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Design validation of the CMS Phase-2 Triple-GEM detectors

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Abstract: The High-Luminosity LHC will deliver proton-proton collisions at 5.0–7.5 times the nominal LHC luminosity, with an expected number of 140–200 pp-interactions per bunch crossing. To maintain the performance of muon triggering and reconstruction under high background, the forward part of the Muon spectrometer of the CMS experiment will be upgraded with Gas Electron Multipliers (GEM) and improved Resistive Plate Chambers detectors. Particularly challenging is the extension of the pseudorapidity of the muon system up to $|\eta| < 2.8$ with a 6-layer station, named ME0, that will be installed behind the new high granularity calorimeter and that will see particle rates up to 150 kHz/cm^2 and integrate a dose of 250 krad by the end of the High Luminosity phase of the LHC. In this contribution we will present the major design changes of the Triple-GEM detectors to adapt them for the harsh radiation environment and the high particle rate. We shall summarize the performance of prototype Triple-GEM detectors measured with X-rays and gamma at the CERN GIF++ irradiation facility.

Keywords: Electron multipliers (gas); Muon spectrometers

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1 Introduction

In the High Luminosity phase of the LHC [1] (HL-LHC), the CMS experiment will deal with unprecedented levels of pile-up interactions and consequently with high background rates in the detectors. The muon system will therefore be upgraded with new detectors based on the Gaseous Electron Multiplier (GEM) technology, which is well suited to muon detection in high-background and high-radiation environments [2].

A new GEM detector, named ME0, will be installed in the endcaps of the muon system, behind the new high-granular calorimeter HGCAL, as shown in figure 1. The ME0 station will cover the pseudorapidity region $2.0 < |\eta| < 2.8$, thus complementing the muon transverse momentum measurement of the GE1/1 and ME1/1 stations within $|\eta| < 2.4$ while extending the geometrical acceptance of the muon system. Each station will be made of 18 chambers per endcap, each made of six layers of triple-GEM detectors for efficient tagging of the muon tracks.

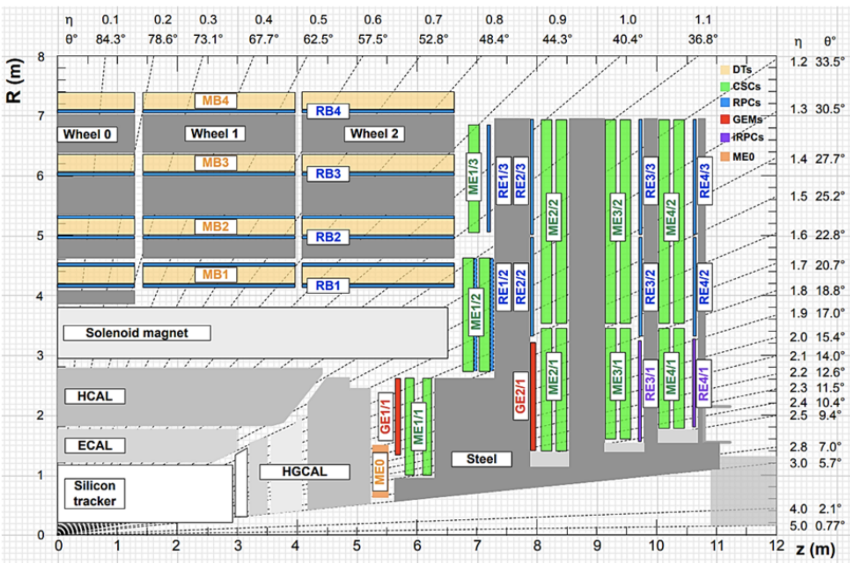

Figure 1. Quadrant of the CMS muon spectrometer after the planned upgrade for HL-LHC, including the ME0 station in orange. Reproduced from [2]. CC BY 4.0.

The requirements for the ME0 detector include space resolution under 500 µrad, time resolution under 10 ns and longevity over an integrated charge of 7.9 C/cm^2 [2]. Given the vicinity to the proton-proton interaction point and to the beam pipe, the ME0 station will be burdened by background particle rates up to 150 kHz/cm^2 [3], the highest of any large-area gaseous detector station in the CMS experiment. The expected background rate and composition estimated from simulation is shown in figure 2 (left).

