PROCEEDINGS OF SCIENCE

The GEM GE1/1 station of the CMS muon detector status, commissioning and operation in magnetic field

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During Run3, the LHC will deliver instantaneous luminosity in the range $5 \times 10^{34} cm^{-2}s^{-1}$ to $7 \times 10^{34} cm^{-2}s^{-1}$. To cope with the high background rates and to improve the trigger capabilities in the forward region, the muon system of the CMS experiment has been upgraded with two new stations of detectors (GE1/1), one in each endcap, based on triple-GEM technology. The system was installed in 2020 and consists of 72 ten-degree Super Chambers, each made up of two layers of triple-GEM detectors. GE1/1 provides two additional muon hit measurements which will improve muon tracking and triggering performance. We report on the status of the ongoing commissioning phase of the detector and present preliminary results obtained from cosmic-ray events. We discuss detector and readout electronics operation, stability and performance, and preparation for Run 3. Particular attention will be given to issues encountered during CMS magnet commissioning which induced trips and short-circuits in the GEM detectors.

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1. Introduction

The Large hadron Collider (LHC) [1] will deliver an instantaneous luminosity in the range $5 \times 10^{34} cm^{-2}s^{-1}$ to $7 \times 10^{34} cm^{-2}s^{-1}$ to its experiments in the high luminosity (HL) after Long Shutdown (LS) 3 from 2027. The Compact Muon Solenoid (CMS) experiment [2] is undergoing detector upgrades, especially in forward regions, to cope with a higher number of collisions per bunch crossing, larger trigger rates, and greater absorbed radiation dose. Therefore, the forward region of the CMS muon system will be equipped with new Gas Electron Multiplier (GEM) detector [3] in the first two stations as shown in Fig 1. A new station of triple-GEM detectors denoted GE1/1 has already been installed during LS2, complementing the first station of CSC, called ME1/1. Other two stations of GEM detectors, denoted GE2/1 and ME0, will be installed respectively in 2025 and 2027. In total, they will cover the pseudo-rapidity range in the $1.5<|\eta|<2.8$. These additional layers will help obtaining a highly efficient muon momentum resolution in the CMS Level-1 trigger [4]. This report will focus on the commissioning of the newly installed GE1/1 detectors.

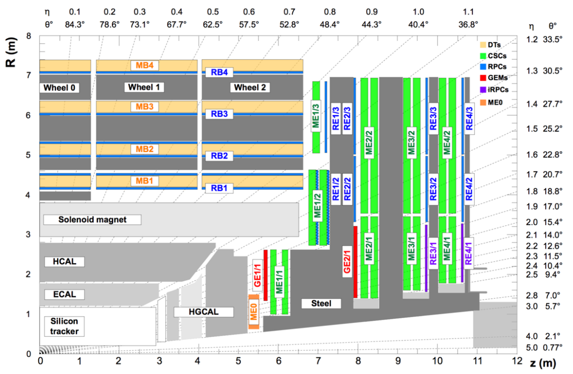

Figure 1: A quarter of the $R-z$ cross-section of the upgraded CMS detector with the GEM (red color: GE1/1, GE2/1 and orange color: ME0) along with CSC (green), RPC (blue) detectors.

2. The GEM GE1/1 station

The GE1/1 chamber is a triple-GEM detector covering $1.5<|\eta|<2.18$ and designed to fit inside the first station of the first ring of the muon system. A pair of GE1/1 chambers (L1 and L2) are combined together to form super chambers (SC) that provide two measurement planes and each SC cover 10.15^o in ϕ. These SC alternates in ϕ in long and short versions for maximum coverage as well as to cope with the mechanical constraints of the CMS endcap. In total, the GE1/1 station has 144 chambers organized into 36 SC in each of the CMS endcaps for full azimuthal coverage.

These GEM detectors are trapezoidal in shape and made up of three foils GEM1, GEM2 and GEM3. GEM foils consist of a thin layer of insulating polymer coated with copper and chemically perforated with a high density of microscopic holes. They are embedded between a drift cathode and a readout board along with the external frame that defines the gas volume, filled with Ar/CO_2 gas mixture in the ratio 70:30. The induced electrical signal produced by the particles is picked up by the anode readout board and induced on the radial strips, amounting to a total of 3072 per chamber. Groups of 128 strips are read out by 24 analog to digital frontend chips (VFATs [5]), organized into 8η partitions and 3ϕ. The key features here include time (~8 ns) resolution, spatial resolution (~300 μm), efficiency (>97%), and rate capability (up to O(MHz/cm^2)) and are well suited for HL-LHC environment.

3. Commissioning: GE1/1 in CMS

The GE1/1 chamber design and production procedures have been optimized along the years thanks to the efforts from the involved research laboratories and industries. GEM detectors were proposed to be included in the muon system in 2009. In the following years, R&D on the prototypes of the GEM detector, electronics, and DAQ was carried out. A small GEM slice was installed in 2017 and commissioned during the Run2. In September 2020, GE1/1 was fully installed in the CMS detector. The commissioning of the detector is performed in various steps after installation and is in its final phase. Optimization of the readout electronics threshold and determining the optimal HV working point is currently under study.

