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Fast triggering of high-rate charged particles with a triple-GEM detector

M. Alfonsi[a], G. Bencivenni[a], W. Bonivento[b], A. Cardini[b], P. De Simone[a], F. Murtas[a], D. Pinci[c], M. Poli-Lener[a], D. Raspino[b,d,*]

[a]Laboratori Nazionali di Frascati - INFN, Frascati, Italy
[b]Sezione INFN di Cagliari - Cagliari, Italy
[c]Università degli Studi di Roma 'La Sapienza', Italy
[d]Università degli Studi di Cagliari, Cagliari, Italy

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Abstract

A 3 year long R&D activity on triple gas electron multiplier (GEM) detectors is reported. This activity was made in the framework of the LHCb experiment in order to find the technology to instrument the central region of the first muon station (M1R1) where a high particle rate is expected. Detector geometry, gas mixture and electric field configuration have been optimized in order to achieve the performance required by the experiment. The use of a very fast, CF_4 based, gas mixture provides a time resolution of about 4.5 ns (r.m.s.) with a single chamber with gain less than 10^4. In addition, an optimized gain sharing between the three GEMs allows to keep the discharge probability per incident hadron below 10^{-12}. The average number of firing pads per crossing particle have been found to be lower than 1.2. In a global aging test two detectors were exposed to a dose rate of 16 Gy/h. Each detector integrated about 2 C/cm^2 equivalent to more than 10 years of operation at LHCb. Good aging properties were measured. These results make the triple-GEM detectors a good solution for M1R1 and, in general, for a fast trigger in the presence of a high rate of charged particles.

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1. Introduction

The Gas Electron Multiplier (GEM) [1] is a thin (50 μm) metal-coated kapton foil, perforated by a high density of holes (70 μm diameter, pitch of 140 μm). By applying voltages of 400–500 V between the two copper sides, an electric field as

*Corresponding author. Sezione INFN di Cagliari - Cagliari, Italy.
E-mail address: davide.raspino@ca.infn.it (D. Raspino).

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high as $\sim 100\,kV/cm$ is produced inside the holes, which act as multiplication channels for electrons produced in the gas by an ionizing particle. Gains up to 1000 can be easily reached with a single GEM foil. Higher gains (and/or safer working conditions) are usually obtained by cascading two or three GEM foils. The triple GEM detector is an interesting device for triggering in a high-rate charged-particle environment because of its high rate capability, good spatial resolution, extremely low spark probability, and good timing performance. We have developed this detector for the innermost region of the first muon station of the LHCb experiment. The requirements of the experiment in this region are [2]: the detector must be able to work at a rate up to $\sim$0.5 MHz/cm^2, the efficiency of a station (made of 2 detectors in OR) must be higher than 96% in a time window of 20 ns, the average multiplicity must be less than 1.2 (with $1\times2.5\,cm^2$ pad size), and this performance must be maintained for 10 years at LHCb. The detector geometry optimization and the gas mixture choice to satisfy the LHCb requirements are presented here. The results of the measurements to verify if the detectors satisfy the LHCb requirements are also reported.

2. The detector

The triple GEM detector consists of three GEM foils as shown in Fig. 1 ($20\times24\,cm^2$). GEM foils are stretched and glued on frames to hold the mechanical tension. The frames are the only spacers between GEM foils. They are glued to each other between two gold planes that act as cathode and anode. This sandwich is gas-tight.

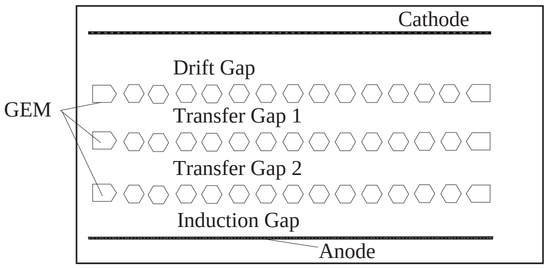


Fig. 1. Cross-section of a triple GEM detector.

The anode is segmented into pads to provide the spatial information and these electrodes are read out with charge/current preamplifiers. The volume between the cathode and the first GEM (3 mm) is usually referred to as the drift gap. This is also the sensitive volume of the detector. The transfer gaps (1 mm the first, 2 mm the second) are the volumes between the GEMs, as shown in Fig. 1. The volume between the last GEM and the anode is usually called the induction gap (1 mm). Two such sensitive volumes are used to make an M1R1 chamber at LHCb.

