Journal of
Instrumentation

Performance of the CMS GE1/1 system at LHC Run-3 and prospects of the future ME0 system

Published by IOP Publishing for Sissa Medialab

Received: *November 3, 2024*
Revised: *January 15, 2025*
Accepted: *February 11, 2025*
Published: *March 20, 2025*

Topical Workshop on Electronics for Particle Physics
University of Glasgow, Scotland, U.K.
30 September–4 October 2024

Performance of the CMS GE1/1 system at LHC Run-3 and prospects of the future ME0 system

G. De Lentdecker on behalf of the CMS collaboration

Université libre de Bruxelles,
Av. F. Roosevelt 50, 1050 Brussels, Belgium

E-mail: gilles.de.lentdecker@ulb.be

Abstract: We report on the operational performance and reliability of GE1/1, a new muon tracking and triggering station made of Triple-GEM detectors installed in the most forward region of the CMS muon spectrometer as part of the Phase-2 upgrades for LHC Run-3. The GE1/1 station, comprising 144 Triple-GEM detectors, has been collecting data since 2022. We detail its front-end electronics architecture, including VFAT3, GBTx, and VTRx components, and discuss issues encountered with VTRx transceiver outgassing and the mitigation strategies implemented. By optimizing the front-end electronics, we achieved significant improvements in time resolution, reaching 12 ns, and stabilized detector performance with 94% detection efficiency. Additionally, we provide insights into the planned ME0 station, focusing on the design advancements that will improve background rejection and timing capabilities in the forward region. These results contribute to the ongoing efforts to enhance the CMS muon detection and triggering system as the LHC luminosity increases.

Keywords: Electronic detector readout concepts (gas, liquid); Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc)

2025 JINST 20 C03038

https://doi.org/10.1088/1748-0221/20/03/C03038

Contents

1 Introduction **1**

2 VTRx optical transceiver outgassing **2**

3 GE1/1 and Level-1 trigger **4**

4 ME0 status **5**

5 Summary **5**

1 Introduction

GE1/1 represents the pioneering phase-2 upgrade within the CMS program for the high-luminosity LHC. Comprising 144 Triple-GEM (Gas Electron Multiplier) [1] detectors, each spanning 1.2 meter in length, this innovation has been integrated into the forward region of the CMS muon endcap (see figure 1) [2], actively collecting data since the start of LHC Run-3 in 2022. Serving as a precursor to two additional Triple-GEM stations, GE2/1 and ME0, slated for installation within CMS in the near future.

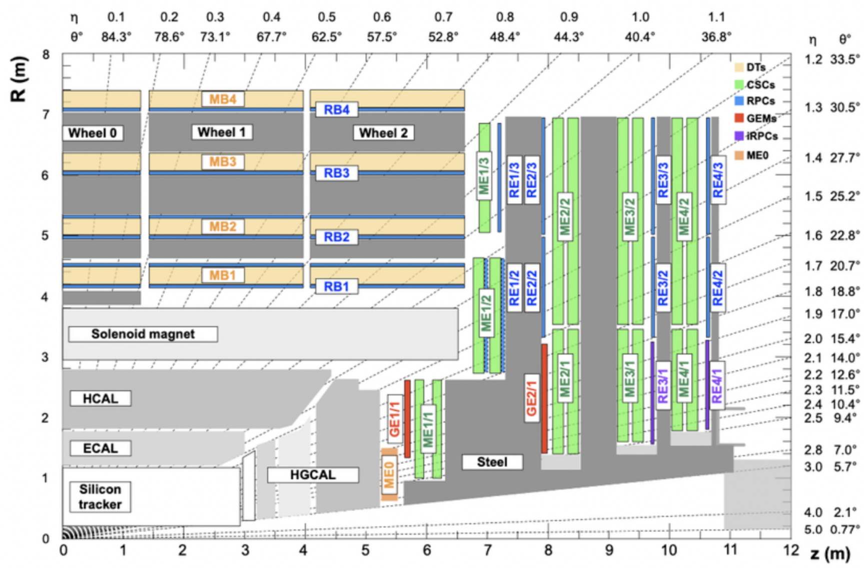
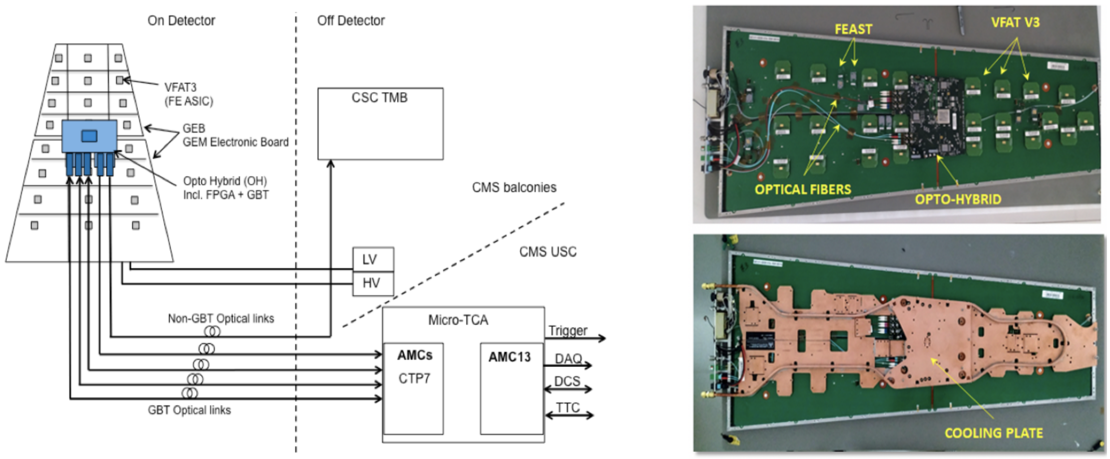


