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Aging measurements on triple-GEM detectors operated with CF_4-based gas mixtures

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We present the results of a global irradiation test of full size triple-GEM detectors operated with CF_4-based gas mixtures. This study has been performed in the framework of an R&D activity on detectors for the innermost region of the first muon station of the LHCb experiment. The prototypes have been irradiated at the Calliope facility of the ENEA-Casaccia with a high intensity 1.25 MeV γ ^{60}Co source. After the irradiation test the detectors performances have been measured with X-rays and with a 3 GeV pion beam at CERN. A SEM analysis on several samples of the detectors has been performed to complete the understanding of the physical processes occurring in a GEM detector during a strong irradiation.

1. Introduction

The innermost region (R1) of the first muon station (M1) of the LHCb experiment [1] will be equipped with triple-GEM detectors with pad readout [2]. The GEM (*Gas Electron Multiplier*) [3] used in these detectors is a thin (50μm) kapton foil, copper clad on each side, chemically perforated with an high density bi-conical holes, with an external (internal) diameter of 70μm (50μm) and a pitch of 140μm. GEM holes act as multiplicative channels for gaseous detectors by applying a voltage difference between the two copper surfaces. The cross section of LHCb triple-GEM detectors, together with the labeling used in this paper, is shown in Fig. 1.

At LHCb such a detector must tolerate, without damages or performance losses, an integrated charge of $\sim$ 1.76 C/cm^2 in 10 years of operation at a gain of $\sim$ 6000 and an average particle flux of $\sim$ 184 kHz/cm^2. Because the experiment requires for a very fast detector response, triple-GEM detectors must be operated with high drift velocity and high yield gas mixtures. Among the tested gas mixtures the $Ar/CO_2/CF_4$ (45/15/40) [4] largely fulfill the LHCb requirements in terms of time performance as well as efficiency in 20 ns time window [1].

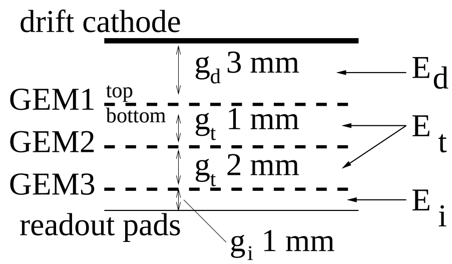

Figure 1. Cross-section of the triple-GEM detector. E_d, E_t and E_i are the drift, transfer and induction fields respectively; g_d, g_t, and g_i are the drift, transfer and induction gaps respectively.

[1]The most important requirement for M1R1 is that a muon detection station must have an efficiency in 20 ns time window better than 96%. This requirement is fulfilled by two logically OR-ed triple-GEM detectors.

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Aging properties of triple-GEM detectors operated with the standard Ar/CO_2 (70/30) gas mixture have been extensively studied by other authors [5].
Local aging tests on triple-GEM detectors (10×10 cm^2 large prototypes) operated with CF_4 based gas mixtures, were performed for the first time by our group [4], either with a high intensity X-ray radiation or with hadrons from the πM1 beam at the Paul Scherrer Institute (PSI). In both cases, after an integrated charge equivalent to several years of operation at LHCb, negligible aging effects were observed with all the gas mixtures used.
Anyway, due to the large amount of CF_4 (40%) present in the gas mixture, in order to check the compatibility between the construction materials (for both detector and gas system) and the gas mixture, a global irradiation test of the final chamber is required.
For this reason we performed a test at the Calliope facility of the ENEA-Casaccia with an intense 1.25 MeV γ ray flux ^{60}Co source.

