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Triple-GEM detector operation for high rate particle triggering

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

[a]Laboratori Nazionali di Frascati, Frascati, Italy

[b]INFN Sezione di Cagliari, Cagliari, Italy

[c]Università degli Studi di Cagliari, Cagliari, Italy

We report the results of a study of triple-GEM detectors for high rate charged particle triggering. This study was performed in the framework of an R&D activity on detectors for the Level-0 LHCb muon trigger and, in particular, for the inner regions (R1 and R2) of the first station (M1), where particle rates up to 460 kHz/cm^2 are expected. A crucial requirement in this application is an efficiency higher than 99% per station (two detectors logically OR-ed) in a 25 ns time window. Results of the time performance are compared with the discharge probability per incident particle as results from a study performed with a high intensity hadron beam. We show here the considerable improvement obtained with the addition of CF_4 and/or iso-C_4H_{10} to the widely used Ar/CO_2 mixture. Which allows to satisfy the experiment requirements.

1. Principle of operation

A GEM [1] is a 50 μm thick kapton foil, clad on each side with a thin copper layer (5 μm) and perforated with a high surface density of holes.

By applying a voltage difference of the order of 500 V between the two copper sides, an electric field as high as 100 kV/cm is produced within the holes. Primary electrons created in a gas by an ionizing particle can be led towards the GEM by a suitable external electric field called *drift field* (E_d). The high field inside the channels (E_c) induces an avalanche process making them working as multiplication channels. Another electric field in the region below the GEM, the *transfer field* (E_t), extracts secondary electrons resulting in an effective gain of the order 10 $\div$ 100. In the case when the secondary electrons are drifted towards the readout strips or pads, the electric field is called *induction field* (E_i).

2. The triple-GEM based detector

A triple-GEM detector consists of 3 GEM foils sandwiched between two conductor planes: the *cathode*, which together with the first GEM defines the so called *drift gap*, and the *anode* which could be segmented in strips or pads. The use of 3 GEM in cascade gives an overall gain of the order of $10^4 \div 10^5$, which is a good solution for minimum ionizing particle detection.

The regions between two GEM are called *transfer gaps* while the *induction gap* is the gap between the last GEM and anode. The cross-section of this detector is shown in Fig. 1.

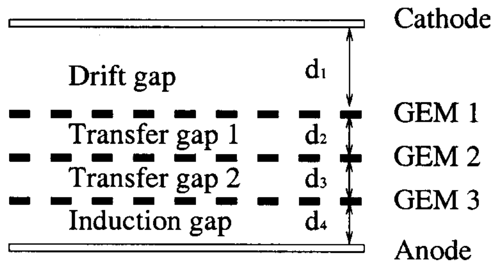

Figure 1. Triple-GEM based detector cross-section.

*Corresponding author, now at the University "La Sapienza" of Rome: davide.pinci@roma1.infn.it

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The ionisation electrons produced in the drift gap by a charged particle drift towards the first GEM where they get multiplied. By means of the transfer electric fields the electron clouds reach the second and then the third GEM. Once the electrons cross the last GEM and appear in the induction gap, they give rise to an induced current signal on the anode. This current is then amplified and shaped by the readout electronics.

3. Detector prototypes layout

The detector prototypes were built by using 10×10 cm^2 GEM. The GEM foils are stretched and glued on fiberglass frames.

After the glueing, the GEM are stacked in the gas tight box, together with the pad plane (used as anode) and with a conductive plane (the cathode) used to define the drift field. The pads used in our prototypes have 1×2.5 cm^2 dimensions. The gap thicknesses are determined by the GEM frames and no spacers are used between the GEM.

3.1. The read-out board

The signals on the pads are readout with VTX electronic boards [2]. The main characteristics of the electronic were measured in laboratory: rise time of 9.2 ns, sensitivity of 12.3 mv/fC and noise of about 1820 e^-.

Cross talk between different channels on the board was found. The height of the cross-talk induced signal was measured to be 5% of the height of the original one.

