The Operational Experience of the Triple-GEM Detectors of the LHCb Muon System: Summary of 2 Years of Data Taking

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***Abstract*—The LHCb muon system consists of more than a thousand gas detectors, mostly MWPC, located in five different stations. The muon detector is used to define the muon trigger and to identify muons at the high-level triger and at the reconstruction stage. The first station of the muon detector, located in front of the calorimetric system, is made of 274 chambers. The 12 most irradiated chambers, the ones closer to the beam pipe, are double triple-GEM detectors with pad readout. These detectors have an active area of 200x240 mm^2 and are routinely operated at rates close to 300 kHz/cm^2. With the gas mixture used (Ar/$CO_2$2/CF_4 at 45/15/40) these detectors have the requested efficiency (>96% in a 20 ns time window for the logical OR of the two sensitive gaps) when operated at gains of about 4300. In this presentation we will report on the performance of these 24 triple-GEM detectors after more than 2 years of operation in the harsh LHCb conditions. We will also show some problems occurred during data taking, in particular on the failure of a few GEM foils following repeated discharge phenomena, and the solutions implemented to reduce the occurrence of such problems.**

***Index Terms*—Gaseous Detectors, Triple-GEM, LHCb, High-Rate Operation.**

I. Introduction

The LHCb detector at the Large Hadron Collider (LHC) has been designed for precision studies of CP violation and rare decays of heavy flavours. As the $b\bar{b}$ pairs are predominantly produced at small angles at high energies, the LHCb detector is a single forward arm spectrometer with a unique pseudo-rapidity acceptance of $1.9 < \eta < 4.9$. The Muon Detector is a fundamental part of the detection system, which allows to trigger on muons with large transverse momentum The muon detector is also used at the high-level trigger and at the reconstruction level to unambiguously identify muons.

The Muon System consist of five stations [1]. The first muon station (M1) is located before the calorimeters: this is used to provide, at the muon trigger level, a better estimate of the muon trasverse momentum because the muon impact point on the first station is not affected by the muon multiple scattering in the calorimeter and in the muon system iron walls.

The information provided by M1 increases the purity of the muon triggered sample (for a fixed muon trigger bandwidth) by approximately 20%. However, the particle rates in front of the calorimeters are much higher than on the other muon stations. This requires, in particular for the M1 detectors close to the beam pipe (in the so-called region 1, R1), the use of a different technology with respect to the Multi-Wire Proportional Chamber technology used in the rest of the detector.

After a long and accurate R&D program we were able to demonstrate that Triple-GEM detectors with pad readout fullfill the requirements for the M1R1 detectors [2]: they can operate at rates in excess of 500 kHz/cm^2, they have the requested efficiency in a 25 ns time-window (the time distance of two successive bunch crossings at LHC), they are robust against discharges and they will safely operate for 10 years in these conditions thanks to their radiation hardness.

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II. The Triple-GEM Detector

The central region of the first muon station, M1R1, is equipped with 12 chambers built using the triple-GEM technology. Each chamber (Fig. 1) is made of two superimposed triple-GEM detector with pad readout. The pads of the two detectors are logically OR-ed to improve the efficiency and to provide some redundancy in the trigger logic, which requires 5 aligned hits in 5 different stations to define a muon track. Each triple-GEM detector uses GEM foils built with the standard technique [3]. The ionization gap is 3 mm-thick, while the two successive transfer gaps are respectively 1 mm- and 2 mm-thick. The induction gap is 1 mm-thick to reduce the duration of the signals induced on the pads; This also increase the current sensed by the preamplifier. The pad are readout using a charge-amplifier followed by a discriminator [4]. Signals above threshold are sent to a TDC [5] and acquired. The LHCb triple-GEM detectors use a ternary gas mixture made of Ar/CO2/CF4 in the ratio 45/15/40. With an appropriate choice of the total gas gain ($4000 \div 6000$) and of the transfer and induction field values ($3 \div 5$ kV/cm) a double triple-GEM detector with logically-ORed signal have a time resolution of about 2.9 ns RMS (see Fig. 2), which translates in an efficiency larger that 96% in a 20 ns window. The spark probability per incident particle was measured on a mixed pion-proton beam and was found to be adequate [6]. Aging tests [9] have shown that the GEM detectors can safely operate for 10 years at the standard LHCb working conditions. The 24 triple-GEM detectors high-voltage is supplied by custom-made 7-channels floating power supplies [6], allowing to individually set the operating voltage of each GEM and of each transfer field. The power supply is designed to provide currents (both in

