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Characterization of GEM Detectors for Application in the CMS Muon Detection System

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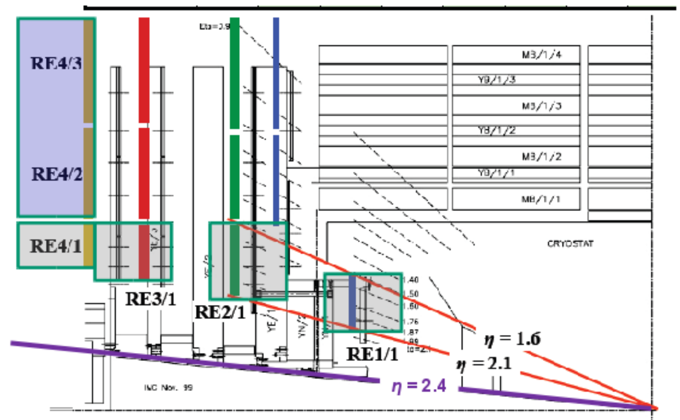
***Abstract*—The muon detection system of the Compact Muon Solenoid experiment at the CERN Large Hadron Collider is based on different technologies for muon tracking and triggering. In particular, the muon system in the endcap disks of the detector consists of Resistive Plate Chambers for triggering and Cathode Strip Chambers for tracking. At present, the endcap muon system is only partially instrumented with the very forward detector region remaining uncovered. In view of a possible future extension of the muon endcap system, we report on a feasibility study on the use of Micro-Pattern Gas Detectors, in particular Gas Electron Multipliers, for both muon triggering and tracking. Results on the construction and characterization of small triple-Gas Electron Multiplier prototype detectors are presented.**

I. Introduction

THE muon system of the Compact Muon Solenoid (CMS) detector [1] at the CERN Large Hadron Collider (LHC) is based on different technologies for muon tracking and triggering. While Drift Tubes and Cathode Strip Chambers provide muon tracking in the barrel and endcap region, respectively, Resistive Plate Chambers (RPCs) are used for level 1 muon triggering in both the barrel and endcap detector parts. The latter RPC endcap chambers are double-gap Bakelite based RPCs with strip readout. They are operated in avalanche mode at 9.5 kV with a $C_2H_2F_4$:iC_4H_{10}:SF_6 (94.7:5.0:0.3) gas mixture humidified at about 40%. As shown in Figure 1, the RPC endcap system is presently incomplete as only the low pseudo-rapidity region, $|\eta| < 1.6$, of the three existing endcap disks is equipped with chambers, REi/2-3. To maintain a good muon trigger performance during the future LHC running at full luminosity and beam energy, an extension of the RPC endcap system is foreseen for 2012 with the addition of a fourth station with RE4/2-3 chambers. However, the very forward region, $|\eta| > 1.6$, of all endcap disks will remain uninstrumented and presents an opportunity to add more capable and robust detectors in the vacant REi/1 locations. For the planned LHC luminosity upgrade ($\sim 10^{34-35}$ cm^2/s), the expected particle flux in that detector region amounts to several tens of kHz with a total integrated charge over 10 years of several tens of C/cm^2. To cope with such a hostile environment, technologies other than the existing Bakelite RPCs will have to be found.



	RE 1/1	RE 1/2	RE 1/3	RE 2/1	RE 2/2	RE 2/3	RE 3/1	RE 3/2	RE 3/3	RE 4/1	RE 4/2	RE 4/3
No. of chambers	36*2	36*2	36*2	18*2	36*2	36*2	18*2	36*2	36*2	18*2	36*2	36*2

Fig. 1. The CMS RPC endcap system. RPCs (REi/1 and RE4/2-3) enclosed in boxes have yet to be installed.

II. The Case for Micro-Pattern Gas Detectors

A dedicated R&D program was launced in 2009 to study the feasibility of using micro-pattern gas detectors (MPGD) for the instrumentation of the vacant $|\eta| > 1.6$ region in the present RPC endcap system. Micro-pattern gas detectors can offer an excellent spatial resolution of order 100 μm, a time resolution below 5 ns, a good overall detector efficiency above 98% and a rate capability of order 10^6 Hz/mm^2 that is sufficient to handle the expected particle fluxes in the LHC environment. In the case of the existing RPC system, the large volume, the cost of the gas mixture, and the need to constantly remove impurities from the gas circuit to guarantee a stable detector operation, make the use of a rather complex closed-loop gas system including filtering mandatory. For MPGDs, their operation

