Performance of a triple-GEM detector for high rate charged particle triggering

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Abstract

We report the results of a systematic study of the performance of $10 \times 10$ cm$^2$ triple-GEM detectors operated with several gas mixtures.

In a previous paper we pointed out that adding CF$_4$ to the standard Ar/CO$_2$ gas mixture allows to improve the time resolution of the detector from $\sim 10$ ns down to $\sim 6$ ns (r.m.s.). In this paper we discuss the results obtained with CF$_4$ and iso-C$_4$H$_{10}$ based gas mixtures, during a beam test at the $\pi$M1 beam facility of the Paul Scherrer Institute (PSI).

Preliminary results concerning the discharge probability of triple-GEM detector, when exposed to both high intensity pion/proton beam and $\alpha$-particles from a radioactive source are presented. Gain measurements and aging tests, using a high intensity 5.9 keV X-ray tube, are eventually discussed.

Key words: GEM, tracking, aging, discharge
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1 Introduction

The triple-GEM detector used in these measurements is a gas detector which consists of three gas electron multiplier (GEM) foils [1] sandwiched between a cathode and an anode electrode. The cathode, together with the first GEM

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foil defines the drift gap, whilst the anode segmented in pads is connected to the readout electronics. This detector has been developed in the framework of an R&D activity on detectors for the innermost parts (regions R1 and R2) of the first muon station (M1) of the LHCb experiment. The requirements [2] for the detector, in terms of rate capability (\(\sim 500 \text{ kHz/cm}^2\)), efficiency (\(\sim 99\%\) in a 25 ns time window) and radiation hardness (\(\sim 6 \text{ C/cm}^2\) in 10 years of operation, for a gain of \(\sim 10^4\)) are quite stringent. 

Good time performances of the detector are reached using high drift velocity and high yield gas mixtures. In a previous work [3] we showed that with the Ar/CO\(_2\)/CF\(_4\) (60/20/20) gas mixture we obtained a time resolution of about 6 ns (r.m.s.) and an efficiency of single detector of \(\sim 96\%\) in a 25 ns time window, considerably improving the detector time performance achieved with the standard Ar/CO\(_2\) (70/30) gas mixture (\(\sim 10\) ns and \(\sim 89\%\) efficiency in 25 ns time window).

In this paper we discuss the results obtained with 10\(\times\)10 cm\(^2\) triple-GEM detectors, operated with isobutane/CF\(_4\) based gas mixtures, tested at the \(\pi\)M1 beam facility of PSI. The addition of a small fraction of isobutane, inside the non-flammable limit of 7\%, resulting in a higher drift velocity, allows a further improvement on the time performance of the detector. In addition, preliminary results concerning the occurrence of discharges, induced by high intensity hadron beam as well as \(\alpha\)-particles from a radioactive source are presented. Gain measurements and aging tests, using a high intensity 5.9 keV X-ray tube, are also discussed.

2 The triple-GEM detector

The gas electron multiplier [1] consists of a thin (50 \(\mu\)m) kapton foil, copper clad on each side, chemically perforated by a high density of holes having bi-conical structure, with external (internal) diameter of 70 \(\mu\)m (50 \(\mu\)m) and a pitch of 140 \(\mu\)m. Under a suitable voltage application, 300−500 V, between the two GEM electrodes, electric fields up to 100 kV/cm are reached into the hole which acts as an electron multiplication channel for the ionization released by the radiation in the gas.

In safe condition, effective gas gains (i.e. the product between the electron multiplication and the transparency [3], [4]) up to \(10^4\div10^5\) are reachable using multiple structures, realized assembling more than one GEM at close distance one to each other.

In our tests we used 10\(\times\)10 cm\(^2\) triple-GEM detectors: the cross-section of the chamber, together with the labelling of the different detector parameters used in this paper, is shown in Fig. 1. A detailed description of the mechanical assembly of the detector is reported in [3]. The high voltage powering is
realized using individual units for each detector electrode (either GEM foils or drift cathode) through an R-C-R filter, with $R=1\ \text{M\Omega}$ and $C=2.2\ \text{nF}$. The anode was segmented in forty $10\times25\ \text{mm}^2$ pads connected to KLOE-VTX chip based pre-amplifiers [3], [5]. The main characteristics of the pre-amplifier are: $5\ \text{ns}$ peaking time, $1300\ \text{e}^-$ r.m.s. equivalent noise (at few pF input capacitance), $10\ \text{mV/fC}$ sensitivity and $110\ \Omega$ input impedance for a delta pulse input.