4. Time performance study

The main request for triggering in LHC experiments is to provide a high efficiency in the bunch-crossing time-window (25 ns). Thus, the detectors should ensure a good time performance. Given the Poisson distribution of number of clusters created in the drift gap, the probability-distribution of the arrival time on the first GEM for the nearest cluster is [3]:

$$P_1(t_d) = v_d \cdot \bar{n} e^{-\bar{n} v_d t_d} \quad \text{and} \quad \sigma_1(t_d) = 1/\bar{n} v_d$$

where $\bar{n}$ is the average number of clusters created per unit length and v_d is the drift velocity in the drift gap.

This gives the intrinsic value for the time resolution of a GEM-based detector if the first cluster is always detected. The signal is given by the convolution of the currents induced by the motion, in the induction gap, of the electron clouds due to the different clusters released in the drift gap by a track. Due to the statistical fluctuations of the detector gain and of the electron transparency, it could happen that the signal induced by the first cluster cannot be discriminated. In this case the second cluster is needed to make the signal go beyond the threshold. When also with the second cluster contribution the signal is not high enough, the third is needed and so on. This effect is the main cause in deteriorating the detector time resolution. In order to avoid this effect or to reduce its impact, it is necessary to increase the single electron detection capability and to reduce the time distance between the clusters and the statistical fluctuations. In particular, the latter two parameters behave, for all clusters, as the term $1/nv_d$. Thus, the choice of a *fast* and *high yield* gas mixture should help in optimising the detector time response.

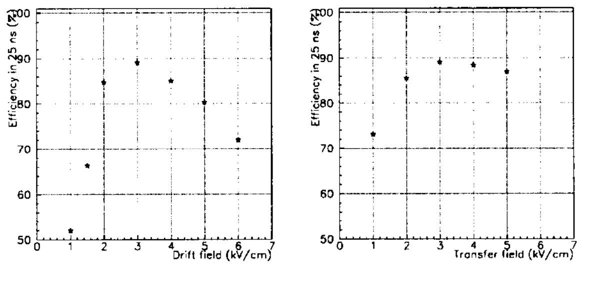
4.1. Chamber electric optimization

We measured the efficiency in a 25 ns (ϵ_{25}) window as a function of the electric fields in the drift gap (Fig. 2 (a)) and in the transfer gap (Fig. 2 (b)). In both cases we found losses in the time performance for electric field giving a poor electron transparency. The results suggested to work with E_d, E_{t1} and E_{t2} in the range $3 \rightarrow 4$ kV/cm.

4.2. Gas mixture studies

In order to improve the time performance of the chamber, a detailed study on the time response for different gas mixtures was performed. We computed the drift velocity and the specific clusterization by means of two programs: Magboltz [4] and Heed [5].

We started our tests with an Ar/CO_2 (70/30) mixture, which shows a drift velocity of 70 μm/ns for an electric field of 3 kV/cm and a production of 12 clusters in 3 mm resulting in a $\sigma_1(t_d)$=3.5 ns (Fig. 3). Even for a gain of order of 10^5 an ϵ_{25} lower than 90% was obtained (Fig. 4).



(a) (b)

Figure 2. Chamber efficiency in a 25 ns time window as a function of: the drift field (a) and the transfer field (b).

In order to improve the chamber time performance some CF_4 was added to the mixture. The pure CF_4 has a drift velocity of 130 μm/s (for E=3 kV/cm) and a production of 25 clusters in 3 mm, resulting in a $\sigma_1(t_d)$=1.5 ns.

The first gas mixture studied was a $Ar/CO_2/CF_4$ 60/20/20. In this case $\sigma_1(t_d)$=2.2 ns (Fig. 3) and an ϵ_{25} of 96% was achieved (Fig. 4). For new improvements we had interesting results with two different possibilities:

- $Ar/CO_2/CF_4$ (45/15/40);
- $Ar/CF_4/Iso\text{-}C_4H_{10}$ (65/28/7);

As the term $1/nv_d$ for these gas mixtures is the same at 3 kV/cm (1.75 ns as shown in Fig. 3), they were supposed to give the same time performance. With both the gas mixtures an ϵ_{25} of about 98 % was achieved at moderate gain ($2 \cdot 10^4$) (Fig. 4).