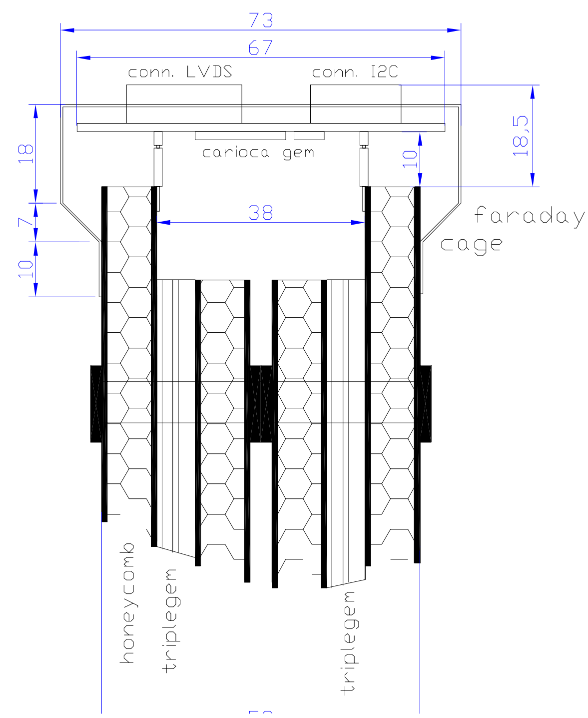


Fig. 1. Cross-section of the double triple-GEM detector used in the LHCb Muon System. Dimensions are in mm. The front-end board is also shown.

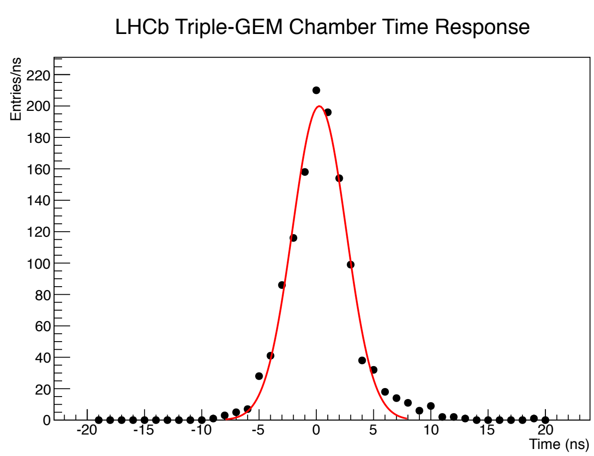


Fig. 2. Time resolution of a double triple-GEM detector with logically-ORed pad readout using a Ar/CO_2/CF_4 45/15/40 gas mixture and operating at a gain of 6000. The RMS of the time distribution is 2.9 ns.

source and in sink) up to approximately 10 μA/channel. The detector current can be monitored with a 0.1 nA sensitivity on the GEM electrode facing the readout pads.

III. The Operational Experience

The 24 triple-GEM detectors have been installed in 2009 (see Fig. 3 and Fig. 4) and have been successfully in operation since the first LHC run. In the following we will report on how these detectors performed in a hardon collider environment, which problems we found in operating them and some proposal to solve the problems found.

Fig. 3. View of the M1 (left) and M2 (right) LHCb Muon Stations from the cavern floor, with the Calorimetric System is in the open position.

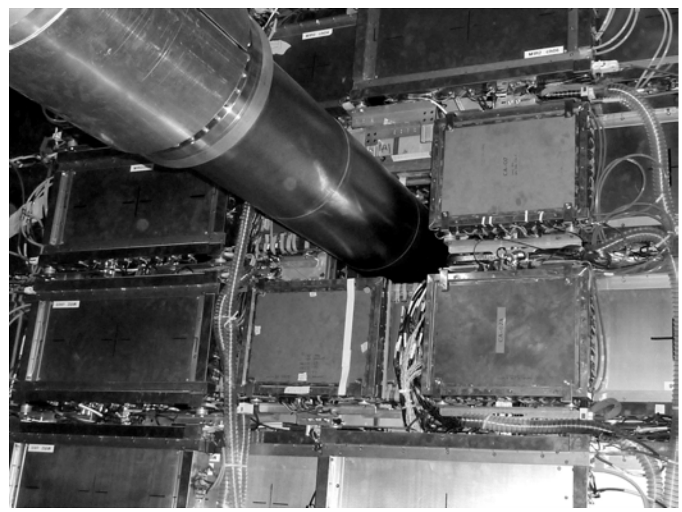


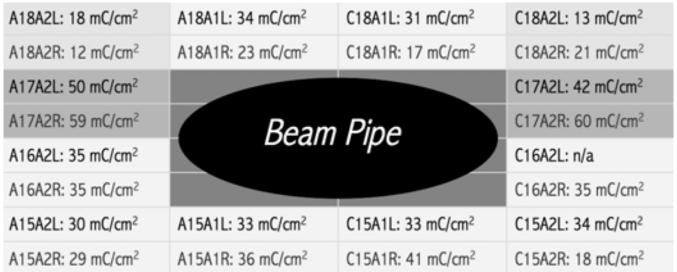
Fig. 4. View of M1 detectors around the LHC beam pipe. Detectors near the beam pipe are Triple-GEM chambers. There are six Triple-GEM chambers (of which only 3 are clearly visible in the picture) on each side of the M1 support wall.