3 Experimental measurements

3.1 Effective gain measurements

The effective gain, $G_{\text{eff}}$, of the triple-GEM detector was measured for the three gas mixtures using a high intensity $5.9\ \text{keV}$ X-ray tube. It was obtained from the relation $G_{\text{eff}} = I (eNR)^{-1}$, where $I$ is the measured current on the pads, $eN$ the ionisation charge produced in each conversion (we assumed $\sim 200$ ionisation electrons per photo-interaction) and $R$ the measured particle rate on the pads with a scaler at the discriminator output. The discriminator threshold for these measurements was set to $70\ \text{mV}$ in order to be well above the electronic noise, without affecting the detection efficiency even at the lowest GEM gain.

Fig. 2 shows the effective gain as a function of the sum of the voltages applied on the three GEM foils. For each gas mixture the detector has been operated with fields configuration optimizing the electron transparency and the detection efficiency [3]. For comparison we also measured the effective gain for the Ar/CO$_2$ (70/30) gas mixture, commonly used from other authors for GEM operation.
Fig. 2. Effective gain vs. sum of the voltages applied to the three GEM foils. The setting of the electric fields are those of Fig. 4.

3.2 Beam test setup

The performance of the triple-GEM detector has been studied at the πM1 beam facility of the PSI. The πM1 beam is a quasi-continuous high intensity secondary beam providing up to \( \sim 10^7 \) π−/s or \( \sim 10^8 \) π+/s at 350 MeV/c for each mA of beam current in the primary beam. The study of the efficiency and time resolution of the detector has been performed with beam intensity of \( \sim 30 \) kHz, whilst discharge studies with a beam intensity of \( \sim 50 \) MHz. The size of the beam spot on detector prototypes was \( \sim 2 \times 2 \) cm².

The trigger consisted of the coincidence of two scintillators \( S_1 \odot S_2 \), centered on the beam axis, about 1 m from each other and covering the detectors active area \((10 \times 10 \) cm²). A third scintillator \( 1 \times 1 \) cm² has been used to monitor the peak beam intensity impinging the triple-GEM detector. The coincidence of the \( S_1 \) and \( S_2 \) signals was sent to a constant fraction discriminator and delayed to give the common stop to a 20-bit multi-hit CAEN TDC, with 0.8 ns resolution and 10 ns double edge resolution.

The discriminator threshold on the triple-GEM detector signal was set to about 30 mV, in order to keep the noise count rate at a level of few tens of count/sec.

All signals were sent to a 12 bits charge ADC with 50 fC/count sensitivity.

3.3 Time resolution and efficiency measurements

Three gas mixtures have been tested: the Ar/CO₂/CF₄ (60/20/20), which we used as reference gas mixture since it has been studied in the previous
beam test [3]; the Ar/CO$_2$/CF$_4$/iso-C$_4$H$_{10}$ (65/8/20/7) and the Ar/CF$_4$/iso-C$_4$H$_{10}$ (65/28/7), which are characterized by larger drift velocity at lower drift field, thus optimizing either time performance or electron transparency of the detector [3], [4]. As shown in Fig. 3 the most promising gas mixture seems to be the ternary-isobutane based one, which exhibits a drift velocity of $\sim 11$ cm/$\mu$s at 2 kV/cm.

In Fig. 4 we report the best time distributions obtained with the Ar/CO$_2$/CF$_4$,

![Fig. 4. Time distributions for: a) $\Sigma V_{GEM}$=1250 V, $E_d$ = 3 kV/cm, $E_t$ = 3.5 kV/cm; b) $\Sigma V_{GEM}$=1125 V, $E_d$ = 2.5 kV/cm, $E_t$ = 3 kV/cm; c) $\Sigma V_{GEM}$=1060 V, $E_d$ = 2 kV/cm, $E_t$ = 3 kV/cm. d) $\Sigma V_{GEM}$=1230 V, $E_d$ = 3 kV/cm, $E_t$ = kV/cm. The induction field $E_i$ was set at 5 kV/cm for all gas mixtures.](image)

Ar/CO$_2$/CF$_4$/iso-C$_4$H$_{10}$, Ar/CF$_4$/iso-C$_4$H$_{10}$ and the Ar/CO$_2$ gas mixtures: the r.m.s. of the distributions are respectively 5.3 ns, 4.9 ns, 4.5 ns, to be compared with the 9.7 ns obtained with the Ar/CO$_2$ gas mixture.

