Status of the installation and commissioning of the first GEM station at the CMS experiment

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Abstract. The foreseen upgrade of the Large Hadron Collider (LHC) will lead to an increase of its luminosity up to $5-7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, five times more than the original design value. The CMS muon system must be able to sustain a physics program after the increase of luminosity and maintain sensitivity for electroweak physics for TeV scale searches achieved during Run2. To cope with the corresponding increase in background rates and trigger requirements, the installation of additional sets of muon detectors based on Gas Electron Multiplier (GEM) technology, referred to as GE1/1, GE2/1 and ME0, has been planned. The installation and commissioning of the GE1/1 detectors in the CMS experiment have been scheduled in two separate phases: the first 72 detectors have been already installed together with their services (gas, cooling, low voltage and high voltage) in 2019 and they are undergoing the commissioning phase, while the completion of the station is foreseen in autumn 2020. The author will describe the detector design, the quality assurance and certification path, as well as will present the status of the installation and commissioning, worth its preliminary results and an overview for the complete integration of the GE1/1 project on the CMS experiment.

1. Description of the GE1/1 project
To extend the sensitivity for new physics searches, a major upgrade of the LHC machine has been decided and is being prepared, the High Luminosity LHC (HL-LHC). The instantaneous luminosity of LHC is expected to exceed the nominal value and reach $2.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, after the second Long Shutdown (LS2) in 2019 - 2021. A further increase is planned during the third Long Shutdown (LS3) in 2025 - 2027, up to $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, i.e. a yield five times greater than the initially design value of the LHC machine. The increase of the luminosity during the future upgrades of the LHC machine will deeply affect the performance of the detectors in the CMS Muon System due to the harsh background environment and the high pile-up. As a consequence, a general upgrade of the present detectors and their electronics is mandatory. In order to cope with very high operation condition, high pile-up and background environment in particular in the forward region of the CMS muon endcaps, the Muon Collaboration is planning to install detectors based on the Gas Electron Multiplier technology during the second Long Shutdown [1,2]. The project is named GE1/1, where "G" stands for GEM, "E" for Endcap, the first "1" corresponds to the first muon station and the second "1" the first ring of the muon station (see figure 1). In the GE1/1 Muon System, a pair of such GE1/1 detectors are combined in order to form the so-called GE1/1 "superchamber" that provides two measurement planes in the muon endcap and optimizes the detection efficiency. Each superchamber covers a $10^\circ$ sector so that 72 superchambers are required (36 per each endcap of the CMS Muon System) to
form a ring of superchambers that gives full azimuthal coverage. The superchambers alternate in $\phi$ between long ($1.55 < |\eta| < 2.18$) and short ($1.61 < |\eta| < 2.18$) versions. Each endcap holds 18 long and 18 short superchambers, for a total of 144 detectors in all CMS Muon System.

**Figure 1.** A quadrant of the muon system, showing DT chambers (yellow), RPC (light blue), and CSC (green). The new GEM detector station, GE1/1, is indicated in red.

**Figure 2.** Exploded view of the mechanical design of a GE1/1 triple-GEM detector and its main assembly components.

### 2. GE1/1 detector technical design

The CMS GE1/1 detector 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 drift board, the readout board and the external frame define the gas volume. Two rubber O-rings placed in the groove of the external frame ensure the gas tightness. Figure 2 shows the exploded view of the mechanical design of a CMS GE1/1 triple-GEM detector prototype and its main assembly components starting from bottom: drift board mounted all around with stainless steel pull-out posts used for mechanical stretching of GEM-foils, 3 mm internal frame, first GEM-foil, 1 mm internal frame, second GEM-foil, 2 mm internal frame, third GEM-foil, 1 mm internal frame, first O-ring, external frame, second O-ring and the readout board.

The new self-stretching technique has been introduced to mechanically stretch the GEM-foils without using spacer grids or glue inside the gas volume in order to avoid dead regions (several percent) or possibly outgassing contaminants which could trigger premature aging processes. The three GEM foils are sandwiched at their edges between four thin internal frames.
Square stainless steel nuts are embedded into the frames every few centimeters to host stainless steel screws which are inserted into the pull-out posts: when the pull-out screws are tightened manually, the GEM-foils in the stack are tensioned against the pull-out posts. Additional details and technical aspects of the GE1/1 detector design and assembly techniques are available in [4,5].

Since very limited space is available within the current mechanical structures of the forward region of the muon endcap at the CMS experiment, the CMS GE1/1 detectors are very compact in size. The standard gas mixture for operating and testing these CMS triple-GEM detectors is Ar/CO$_2$ (70/30%).

