GEM DETECTORS FOR THE UPGRADE OF THE CMS MUON FORWARD SYSTEM

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The CMS experiment is one of the two general purpose experiments at the LHC. For LHC Phase-2, the instantaneous luminosity delivered to the experiment will reach 5×10^{34} $cm^{-2}s^{-1}$, resulting in high particle fluxes that require the detectors to be upgraded. The forward regions, corresponding to the endcaps of the detectors, will receive the largest doses. In the CMS experiment, to cope with the higher event rates and larger radiation doses, triple-layer Gas Electron Multipliers (GEM) will be installed in the muon endcaps. Triple-GEM chambers will complement the existing muon system, leading to a better identification of the muon tracks and a reduction of the trigger rate due to the increase in lever arm and hence better momentum resolution. In addition, the forward coverage will be further extended. The tracker coverage will be increased up to $|\eta|<4$, so the muon system will also be extended from $|\eta|<2.4$ to the maximum possible value of $|\eta|<2.8$. For the inner ring of the first station of the muon endcaps, 144 GEM chambers are being built in production sites spread in 7 countries around the world. For the first time, such detectors will have large sizes of order m^2, thus high requirements on the uniformity across the detector are needed. Before the final installation in the CMS detector, to test their integrity, quality and performance, the GEM chambers undergo multiple quality control tests. This talk gives an introduction to GEM detectors and presents results of the performance tests.

Keywords: CMS, HL-LHC, GEM, Upgrade, Muon System

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1. GEM detectors for the upgrade of the CMS Muon System

During Runs 1 and 2 the Muon System [1] of the CMS experiment was instrumented with three different types of gas detectors: Drift Tubes (DTs), Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs). The coverage in the detector's forward region was ensured by CSCs up to a pseudorapidity of 2.4 and by RPCs up to a pseudorapidity of 1.6.

By 2023 the instantaneous luminosity of the the Large Hadron Collider (LHC) will increase up to about 5 to 7.5 · 10^{34} cm^{-2} s^{-1}, with a consequent increase of the particle background up to 10^6 cm^{-2} s^{-1}. In this new environmental condition it will not be possible to maintain low transverse momentum trigger thresholds to select muons from electroweak bosons at an acceptable Level-1 (L1) trigger rate in the forward muon endcap with the current detector configuration. The installation of triple Gas Electron Multiplier (GEM) detectors [2] is one of the upgrades introduced in order to improve the muon L1 trigger performance during the High Luminosity LHC (HL-LHC) [3].

The GEM upgrade involves three new muon stations (shown in figure 1): the GE1/1 station, being installed in 2019-20 in the region 1.55<|η|<2.18 in the muon disk closest to the interaction point, the GE2/1 station to be installed in 2022-23 in the region 1.6<|η|<2.4 and the ME0 station to be added in front of the other muon stations in 2024 at 2.4<|η|<2.8. They consist of two (GE1/1 and GE2/1) or six (ME0) layers of triple-GEM detectors that will add up to 2 or 6 hits respectively to the muon reconstruction of the CSC stations, increasing the total path length traversed by muons in the muon endcap. This will lead to a more efficient reconstruction and reduced trigger rates [4]. A representation of the combined GEM-CSC muon reconstruction and the impact of the GE1/1 station on the L1 muon trigger are shown in figure 2.