3.1 Hardware Commissioning

The first step after installation focuses on the integration of the necessary services. It includes connecting optical fibers for readout and trigger purposes between front-end to the back-end electronics, fibers for temperature sensors, RADMON sensor cables for radiation monitoring, gas system, and water cooling for frontend chips and FPGA powering. The two layers of each GE1/1 SC are powered with a multi-channel high voltage (HV) power supply, thus sharing the same HV working point. The readout electronics of each layer are powered with an independent low voltage (LV) power supply. All electrical cables and readout fibers have been thoroughly tested.

One of the most important features of GEM detectors is the need for HV training. Initially, after the installation, all chambers have been trained for HV in CO_2 followed by the final mixture of Ar/CO_2. HV training during the commissioning phase poses one of the basic concerns for the safe operations of detectors. After any mechanical movement of the muon endcaps during LS2, after the year-end break, or when they were commissioned in a magnetic field a dedicated HV training procedure is incorporated. This procedure was defined with pure CO_2 in which the different electrodes of the triple-GEM stack were powered separately to check for any failure of the powering system or short circuit between adjacent electrodes. Then different layers of the GEM stack were powered sequentially, starting from the drift gap down to the third amplification gap. This procedure was followed until stability for that chamber was achieved. For the safe operation of chambers, a stringent procedure was defined, based on the careful investigation of discharges in a magnetic field, discussed in section 4

3.2 Software commissioning:

This section focuses on the commissioning of Detector Control System (DCS) and Data Acquisition System (DAQ), which are directly connected to the hardware. DCS provides continuous control and monitoring of the GE1/1 detectors e.g. the high-voltage and low-voltage status, trending plots, gas mixture composition status, electronics overheating monitoring, gas and cooling distribution rack flow rate status, etc. It automatically takes appropriate corrective actions in order to reduce human errors and optimize recovery procedures. The commissioning of the electronics has been carried out in different stages. First, the connectivity of all the readout fibers has been tested and communication with all the VFATs through the opto-hybrid (OH) [5] has been ensured. Secondly, the frontend response has been measured using the internal pulser and the electronic noise has been evaluated. Lastly, optimal thresholds have been set corresponding to the optimal noise rate for each VFAT. The online data quality control is ensured using Detector Quality Monitoring (DQM) system providing in-play information on the data collected by the GEM detectors. DQM offline also provides early performance information on the promptly reconstructed data.

3.3 Global commissioning:

During LS, CMS collected global cosmic data at regular intervals to test and commission sub-detectors, trigger, DAQ software in view of pp collision runs. GE1/1 station took part in global commissioning and data taking. GEM DAQ was integrated in September 2020 in the CMS DAQ for data taking and after that GEM participated successfully in global commissioning during all the runs with all other subsystems. Latency and HV scans were performed to find the optimal operating point of the detector. Preliminary performance of the detectors has been measured by analyzing early cosmic-event data. Continuous data for six week during cosmic run at zero Tesla (CRUZET) in 2021 was accumulated where GE1/1 DAQ system was further tested and operating protocols in preparation for Run 3 of the LHC have been established. The CMS magnet was ramped to its full strength, 3.8 Tesla, in early 2022 and a campaign of cosmic data taking at four Tesla (CRAFT) was carried on.

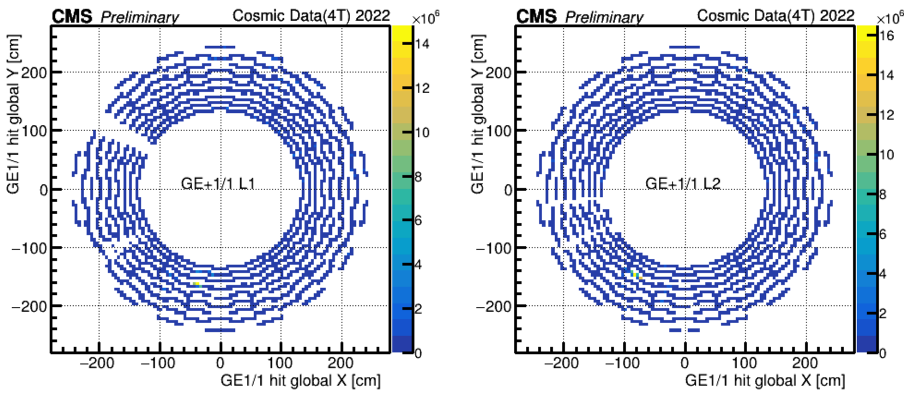

Figure 2: Occupancy of GE1/1 reconstructed hit during cosmic ray muon run collected by CMS detector at 3.8T in April 2022 for L1 and L2 for negative endcap.

The Fig 2 show the occupancy of GE1/1 reconstructed hit during cosmic ray muon run collected by CMS detector at 3.8T in April 2022. The axes represent distance to the interaction point. During this run, all chambers were successfully read out except L1 of SC 16 in the positive endcap. It was not configured and was masked due to communication instabilities with the front-end electronics. Some noisy strips with higher occupancy were also noticed scattered around the chambers.

