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Triple-GEM detectors gas mixture studies

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Abstract: Good and safe long-term operation of gaseous detectors are mainly guaranteed by the quality and stability of their gas mixture. Among Micro Pattern Gaseous Detectors (MPGD), Triple Gas Electron Multipliers (Triple-GEMs) have lately been more and more considered as tracking devices for LHC Experiments Muon Systems, as well as for others physics applications. Triple-GEM detectors are commonly operated with Ar/CO_2 or $Ar/CO_2/CF_4$ gas mixtures, and the correct proportion between the different gas mixture components is fundamental for stable detector operation. Moreover, common impurities such as N_2, O_2 and H_2O can affect their performance, mining their response reliability. This study presents a characterization of Triple-GEM detectors performance in relation to their gas mixture composition. Results are reported in terms of experimental measurements as well as computer simulations of the Triple-GEM electron amplification process.

Keywords: Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Gaseous detectors

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1 Introduction

The gas mixture is a key factor influencing gaseous detector performance, and its quality and stability are fundamental for good and safe long-term operation. Among others, Gas Electron Multiplier (GEM) detectors [1] have lately been considered as tracking devices, in particular in the Triple-GEM configuration. For example, they were successfully operated in the LHCb Muon System during the LHC Run 1 and Run 2, and they are currently installed in the CMS Muon System to be operational for the LHC Run 3 [2, 3]. Triple-GEMs are also widely used in applications such as beam diagnostics, medical imaging and nuclear reactors [4].

Triple-GEM detectors can be operated with various gas mixtures, of which the most common ones are Ar/CO_2 70/30 and Ar/CO_2/CF_4 45/15/40. Whether the gas mixture comes from a pre-mixed gas bottle or a mixer module, having the exact content of each component is fundamental to obtain the desired detector performance. Moreover, the gas mixture composition can be affected by the presence of impurities such as H_2O, N_2 and O_2. They could come from the supply gas bottle, the gas system or the detector itself, and their presence could become critical for detectors operated with gas recirculation [5], as impurities would accumulate in the system and potentially compromise detector performance.

The aim of this work is therefore to characterize Triple-GEM detectors response with respect to specific changes in the gas mixture composition, such as components concentrations and presence of impurities, in way to better identify the effect that each of these factors could have on detector performance. Triple-GEMs behavior is characterized in terms of its effective amplification gain, through both experimental measurements and computer simulations.

2 Experimental setup

The experimental characterization was realized using a (10×10) cm^2 Triple-GEM detector, assembled using the standard kit provided by the CERN MPT workshop. The chamber was made with 50 µm

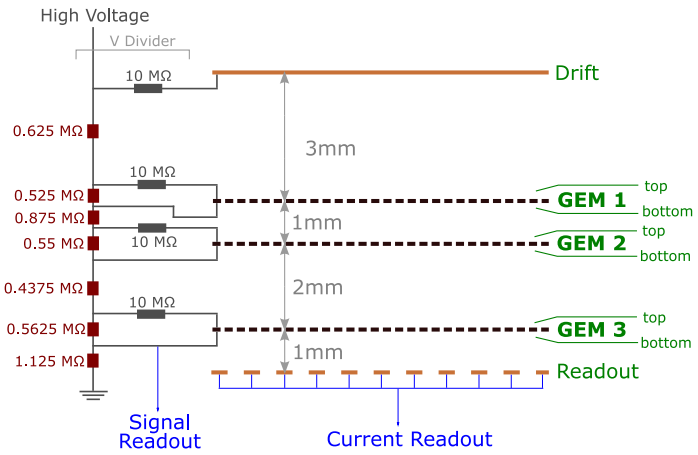

Figure 1. Schematic representation of the Triple-GEM foils stack with the electronics for voltage supply and output readout.

