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The CMS Muon Endcap (ME0) GEM Detector

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Abstract

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The CMS Muon Endcap (ME0) GEM Detector

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1. Introduction

The High-Luminosity Large Hadron Collider (HL-LHC) aims to increase the instantaneous luminosity by five to seven folds (5 - 7 x $10^{34} cm^{-2} s^{-1}$) of its nominal value. Although the Compact Muon Solenoid (CMS) experiment [1] benefits from robust shielding, it remains vulnerable to the increasing luminosity effects, particularly in forward regions. To mitigate this, the CMS experiment is upgrading its forward muon system by adding new Gas Electron Multiplier (GEM) detectors [2] (GE1/1, GE2/1, ME0) as illustrated in figure 1, to strengthen tracking and triggering capabilities in the face of high particle fluxes. A new station of triple-GEM detectors denoted GE1/1 has already been installed during LS2, complementing the first station of Cathode strip chambers (CSC). The GE2/1 and ME0 systems, both are designed to further enhance the performance. This report will focus on the ME0 detectors for HL-LHC.

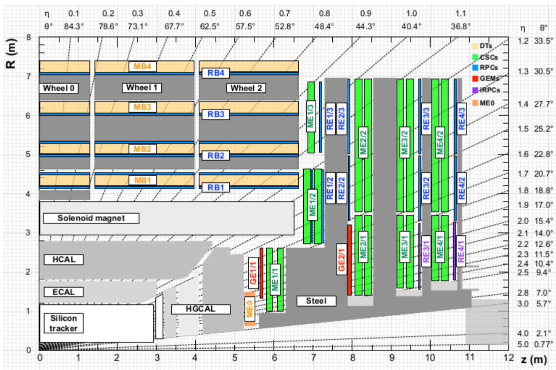

Figure 1: A quadrant of the *R* - *z* cross-section of the CMS detector, highlighting in red color: GE1/1, GE2/1 and orange color: ME0 detector, within the CMS muon system

2. The ME0 GEM Detector

2.1 ME0 Design and Performance

The "ME0" designation refers to the Muon Endcap (ME) system, with the "0" indicating that this new muon station is positioned in front of the original muon endcap system. The introduction of the ME0 detector [3] addresses several critical challenges faced by the current infrastructure, including aging components, declining detector efficiency, and reduced resolution in environments with high collision rates and radiation. The ME0 aims to mitigate these issues, ensuring the CMS experiment remains efficient under the extreme conditions expected at the High-Luminosity LHC (HL-LHC).

The ME0 detector is composed of trapezoidal stacks of triple-GEM modules arranged in a planar ring in each muon endcap. These rings, which have an inner radius of approximately 0.6 meters and an outer radius of 1.5 meters, are centered on the beamline. Each ring consists of 18 stacks, with each stack containing six layers of modules. Positioned at a radial distance of 63 cm from the beamline, the ME0 provides coverage in the pseudorapidity range of 2.0 < $|\eta|$ < 2.8, with each stack covering an angular region of $\triangle\phi \approx 20°$. The rings will be mounted directly behind the High-Granularity Calorimeter (HGCAL) in the endcap region, which upgrades the calorimeter system.

The ME0 design is similar to other CMS GEM chambers but faces more stringent performance requirements due to the harsher background environment in the innermost region. The performance goals for ME0 include:

- Maximizing geometric acceptance for muons,
- Achieving a single-module efficiency of greater than 97%, and a stack efficiency of 98.8%,
- Handling particle rates of at least 150 kHz/cm^2,
- Achieving a spatial resolution of 390 μm and an angular resolution better than 500 μrad,
- Maintaining timing resolution between 8 and 10 ns,
- Ensuring gain uniformity within 15% across and between modules,
- Preventing gain loss after accumulating 840 mC/cm^2 of charge, and Withstanding radiation levels of up to 7.9 C/cm^2.

Additionally, the discharge rate must have a minimal impact on the detector's performance and operation.

2.2 ME0 Electronics

The design of the ME0 electronics system is tailored to handle high hit rates and minimize data loss during readout. Given the intense background conditions expected, the electronics must meet rigorous performance standards. The key front-end components of the ME0 station include:

- VFAT3 [4] chips, which manage digital readout for 128 strips, ensuring efficient signal processing,
- GEM Electronic Board (GEB), a 1mm printed circuit board that provides electrical links and shielding for the system,
- bPOL DC-DC converters, which regulate the input low-voltage power for the on-detector electronics, ensuring stable operation,
- OptoHybrid (OH), which functions as a front-end concentrator, handling the readout from six VFATs.

