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Aging Studies of the triple-GEM detectors for future upgrades of the CMS muon high rate region at the HL-LHC

Francesco Fallavollita[1,2]
on behalf of the CMS Muon Group
[1] *Dipartimento di Fisica, Università degli Studi di Pavia*
[2] *INFN sezione di Pavia*
Francesco.Fallavollita@cern.ch

1. Motivation

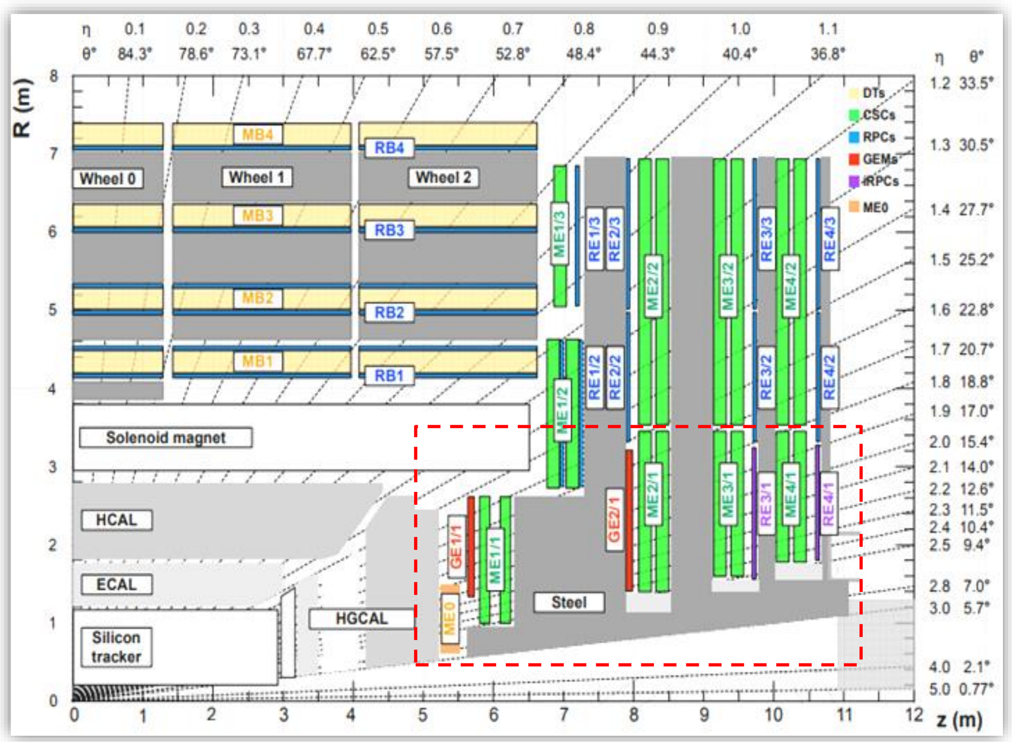


Figure 1. *An $R-z$ cross section of a quadrant of the CMS detector, including the Phase-2 upgrades ($RE3/1, RE4/1, GE1/1, GE2/1, ME0$).*

The high-luminosity LHC (HL-LHC) upgrade is setting now a new challenge for particle detector technologies. In the CMS muon system gas detectors, the increase in luminosity will produce a particle background ten times higher than under conditions at the LHC.

To cope with the high rate environmental and maintain the actual performance, the new triple-Gas Electron Multiplier detectors will be installed in the innermost region of the forward muon spectrometer of the CMS experiment.

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.

For this reason, aging tests of full size triple-GEM detector operated with Ar/CO_2 $(70:30)$ gas mixture at an effective gas gain of 2×10^4, are in course at GIF++, the CERN Gamma Irradiation Facility, and in parallel, with the second similar detector, in the CMS - GEM QA/QC Lab.

2. Longevity and Operational Stability of 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 performences of the gaseous detectors: gain drop, non-uniformity, dark current, discharge, etc.

The main causes behind the detector performance deterioration are chemical processes largely occurring in the hot plasma inside electron multiplication avalanches. Gas molecule fragments produced inside avalanches may form polymers growing on anode wires, cathode surfaces, and anode-cathode insulating elements.