Kapton foils (two-side Copper-clad of 5 µm), with 70 µm diameter holes (140 µm pitch). The GEM foils spacing was realized with fiberglass spacers, with configuration 3-1-2-1 mm, i.e. with the thickness of the drift gap of 3 mm, the transfer gaps of 1 mm and 2 mm, and the induction gap of 1 mm. The foils stack was kept inside an epoxy gas box frame. Voltage was supplied to the GEM foils through a single high voltage line, connected to a custom-made ceramic voltage divider that allowed to supply each foil with the required voltage [6]. The voltage divider acts as a resistors chain, where the current creates a voltage drop on each of the resistors, which values are chosen to deliver the desired voltage difference across each GEM foil. The schematics in figure 1 illustrate the foils layout and their voltage distribution.

The Triple-GEM detector was operated with a dedicated mixer module to prepare the desired gas mixture. Three Mass Flow Controllers (MFC[1]) were connected to the gas supply panel (Ar, CO_2, CF_4) and gas bottles (O_2 and N_2 small concentrations in Ar), and they were controlled by a dedicated software to set the desired flux of each component. A mixing volume was placed after the MFCs, in way to allow the primary component to properly mix before being injected in the chamber. A rotameter and a flow sensor[2] were used to regulate and precisely measure the input gas flow rate. Two sensors were installed on the exhaust line of the Triple-GEM to measure O_2 and H_2O concentrations in the output gas (0 ppm — 25% Oxygen Transmitter[3] and ± 60° Dewpoint Transmitter[4]). Moreover, a Gas Chromatograph[5] was connected at necessity to the exhaust line to obtain precise measurements of the gas mixture composition. Temperature and atmospheric pressure were monitored with dedicated sensors. An ADC Data Logger[6] was used to collect the output signals from all the sensors, allowing to record and continuously monitor relevant parameters. A schematic representation of the experimental setup is reported in figure 2.

[1]Bronkhorst EL-FLOW® Select series, https://www.bronkhorst.com/int/products/gas-flow/el-flow-select/.
[2]OMRON D6F-P MEMS Flow Sensor, https://omronfs.omron.com/en_US/ecb/products/pdf/en-d6f_p.pdf.
[3]GE Sensing O2X1, https://www.bakerhughesds.com/panametrics/oxygen-analyzers.
[4]Vaisala DMT242, https://www.vaisala.com/en/vaisala-drycapr-technology.
[5]Agilent 3000 μGC, https://www.agilent.com/en/product/gas-chromatography/gc-systems.
[6]PicoLog ADC-24, https://www.picotech.com/products/data-logger.

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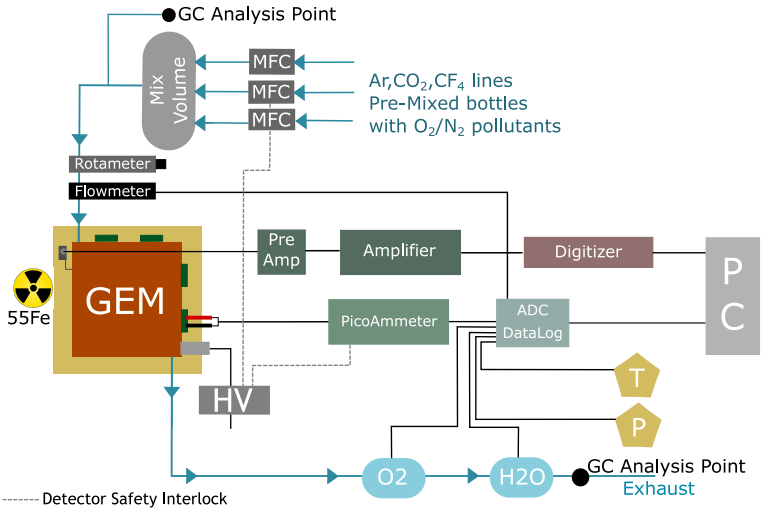

Figure 2. Schematic representation of the experimental setup.