4. Operations in Magnetic field:

Although GEM detector prototypes for the CMS upgrade have been tested in a high irradiation environment, showing stable performance and lower discharge rate but due to GE1/1 chamber size, any contamination present in gas or on the copper electrode can trigger discharges. During the first operations of CMS magnet, GE1/1 experienced the occurrence of many discharges, which triggered trips on HV channels. In order to reproduce this unstable behavior a similar setup was made with a Goliath magnet in CERN with four spare GE1/1 chambers. The aim was to define a safe and smooth operational procedure for GE1/1. During the test, many magnetic field variations were performed adopting different chambers' parameters like HV working point and gas flux.

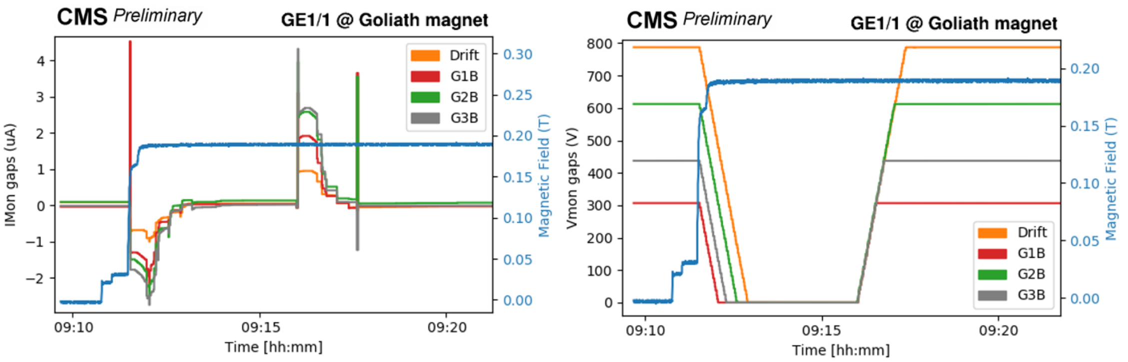

Figure 3: Volatge and current data for Drift, G1,G2,G3 bottom electrode

Fig 3 displays the time evolution of the current and the voltage data for the Drift, G1,G2,G3 bottom electrode. Blue line indicates the magnet field ramp-up. An occurrence of a discharge as a current spike as well and HV ramp down were observed around 9:12.

Fig 4 shows the discharge events observed per magnetic field ramp-up. It comes out that these discharges are uncorrelated to the HV working point. The procedure shown in Fig3 was repeated several times in a series of tests (2,12,12,12 times) with magnetic field ramps down/up and HV off as indicated. The horizontal bottom panel corresponds to the gas flux and equivalent divider current applied to the Drift, G1,G2,G3 electrodes. As a result of this test, the rate of discharges decreases with the number of magnet ramps performed, while it increases when mechanical stress is applied (as in CMS during disk movements). So to avoid any short, the dust or other residual should immediately burn and HV on the foils should be kept ON during the magnet ramps.

5. Issues encountered and possible solution

Different issues appeared while commissioning which have been fixed or satisfactorily implemented. High noise levels in the readout electronics have been found due to parasitic currents in the LV power system and were reduced by the installation of LV filters. It was also discovered during each run some instabilities in the GBT communication and locking capability. Upon investigation, it was linked to the outgassing of VTRx optical modules installed on the OH and a possible solution was to bake it for a long time. The GE1/1 detector parameters are being refined: the high-voltage working point is being adjusted for each chamber and the front-end parameters are being optimized.

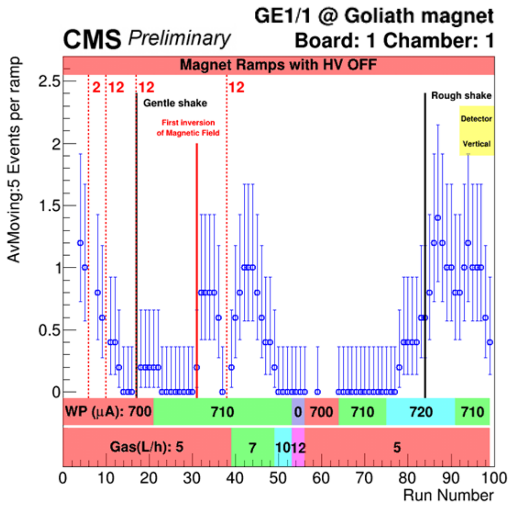

Figure 4: Discharges per magnetic field ramp up. Horizontal bottom bands represent the gas flux and the equivalent divider current (corresponding to HV) working point used. The vertical dashed red lines represent the number of magnetic field ramps that were performed with chamber HV off as indicated (red band). The mechanical shaking of chambers is marked with vertical black lines.

6. Conclusion

For the first time completely new triple-GEM technology for the sub-detector has been introduced to the CMS detector and successfully installed and commissioned. GEM commissioning is in overall good shape. It participated in all CMS global data taking and will be fully operational during the Run3 data taking. However, some issues were noticed and tackled with a potential solution. As LHC resumes, the upcoming collision data to be taken in the next months will be very crucial to understand and scrutinize it with current findings.

References

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