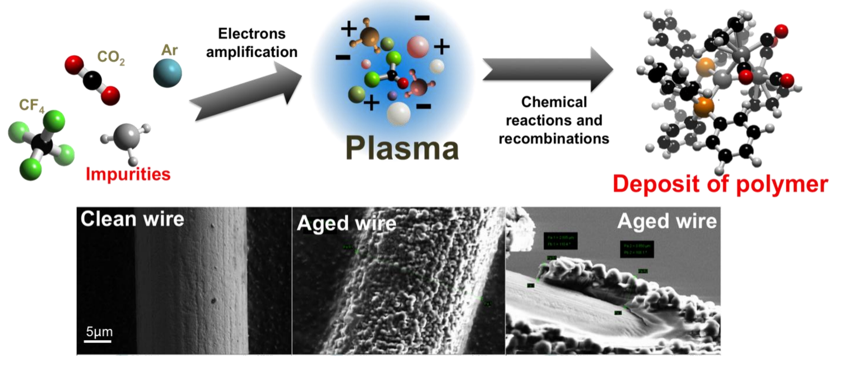


Figure 2. *Top: schematic view of the classical aging process. Bottom: SEM photographs of a clean detection wire (left) and aged wires (right) after few weeks of operation in a proportional counter and a dirty environment.*

Since the aging phenomena depends on a large number of input parameters and relies on several possible chemical mechanisms, it is not possible to build reliable models or simulation tools that can predict the long-term behavior of gaseous detectors. To evaluate the potential detector performance deterioration over the lifetime of an experiment, detector prototypes are subject to accelerated aging tests performed at a higher instantaneous radiation rate. It is prudent to use the exact same materials and their vendors in construction of prototypes as those envisioned for the ultimate detector.

As for all gaseous detectors, the Triple-GEM technology might be subject to aging effect due to polymer depositions when operating in a high-rate environment. The goal of the CMS GEM aging test campaign is to reproduce ten years of operation at HL-LHC, with a minimum safety factor of three.

3. Gamma Irradiation Facility

In order to study the longevity of detector components in the context of HL-LHC radiation doses, the GIF++ test zone (Gamma Irradiation Facility) started user operation at CERN in 2015, replacing its predecessor GIF.

It consists of an intense $14\,TBq$ (in 2015) ^{137}Cs source emitting $662\,keV$ photons. The GIF++ photons have an energy fairly representative of the energy of HL-LHC photons seen by the muon detectors, $0.1 - 10\,MeV$.

Longevity tests of GEM chambers at the GIF++ zone are ongoing: the Triple-GEM detector under test is placed at $1\,m$ from the source point.

With the interaction flux in the detector of the order of $3 \times 10^4\,Hz/cm^2$, the resulting aging acceleration factor is estimated at 30 at the CMS gas gain equal to 2×10^4.

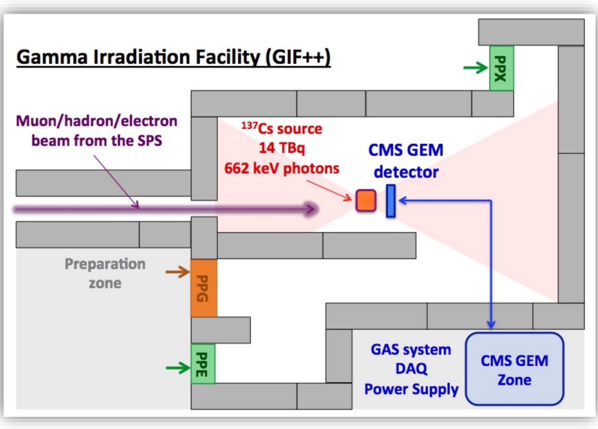


Figure 3. *Schematic view of the GIF++ irradiation facility at CERN used for the triple-GEM aging studies.*

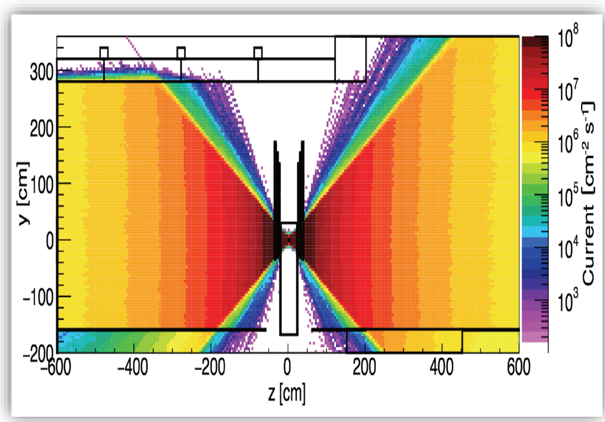


Figure 4. The GIF++ floor plan in the (y, z)-plane, and the photon current map for the open source.

