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Performance of triple-GEM detectors for the ME0 system of the CMS Phase-2 Upgrade

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ABSTRACT: The High-Luminosity LHC will deliver proton-proton collisions at 5–7.5 times the nominal LHC luminosity, with 140–200 pp-interactions per bunch crossing. To maintain the performance of muon triggering and reconstruction under high-rate background, the forward part of the CMS muon spectrometer will be upgraded with Gas Electron Multiplier (GEM) detectors. The ME0 station will consist of stacks of six triple-GEM detectors, designed to extend the muon system pseudo-rapidity coverage up to $|\eta| < 2.8$. The operating environment for ME0 will be characterized by extremely high rates, estimated from simulation studies to reach approximately 150 kHz/cm^2.

To ensure the ME0 system performs effectively in this challenging environment, a detailed study of its rate capability and timing performance is critical. The current paper provides an overview of the ME0 project and its current status. It is presented the integration of a final-design prototype for a six-layer ME0 stack, along with performance measurements for muon segment reconstruction efficiency and timing, using cosmic rays and a dedicated test beam campaign at the CERN Gamma Irradiation Facility (GIF++). The outlined results confirm that the ME0 design meets the Phase-2 CMS muon system upgrade requirements.

KEYWORDS: Gaseous detectors; Gaseous imaging and tracking detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc)

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1 The CMS Gas Electron Multiplier (GEM) project

In 2029, the High Luminosity LHC (HL-LHC) project will deliver a luminosity up to 5–7.5 times the nominal LHC luminosity (i.e. $10^{34}\,\mathrm{cm^{-2}s^{-1}}$) [1], resulting in a significant increase in the rate of particles traversing the detectors. As a consequence, current detectors will experience a faster ageing, and under Run-3 conditions, the trigger rate would grow significantly. Therefore, the CMS experiment will face a full upgrade called "Phase-2 Upgrade"[2], that will involve the whole detection apparatus, from the inner tracker to the calorimeters and the muon system. In particular, the latter will be equipped, in the forward region, with two new stations of innovative RPC (iRPC) chambers and with three new stations leveraging triple-GEM detectors. In figure 1(a), the Phase-2 CMS muon system is depicted.

The GEM stations, i.e. GE1/1, GE2/1 and ME0, are aimed to work in tandem with the already existing CSC chambers to improve the p_T measurement at trigger level, allowing to keep the trigger rate under control. Besides, the increased number of hits measured per muon in the endcaps will enhance the robustness of track reconstruction at the Level-1 trigger. Additionally, the ME0 station will also extend the muon trigger coverage in pseudo-rapidity up to $|\eta| < 2.8$ (with respect to the precedent limit value of 2.4); this station will be installed right behind the new endcap calorimeter HGCAL, so it will be the closest detector of the muon system to the interaction point. Consequently, ME0 GEM detectors will operate in an unprecedently high-rate environment, with an expected rate of particles up to $150\,\mathrm{kHz/cm^2}$ [3] as shown in 1(b).

The current paper contains an overview of the performance of the first prototype of the ME0 detector with data collected using cosmic rays and in a test beam performed in July 2024 at the Gamma Irradiation Facility (GIF++) at CERN [4]. Section 2 outlines the final design of the ME0 detector together with the setup used for conducting the discussed measurements; in section 3, the measurements of the timing performance of the detector without and with a background photon flux are described. Section 4 focuses on the measurement of the detector efficiency.

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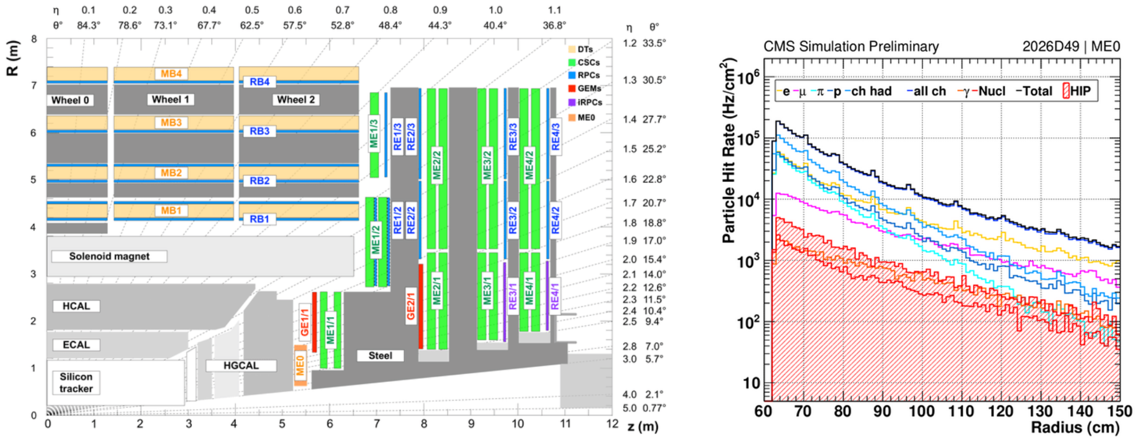

