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Triple-GEM Detectors Operation under Gas Recirculation in High-Rate Radiation Environment

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Abstract

At the CERN LHC experiments, several gaseous detector technologies are operated in gas recirculation mode to lower operational costs and gas emissions. In the next years, Micro Pattern Gaseous Detector (MPGD) technologies will be largely implemented in the LHC experiments, with dedicated gas systems, and they will experience a significantly increased background radiation rate, especially in the HL-LHC phase. It is therefore fundamental to study MPGD operated with LHC gas systems, especially under gas recirculation, to be able to guarantee their safe long-term operation. In this context, the performance of Gas Electron Multiplier (GEM) detectors operated in gas recirculating systems have been studied at the CERN Gamma Irradiation Facility (GIF++), which provides an intense gamma irradiation along with a Muon beam from the SPS accelerator. Triple-GEM detectors performance has been studied in relation to operation stability during long-term high rate irradiation, as well as in terms of Muon detection efficiency with different gamma background rates. Both tests were realized with various gas mixtures and gas system conditions. A complete overview of the results obtained at the GIF++ is presented, showing the successful operation of Triple-GEM detectors during long-term high-rate irradiation and good Muon detection efficiency in LHC HL-like background radiation.

Keywords: MPGD, Triple-GEM, GIF++, HL-LHC, Gas Recirculation, Gas Purity

1. Introduction

Gas Electron Multiplier (GEM) detectors belong to the new generation of Micro Pattern Gaseous Detectors (MPGD) [1], and in the last years they have been considered as tracking devices for Muon Systems in LHC experiments. In particular, Triple-GEM detectors have successfully been part of the LHCb experiment [2] during Run1 and Run2 as well as of TOTEM2 [3], and they are being installed in the CMS Muon System to be operational from Run3 onwards, to cope with the high rate environment of the future phases of the LHC [4].

As for all gaseous detectors, quality and stability of Triple-GEM detectors gas mixture composition is fundamental to guarantee optimal and safe long-term operation. The presence of impurities, that could come from the gas system or from the detector volume itself, can indeed compromise the performance and reliability of the chambers. Common impurities are H₂O, N₂ and O₂, complex molecules from material outgassing, and radiation-induced pollutants when Freon (as CF₄) is present in the gas mixtures.

The problem of impurities accumulation becomes even more significant when gas systems are operated under gas recirculation, necessary to reduce Greenhouse Gases (GHG) emission and detector operational costs [5]. For example,

LHCb GEM system, operated with Ar/CO₂/CF₄ 45/15/40 gas mixture, moved from an open gas system to gas recirculation between Run1 and Run2, with a reduction of 90% in GHG emission. On the other hand, when gas is recirculated, its purity could be compromised as only part of it comes from freshly mixed primary components [6].

As LHC is moving to its high-luminosity (HL) Phase [7], instantaneous luminosity in the experiments will increase of about a factor four with respect to Run1/Run2. Triple-GEM detectors, as well as all other gaseous chambers, will be operated in an environment with significantly increased high-rate radiation, with hit-rates up to 5×10⁴ Hz/cm² and a total ionization dose of 5×10³ Gy by the end of HL-LHC (CMS ME0 region [4]). Therefore, detectors efficiency for Muon detection could be affected by the presence of the intense background. Moreover, operation in such condition could cause detector aging that would compromise long term performance stability.

Triple-GEM detectors performance was therefore studied in a LHC-like high-rate radiation environment, testing long-term operation stability and Muon detection efficiency operating the detector under gas recirculation.

2. Experimental Setup

The test was carried on at the CERN Gamma Irradiation Facility (GIF++), a dedicated test zone for large-area Muon chambers, for performance characterization and aging tests

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[8]. The facility provides irradiation with a source of ^{137}Cs (662 keV photons), which intensity can be varied through the integrated filter-system. The 14 TBq source activity makes it capable of delivering a dose rate that mimics the high radiation rate of the HL-LHC phase (Figure 1). The dose rate and gamma photon rate of the ^{137}Cs source at setup position are reported in Table 1, for different attenuation filters. The maximum irradiation level (ABS 1) corresponds to a background radiation condition about 16 times higher than what is foreseen for CMS ME0 region [4]. Moreover, a Muon beam is available from the SPS accelerator, with a trigger signal provided by the facility thanks to two scintillators placed at the two sides of the irradiation bunker.