A. Looking for Classical Aging Effects

The detectors have been operated at a gas gain in the range $4000 \div 6000$. In these conditions, and with the current LHCb luminosity, the average currents monitored on each detector range from 2 μA to 6 μA, depending on the position of the detector with respect to the LHCb beam pipe. The total charges integrated on each detector during the 2012 run up to mid-October are shown in Fig. 5. Extrapolating to the whole LHCb data taking period (2010 - end of 2012), the most irradiated detector will integrate approximately 0.12 C/cm^2, smaller than previous estimate [9], due to the reduced gain ($\sim$ 4300) at which the detectors are now operating. As of today we don't observe classical aging effects on our GEM detectors.

B. Tuning the High Voltage

Prior to the start of the LHC, we performed a lot of studies to define the optimal working point. The efficiency curve as



A18A2L: 18 mC/cm²	A18A1L: 34 mC/cm²	C18A1L: 31 mC/cm²	C18A2L: 13 mC/cm²
A18A2R: 12 mC/cm²	A18A1R: 23 mC/cm²	C18A1R: 17 mC/cm²	C18A2R: 21 mC/cm²
A17A2L: 50 mC/cm²	Beam Pipe		C17A2L: 42 mC/cm²
A17A2R: 59 mC/cm²			C17A2R: 60 mC/cm²
A16A2L: 35 mC/cm²			C16A2L: n/a
A16A2R: 35 mC/cm²			C16A2R: 35 mC/cm²
A15A2L: 30 mC/cm²	A15A1L: 33 mC/cm²	C15A1L: 33 mC/cm²	C15A2L: 34 mC/cm²
A15A2R: 29 mC/cm²	A15A1R: 36 mC/cm²	C15A1R: 41 mC/cm²	C15A2R: 18 mC/cm²

Fig. 5. Integrated charge on LHCb Triple-GEM detectors for 1.5 fb^{-1} integrated luminosity during the 2012 LHC run. Each case representing the detector is also approximately located in its correct position around the LHC beam pipe.

a function of the voltage [10] shows a plateau starting at a gain of about 4000. The discharge probability, measured at the mixed pion-proton beam πM1 at PSI [6], increases exponentially with the gain. It was estimated that operating the detectors at a gain of about 6000 would guarantee a safe operation for the 10 years of LHCb running. According to our studies with α-particles [7], in order do not exceed the Raether limit, we set a decreasing gain between the three GEM foils, ranging their HV from 435 V to 415 V. During these years of data taking we experienced the short of four GEM foils, one in 2010, two in 2011 and one in 2012. All of these shorts occurred on the first GEM foil, the one set at the highest voltage. This occurred, in three of the four cases, after a short period of instabilities of the current of the detector, which eventually lead to the short of the GEM foil. Such events were not detected in time because our HV system does not have an hardware over-current protection. An earlier detection of this current instability, followed by a reduction of the detector high-voltage, would probably have avoided the occurrence of these shorts. The last detector suffered of a sudden GEM short not preceeded by any current instabilities.

To prevent the occurrence of such events we have, during 2011 and 2012, progressively reduced both the total gain from 6000 to approximately 4300 and the gain sharing between the GEM foils. We are currently using a uniform HV setting, 415 V on every GEM foil. The positive effect of this is visible from the behavior of the detectors during a fill, which show a much more stable current and discharge events are very rare. We have performed some investigations in order to understand why the first GEMs seem to be more sensitive to discharges. We suspect that the discharge rate, in particular on the first GEM, is higher than what we expected because of the neutrons which are present in this region. Neutrons convert on the detector material surrounding the gas volume and create heavy ionizing protons which deposit a huge charge in the detector gas, in particular in the ionization gap, possibly triggering discharges. Slightly reducing the voltage on the first GEM substantially reduces the discharge probability of the first GEM, providing a more reliable operating point for our detectors.