4. GIF++ Installation

The ongoing test involve a full size Triple-GEM detector filled with a gas mixture of Ar/CO_2 $(70:30)$ and running at an effective gas gain of 2×10^4. The readout system for the Aging Studies at GIF++ consists of two main readout channels:

- In order to measure the gain variations in the GEM detectors, two KEITHLEY 6487 pico-ammeters are connected to several R/O sectors of the readout board. The anode current is recorded every 5 minutes for each sector;
- The environmental fluctuations, responsible for the temperature and pressure variations of the gas mixture, are measured every minutes.

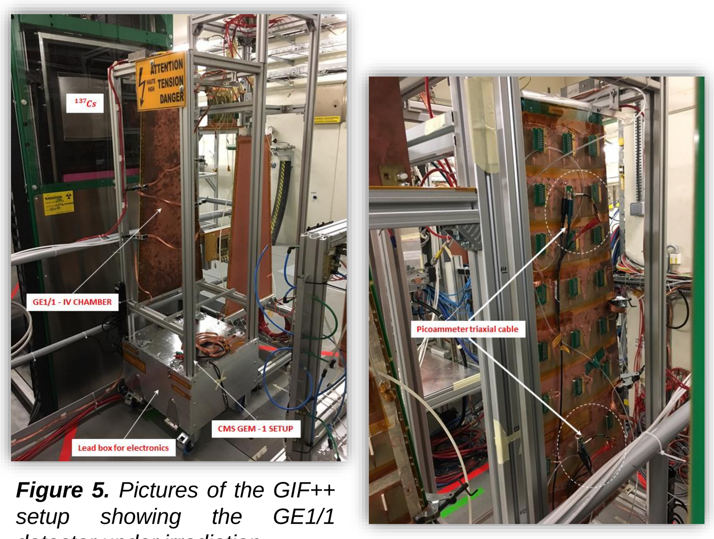


Figure 5. *Pictures of the GIF++ setup showing the GE1/1 detector under irradiation.*

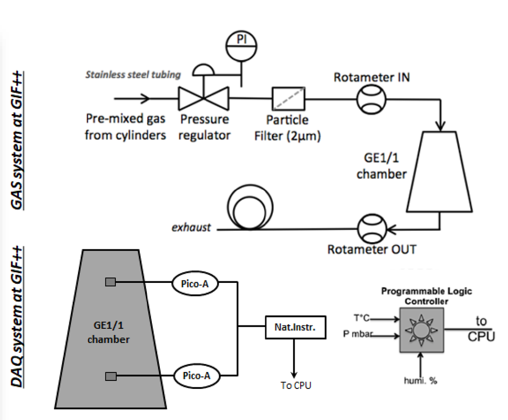


Figure 6. *Schematic view of the gas system and DAQ for the for the classical aging test at GIF++.*

5. Data Analysis Procedure

For long-duration aging tests, the response of the detectors can fluctuate not because of aging effects but because of variations of the density of the gas, themselves induced by variations of the ambient temperature and pressure.

It is thus essential to remove the environmental effects to isolate the possible aging effects.

The analysis procedure consists of four main steps:

- data synchronization and event building;
- data zero-suppression;
- correlation of the detector's output with the environment;
- environmental fluctuation correction and normalization.

After the corrections based on T and P, the resulting data is totally independent from the external perturbations and, plotted as function of the integrated charge per unit area, represent the intrinsic behavior of the detector when operating under sustained radiations.