ABS Filter	Photon Rate [Hz/cm ²]	Dose Rate [mGy/h]
1	50×10^6	200
10	4.5×10^6	22.5
22	2.5×10^6	12.5
46	1.5×10^6	6.15
100	0.65×10^6	2.8
220	0.3×10^6	1.55
2200	0.03×10^6	0.2

Table 1: Photon rate and dose rate at 1 m distance from the ^{137}Cs source, for different absorption factors [9].

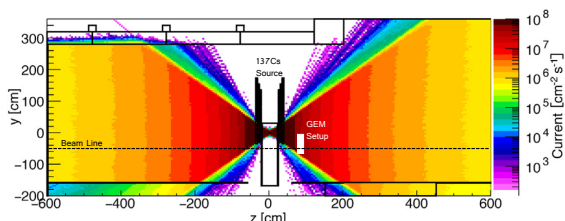


Figure 1: Simulated photon current distribution inside the GIF++ irradiation bunker [10] (colour online).

Two 10×10 cm² Triple-GEM detectors are used for the test, provided by the CERN PCB workshop. The chambers are made with three 50 μm Kapton foils (two-side Copper-clad of 5 μm), with 70 μm diameter holes (140 μm pitch), and a drift foil on top of the stack. The foils are spaced with fiberglass spacers of 3-1-2-1 mm respectively, starting from the drift foil to the readout plane, and stacked inside an epoxy gas box frame. The spacers and frame are made of EM-470 FR4 base material from EMC, and covered with polyurethane NUVOWERN. The frame is fixed to a custom-made readout board with metallic screws [11]. The foils and readout board are cleaned in several steps, including baths with KMnO_4 , H_2SO_4 , Chromic acid and final rinse with deionized water. Voltage is supplied to the GEM foils through a single High Voltage line, connected to a custom-made ceramic voltage divider [12] that allows to supply the required voltage to each foil (between 300 V and 400 V).

Detectors are operated with a dedicated gas system, with a gas flow rate of 10 vol/h (about the same flow rate of LHCb GEM system). The gas system, a small replica of LHC gas systems [13], can be operated either in open mode, i.e. constantly injecting fresh gas mixture, or with recirculating gas, with Ar/CO_2 70/30 or $\text{Ar}/\text{CO}_2/\text{CF}_4$ 45/15/40 gas mixtures. The standard purifier module for H_2O and O_2 removal is included in the system. It is composed by three 1 liter cartridges, two of them used in parallel. One is filled with Molecular Sieve 5 \AA (MS5A), used for H_2O removal (130 g(H_2O)/kg). The other contains the catalyst NiAl_2O_3 , efficient in removing both H_2O and O_2 (15/50 g($\text{H}_2\text{O}/\text{O}_2$)/kg) [14]. The third cartridge contains a mix of the two materials, allowing to keep the system in operation when regeneration is needed for the other two, about once a year. A gas analysis module is also present, with sensors measuring the concentration of H_2O and O_2 at the exhaust of the chambers. Moreover, two Single Wire Chambers are installed as a monitoring system for fresh gas mixture and recirculated gas [15].

Relevant gas parameters (pressure, flow rate) and environmental parameters (temperature, atmospheric pressure) are measured with dedicated sensors, recording their output with an ADC Data Logger (PicoLog ADC-24), to allow a continuous monitoring of the system (Figure 2).

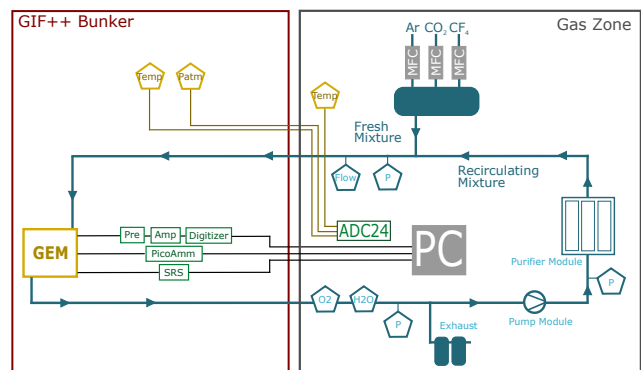


Figure 2: Schematics of the setup at the GIF++. In the red section, the setup located inside the irradiation bunker. In the blue section, the external gas system, sensors and electronics.