Figure 1. Quadrant of CMS experiment highlighting the new Triple-GEM muon stations, GE1/1, GE2/1 and ME0.

Figure 2(a) shows a block diagram of the GE1/1 electronics [3] and figure 2(b) shows one GE1/1 detector dressed with the Front-End electronics and then covered with the copper cooling circuit. Each GE1/1 detector is read-out by 24 VFAT3 chips, binary chips endowed with 128 channels, delivering essential trigger and tracking data. This data is subsequently relayed via a large printed circuit board, known as the GEM Electronics Board (GEB), to a compact mezzanine, the Opto-Hybrid (OH), positioned at the heart of the GEB. The OH encompasses essential components such as 1 Virtex-6 FPGA, 3 GBTx and 1 SCA chips, complemented by 3 VTRx and 2 VTTx optical modules. The optical communication with the xTCA backend boards, notably the CTP7 [4], is made through versatile links [5]. Powering this intricate front-end electronics setup are 10 FEAST DCDC converters [6].



(a) (b)

Figure 2. GE1/1 electronics block diagram (a). Zoom on GE1/1 Front-End electronics (b).

2 VTRx optical transceiver outgassing

Soon after its installation in CMS, in 2020, the GE1/1 system [7] started to face communication issues with some VTRx optical transceivers [8]. Similar troubles were observed by other CMS sub-detectors and other LHC experiments. By the time the origin of the issue was identified and a mitigation technique was proposed, it was too late for GE1/1: there was not enough time left for repair before the closure of CMS and to be ready for the LHC Run-3 start. The VTRx communication instability is known as VTRx outgassing and detailed in ref. [9]. It is due to the outgassing of the glues present in the VTRx Receiver Optical Sub-Assembly (ROSA), that then condenses on the optical fiber ferrule, leading to a loss of the light transmission.

The mitigation solution implies (i) to bake the VTRx during more than 500 hours and (ii) to cool down the VTRx during operation such that the difference of temperature between the VTRx and the optical fiber tip remains below 10°C. For GE1/1, we plan to rework all the OH boards during the next LHC Long Shutdown, LS3, in 2026–2029.

Figure 3 shows the new cooling parts made of copper, which will be added on the 3 VTRx's of the GE1/1 OH board. As the VTRx's are fixed to the bottom side of the OH, every OH has to be unplugged from the GEB board for the repair. Note also the limited space; the gap between the OH and GEB is 1 cm. In addition, the OH will be modified to enable the readout of the VTRx Receiver Signal Strength Indicator (RSSI) which monitors the intensity of the light received by the VTRx. During the last LHC technical stop of winter 2023–2024, 4 GE1/1 chambers have been extracted and modified as described above. Since then, the RSSI signals from those four detectors have shown very high stability, with variations within a couple of %.