The GEM foils are segmented, meaning that the electrodes are divided into isolated sectors of about 100 cm^2 surface, each connected to the power supply through a protection resistor, as depicted in figure 3, to reduce the energy of possible discharges. In the ME0 design, the segmentation is transverse to the beam pipe, leading to very high average rates ($\sim$ 150 kHz/cm^2) in the highest $|\eta|$ sector [3], as shown in figure 2 (right).

In this contribution we discuss the limitations of the ME0 design in terms of rate capability and the strategies adopted to meet the detector requirements.

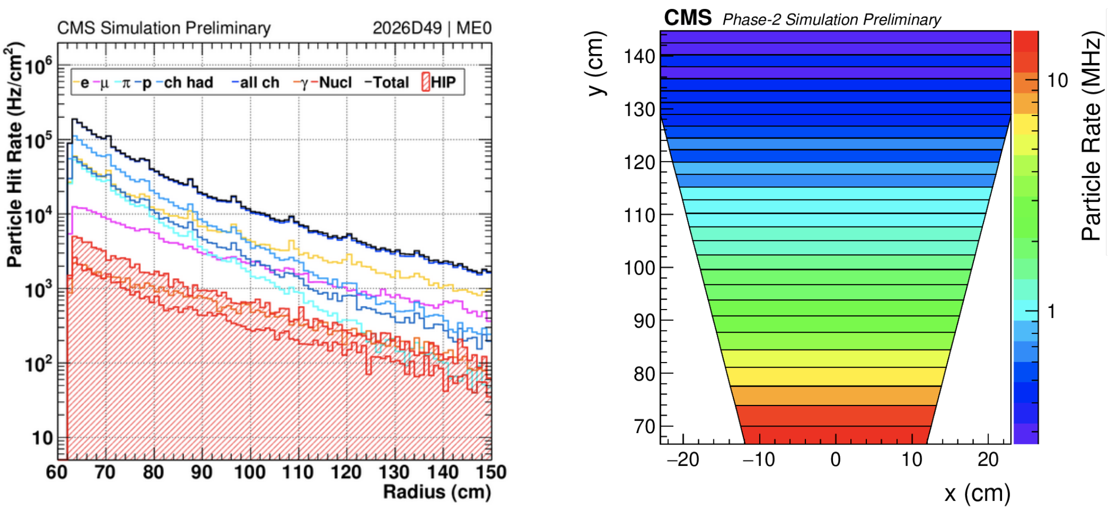

Figure 2. Expected background particle rate in the ME0 location at HL-LHC (left) and expected rate per sector on ME0 detector with transverse GEM foil segmentation. © [2021] IEEE. Reprinted, with permission, from [3].

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2 Rate capability of GEM detectors and the voltage compensation method

The rate capability of GEM detectors is dominated by local effects due to the distortion of the electric field caused by moving ion clouds in the gas volume. While this effect is intrinsic to the GEM technology, the rate capability of triple-GEM prototypes under local X-ray irradiation has been verified up to 10^4 MHz/cm^2 [4].

On the other hand, if a whole sector of a segmented GEM foil is irradiated, the rate capability is dominated by the ohmic voltage drop on the protection resistors and high voltage (HV) filters caused by the collected charge on the GEM sector. This effect has been verified on triple-GEM detector prototypes under X-ray irradiation, as shown in figure 4 (left) reporting the gas gain as a function of the impinging particle flux (black points), compared to the gain measured at low irradiation while externally applying the expected voltage drop (blue points).

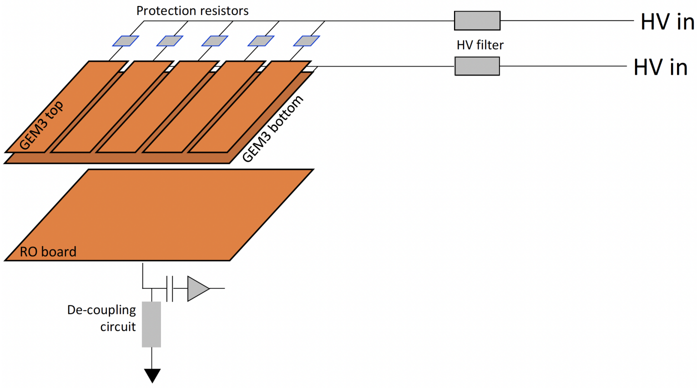

Figure 3. Schematic of the resistive circuit in the ME0 design, focusing on the single-segmented GEM foil facing the readout plane. Image courtesy of J. Merlin.