3. Data acquisition and Methods

Data acquisition is performed with two different systems, one used during the irradiation campaign and the other specifically installed for the Test Beam period.

3.1. Irradiation campaign

During the irradiation campaign, detector current and signal are collected. Detector current is measured through the standard 10×10 cm² readout board [16]. The board is composed of two sets of 256 parallel metal strips engraved on the two sides of a thin Kapton foil. For each set of 256 strips, two 128-pin connectors allow to sum-up the signal from 128

120 readout strips. The current output of one of these connectors is
 is readout with a PicoAmperometer (RDB Instrument 9103),
 therefore accounting for half of the current collected by one
 of the readout planes. Detector signal is collected instead
 from the bottom of the third GEM foil. Signal is then shaped¹⁶⁵
 125 and amplified by a pre-amplifier and amplifier chain (CAEN
 A1422 Charge Sensitive Preamplifier and ORTEC 474 Timing
 Filter Amplifier), and recorded to be processed offline using
 a multichannel ADC device (CAEN Waveform Desktop
 Digitizer, DT57242).

130 During the weekly access to the GIF++ bunker (¹³⁷Cs
 source off), detector performance is tested with high voltage
 scans irradiating the chambers with ⁵⁵Fe X-rays (activity 35
 MBq). Detector signal is collected and processed to obtain
 135 the pulse height spectrum (Figure 3). The mean value of the
⁵⁵Fe main peak is used as a weekly check for the Triple-GEM
 detector amplification gain along the duration of the campaign.
 Such scans are also used to fix detectors working point,
 identified with the voltage at which the X-ray counting rate
 140 reaches a plateau. Detector current measurement showed that
 at such working point the amplification gain is around 10⁴, the
 typical working gain for Triple-GEM detectors.

Triple-GEM detectors operation stability is monitored via
 145 continuous acquisition of detector current. The measured value
 is corrected offline for temperature and atmospheric pressure
 variations, given the dependence of amplification gain on
 $exp(T/p)$ [17].

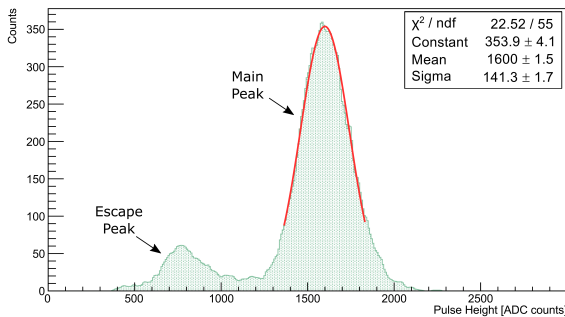


Figure 3: Typical ⁵⁵Fe pulse height spectrum, with the Gaussian fit on the main¹⁸⁰
 peak and the Argon escape peak.

3.2. Test Beam

150 During the Test Beam campaign, detector signal is read¹⁸⁵
 via four APV25 hybrids [18], 128-channel analogue pipeline
 chips designed for the readout of microstrip detectors. Each
 channel of the APV25 is composed of a low noise amplifier,
 an analogue pipeline and a deconvolution readout circuit. The
 155 output signal is transmitted to the Scalable Readout System
 (SRS), a general purpose multi-channel readout system,
 provided by the RD51 collaboration [19]. The SRS allows to¹⁹⁰
 collect and online-process detector signal through a dedicated
 DAQ software. The SRS trigger signal was obtained with the
 160 coincidence of the trigger signal supplied by the facility and

the signal of a 4×4 cm² scintillator placed right in front of the
 detector surface. Figure 4 shows a picture and a sketch of the
 setup configuration. Detector current is monitored connecting
 the PicoAmperometer to the bottom of the third GEM foil, as
 the microstrip connectors were already occupied by the APV25
 chips.