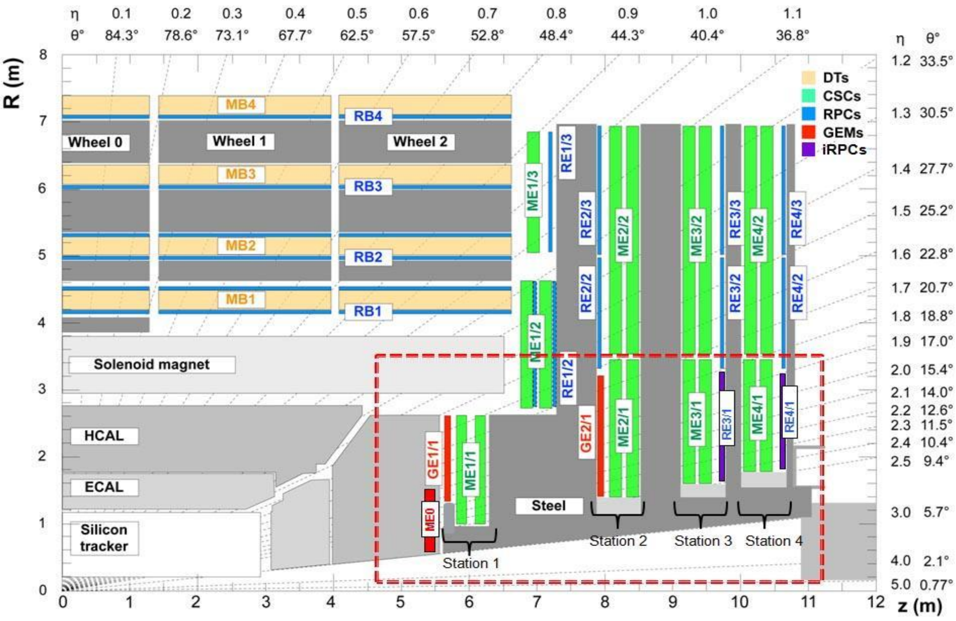

Figure 1. Schematic representation of a quadrant of the CMS detector with the muon detectors for the Phase II Upgrade. On the axes, z and R represent the distance from the interaction point along the beam direction and perpendicularly to it respectively [4].

2. The GE1/1 Demonstrator

The GE1/1 station is composed of 36 superchambers per endcap, a superchamber being a stack of two layers of 10-degrees triple-GEM detectors. Its final installation is taking place in this period during the Long Shutdown in 2019-20. A demonstrator (or *Slice Test*) composed of five superchambers in the negative muon endcap (shown in figure 3) was already installed at the beginning of 2017 and operated in 2017-18 with the goal of acquiring installation and operation expertise, proving the system's operability and operational conditions and demonstrating the integration into the CMS online system.

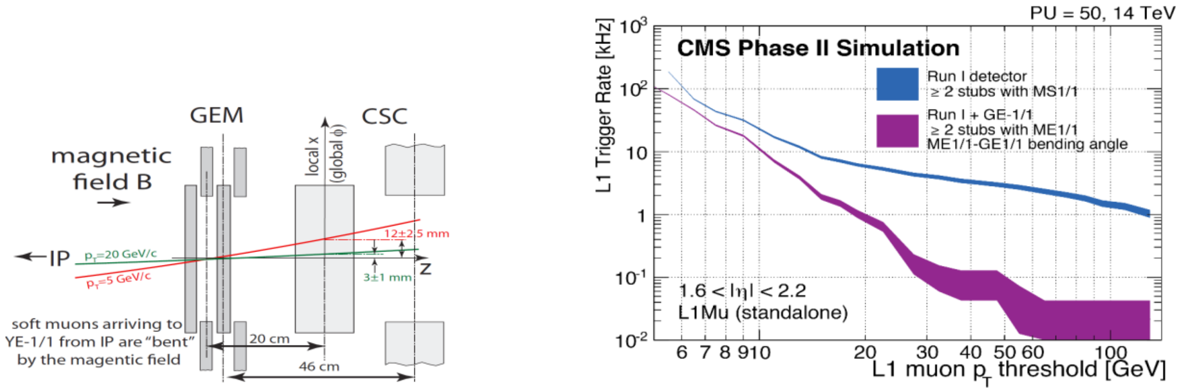

Figure 2. Representation of the measurement of the bending angle performed together by a CSC and a GEM chamber (left) and of the discrimination between lower and higher momentum muons [4]. Level-1 muon trigger rates (right) in the region $1.6 < |\eta| < 2.2$ at a luminosity of 2×10^{34} $cm^{-2}\ s^{-1}$ with (purple) and without (blue) the GE1/1 station [4].

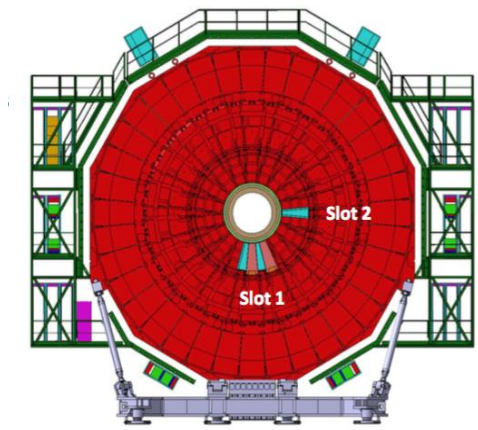

Figure 3. Schematic drawing of the negative muon endcap showing the location of the five superchambers of the GE1/1 demonstrator. Four of them are installed almost vertically close to each other (slot 1), one of them is located horizontally (slot 2).

