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Irradiation effects on GEM detectors operated at RUN1 and RUN2 at the LHCb experiment

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ABSTRACT

Triple-GEM detectors with pad readout have been employed to equip the innermost region (R1) of the first station (M1) within the Muon system of the LHCb experiment. The GEM detectors have been operated with an $Ar/CO_2/CF_4$ = 45/15/40 gas mixture at a gas gain of about 4000 with an average particle flux of about 250 kHz/cm^2. Throughout RUN1 and RUN2, spanning approximately 440 days of colliding beams, the GEM detectors accumulated a charge of up to 0.5 C/cm^2. This paper presents a comparative analysis between a global irradiation test of GEM detectors at the Calliope facility (ENEA-Casaccia, 1.25 MeV γ ray flux from a ^{60}Co source) and the GEMs operated at LHCb, focusing on the impacts of a CF_4-based gas mixture. In both instances, the detectors were opened and the GEM foils were examined by the EN-MME-MM CERN group with a Field Emission Gun Scanning Electron Microscope (FEG-SEM) for a magnified image analysis and an X-Max Energy Dispersive X-ray Spectroscopy (EDS) for the chemical one.

1. Introduction

The innermost region (R1) of the first muon station (M1) of the LHCb experiment [1] has been equipped with twenty-four triple-GEM detectors with pad readout [2,3]. In the LHCb experiment, such detectors had to tolerate an integrated charge of 1.2 C/cm^2 over 10 years of operation, at a gas gain of 4000 and an average particle flux of 184 kHz/cm^2, without experiencing damages or performance losses. Due to the experiment requirement for a very fast detector response, GEM detectors had to operate with high drift velocity and high-yield gas mixtures. Among the tested gas mixtures, the $Ar/CO_2/CF_4$ = 45/15/40 [4] fulfills the LHCb requirements resulting in an efficiency better than 96% in a 25 ns time window achieved by two logically OR-ed GEM detectors.

2. Detector description and construction materials

The triple-GEM chamber features an active area of 20×24 cm^2. The GEM foils[1] have been manufactured by the CERN-EST-DEM workshop and subsequently stretched to a mechanical tension of approximately 1 kg/cm using a tool developed by our team [5]. The stretched GEMs have been glued using ARALDITE 2012 to a fiberglass frame. The detector has been assembled by gluing three framed GEMs on top of the cathode PCB using ARALDITE AW103 + HY991 epoxy. The chamber has been finally sealed by gluing the last 1 mm (bare) frame and the readout pad PCB. The cathode and readout pad electrodes house two gas inlets and two gas outlets, realized with brass connectors glued with the ARALDITE 2012 on fiberglass machined inserts. Table 1 summarizes the materials used in chamber production that come into contact with the gas mixture.

3. Global irradiation test of the full size prototype

A global irradiation test has been conducted to assess the compatibility between the construction materials and the gas mixture, notably due to the substantial CF_4 (40%) content. The test has been performed at the Calliope facility of the ENEA-Casaccia with an intense

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[1] Throughout the text, the term "GEMs" will refer to these foils.

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Table 1
List of the materials used in the detector assembly.

Material	Type	Note
ARALDITE 2012	Epoxy Glue	GEM framing and gas in/outlets passivation (only readout PCB)
ARALDITE AW103 + HY991		Detector assembly and sealing
FR4		Frame
Gold plated PCB	Rigid materials	PCBs active area
FR4 and brass connector		Gas inlet and outlets
Polypropylene and Cu tubes	Piping	Gas tubes used in the experiment
Cu + Kapton	Flexible materials	GEM base material

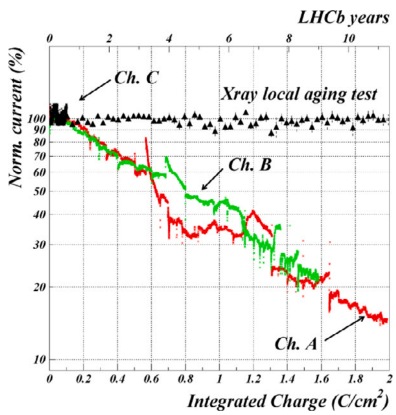

Fig. 1. Comparison between local aging and the global irradiation test at the ENEA-Casaccia.