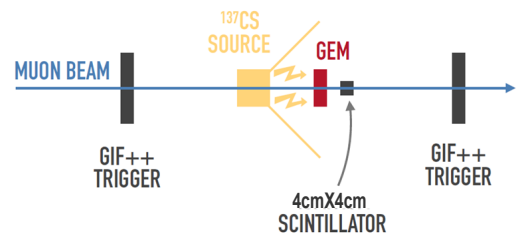
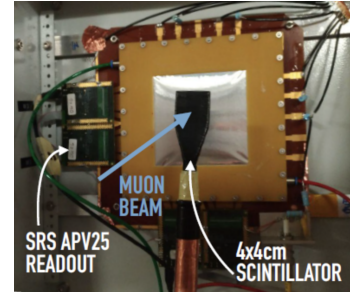


Figure 4: On top, picture of the Triple-GEM detector with the APV25 readout
 and the small scintillator. Below, a schematic of the setup configuration with
 the facility trigger system and position of the ¹³⁷Cs source.

A calibration run is done before every acquisition, to allow
 the optimization of S/N performed by the SRS. Detector
 170 signal is recorded as collected charge distribution in the 25
 ns time window of the acquisition. The maximum deposited
 charge and the time of such maximum are stored in ROOT files
 for offline processing, together with position tags that allow
 to reconstruct signal location on the 256 strips of each of the
 175 readout planes. Muon events are selected as the ones with a
 cluster of consecutive fired strips in the range correspondent
 to the projection of the small scintillator area over the detector
 surface (about 100 strips) and the time of maximum deposited
 charge of such cluster within 5 ns of the trigger time (Figure
 5). Muon detection efficiency is defined as the ratio between
 Muon events and total events triggered by the scintillators
 coincidence. The total charge deposited on the readout plane
 by the passage of a Muon in the detector volume is measured
 for each selected event. As the electron avalanche size is
 proportional to the energy lost by the Muon, the distribution of
 the total deposited charge is a Landau, whose Most Probable
 Value (MPV) gives an estimation of the amplification gain.
 Figure 6 shows an example of the charge distribution.

4. Long-term Irradiation Campaign

Long-term performance of Triple-GEM detectors was tested
 during a two-years campaign, with the aim of validating their
 operation with recirculating gas when exposed to high-rate
 radiation. The campaign is mainly focused on operation with

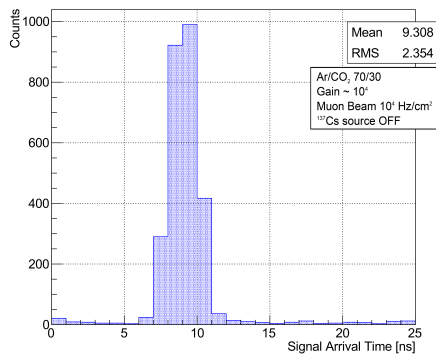


Figure 5: Distribution of the signal arrival time in the 25 ns acquisition window.

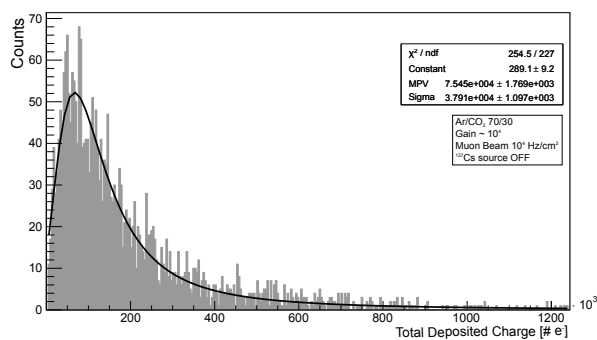


Figure 6: Distribution of the total measured charge deposited at readout plane. A Landau fit is performed to extract the MPV.

Ar/CO₂/CF₄ 45/15/40 gas mixture, with an initial period of operation with Ar/CO₂ 70/30 gas mixture. Each gas mixture was tested first in open mode, then with recirculating gas, progressively increasing the recirculating fraction (70%, 90%, 95%). Throughout the irradiation campaign, the ¹³⁷Cs source was operated with different attenuation filters, allowing to study Triple-GEM detectors behaviour under background irradiation of different intensities. Triple-GEM detectors were operated at a working point yielding to an amplification gain of about 10⁴ at the beginning of the campaign, and the correspondent high voltage supply was kept constant for the entire duration of the test.