2. Global aging test of the full size prototype

Three full scale prototypes were irradiated on the whole active area (20×24 cm^2) at different gamma rates from $\sim$ 1 MHz/cm^2 (chamber C) up to $\sim$ 15 MHz/cm^2 (chamber A) and 20 MHz/cm^2 (chamber B). The gas flow rate was 350 cm^3/min, to be compared with the single detector volume of $\sim$ 350 cm^3. The lowest irradiated detector was used as reference chamber and installed upstream in the same gas line of the high irradiated detectors. 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 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.
The total accumulated charges on the three prototypes were $\sim$ 0.16 C/cm^2 for the lowest irradiated detector, $\sim$ 1.6 C/cm^2 and $\sim$ 2.2 C/cm^2 for the highest irradiated ones, corresponding respectively to about 1 (chamber C), 8.5 (chamber B) and 11.5 (chamber A) years of operation at LHCb. At the end of the test the chamber C has shown no aging, while current drops of $\sim$89% and $\sim$80% were observed respectively for chamber A and B, Fig. 2.
The result obtained in the global aging test has

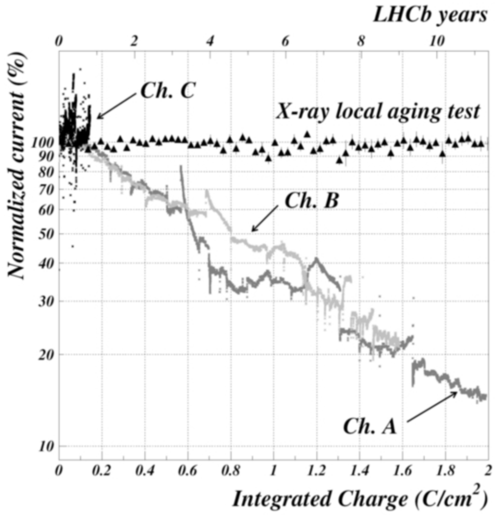

Figure 2. Comparison between local aging and the global irradiation test at the ENEA-Casaccia.

been attributed to the insufficient gas flow rate (350 cm^3/min, the maximum flow reachable with our mass-flowmeters) with respect to the very high gamma rate (up to $\sim$ 20MHz/cm^2 equivalent m.i.p. on the whole detector area, corresponding to a pad current of the order of 400-500 μA) at which chambers were exposed during the irradiation test. On the contrary local tests were performed in completely different experimental conditions: a gas flow rate of 100 cm^3/min for a global detector current of 0.2-0.4 μA (over an irradiated area of the order of 1 mm^2).
In this framework we believe that the Casaccia

test has been performed in strong *gas pollution* conditions and then should be considered pessimistic and misleading. In fact, in such test conditions chambers were probably submitted to a strong plasma etching by fluorine, produced in the fragmentation of the CF_4 , and not quickly removed by the gas flow. As a consequence, permanent changes should be found on the GEM foil, in particular on the GEM holes diameter and probably also on the holes shape, especially on the third GEM foil, where the global amplification is larger.
Several checks and measurements successively done on the aged chambers support such hypothesis.

3. Beam test results on aged chambers

The performance of the two chambers, A and B, were measured before the Casaccia test at the electron beam facility (BTF) of the Frascati Laboratory. After the aging test both chambers have been tested at the PS beam facility at CERN. We thus had the possibility to compare the performances of the aged chambers with those of the same chambers before their irradiation.

The results show that aged chambers exhibit practically the same performances in terms of efficiency in 20 ns time window as before their irradiation, except for moderate shifts, at higher voltages, in their working points. For chamber A the shift of the operating voltage, Fig. 3 (top), is about 15 V, without any reduction of the range of stable operation (80-90 V); for chamber B this shift results to be negligible. For a station made with these two detectors logically OR-ed, the efficiency in 20 ns time window is practically unaffected, Fig. 3 (bottom).
A possible explanation of this behaviour could be that fluorine etching results in GEM holes widening, especially on the third GEM foil, thus decreasing the global gas gain of the detector.