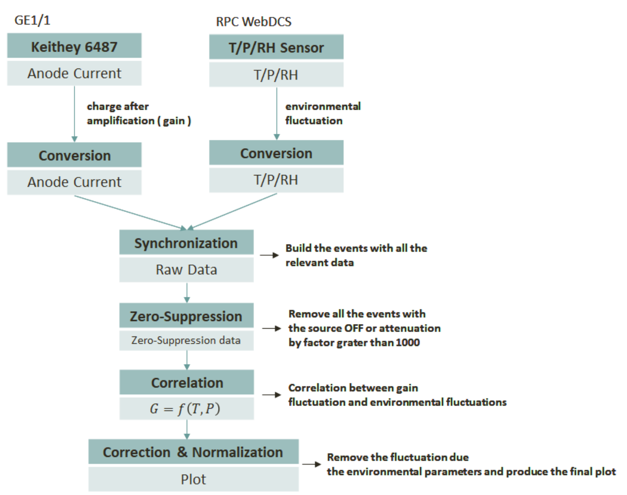


Figure 6. *Schematic representation of the analysis steps.*

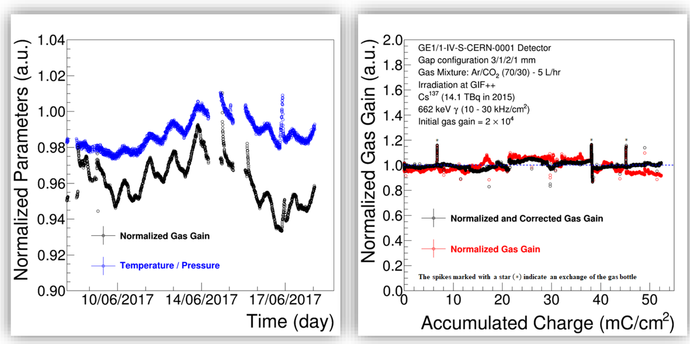


Figure 7. *Left: Typical data points taken at GIF++ showing the normalized gain (black) and the ratio temperature over pressure of the gas (blue). Right: Normalized gas gain (red) and normalized corrected gas gain (black) of the GE1/1 detector as a function of the accumulated charge.*

6. GIF++ Aging Test Results

The classical aging test is currently in course at GIF++ facility with a GE1/1 detector of the 4^{th} generation operating in Ar/CO_2 $(70:30)$.

After 10 months of sustained operation in front of the ^{137}Cs source, the GE1/1 detector accumulated a total charge of $110\,mC/cm^2$.

It represents ten years of GE1/1 operation with a safety factor 18, ten years of GE2/1 operation with a safety factor 36, and 39% of the total ME0 operation.

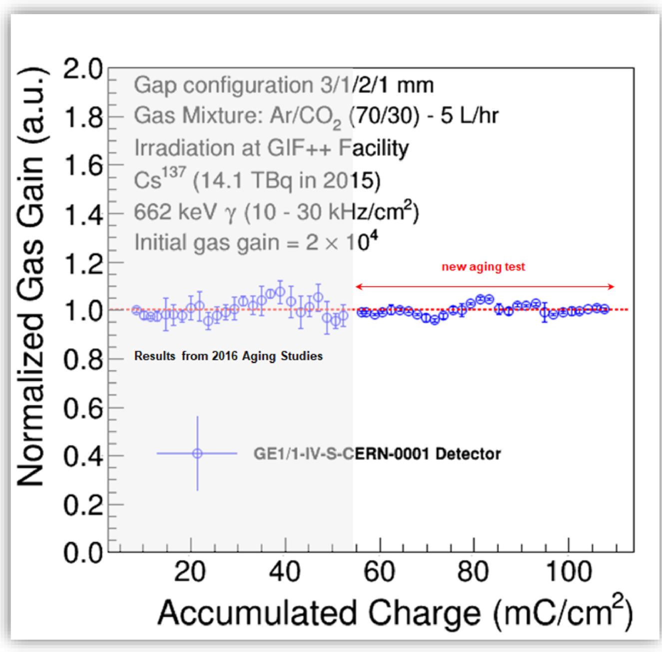


Figure 8. *Results of the GEM aging test showing the normalized effective gain (corrected for pressure and temperature variations) as a function of the accumulated charge.*

The results of the effective gain measurements indicate that the CMS Triple-GEM detector does not suffer from any kind of aging effects or long-term degradation.