An iterative procedure has been developed to compute the voltage needed for operating the detector at the desired gain. The voltage drop depends on the total resistance between the GEM foil and the power supply (R_{tot}) and the current flowing in each electrode (i), which in turns depend on the particle flux, the number of primary electron-ion pairs produced and the gas gain. Given the dependency between the effective voltage V_{eff} and the currents, the following relation is used iteratively until V_{eff} corresponds to the desired gain:

$$V_{\text{eff}} = V_{\text{set}} - R_{\text{tot}} \times \text{i} \tag{2.1}$$

Applying the resulting overvoltage, hereinafter referred to as *voltage compensation*, has been proved to effectively recover the detector performance of a GEM detector prototype under X-ray irradiation, as shown in figure 4 (right).

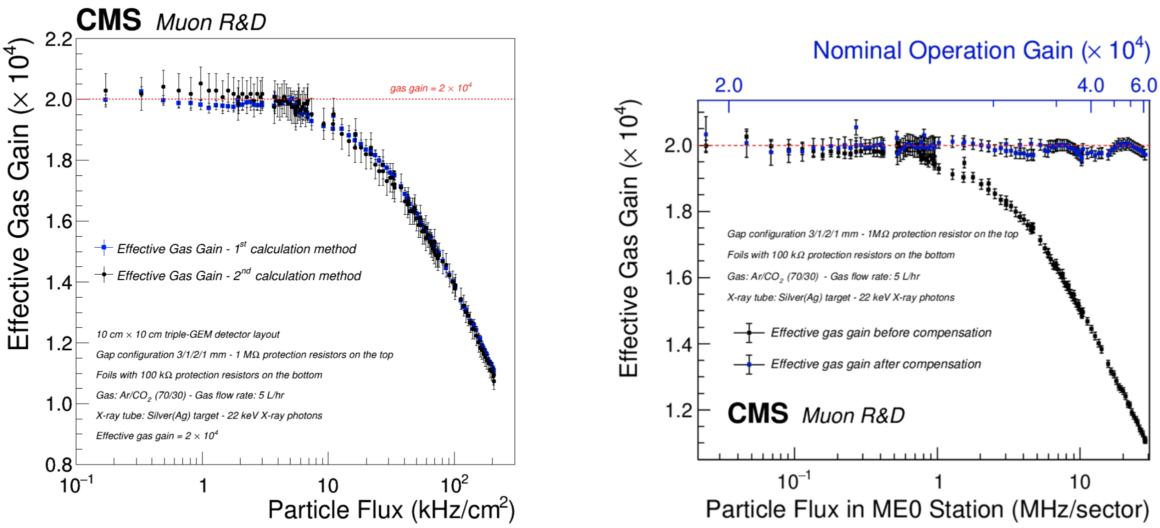

Figure 4. Left: gain drop of the irradiated prototype comparing the gain measurement under irradiation (in black) and the gain measurement by applying the expected voltage drop (in blue). Right: measured gas gain under X-ray irradiation before (black) and after (blue) applying the voltage compensation. © [2021] IEEE. Reprinted, with permission, from [3].

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However, in the case of transverse segmented ME0 detectors, the voltage compensation method would require a different voltage to be applied to the different sectors due to the very different expected background rates as a function of the η region. Moreover, the voltage compensation has no effect on the rate capability of the readout electronics, that can be potentially limited by the dead time, which directly depends on the signal rate per readout channel.

In the following, the modifications to the ME0 design and the measurements carried out to validate them will be discussed.

3 Azimuthal segmentation

In order to reduce the gain drop under irradiation by the LHC background and to equalize it across different sectors, an alternative foil segmentation design has been developed, with azimuthal sectorization with respect to the beam axis. As shown in figure 5, an expected background rate of about ~ 1.70 MHz/sector is expected, uniformly across the sectors. Moreover, the foil is segmented into 40 sectors, each smaller than 100 cm^2, to further reduce the discharge energy. The main drawback of the new design is the wider dead area due to the sector separation, which can be reduced adopting an alternative manufacturing technique, the *random hole* segmentation, consisting of maintaining the hole pattern in the separation between sectors thus reducing the dead area [5].