(a) (b)

Figure 1. (a) Transverse section of one quadrant of the CMS detector showing the present muon system and the proposed locations for the triple GEM (i.e. GE1/1, GE2/1 and ME0) and iRPC (i.e. RE3/1 and RE4/1) detectors. Reproduced from [5]. © CERN 2013 for the benefit of the CMS collaboration. CC BY 3.0. (b) Expected background flux in the ME0 environment as a function of the distance from the LHC beam line. © [2021] IEEE. Reprinted, with permission, from [6].

2 Measurement setup

The baseline design of the ME0 detector station [7] comprises 36 module stacks (18 per endcap), each composed of six layers of triple-GEM chambers covering $\Delta\phi = 20°$, divided into 384 radial strips, and $\Delta\eta = 0.8$, split into eight partitions.

Each detector in the ME0 system is a large trapezoidal triple-GEM detector. The detector itself consists of a trapezoidal gas volume containing a stack of three identical large area trapezoidal shaped GEM-foils embedded between a drift electrode and a readout board. The dimensions of the different regions in the CMS triple-GEM detectors are: drift region of 3 mm between drift cathode and the first GEM, spaces of 1 mm and 2 mm in the electron transfer gaps between GEM foils, and a 1 mm space in the signal induction region. The baseline gas mixture for operating the CMS triple-GEM detector is Ar:CO_2 (70:30).

The trapezoidal GEM foil surfaces oriented towards the readout board are a single contiguous conductor whereas the GEM foil surfaces oriented towards the drift board are segmented into 40 HV sectors running longitudinally through the foil to protect against destruction due to discharges and to compensate for the gain drop due to irradiation. The average rate per HV sector in the CMS background can be contained to 1.5 MHz, while the effective gain drop can be minimized to about 10% of the expected value of 2×10^4 [6].

As stated in section 1, the ME0 station will operate in a high-rate background environment; therefore, to characterize the detector, it is necessary to perform measurement in an environment as similar as possibile to the expected one at HL-LHC. The chosen place to emulate such background is the GIF++, located at CERN in the North Area, on the H4 beam line. The GIF++ provides a 14 TBq[1] ^{137}Cs radioactive source, together with a high energy (~ 80 GeV) muon beam. This allows

[1] In March 2015 [4].

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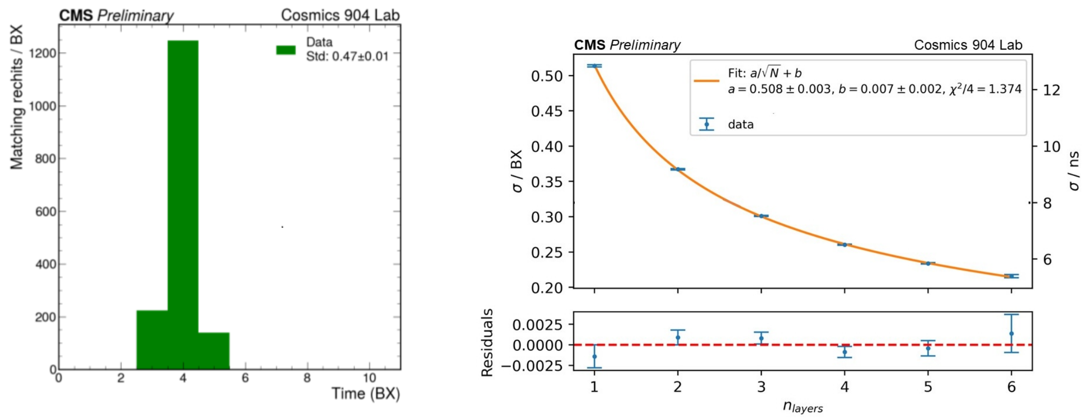
the measurement of MIP detection efficiency under irradiation, whose intensity can be tuned using a set of absorbers installed in front of the radioactive source.

The detector under test is the first full prototype of the 6-layer ME0 stack, used standalone for reconstruction. The trigger system is made of two 30×30 cm^2 scintillators provided by the GIF++ and located outside of the irradiation cone of the source in such a way to trigger only on the muon beam. The two scintillators are read out by PMTs and the trigger signal is their coincidence. Regarding the readout system, the front-end electronics coincide with the ME0 foreseen electronics: the VFAT3 is the front-end chip [8] and the concentrator OptoHybrid (OH) handles the communication with the backend, i.e. the X2O board. The same setup, arranged vertically, is used to collect data with cosmic rays. It is worth noting that during the test beam operations, one chamber of the stack was turned off during the test beam because of an issue in the HV supply; as a result, tracking was performed using 5 chambers instead of 6.