From the installation point of view the Slice Test experience allowed to test a dedicated insertion jig for the installation of the superchambers. The integration of the new test subsystem was successfully achieved on different levels: a Detector Control System (DCS) was developed to safely monitor and operate the detectors and to follow the LHC operations together with the rest of CMS, a Data Acquisition (DAQ) system was developed and used to acquire data centrally both during cosmics runs and with proton beam, the full chain of processing the data online and monitor its quality (Data Quality Monitoring, DQM) was successfully tested. Such tools developed for and refined during the Slice Test represent the starting point for the development of their extended version for the complete GE1/1 station and later for the GE2/1 and ME0 stations.

The observed performance was consistent with values measured during the qualification of the detectors in terms of reconstruction efficiency and cluster size. The detection efficiency measured during proton-proton collisions in 2018 and an example of muons emerging from proton-proton collisions detected by one of the slice test detectors are shown in figure 4.

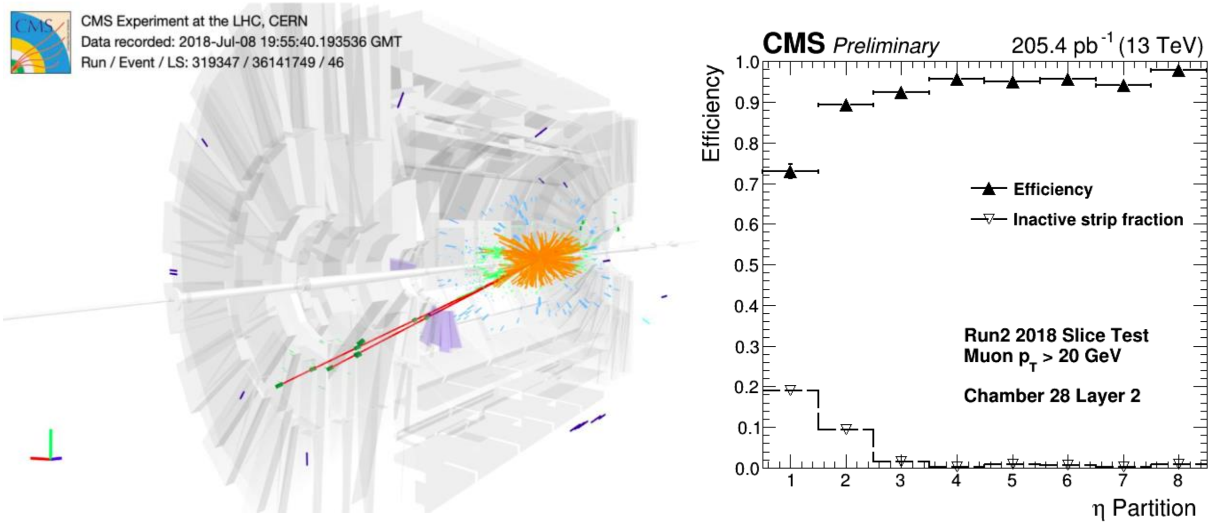

Figure 4. Event display of a proton-proton collision (left) with two muons (red lines) with associated hits in one of the slice test superchambers (blue trapezoidal boxes) and detection efficiency (right) of a GE1/1 slice test chamber (in position 28, layer 2) for muons with $p_t > 20$ GeV as a function of the detector eta partition measured in a subset of data samples taken in 2018. The lower detection efficiency in the first two eta partitions is a known effect of the higher fraction of dead or inactive strips (mainly due to higher thresholds applied) in such partitions. The fraction of inactive strips is also shown

3. GE1/1 Assembly and Quality Controls

The production and test of the GEM chambers for the GE1/1 station was distributed among different sites located in the USA, India, Pakistan, Italy, Belgium and Germany, applying the same procedures and quality controls. In addition, this effort also served the goal of training experts for the future production of chambers for the GE2/1 and ME0 stations. Components are first inspected and GEM foils tested at CERN before being sent to the production sites. There, further tests are performed after the assembly to re-test the integrity of GEM foils, to verify the chambers gas tightness, the proper behaviour when the high voltage is applied to the detector and finally to measure the detector gas gain.