3. The gas mixture

The gas mixture has been chosen in order to achieve a high time resolution of the detector. The intrinsic limit on the time resolution of a triple-GEM detector for leading edge triggering is given by: $\sigma_t = 1/nv_d$, where n is the average number of primary clusters per unit length and v_d is the electron drift velocity [3]. The gas mixture $Ar/CO_2/CF_4$ (45/15/40) minimizes the intrinsic time spread when working with drift fields $\sim$3.5 kV/cm, as shown in Fig. 2(a).

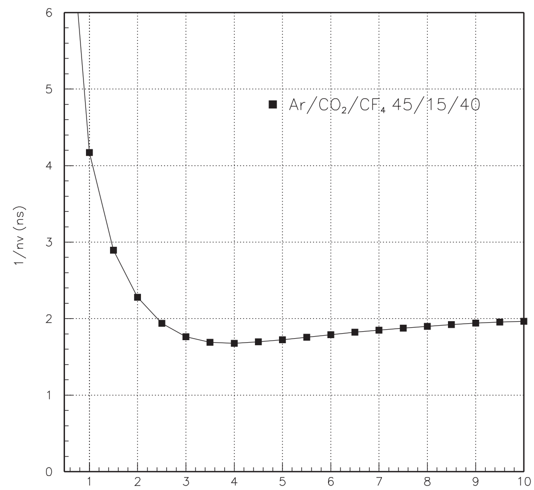
4. The electric field

The electric field in the drift gap has been set to the value (3.5 kV/cm) at which the electron drift velocity is maximized. The electric field in the transfer gaps has been set to the value (3.5 kV/cm) that maximizes the electron GEM transparency (the product of the electron collection and extraction efficiency). Transparency has been studied by measuring the gain of the detector as a function of the field in the transfer gaps. The electric field in the induction gap has been set to 5 kV/cm in order to maximize the extraction efficiency from the last GEM.

5. Measurements

5.1. Rate capability

The rate capability of the detector has been studied by irradiating the detector with a



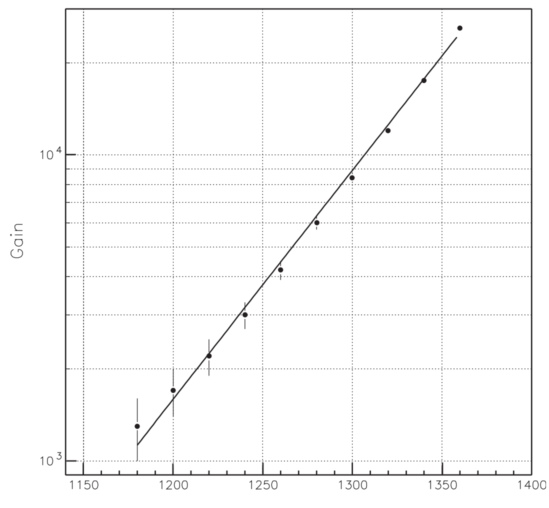


Fig. 2. (a) Calculated intrinsic time spread of a triple GEM detector vs. electric field, (b) measured detector gain vs. the sum (V_{tot}) of the voltages across the three GEMs ($V_{1,2,3}$).

high-intensity 5.9 keV X-ray beam. No drop in gain has been measured at rates up to ~50 MHz/cm^2, which is much higher than the rate expected at LHCb in M1R1 (up to ~0.5 MHz).

5.2. Gain

By using soft X-rays we have also measured the gain of the detector as a function of the sum (V_{tot}) of GEM voltages ($V_{1,2,3}$). Results of these measurements are shown in Fig. 2(b).

5.3. Efficiency in 20 ns time window

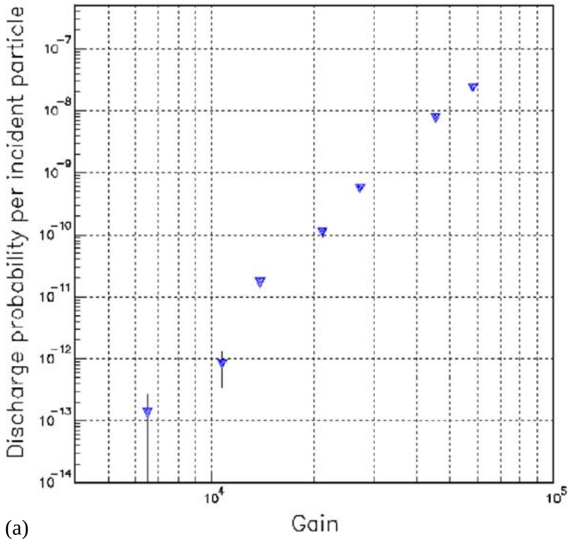
The efficiency within a 20 ns time window of two detectors in OR has been measured at BTF [4] by illuminating the detectors with an electron beam. A time resolution of 4.5 ns (RMS) for a single detector and 3.5 ns for 2 detectors in OR has been measured. The efficiency of two detectors in OR within 20 ns is reported in Fig. 3(b) as a function of V_{tot}. The efficiency is higher than 95% at $V_{tot} = 1260$ V ($G \sim 4 \times 10^3$). This represents a lower limit of the region where the detector will be operated at LHCb.