All of these components are currently in production and have undergone extensive testing in laboratories and test beams to validate their performance and reliability.
The ME0 Data Acquisition (DAQ) system mirrors the design of the GE1/1 and GE2/1 detectors, which ensures that the manufacturing processes for custom boards and component selection are well-established and thoroughly understood.

3. Rate Capability Studies

Rate capability refers to a detector's ability to handle high particle flux without a significant loss in performance, particularly in terms of gas gain. This capability is affected primarily by two factors: the ion space-charge effect and resistive components in the high-voltage (HV) circuits.

The ion space-charge effect occurs when an accumulation of positive ions distorts the electric field, causing a reduction in gain as particle rates increase. GEM detectors have demonstrated excellent performance in this regard, maintaining stable gain at fluxes up to 100 MHz/cm² [5].
A secondary factor influencing gas gain is the ohmic voltage drop, which is caused by resistive elements in the HV circuits, such as the resistors in the HV filter and those on the GEM foils. When irradiated, the charges generated during the avalanche process create currents that flow through these protective circuits (Figure 2), causing a voltage drop across the electrodes. This drop impacts the entire GEM foil, and the effect increases as the size of the irradiated area grows. Thus, to fully assess the rate capability of CMS triple-GEM detectors, it is important to test the entire detector surface at high hit rates with moderate particle flux.

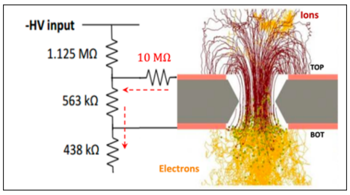

Figure 2: Scheme of the avalanche-induced currents flowing through the protection resistors of a single GEM foil.

To evaluate the GEM detector's ability to withstand high-rate conditions in CMS, a measurement campaign was conducted to examine the voltage drop effects under intense irradiation. Initial large-area rate capability tests were performed using a 10 × 10 cm² triple-GEM prototype chamber, irradiated simultaneously by two silver-target X-ray guns at progressively increasing fluxes, reaching up to 30 MHz/sector [6]. As shown in Figure 3 (left), the highest observed gain drop was 40% of the expected gas gain at an irradiation of 100 kHz/cm². This drop varies based on the size of the irradiated surface and the values of the protection resistors.

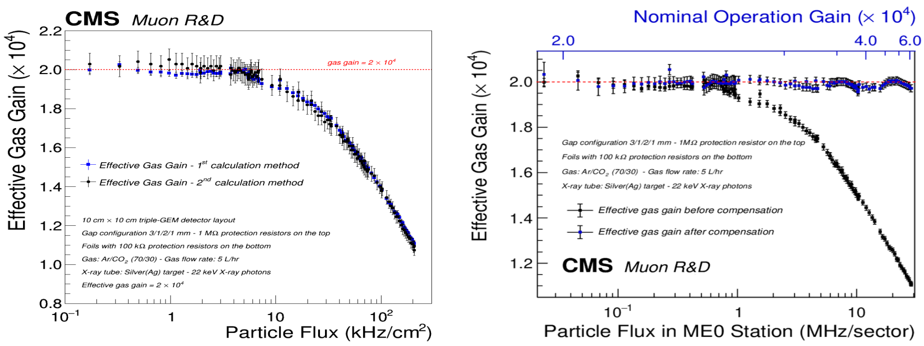

Figure 3: Left: gain drop of the irradiated prototype comparing the gain measurement under irradiation (in black) and the gain measurement by applying the expected voltage drop (in blue). Right: measured gas gain under X-ray irradiation before (black) and after (blue) applying the voltage compensation [7].

To counteract the voltage drop caused by these currents, a "gain compensation" algorithm was employed. This algorithm iteratively adjusts the voltage on each GEM electrode to maintain a desired gain of 2×10^4. The Detector Control System (DCS) monitors the current (I_{mon}) and the output voltage (V_{mon}) of each HV channel and computes the effective voltage (V_{eff}) using the formula:

$$V_{eff} = V_{mon} - I_{mon} \times R$$

where R is the total resistance between the HV power supply and the chamber electrode. The voltage on each GEM electrode is increased iteratively until the computed effective voltage matches the required voltage needed to achieve the nominal gain. Figure 3 (right) illustrates the rate capability curve alongside the recovered gain curve after applying voltage compensation, with the detector powered to operate at an effective gain of 2×10^4 for each background rate level.
While gain compensation through overvoltage is achievable, the results indicate that effective operation of the ME0 detector in the highest-η region would require a nominal gain of approximately 6×10^4. However, this comes with an increased risk of damage, particularly in the event of sudden beam loss during LHC operations. Furthermore, due to the uneven background rates at higher pseudorapidity (η), each GEM foil sector would need to be powered at different voltage levels. To address this, the ME0 detector employs an azimuthal segmentation of its chambers (Figure 4), which is expected to reduce gain loss during CMS operations to less than 10%.