7. Highly Accelerated X-ray Aging Test

The Aging Test will continue at the GIF++ facility under the same conditions until the detector accumulates a total charge equivalent to ten HL-LHC years in the ME0 environment. This will take another 2-3 years of exposure because of the duty factor of the GIF++ and its concurrent use by other experiments.Given this time scale, an additional, faster aging test was mounted in summer 2017 that exposes a full size Triple-GEM detector to X-rays from an X-ray source with Ag target at a higher rate.

CMS-GEM QA/QC Lab. Installation

The classical aging test takes place at CMS-GEM QA/QC Lab. and involves a Triple-GEM detector of the 10^{th} generation flushed with Ar/CO_2 $(70:30)$ and running at an effective gas gain of 2×10^4. We continuously monitor the response of the detector irradiated by a $22\,keV$ $X-ray$ source. The entire experiment is designed so that all relevant parameters are understood and monitored. This allows isolating the effects of possible aging and therefore understand its origin.

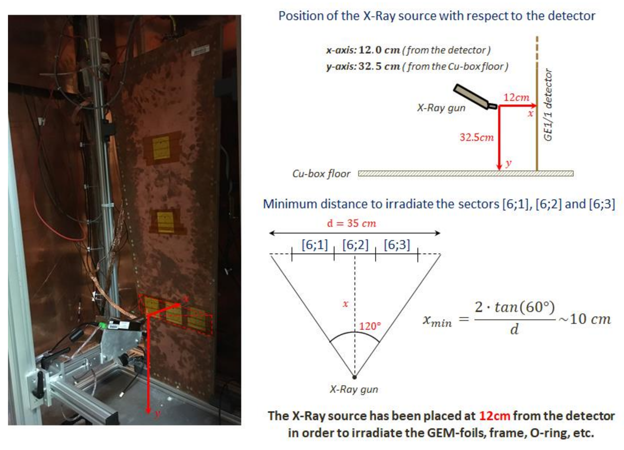


Figure 9. *Pictures of the X-ray setup showing the GE1/1 detector under irradiation.*

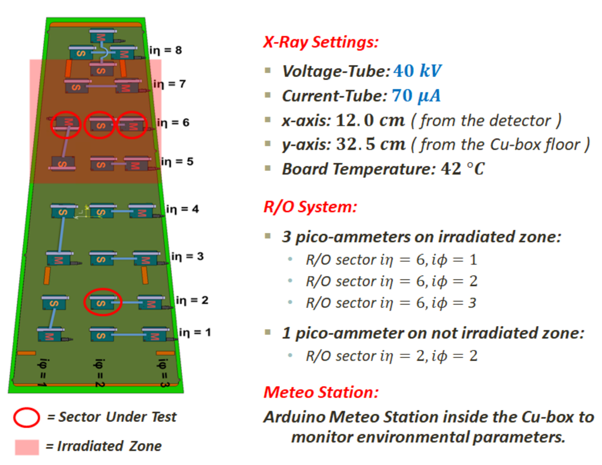
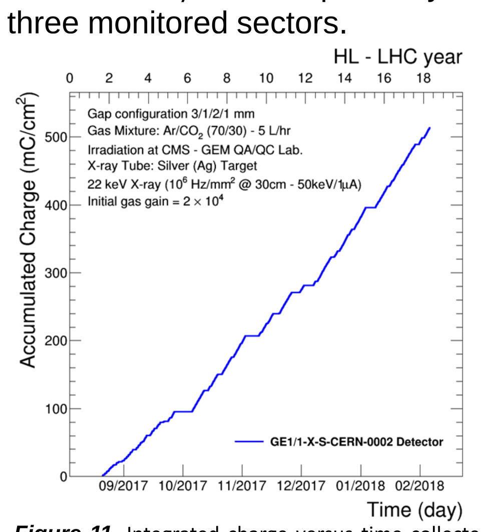


Figure 10. *Final configuration for the X-ray aging studies at CMS-GEM QA/QC Laboratory.*

Integrated Charge Rate

The overall duty factor since August 2017 is about 77%, i.e. $18hr$ of continuous irradiation per day. About $515\,mC/cm^2$ have been accumulated until February 2018 in the in hottest R/O sector and more than $850\,mC/cm^2$ are expected by May 2018, thus providing a safety factor about 3 with respect to 10 years of HL-LHC operations in the ME0 environmental. The other two irradiated sectors have accumulated $214\,mC/cm^2$ and $107\,mC/cm^2$, respectively. No gas gain drop has been observed in any of the three monitored sectors.