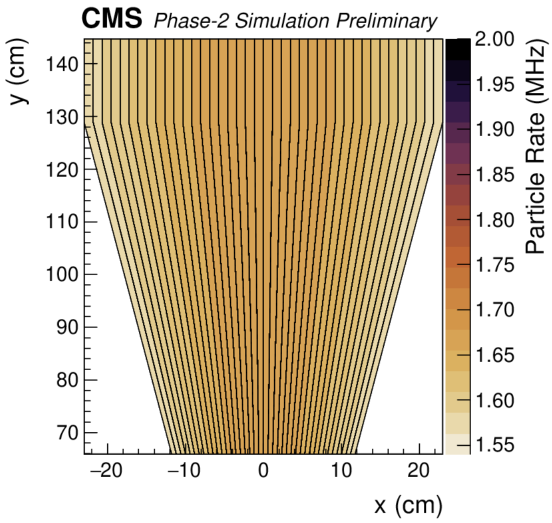

Figure 5. Expected background particle rate per sector in Phase-2 conditions for azimuthal segmented detectors. © [2021] IEEE. Reprinted, with permission, from [3].

4 Validation of the ME0 design with azimuthal segmentation

An ME0 detector prototype with azimuthal segmentation has been tested under X-ray irradiation. Two X-ray tubes with Ag target were placed a few cm away from the drift plane of the detector, one pointing towards the wide side of the trapezoidal chamber, while the second tube was focused on the narrow side, to simulate the high LHC rate at high $|\eta|$. This configuration provided intense irradiation in the sector under test, thus being sensitive to the voltage drop on the protection resistors. On the other hand, the X-ray tube flux was neither sufficiently high nor uniform for probing the voltage drop on the HV filters.

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The gas gain was measured as a function of the particle flux, normalised to the readout sector surface and to the expected particle rate at the LHC. The gain drop due to the ohmic voltage drop on the protection resistors has been found to be the same for different $|\eta|$ regions, as shown in figure 6 (left). This demonstrated that a voltage compensation common to all sectors could be applied for recovering the gain. Figure 6 (right) reports the impact of the voltage compensation on the gas gain as measured on one sector, as an example. The voltage compensation method withouth HV filters is validated up to rates of 10 MHz/sector.

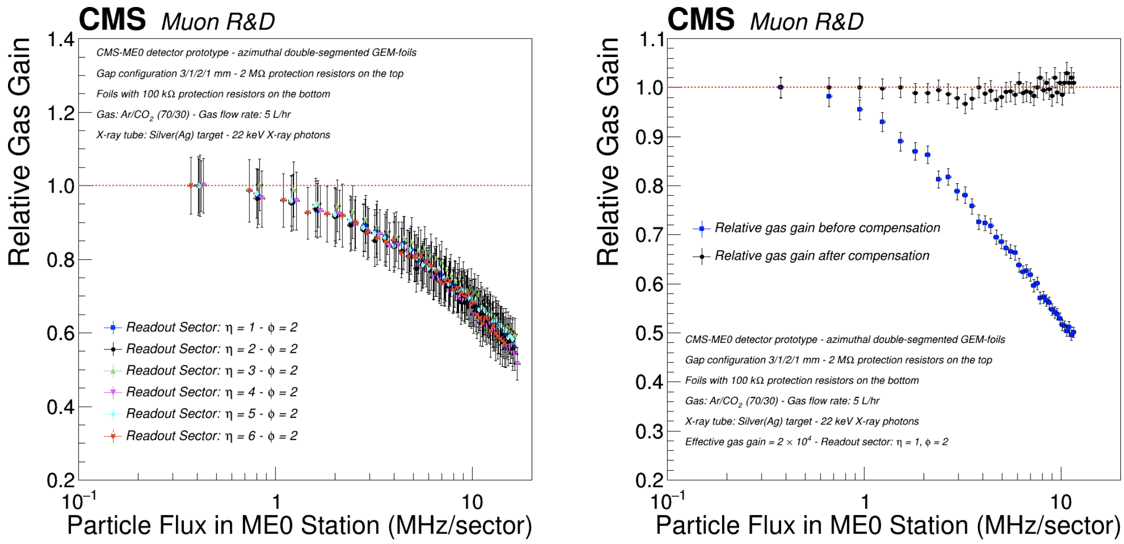

Figure 6. Left: gain drop as a function of the background particle flux measured on an ME0 detector with azimuthal segmentation under X-ray irradiation, probing different readout sectors. Right: measured gas gain under X-ray irradiation before (blue) and after (black) applying the voltage compensation, measured from one readout sector.