3 Time resolution measurement

The role of the ME0 station in the CMS L1 trigger imposes time resolution requirements to ME0 GEM chambers. In particular, this station will be used in CMS to trigger on forward muons at the level-1 in coincidence with other objects. To obtain a bunch-crossing (BX) identification with 99% efficiency, the ME0 stack must have a time resolution on the segment better than 4 ns. Accordingly, a time resolution of ∼ 10 ns is required for the single chambers [2].

To measure the time resolution of the single ME0 GEM chambers, the distribution of the arrival time has been taken into consideration. The hits considered in the analysis are obtained by clustering adjacent fired strips, assigning the arrival time as that of the last strip fired within the cluster. This approach helps suppress contributions from adjacent crosstalk hits. Subsequently, noise and non-adjacent crosstalk contributions are subtracted by selecting only the hits that are matched to muons. As shown in figure 2(a), the time resolution with muons from cosmic rays reaches 10.00±0.25 ns, lying within the trigger requirements.



(a) (b)

Figure 2. (a) Example distribution of the arrival times of the matching rechits for one of the six chambers in the stack. (b) Average time resolution of track segments as a function of the number of ME0 chambers used to reconstruct the segment. The orange solid line results from a fit with the function and the values of the fitting parameters shown in the plot. For 6-layer segments the time resolution is ∼ 5.3 ns. Reproduced with permission from [9].

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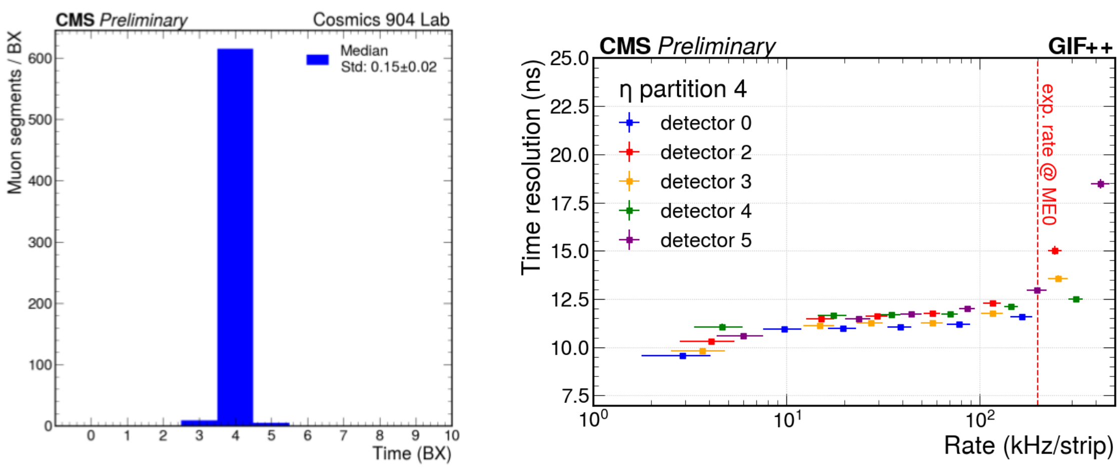
Moreover, it is noteworthy to observe that ME0 trigger primitives are multi-layer segments. Accordingly, an additional important feature to be considered is the time resolution of the segment, which scales with the reciprocal of the number of layers used for the reconstruction. The aforementioned trend is shown in figure 2(b), and the time resolution with 6 layers goes down to 5.25 ± 0.18 ns. A possible alternative to averaging consists of computing the median of the arrival times. The latter results in a time resolution of 3.75 ± 0.5 ns, as shown in figure 3(a).

Then, timing performances are also evaluated in the GIF++ irradiation field. Figure 3(b) shows how the time resolution of the single chambers is affected when irradiated. The observed increase in resolution is attributed to the cluster reconstruction technique (where the time of the cluster is taken as that of the last firing strip) and to the contamination of the clusters by background hits, which are uniformly distributed in time. At the expected ME0 rate, ranging from 10 to 200 kHz/strip, the time resolution increases up to ∼ 12.5 ns. As a consequence, the time resolution of the track increases, too. In particular, figure 4(a) shows an increase from 4 ns in low background regime to 6–8 ns in the ME0 expected rate range. Since it is important to evaluate how the efficiency of the single chambers is affected by this degradation of timing performance, section 4 will outline the change in efficiency related to the time resolution.



(a) (b)

Figure 3. (a) Distribution of the arrival time of the six-layer segments computed with the median of the arrival times of the hits on all the single layers. The median is evaluated taking the third hit, in order of arrival time. Reproduced with permission from [9]. (b) Time resolution of the reconstructed hits matching the propagated muon hits. The standard deviation is used for the lowest rate points, while a gaussian fit is employed for the highest rates. The red dashed vertical line represents the maximum expected background rate in the ME0 station. Reproduced with permission from [10].

