A Fast Multi-GEM based Detector for High-Rate Charged-Particle Triggering

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Abstract—**In this paper results of a time performance study of Gas Electron Multiplier (GEM) based detectors are discussed. This study was driven by an R&D activity on detectors for the Level 0 LHCb muon trigger. Results presented in this paper are of more general interest, i.e. for experiments in which high-rate charged-particle triggering is needed. Little interest was given so far to time performance of GEM-based detectors, with the exception of one paper reporting the measurement of a double-gem detector time resolution with an Ar/CO$_2$ (70/30) gas mixture where the authors quoted a time resolution such that high efficiency muon triggering at LHCb would be impossible. The results reported here, obtained with the addition of CF$_4$ and isobutane to the Ar/CO$_2$ standard mixture, considerably improve the time performance discussed in the above mentioned paper, allowing to reach a time distribution r.m.s. of 5 ns with an isobutane based mixture. In these conditions a spark probability per incoming hadron has been preliminary measured to be in the range $5{\cdot}10^{-12}\div10^{-11}$ at 95 % confidence level. These facts make the triple-GEM detector a promising option for high-rate charged-particle triggering.**

Keywords—**GEM, tracking, PACS 29.40.Cs, 29.40.Gx**

I. Introduction

Detectors with one or more GEM foils [1] have been extensively studied in the last four years and are currently used as tracking device [2] or as a part of a tracking device [3] in high rate experiments. In particular, when space resolution in the range 50 μm to few mm is required, they represent a cheaper solution compared to the well established solid state detector technique. Multi-GEM detectors have also be found to be quite robust against radiation damage.

However, little interest was devoted so far to the optimisation of the time response of GEM detectors. One important application of a tracking detectors is triggering. In a collider environment a critical issue is bunch crossing identification, which sets an upper limit to the detector time resolution, when requiring high trigger efficiency. The work described in this paper originated from an R&D activity on detectors for the Level 0 LHCb muon trigger.

Only one paper [4] has so far presented a measurement of a double-GEM detector time resolution, with the gas mixture Ar/CO$_2$ (70/30). The authors of that paper quote a resolution of about 10 ns r.m.s. without software corrections. If one considers the fact that at the LHC collider the time between bunches is 25 ns, for such a detector only about 80% of the hits will fit in a time window of 25 ns width, implying that no high-efficiency muon-triggering could be performed at LHCb.

In this paper we present the latest test-beam results on time-resolution measured with different gas mixtures. Preliminary results on discharge probabilities are also given.

II. The triple-GEM detector

A GEM is made by a thin (50 μm) kapton foil, copper clad on each side, perforated with high surface density of holes, each one acting as an electron multiplication channel. Each hole has a bi-conical structure with external (internal) diameter of 70 μm (50 μm) and a pitch of 140 μm. The bi-conical shape of the hole minimises the effect of charging-up of the kapton inside the holes (with respect to GEM with holes with conical shape) and is a consequence of the double mask process used in standard photolitographic technologies. A typical voltage difference of 350 to 500 V is applied between the two copper sides, giving fields as high as 100 kV/cm into the holes, resulting in an electron multiplication up to a few thousands. Multiple structures realized by assembling two or more GEMs at close distance allow high gains to be reached while minimising the discharge probability.

The triple-GEM detector, which consists of three gas electron multiplier (GEM) foils [1] sandwiched between two conductive planes, one of which, the anode, is segmented in pads and connected to the readout electronics, can be effectively used as a tracking detector. A cross-section of this detector is shown in Fig. 1.

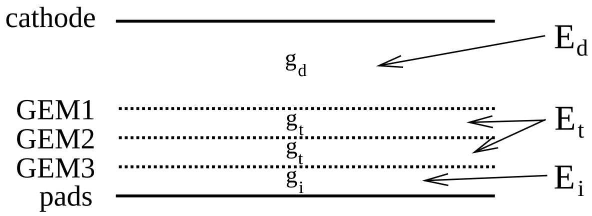

Fig. 1. Cross-section of the triple-GEM detector. E_d, E_t and E_i are the drift, transfer and induction fields, respectively. g_d, g_t, and g_i are the drift, transfer and induction gaps, respectively.

