Effects of gas mixture quality on GEM detectors operation

R Guida¹, B Mandelli¹ and M Corbetta²

¹ CERN, Geneva, Switzerland
² PHAST, Université de Lyon, France
E-mail: mara.corbetta@cern.ch

Abstract. Gas Electron Multiplier (GEM) detectors have been successfully operated in the LHCb experiment and they will be installed in the CMS and ALICE experiments during LHC Long Shutdown 2. As for others LHC gaseous detector systems, gas mixture is individually provided by dedicated Gas Systems. Several studies have been performed in laboratory to characterize GEM performance from the point of view of their use in LHC Gas Systems, where many variables can influence detectors operation. A Triple-GEM prototype was tested with the aim of probing the possible effects of specific changes that could occur in the Gas System, such as variations in gas mixture composition, input gas flow and presence of impurities. A complete overview of the obtained results will be presented. The test confirms the importance of having a stable gas mixture composition, as it influences GEMs working point, with significant variations in the amplification gain. It was also seen how the input gas flow can affect GEMs performance, since it conditions the accumulation of humidity and air. Moreover, it was found that the presence of pollutants such as O₂, N₂ and H₂O, commonly present during operation in the experiments, influences GEMs performance in terms of signal efficiency and amplification gain. While detector gain is weakly affected by the presence of N₂, the presence of even small concentrations of O₂ causes a significant performance decrease in terms of amplification gain.

1. Introduction

Gas mixture is the primary element influencing Gaseous Detector performance, as its quality and stability are fundamental for good and safe long-term operation. Some of the gases used in LHC Experiments have however a high Global Warming Potential (GWP) and CERN is taking steps to reduce their emission and the cost of gas systems [1]. While R&D is ongoing to find efficient ways to recuperate Greenhouse gases (GHG) and eco-friendly alternatives, gas systems can be operated with gas recirculation [2].

Among other detectors, the issue of GHG emission could also concern Gas Electron Multiplier Detectors [3], which gas mixture can indeed contain CF₄, a GHG with GWP equal to 7390. Triple-GEMs were successfully operated in LHCb Muon System, moving from an open gas system to gas recirculation, with a reduction of 90% in GHG emission from LHC Run1 to Run2. Triple-GEMs will also be installed in the CMS Experiment during the upgrades taking place in LS2, to cope with the high rate environment that will be present in the future phases of the LHC [4, 5].
Nevertheless, operation with recirculating gas could have its drawbacks, since gas systems become very complex and this could favour impurities accumulation. Common impurities are H$_2$O, N$_2$ and O$_2$, that could come from detectors or the system itself, and they can be reduced with the use of purifier modules.

Due to the complexity of the large Gas Systems dedicated to LHC experiments, many parameters can play a role in influencing detectors operation (mixture composition, gas flow rate, pressure, impurities accumulation,...)[6]. Triple-GEM response is therefore studied with respect to single and specific changes in the gas mixture, in way to better identify the global effect that each of these factors can have in the context of the whole Gas System.

2. Experimental Setup
A laboratory setup was implemented to modify the composition of the standard Ar/CO$_2$ (70/30) gas mixture and study their impact on the detector behaviour. The chamber used for the test is a 10×10 cm$^2$ Triple-GEM prototype (called GEM in the following), with gaps configuration 3-1-2-1 mm and 70 µm holes (140 µm pitch). A scheme of the experimental setup is reported in Figure 1.

![Figure 1. Schematics of the experimental setup, with gas mixer and DAQ electronics.](image)

A three-components mixer is used to prepare the gas mixture for the test, and a rotameter and a flowmeter are installed after the mixer volume, to allow gas flow regulation and continuous monitoring (output signal of flowmeter is recorded with an ADC Data Logger, PicoLog ADC-24 [7]). At the detector gas exhaust, the values of O$_2$ and H$_2$O concentrations are measured with dedicated sensors. The O$_2$ sensor is a O2X1 Panametrics Oxygen Transmitter ([8]), based on a galvanic fuel cell technology. It can measure O$_2$ concentration from 10 ppm up to 25%, with user-programmable ranges. The H$_2$O sensor is a Vaisala Dewpoint Transmitter (DMT242, [9]), based on the Vaisala DRYCAP® thin film polymer sensor, that covers a dew point measurement range of $-80^\circ/ + 20^\circ$ degrees. Environmental parameters such as temperature and atmospheric pressure are also recorded. A Gas-Chromatograph is connected to the gas line, with an analysis point located after the mixer volume, in way to obtain precise measurements of the gas mixture composition (specifically for O$_2$ and N$_2$ concentrations).