Fig. 5 shows the detector efficiency in a time window of 25 ns as a function of the global GEM voltage. The maximum values of the efficiency obtained with a single chamber are: 98.7% for the ternary isobutane based gas mixture, 97.8% for the quaternary gas mixture and 97.2% for the reference one.

The requirement of 99% for the muon detection efficiency is achieved, as shown in Fig. 6, with two detectors logically OR-ed pad by pad. We define the working points for the different gas mixtures as the operating voltages for which the efficiency is greater than 99%: $\sim 1010$ V for Ar/CF$_4$/iso-C$_4$H$_{10}$, $\sim 1075$ V for Ar/CO$_2$/CF$_4$/iso-C$_4$H$_{10}$, $\sim 1210$ V for Ar/CO$_2$/CF$_4$. They roughly correspond to a single detector efficiency (in 25 ns time window) of $\sim 95\%$ and an effective gain of the order of $10^4$. 5
Discharge studies

The occurrence of discharges in gas detectors is correlated with the transition from avalanche to streamer [6]. This transition is voltage and ionization density dependent. Indeed, for a given ionizing radiation, the increasing of the applied voltage above a certain threshold value, results in propagating streamers; on the other hand, the threshold value depends on the ionizing radiation type, being lower for highly ionizing particles. The voltage threshold is correlated with the reaching of the Raether limit, that is when the primary avalanche size exceeds $10^7 \div 10^8$ ion-electron pairs [7],[8],[9]. In wire chambers the streamer propagation from the anode towards the cathode is spatially limited by the fast decrease of the electric field far from the wire. In GEM detectors, and more generally in micro-pattern detectors, due to the very small distance between anode and cathode, the formation of the streamer can be easily followed by the discharge.

Discharge studies have been performed in two different experimental environments:

- α-particles from a radioactive source, which, because of their ionization capability of $\sim 2 \times 10^4$, allow to measure in a reasonable time (few hours) discharge probabilities of the order of $10^6 \div 10^7$ even with a moderate source rate (a few hundred Hz);
- low energy hadrons (pions and protons of the πM1 test beam at PSI), which simulating the typical environment at hadron colliders, allow to estimate the discharge probability in a quasi-realistic situation.

In both cases the discharge probability is defined as the ratio between the observed frequency of discharges and the incident particle rate.
3.4.1 Discharges induced by hadrons

The discharge probability has been evaluated at PSI irradiating the detectors with a hadron flux of about 50 MHz. The measurement has been performed by monitoring and acquiring the currents drawn by the various GEM electrodes. Discharge counting has been performed detecting the current spikes. Fig. 7 shows the discharge probability for the three gas mixtures. Each point corresponds to a six hours run, where about $10^{12}$ hadrons were integrated on each detectors. The solid dots, corresponding to runs in which no discharges have been observed, give an upper limit (at 95% C.L) for the discharge probability. At working points the discharge probability is of the order of $4 \times 10^{-12} \div 2 \times 10^{-11}$ per hadron, corresponding to $\sim 200 \div 1000$ discharges/cm$^2$ in 10 years at LHCb.

3.4.2 Discharge studies with $\alpha$-particles

An $^{241}$Am radioactive source emitting 5.6 MeV $\alpha$-particles has been placed inside the detector on the drift cathode, realized with a GEM foil, in order to allow the penetration of the radiation in the drift gap. The measured rate was $\sim 100$ Hz/cm$^2$.

Fig. 8 shows the discharge probability as a function of the effective gain of the detector, operated with the reference gas mixture. The two curves are obtained as following: (curve a) varying the voltage applied to the third GEM in the range $390 \div 430$ V, while keeping $V_{g1}=460$ V and $V_{g2}=390$ V; and, (curve b), varying the voltage of the second GEM in the range $390 \div 460$ V, with $V_{g1}=460$.
V and $V_{g3}=390$ V. The result suggests that, for a given discharge probability, higher gains are reached increasing $V_{g2}$, while keeping $V_{g3}$ at moderate value, in order to operate the detector with a decreasing voltage configuration: $V_{g1} \gg V_{g2} > V_{g3}$. In conclusion, it is convenient to keep low the voltage of the last stage in order to reduce the probability of the transition from avalanche to streamer, responsible for discharges inside the detector. Of course the voltage configuration optimizing the gas gain and minimizing the discharge depends, for a fixed gas mixture, on the size of the second transfer gap. In fact a larger gap, increasing the electron diffusion, should decrease the electron density before the last amplification stage, reducing the discharge probability and increasing the gas gain.