2025 JINST 20 C03038

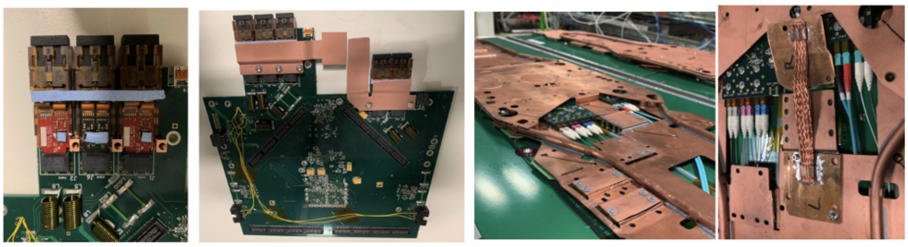


Figure 3. Improved cooling of the VTRx's on the GE1/1 Opto-Hybrid board.

Figure 4 shows the fraction of GE1/1 VFAT3 correctly communicating over time in 2023 and 2024. This fraction stabilizes around 94% in 2024; a little higher than in 2023 thanks to the refurbishment of the 4 chambers described above. The period Feb.28–Mar.19 of 2024 corresponds to the commissioning during the last technical stop where various tests are being done and should not be considered. Most of the 6% of the VFAT3 not properly communicating are due to the VTRx outgassing. The variations are due to the volatile nature of the outgassing. On top of that, 1.3% of VFAT3 channels are "masked" because of high noise and less than 0.3% of channels have been damaged by discharges. Regarding the Opto-Hybrid FPGA, it is regularly reprogrammed during operations, every 30 minutes, and so far does not show any issue that could be related to radiation.

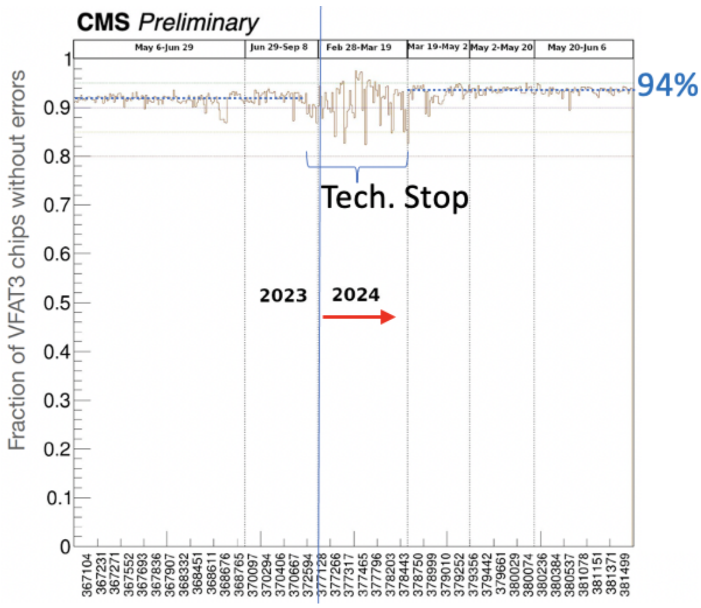


Figure 4. Fraction of GE1/1 VFAT3 correctly communicating over time (run number).

Finally, in 2024, we have proceeded with the optimization, chamber by chamber, of the high-voltage (HV) working point and of the VFAT3 settings, to reach an average detection efficiency of 94% (excluding the chambers with VTRx communication issues). For the HV working point, we optimized the detector efficiency while maintaining a reasonable discharge rate (~ 1 discharge/hour, per detector). For the electronics settings, we optimized the detection efficiency and the timing by scanning the three VFAT3 pre-amplifier gains (high, medium, or low), and the two VFAT3 discriminator modes (arming or constant fraction discriminator mode). To test all the configurations, we used data corresponding to $\sim 10\,\mathrm{fb}^{-1}$ of LHC integrated luminosity.

2025 JINST 20 C03038

3 GE1/1 and Level-1 trigger

One of the main objectives of GE1/1 is to improve the muon triggering capability, namely by combining the data from GE1/1 with the data from the ME1/1 Cathode Strip Chamber (CSC) located just behind (see figure 1). To reach that goal, the GE1/1 and ME1/1 chambers have to be aligned in space and in time. Once the alignment parameters are implemented in the CSC trigger electronics firmware (FW), the muon track bending angle between both systems is measured. Figure 5 shows the bending angle for 2 types (odd and even) of GE1/1 chambers, before and after alignment, compared to the ideal geometry, for "global (GLB) muons", that combine tracker and muon system signals, with transverse momentum $30 < p_T{}^{GLB} < 35$ GeV/c.