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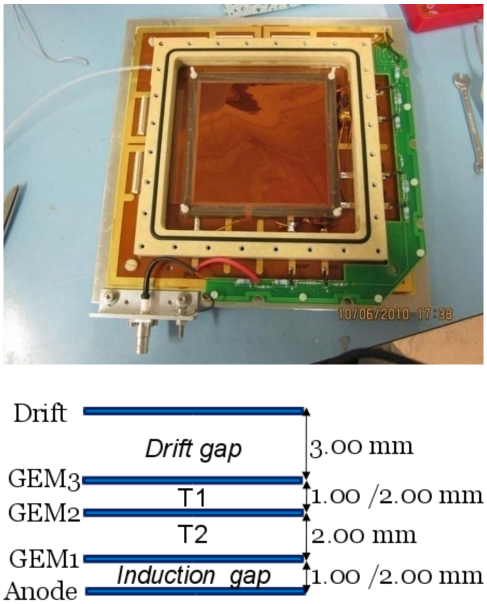

Fig. 2. The standard double-mask triple-GEM prototype. The picture on top shows the detector during assembly; the diagram at the bottom depicts the gap sizes.

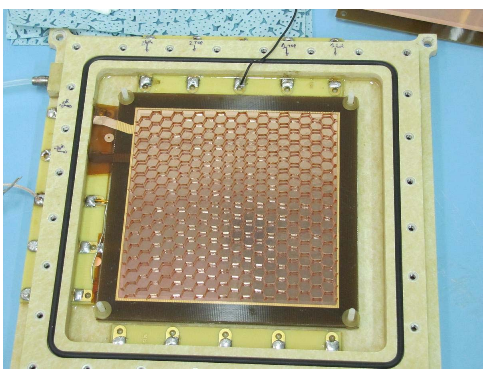

Fig. 3. The triple-GEM prototype with honeycomb spacers.

with a non-flammable gas mixture, e.g. Ar:CO_2, is therefore also advantageous compared to the present RPC system.

With the enhanced (η, ϕ) readout granularity and rate capability of the MPGDs, one could effectively improve the level 1 muon trigger efficiency and even offer both triggering and tracking functions at the same time. In this case, one could even consider to extend the pseudo-rapidity range of the system up to $|\eta| = 2.4$, to match the coverage of the Cathode Strip Chambers in the endcaps.

III. Small MPGD Prototypes

In a first step of the study a characterization was done of two different small MPGD prototypes : one Micromegas [2] and one triple-GEM [3] detector. Both prototypes with an active area of 10×10 cm^2 were produced in the CERN EN-ICE surface treatment workshop and were subsequently tested in the RD51 [4] lab of the CERN Detector Technology Group (DT). Using standard Ar:CO_2 gas mixtures, the two detectors were characterized by measuring gain and pulse height spectra with radioactive sources and Cu X-rays from a generator. Their

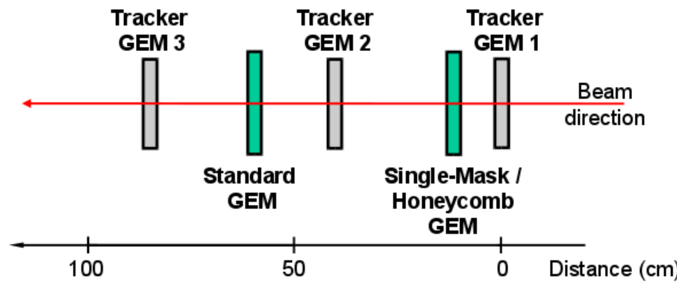

Fig. 4. The RD51 beam telescope at the CERN SPS H4 beam line. The triple-GEMs of the telescope are labeled "Tracker GEM".

efficiency plateaus were measured and the optimal operational voltages were determined. In October 2009, the two prototypes were put into a pion/muon test beam at the CERN SPS H4 beam line [5]. A good detector performance was observed for the triple-GEM, while the Micromegas prototype showed a substantial discharge probability and hence a poor data quality. The discharge probabilities of the two detectors were measured in the RD51 lab. For the triple-GEM a probability of 10^{-6} was measured for gains up to $2 \cdot 10^4$, while the Micromegas was discharging with a probability of 10^{-4} at a gain of less than 2000, which is consistent with previous studies [6]. Consequently, based on these findings and the available general expertise on GEMs in the research group, the triple-GEM prototype was selected for further studies.