During the irradiation campaign the efficiency of the purifier module was tested for H₂O and O₂ removal. H₂O and O₂ concentrations were measured before irradiation with the gas system at 50% gas recirculation, bypassing the purifier module. The level of H₂O intake was measured to be around 2000 ppm, while the O₂ concentration around 200 ppm. Moreover, such concentrations were found to be oscillating depending on the gas flow rate and environmental parameters variation. For the entire duration of the irradiation campaign the purifier module was put back in the gas system (before gas reinjection, Figure 2). Figure 7 shows the impurities concentration during the period of operation with Ar/CO₂/CF₄ gas mixture. Concentrations of H₂O and O₂ are kept around

50 ppm (typical LHC gas system concentrations [20]) during the full period, showing how the gas purity of open mode operation is also maintained with gas recirculation. Measured impurities showed oscillations of 4% and 1% respectively. These variations are acceptable for stable operation, as it was shown that they would affect Triple-GEM detectors amplification gain for less than 0.5% [21]. It was therefore concluded that the purifier module successfully contributes to the removal of accumulated impurities, allowing operation with low and very stable concentrations of H₂O and O₂.

Triple-GEM detectors operation was monitored continuously along the irradiation campaign measuring detector current, proportional to the chamber amplification gain. Figure 8 and Figure 9 show the trend of detector current during the periods of operation Ar/CO₂ and Ar/CO₂/CF₄ gas mixtures respectively, with different gas recirculating fractions.

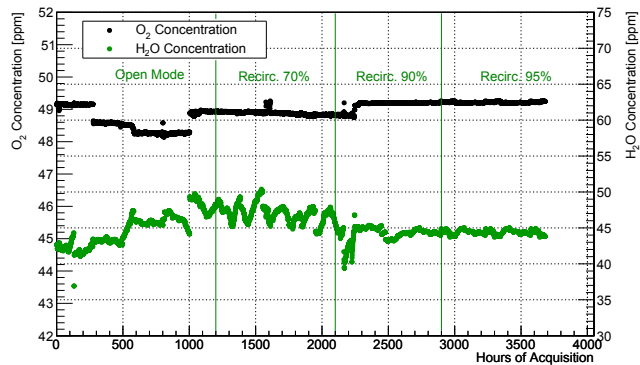


Figure 7: H₂O and O₂ concentrations along the long-term irradiation campaign period with Ar/CO₂/CF₄ gas mixture, for different gas recirculating fractions.

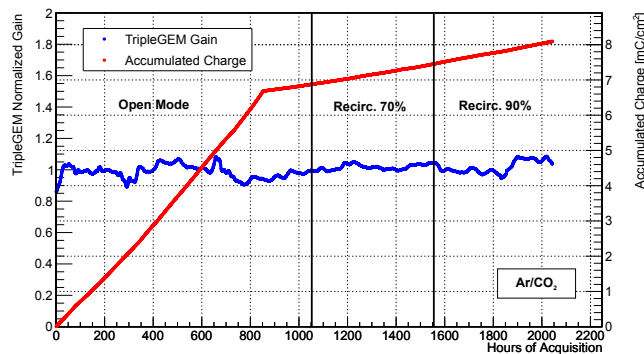


Figure 8: Normalized amplification gain, corrected for T/P_{atm} variations, and charge accumulation during operation in gas recirculation (Ar/CO₂).

The plots also show the progressively accumulated charge due to the exposition to high-rate radiation. The different slope of the curves represent different accumulation rates, given by the different irradiation source intensities. Around 150 mC/cm² were accumulated along the campaign for each detector, of which about 80 mC/cm² during operation with Ar/CO₂/CF₄ gas mixture and gas recirculating fraction higher than 90%. As

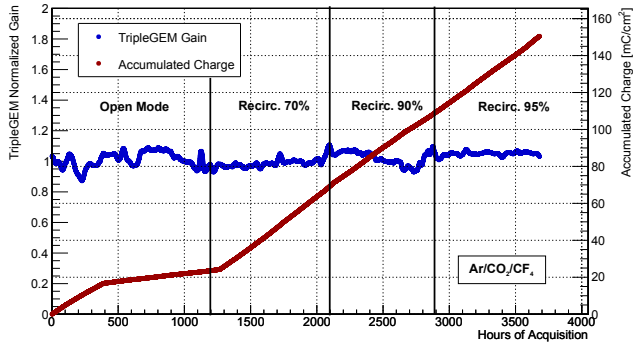


Figure 9: Normalized amplification gain, corrected for T/Patm variations, and charge accumulation during operation in gas recirculation (Ar/CO₂/CF₄).

