Advanced Aging study on Triple-GEM Detectors

F. Fallavollita$^1$, D. Fiorina$^2$ and J.A. Merlin$^3$

$^1$CERN, Espl. des Particules 1, 1211 Meyrin, Switzerland
$^2$Università & INFN di Pavia, via Agostino Bassi 6, Pavia 27100, Italy
$^3$INFN, Sezione di Bari, via Edoardo Orabona 4, Bari 70125, Italy

E-mail: davide.fiorina01@universitadipavia.it
francesco.fallavollita@cern.ch
jeremie.alexandre.merlin@cern.ch

Abstract. We present here a new study of the aging of Triple-GEM detectors in contaminated environment. The goal of this experiment is to evaluate the influence of the ionization power of particles on the longevity of the gaseous detectors and therefore determine the best configurations required to reliably reproduce the classical aging phenomena in laboratory. A 100 cm$^2$ triple-GEM detector operating in Ar/CO$_2$ (70/30\%) was irradiated simultaneously with low energy X-rays and 5.5 MeV alpha particles. Hydrocarbons and Si-based molecules were added to the gas mixture in order to accelerate the aging and simulating many years of slow gas pollution. We measured the evolution of the detector performance in two irradiated zones and we performed a systematic chemical analysis of the GEM foils to measure the polymer concentration and thus the potential aging effects. The detector collected a total charge of 165 mC/cm$^2$ in the two irradiated sectors with no performance loss. Chemical analysis revealed a greater Si-based polymers concentration in the region irradiated with alpha particles. This is due to their higher ionization power, with respect to low energy X-rays, which generate denser electron avalanches and, thus, a higher polymerization rate. Further studies have to be performed in order to validate this result, at different experimental conditions and with different detector technologies.

1. Introduction

Future experiments at colliders will set new challenges for particle detector technologies. The trend in experimental particle physics is to increase machines energy and luminosity. High Luminosity LHC (HL-LHC): the foreseen upgrade for the Large Hadron Collider at CERN [1] will provide a background dose to the CMS detector 10 times higher with respect to today LHC. For future colliders such as High-Energy LHC and Future Circular Collider the foreseen dose will be respectively 42 and 208 times more than today LHC [2].

In the case of HL-LHC, to cope with the foreseen high rate environment and maintain the actual detector performances, Triple-GEM detectors [3] will be installed in the innermost region of the forward muon spectrometer of the CMS experiment (ME0 project) [4]. The detailed knowledge of the detector performance in the presence of such a high background is crucial for an optimized design and efficient operation after the HL-LHC upgrade and for future experiments which will exploit gaseous detectors. For this reason, aging tests on final size triple-GEM detector were performed [5], [6]. Nevertheless new type of aging studies have to be invented and performed in order to ensure the radiation hardness of GEM detectors in environments rich of densely ionizing particles since longevity issues can emerge in these extreme conditions.
Understanding these issues is a priority for the future CMS GEM-based upgrade and in general for all the future experiments which will employ gaseous detectors in high rate and high ionizing environments.

2. Aging processes in Gaseous Detectors

Aging is one of the most critical limitations of the use of gaseous detectors in strong radiation environments. It includes all the processes that lead to a significant and permanent degradation of the performances of a gaseous detector: gain drop and non-uniformity, dark current, discharge, etc. The main causes of the deterioration of the detector’s performance are the chemical processes that occur largely in the hot plasma within the electron multiplication avalanches. The fragments of gas molecules produced inside the avalanches can form polymers that grow on anodic wires, cathode surfaces and anode-cathode insulating elements (see figures ?? and 1). Since the aging phenomena depends on a large number of parameters and is based on different possible chemical mechanisms, it is not possible to build reliable models or simulation tools capable of predicting the long-term behavior of gaseous detectors. Most contaminants usually come from the outgassing of some materials that release some of their molecules into the gas, triggering polymerization and further degrading detector performance. When a high percentage of highly ionizing particles is involved, aging processes could be dramatically worsened over the life of the detector. A higher density of deposited energy can lead to the formation of different polymers at different speeds i.e. they can trigger different chemical reactions and modify their kinematics.