The triple-GEM mentioned above was constructed using the standard double-mask technique for the etching of the GEM foils. The foils are made of 50 μm thick kapton sheets with a 5 μm copper cladding on both sides. The GEM and cathode drift foils were glued on fiberglass frames and mounted inside a gas-tight box as shown in Figure 2. The detector has 128 strips with a pitch of 0.8 mm. Two different gap size configurations were tried to study the effect on the detector performance (drift, transfer 1, transfer 2, induction gap size): 3/2/2/2 mm and 3/1/2/1 mm.

In addition to the standard double-mask GEM prototype another $10{\times}10$ cm^2 triple-GEM prototype was constructed using the single-mask technique [7], which overcomes the problems with the alignment of the masks on either side of the foils during the photolitographic etching of the holes. This prototype has 256 strips in two perpendicular directions, with a strip pitch of 0.4 mm.

Futhermore, to avoid the need for foil stretching during detector assembly, a technique based on inserting honeycomb spacers into the detector gaps was tested with a triple-GEM as shown in Figure 3. Three different configurations were tried with varying honeycomb cell sizes (in drift, transfer 1, transfer 2, induction gap): 12/12/12/12 mm ("config 1"), 6/12/12/12 mm ("config 2"), 6/0/0/0 mm ("config 3"). This prototype also has 256 strips in two perpendicular directions, with a strip pitch of 0.4 mm.

IV. Test Beam Measurements

A. Setup

The triple-GEM prototypes were tested with a 150 GeV muon/pion beam at the CERN SPS H4 beam line during

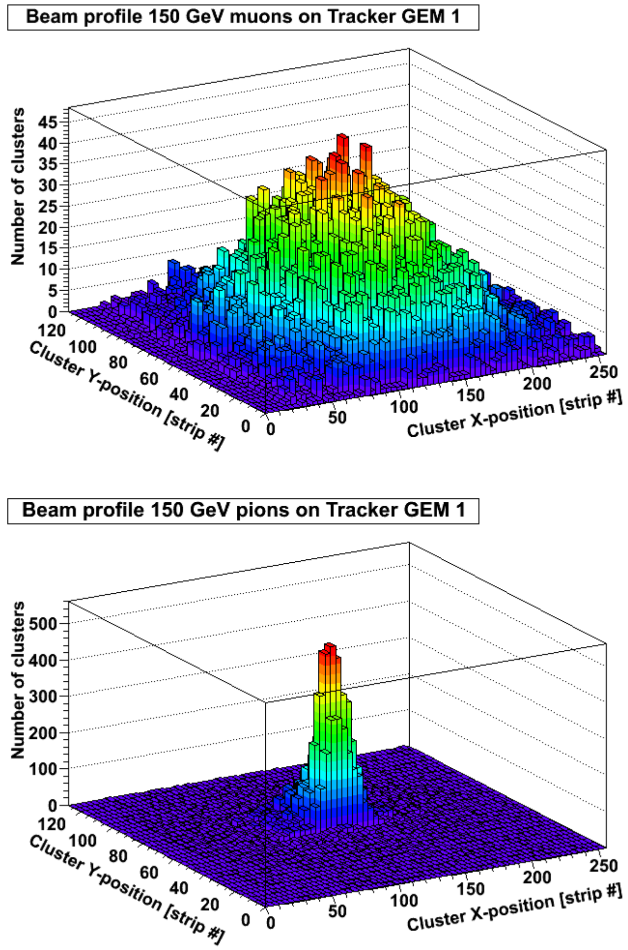

Fig. 5. The beam profiles for muons and pions obtained with the tracker GEMs.

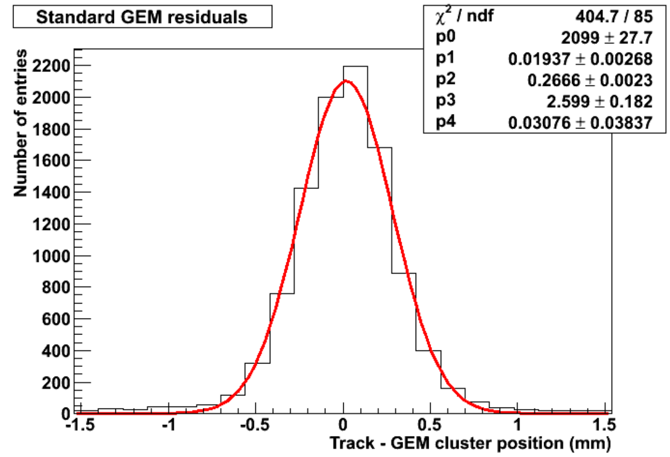

Fig. 6. The obtained residual distribution for the standard triple-GEM, fitted with a Gaussian of the form $p_0 \cdot \exp(-0.5 \cdot ((x-p_1)/p_2)^2)$, plus a first-order polynomial of the form $p_3 + p_4 \cdot x$ to account for noise hits.

several RD51 test beam campaigns. The detectors under test were mounted into the RD51 triple-GEM beam telescope as depicted in Figure 4. The telescope consists of three standard triple-GEM detectors, hereafter referred to as tracker GEMs, with a 10×10 cm^2 active area, running with a Ar:CO_2 (70:30) gas mixture. They have 256 strips in both horizontal (y-coordinate) and vertical (x-coordinate) directions transverse to the beam, with a pitch of 0.4 mm. The telescope detectors were always operated at a gain larger than 10^4. This setup served as tracking device for the detectors under test.