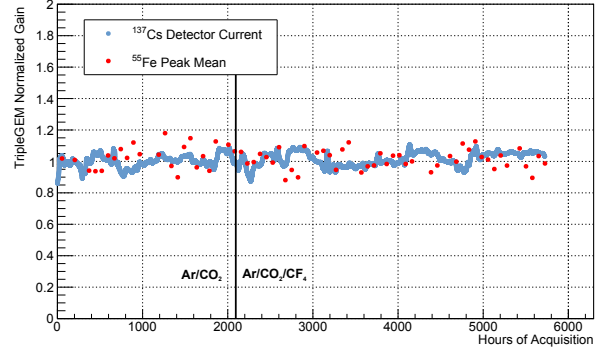


Figure 10: Triple-GEM detector normalized gain trend obtained from ¹³⁷Cs detector current monitoring and from weekly ⁵⁵Fe acquisition, during the entire long-term irradiation campaign.

an example, an accumulated charge of 80 mC/cm² corresponds to 13 times the accumulated charge of 10 years of operation in CMS during the HL-LHC Phase (Ar/CO₂ gas mixture, CMS GE1/1 region [4]).

From the reported trends, it can be seen that Triple-GEMs performance is found to be stable, with average gain oscillations of 5% around its initial value. In some periods larger oscillations are recorded (10%-15%), but they can be traced back to large environmental parameters variation. In particular, given the impossibility of stabilizing environmental temperature in the facility, it showed oscillations up to 10 °C in short time periods (day/night). Such variations do not allow a proper correction of the measured detector current for the $exp(T/p)$ dependence. The overall stability is maintained regardless of the gas recirculating fraction and the irradiation rate, therefore it can be concluded that 10×10 cm² Triple-GEM detectors performance stability is guaranteed during operation in gas recirculating systems with recirculating fractions up to 95%.

Moreover, the weekly performance monitoring realized with ⁵⁵Fe irradiation is found to be aligned with the results of ¹³⁷Cs irradiation. Figure 10 shows the amplification gain trend obtained from ¹³⁷Cs detector current for the entire irradiation campaign, together with the trend of the weekly scans, in which the amplification gain is estimated from the main peak of the ⁵⁵Fe spectrum obtained measuring detector signal.

curves: Muon detection efficiency reaches almost 100% with both gas mixtures. This scan also allowed to define the working point of the detector, taken 100 V after the point at 90% efficiency. The goodness of the efficiency parameter and working point choice is confirmed by the measurement of amplification gain, found to be around 10⁴, which is the typical gain value of Triple-GEMs at full efficiency.

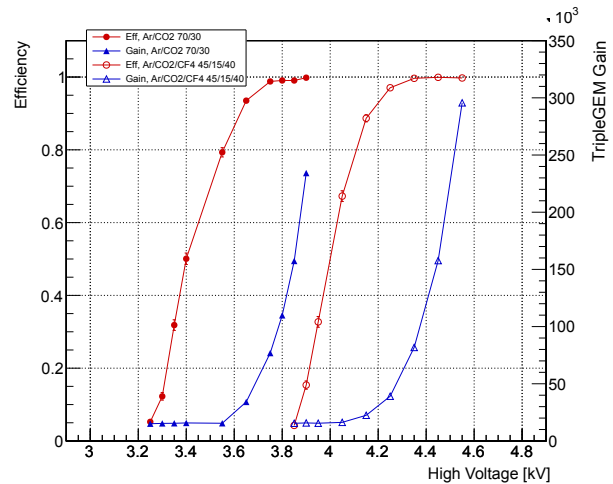


Figure 11: Efficiency curve and amplification gain trend for the two tested gas mixtures, measured with Muon beam only in open mode.