R/O sector	Integrated Charge	Integrated Charge Rate	Gas Gain Stability	Energy Resolution
$\eta = 6, \varphi = 1$ ($f_{GIF++} \sim 3.1$)	$213.9\,mC/cm^2$	$1.8\,mC/cm^2 \cdot day$	No gain drop observed	$(17.3 \pm 0.1)\%$ Energy Res. Stable
	~ 76% of the total ME0 operation @ HL-LHC			
$\eta = 6, \varphi = 2$ ($f_{GIF++} \sim 8.1$)	$515.2\,mC/cm^2$	$4.3\,mC/cm^2 \cdot day$	No gain drop observed	$(16.8 \pm 0.1)\%$ Energy Res. Stable
	18 years of ME0 operation @ the HL-LHC			
$\eta = 6, \varphi = 3$ ($f_{GIF++} \sim 1.9$)	$106.7\,mC/cm^2$	$0.9\,mC/cm^2 \cdot day$	No gain drop observed	$(16.9 \pm 0.1)\%$ Energy Res. Stable
	~ 38% of the total ME0 operation @ HL-LHC			

Figure 11. Integrated charge versus time collected during the X-ray aging studies. At the time of the finalization of this poster, $515\,mC/cm^2$ have been accumulated in one sector of this chamber and smaller amounts in two other sectors under test.

8. X-ray Aging Studies: Effective Gas Gain

The new aging studies are in course at CMS-GEM QA/QC Lab. with a GE1/1 detector of the 10^{th} generation operating in Ar/CO_2 $(70:30)$ and running at an effective gas gain of 2×10^4. The detector is irradiated by a $22\,keV$ $X-ray$ source.

After 92 days of continuous irradiation, the GE1/1 detector accumulated a total charge of $515\,mC/cm^2$, i.e. 10 years of real operation in ME0 region with a safety factor 1.8.

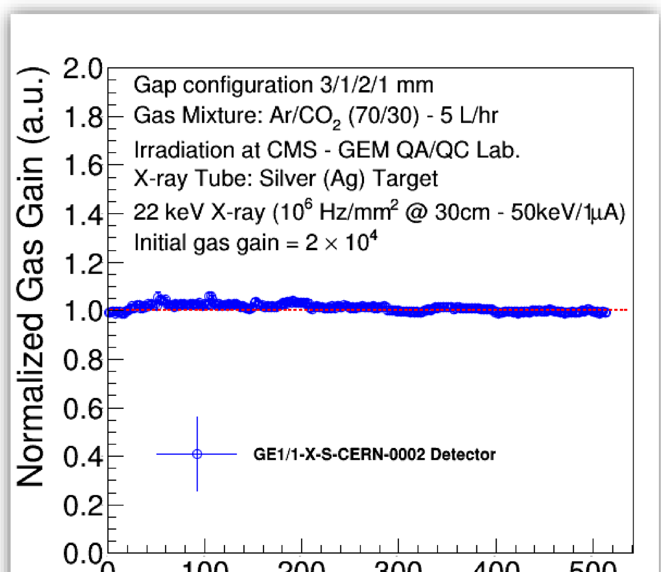


Figure 12. *Results of the GEM aging test showing the normalized effective gain (corrected for pressure and temperature variations) as a function of the accumulated charge.*