3. GE1/1 detector quality control protocol

The GE1/1 detectors mass production has been optimized during years with many efforts from the research laboratories and the involved industries. The GE1/1 detector assembly and quality control took place at several production sites namely Switzerland (CERN), Italy (INFN Bari and Frascati), Belgium (University of Ghent), India (University of Delhi, BARC, Punjab University), Pakistan (National Centre for Physics) and USA (Florida Institute of Technology), and in addition the University of Aachen operated as satellite site qualifying detectors produced in the different production sites. The Quality Assurance (QA) and the Quality Control (QC) are key elements to ensure the delivery of fully efficient GE1/1 detectors by yielding their best performance when installed in the Muon Spectrometer of the CMS experiment. Standardized QA/QC procedures have been established in order to prevent any mechanical or electrical issues that might affect the detector performance. These procedures are identical as far as possible for all production and quality control sites. The quality control tests involve all the principal GE1/1 detector components and focus on the following aspect: gas tightness, electric test, noise, effective gas gain and response uniformity measurement. The detailed step-by-step description of the assembly and QA/QC procedure is available in [4,6].

As for the external production, the GE1/1 detectors passing the intermediate quality control are send back to the CERN production site. The CERN, being the final recipient of the assembled detectors, has implemented additional quality controls to verify and test the performance of the received detectors as well as those of the detectors assembled directly at CERN production site. At this stage, the detectors are equipped with the latest CMS front-end electronics (VFAT3 - trigger and tracking front-end ASIC device [7]), cooling system, mechanical elements, etc. and an appropriate front-end electronics test is performed in order to check the connectivity of the electronics components, monitor the communication stability, check noise level and output signals. Then, two GE1/1 single detectors are coupled together in order to fabricate the so-called superchamber by paring the detectors with similar effective gas gain. Whereas the GE1/1 single detectors assembly and quality control are done by the different production sites, the assembly of the superchambers and the their quality control tests are performed at CERN exclusively. After the mechanical assembly of a superchamber, the relevant parameters (muon detection efficiency, spatial resolution, noise, cluster size, etc.) are measured with a dedicated cosmic stand. The cosmic stand allows several detectors (up to 15 superchambers) to be tested at the same time. The experimental setup includes the following features:

- Fully automatic high voltage scan, to allow measurement of the muon efficiency and spatial resolution;
- Measurement of cosmic muon tracks over a large area of the detector;
- A Detector Control System (DCS) and Data Acquisition System (DAQ) comparable to those used in the CMS experiment, to monitor and control the high and low voltage, environmental conditions, gas mixture quality and test the on-detector electronics;
Figure 3. Muon detection efficiency (a) and spatial resolution (b) as a function of the high voltage as measured at the cosmic test stand for one of the superchambers installed in the GE1/1 station of the CMS experiment. The superchamber is operating with Ar/CO$_2$ (70/30%) gas mixture and read out with VFAT3 chip, configured with 2.5 – 3.5 fC average strip-hit thresholds.

- Data storage and analysis. Raw data is stored on disk for further offline processing. A dedicated Data Quality Monitoring (DQM) has been developed to allow fast online data analysis.

Figure 3 shows an example of the muon detection efficiency (figure 3 (a)) and spatial resolution (figure 3 (b)) as a function of the high voltage as measured at the cosmic test stand for one of the superchambers installed in the GE1/1 station of the CMS experiment. The high voltage is expressed in terms of equivalent divider current, i.e. the current drawn by the 4.7 MΩ resistive divider used to distribute the voltage within the different GEM electrodes. The efficiency measurement is performed using the detectors in the stand as trackers and comparing the reconstructed track with the muon hits on the detector under test. The front-end threshold is set through a calibration procedure such that a maximum intrinsic noise rate of 100 Hz per sector is read out when the detector is not powered. The GE1/1 superchamber under test reaches a plateau efficiency of 98% for muons when operated with Ar/CO$_2$ (70/30%) gas mixture and has a read out with VFAT3 chip, configured with 2.5 – 3.5 fC average strip-hit thresholds. The average spatial resolution for the GE1/1 superchamber under test with an angular strip pitch of 463 μrad and binary signal readout is measured to be 146.4 ± 3.6 μrad on the efficiency plateau. This performance exceeds the minimum requirement of 300 μrad with a comfortable performance margin [2,3]. Once this stage is completed, the superchamber is declared ready for final installation in the Muon Spectrometer of the CMS experiment.

4. GE1/1 detector installation and commissioning
The installation of the 36 superchambers for the first endcap has been successfully completed in October 2019, with multiple installation windows from September to October 2019, while the installation of the 36 superchambers for the second endcap has been successfully carried
out during July and September 2020 after the lockdown imposed by the SARS COV-2 health crisis. The installation of the first endcap has been anticipated by the installation of two GE1/1 superchamber in July 2019. This pilot project has been carried out in order to validate the final mechanical installation procedure of the superchambers in the endcap, the correctness of the services previously installed in the experimental cavern, and to get an early feedback about the front-end and back-end electronics response in the final CMS environment with the superchambers powered and read out through the final services [8].

