seen in Figure 5.12, it varies accordingly to the filter applied. The total accumulated dose is also reported, and it can be seen that it increases with a slope that depends on the source intensity.

Nonetheless, even if it is not detected by the dosimeter, the presence of \(^{55}\text{Fe}\) sources cannot be totally neglected. Looking at Table 5.1, it can be seen that the difference in activity of the two \(^{55}\text{Fe}\) source used to monitor GEM1 and GEM2 are substantially different. This leads to different detected rates by the detectors: while for GEM1 it is around 50 Hz, GEM2 detects around 10 kHz. In the latter case, the activity is high enough to compete with the one of \(^{137}\text{Cs}\) in case attenuation filters are applied. Figure 5.13 shows the spectrum acquired with GEM2 for different attenuation filters, from 1 (source fully open), to 100. The last distribution is instead the one
5.2. Measurement Campaign

Figure 5.12: Example of the RDS-31iTx Dosimeter data acquired during a filter scan.

Figure 5.13: Pulse height distribution collected with GEM2 during a filter scan, in which attenuations 1, 2.2, 4.6, 10, 22, 46 and 100 were progressively selected. The last distribution is instead acquired with the source OFF.
obtained then the $^{137}$Cs source is set to OFF, and only $^{55}$Fe is detected. It is evident from the plots that the higher is the filter, the more the $^{55}$Fe main peak emerges from the $^{137}$Cs broad distribution, until it becomes predominant, with the higher attenuation factors. It should be noticed that though filters higher than 100 are available, the effect on the spectrum is more or less the same for all of them. The presence of backscattered radiation creates in fact a uniform baseline that does not allow to measure the difference between very high attenuations.

This difference in the $^{55}$Fe activities is also noticeable looking at the trends of rate and detector current as a function of the applied attenuation.

Figure 5.14 shows the detected rate of the two GEMs with the increase of the filter in use. A first feature that can be noticed, present for both detectors, is the rate saturation for attenuations lower than 22. As already mentioned, the desktop digitizer that is used to collect the pulse shape from GEMs has an intrinsic limit in rate detection, that correspond to about 26 kHz. The significant difference between the two trends sits however in the minimum detected rate. For high attenuation factors, when the $^{137}$Cs source is almost totally suppressed, the rate detected by GEM1 is very low, around 50 Hz, while the offset of GEM2 rate is much higher, around 15 kHz. This is given by the difference in the activity of the two $^{55}$Fe, that remains as a baseline irradiation only detected when the $^{137}$Cs radiation is sufficiently low.

![Figure 5.14: Measured rate from GEM1 (Left Y axis) and GEM2 (Right Y axis) against the attenuation factor applied (in logarithmic scale).](image)

The same feature can be observed in Figure 5.15, in which the trend of detectors current is reported against the attenuation value. For high filter values, the measured current sits on a plateau, that has nevertheless a different offset for the two GEMs. While for GEM1 it is almost at zero (about -0.02 nA), for GEM2 it has a constant value around -3 nA. Also in this case, the offset is given by the presence of the $^{55}$Fe, whose difference in activity also leads to a difference in the current measured by the detector.
5.2. Measurement Campaign

In both cases, it is observed that the measured values of rate and current follows the expected trend, that can be expressed as a function of the applied filter:

\[
Rate(\text{Att}) = \frac{Rate(A = 1)}{\text{Att}} \quad \text{and} \quad Current(\text{Att}) = \frac{Current(A = 1)}{\text{Att}}
\]

Filter studies proved useful along the measurement campaign in particular when the standard attenuation of the $^{137}$Cs source was changed from 1 to 15. For specific needs of other users at GIF++, the facility was run for some months with attenuated source. Though from an irradiation point of view this could be a disadvantage, in the particular case of GEM2 it turned out to be a way to have both detector current and pulse height spectrum monitored in time. In fact, as it can be seen in Figure 5.13, a factor 15 of attenuation is high enough to make the main peak of the $^{55}$Fe distribution well distinguished over the spread $^{137}$Cs distribution.