5. Discharge studies

The long tail in the energy loss distributions for a charged particle in a thin gas sample allows to have few events with a large amount of pairs created in the gas. In these events, the charge amount in the GEM channels may become huge, giving raise to a *streamer formation.* The streamer acts as a short circuit between the two copper sides of the GEM and the electric field in

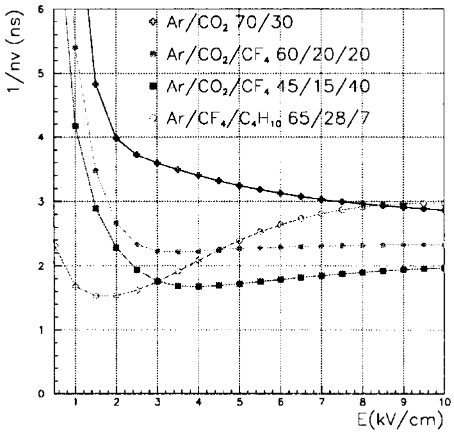


Figure 3. The 1/nv term for the gas mixture tested (the drift velocity was calculated using Magboltz [4].

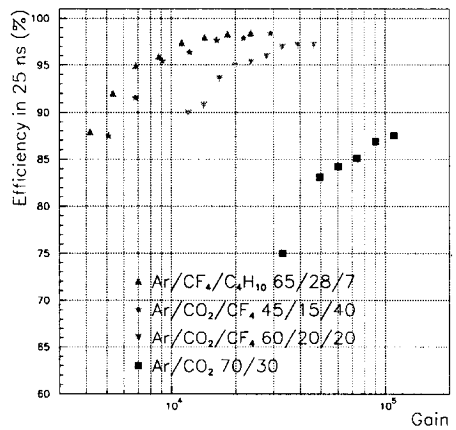


Figure 4. Chamber efficiency in a 25 ns time window as a function of the gain for the 4 gas mixtures studied.

the channels drops to zero.

This process is called *discharge* and was investigated in order to understand how to reduce the discharge probability and how many discharges a GEM detector can stand without damages or ageing effects.

The ratio n_d/N_p where N_p is the number of particle crossed the detector causing n_d discharge it is in general defined as *discharge probability per incident particle.*

5.1. Test at the Paul Scherrer Institute

In order to evaluate the discharge probability per incident particle, two chambers were built and tested on the high intensity (300 MHz) hadron beam (π^+ with 350 MeV/c momentum with a proton contamination of 7%) at the Paul Scherrer Institute (PSI).

Discharge counting has been performed by monitoring and acquiring the currents drawn by the various detector electrodes.

5.2. Ageing properties and discharge probability

In the inner regions of M1, the chambers will integrate 5 $\cdot 10^{13}$ particles and a total charge of about 13 C each cm^2. Is this detector able to survive?

The detector gain stability was investigated using an X-ray tube (5.9 keV) with two $Ar/CO_2/CF_4$ based mixtures: a (60/20/20) and a (45/15/40). In both cases gain variations less than 5 % were observed after a total integrated charge of 20 C/cm^2. Studies on the ageing caused by the $Ar/CF_4/C_4H_{10}$ (65/28/7) mixture are under way.

Because of the high particle rate, a high amount of discharges can occur and could deteriorate the detector performance. In order to evaluate the maximum amount of discharges the detector can tolerate, we plan to make a long and "destructive" test. Anyway, we can extract some useful information considering the PSI test during which the chambers had both integrated about 5000 discharges.

After the test we measured the time performance of the chambers and we did not find any deterioration in the chamber behavior. Thus, the amount of 5000 discharges seems to be a safe limit for proper detector operation. Taken into account the maximum particle rate expected in M1R1 and M1R2, this means that the discharge probability has to be kept less than 10^{-12}.

6. The working region

In order to be used in LHCb, the GEM detector should ensure a range of V_{tot} values where all the performances are within the experiment requirements. This range in V_{tot} is called *working region.* We compared the results on the time performance with the discharge probabilities in order to visualize the different working regions for the three gas mixtures.