4. SEM analysis and X-rays test results on aged chambers

In order to understand the etching mechanism occurred during the Casaccia test, a scanning

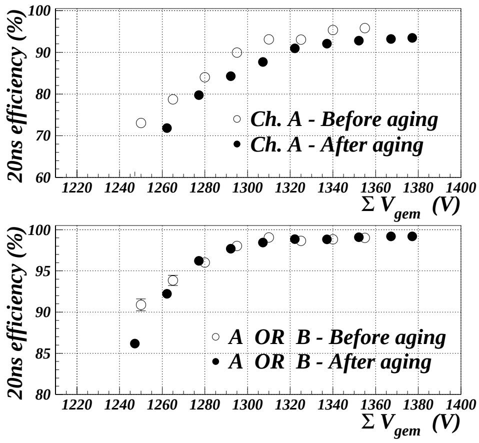

Figure 3. Efficiency in 20 ns time window before and after irradiation: (top) for chamber A; (bottom) for the two chambers logically OR-ed

electron microscope (SEM) analysis has been performed on various samples of the aged chambers. The results obtained are clearly compatible with a fluorine etching: no polymerization deposits (typical of the so called classical aging [6]) have been observed on the surfaces. As expected the etching effects are larger on the third GEM foil, minor effects are found on the second GEM, while the first GEM does not present any appreciable etching effects. The cathode (drift electrode) and the anode (the pad PCB) are perfectly clean. On both third and second GEMs the observed effect consists in a appreciable widening of the external (copper) holes diameter, from the standard 70 μm up to 80 μm. On the third GEM, where the etching processes were clearly larger, also the kapton inside holes has been etched: the effective holes diameter from the standard 45-50 μm becomes 60-65 μm, Fig. 4. Fluorine has been found only on the bottom surface of the third and second GEM, being larger on the third GEM and smaller on the second one. Fluorine is mostly located on the copper near the holes edge, leading to the formation of a thin non conductive layer (a fluorine-copper compound) in proximity of the

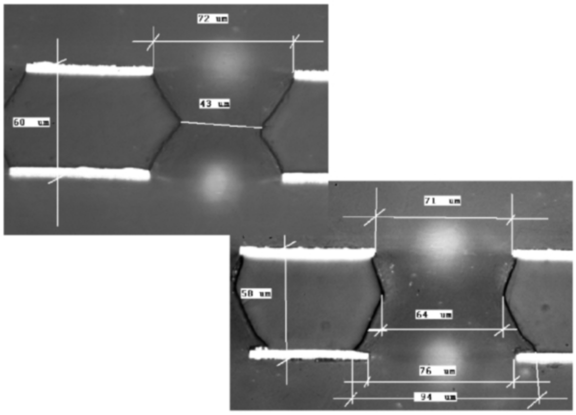

Figure 4. Cross section of first GEM foil (left) and third GEM foil (right) of aged chamber A.

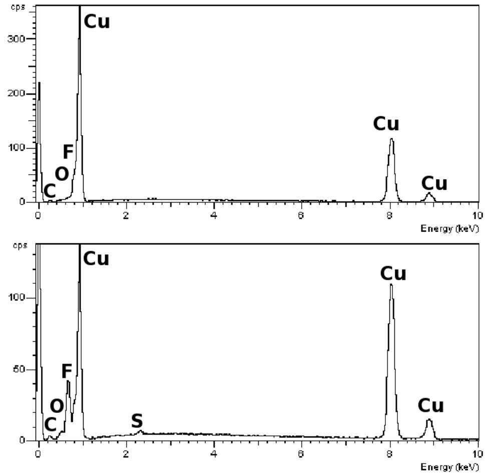

Figure 5. X-ray spectroscopy of the third GEM surfaces (top and bottom respectively) near the hole edge shows presence of fluorine only on the bottom surface.

holes, Fig. 5.