5.2.2 Environmental Parameters Effect

As already illustrated in Section 4.2, GEMs performance is significantly influenced by the variation of environmental parameters, in particular atmospheric pressure and temperature. When detectors and gas systems are installed in a controlled condition, such as the laboratory set-up described in the previous Chapter, these variations can be measured and properly corrected, to eliminate the amplification gain dependence on environmental factors.

Nevertheless, the GEM set-up at GIF++ showed to have a further issue regarding the dependence of detectors response on environmental parameters, in particular on the temperature. Indeed the location of the gas distribution racks is not the same in which detectors are actually operated and then the entire system is subject to the influence on the temperature of two distinct environments: the bunker and the gas racks zone.
As it can be clearly seen in Figure 5.16, the temperature inside the bunker is extremely stable, with oscillations smaller than one degree, and it is kept in this way by a heating system always in operation. As a general principle, most of the gaseous detectors tested in the facility have optimum operation when they are kept at a constant temperature around 20 - 21°C. On the other hand, the gas distribution racks are located in an area exposed to temperature variations, mainly given by a day-night regular oscillation and by seasonal changes. Moreover, the building is not always kept closed, for users transport necessities, and this inevitably leads to rapid temperature variations, in particular during winter time when the external temperature can go close to 0°C.

![Temperature Trend](image)

**Figure 5.16**: Temperature in the Gas Rack (Blue) and inside the Bunker (Green).

Though the detectors are located in the bunker area and the gas mixture takes approximately six hours to reach them from the distribution point, it is showed that GEMs response has a well defined dependence on the gas rack temperature rather than on the bunker one. Figure 5.17a and 5.17b respectively show examples of the correlation plot between the detector current measured during a week of acquisition and the bunker or gas rack temperature. Given the very little variation in the bunker temperature, it can be seen that no real correlation in present between the two. Differently, the detector response is found to be sharply influenced by the temperature of the gas coming from the rack zone.

![GEM - Gain VS Temperature Bunker](image)

![GEM - Gain VS Temperature Rack](image)

**Figure 5.17**: GEM gain correlation with a) bunker and b) gas racks temperature.
Moreover, when trying to apply the classical $T/p$ correction, two other factors have to be faced for the specific case of GEMs set-up installed at the GIF++ facility.

A first consideration has to be done concerning the entire set of relevant parameters that are influencing the performance of this complex system. It is well known that, in first place, Oxygen and Water concentration in the gas mixture can have sensitive effects on detector performance, as well as gas flow and system pressure variations. At least once per week detector or system maintenance had to be done, typically during the weekly access to the irradiation bunker, to keep operating in the best possible conditions. This involved mainly the water addition to the bubbler on the Closed Loop line and mechanical interventions to minimize the noise eventually appeared on detectors pulse height acquisition. As previously illustrated, GEMs boxes are flushed with Nitrogen to avoid Oxygen contamination, and opening the boxes to intervene on detectors and connection was one of the main sources of gas system parameters to change and possibly show jumps and oscillations. Given all that, it has been hardly possible to operate the $T/p$ correction on the whole set of data, since the correlation becomes not so well defined when other variables change during the data acquisition. Figure 5.18a shows very well how multiple correlation trends are present in the long-term acquisition, that are then showed separately on Figure 5.18b. The separation was done on a time-basis, that typically coincided with the time of weekly maintenance intervention. It has been then decided to perform the $T/p$ correction separating the whole dataset into weeks, for which a well defined correlation is obtained and the correction is coherently performed.