Figure 1. General view of the silicon deposits covering the irradiated zone of the anode wire aged in the Ar/CO\textsubscript{2} (70/30) mixture [8]

3. Aging studies state of art and new ideas

Aging studies are usually performed in the framework of a certain experiment for ensuring the long term stability of its gaseous detectors during the data acquisition period. Standard aging studies commonly require a detector in its final version, ready to be mounted into the experiment, which will integrate an amount of charge similar to the one expected in the lifetime of the experiment; all of that in a clean gas environment. Usually the detectors are irradiated with photons (X-rays or \(\gamma\)-rays) because of the simplicity to produce and contain them. In order to perform this test in a reasonable time, the hit rate and/or the detector gain is increased with respect to the one foreseen in the experiment [9], [10], [11]. These methodologies may not reproduce the exact particle environment in the experiment preventing certain aging processes.
to happen. The understanding of the limits of the standard aging tests, if any, will be important for the future experiments and for this reason new irradiating particles and new accelerating method are needed.

4. Experimental Setup
The aim of this test is to understand the limits of the standard aging tests and to determine how particles with different ionization powers can affect the long term stability operation of a Triple-GEMs in the CMS framework. For this reason, the test is performed on a $10 \times 10 \text{ cm}^2$ Triple-GEM prototype with a configuration used in large experiment like CMS [4] and LHCb [12]: 3/1/2/1 mm. Two breaking points with respect to the standard aging tests: the use of highly ionizing particles and a new method to accelerate the test. The latter is done by contaminating the gas mixture to simulate years of minor contamination in a clean gas system. This is obtained by inserting two types of glues into a stainless steel cylinder placed in series to the gas flow, these glues release some of their molecules inside the gas volume. These molecules are hydrocarbons (figure 2) and Si-based (figure 3); their dissociation during the electron avalanche may create radicals that can potentially impact the detector behaviour.

![Figure 2. MethylMethacrylate molecule from 3140 RTV Coating®](image1)

![Figure 3. Methyltrimethoxysilane molecule from Acrifix 1R 0192®](image2)

Secondly, in order to understand the differences between photons HIP irradiation, the detector under test was exposed to an $^{241}\text{Am}$ source (5.5 MeV alpha particles) on one corner region and to a $^{55}\text{Fe}$ source (5.9 keV photons) on the other corner region. Furthermore, in order to monitor the polymer formation, a detector based on a technology more prone to aging - Single Wire Proportional Chamber (SWPC) - is placed along the same gas line irradiated with an $^{55}\text{Fe}$ source. In order to permit alpha particle to enter the gas volume, a window in the drift plane is performed, a thin polyamide layer is placed in here to ensure the gas tightness.

4.1. Characterization of the GEM detector
A typical GEM detector characterization was performed aimed to verifying the correct operation of the prototype and find the correct working point. Gas gain measurement was performed by measuring the anodic current $I_A$ and the hit rate $R$ with a known source ($^{55}\text{Fe}$) and calculated via the following equation:

$$\text{Gain} = \frac{I_A}{e n_0 R},$$

where $n_0$ is the average number of primary electrons released in the detector by the incoming particles ($n_0 = 214$ for $^{55}\text{Fe}$). The detector was fully operational and the working point was chosen to be 700 $\mu$A, this means an effective gas gain of $5 \times 10^4$ and $6 \times 10^4$ respectively for the X-rays irradiated sector and the Alpha one. This working point was chosen in order to have a
gas gain 2.5/3 times higher than the CMS GEM one ($2 \times 10^4$), this will introduce an additional acceleration of the aging process.