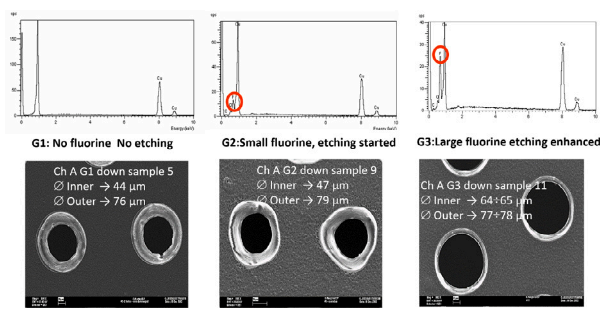

Fig. 2. Picture of the three GEMs; it is visible the widening of the holes from the first to the third foil.

1.25 MeV γ ray flux from a ^{60}Co source [6]. After an irradiation period of about 35 days, the total accumulated charge for each three prototypes 20 × 24 cm^2 was ∼0.16 C/cm^2 for the least irradiated detector, ∼1.6 C/cm^2, and ∼2.2 C/cm^2 for the most irradiated ones, corresponding respectively to about 1 (chamber C), 8.5 (chamber B), and 11.5 (chamber A) years of operation at LHCb. The gas gain of all prototypes was fixed to ∼6 × 10^3. The lowest irradiated detector (Chamber C) was installed upstream in the same gas line of the high irradiated detectors (first the Chamber A and then the Chamber B). The whole gas inlet line was made of stainless steel tubes, while the exhaust gas line was made of polypropylene tubes (not hygroscopic). A probe was directly installed on the gas line, downstream of the test chambers, in order to monitor the temperature and humidity of the gas mixture. The water content in the gas mixture was substantially kept under few ppm during the whole test. An additional probe supplied the monitor of the atmospheric pressure. At the end of the test, chamber C has shown no aging, while current drops of 89% and 80% have been observed for chambers A and B, respectively (Fig. 1).

The result obtained in this test has been attributed to the insufficient gas flow rate (350 cm^3/min, the maximum flow reachable with our mass-flowmeters, equivalent to one volume exchange every minute) in relation to the very high gamma flux (up to 20 MHz/cm^2 equivalent m.i.p. on the entire detector area, corresponding to a pad current of the order of 500 μA) to which chambers have been exposed during the irradiation test. On the contrary local aging test was performed by irradiating a 10 × 10 cm^2 GEM at a gas gain of 6 × 10^3 with a high intensity 5.9 keV X-ray tube. The experimental conditions was completely different: a gas flow rate of 100 cm/min, equivalent to 0.7 volume exchange every minute, for a global detector current of 0.2–0.4 μA over an irradiated area of the order of 1 mm^2.

In this context, the global irradiation test has been conducted under strong gas pollution conditions and should be considered pessimistic and misleading. Indeed, the chambers have been subjected to significant plasma etching by fluorine, produced in the fragmentation of the CF_4, and not quickly removed by the gas flow. Consequently, permanent changes have been observed on the GEM, particularly in the diameter and shape of the holes, especially on the third foil where the charge density is higher (Fig. 2).

4. Irradiation effect at LHCb

The 24 GEM detectors were installed in 2009 and have been operational since the first LHC run. The detectors have been operated at a gas gain in the range of 4000 to 6000 at a gas flow of about 40 cc/min [7]. Under these conditions during RUN1-RUN2 LHCb luminosity, the average currents of the third bottom GEM ($I_{det.}$) monitored on each detector ranged from 2 μA to 8 μA, depending on the detector's position relative to the LHCb beam pipe. In Fig. 3 is shown a typical hit map of the first station of the LHCb Muon Apparatus during a physics run [8], where the innermost region was equipped by the 12 logically OR-ed GEMs. To achieve the real particle flux on the GEMs, the log scale must to be multiplied by the physic readout pad size (1 × 2.5 cm^2) and the 1 MHz trigger, which give a particle flux for the inner region of about 250÷300 kHz/cm^2. The few holes present on the maps correspond to dead channels. Most of them were due to hardware problems in the readout chain known since the beginning of the data taking. The level of detector noise was checked regularly with dedicated runs of random triggers in absence of beam and the noise rate per physical channel was computed for each detector region from the multiplicity of firing logical channels or logical pads. The fraction of channels having a noise rate larger than 10 kHz is typically lower than 0.1%. Such values are well below the noise level causing a measurable rate of accidental triggers. After RUN2, the first station of the Muon Apparatus was disassembled, and two GEM detectors, namely A15A1L and A15A1R, have been selected for analysis by the EN-MME-MM CERN group using SEM and EDS analyses. Both these detectors (chamber number 1 in figure) exhibit no sign of performance loss as shown in Fig. 4, where the black and red dots represents the efficiency in the single bunch-crossing for the 12 logically OR-ed GEMs detectors at the beginning of RUN1 and at the end of RUN2, respectively. To point out that GEMs during their operation have shown some detector instabilities, sparks of few hundred of nA, and an increase of dark current on GEM electrodes, of the order of tens of nA, has recorded at the end of RUN2. During RUN1 and RUN2, corresponding to about 440 days of colliding beams at a