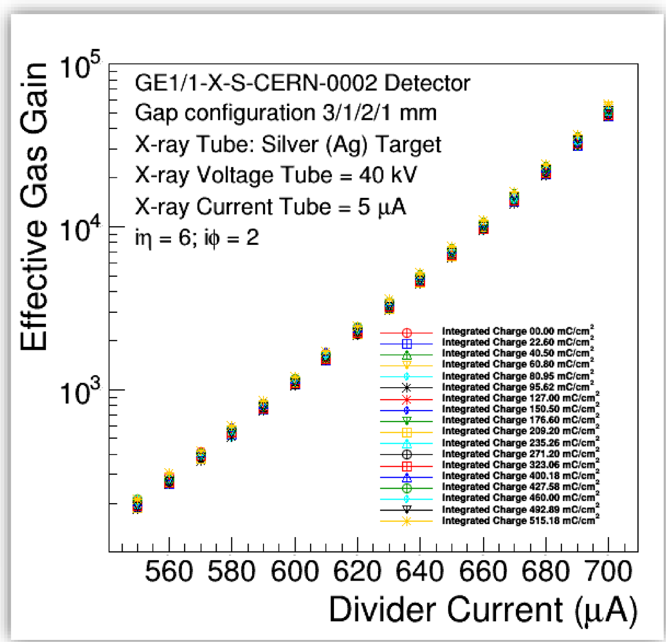


Figure 13. *Results of the GEM aging test showing the weekly QC5 - Effective Gas Gain measurement for several accumulated charge values.*

The aging tests currently underway at CMS-GEM QA/QC Lab. demonstrated that the CMS Triple-GEM detector can operate in the CMS - ME0 environment during at least 10 HL-LHC years (with safety factor 1.8) without suffering from gain drop, unstability or any other long-term degradations.

9. X-ray Aging Studies: Energy Resolution

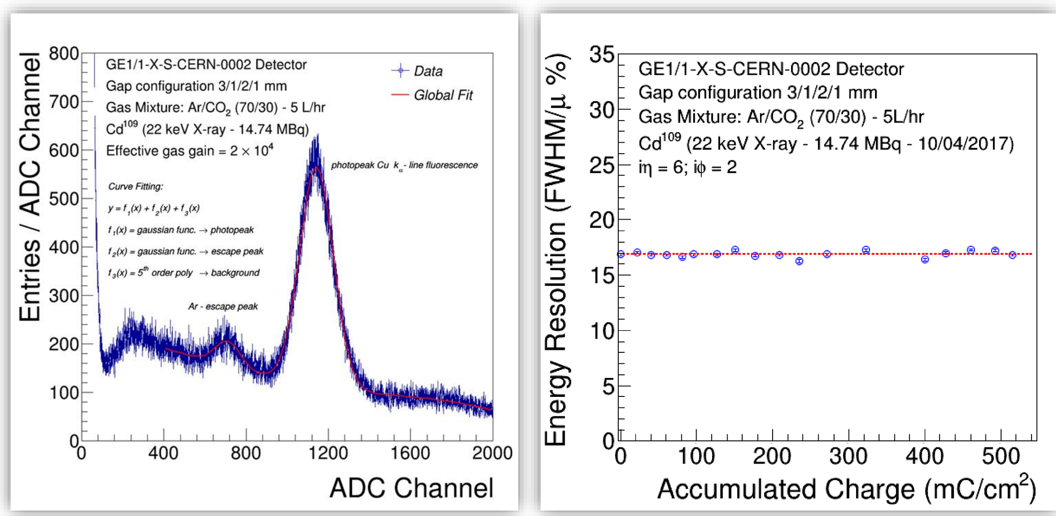


Figure 14. *Typical energy spectrum of the ^{109}Cd source (left) and energy resolution as a function of the accumulated charge (right) of the GE1/1 detector operating in Ar/CO_2 $(70:30)$ at an initial gas gain of 2×10^4.*

The result of the X-ray Triple-GEM aging test showing the energy resolution as a function of the accumulated charge.

The detector under test is a GE1/1-X-S-CERN-0002 chamber operating in Ar/CO_2 $(70:30)$ and running at an initial gas gain of 2×10^4.

The energy spectrum of the ^{109}Cd source is measured every weeks and the corresponding energy resolution stays stable during the entire test.

6. Conclusion

The ongoing aging studies at GIF++ facility and in parallel at CMS-GEM QA/QC Lab. aims to identify the possible aging of Triple-GEM detector for CMS experiment and understand the long-term operation in HL-LHC with its future upgrades. The preliminary results presented in this poster indicates that the CMS Triple-GEM detector can sustain the continuous operation in the CMS endcap environment during at least 10 years at HL-LHC without suffering from any performance degradation.

[1] J. A. Merlin, *Study of long-term sustained operation of gaseous detectors for the high rate environment in CMS*, CERN, May 2016.
[2] A. Colaleo et al., *CERN-LHCC-2017-012, CMS-TDR-016*, 12 September 2017.