The standard double-mask triple-GEM prototypes under test were studied with different gas mixtures, Ar:CO_2 (70:30, 90:10) and Ar:CO_2:CF_4 (45:15:40, 60:20:20), with a gas flow of about 5 l/hour corresponding to roughly 50 detector volume exchanges per hour. The single-mask and honeycomb triple-GEMs were operated with an Ar:CO_2 mixture only.

The readout of all detectors including the tracker GEMs was done with electronics boards based on VFAT chips [8] developed for TOTEM [9] by INFN Siena-Pisa. The VFAT (Very Forward Atlas and Totem) ASIC was designed at CERN using radiation tolerant technology. It has a 128 channel analog front-end and produces binary output for each of the channels for tracking. In addition, it can provide a programmable, fast OR function on the input channels depending on the region of the sensor for triggering. The chip offers adjustable thresholds, gain, and signal polarity, plus a programmable integration time of the analog input signals. The signal sampling of the VFAT chip is driven by a 40 MHz internal clock.

During the test beam campaign the readout of all GEM detectors with the VFAT electronics was digital. The tracker GEMs were read out in two dimensions with two VFATs connected to the 256 vertical strips, but only one VFAT connected to 128 out of the 256 horizontal strips. The standard double-mask prototype had a one-dimensional readout with one VFAT connected to the 128 vertical strips, while the single-mask and honeycomb triple-GEMs had two-dimensional readout with two VFATs connected to the 256 vertical strips and one VFAT connected to 128 out of the 256 horizontal strips.

B. Data Analysis Results

The results presented below for the different triple-GEM prototypes were obtained with the data taken during the RD51 SPS test beam campaign from June 28 to July 8, 2010.

The typical beam profiles for the muon and pion beam as reconstructed with the tracker GEMs of the RD51 beam telescope are shown in Figure 5. For the track reconstruction, events were selected in which the beam telescope GEMs had only one single cluster of fired strips. Straight tracks were fitted to these tracker GEM clusters and extrapolated to the detectors under study. The alignment of the detectors was done relative to the first tracker GEM, using the position of the clusters in each detector for single cluster events.

1) Standard Double-Mask Triple-GEM: The typical value obtained for the position resolution for the standard double-mask triple-GEM operating is about 270 μm as displayed in Figure 6. This value includes the uncertainty on the position of the extrapolated track at the detector, and agrees with the value of 231 μm (=$0.8/\sqrt{12}$ mm) expected from the strip pitch. No strong influence on this resolution value was found from the detector gap size configuration, the used gas mixture, or the operating gain.

The measured efficiency for the standard triple-GEM is displayed in Figure 7. The efficiency was determined as

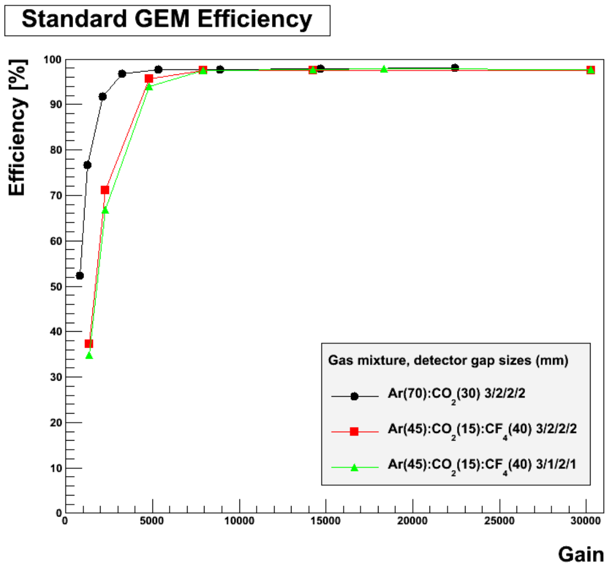

Fig. 7. Detector efficiency for the standard triple-GEM with different gas mixtures and gap size configurations.