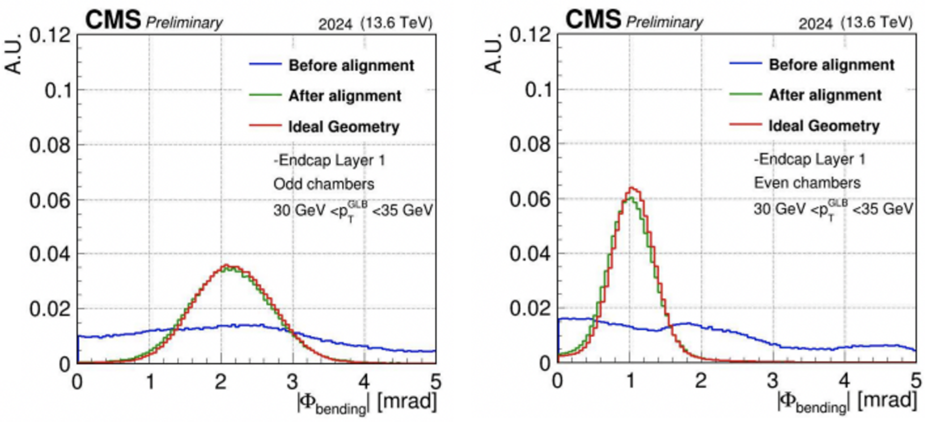


Figure 5. Bending angle for 2 types (odd and even) of GE1/1 chambers, before and after alignment, compared to the ideal geometry, for global muons with $30 < p_T{}^{GLB} < 35$ GeV/c.

Figure 6 shows the improvement of the GE1/1 time resolution obtained in 2024, after optimizing the VFAT3 configuration (see above) and improving the GE1/1 OH FW which now masks the out-of-time signals induced on adjacent strips by cross-talk. The peak value of the distribution has reduced from 15 to 12 ns. This was the last step before enabling the GE1/1-ME1/1 CSC combined trigger.

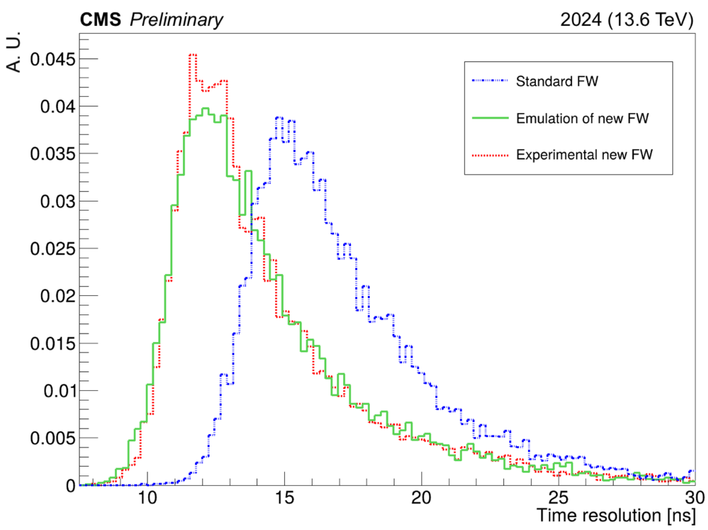


Figure 6. Time resolution of GE1/1 chambers before and after optimization.

2025 JINST 20 C03038

4 ME0 status

As seen in figure 1, the ME0 station will be installed in the most forward region of the CMS muon spectrometer, in the pseudorapidity range $2.0 < |\eta| < 2.8$; and at $|\eta| > 2.4$, it will be the single muon detector. Therefore, to be able to reject particle background, ME0 is made of stacks of 6 Triple-GEM detectors (GE1/1 is made of 2 layer stacks). The particle rate in ME0 will reach up to 150 kHz/cm^2. While the electronics concepts remain the same as in GE1/1, we can highlight that the ME0 Opto-Hybrid is FPGA-less and is equipped with LpGBT [10] chips and VTRx+ [11], instead of the GBT chips and VTRx's used for GE1/1.

As for GE1/1, the time resolution is a key parameter to participate to the CMS Level-1 trigger. Figure 7 shows the time resolution on the reconstructed track segment as a function of the number of layers in the ME0 stack, during a test beam at the CERN Gamma Irradiation Facility (GIF++) facility. As expected the time resolution on the tracks segment improves as $1/\sqrt{\ }$ of the number of layers included in the time estimation of the track, reaching a time resolution of 5 ns with 5 layers, which is in agreement with the ME0 specifications. At the time of this writing, the first ME0 stacks are being built at CERN with all the final components.