![GEM - Gain VS ToP](image.png)

**Figure 5.18**: GEM gain correlation plot with Temp/Pressure (ToP), for a) an extended acquisition period and b) for separated time slots.
A second issue was instead closely related to the already mentioned temperature variation of the gas distribution racks. Being the measured temperature significantly influenced by the external one, this seldom leads to very high variations. During these periods a peculiar behaviour of GEMs was noticed, in relation to the correlation of the detector current with temperature. Though it was still evident the expected dependence, i.e. increasing multiplication gain for increased temperature (Figure 5.19), the correlation plot showed an irregular pattern that made impossible to perform the usual exponential correction (Figure 5.20).

![GEM Gain and Rack Temperature Trend](image)

**Figure 5.19:** GEM gain (Black) and Gas Rack Temperature trend (Blue), in one of the periods without well-defined correlation between the two.

A possible explanation of this phenomenon is based on the fact that the gas mixture takes some hours to flow from the rack to detector, and since the temperature variation is very wide in a short amount of time, GEMs react much slower and this fact leads to a variable delay in its oscillations. It can be clearly seen in Figure 5.19 that the detector current follows the temperature oscillation with a sort of time-shift, that is however not constant over the considered period of time. It should be anyhow noticed that these periods were just two/three weeks over the nine months duration of the test, happening to be both during summer, when it is harder to keep the building temperature event partly under control and when then difference in day-night outside temperature is the widest.

![GEM Gain VS ToP](image)

**Figure 5.20:** GEM gain correlation with respect to the ratio Track/Patm, in the same period as the previous plot.
Given the impossibility of performing the $T/p$ correction on the measured current, other means to eliminate this dependence were used in these particular time spans in which the correlation was not well defined. As previously mentioned, the decision of placing the two SWPCs on the same gas system was driven by gas monitoring motivations, that proved to be fundamental in this particular situation. The SWPC that was installed within the Closed Loop of the two GEMs, can in fact be seen as a thermometer of their performance. Being wire chambers in general a lot subject to environmental parameters variations, their reaction to temperature changes was as evident as the one measured for GEMs. This is very well showed in Figure 5.21, that shows the correlation between one of the GEMs and the SWPC2, both in the CL.

The linear dependence could then be fitted and from the obtained fit parameters a correction on GEMs gain was operated. As it can be seen in Figure 5.22, this procedure works well to indirectly eliminate the gas rack temperature and pressure dependencies of GEM gain.

The described procedure was nonetheless only applied in those periods in which the classical $T/p$ correction was not performing well, to be able to still keep the data collected in those days. For all the others acquisition weeks, the ordinary correction was applied.
Chapter 5. Studies on GEM Detectors operated with a Recirculation Gas System

5.3 Recirculation Studies and Long Term Monitoring

As widely illustrated in the previous Chapters, one of the key actions in facing gaseous detector upgrades is to limit the gas mixture consumption, and in particular the aim for GEM detectors is to efficiently operate them with recirculated gas. Nonetheless, closed loop systems may imply some drawbacks, such as the impurities accumulations, whose effects have to be kept under control. Moreover, the operation of GEM detectors in such system has to be validated against possible issues raising from the exposure to high rate irradiation, as it will be present in the future HL-LHC experiments.

The Closed Loop system for the GEMs set-up at GIF++ (presented in Section 5.1.2) was realized with the aim of being the most similar to a real LHC experiment system, with a good grade of complexity coupled with the possibility of irradiation with an high activity source.

5.3.1 Gaseous Detectors Aging

The main concern regarding gaseous detectors in the High Luminosity phase of the LHC is the possible risk of a performance degradation due to aging processes taking place during operation.