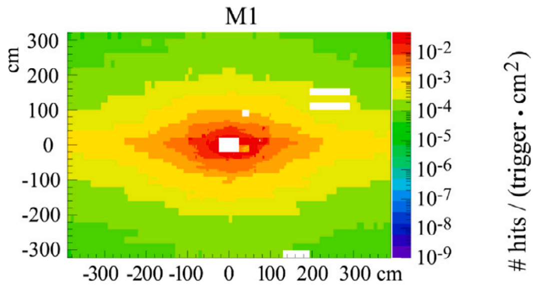

Fig. 3. Illumination map of the first detector station (M1) in a typical 2010 physics run. The log color scale gives the average number of hits of physical FFE channel per cm2 per trigger.

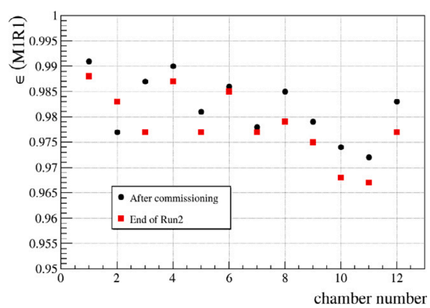

Fig. 4. Efficiency in the single bunch-crossing for the 12 logically OR-ed GEMs: after the commissioning and before the dismount.

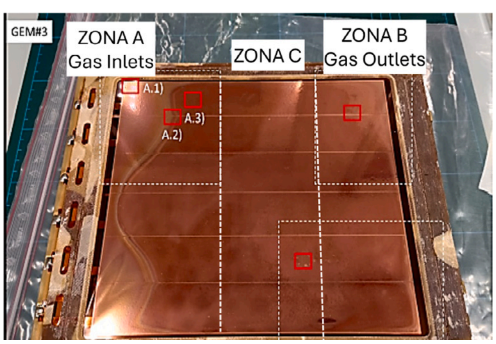

Fig. 5. General aspect and areas under study of the third GEM of the A15AR detector. The red squares correspond to areas inspected at higher magnification.

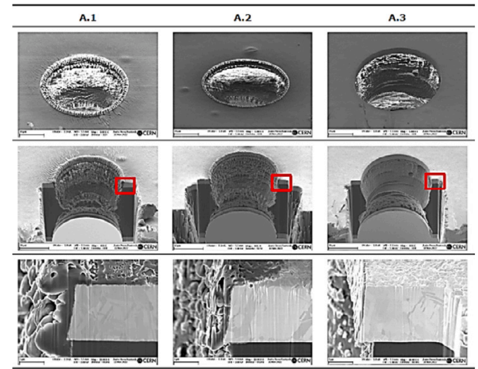

Fig. 6. SEM images of holes in locations (A.1), (A.2) and (A.3), before and after FIB cross sectioning, and the deposit detail on the bottom copper edge of third GEM.

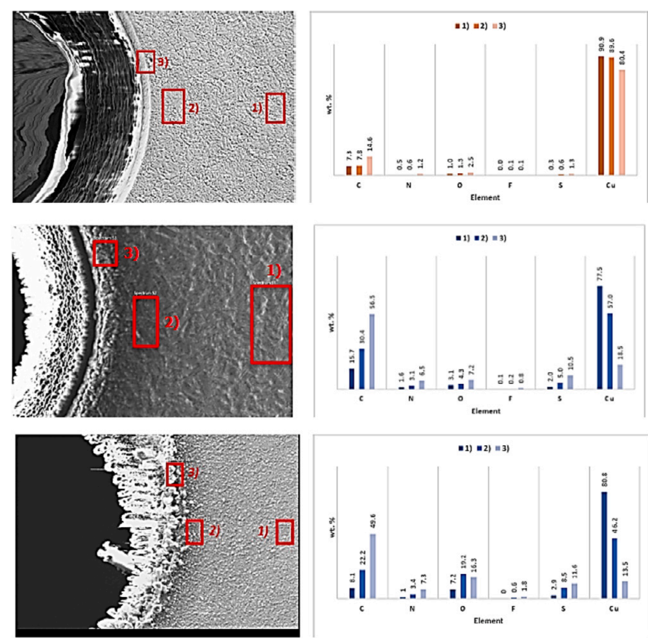

Fig. 7. Chemical analysis by EDS on the hole's surrounding areas. The results are presented in wt. % and normalized. Top: first GEM; Center: second GEM; Bottom: third GEM.

particle rate of approximately 250 kHz/cm^2, each of the two detectors integrated[2] about 0.5 C/cm^2.