In order to test the ME0 detector under uniform and intense irradiation, thus also probing the voltage drop on the HV filters, rate capability measurements were carried out at the Gamma Irradiation Facility (GIF++) at CERN [6], where the prototype was irradiated with 662 keV photons from a ^{137}Cs source. The detector was read out using the final electronics and data aquisition based on the VFAT3 frontend [7]. The effective gas gain was measured as a function of the background flux per readout strip, for different configurations of the HV filters. As reported in figure 7 (left), the choice of the HV filter has a marginal impact on the rate capability, which is once again fully recovered by voltage compensation.

A test beam campaign at the GIF++ allowed for efficiency measurement of the ME0 detector using a muon beam. The efficiency was computed with respect to reference GEM tracking detectors using the final ME0 readout electronics. As shown in figure 7 (right), a drop in the muon detection efficiency is observed, which is not recovered by voltage compensation. Therefore, this effect is not related to the gain drop due to the protection resistors. After compensation, an inefficiency of about 1% is measured at ~ 125 kHz/strip rate, which has been found to be compatible with the dead time of the VFAT3 chip. Nevertheless, at the CMS expected rates, this effect will have a limited impact on the overall ME0 chamber performance thanks to the redundancy given by the presence of six triple-GEM layers.

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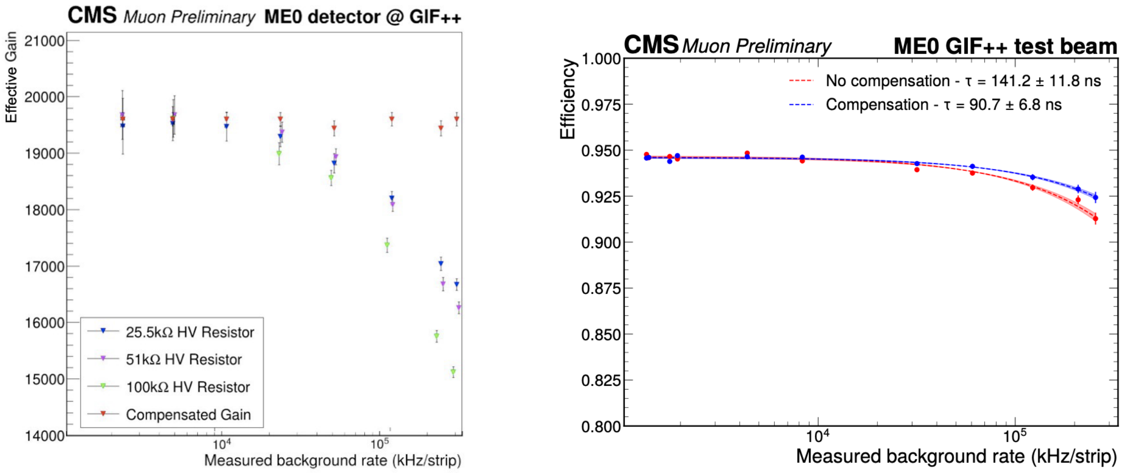

Figure 7. Left: effective gas gain as a function of the measured background rate per readout strip for an ME0 detector with azimuthal segmentation with different HV filter configurations. Right: muon detection efficiency as a function of the measured background rate per readout strip before (red) and after (blue) voltage compensation. The data points are fitted with the function $y = y_0/(1 + \tau x)$, where y_0 is the plateau efficiency at low rate. The parameter τ, extracted from the fit, indicates the dead time of the overall detector system, including the readout electronics.

5 Conclusions and perspectives

The design of the CMS endcap muon detector ME0 has been modified to meet the rate capability requirements driven by the harsh environment expected at the ME0 location during the High-Luminosity phase of the LHC. The foil design was changed to implement the azimuthal sectorization, which is expected to provide equalised background rates across the sectors. With the new design, the voltage compensation method has been validated under X-ray irradiation in the laboratory and under gamma irradiation at the facility GIF++. The ME0 detector has been tested along with its final readout electronics. While the dead time of the VFAT3 chip used for the readout plays a role in the rate capability of the detector, the impact on the ME0 efficiency has been found to be limited. The ME0 design is therefore validated and the detector is in pre-production phase, towards the installation foreseen in January 2027.

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