The detector response was studied irradiating the Triple-GEM with an ^{55}Fe source, with an activity of about 15 MBq, through the measurement of the amplification gain, evaluated from both detector current and detector signal. The detector current was measured through the standard (10×10) cm^2 readout board [7], connected to a PicoAmperometer.[7] The measured value was then used to estimate the amplification gain through calculation, taking into account the source activity. The detector signal was instead measured connecting a lemo cable to the bottom of the third GEM foil, where the signal development is already equivalent to the one that can be collected at the readout board. The two different readout positions are shown in figure 1. The signal was collected by a pre-amplifier.[8] Signal amplification and optimization of the signal-to-noise ratio was realized with an amplifier,[9] which output was recorded using a multi-channel ADC device,[10] to be processed offline and obtain a pulse height spectrum. The typical ^{55}Fe spectrum is reported in figure 3. The mean value of the ^{55}Fe main peak was taken as a reference for the amplification gain, together with the one calculated from detector current, as its value in ADC counts is directly proportional to the number of electrons at the readout plane.

The detector performance was characterised with high voltage scans, progressively recording the detector signal, detector current and the chamber counting rate registered by the ADC Desktop Digitizer. The latter was used to reconstruct the efficiency curve, where full efficiency is assumed once the counting rate reaches a plateau. The high voltage working point was defined as 100 V above the 90% efficiency point of the efficiency curve. An example of curves collected in the high voltage scan is reported in figure 3, showing the difference in the operating voltage for the Ar/CO_2 and Ar/CO_2/CF_4 mixture.

[7] 9103 USB Picoammeter, https://rbdinstruments.com/products/files/9103-picoammeter.pdf.
[8] CAEN A1422 Charge Sensitive Preamplifier, https://www.caen.it/products/a1422/.
[9] ORTEC 474 Amplifier, https://www.ortec-online.com/products/electronics/amplifiers/474.
[10] CAEN Waveform Desktop Digitizer DT5724, https://www.caen.it/products/dt5724/.

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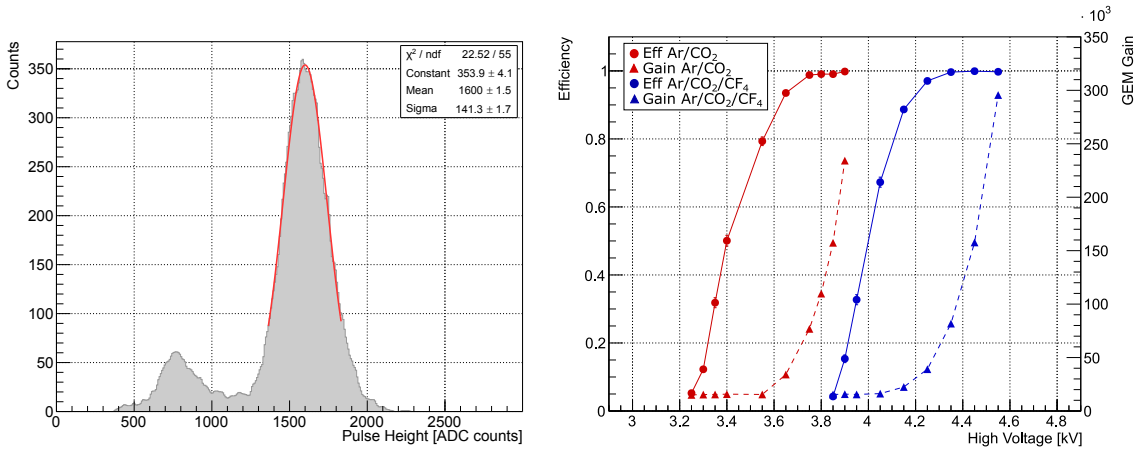

Figure 3. Typical ^{55}Fe spectrum with a Gaussian fit on the main peak (left), and high voltage scans for Ar/CO_2 and $Ar/CO_2/CF_4$ gas mixture in terms of efficiency and amplification gain, estimated respectively from the X-ray counting rate and from the detector current.