Digital microscope inspections have been performed by the EN-MME-MM CERN group on the entire 20 × 24 cm^2 surface of all three GEM foils of both A15A1L and A15A1R detectors [9]. Three zones have been selected for each foil: the zone facing a gas inlet (A), a gas outlet (B), and one in the middle (C) (Fig. 5). For the first GEM, i.e. the foil nearest to the cathode, the entire copper surface is homogeneous and does not show residuals. On the contrary, an high color contrast area, mainly concentrated in zone A, has been found on the second GEM and an even higher halo has been observed on the third GEM. A representative SEM image of holes of the third GEM in zone A is shown in Fig. 6: the deposit thickness is approximately 2 μm in A.1, about 1 μm in A.2, and nanometric in A.3.

In Fig. 7, the elemental composition analysis by EDS on the areas surrounding the holes of the three foils in zone A is reported. This analysis points out that, as approaching the edge of the holes, no residues have been found on the first GEM. However, an increasing content of *N* and S (≤10%) on the second GEM and N, F (≤2%), and S (≤12%) on the third GEM has been observed. Moreover, the SEM inspection confirmed that the residues observed on the hole edges are also deposited onto the internal hole surface, covering the Kapton and modifying the hole geometry. Fig. 8 shows a detail of the deposit thickness variation along a hole axis of the third GEM in zone A1. The deposit thickness is nanometric on the top GEM surface, increases on the Kapton, and reaches a thickness of ∼2 μm on the bottom surface. To investigate the possible source of sulfur contamination, the two glues used in the detector assembly were analyzed using Energy-dispersive X-ray spectroscopy (EDS) and X-ray Fluorescence (XRF) techniques. These analyses indicate that only the ARALDITE 2012 contains sulfur in the hardener molecules of the glue (2.2'-(ethylenedioxy) diethanethiol). The glue polluted the incoming gas which transported the S residue inside the detector itself.

[2] The integrated charge is estimated as follows: $Q_{int.} = 2 \times I_{det.} \times \Delta t_{LHCb}$, where the factor 2 takes into account the equal current sharing between the pad readout and the electrode of the third GEM I_{det}.

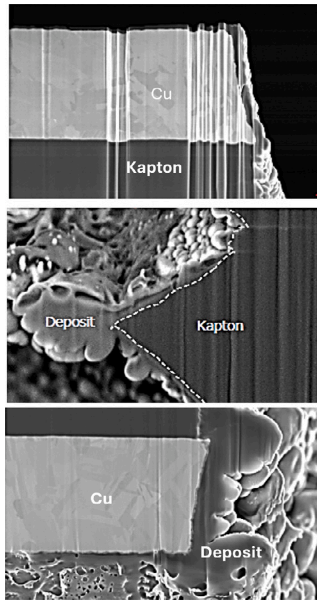

Fig. 8. SEM images of the hole cross section on the third GEM in zone A1.

5. Conclusions

After the accelerated Calliope test, integrating a charge of up to 2.2 C/cm^2 within 30 days, fluorine etching on the GEM foils has been distinctly revealed. The third GEM has shown a larger effect on the hole diameter (increasing from the standard 70 μm to 80 μm), while minor effects have been found on the second and the first GEMs. Fluorine is primarily located on the copper around the hole edges, leading to the formation of a thin non-conductive layer (a fluorine–copper compound). This fluorine etching effect is due to the inadequate gas flow conditions (350 cc/min) in relation to the very high particle irradiation (∼20 MHz/cm^2) used during the Calliope test. On the contrary, the preliminary results on GEM detectors after their operation in LHCb do not show fluorine etching. Instead sulfur contamination (∼12%) has been manly found in the third GEM zone which overlooks the gas inlets, over the hole bottom edges and into the internal hole surface. The sulfur deposit thickness varies from a few nanometers (top GEM3) to ∼2 μm (bottom GEM3). The origin of sulfur is due to the outgassing of ARALDITE 2012, which has polluted the incoming gas, transporting sulfur residues inside the detector itself. The investigation into the LHCb GEM chambers is ongoing and not yet conclusive. A more detailed investigation of the effects of sulfur deposits on the stability of detector operation is foreseen with the analysis of other dismounted GEM detectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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