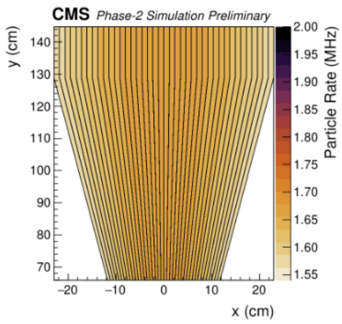

Figure 4: Design of the adopted azimuthal segmentation for the ME0 detectors, showing the expected background particle rate per sector in the CMS environment.

4. ME0 Validation at GIF++

The performance of an ME0 detector prototype with azimuthal segmentation was evaluated under intense X-ray irradiation at CERN's Gamma Irradiation Facility (GIF++). This testing used two silver-target X-ray tubes: one aimed at the wide side of the trapezoidal chamber and the other at the narrow side. The setup simulated the high radiation rates expected in the forward $|\eta|$ region during LHC operations. To further evaluate the detector's robustness, 662 keV photons from a ^{137}Cs source were used [8]. These tests aimed to assess both the detector's performance under uniform irradiation and the voltage drop effects on the high-voltage (HV) filters. The rate capability and efficiency measurements were conducted as a function of background flux per readout strip for different HV filter configurations. As shown in Figure 5 (left), the choice of HV filter had minimal impact on the rate capability, which was fully restored by applying voltage compensation. This demonstrates the effectiveness of voltage compensation in maintaining detector performance even under high flux conditions.

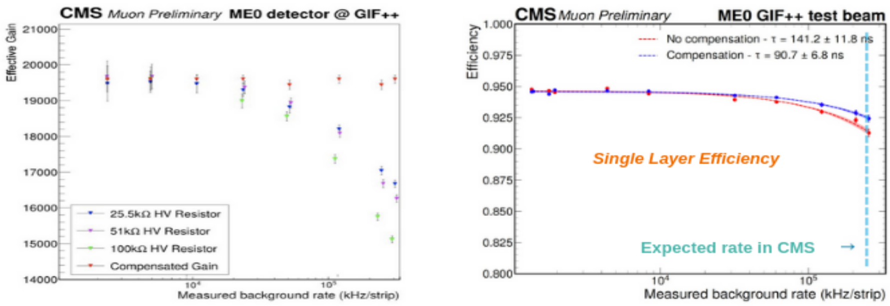

Figure 5: Left: effective gas gain as a function of the measured background rate per readout strip for an ME0 detector with azimuthal segmentation with different HV filter configurations. Right: muon detection efficiency as a function of the measured background rate per readout strip before (red) and after (blue) voltage compensation.

During a test beam campaign at GIF++, the efficiency of the ME0 detector was further measured using a muon beam and compared against reference GEM tracking detectors equipped with the final ME0 readout electronics. Figure 5 (right) shows a decrease in muon detection efficiency that voltage compensation could not fully correct. This suggests that the observed inefficiency was not due to gain reduction from protection resistors.
After compensation, an inefficiency of approximately 1% was observed at a rate of $\sim$ 125 kHz/strip, which is attributed to the dead time of the VFAT3 chip. However, this minor inefficiency is expected to have a limited impact on the overall performance of the ME0 chambers due to the redundancy provided by the six-layer triple-GEM design.

5. Conclusion

In conclusion, the ME0 detector represents a pivotal advancement for the CMS Muon System, with its innovative six-layer structure and rigorous validation ensuring it can meet the extreme demands of the HL-LHC. Extensive testing and validation at CERN's GIF++ have demonstrated that the ME0 system meets the stringent performance requirements, including high rate capability, gain uniformity, and radiation resistance. The incorporation of azimuthal segmentation and a gain compensation algorithm has proven effective in maintaining operational stability under intense irradiation, particularly in high-rate environments. Although some minor inefficiencies were observed, particularly related to the VFAT3 chip's dead time, they are expected to have a minimal impact on overall performance. With these validation results, the ME0 design is now confirmed and ready for full-scale production, scheduled to begin in 2024. Installation is planned for 2026-2027, aligning with the HL-LHC upgrade schedule.

Acknowledgments

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