Detectors have to be able to tolerate a considerable rate of heavily ionizing particles, that in many cases are the cause of enhanced aging effects. Two of the main issues for GEM detectors, and generally for Micro Pattern Gaseous Detectors, are destructive micro-discharges and the surface deposition of polymers. In the first case, the small area available for charge multiplication leads to a higher energy density in the avalanche plasma, with then an increased probability of hazardous discharges. Polymer deposition is instead caused by the formation of free-radicals\(^2\): gas molecules can break up in collisions with electrons, since it requires a lower energy than the ionization process, with the consequence of having a high concentration of free-radicals in the gas mixture. They will then recombine, forming molecules of other volatile species (conductive or insulating), that can very easily deposit on the electrodes surface. This will lead to the modification of the electric field in the detector, with the effect of reducing it multiplication gain.

\[\text{Figure 5.23: Example of impurities deposit on wire chambers due to aging. [35]}\]

\(^2\)Free-radicals are un-ionized atomic or molecular species with one or more unsatisfied valence bond. They are chemically very active and typically short-lived.
The degree of use of a gaseous detector is indeed normally given by the quantity of electric charge, per unit length or area, with which it was irradiated during its time of operation, the so called accumulated charge. Aging studies are then generally based on the accelerated accumulation of charge, in way to be able to foresee which would be the radiation hardness of the detector in much less time than it takes with normal operation. As already mentioned, GIF++ is capable of delivering a significantly high dose rate, which means that detectors can receive a high quantity of electric charge in a short time span. In particular, the charge that gaseous detectors would accumulate in one year of operation in the HL-LHC experiments can be accumulated within some days of operation.

In the specific case of the GEMs set-up presented in this work, the accumulated charge can be calculated from the measured detector current. In the approximation of considering that value constant for each hour of acquisition, the accumulated charge is obtained as:

\[ q_{Acc} = \frac{2 \cdot I_{GEM} [nA] \cdot Time [s]}{100 [cm^2] \cdot 10^9} \]

where the factor 2 takes into account that the detector current is only measured from half of its surface.

The distance of 2 m from the source allows to accumulate around 1 mC/cm\(^2\) for every week of operation. However, as mentioned in Section 5.2.1, the period in which the \(^{137}\)Cs source was operated with a factor 15 of attenuation is characterized by a lower accumulation of charge (0.2 mC/cm\(^2\) per week). The difference can be very well seen in Figure 5.24, where the trend of the integrated charge for GEM detectors is reported as a function of time. From the end of November 2017 the trend slope shows a visible decrease, since charge started to accumulate much slower than before. Nonetheless, during the nine months of test a total of about 13 mC/cm\(^2\) were accumulated for GEM1 and around 10 mC/cm\(^2\) for GEM2. Flat portions of the plots indicate the periods in which the detectors were not irradiated, during GIF++ test beams and End-Of-Year stop.

![GEM - Accumulated Charge](image-url)

**Figure 5.24:** Progressive accumulation of charge for the two GEM detectors along the nine months of the test.
5.3.2 Purpose of the Test

The validation of GEMs operation in a recirculated gas system is achieved by long-term monitoring of their performance under high rate irradiation.

GEMs performance in a Closed Loop system were in the past validated with laboratory tests [36], in which the detector was irradiated with an $^{55}$Fe source similar to the ones mentioned in this work, different recirculating fractions were tested along some months of data acquisition. As visible in Figure 5.25a, the measured multiplication gain appears to decrease when increasing the recirculation fraction (by keeping constant the HV), but it is fundamental to notice that this corresponds to an increase of accumulated impurities (mainly Oxygen), that are the actual cause of the gain reduction (Figure 5.25b). This means that if those impurities can be kept under control and their concentration can be lowered to very few ppm, detector performance should be maintained constant for any recirculating fraction of the CL.

![Figure 5.25: a) Gain trend for different recirculating fractions and b) Gain and Oxygen concentration comparison with respect to gas recirculating percentage.](image)

The aim of the measurement campaign at GIF++ is then to progress with the system validation with the introduction of an increased irradiation rate, as well as the study of the effects of the purifiers system introduced in the Closed Loop. Data were acquired almost continuously for a nine-months period, during which the recirculating gas fraction has been varied (50%, 70%, 90%), and the purifiers system was alternatively open or bypassed.

5.3.3 Results

The most significant result emerged from the measurement campaign is that no steady decrease was found in the performance of the detectors under study.