Detector performance is studied irradiating the GEM with a $^{55}$Fe radioactive source (activity of 35 MBq), collecting both detector current and signal. Detector current is measured from a 256×256 strip readout board, through a Panasonic strip reader that groups half of the strips of the readout plane. The reader is then connected to a PicoAmperometer (Keithley Series 6400) to
record current values. Detector signal is instead collected from the bottom of the third gem foil, therefore counting signals form the entire foil surface. Signal is then shaped and amplified by a pre-amplifier (CAEN A1422) and amplifier (ORTEC 474 Timing Filter Amplifier) chain, and then recorded using a digitizer (CAEN Waveform Desktop Digitizer, DT57242). The acquisition is done in threshold-trigger mode, setting the digitizer threshold to be slightly higher than the noise level measured with the detector at 0 V. An acquisition of about $10^4$ events is performed every hour with a ROOT based software, to continuously monitor detector performance. The signal rate is given by the Desktop Digitizer software (CAEN WaveDump), and stored in a text file after each acquisition. Collected waveforms are processed offline, obtaining the pulse height spectrum. In Figure 2 the typical GEM spectrum for $^{55}$Fe is reported, with a Gaussian fit on the main peak. The mean value of this peak is used as a reference to monitor detector’s gain, as well as the measurement of its current, as they are both proportional to the effective amplification gain.

GEM efficiency to X-ray is tested with High Voltage scans, in which main peak position and counting rate are recorded. Counting rate is used to reconstruct the efficiency curve: GEM is considered to be efficient when the plateau due to maximum rate is reached (Figure 3).

![Figure 2. $^{55}$Fe spectrum, with the main peak and the Argon escape peak.](image)

![Figure 3. GEM counting rate and peak position as a function of the High Voltage applied (higher axis) and of the average Voltage on single foils (lower axis).](image)

### 3. GEM performance with different Ar/CO$_2$ ratios

The stability of gas mixture composition is a key element for the long-term operation and stability of gaseous detectors. It is therefore studied the influence of variations in the ratio of Ar and CO$_2$ in the standard mixture, conventionally used for GEMs in the ratio 70/30. As CO$_2$ is a quencher gas, it has the tendency to absorb the photons from excitation produced in the avalanche, and the more it is present in the mixture the more the electron avalanche development is limited.

The test showed how increasing the CO$_2$ concentration leads to a higher Working Point, with +25 V for 1% of CO$_2$ increase. It was also studied how the measured rate becomes lower with more CO$_2$ in the gas mixture. Moreover, detector gain presents a non-linear decrease with the increase CO$_2$ concentration, more significant for CO$_2$ concentration below 30% (Figure 4 and 5). Indeed, the less Ar is present in the mixture, the lower is the probability of primary ionization, even when the efficiency is reached, leading to lower amplification gain. The obtained results are confirming the importance of stable gas mixture composition for GEMs operation.
Figure 4. GEM gain at fixed HV for increasing percentage of CO\textsubscript{2}. Values are normalized with respect to the reference value with 30\% of CO\textsubscript{2}.

4. GEM performance with different gas flow rates

Another parameter that can influence detector performance is the input gas flow rate. The operation flow of gaseous detectors is normally around 0.5-1 volume/hour, while GEMs are sometimes operated with higher flows [4]. In this study input rates were tested up to 20 volumes/hour, to determine whether there is an optimal operation flow.

The most significant result is that GEM gain considerably increases with higher gas flows, up to the 20\% (Figure 6). It was found that the loss in performance for low flows is caused by the presence of impurities (Air and H\textsubscript{2}O), which is due to their absorption from the detector volume box. The impurities accumulation decreases exponentially with the increase of the gas flow sent through the chamber. It is thus concluded that high flows (from 10 volumes/hour) could allow to reduce impurities concentration thus work with an higher gain for the same applied voltage.

Figure 5. GEM measured rate at fixed HV for increasing percentage of CO\textsubscript{2}. A saturation plateau is seen for fractions lower than 25\%.

Figure 6. GEM gain at fixed HV and mixture impurities concentration (H\textsubscript{2}O and O\textsubscript{2}), with respect to the increase of input gas flow. Gain is normalized to the value at lowest flow rate.
5. GEM performance in presence of O\textsubscript{2} as pollutant

As O\textsubscript{2} is a common impurity in LHC Gas Systems, it is fundamental to understand what is its impact on GEMs performance. O\textsubscript{2} has a high electron attachment coefficient, so it has the tendency to attract electrons produced in the avalanche. Controlled quantities of O\textsubscript{2} were added to the standard mixture, from 10 ppm to 5000 ppm.

The effect of the impurity was seen on both rate and gain measurements. Detector rate showed a decrease of 20% with respect to its saturation value for O\textsubscript{2} concentration higher than 50 ppm (Figure 7). The gain drop reaches instead the 60%, with most of variation in the range 0-500 ppm (Figure 8). It is then deduced that O\textsubscript{2} presence limits both primary ionization and avalanche development. Nonetheless, working at O\textsubscript{2} concentrations higher than 500 ppm could improve performance stability, as the amplification gain is subject to smaller variations with respect to the O\textsubscript{2} oscillations that could occur in the system.