5. Test Beam Campaign

During the Test Beam period, Triple-GEM detectors efficiency to Muon detection was tested with high-voltage scans in different conditions. Concerning the gas system, two gas mixtures were used (Ar/CO₂ 70/30 and Ar/CO₂/CF₄ 45/15/40), both in open mode and with a gas recirculating fraction of 90%. The purifier module was used for the entire campaign, to maintain low and stable the concentration of O₂ and H₂O.

A reference scan was performed with the Muon beam only, in absence of photon irradiation (¹³⁷Cs source off) with the gas system in open mode. Figure 11 shows the efficiency

The same scan with Muon beam only was repeated with the gas system in gas recirculation configuration. In Figure 12 the efficiency curve and amplification gain are reported for the scans with Ar/CO₂/CF₄ 45/15/40 gas mixture, with open gas system and 90% gas recirculation. It can be seen how the curves are almost superposed, and that in both cases the maximum efficiency is reached. The same result was obtained for the Ar/CO₂ 70/30 gas mixture. It can thus be concluded that, as already seen during the long-term irradiation campaign, the presence of the purifier module allows the removal of impurities before the gas mixture is reinjected in the system, making the operation with gas recirculation as good as in open mode.

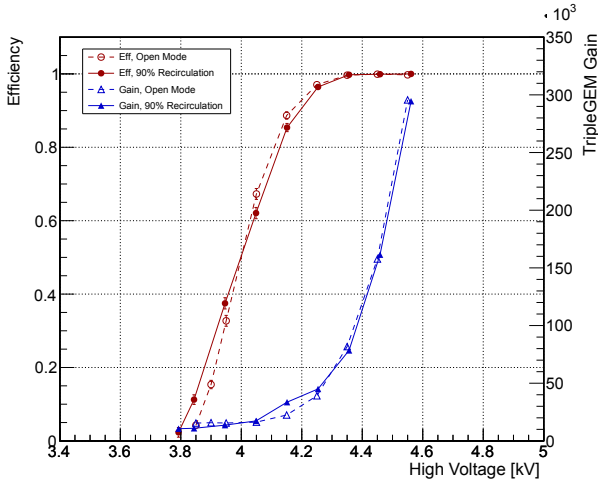


Figure 12: Efficiency curve and amplification gain trend measured with Muon beam only, for the open mode and 90% gas recirculation operation, with Ar/CO₂/CF₄ 45/15/40 gas mixture.

To evaluate the performance of Triple-GEM detectors operated with gas recirculation in presence of high-rate radiation, high-voltage scans were performed with gamma irradiation of increasing intensities. Three different source intensities (ABS 2200, 220, 22) were tested for the Ar/CO₂ mixture (in open and recirculation modes) and for the Ar/CO₂/CF₄ mixture in open mode. The full filter scan was performed for the Ar/CO₂/CF₄ mixture with 90% gas recirculation, being the most relevant gas system configuration (ABS 2200, 220, 100, 46, 22, 10).

The source intensity scan results show how Triple-GEM detectors can reach full efficiency even in presence of significantly high radiation background. The efficiency curves for recirculating gas operation with Ar/CO₂/CF₄ 45/15/40 gas mixture are reported in Figure 13. The reference curve is the one obtained without any gamma background, i.e. with Muon beam only. The other curves are obtained progressively increasing the ¹³⁷Cs radiation rate, from 3×10^4 Hz/cm² (ABS 2200) up to 4.5×10^6 Hz/cm² (ABS 10). As an example, the background rate foreseen for the CMS GE1/1 region during the HL-LHC phase corresponds to a gamma background intensity around ABS 220 (10^5 Hz/cm² [4]), in which the Triple-GEM detector still shows a Muon efficiency higher than 95%.

Figure 14 shows the Triple-GEM detector amplification gain, estimated from the readout deposited charge, measured for different source intensities at the chamber working point. The latter is defined 100 V after the 90% efficiency point of the Muon beam efficiency curve with no background of Figure 13, and corresponds to an amplification gain of about 4×10^4 . It can be seen how the amplification gain remains stable for increasing background rate. This is indeed coherent with what is found in literature, as Triple-GEM detectors are expected to lose in amplification gain for incoming rates higher than 100 MHz/cm² [4]. As the APV25 front-end electronics does not normally suffer of dead-time in the conditions of this study,

the loss in efficiency for radiation rate higher than 10^6 Hz/cm² (Figure 13) could be traced back to an excessive occupancy of the detector. Being the gamma rate much higher than the Muon rate, the probability of detecting a Muon in a given time window (opened by the external trigger) becomes lower and the chamber efficiency is therefore affected.