3 Simulation tools

The Triple-GEM performance for different gas mixture compositions was analyzed through a computer simulation in parallel to the laboratory tests. The electron avalanche simulation was composed of sections developed in GEANT4 [8] and Garfield++ [9], while ANSYS APDL [10] was used to model the structure of the foils and the electric field. The ANSYS model includes the drawing of the basic element of the detector, i.e. a section with two quarter-of-hole (figure 4), which is repeated at the 1-2-1 mm distance which characterizes the gap configuration of the Triple-GEM prototype used in the experimental setup. The materials of each element are defined (Kapton and Copper) and voltage differences are set on each copper layer, in way to reproduce the voltage distribution across the three GEM foils. The output of the ANSYS model is then used as an input of the Garfield++ application for geometry and electric field.

The GEANT4 physical toolkit is used to simulate the primary ionization process by ^{55}Fe photons, obtaining electrons with defined position and momentum as Garfield++ starting point. Figure 4 shows a schematics of the simulation structure in relation to the process geometry, showing the separation between the GEANT4 section and the Garfield++ one.

The GEANT4 geometry consists of the physical space between the ^{55}Fe source and the first GEM foil. Photons from the ^{55}Fe source encounter the detector box window (10 mm aluminum) and the drift foil, moving then to the gas-filled drift gap where primary electrons are produced. Voltage difference in the drift gap is neglected as the ionization process does not depend on the electric field. The GEANT4 application hence takes care of the photon-electron conversion process, saving the initial characteristics of the electrons right after their creation. The electron properties are stored in a ROOT file (x, y, z coordinates, projections of momentum, energy, time, id of the parent particle and PDGcode), which is given as an input file to the Garfield++ application.

The Garfield++ application takes care of computing the electron avalanche process through the GEM foils. As shown in figure 4, it covers the process from the first GEM foil to the readout. It gives

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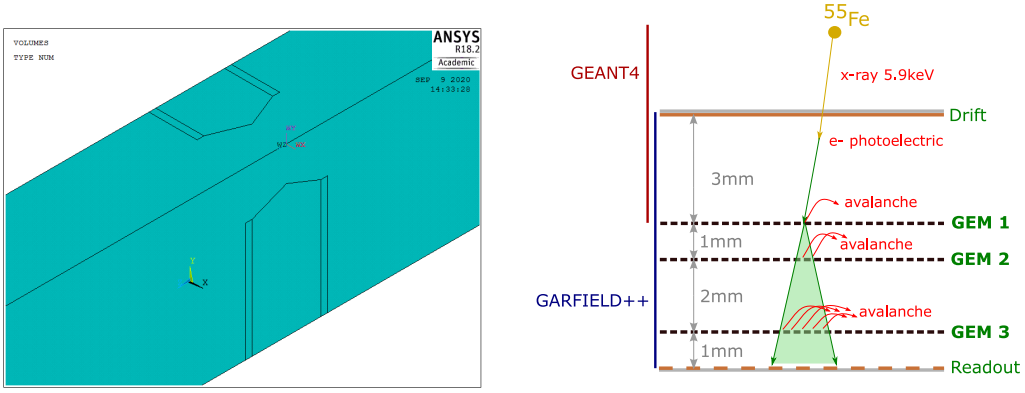

Figure 4. Picture of the GEM foil basic element (left) and schematics of the geometry layout of the simulation.

as output the properties of electrons formed in the avalanche, such as their final position on the readout plane. Figure 5 reports an example of the obtained data for the mixture composition $Ar/CO_2/CF_4$ 45/15/40. The scatter plot on the left shows the x-y distribution of the electrons position at the level of the third GEM foil ($z = -0.2$ cm), clearly showing the round shape of the electron cloud projection on the plane perpendicular to its development direction. It can also be seen that in some areas there is a higher concentration of electrons, and they are shaped as circular crowns, corresponding to the outline of the GEM foil holes. This happens as in these regions, given the shape of the electric field lines in the holes, many electrons are lost at the level of the hole walls. Figure 5 also reports the z-distribution of the electrons final position, i.e. along the direction perpendicular to the GEM foils area. It can be seen that the total number of electrons stopped at the foil position is higher in the second and third foils, as they are reached by a higher number of them thanks to the multiplication happened in the previous stages. This results confirms the known phenomenon of electron loss at the holes walls [1], which also defines the difference between the real amplification gain and the effective one, the latter being the total number of electrons actually reaching the readout board.