Fig. 9 shows the discharge probability as a function of the effective gain for Ar/CO$_2$/CF$_4$ (60/20/20) and Ar/CO$_2$/CF$_4$/iso-C$_4$H$_{10}$ (65/8/20/7) gas mixtures. The addition of a moderate quantity of photon gas quencher (inside the non-flammable limit of 7%), which reduces the discharge probability, allows to reach higher gains. In both figures the statistical significance of the zero baseline corresponds to less than one discharge during a measurement time of 12 hours, or equivalently a probability $\leq 2 \times 10^{-7}$.

During $\alpha$-particle tests the detector integrated about 200 discharges/cm$^2$ without damages, corresponding to $\sim 3$ LHCb years.
3.5 Aging studies with high intensity X-rays

The aging test has been performed by irradiating, with a high intensity 5.9 keV X-rays, a $10 \times 10$ cm$^2$ triple-GEM detector operated with the Ar/CO$_2$/CF$_4$ (60/20/20) gas mixture at $\Sigma V_{GEM} = 1230$ V, corresponding to a $G_{eff} \sim 2 \times 10^4$. The X-ray flux was $\sim 50$ MHz/cm$^2$ and the irradiated area about 1 mm$^2$, this resulted in a detector current of about 270 nA. Ambient parameters (temperature, relative humidity and atmospheric pressure) variations have been corrected by a second, low irradiated, triple-GEM detector used as a reference chamber, installed in the same gas line downstream the high irradiated chamber.

The gas was supplied with an open flow system by using Polypropylene tubes, avoiding the bubbler on the exhaust gas line. The constant gas flow was 100 cc/min, sufficiently high to avoid the gas poisoning due to the ionising radiation flux used in the measurement. The total accumulated charge is about

![Graph: Normalized gain versus accumulated charge for the Ar/CO$_2$/CF$_4$ (60/20/20) gas mixture with $\Sigma V_{GEM} = 1230$ V.]

23 C/cm$^2$, that corresponds to about 18 years of normal operation at LHCb experiment, considering the gain of $\sim 2 \times 10^4$. As shown in Fig. 10 a negligible gain variation of about 5% has been observed.

4 Conclusions

Time performances and efficiencies of triple-GEM detectors operated with three different gas mixtures have been studied at PSI. A time resolution of
5.3 ns (r.m.s.) is obtained with the Ar/CO$_2$/CF$_4$ (60/20/20) gas mixture, considerably better than that obtained (9.7 ns r.m.s. [3]) with the standard Ar/CO$_2$ (70/30). Further improvements are obtained with isobutane based gas mixtures, which allow to reach excellent time resolutions: 4.9 ns (r.m.s.) with the Ar/CO$_2$/CF$_4$/iso-C$_4$H$_{10}$ (65/8/20/7); and 4.5 ns (r.m.s.) with the Ar/CF$_4$/iso-C$_4$H$_{10}$ (65/28/7).

Discharge studies have been performed exposing a triple-GEM chamber to both high intensity hadron beam at PSI and $\alpha$-particles from an $^{241}$Am source. Data taken at PSI give a discharge probability of the order of $4 \times 10^{-12} \div 2 \times 10^{-11}$ per hadron, corresponding to $\sim 200 \div 1000$ discharges/cm$^2$ in 10 years at LHCb.

The test with heavily ionising $\alpha$-particles allowed to integrate, without any appreciable change in detector performance, $\sim 200$ discharges/cm$^2$ corresponding to at least 3 years of normal operation at LHCb.

The aging properties were investigated exposing the detector to high intensity 5.9 keV X-rays. The detector was operated with the Ar/CO$_2$/CF$_4$ (60/20/20) gas mixture at an effective gain of $\sim 2 \times 10^4$. After accumulating 23 C/cm$^2$, corresponding to about 18 years of normal operation at LHCb experiment, only a negligible gain change of $\sim 5\%$ was observed.

References