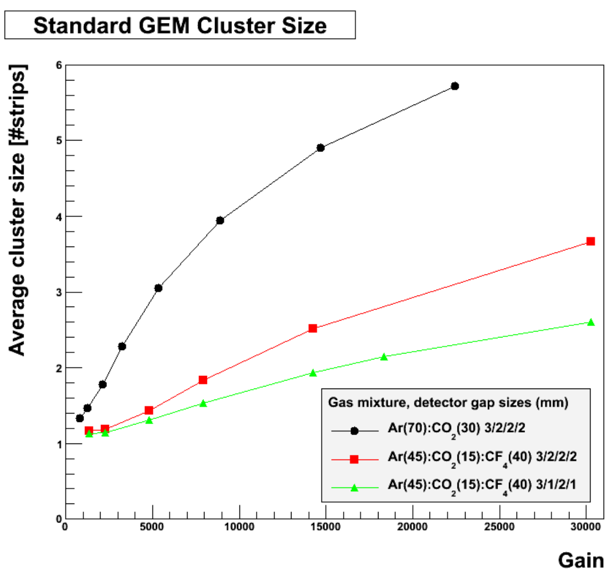

Fig. 8. Strip cluster size for the standard triple-GEM with different gas mixtures and gap size configurations.

function of the detector gain, for different gas mixtures and gap size configurations. Although for the standard Ar:CO_2 (70:30) gas mixture a slightly better performance is observed for low gain values, in each of the cases the efficiency reached the same plateau at about 98 % for a gain above 8000. Note also the stability of the detector performance up to high gains of about $3 \cdot 10^4$.

The effect of the different gas mixtures and the gap size configurations for the standard triple-GEM on the measured average cluster size, expressed in number of detector strips, is shown in Figure 8. Clearly, the use of the Ar:CO_2:CF_4 (45:15:40) gas mixture yields a much better performance for a digitally read out detector than the standard Ar:CO_2 (70:30) mixture because there are fewer strips per cluster. Also, the

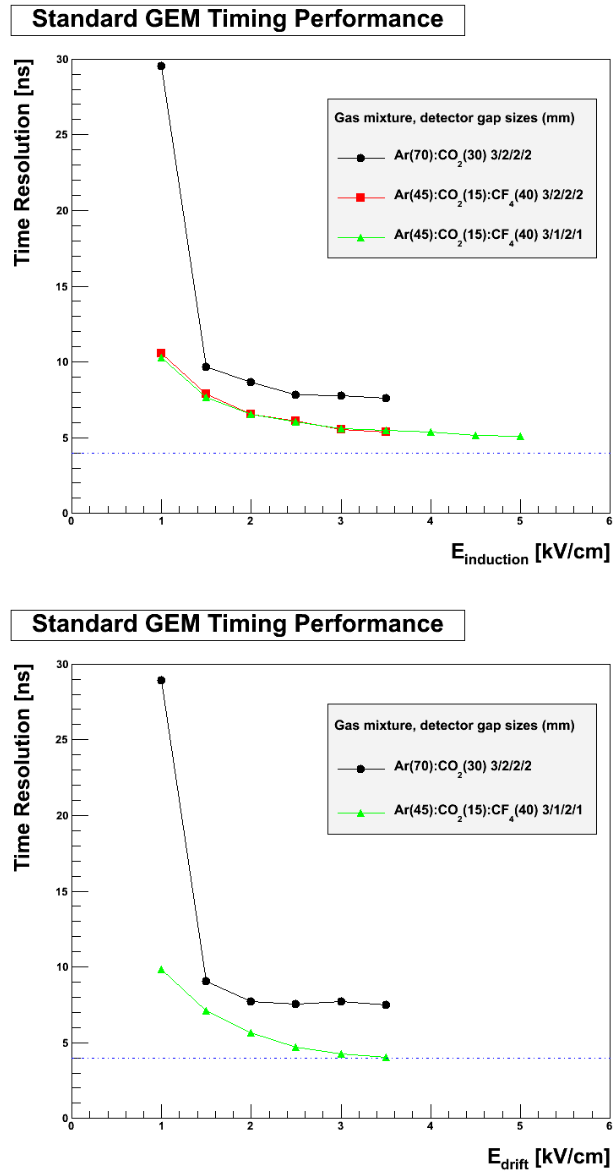

Fig. 9. Detector timing resolution as function of the induction (top) and drift (bottom) field for the standard triple-GEM with different gas mixtures and gap size configurations.

configuration with the smaller transfer 1 and induction gap size gives slightly better results.