A first positive outcome comes from the monitoring of the fresh mixture injected into the closed loop system, that was realized with one of the Single Wire chambers (SWPC1). The measurement of its amplification gain, once corrected for $T/p$ dependence, shows a steady trend around the initial value long the entire data acquisition period (Figure 5.26). The distribution of the gain is very well fit with a Gaussian shape, that is found to be centred on 1.018 and to have a Sigma of 0.0304. The gain oscillation is then of about 3%, which allows to conclude that the injected gas mixture always had a stable composition, validating the action of the MFCs in use to prepare it in the gas system.
The amplification gain of the three detectors in the recirculated gas system is found as well to have a very good stability. Figure 5.27 shows the trend of the normalized and corrected gain of the two GEMs and the Single Wire chamber (SWPC2). The gain trend of SWPC2 comes from the measurement of the peak position of the $^{55}$Fe spectrum, while the one of GEMs was measured through the monitoring of the detector current from $^{137}$Cs. It should be noticed that the normalization was done with respect to the first measured values, and that the normalization factor was adapted to the source attenuation factor when it was changed to 15.

As mentioned in the previous Sections, the SWPC2 is installed in the closed loop system to allow the monitoring of the recirculated gas mixture. The gas conditions of the chambers are then the same of the two GEMs. The gain measurement, coming from the monitoring of the $^{55}$Fe main peak position, is stable with respect to its initial value. Parameters from its distribution are quite similar to the ones of SWPC1, that is a good Gaussian shape with mean value 1.023 and Sigma 0.0323. It can than
be deduced that the gas mixture flowing in the closed loop has been overall of stable composition. Nonetheless, it can be seen from the plot that in the initial part of the test the fluctuation of its amplification gain are slightly more marked than in the following period, even if the $T/p$ correction was performed in the same manner. This can be explained taking into account the high variation in Temperature that was present in the initial months of the campaign (May/August). As illustrated in Section 5.2.2, this leads to a less precise correlation between the measured gain and the environmental parameter, that gives as a consequence a less effective correction.

A similar behaviour was observed also for one of the two GEMs. The gain trend of GEM1 (Black in Figure 5.27), in general quite stable and without particular decrease, shows a wider oscillation in the first months of acquisition, with a variation of nearly the 10% in the very first period. Also in this case, the explanation can be given looking at the quality of the gain correction for environmental parameters. Though it was performed exploiting the trend of SWPC2 when necessary, the result was in some cases not optimal. On the other hand, the performance of GEM2 (Red in Figure 5.27) was instead found to be markedly stable over the entire period of acquisition. The difference can be justified by some diversities between the two detectors, in particular in the grounding of the read-out strips, as in GEM1 some of them were not well grounded due to problems with the connector.

A more detailed analysis of GEMs performance was carried out to understand possible correlation between their response and the changes in the recirculated gas parameters. Figure 5.28 and 5.29 report respectively the normalized amplification gain of GEM1 and GEM2, from the detector current of $^{137}$Cs irradiation. Superposed to this, it is plotted the normalized gain measurement realized with the spectrum of $^{55}$Fe (Black markers), during the days in which the $^{137}$Cs source irradiation was interrupted. Finally, the progressive charge accumulation of each detector is plotted in the background.

![Figure 5.28](image)

**Figure 5.28:** Overview on GEM1 performance, with the trend of normalized and corrected Gain from detector current (coloured markers). In superposition, the trend of amplification gain measured with $^{55}$Fe spectrum (Black markers).

On the right Y axis, the trend of accumulated charge of the detector.

A first conclusion that can be drawn for both detectors is that the gain measurement from $^{55}$Fe irradiation is totally coherent with the one obtained from detector current.
The points (Black markers on both plots) were obtained taking the average of the corrected and normalized trend of the peak mean position of the $^{55}$Fe spectrum acquired during source off days, and they are always superposed with the progressive trend of the detector current.