The ionisation electrons, produced in the gap between the cathode and the first GEM foil (drift gap) by the charged particles crossing the GEM, are attracted by electric fields through the three GEM foils where they get multiplied. Once they cross the last GEM foil they drift to the anode in the so called induction gap, giving rise to an induced current signal on the pads.

III. Detector requirements

The LHCb muon detector system consists of five stations of chambers. The first station (M1) is located in front of the electromagnetic calorimeter while the other four (M2 to M5) are

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located behind the calorimeters and are separated one from the other by iron walls [5].
The main purpose of the muon system is to give the Level 0 trigger for muons coming from b-flavoured hadron decays. To do this, the trigger requires for a muon candidate to give a hit in all five stations with unambiguous bunch-crossing identification with an efficiency of 95% for the muons inside the acceptance.

Most of the muon system will be equipped with Multi-Wire Proportional-Chambers (MWPC), while the outer part of stations 4 and 5 will be equipped with Resistive Plate Chambers (RPC). No technology has been chosen yet for the inner part of station 1, where particle rates of the order of 500 kHz/cm^2 are expected. The total area of this part of station 1 is about 1 m^2.

A detector located in region 1 should satisfy very tough requirements in terms of rate capability, efficiency, dead time, number of adjacent pads fired per track and radiation hardness.

To achieve 95% overall trigger efficiency on muons in a bunch crossing interval, each station must have an efficiency of more than 99%. For redundancy, two independent detector layers per station are foreseen, which will be logically OR-ed; therefore, the requirement for the single chamber is of at least 90% efficiency. MWPC and RPC detectors already selected for LHCb already satisfy the efficiency requirement with a leading-edge time pick-off method. For uniformity of the readout chain, this method should be used for the inner regions of M1. However, the high rate indeed prevents methods lenghtening the pulse shape such as zero-crossing or constant-fraction, increasing inefficiency by dead time. Measurements of GEM-based detector time-resolution, as discussed in the Introduction, indicate that the 90% efficiency in a 25 ns time-window requirement is not met by the GEM-based detectors with the Ar/CO$_2$ (70/30) gas mixture.

The detector will be operated up to a rate of 500 kHz/cm^2; correct detector response of a triple-GEM detector operated at similar high flux of charged particles was already verified [4].

The pad multiplicity, i.e. the number of adjacent detector pads fired when a track crosses the detector perpendicular to it, should not be larger than 1.2 for a 10 mm x 25 mm pad size. Published results indicate a transverse avalanche size of about a millimeter [4].

Dead time should be less than 50 ns; this puts stringent limits on both pulse width and on the maximum tolerable discharge rate. Discharge probabilities for triple-GEM detectors were already measured both with α sources [6] and charged particle beams [2]. However, the discharge probability strongly depends on detector parameters and gas mixture and measurements need to be performed with the final chosen configuration.

The detector should also operate in a harsh radiation environment. If it is operated with the Ar/CO$_2$ (70/30) gas mixture and a total gain of 10^4, it would integrate a charge of about 6 C/cm^2. Aging measurements were so far performed on multi-GEM devices only with the Ar/CO$_2$ (70/30) gas mixture [7] and no degradation of the response was observed up to 27 mC/mm^2.

IV. OPTIMIZING TIME PERFORMANCES

Signal formation in GEM detectors takes place in the induction gap, which behaves in this respect as an ionisation chamber.

Assuming no cross-talk to adjacent pads and a constant electric field, the signal induced on a pad by one electron drifting in the induction gap for a time $t_{drift} = g_i/v_{drift}$, where v_{drift} is the drift velocity of electrons and g_i is the induction gap size, is a current pulse of intensity $I = e/t_{drift}$ and duration t_{drift}.

The total signal induced on a pad by a track crossing the GEM is given by the sum of signals due to the single ionisation electrons, amplified by the multiplication through the GEM foils, each one delayed in time by the corresponding electron drift time in the drift gap. The total signal has then to be convoluted with the amplifier response to get the signal at the discriminator input. The discriminator crossing on the signal rising edge gives the time of the event.