C. Monitoring the Gas Mixture

The LHCb Triple-GEM detectors use an $Ar/CO_2/CF_4$ (45/15/40) gas mixture flowing at about 7 chamber volumes/hour. The gas system was built and is operated by the CERN Gas Group [8]. It is an open-loop system. The gas mixture is analyzed with a gas chromatographer and a water and oxygen measuring system. The return gas is sent in an exahust line common to all the other gas detectors of the experiment, preventing the analysis of the output gas. A portable gas chromatographer can be used occasionally to perform such analysis. During this year's data taking period

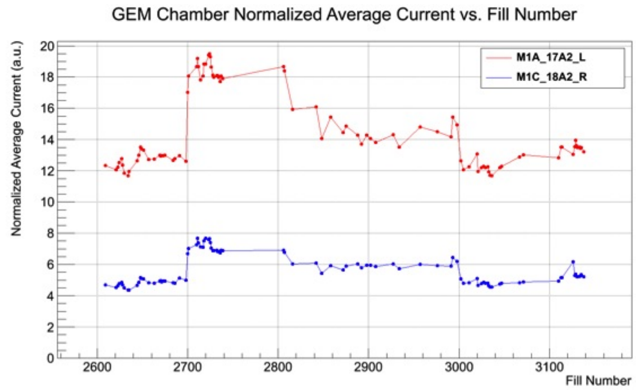


Fig. 6. Luminosity-normalised average fill currents on two Triple-GEM detectors during LHC fills in 2012. The current "jumps" at around fill 2700, 2805, 3000 are correlated with a change in the CF_4 gas bottle. Current variations are approximately +40% at fill 2700 and -20% at fills 2805 and 3000.

we have found occasional but sudden variations, up to $\pm 40\%$, in the all detectors gain (see Fig. 6). To understand these gain variations the CERN Gas Group carefully checked the gas mixture with the gas chromatographer. Although initially the gas mixture appeared to be the correct one, and also completely compatible with the content of one of our reference premixed gas bottle, some variations were eventually found on oxygen and nitrogen content. It was also discovered that these sudden gas gain variations were correlated in time with the change of the CF_4 gas bottle. At the moment, although the situation has not been clarified yet, we suspect that the CF_4 bottles may contain a small percentage of some contaminants that are responsible of the variation of the detector gains.

This problem shows how difficult it can be to have a good knowledge on the detector gas mixture in an experiment, where stable detector operating conditions are required. It appears to us extremely important to implement redundant gas checking tools, to be able to provide cross-checks of the gas mixture.

We have built a gas monitoring station which consists of a small Triple-GEM detector illuminated with a low intensity radioactive source, to be used as a gain monitoring device. This device will be put in operation during next year shutdown period.

IV. Triple-GEM Performance

The detectors have the expected performance in term of efficiency, ($> 96\%$), as shown in Fig. 7.

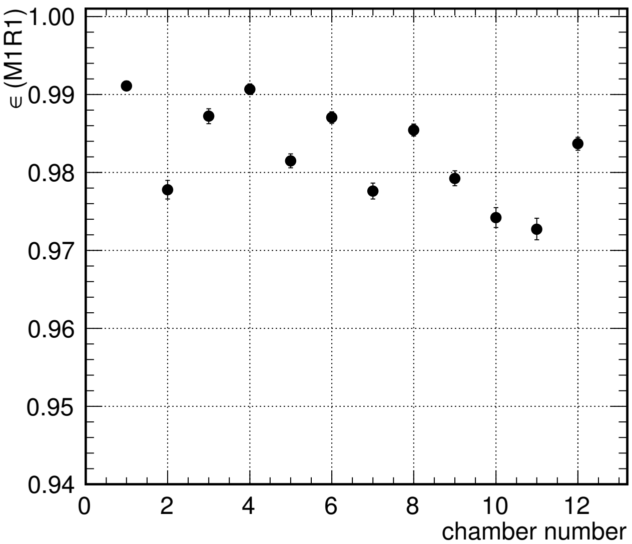


Fig. 7. Efficiency of all the twelve GEM chambers during 2012, when operating at a gain of about 4300.

V. Conclusion

The 24 Triple-GEM detectors used in the LHCb Muon System are in operation since 2010. Shorts occurred on the first GEM foil of some detectors indicated that it was necessary to slightly reduce the global the gain and to adjust the gain sharing among the trhree GEM foils. Some studies to improve the working point are still ongoing. Concerning the observed failures of the first GEM foil, we believe that these are likely due to neutrons converting in the detector material. More investigation are continuing to completely clarify this effect, an important fact to take into account when operating micropattern gaseous detectors in a hadron collider environment.

The problems we are experiencing with the gas mixture suggested us to implement a redundant system to directly monitor the detector performance.

Despite the few issues we had in operating Triple-GEM detectors in the LHCb experiment, these detectors continue to perform according to their specification in the very harsh LHCb environment.

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