The timing performance of the standard triple-GEM was studied using a custom-made high voltage divider that allowed to modify the fields over the different detector gaps individually. For this study, plastic scintillators positioned in front and behind the beam telescope were used to generate a trigger to signal the passage of a beam particle through the detector. The spread in arrival time of the GEM signal from the VFAT board with respect to this external trigger was measured with a TDC module. In these measurements one has to take into account the 40 MHz clock cycle of the VFAT chip, which introduced a 25 ns jitter in the arrival time of the detector signals. Note that in case of the LHC, this jitter can be avoided with a proper synchronization of the VFAT cycle with the LHC clock. The obtained time resolution after a deconvolution of the 25 ns

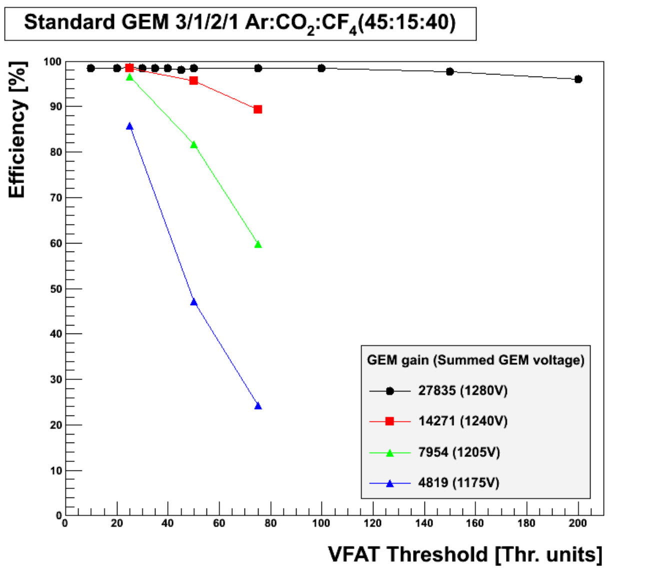

Fig. 10. VFAT threshold scan for the standard triple-GEM with the 3/1/2/1 mm gap size configuration and $Ar:CO_2:CF_4$ (45:15:40) gas mixture.

VFAT jitter is displayed in Figure 9. The field across either the induction or drift gap was varied, while keeping the other fields constant at (drift, transfer 1, transfer 2, induction gap) 2/3/3/3 kV/cm. The different gap size configurations had no visible effect on the timing performance. However, the timing performance is clearly better with the $Ar:CO_2:CF_4$ (45:15:40) gas mixture. With this mixture, a timing resolution of 4 ns could be obtained.

Based on the observed noise in the detector without beam, a minimum VFAT threshold of 25 units[1] was used for all measurements. To check the effect of the VFAT threshold on the apparent detector performance, a VFAT threshold scan was performed for the standard triple-GEM operating at different gain values as displayed in Figure 10. With the VFAT threshold set at 25 units, no effect on the efficiency can be observed when the detector is operated at a gain larger than 10^4.

2) Single-Mask Triple-GEM: Several measurements as described above were also performed on the single-mask triple-GEM to compare its performance to the standard double-mask triple-GEM. Figure 11 shows the measured efficiency and average strip cluster size for the single-mask triple-GEM. The single-mask GEM reaches a comparable performance level as the corresponding double-mask GEM (see Figures 7-8) albeit the efficiency plateau is attained only at a gain level well above 10^4.

3) Honeycomb Triple-GEM: Measurements were performed on the different honeycomb triple-GEMs to check the effect of the honeycomb spacers on the detector efficiency. For configuration 1 an overall efficiency of about 50% was obtained, while configurations 2 and 3 reached an efficiency of about 75%. The reconstructed cluster positions in a subregion of the latter two prototypes are displayed in Figure 12. One can clearly observe the location of the honeycomb spacer material,

[1]One VFAT threshold unit corresponds to a charge of about 0.08 fC at the input channel comparator stage.