The full simulation process was repeated for each gas mixture tested, defining the mixture composition both in GEANT4 and Garfield++, with about 10k events at the Garfield++ application starting point. The effective amplification gain for a given gas mixture was calculated as the mean value of the distribution of the number of electrons reaching the read-out plane for every primary electron released in the drift volume. Such value was used to compare the simulation performance to the experimental results.

4 Variations in gas mixture composition

The stability of gas mixture composition is the primary element that ensures stable and reliable performance of Triple-GEM detectors. Especially when operated with gas mixing modules, the precision of the concentration of each element could be compromised by the malfunctioning of mixer components, as the MFCs that also have an intrinsic limited accuracy that depends on the flow scale and reading value over the full scale. The response of Triple-GEM detectors was therefore studied in relation to variations of the standard gas mixtures composition, to better estimate the effect of possible instabilities in the components concentration.

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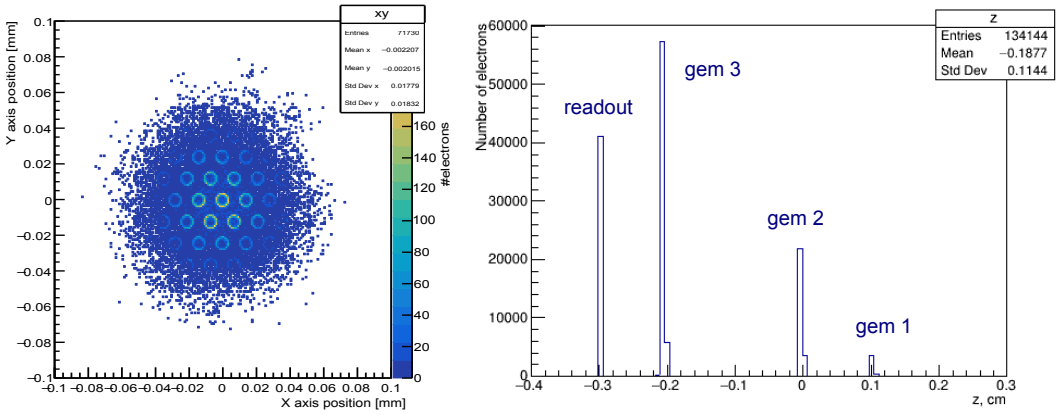

Figure 5. Scatter plot of the x-y plane electron distribution at the level of the third GEM foils (left) and electron final position distribution along the avalanche development direction (right).

The ratio of Ar and CO_2 in the gas mixture was varied, starting from the standard composition 70/30, in steps of 2.5%. The top left plot in figure 6 reports the trend of the Triple-GEM amplification gain for variations of the CO_2 concentration, normalized with respect to the value obtained for the standard mixture. Measurements were obtained keeping the operational voltage at the working point for the Ar/CO_2 70/30 gas mixture (amplification gain around 10^4). It was found that the Triple-GEM gain exponentially decreases for increasing CO_2 concentration (up to 10% per 1% of CO_2) and that an increase of 25 V across the Triple-GEM high voltage chain is necessary to compensate the increase of 1% of CO_2. The increase of CO_2 in the mixture and the contextual decrease of Ar hence contribute to limit the primary ionization and electron avalanche development, yielding to the decrease of effective amplification gain.

The same test was performed with the CF_4-based gas mixture Ar/CO_2/CF_4 45/15/40. Triple-GEM detector response was characterized first keeping the Ar concentration constant at 45%, then keeping the CO_2 concentration constant at 15%, and finally varying the CF_4 concentration while keeping fixed the ratio Ar/CO_2 to 45/15. Figure 6 reports the trends of the Triple-GEM amplification gain as a function of the CF_4 concentration in the gas mixture for the three performed tests, normalized with respect to the value obtained with the standard concentrations 45/15/40. In all cases the amplification gain shows a decrease for increasing CF_4 concentration, but its slope is found to be more significant when the Ar concentration is kept constant. In this case there is about 10% in gain variation per 1% of CF_4, while for constant CO_2 fraction the gain variation is only 3%.