The signal rising edge at the amplifier input has a stepwise profile, each step corresponding to the signal of an ionisation cluster (the time spread of electrons within a ionisation cluster is much smaller than the time difference between clusters). Then, the detector time resolution will be determined by the time distribution of the first ionisation clusters and the corresponding signal amplitude fluctuations, both in the ionisation process and in the multiplication through the GEMs.

The number of ionisation clusters produced in the drift gap follows a Poisson distribution. Therefore, the distance x of the ionisation cluster nearest to the first GEM has the probability distribution $P(x) = n \cdot exp(-nx)$, with $\sigma(x) = 1/n$, where n is the number of ionisation clusters per unit length [8]. In the ideal situation where the first ionisation cluster is always triggered and without the time-walk effect, the detector time resolution would be $\sigma(t) = (n \cdot v_{drift})^{-1}$. The other ionisation clusters have a probability distribution with larger $\sigma(x)$ than the first one, though still proportional to $1/n$. Thus, in order to optimise the time performance of the detector, a large average atomic number and high drift velocity gas mixture should be used [8].

As explained before, to optimise the time resolution, it is important to maximise the detection efficiency of the first ionisation clusters. The distribution of the number of electrons per ionisation cluster [10] is such that in about 70% of the cases only one electron is produced. This shows that high efficiency in single electron detection - at the first GEM - is required.

This efficiency critically depends on the configuration of the electric fields. While higher electron multiplication in the gas and therefore voltage across the GEM clearly leads to higher efficiency (until the space charge limitation becomes effective, which happens at very high gains), the dependence on the drift (E$_d$) field and on the transfer field (E$_t$), i.e. the field below the GEM, is less obvious and had to be studied in detail.

V. OPTIMIZING DETECTOR GEOMETRY

It is clear from the previous discussion that detector optimisation for high rate triggering is the result of a compromise among some conflicting requirements.

The size of the drift gap g_d has to be large enough to minimise inefficiencies in charged particle detection but should be kept small to reduce the dead time due to pulse width. With a 3 mm gap and fast amplifiers, the pulse width would be less than 40-50 nsec, which satisfies the requirements.

Since the longitudinal diffusion is minimal due to the small drift path of the electrons in the detector, the only effect of the transfer gap is to give a delay to the detected pulse. However, a large ionization in the first transfer gap might result in a signal exceeeding the discriminator threshold. This will be seen as a hit early in time with respect to hits coming from the amplification of the charge deposited in the drift gap. To minimise the impact of this effect, called by us the *bi-gem* effect, the size of the first transfer gap g_t was set to 1 mm. We did not want to reduce more the size of the gap because below 1 mm it is very difficult to keep a good uniformity in the gap thickness all over the detector active area.

Given the fast amplifiers we used in this test, the size of the induction gap g_i should be small to increase the amount of charge integrated by the amplifier (with a charge integrating amplifier with large integration time constant the gap size would not matter). A lower limit to the size of the induction gap was considered again to be of about 1 mm to guarantee a good uniformity in gap thickness. This seems also a good choice in order to minimise the discharge probability, which is likely to be affected by the gap width itself [6].

VI. DETECTOR CONSTRUCTION

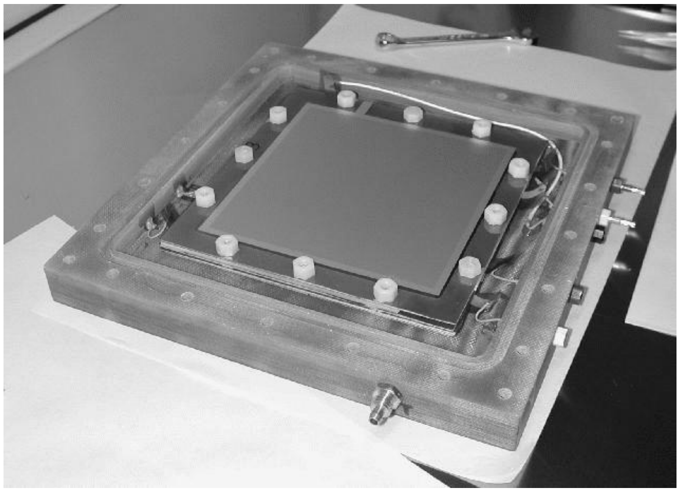

Fig. 2. Three GEMs stacked in the box. The box acts as both GEM support and gas container.