The different colours of GEMs gain trend refer to the different recirculating gas fraction in the closed loop system. The test was started with 50% recirculation (Blue makers), than changed to 70% (Red markers) and 90% (Green markers). Working with a recirculating fraction of 50% is indeed almost as working in an open system, while the maximum recirculating fraction used in LHC gas system is normally 90%. It should be noticed that in the plot of GEM2 a period is marked in Yellow, around the end of September. In that period, acquisition was performed but the sharp decrease in the amplification gain showed that one of the foil was not properly working any more. This specific case is the one illustrated in Chapter 2 (Section 2.3.3), in which the third foil was damaged by a short-circuit. The damage is therefore not linked to gas system operation. The foil was then substituted and the test continued. Though the portion of charge accumulated on the broken foil was clearly not present on the new one that was installed, it was convened that it only contributed for one third of the total charge, so the overall test reliability was not compromised.

Within the period in which the recirculation was set at 50%, during the first weeks the action of the purifier module was tested (lighter markers). Looking at the $O_2$ and $H_2O$ concentrations measured with the respective sensors, it was seen a quick jump at the moment in which the module was bypassed. The $O_2$ concentration went from 50 ppm to 100 ppm, and the $H_2O$ concentration raised from -12 degrees (around 2000 ppm) to -8 degrees (around 1000 ppm). The purifiers were then contributing to keep the impurities concentrations at a level of the 50% lower than the one present in the closed loop without cleaning agents.

Nonetheless, the operation of the module was still not optimal. For the Nickel one, installed to absorb $O_2$, the effect was expected to be more marked, since in the past
concentrations lower than 10 ppm were obtained. Regarding instead H$_2$O concentration, even if the MolSiev purifier contributes to improve the gas mixture condition, the 1000 ppm concentration that was obtained with the purifiers is at the limit of acceptance for safe operations. If indeed GEMs were operated with the gas mixture Ar/CO$_2$/CF$_4$, the risk would be to damage the detector due to the interaction of CF$_4$ with H$_2$O molecules accumulated in the closed loop. Further actions are then necessary to improve the functioning of the two purifiers, to guarantee safer operation. It is also clear from both plots that having the purifiers open or closed did not sensibly changed the performance of GEMs, since O$_2$ and H$_2$O levels were still reasonably low.

Finally, comparing the response obtained with the three different recirculating fractions, it can be seen that the impact on GEMs response is not particularly marked. Looking at the gain distribution in the three periods, a slight decrease can be seen for both detectors for the increase of the recirculating fraction. This decrease is justified by the increase of accumulated impurities in the closed loop, happening when the fraction of pure gas injected in the system is diminished.
Conclusions

The future Physics Program established for the Large Hadron Collider (LHC), with the upgrade of the accelerator, sets important challenges for all detector systems. Gaseous detectors are part of these systems, widely used for tracking, triggering and particle identification. In particular, the Muon Systems are fundamental for muon identification and momentum measurement. The strategies to guarantee optimal operational conditions include the addition of more detector planes and the upgrade of the present read-out and infrastructure systems.

In parallel to detector upgrades, the quality of gas mixtures used in the Muon Systems is of fundamental importance, since their stability and correct composition are at the basis of safe long-term operation. Some of the gases in use are considered greenhouse gases, or they are significantly expensive. The goal is to reduce operational costs and gas emission, while maintaining high performance levels. The most common solution is to operate the gas systems in recirculation mode. Nonetheless, gas mixture quality can deteriorate in such systems, mainly due to impurities accumulation. The contamination can either come from the gas system or from detectors themselves, and it could significantly affect their performance.

Within this thesis work detailed studies of the performances of Gas Electron Multiplier detectors (GEM) were realized, currently installed in the Muon System of LHCb and, in the future, in the one of CMS. GEM detectors are commonly operated with Ar/CO$_2$ gas mixtures, but they can also be operated with the addition of CF$_4$, to obtain an improved time resolution. The use of CF$_4$, that is considered a greenhouse gas, force the operation in recirculated gas systems, that makes fundamental to guarantee optimal detector operation in such condition.