In the plots of figure 6 it is also reported the result of the simulation of the Triple-GEM amplification gain for the different gas mixtures under test. Comparing the simulation to the experimental data it can be concluded that the two are generally coherent with each other. The discrepancy obtained for some of the points could be caused by the exclusion from the simulation process of the possible effects of readout electronics on the detector signal amplitude.

5 Gas mixture pollutants and gas flow rate

Even with precise and stable gas mixture composition, the presence of gas pollutants can influence the detector performance. The most common impurities are N_2, O_2 and H_2O, as they can easily

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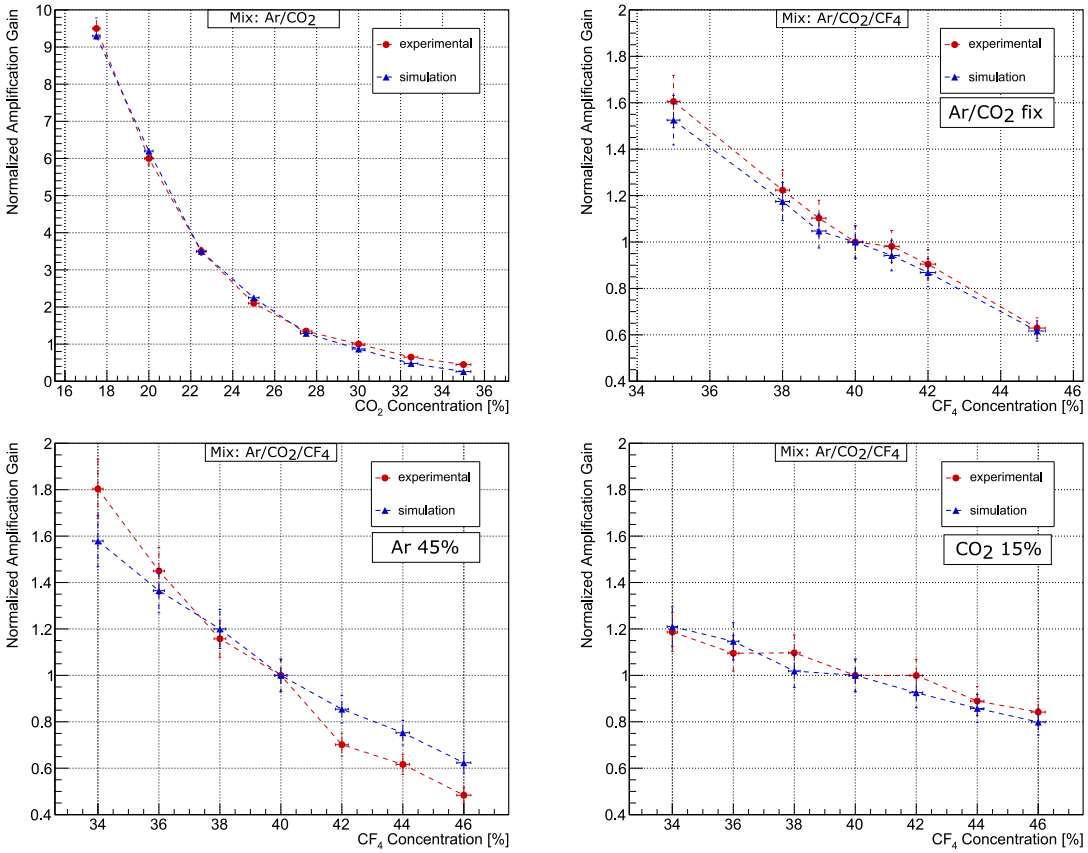

Figure 6. Triple-GEM amplification gain as a function of the CO_2 (top left) and CF_4 concentration in the gas mixture, all values normalized by the gain value measured for operation with the standard mixture composition.