4 Efficiency measurement

In order to evaluate the performance of the ME0 prototype to detect muons under a high background rate, a measurement of the efficiency is performed. The efficiency is computed as the fraction of muon hits matching the reconstructed hits. A correction is then applied to subtract the contribution of background hits causing a faulty increase in efficiency.

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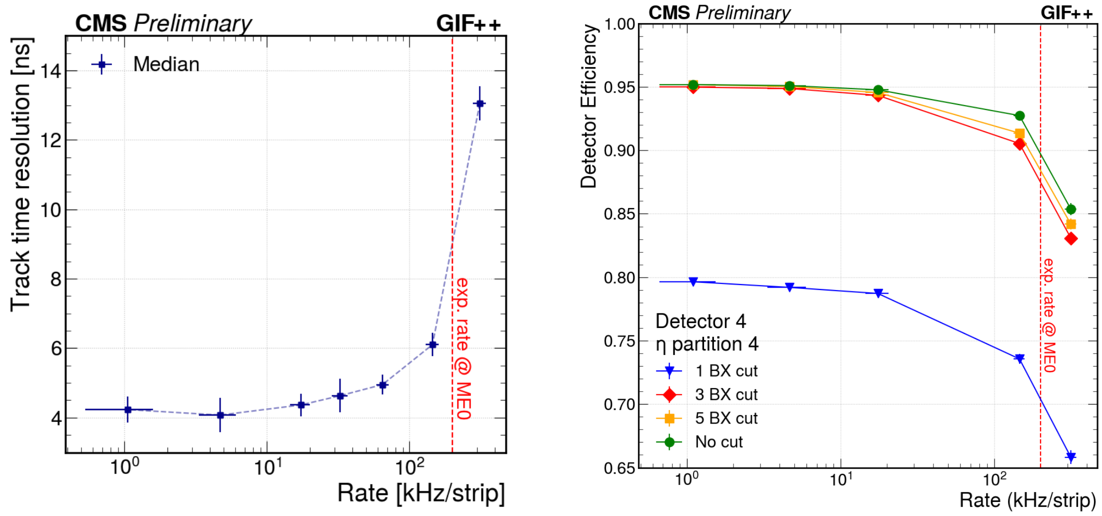
ME0 GEM chambers operating in a high-intensity background experience a drop in efficiency. The reasons for this drop are outlined below. First, the effectively applied High Voltage (HV) decreases due to the high current that flows through the foil and their protection resistors. To mitigate this effect, an iterative HV compensation procedure is performed to apply the correct voltage to the electrodes (more details in [11]). Second, offline reconstruction with the standalone stack can reduce efficiency because of the reconstruction of faulty tracks composed of background hit combinations. This effect is mitigated by using the Road-Usage algorithm [12]. Eventually, the read-out electronics is the dominant source of dead time, which cannot be further reduced. Figure 4(b) shows the trend of the efficiency at increasing background rate, resulting in an efficiency drop of 3%, which corresponds to $\sim$ 150–200 ns in terms of dead time of the single layer. The dead time is compatible with the expected VFAT3 dead time due to different cluster sizes of muons, on average equal to 3, and background single-strip clusters. At the maximum expected ME0 rate, i.e. $\sim$ 150 kHz/cm^2, the chambers retain a muon efficiency of about 90%.



(a) (b)

Figure 4. (a) Time resolution of the track reconstructed by the stack as a function of the background rate. The red dashed vertical line represents the maximum expected background rate in the ME0 station. (b) Efficiency on the tracks with different cuts on the arrival times. The cuts are symmetric around the peak of the arrival time distribution. Reproduced with permission from [10].

The spatial efficiency, analysed in section 4, is combined with the time efficiency, i.e. clusters that fall within a window of N bunch-crossings (BX) around the central one. Figure 4(b) shows how the efficiency changes depending on the timing cut applied. Although $N = 5$ provides the best efficiency, it is not feasible because of the limits imposed by the VTRx bandwidth. The most reasonable choice is to apply a 3 BX cut, because it both preserves high efficiency (only a 4–8% drop) while reducing background contamination.

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5 Conclusions

The ME0 prototype, based on six-layer triple-GEM detectors, was validated through test beam and cosmic ray measurements. An efficiency drop of ~ 3% was observed at rates up to 200 kHz/strip, consistent with a dead time of 150–200 ns as expected from the VFAT3 response. Single-chamber time resolution is 10 ns, increasing to 13 ns at operational rates. The full stack achieves a resolution of 3.75 ± 0.5 ns, rising to 6–8 ns under expected background conditions. These results meet the Phase-2 L1 trigger requirements and confirm readiness for large-scale production.

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