Once chambers are assembled and successfully tested they are shipped back to the CERN site where they are coupled to form superchambers and equipped with the final electronics. The final quality controls performed at CERN include testing the connectivity of the electronics and the measurement of the detection efficiency using cosmic rays. An example of a gas tightness test and an efficiency measurement performed on some of the GE1/1 chambers are shown in figure 5.

4. Status of the GE1/1 Installation

The final installation of the complete GE1/1 station is taking place during the current Long Shutdown (2019-20), with the installation of the chambers in the negative endcap in autumn 2019 and the installation in the positive endcap in spring 2020. In addition, two of the superchambers of the negative endcap were already installed in July 2019 to certify the transportation and installation procedure. This work showed that the installation of two superchambers per day is feasible, proving the basis for the installation schedule. Furthermore, the two superchambers were operated for the first time at the end of August 2019, verifying the proper communication with the backend electronics and successfully calibrating and configuring the frontend electronics after the transportation and installation process. The installation of the detectors in the first endcap was completed at the end of October 2019.

5. Summary and Conclusions

The goal of the upgrade of the CMS muon system with GEM detectors is to improve the redundancy and sustain the muon trigger in the forward region during the HL-LHC. The upgrade involves three new stations in the muon endcap: GE1/1, GE2/1 and ME0. The first one in the installation timeline is the GE1/1 station (2019-20). A demonstrator composed of five superchambers (over 36 in one endcap) was already installed at the beginning of 2017 and operated in 2017-18 and led to the development of installation tools and procedures and the development of an initial version of DAQ, DCS and DQM, besides proving the operability of the system in the CMS environment.

The assembly of the GE1/1 chambers was distributed among different production sites and required the detectors to pass a chain of 8 quality controls to be ready for the installation. The final installation in the CMS detector is in progress, first tests performed involve connectivity tests and calibration scans.

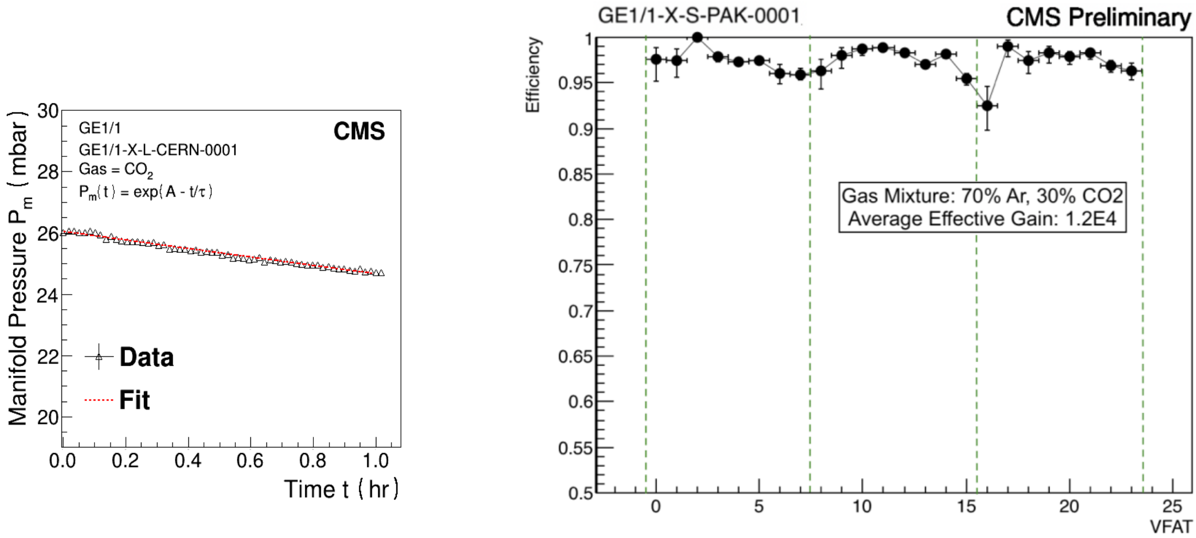

Figure 5. Example of a gas tightness quality control (left) performed on a GE1/1 chamber during the production. A gas leak constant τ>3.04 hr is requested to pass this test. Efficiency per VFAT (right) measured with cosmic rays. Drops in the efficiency correspond to regions next to the detector's edge and are caused by the geometrical acceptance of the setup

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