come from air intake in different parts of the system. The impact of N_2 and O_2 was studied injecting a controlled quantity of such impurities in the standard Ar/CO_2 70/30 gas mixture, adjusting the content of Ar and CO_2 consequently, i.e. maintaining the same ratio of the two components. The injection procedure consisted in substituting the Argon supply line with certified pre-mixed bottles containing the required concentration of N_2 or O_2 in Argon. N_2 was injected in concentrations from 100 ppm to 5%, while O_2 was added in concentrations from 10 ppm to 5000 ppm. As N_2 can not be measured with standard gas sensors, Gas-Chromatograph analysis was performed to obtain a precise measurement of the injected quantity, while O_2 was measured with the O2X1 sensor. Figure 7 reports the trend of Triple-GEM amplification gain at working point, flushed with a gas flow rate of 10 vol/hour, as a function of the total measured N_2 concentration (left) and O_2 concentration (right).

The Triple-GEM detector performance is found to be reasonably stable up to N_2 concentration of 1%, while after this value the amplification gas linearly drops down by 80% for N_2 concentration of 5%. N_2 impact on Triple-GEM performance can therefore be considered negligible for low concentrations, but the performance deteriorates significantly for values above 1%. The O_2 presence in the mixture showed instead a decrease of the Triple-GEM gas gain with the increase of O_2 concentration, with a gain drop of 50% in the range 0-1000 ppm. Given the obtained results, it can

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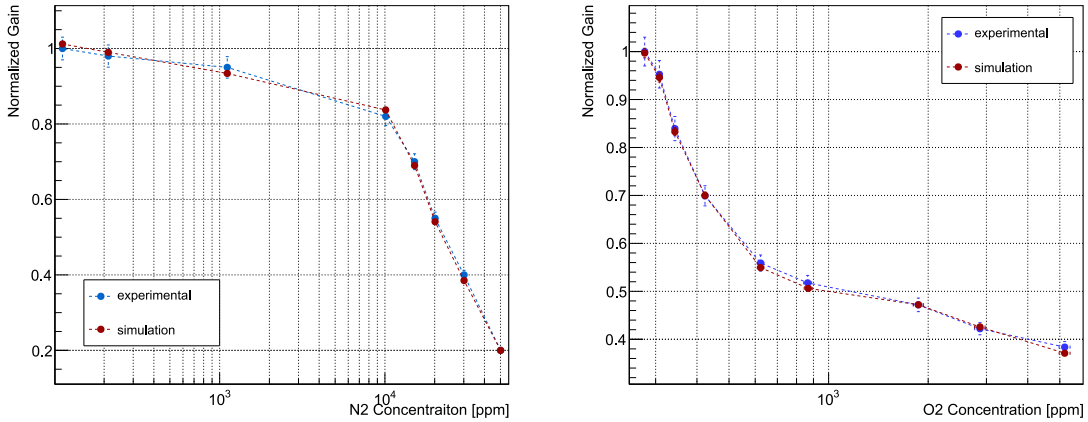

Figure 7. Triple-GEM amplification gain trend as a function of N_2 (left) and O_2 (right) concentration, measured at the detector working point and normalized for the amplification gain obtained without pollutants in the gas mixture.

be concluded that O_2 presence limits the avalanche development, with a consequent reduction of the measured gain. Nonetheless, working at O_2 concentrations higher than 500 ppm could improve performance stability, as the amplification gain is subject to smaller variations with respect to the O_2 oscillations that could occur in the system. As in the mixture composition test reported in the previous paragraph, also in this case the experimental results are found to be coherent with the simulation.

The Triple-GEM operational gas flow rate was varied to evaluate its possible impact on pollutants presence in the chamber volume, which could be adsorbed from the non-airtight and permeable elements of the detector gas box. The operation flow rate of gaseous detectors is normally around 0.5–1 volume/hour, while Triple-GEMs are usually operated with higher flows [2]. In this study, input gas flow rates were tested up to 20 volumes/hour, measuring the O_2, N_2 and H_2O concentrations at the chamber exhaust. Figure 8 shows the Triple-GEM amplification gain and impurities concentration as a function of the input gas flow rate. While the amplification gain increases up to +25% for a flow increase of 20 vol/hour, the impurities content drops significantly for higher flow rates. Their concentrations are reduced by nearly 90% of the initial value with flows higher than 15 vol/hour. Though the quantitative result obtained in this test could depend on the specific detector and pipes material, it can be concluded that operating with relatively high flows, i.e. 10 vol/hour, could allow to reduce impurities concentration.