For the measurements described in this paper, some detector prototypes were built. The three 10 cm x 10 cm active surface GEM foils [11] were fixed on G10 frames with an epoxy glue.The anode was segmented in 10 mm x 25 mm pads. The cathode was made of a kapton foil, with copper on one side, glued on a similar frame. All frames were then fixed to the G10 gas-tight box with nylon screws (Fig. 2). The enclosed gas volume was approximately 0.5 l. The high voltage was fed with individual channels to the top and bottom side of each GEM and to the cathode through an R-C-R filter, for a total series resistance of 2 MΩ. The gas flow rate was set to 2.2 l/h.

For this test, the KLOE-VTX fast amplifier [12] already developed for wire chambers, was used. For few pF input capacitance, such as for the pads of our triple-GEM detector, the characteristics of this amplifier are 5 ns peaking time, 1300 e^- r.m.s. equivalent noise charge, 25 mV/fC sensitivity and 110 Ω input impedance.

VII. BEAM TEST SETUP

The measurements were performed at πM1 pion beam facility at the Paul Scherrer Institute (PSI), Villigen, Switzerland. The beam is a quasi-continuous 350 MeV/c pion beam with a maximum total intensity of 100 MHz on the detectors active area. The trigger consisted of the coincidence of two 10 cm x 10 cm area scintillators, centred on the beam axis, about 1 m from each other. The coincidence of the S1 and S2 signals was sent to a constant fraction discriminator and delayed to give the common stop to a 16-bit multi-hit TDC, with 0.8 ns resolution and 20 ns double-hit resolution. The discriminator threshold on the triple-GEM detector signal was set to about 15 mV, in order to have the noise counts below 100 Hz. For each run 50,000 triggers were collected.

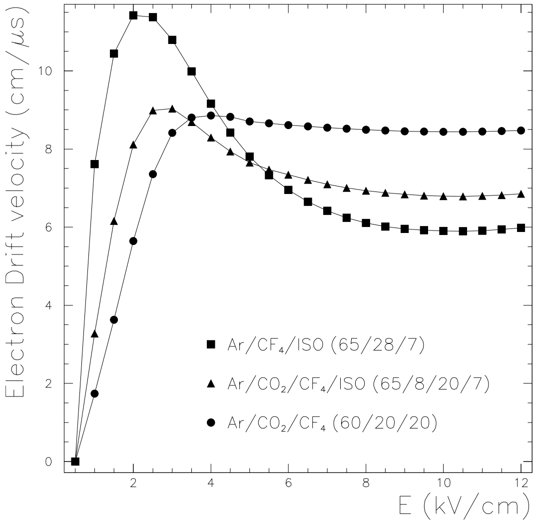

Fig. 3. Simulated electron drift velocities for the three gas mixtures described in the text.

Two different beam settings were used. A low intensity condition (30 kHz on the detectors) was used for efficiency and time-resolution measurements. The maximum beam intensity was chosen for spark probability measurements.

Three different gas mixtures were used: $Ar/CO_2/CF_4$ (60/20/20), $Ar/CO_2/CF_4$/iso-C_4H_{10} (65/8/20/7), and Ar/CF_4/iso-C_4H_{10} (65/28/7). These gas mixtures show a high electron drift velocity at low field (Fig. 3). This is a very interesting property for fast GEM-based detectors since electron collection by GEM holes is higher at low field.

VIII. RESULTS

For the data analysis, events with large ADC signals in the trigger scintillators, which might have originated from two tracks coming within the ADC gate of 200 ns were rejected. No significant correlations between analysis cuts and detector time resolution were found. For efficiency measurement, the time of the event measured with each detector was defined as the first time of threshold crossing among those channels which were above threshold.

