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A new design using GEM-based technology for the CMS experiment

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Abstract

The muon system of the Compact Muon Solenoid (CMS) experiment at the LHC is currently not instrumented for pseudorapidity higher than $|\eta| > 2.4$. The main challenges to the installation of a detector in that position are the high particle flux to be sustained, a high level of radiation, and the ability to accommodate a multilevel detector into the small available space (less than 30 cm). A new back-to-back configuration of a Gas Electron Multiplier (GEM) detector is presented with the aim of developing a compact, multi-layer GEM detector. It is composed of two independent stacked triple-GEM detectors, positioned with the anodes toward the outside and sharing the same cathode plane, which is located at the center of the chamber, to reduce the total detector's thickness. A first prototype has been produced and tested with an X-Ray source and muon beam. First results on its performance are presented.

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A new design using GEM-based technology for the CMS experiment

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ABSTRACT: The muon system of the Compact Muon Solenoid (CMS) experiment at the LHC is currently not instrumented for pseudorapidity higher than $|\eta| > 2.4$. The main challenges to the installation of a detector in that position are the high particle flux to be sustained, a high level of radiation, and the ability to accommodate a multilevel detector into the small available space (less than 30 cm). A new back-to-back configuration of a Gas Electron Multiplier (GEM) detector is presented with the aim of developing a compact, multi-layer GEM detector. It is composed of two independent stacked triple-GEM detectors, positioned with the anodes toward the outside and sharing the same cathode plane, which is located at the center of the chamber, to reduce the total detector's thickness. A first prototype has been produced and tested with an X-Ray source and muon beam. First results on its performance are presented.

KEYWORDS: Performance of High Energy Physics Detectors, Muon spectrometers, Particle tracking detectors (Gaseous detectors).

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1 The ME0 station for the CMS muon system

The muon system of the Compact Muon Solenoid (CMS) experiment is currently instrumented with three different detector technologies: Drift Tubes (DTs), Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs). They are located such that the redundancy of technologies diminishes as the pseudorapidity increases: complementary technologies are provided by CSCs and RPCs up to $|\eta| < 1.6$, the region $1.6 < |\eta| < 2.4$ is currently instrumented only with CSCs, while for $|\eta| > 2.4$ the muon system is currently not instrumented.

The ME0 station is proposed for the installation in 2024 in the region $2.0 < |\eta| < 2.8$, behind the upgraded, shorter hadron calorimeter, which will replace the existing HCAL calorimeter. A slot less than 30 cm thick will become available in front of the muon system endcap. This station will partially overlap in eta coverage with CSCs, restoring redundancy in the region $2.0 < |\eta| < 2.4$, but its major goal will be the extension of the muon system acceptance up to $|\eta| = 2.8$. It will provide an improved trigger and improved tagging of high-eta muons. The current configuration of the muon system, along with the stations proposed for its upgrade, are shown in figure 1.

The high-eta position of the ME0 station requires a detector with high rate capability $O(MHz/cm^2)$, good time (few ns) and spatial resolution $O(100 \mu m)$ for triggering and tracking. In addition, the ME0 station needs to provide at least three hits for muon track reconstruction with high efficiency [1]. For this reason a multilayer structure with at least 6 layers of detectors is necessary.

Figure 1. Cross sectional view of a quadrant of the CMS muon system. Both current (DTs, CSCs, RPCs) and future (GEMs, iRPCs, ME0) installations are shown.

Gas Electron Multiplier (GEM) detectors have already been chosen and widely studied for another high-eta upgrade of the muon system endcap, the GE1/1 station [2, 3]. Consequently, this technology provides an appealing choice for the ME0 location as well.

2 The Back to Back GEM detector

In order to fit a multilayer structure into the small space available for the ME0 station, a new design of a GEM-based technology detector has been developed, referred to as a *back-to-back* (B2B) GEM detector, whose structure is shown in figure 2. It is composed of two independent triple-GEM detectors positioned with the anodes toward the outside and sharing the same cathode at the center of the system. This design allows us to reduce the total thickness occupied by two triple-GEM detectors.

We report on the studies performed on a prototype with $10 \times 10 \text{ cm}^2$ active area operated with Ar:CO₂ 70:30 and Ar:CO₂:CF₄ 45:15:40 gas mixtures. Each triple GEM detector has a 3/1/2/1 mm spacing and is supplied through a voltage divider using the same resistor values used in the GE1/1 station [3]. The two dividers are supplied in parallel by the same high voltage supply. The electric fields of drift and amplification stages can be determined from the value of the resistors, the spacing between the foils and their thickness.

Each GEM detector has its own readout plane with 128 parallel strips and $800 \mu\text{m}$ pitch. One readout plane has strips along the x direction, the other one along the y direction. For this reason each GEM detector will be identified as *X-axis GEM* or *Y-axis GEM* (reading the x or y coordinate respectively). The readout is made through VFAT2 chips [4]; each GEM detector (or axis) is read by two VFAT2 ASICs. They have been numbered from 0 to 3, such that VFAT2-0 and VFAT2-1 read the x coordinate, VFAT2-2 and VFAT2-3 read the y coordinate. The total detector thickness is 2.64 cm.

Figure 2. Left: Schematic representation of the structure of the back to back detector. Two independent GEM detectors are positioned in opposite directions sharing the same cathode at the center of the system, with readout planes at the two opposite ends. G1, G2, G3 indicates the three GEM foils of each GEM detector. Right: The back to back GEM detector.

3 Detector performance

The detector performance results are presented as a function of the voltage divider current.