A detailed characterization of Triple-GEM detector was realized in different gas mixture conditions, to better understand its response to specific changes. Three different types of test were performed: variations in the gas flow and in gas mixture composition, as well as the injection of impurities (O$_2$).

- The study of GEM performance with variations of the gas flow rate showed that even if it seems to have limited effects, detector performance results more stable when gas flow of more than 10 volumes/hour are used. Gas-Chromatograph analyses also showed that low gas flows can favour the accumulation of impurities, such as O2 and H2O;

- An analysis of the consequences of changes in standard mixture concentrations (Ar/CO2) was performed, proving how the increase of the quencher gas (CO$_2$) contributes to the increase of the voltage working point, as well as diminishing its maximum rate capability;

- A test on GEM response under the introduction of different Oxygen concentrations in the standard gas mixture was realized, as O2 is a common impurity
present in the LHC gas systems. Given $O_2$ electronegative properties, it was seen how its presence in the gas mixture can limit the electronic avalanche development, leading to a lower amplification gain.

Studies on GEM performance when operated in a gas recirculation system and under high irradiation rate were realized at the CERN Gamma Irradiation Facility (GIF++). The facility provides irradiation with gamma emission (662 keV photons) from a $^{137}$Cs source, with an activity of about 14 TBq. This allows to deliver approximately 1 Gy/h at a distance of 1 meter, a dose rate suitable to mimic the foreseen High Luminosity phase of the LHC.

Two Triple-GEM detectors are installed inside the GIF++ facility, irradiated with $^{137}$Cs, flushed with an Ar/CO$_2$ gas mixture in a gas recirculated system with a purifier module. The aim is to reproduce a system as close as possible to the ones in LHC experiments. The two GEMs are also irradiated in $^{55}$Fe, to allow the measurement of amplification gain, that would not be doable with $^{137}$Cs, given the lack of characteristic peaks in its spectrum. $^{55}$Fe spectrum and $^{137}$Cs detector current measurements allow a long-term monitoring of the GEM response stability, for a period of nine months. Two wire chambers installed in the same gas system allow the continuous monitoring of recirculated gas and fresh gas mixture.

The aim of the measurement campaign at GIF++ is to progress with the validation of the gas recirculation system for GEM detectors, operated in an high irradiation rate. A total charge of about 13 mC/cm$^2$ and 10 mC/cm$^2$ was accumulated for the two GEMs respectively.

- The monitoring of the fresh mixture injected into the closed loop system, realized with one of the Single Wire chambers showed that the injected gas mixture always had a stable composition;
- It was seen how the Single Wire chamber installed in the closed loop behaves coherently with GEMs detector, providing then a useful instrument to monitor the recirculated gas mixture stability;
- No steady decrease emerged in the performance of the GEM detectors in the closed loop, within the limits of fluctuations caused by environmental factors (about 5%). Different source intensities and recirculating fractions (50%, 70%, 90%) were tested, showing a very good stability in all the conditions. The slight decrease in detectors gain with the increase of gas recirculated fraction is justified by the increase of impurities in the closed loop, and it is not caused by a performance degradation of the detectors;
- Purifiers operation were tested at the beginning of the campaign, and it was seen how they actually contribute to reduce the concentrations of $O_2$ and $H_2O$, which presence could deteriorate detector performance.

The test campaign at GIF++ will continue during the next years, to better understand purifiers action and to extend GEM operation to the gas mixture Ar/CO$_2$/CF$_4$. It will be then of fundamental importance to maintain a pure mixture in way to avoid possible aging effects caused by the interaction of CF$_4$ with accumulated impurities. $H_2O$ molecules can indeed interact with CF$_4$ molecules, creating deposits on GEM electrodes that can distort the electric field worsening detector performance.
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