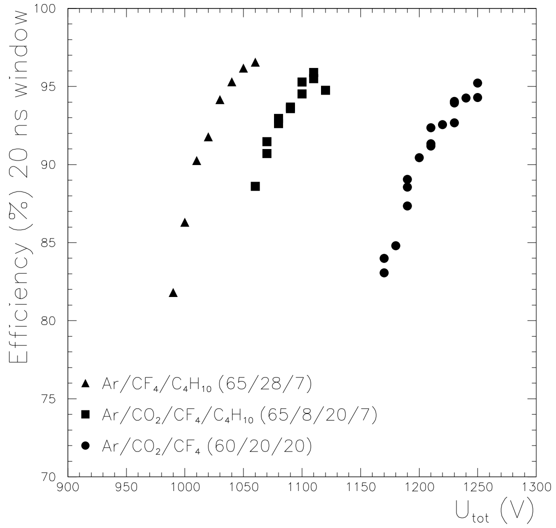

Fig. 4. Detector efficiencies in a 20 ns time window for the gas mixtures described in the text, as a function of the sum of the high voltages applied on all GEMs.

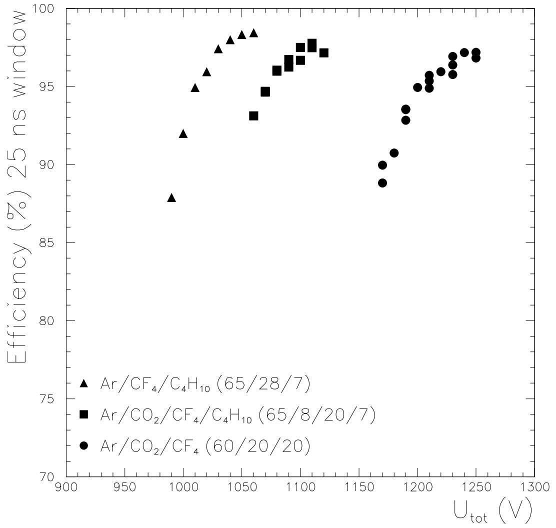

Fig. 5. Detector efficiencies in a 25 ns time window for the gas mixtures described in the text, as a function of the sum of the high voltages applied on all GEMs.

The best values for the electric fields E_d, E_t and the voltage applied to the GEM (U_{gem}) were experimentally determined by optimising the detector efficiency in a given time window. The value of E_t and E_i were fixed at 3kV/cm and 5 kV/cm respectively. The value of E_d was fixed at 3 kV/cm when using Ar/CO_2/CF_4 (60/20/20) and at 2 kV/cm for the isobutane-based gas mixtures.

The threshold value was kept small to reduce the influence of the time-walk effect and to increase the probability to trigger on the first ionisation cluster. As mentioned above, to improve the detection efficiency of the first cluster and reduce the influence of the time-walk effect it is also useful to have large amplification in the gas and therefore a high total GEM gain. To achieve a given total gain, instead of raising the three GEM voltages at the same time, it is better to increase only U_{gem1}. Beyond improving slightly collection efficiency, this minimises gain fluctuations where they are larger, i.e. in the first gap where a small charge is produced. In this way the influence of the *bi-gem* effect, i.e. the amplification of the ionisation electrons produced in the first transfer gap, out of time with respect to those coming from the drift gap by $\Delta t = g_t/v_{drift}$, where g_t is the transfer gap size, is also reduced.

Fig. 4 and 5 show the detector efficiencies in various time windows as a function of U_{tot}, the sum of the high voltages applied on all GEMs, for the various gas mixtures tested.

The time distributions for a detector efficiency of 90 % in a 20 ns time window are shown in Fig. 6 and 7 for the Ar/CO_2/CF_4 (60/20/20) and the Ar/CO_2/CF_4/iso-C_4H_{10} (65/8/20/7) gas mixtures respectively (the time distribution for the other isobutane-based gas mixture is similar to the one in Fig. 7).

A very good time resolution is obtained for the Ar/CO_2/CF_4 (60/20/20) gas mixture, resulting in a distribution r.m.s. of 5.4 ns. For the two isobutane-based gas mixtures an even narrower time distribution with an r.m.s. of 5.0 ns is obtained.

It should be noticed that these values of the r.m.s. of the time distribution are obtained for the lowest possible detector gain that allow LHCb requirements to be fulfilled. A further increase in gain will continue to improve the detector time resolution.