6 Conclusions

A detailed characterization of Triple-GEM detectors operation was realized with respect to gas mixture composition (Ar/CO_2 and $Ar/CO_2/CF_4$) and the presence of pollutants in the standard Ar/CO_2 70/30 gas mixture. The studies were based on both experimental measurements and GEANT4/Garfield++ simulations.

With variations in the standard gas mixture composition it was seen how changes in the ratio of the Ar/CO_2 70/30 and $Ar/CO_2/CF_4$ 45/15/40 gas mixture as small as 1% in concentration can affect Triple-GEMs working point, with significant variations in the amplification gain. The overall results confirm

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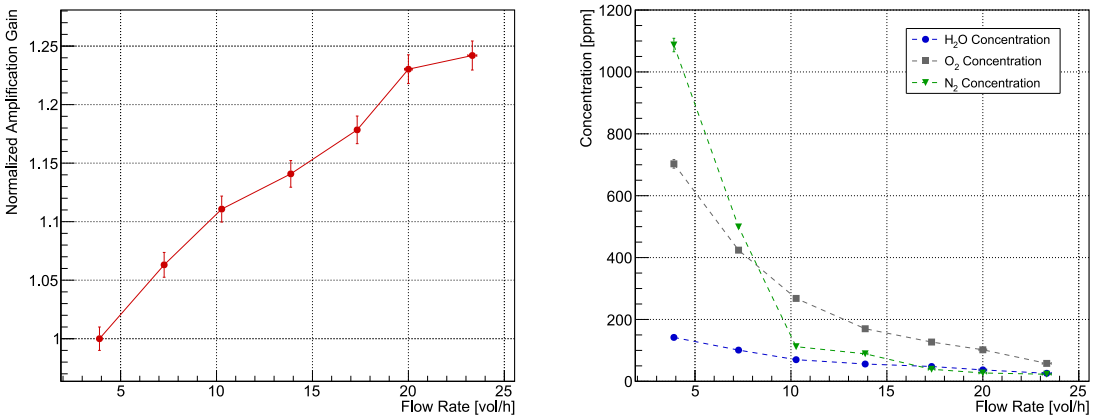

Figure 8. Triple-GEM amplification gain (left graph) and O_2/$N2_2$/H_2O concentrations (right graph) as a function of the input gas flow rate. The amplification gain is measured at the detector working point and normalized for the value obtained with the lowest flow tested.

the importance of high precision and stability in the gas mixture composition, given the non-negligible effects of the variations in the components concentrations on Triple-GEM detectors performance.

Triple-GEM response was also tested with the injection of different O_2 and N_2 concentrations in the Ar/CO_2 gas mixture, as they are common impurities present in gas systems. From the obtained results, it is concluded that N_2 concentrations are safe up to 1%, while a higher content significantly affects the detector performance even for small variations in N_2 concentration. Working with low O_2 concentrations (up to 1000 ppm) could give rise to instabilities in Triple-GEMs performance as it considerably affects its amplification gain and counting rate. Nonetheless, a higher O_2 concentration could guarantee more stable operations as its variations have less impact on detector performance. It was found how Triple-GEMs performance could be more stable when higher input gas flow rates are used (around 10 volumes/hour), minimizing the consequences of the non-airtight frame of the detector box, that could cause accumulation of impurities in the detector gas volume.

Finally, comparing the experimental measurements with the simulation results, it is found that they are in good accordance for all the reported tests. It is hence concluded that the simulation can represent a useful tool to evaluate Triple-GEM detectors performance for variations in the operational gas mixture composition.

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