Figure 4 and 5 show the calibration results. The first plot shows the measured values of the Effective gas gain of the Triple-GEM prototype under test as a function of the divider current. Gain differences in the two sectors are due to a hole in the drift plane which distort the electric field, provoking a loss of primary electrons. Figure 5 shows the Hit Rate of the Triple-GEM prototype irradiated with a $^{55}$Fe source as function of the Divider Current. Rate in the alpha sector is lower because of a hole in the drift plane, resulting in less photon converted into the drift gap.

![Figure 4.](image1.png)  
*Effective gas gain in function of the divider current*

![Figure 5.](image2.png)  
*Interaction rate of a $^{55}$Fe source in function of the divider current*

### 4.2. Data acquisition and analysis procedure

Charge spectrum from both the X-ray and alpha particles irradiated GEM sectors and from the Wire Chambers are acquired, figures 6, 7 and 8 show examples for each of these channels. A scheme of the data acquisition chain is shown in Figure 9. Each spectrum contains data obtained in 30 minutes of acquisition. Every spectrum is fitted with 3 gaussian functions in order to find the peaks positions with respect to the Pedestal position. Three gaussians are also used to fit the alpha charge spectra: due to the many $^{241}$Am alpha emission lines and the GEM energy resolution, the resulting signal peak is the convolution of two gaussians. The position difference of the signal from the pedestal is proportional to the gain of the detector, *i.e.* related to its performances.

Since the gain is influenced by environmental fluctuations it is important to correct each measurement. The environmental parameters (temperature and pressure) are monitored by an Arduino-based meteo station and the peak positions are corrected using a power function [5], [6].

### 5. Results

#### 5.1. Gain evolution

After a total integrated charge of 165 mC/cm$^2$ on the Alpha Sector and 170 mC/cm$^2$ on the X-ray Sector, a 20% gain drop in the SWPC was observed (figure 10). The polymer concentration was sufficiently high to impact the performance of the wire chamber. On the other hand the
Figure 6. Charge spectrum of the SWPC irradiated with an $^{55}$Fe source.

Figure 7. Charge spectrum of the GEM X-rays sector irradiated with an $^{55}$Fe source.

Figure 8. Charge spectrum of the GEM Alpha sector irradiated with an $^{241}$Am source.

Figure 9. The figure shows the scheme of experimental chain.

GEM detector revealed to be radiation hard in a contaminated gas volume up to 165 mC/cm$^2$ in both the irradiated sectors (figures 11, 12). The data are normalized with respect to the average value of a selected set of data points.

Figure 10. Corrected and Normalized gas gain of the SWPC during the whole data taking period.

Figure 11. Corrected and Normalized gas gain of the GEM X-rays sector during the whole data taking period.

Figure 12. Corrected and Normalized gas gain of the GEM X-rays sector during the whole data taking period.
5.2. Analysis of the irradiated GEM foils

After completion of the irradiation test, the detector was opened to collect GEM foil samples. For each of the three foils a sample was collected from the X-rays irradiated sector, the alpha irradiated sector and from a non-irradiated sector as reference. Figure 13 shows samples collected from the bottom GEM foil. It is possible to notice that the alpha irradiated sector presents a clear shadow with same shape as the irradiation window, while this is not present in the other two samples.

In order to better understand the effect of different particles on the GEM structure, an electron microscope analysis of the hole edges was performed. Figures 14, 15 and 16 show respectively pictures of one hole from the reference, X-rays and alpha sector samples from the bottom GEM foil. In the following only the bottom GEM foil will be analyzed because it is subjected to the largest charge density during the electron amplification. It is possible to notice,