The commissioning phases are required to bring the GE1/1 subsystem into an operational state suitable for the future physics data-taking campaigns. Due to the high level of interdependence between different system: service cabling, power system, gas and cooling system, data acquisition and online monitoring system, the commissioning procedures of the GE1/1 detectors will take place in several and well defined steps. Every single GE1/1 detector and its front-end/back-end electronics are tested individually after the installation in the Muon Spectrometer of the CMS experiment through a series of rigorous tests in order to ensure fully efficient detectors by yielding their best performance operating characteristics in the CMS environment. Therefore, any potential damage and performance losses which could have occurred during the detector transportation and installation can be immediately identified and repaired. Moreover, the GE1/1 detectors’ basic parameters, such as no leaks in the gas and cooling circuit, high-voltage stability of the GEM-foils with the operational Ar/CO\textsubscript{2} (70/30\%) gas mixture, low background noise, appropriate connectivity of the electronics components, and the operational characteristics of the front-end and back-end electronics, are set to optimal settings in preparation for the cosmic rays and physics data taking.

4.1. Hardware components commissioning

The hardware commissioning includes the following main parts: service cabling, power and readout systems, gas and cooling systems. The services for the GE1/1 subsystem have been successfully integrated in both endcaps: the high and low voltage power system in the underground service cavern (USC55) and the corresponding power lines to the detectors in the experimental cavern (UXC55), the gas mixing system in the gas building on the surface, the gas and cooling circuit, electronics overheating and radiation dose monitoring to the chambers in UXC55, and the optical fibers connecting the front-end to the back-end electronics in UXC55 and USC55, respectively. Additional details and technical aspects of the GE1/1 services and cable routing are available in [2,3]. All electrical cables and readout fibers have been thoroughly tested and any potential detected failures understood and fixed before the final hardware is commissioned by using specific tools made available by the Detector Control System (DCS) and Data Acquisition System (DAQ). These control and cross-check procedures significantly reduced the potential mapping errors of such a complex system. Since January 2020, both the power and readout systems for the first endcap are fully functional, while those for the second endcap are currently under commissioning. Furthermore, during the commissioning phase, each gas and cooling lines have been carefully checked at every stage and a dedicated pressure test have been successfully carried out in order to avoid any possible presence of gas and/or coolant leaks. Since November 2019, both the gas and cooling systems for the first endcap are fully functional: the gas system is currently running with the operational Ar/CO\textsubscript{2} (70/30\%) gas mixture, while the cooling system is running with deionized water in recirculation mode. Finally, the gas and cooling system of the second endcap have been successfully commissioned between September and October 2020.

4.2. Software components commissioning

The software commissioning includes the following main parts: the Detector Control System (DCS) and Data Acquisition System (DAQ), which are directly connected with the hardware of
the detector, and the Data Quality Monitoring (DQM), which accurately monitor the quality of data collected and the performance of the detectors. The GEM - DCS provides continuous control and monitoring of the GE1/1 detectors and automatically takes appropriate corrective actions when pathological conditions occur in order to reduce human errors and optimize recovery procedures. It monitors and controls the high-voltage and low-voltage system (detector status, high voltage and low voltage status, trending plots, etc.), the gas and cooling system (gas mixture composition status, gas and cooling distribution rack and flow rate status, etc.), the RadMon system (absorbed radiation dose monitoring) and the temperature system (electronics overheating monitoring). The GEM - DCS commissioning has been carried out in parallel with the hardware commissioning of the GE1/1 subsystem, leading its evolution. The GEM - DCS will be implemented as a Finite State Machine (FSM) in a common CMS framework which allows a slow control and monitoring of the GE1/1 subsystem.

![Screenshot of the main control room panels showing examples of the DCS tools (a) and DAQ and on-line monitoring tools (b).](image)

**Figure 4.** Screenshot of the main control room panels showing examples of the DCS tools (a) and DAQ and on-line monitoring tools (b).

Finally, the finalization of the Data Acquisition System, Data Quality Monitoring System, and their interfaces and infrastructure in order to properly operate them, will lead to the final integration of the GEM - DAQ and GEM - DQM into the central DAQ of CMS experiment to acquire data together with the other subdetectors. The detailed description of the firmware and software environment as well as the interface between the GEM - DAQ/DQM and the central CMS DAQ/DQM are available in [2,3].

5. **Conclusion**

In July 2019, after a decade of planning and preparation, the first triple-GEM detectors have been installed in the CMS experiment. Located in the endcaps close to the beamline, a total of 144 triple-GEM detectors will make up the GE1/1 subsystem, the first completely new technology for a subdetector introduced into CMS since it was built. The triple-GEM detectors’ ability to cope with very high particle rates will greatly improve the muon measurement in high hit rate and harsh radiation environment region of the CMS experiment. Currently, all the 144 GE1/1 detectors have been assembled and fully validated following a strict quality control protocol and their installation into the CMS experiment has been successfully completed in October 2020. With the installation complete, the next step is to fully commission the GE1/1 subsystem of both end caps: each installed detector will be tested afterwards using the final services together with the Detector Control System, Data Acquisition and Data Quality Monitoring Systems, in preparation for the cosmic ray data taking, which offer a unique
opportunity to commission the functionalities and verify the detection performances, and finally to move to the future physics data taking campaigns.

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