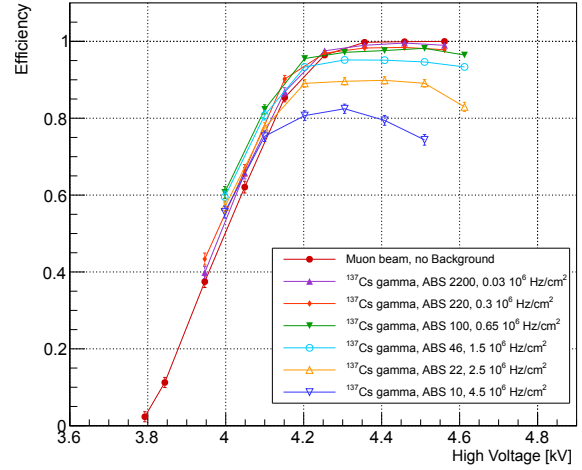


Figure 13: Efficiency curve measured with the Ar/CO₂/CF₄ 45/15/40 gas mixture in 90% gas recirculation, with Muon beam only and in presence of gamma background of different intensities.

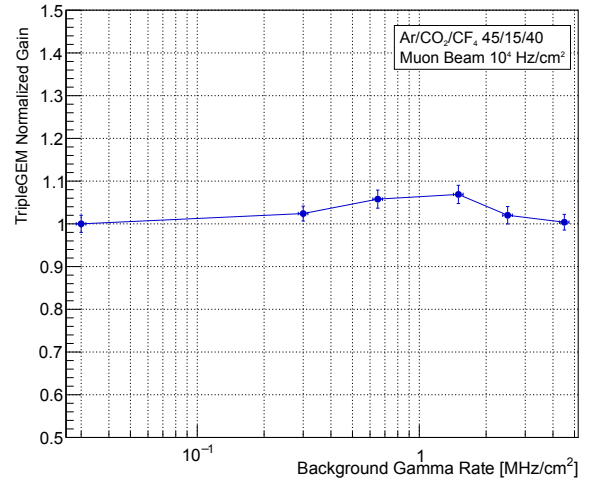


Figure 14: Amplification gain measured with Ar/CO₂/CF₄ 45/15/40 gas mixture in 90% gas recirculation as a function of the background rate.

6. Conclusions

A study on 10×10 cm² Triple-GEM detectors operation was realized to evaluate their performance when operated under gas recirculation and in a high rate (HL-LHC like) radiation environment.

A long-term irradiation campaign was completed exposing Triple-GEM detectors to ¹³⁷Cs gamma emission, accumulating

355 around 80 mC/cm² with detectors operated with recirculating
 gas fraction higher than 90%. Detectors response was found
 to be stable along the entire duration of the test, regardless⁴²⁰
 of the gas recirculating fraction and the background radiation
 rate. Moreover, during the irradiation campaign the action of
 360 the purifier module for removing and stabilizing H₂O and O₂
 concentration in the recirculating gas system was validated.⁴²⁵

Triple-GEM detectors Muon detection efficiency was studied
 during a Test Beam campaign, operating the gas system in open
 365 mode and with gas recirculation (90% recirculating fraction).⁴³⁰
 The obtained results show how the operation of Triple-GEM
 detectors is equivalent in the two different gas system modes,
 thanks to the action of the purifier module. The detector under
 study could reach the maximum efficiency for both Ar/CO₂⁴³⁵
 370 70/30 and Ar/CO₂/CF₄ 45/15/40 gas mixtures with 90% gas
 recirculation.

Furthermore, it was seen how Triple-GEM detectors effi-⁴⁴⁰
 ciency is not compromised by high-rate gamma background.
 375 The maximum efficiency could indeed be reached with all gas
 system configurations with background radiation rate up to 1.5⁴⁴⁵
 × 10⁶ Hz/cm².

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