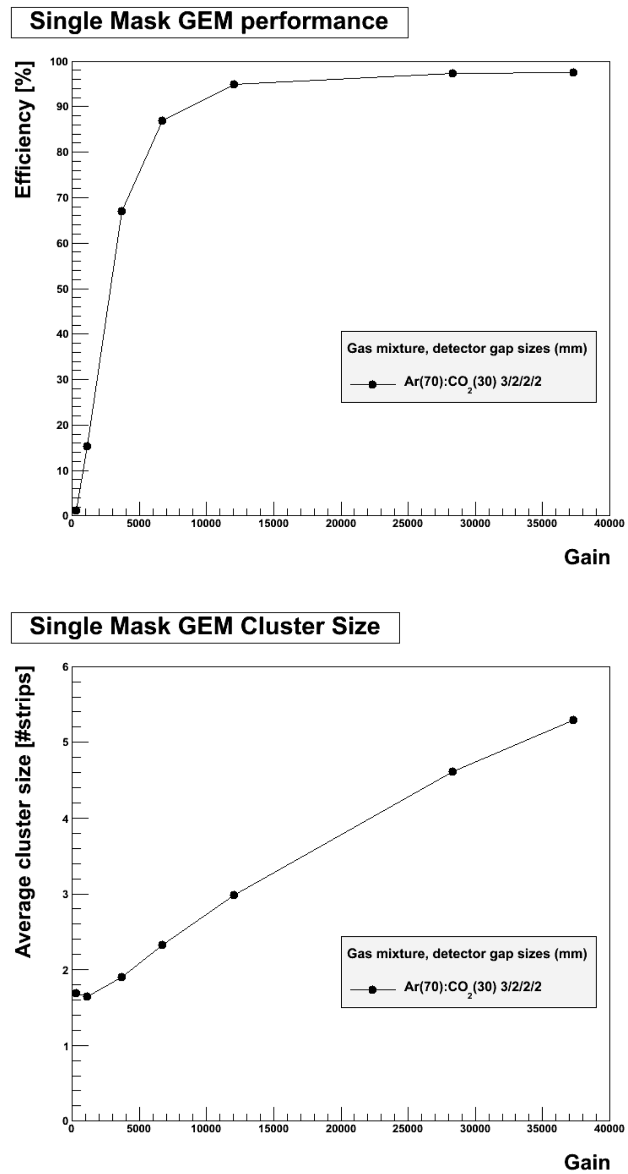

Fig. 11. Detector efficiency (top) and strip cluster size (bottom) for the single-mask triple-GEM.

where a sharp, localized drop in the detector efficiency occurs. More studies are needed to optimize the geometry of the spacer frames to make this technique a viable option for detector production.

V. Full-Size Triple-GEM Prototype

In October 2010 the construction of a first full-size triple-GEM prototype as displayed in Figure 13 was completed. Since it was demonstrated that the single-mask triple-GEM prototype was able to reach a similar performance level as the double-mask GEM, the single-mask technique was used to produce the GEM foils, as this is a more suitable process to produce large size detectors [7]. The detector is divided in 4 η partitions containing 256 radial readout strips each oriented along the long side of the detector. Every η partition is read out by two VFAT chips. The overall dimensions of the active area are $990 \times 220\text{-}450$ mm^2 with the strip pitch

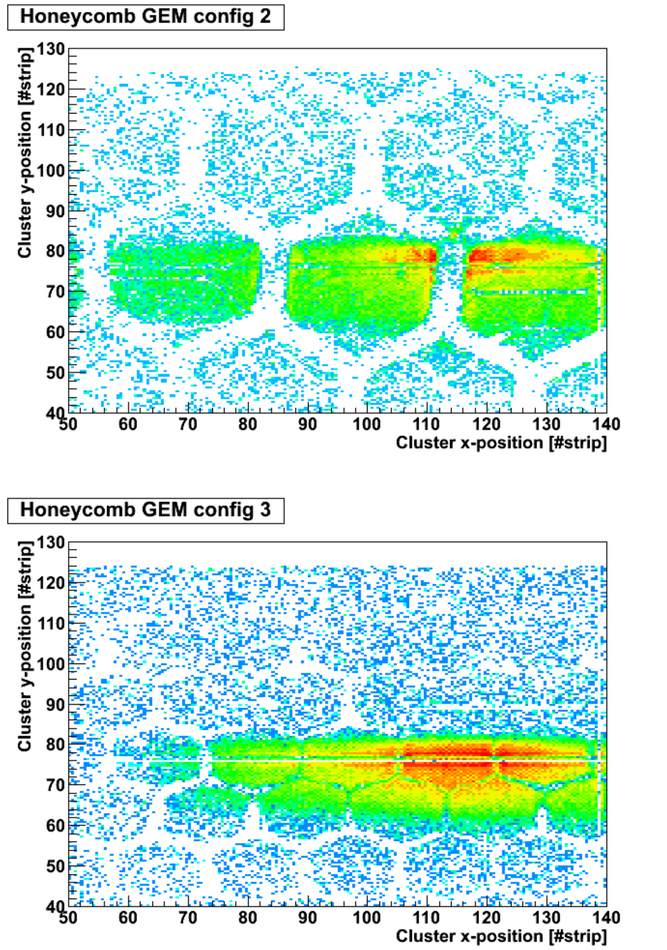

Fig. 12. Reconstructed cluster positions in the subregions near the beam spot of two different honeycomb triple-GEM configurations.