3.1 Gain

First studies have been carried out operating the detector with Ar:CO₂ gas mixture. A ^{109}Cd source was placed on the readout plane of the triple-GEM detector under study. The logical OR of all the strips was read. First, the net rate of observed hits is measured while varying the voltage applied to the detector; then the net current I_{net} is measured at the same voltage. At high voltage (divider

current greater than about $675 \mu A$ and $685 \mu A$ for the two gas mixtures) the rate curve reaches a *plateau*, corresponding to the operational range in which the detector is working at high efficiency. The average rate at the plateau $R_{plateau}$ is used to calculate the detector gain $\mathcal{G}$ at different voltage applied using the formula $\mathcal{G} = I_{net}/(N_p q_0 R_{plateau})$; where q_0 is the elementary charge and N_p is the number of electrons produced by primary ionization, calculated assuming that the ionizing radiation is the luminescence of the copper inside the detector. The rate and gain curves are shown in figure 3. The gain reached at the efficiency plateau is of the order of 10^4 .

Figure 3. Measured rate and calculated gain for each GEM detector for different divider currents.

3.2 Efficiency

The efficiency is evaluated by testing the B2B detector in the H8 muon test beam line at CERN SPS (muon momentum $\sim 150 GeV/c$ and intensity up to $\sim 10^4 muons/spill$). The setup used three scintillators with approximately the same active area as the B2B detector to provide a beam trigger and two triple GEM detectors (*trackers*) with $10 \times 10 cm^2$ active area, operated with an Ar:CO₂ gas mixture, having 3/2/2 mm spacing and bidimensional readout (256 strips both in x and y direction with $400 \mu m$ pitch) for tracking. The trackers are read out by the VFAT2 chips. They provide a reconstructed muon particle track with x and y hit coordinates. An extrapolation from the reconstructed muon particle track to the B2B detector provides the expected location of the x and y hits in the B2B detector.

The efficiency of each triple-GEM is measured, along with the efficiency of their logical AND. For the efficiency calculation it is necessary to align the B2B GEM detector and the two trackers in software through a χ^2 minimization to correct the measured hits both for translational and rotational misalignment between the detectors. Then the distribution of *residual distances*, i.e. the distance between the predicted hit positions on B2B detector and the measured hit positions, is built both for the X and Y-axis GEM. Such distributions are fitted with a gaussian function, whose standard deviations σ_x and σ_y have been used to evaluate the maximum tolerated distance of measured hits on B2B detector from the position predicted by trackers. For the efficiency calculation events are accepted only if the residual distances $x_{res} < 3\sigma_x$ and $y_{res} < 3\sigma_y$. For the calculation of the efficiency of the logic AND of the two triple-GEM detectors both conditions are required. The results for the two considered gas mixtures are shown in figure 4. A high detection efficiency has

been observed in both cases: between 96.5% and 98.1% for a *single* triple GEM and about 94% for their logical AND.

Figure 4. Efficiency of the X-axis GEM (blue markers), Y-axis GEM (green markers) and their logical AND (red markers) measured with Ar:CO₂ (left) and Ar:CO₂:CF₄ (right) gas mixtures. The dashed lines are the best fits with the equation $A/[\exp(B - x)/C]$, whose parameter A gives the efficiency at curve's plateau. In the lower right-hand box the parameter A and its error estimated by the best fit are shown. Ishaper and Icomp are adjustable parameters of VFAT2 chips that influence their response [4].

Figure 5. Time response of the X-axis GEM (blue markers), Y-axis GEM (green markers) and applying the logic condition $(0 \wedge 2) \vee (1 \wedge 2) \vee (0 \wedge 3) \vee (1 \wedge 3)$ (red markers) measured with Ar:CO₂ (left) and Ar:CO₂:CF₄ (right) gas mixtures. Ishaper and Icomp are adjustable parameters of VFAT2 chips that influence their response [4].

3.3 Time resolution

The time resolution has been measured in the muon beam with the setup described in section 3.2. For the timing measurements the first signal after the trigger pulse satisfying a predefined logic

condition has been used. Because four VFAT2 chips (0, 1, 2, 3) are reading the B2B detector (see section 2), the conditions $0 \vee 1$, $2 \vee 3$ and $(0 \wedge 2) \vee (1 \wedge 2) \vee (0 \wedge 3) \vee (1 \wedge 3)$ have been used¹. The first condition uses only signals from the X-axis GEM, the second condition from the Y-axis GEM. Dividing the surface of the detector in four quadrants, the third logic is an AND between X and Y in each sector, plus an OR of the four quadrants. The three logic conditions are designated in the plots as *VFATX*, *VFATY* and *all VFATs* respectively. The VFAT2 have a 40 MHz signal sampling that broadens the time distribution of signals. This has been taken into account by fitting the measured data to a gaussian distribution convoluted with a step function (25 ns width). The detector's time resolution has been taken as the standard deviation of the gaussian evaluated through the fit. As shown in figure 5, time resolutions of the order of 7 ns and 6 ns are measured with Ar:CO₂ and Ar:CO₂:CF₄ gas mixtures respectively.

Summary. The Back-to-Back (B2B) GEM detector was studied for a potential upgrade of the CMS muon system at high pseudorapidity, in a region that is not currently instrumented where a small space less than 30 cm thick will become available. A detector with multilayer structure, high rate capability, good time and spatial resolution is necessary.

The B2B detector is composed of two triple-GEM detectors sharing the same cathode, with anodes towards the outside.

A gain up to $\sim 10^4$ has been measured with a ¹⁰⁹Cd source. Time resolutions up to 6 ns (Ar:CO₂:CF₄ gas mixture) and 7 ns (Ar:CO₂), and efficiency between 96.5% and 98.1% for each triple-GEM were measured with muon beam.

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¹The notation in which $\wedge$ indicates the *logical AND* and $\vee$ the *logical OR* is used.