![Figure 7. GEM measured rate at fixed HV as a function of the O\textsubscript{2} concentration in Ar/CO\textsubscript{2} (70/30) gas mixture.](image1)

![Figure 8. GEM normalized gain at fixed HV as a function of the O\textsubscript{2} concentration in Ar/CO\textsubscript{2} (70/30) gas mixture.](image2)

6. GEM performance in presence of N\textsubscript{2} as pollutant

As a further step, the standard mixture has been polluted with variable concentrations of N\textsubscript{2}, injected in the mixer through the third MFC. The N\textsubscript{2} concentration was varied from 100 ppm to 5%, adjusting the content of Ar and CO\textsubscript{2} consequently, i.e. maintaining the same ratio of the two components. As N\textsubscript{2} can not be measured with standard gas sensors, Gas-Chromatograph analysis were performed to obtain a more precise measurement of the injected quantity.

As it can be seen in the plot reported in Figure 9, GEM gain results to be quite stable up to N\textsubscript{2} concentration of 1%. After this value, an almost linear decrease in the amplification gain is found, with a loss up to the 80% for N\textsubscript{2} concentration of 5%. N\textsubscript{2} impact on GEMs performance can therefore be considered negligible for low concentration, but values higher than 1% could give rise to variations of the amplification gain. No specific effect was instead seen on the detector measured rate. It is thus concluded that N\textsubscript{2} acts as inert gas in the mixture, and the observed effects are due to the fact that its presence in significant concentration lowers the concentration of the other components. In particular, if less Ar is present in the mixture,
there will be less primary ionization thus a lower amplification gain, that could nonetheless be compensated raising the High Voltage applied to the chamber.

![GEM - N₂ Test - Detector Gain](image)

**Figure 9.** GEM normalized gain for fixed HV as a function of the N₂ concentration in standard gas mixture.

### 7. Conclusions

A detailed characterization of Triple-GEM detector was realized in different gas mixture conditions, to better understand its response to specific changes. Different types of test were performed: variations in the gas flow and in gas mixture composition, as well as the controlled injection of impurities (O₂, N₂).

It was studied how GEMs performance could be more stable if higher input gas flow rates are used (around 10 volumes/hour), minimizing the consequences of the non-airtight frame of the detector box, that causes accumulation of impurities in the detector gas volume. Moreover, changes in the ratio of Ar and CO₂ as small as 1% in concentration of the two components can affect GEMs working point, proving how the increase of the quencher gas (CO₂) contributes to the increase of the needed applied voltage, as well as diminishing the measured rate and amplification gain.

A test on GEM response with the introduction of different O₂ and N₂ concentrations in the standard gas mixture was realized, as they are common impurities present in the LHC gas systems. Working with low O₂ concentrations (up to 500 ppm) could give rise to instabilities in GEMs performance as it considerably affects its amplification gain and measured rate. Higher concentrations guarantee instead more reliable operations as O₂ variations are less incisive on detectors performance. On the other hand, while N₂ concentrations in the standard mixture are safe up to 1%, a higher content significantly affects performance stability even for small variations in N₂ concentration.

### References

[1] Capeans M, Guida R and Mandelli B 2016 Strategies for reducing the environmental impact of gaseous detector operation at the CERN LHC experiments *Nucl. Instrum. Methods A* **845** 253-256 0168-9002/2016
[2] Guida R and Mandelli B 2017 A portable gas recirculation unit for gaseous detectors *Journal of Instrumentation* **12** T10002
[3] Sauli F 2015 The gas electron multiplier (GEM): operating principles and applications Nucl. Instrum. Methods A 805 2-24 0168-9002

[4] LHCb Collaboration 2005 Second addendum to the Muon System Technical Design Report Technical Design Report LHCb CERN-LHCC-2015-012/LHCb-TDR-4-Add2

[5] CMS Collaboration 2018 The Phase-2 Upgrade of the CMS Muon Detectors Technical Design Report CMS CERN-LHCC-2017-012/CMS-TDR-016

[6] Guida R, Capeans M, Hahn F, Haider S and Mandelli B 2013 The gas systems for the LHC experiments 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference 1-7 6829415

[7] PicoLog-ADC24 Data Logger, 
https://www.picotech.com/data-logger/adc-20-adc-24/adc-20-and-adc-24-manuals

[8] O2X1 Panametrics Oxygen Transmitter, 
https://www.instrumart.com/products/22593/ge-panametrics-o2x1-oxygen-transmitter

[9] Vaisala Dewpoint Transmitter DMT242, 
https://my.vaisala.net/en/lifescience/products/transmitters/Pages/DMT242.aspx