5.4. Pad-cluster size

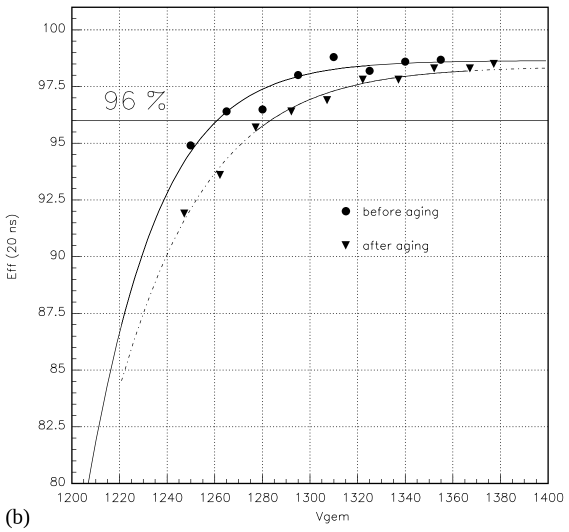
The average number of firing pads per crossing track is called the pad-cluster size. For region M1R1 the pad-cluster size has to be kept smaller than 1.2. Because of the CF_4 electron attachment which squeezes the avalanche, the pad-cluster size was found to be within the requirements over a large voltage range up to $V_{tot} = 1330$ V ($G \sim 1.5 \times 10^4$). This is an upper limit to the region where the detector will operate at LHCb (~70 V wide).

5.5. Discharge test

When a high number of charge-carrier pairs are created in the gas by an ionizing particle, the charge amount within the GEM channel may become larger than the Raether limit (10^8), and this leads to the formation of a streamer [5,6]. The conductive channel created by the streamer acts as a short circuit between the two copper sides of the GEM, thus giving rise to a discharge. A discharge leads to an increase of the current on the GEM electrode needed for the recharging and a drop of current on the pads because of the drop of the detector gain. In order to study the discharge probability per incident hadron, three detectors were for 10 days exposed to a very intense (300 MHz on a spot area of 15 cm^2) positive pion beam with 7% of protons (350 MeV/c) at Paul



(a)



(b)

Fig. 3. (a) Discharge probability per incident particle vs. detector gain, (b) efficiency of two chambers in OR before and after the aging test vs. V_{tot}.

Scherrer Institute. Each detector suffered a total of about 5000 discharges without any damage or deterioration in performance. Therefore a number of 5000 discharges seems to be a safe limit for proper detector operation. Because of the particle rate in R1M1, in order to suffer fewer than 5000 discharges in 10 years of LHCb, the discharge probability per incident particle has to be kept at less than 2.7×10^{-12}. Thus the chamber has to operate at $V_{tot} < 1340$ V ($G \sim 1.7\times10^4$ as shown in Fig. 3(a)).

5.6. Aging test

Because of the high particle flux in M1R1 (184 kHz/cm^2 on average) a detector operated with a gain of 6×10^3 will collect a total charge of $\sim$1.8 C/cm^2 in 10 years. In order to study the aging properties, two full-size prototypes were exposed to 1.25 MeV γ radiation from a 25 kCi ^{60}Co source for 40 days. The radiation dose was about 16 Gy/h and both detectors received about 2 C/cm^2 equivalent to 11 LHCb years of operation. After the test a gain drop of $\sim$50% was measured due to the increase of the GEM holes diameters in the third GEM foil. The efficiency in 20 ns was measured after the aging test in a pion test beam at CERN-PS (T11). Results are compared in Fig. 3(b) with the measurements performed before the aging test. The only visible effect of such a high integrated charge is a shift of about 20 V of the detector performance curve. After the irradiation both detectors still fulfill all other requirements (pad-cluster size and rate capability).

6. Conclusions

After more than 3 years of R&D many different characteristics of the triple-GEM detector have been investigated. The use of the high-yield, fast gas mixture Ar/CO_2/CF_4 (45/15/40) allows to achieve the efficiency and pad-cluster size requirement at a gain of 4×10^3. By working at this gain the detector will suffer fewer than 5000 discharges in 10 LHCb years. The measurements performed at the intense hadron beam of the Paul Scherrer Institute have showed that this is a safe operating condition. After collecting a total charge equivalent to 11 LHCb years, the same detector performances can still be achieved by simply increasing V_{tot} by 20 V.

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