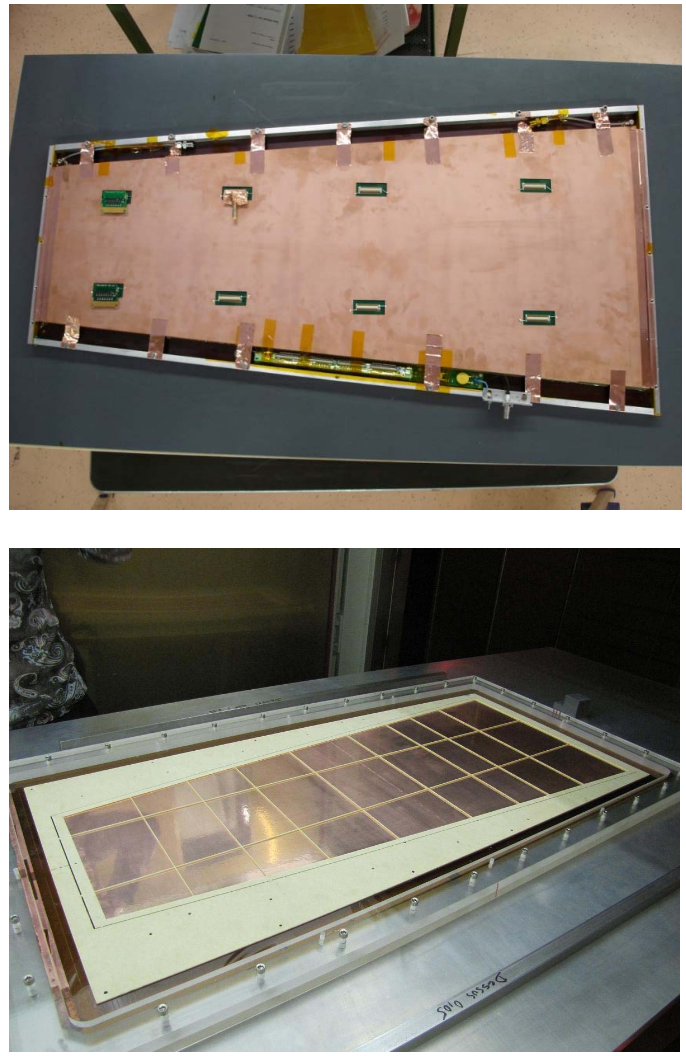

Fig. 13. The first full-size triple-GEM prototype for CMS. The top picture shows the completed detector. The bottom picture shows the detector during assembly while glueing the spacer frames.

varying from 0.8 at the small end to 1.6 mm at the large end of the detector wedge. The GEM foils are sectorized into 35 high voltage sectors transverse to the strip direction, where each sector has a surface area of about 100 cm^2 to limit the discharge probability. More details on the construction can be found in [10].

The detector was tested for the first time with a 150 GeV muon/pion beam using the RD51 Tracking GEM telescope at the CERN SPS H4 beam line. Efficiency scans for different regions of the detector were performed with an Ar:CO_2 (70:30) gas mixture. The data analysis of the measurements is presently ongoing.

VI. Summary and Outlook

Several different $10{\times}10$ cm^2 triple-GEM prototypes were produced at CERN and tested at the CERN SPS H4 beamline with a pion/muon beam to study the feasibility of using such detector technology for extensions of the CMS muon system.

For the standard double-mask triple-GEM, the best detector performance was observed with the use of a Ar:CO_2:CF_4 (45:15:40) gas mixture instead of Ar-CO_2 (70:30) and with a 3/1/2/1 mm gap size configuration compared to 3/2/2/2 mm. Detector efficiencies up to about 98% and timing resolutions down to 4 ns were obtained. The detectors could be operated stably up to high gains of order $3 \cdot 10^4$.

The triple-GEM produced with the single-mask technique was seen to reach a similar performance level as the standard double-mask triple-GEM.

The use of honeycomb spacer frames in the detector gaps in an attempt to avoid the need for GEM foil stretching resulted in a clear localized degradation of the detector efficiency at the position of the frame material.

A first full-size triple-GEM prototype for the CMS muon system was constructed using the single-mask technique. The detector was tested for the first time with a muon/pion beam at the CERN SPS H4 beamline. Lessons learned from the construction and from this first test beam campaign will be taken into account during the production of a second, improved full-size prototype in 2011.

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