- *$Ar/CO_2/CF_4$ (60/20/20).* The discharge probability becomes larger than the safe limit of 10^{-12} for a V_{tot}=1220 V, as shown in Fig. 5. Unfortunately, the ϵ_{25} of two OR-ed chambers is 99 % for V_{tot}=1230 V and then this gas mixture does not show any reasonable working region.

- *$Ar/CO_2/CF_4$ (45/15/40).* The value of V_{tot}=1315 V gives a discharge probability of 10^{-12}. The beginning of the working region can be set at V_{tot}=1250 V. This results in a 65 V wide working region as shown in Fig. 5.

- *$Ar/CF_4/C_4H_{10}$ (65/28/7).* This gas mixture provides both a good stability for the detector operation and good time performance. We found a working region about 40 V wide (Fig. 5) from a V_{tot} of 1035 V up to a V_{tot} of 1075 V.

7. The pad-cluster size

We studied the pad multiplicity as a function of V_{tot} in the working regions seen above. The experiment requirements tolerate a maximum pad-cluster size of 1.20 in all muon stations. The pad multiplicity for the three gas mixtures results within this limit for the V_{tot} values ensuring a discharge probability less than 10^{-12} as shown in Fig. 6.

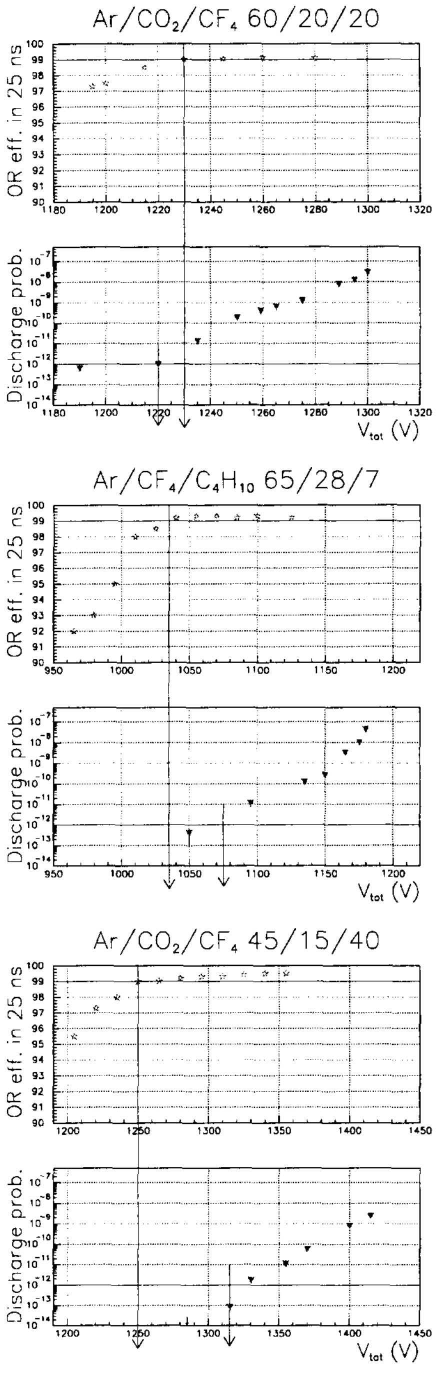


Figure 5. Performances as a function of V_{tot}.

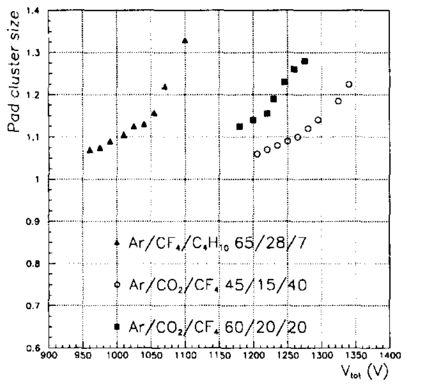


Figure 6. Detector pad-cluster size as a function of V_{tot}.

8. Conclusion

After the studies of the time performance, discharge probability, aging characteristics and on the pad multiplicity, we can conclude that the triple-GEM based detector, operated with an $Ar/CO_2/CF_4$ (45/15/40) mixture, fulfills all the requirements for equipping the two central regions of the first muon station of LHCb.

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