The enlargement of GEM holes leads to a decrease of the gas gain [7], while the etching of the kapton inside the holes and the non conductive layer on the copper near the hole edge, enhancing charging-up effects, reduces the rate capability of the detector (for a new detector a rate capability of $\sim$ 50MHz/cm^2 has been previously measured [8]). For chamber A the gas gain reduction measured with X-rays (at relatively low particle rate, $\sim$ 1.6MHz/cm^2) is of the order of 50-55% Fig. 6 (top), while the loss due to the rate capability reduction, Fig. 6 (bottom), is at a level of 30% at particle rate of $\sim$ 15MHz/cm^2 (the rate capability is fine up to 3-4 MHz/cm^2, well above the LHCb requirements for M1R1, $\sim$500 kHz/cm^2). These results are compatible with the current drop of 89% observed at the Casaccia test.

Finally, in order to demonstrate that the etching observed at the Casaccia test was essentially due to an insufficient gas flow rate compared with the high irradiation level, we reproduced such conditions irradiating with a high intensity X-rays beam a 10×10 cm^2 prototype, flushed with a reduced gas flow, Fig. 7. The current drawn by the chamber was about 1 μA on a 1 cm^2 irradiated area, while the gas flow was $\sim$ 20 cm^3/min. In

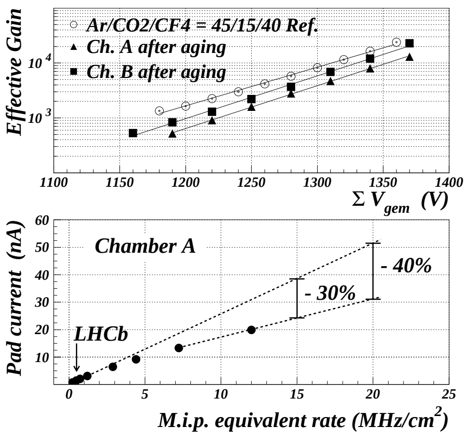

Figure 6. (top) Comparison between the gain measured on a new GEM detector and the gain measured on chamber A and B after the Casaccia aging test. (bottom) Rate capability loss of aged chamber A

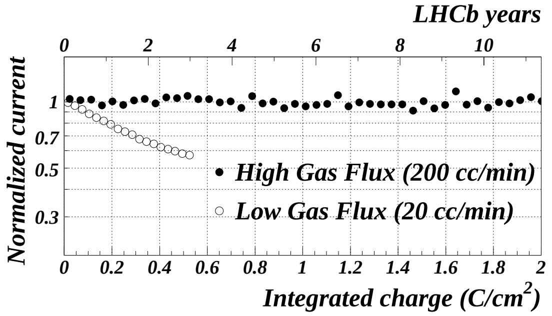

Figure 7. Comparison between the aging measured on a small prototype with low gas flow ($\sim$ 20 cm^3/min) and high gas flow ($\sim$ 200 cm^3/min).

such conditions we observe a permanent gain drop of about 40% in $\sim$3 LHCb equivalent years. The test, repeated with a gas flow of $\sim$ 200 cm^3/min and with a current of 0.5 μA on a 1 cm^2 irradiated area, gave a result compatible with no aging in about 10 LHCb equivalent years.

5. Conclusions

The results of the severe and systematic tests performed on triple-GEM detectors, indicate that the detector is robust and can tolerate the radiation dose foreseen in 10 years of operation in the region M1R1 of the LHCb experiment: detectors, even after a severe irradiation in very bad conditions, exhibit good time and efficiency (in 20 ns) performances, except for a shift of about 10-15 V on the working point, with practically unaffected working ranges.
In addition the results of the Casaccia test, apparently in disagreement with the other aging tests previously performed, have been understood. We have demonstrated that the etching observed during this test is clearly correlated with bad gas flow rate conditions. No aging occur if the gas flow is properly set. In the LHCb running conditions, where the average current collected on pads by one full size chamber will be of the order of 5μA, a safe gas flow rate could be $\sim$ 80-100 cm^3/min.

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