qualitatively, that the X-rays irradiated sector has only a little pollutant build-up on the top rim, while the alpha sector has a wide deposit on both sides.
In order to quantify the difference between the two sectors an Electron Dispersive X-ray Spectroscopy (EDS) was performed on the samples. This analysis permit to measure the concentration of certain atomic specimens such as Carbon, Oxygen, Copper, Silicon, etc. Figures 17, 18 and 19 show the concentration of some atomic specimens in function of the distance from the hole edge in the top rim of the GEM foil. Near the edge, the copper concentration is low due to the lack of the metallic layer while carbon and oxygen concentration became higher because of the Kapton layer of the foil. Silicon deposit should only be due to the polymerization of contaminants previously inserted in the gas system. The reference hole is a typical clean GEM surface with no deposit nor defects. The X-rays irradiated sector has light silicon deposit on the top rim (no silicon detected on the bottom) around the hole (some \(\mu m\)). The polymer deposits in the alpha irradiated hole are more complex: nevertheless in this sector the same charge has been integrated, a wide silicon deposit is present on both the top and bottom surfaces with larger structures in a strip of \(10^{-15}\mu m\) around the hole with respect to the other irradiation area.

6. Conclusion
In this work an original concept of aging study has been presented. Using alpha particles and exploiting an original method to accelerate the test by contaminating the gas, the authors overcome some of the limits of the traditional aging tests. GEM detector revealed to be more radiation hard than wire chambers, in particular no gain variation was observed up to \(165\, \text{mC/cm}^2\) in both the irradiated sectors. The EDS analysis revealed a more pronounced presence of silicon polymers when irradiating with 5.5 MeV alpha particles with respect to 5.9 keV photons at comparable integrated charge. Despite the large amount of silicon deposit in the alpha sector, the GEM detector hasn’t revealed any performance loss. This shows that this detector technology is very radiation hard also when irradiated with HIP in contaminated gas environment.

Since using only photons in aging test can not resemble the particle environment of an experiment like CMS, it is suggested, when performing aging tests, to test multiple detectors in different contamination conditions and with different particles. This will give a more detailed knowledge on the detector aging behaviour and avoid the appearance of unexpected aging issues.

Nevertheless this test demonstrates that HIP have a higher aging power, many variables have to be investigate in the future. For example an higher gas flow rate can reduce the
polymerization rate by removal the radicals, using different interaction rates between particles or current densities could reveal other aging issues. Tests have to be performed in order to confirm the result of this experiment and to determine the contributions of these variables.

References

[1] Apollinari G et al, High-Luminosity Large Hadron Collider (HL-LHC) : Technical Design Report V. 0.1, CERN-2017-007-M.
[2] Benedikt M ; Zimmermann F, Future Circular Collider, CERN-ACC-2015-0165.
[3] Sauli F, Nuclear Instruments and Methods A 386 (1997) 531.
[4] Colaleo A et al, The Phase-2 Upgrade of the CMS Muon Detectors, CERN-LHCC-2017-012 ; CMS-TDR-016.
[5] Fallavollita F, 2018, Triple-Gas Electron Multiplier technology for future upgrades of the CMS experiment: construction and certification of the CMS GE1/1 detector and longevity studies, CERN Ph.D. thesis, CERN-THESIS-2018-349.
[6] Merlin J A, 2016, Study of long-term sustained operation of gaseous detectors for the high rate environment in CMS, CERN Ph.D. thesis, CERN-THESIS-2016-041.
[7] Binkley M, Wagner R L, Mukherjee A, Ambrose D, Bauer G, Khazins D M, Atac M, Nucl. Instr. and Methods A 515, 53 (2003).
[8] Ferguson T, Gavrilov G, Korytov A, Krivchitch A, Kuznetsova E, Lobachev E, Mitselmakher G, Schipunov L, Nucl. Instr. and Methods A 488, 240 (2002).
[9] Abbrescia M et al, Study of long-term performance of CMS RPC underirradiation at the CERN GIF, Nucl. Instr. and Methods A 533, 102 (2004).
[10] Acosta D et al, Aging tests of full-scale CMS muon cathode strip chambers, Nucl. Instr. and Methods A 515, 226 (2003).
[11] Alfonsi M et al, Aging measurements on triple-GEM detectors operated with CF4-based gas mixtures, Nuclear Physics B (Proc. Suppl.) 150 (2006) 159–163.
[12] LHCb Collaboration, LHCb muon system : second addendum to the Technical Design Report, CERN-LHCC-2005-012.