IX. SPARK PROBABILITY

The spark probability was estimated under a high-rate charged-particle flux of about 50 MHz on the detector active area. For the various gas mixtures the detector working point was such that the efficiency in a 20 ns window was of the order of 90 %. For each gas and voltage configuration at least 10^{12} hadrons were integrated on each detector (about 6 hours of data taking). A preliminary analysis of the data set shows that the spark probability is below $5 \cdot 10^{-12} \div 10^{-11}$/hadron at 95 % confidence level. These preliminary results are very encouraging. Work on this subject will continue during 2002. We are currently planning to measure the spark probability per incoming hadron for various fast gas mixtures and also to study how the spark probability varies as a function of the gain of the detector.

X. CONCLUSIONS

A time performance study of triple-GEM detectors was performed through a detailed investigation of the role played by detector geometry, electric fields and gas mixture. With the ternary gas mixture Ar/CO_2/CF_4 (60/20/20) we obtained a time distribution r.m.s. without software corrections of 5.4 ns in the conditions where we measured an efficiency of 90 % in a 20 ns time window. The isobutane-based gas mixtures allow an additional improvement in the time resolution, allowing to reach a time distribution r.m.s. of 5.0 ns in the same efficiency conditions. In these working conditions the triple-GEM detector meets the timing requirements needed for the Level 0 LHCb muon trigger.

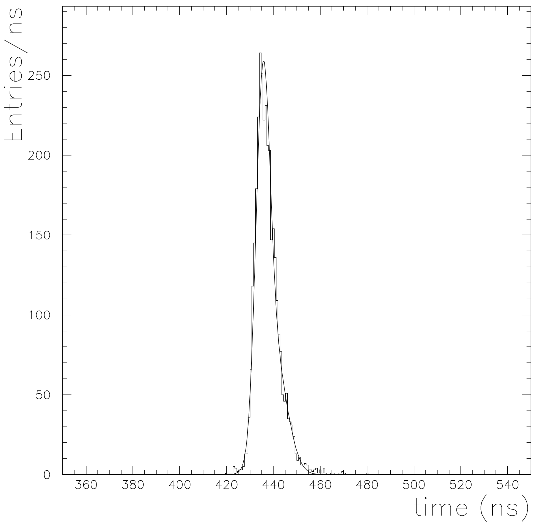

Fig. 6. Detector time response obtained with an Ar/CO_2/CF_4 (60/20/20) gas mixture. In this measurement $U_{gem1} = 430$ V, $U_{gem2} = 410$ V and $U_{gem3} = 390$ V. The r.m.s. of the distribution is 5.4 ns.

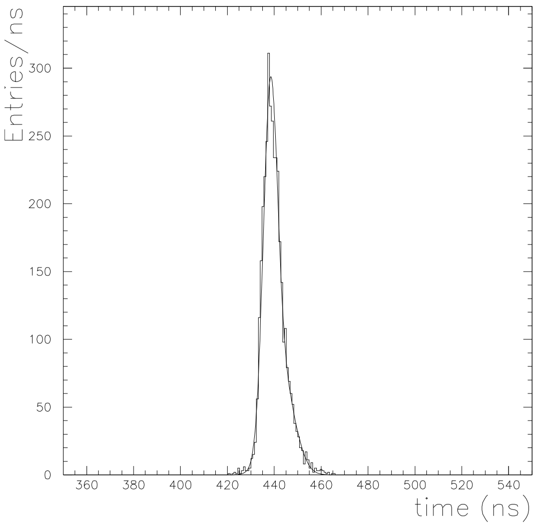

Fig. 7. Detector time response obtained with an Ar/CO_2/CF_4/iso-C_4H_{10} (65/8/20/7) gas mixture. In this measurement $U_{gem1} = 370$ V, $U_{gem2} = 360$ V and $U_{gem3} = 340$ V. The r.m.s. of the distribution is 5.0 ns.

Preliminary analysis of the spark shows that the sparking probability was found to be below $5 \cdot 10^{-12} \div 10^{-11}$/hadron at 95 % confidence level. These results make the triple-GEM detector a promising option for high-rate charged-particle triggering at LHC.

XI. ACKNOWLEDGEMENTS

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