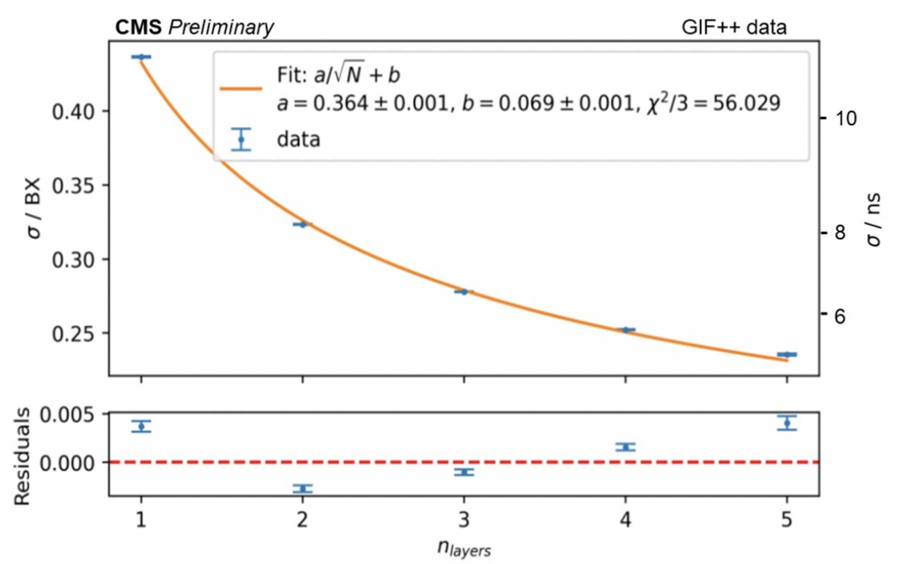


Figure 7. Time resolution (right scale in ns; left scale in bunch crossing (BX)) on the reconstructed track segment as a function of the number of layers in the ME0 stack.

5 Summary

The operational performance of the CMS GE1/1 station in LHC Run-3 demonstrates the successful integration of the Triple-GEM technology for improved muon tracking and triggering capabilities in the forward region. Despite initial challenges with the VTRx optical transceiver outgassing, a series of optimizations in the front-end electronics and detector high-voltage has led to stable communication and an average detection efficiency of 94%. The mitigation strategies and continuous adjustments have also resulted in an improved time resolution of 12 ns, positioning now GE1/1 as a key contributor to the CMS Level-1 muon trigger. Looking ahead, the development of the ME0 station,

2025 JINST 20 C03038

with a multi-layered configuration and refined timing resolution, promises further advancements in background rejection and muon identification.

Acknowledgments

The author acknowledges the enduring support of the Belgian Fonds de la Recherche Scientifique, FRS-FNRS.

References

[1] F. Sauli, *GEM: A new concept for electron amplification in gas detectors*, *Nucl. Instrum. Meth. A* **386** (1997) 531.

[2] CMS collaboration, *The Phase-2 Upgrade of the CMS Muon Detectors*, CERN-LHCC-2017-012, CERN, Geneva (2017).

[3] D. Abbaneo et al., *Development of the data acquisition system for the Triple-GEM detectors for the upgrade of the CMS forward muon spectrometer*, 2014 *JINST* **9** C03052.

[4] A. Svetek et al., *Construction, Testing, Installation, Commissioning and Operation of the CMS Calorimeter Trigger Layer-1 CTP7 Cards*, in the proceedings of the *TWEPP 2015 — Topical Workshop on Electronics for Particle Physics*, Lisbon, Portugal, 28 September–2 October [https://indico.cern.ch/event/357738/contributions/848770/].

[5] R. Martín Lesma et al., *The Versatile Link Demo Board (VLDB)*, 2017 *JINST* **12** C02020.

[6] S. Michelis et al., *DC-DC converters in 0.35 μm CMOS technology*, 2012 *JINST* **7** C01072.

[7] L. Petre et al., *Commissioning and running experience with the CMS GE1/1 system*, 2023 *JINST* **18** C02020.

[8] C. Soós et al., *The Versatile transceiver: Towards production readiness*, 2013 *JINST* **8** C03004.

[9] G. Cummings et al., *CMS HCAL VTRx-induced communication loss and mitigation*, 2022 *JINST* **17** C05020.

[10] N. Guettouche et al., *The lpGBT production testing system*, 2022 *JINST* **17** C03040.

[11] J. Troska et al., *The VTRx+, an optical link module for data transmission at HL-LHC*, *PoS* **TWEPP-17** (2017) 048.

2025 JINST 20 C03038