GEM detectors for the Upgrade of the CMS Muon Forward system

Giovanni Mocellin, on behalf of the CMS Muon Group
RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany
E-mail: giovanni.mocellin@cern.ch

Abstract. The CMS experiment is one of the two general purpose experiments at the CERN LHC. During LHC Phase-2 starting from 2026, the instantaneous luminosity delivered to CMS will reach $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, resulting in high particle fluxes that require the detector to be upgraded. The forward regions, corresponding to the endcaps of the detectors, will be most affected. In the muon endcap system, triple-GEM chambers will complement the existing Cathode Strip Chambers, leading to a better identification of the muon tracks and a reduction of the trigger rate due to the suppression of fake candidates. Additionally, the forward coverage will be extended.

144 GEM chambers are being built in production sites spread in 7 countries around the world for the first station of the muon endcaps. Each chamber has an area of approximately 1 m$^2$. Thus, high requirements on the uniformity across the detector are needed and the GEM chambers undergo multiple quality control tests. In parallel with the production and testing of the chambers, 10 GEM chambers have been integrated in CMS and are currently under commissioning (slice test). Such a test is essential to prepare for the upcoming installation and integration.

This contribution gives an introduction to GEM chambers and presents some results of the performance tests, both for quality control and slice test.

1. Introduction

The Compact Muon Solenoid (CMS) consists of a general purpose particle physics detector at the CERN Large Hadron Collider (LHC)\[1\]. The upgrade of the LHC foreseen during the Long Shutdown 3 (LS3), from 2024 to 2026, will increase the instantaneous luminosity delivered up to $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ (High Luminosity—LHC or HL—LHC). This will necessitate the upgrade of the detectors in order to face higher number of collisions per bunch crossing, larger trigger rates and greater radiation dose absorbed. The most affected regions in the experiments will be the forward regions, corresponding to the endcaps. In the endcap region dedicated to the detection of muons at CMS, it is therefore necessary to complement the present Cathode Strip Chambers (CSC) with a new generation of detectors where the Resistive Plate Chambers (RPC) could not be adopted at the construction. In the first three stations of each of the two endcaps, Gas Electron Multipliers (GEM) will be deployed, while the remaining two stations will be equipped with improved Resistive Plate Chambers (iRPC). They are referred to as ME0, GE1/1, GE2/1, RE3/1 and RE4/1, covering the region $1.5 < |\eta| < 2.8$ (Figure 1, left) \[2\] [3].

The completion of the muon system upgrade will improve the transverse momentum measurement of muons in this particularly critical region where the magnetic field provided...
by the magnetic system is low, and will keep the dramatically increasing trigger rates under control (as shown in Figure 1 (right) for GE1/1).

Hereafter, we will refer only to the GEM upgrade, particularly focusing on the GE1/1 production, tests and integration.

2. GEM integration plans
Since the beginning of 2017, five GE1/1 have been integrated and are currently under commissioning in CMS. Starting from 2019 up to 2020, the installation of GE1/1 in the first disk of the two muon endcaps will take place, giving the possibility to participate in the data taking during the LHC operations between 2020 and 2024. Within this period, during the Year End Technical Stops (YETS) the GE2/1 detectors will be installed in CMS. Finally, by the end of the LS3, ME0 will also be fully integrated.

3. Gas Electron multiplier technology
GEM is a gaseous detector invented by F. Sauli in 1997 [4]. Its key element is the GEM foil, which in the case of CMS consists of a 50 µm thick copper-cladded polyimide foil with holes etched in a hexagonal pattern (figure 2, left). The diameter of the holes is 70 µm and the pitch is 140 µm, resulting in a distance of 70 µm between two consecutive holes. A CMS GEM is composed by a drift board, a readout PCB and a stack of three GEM foils; the chamber is therefore named ‘triple-GEM’.

When a charged particle, e.g. a muon, traverses the chamber, it ionizes the gas. Due to the voltage applied to the drift plane, the top and the bottom electrodes of the foils in an increasing fashion from −3200 V up to ground voltage at the readout plane as in figure 2 (right), the electrons drift towards the readout. In between, they are guided by the electric field lines through the holes of the foils, where a field around 60 kV/cm leads to an avalanche in which the electrons are multiplied. With three stages of amplification, the final expected gain is of the order of 10^4.

The most relevant parameters that make the GEM technology suitable for its deployment in CMS are a rate capability up to $O(\text{MHz/cm}^2)$, an efficiency for minimum ionizing particles greater than 97% and no aging effects after 3000 fb$^{-1}$ (HL–LHC campaign) [2].
4th International Conference on Particle Physics and Astrophysics (ICPPA-2018)  
Journal of Physics: Conference Series  
1390 (2019) 012116  
doi:10.1088/1742-6596/1390/1/012116

Figure 2. GEM detectors. Left: SEM microscope picture of a GEM foil. Right: Schematic view of a GEM chamber, with typical voltages applied to the electrodes (CMS GEM).

Figure 3. Construction and placement of GE1/1. Left: GE1/1 chamber. Center-Right: Super chambers arrangement.

4. GE1/1 chamber
The GE1/1 denomination refers to the type and the position of the detector: ‘G’ stands for GEM, ‘E’ for endcap and ‘1/1’ represent the first disk and ring of the endcaps. The CMS GEM chamber is a triple-GEM detector operated with Ar/CO$_2$ gas mixture at 70%/30%, that is meant for covering $1.5 < |\eta| < 2.2$. Its peculiarity is that the trapezoidal active area covers a much larger area with relation to the previously produced ones, amounting to around 0.5 m$^2$.

The readout board is segmented into 3072 radial strips, divided in groups of 128. The resulting 24 readout sectors are distributed as 8 along the $\eta$ direction and 3 in $\phi$. The readout is digital.

In total, 144 single chambers will be coupled together to give 72 so-called super chambers, each covering 10.15° in the disk, with neighbouring chambers designed to overlap. Two versions of chambers are foreseen, long and short, in order to cover the largest area, given the structural constraints of the CMS endcaps.

5. Production and quality control of the GE1/1 detectors
Even if the GEM technology is well known and it has already been used in other CERN experiments, such as LHCb and COMPASS [2], the CMS GEM chambers have typical peculiarities. First, they are produced in 7 countries around the world (CERN, Belgium, Germany, India, Italy, Pakistan, USA); and the second is the large area covered ($O(0.5\, m^2)$). To ensure that the standards are met, during the production steps, several quality control tests are foreseen. The most critical tests are the gain uniformity (QC5) and the efficiency map with cosmic muon rays (QC8).

A summary of the production steps is proposed in Figure 4.

The status in mid-September 2018 is that 100% (97%) of long (short) chambers has been assembled and 57% (86%) of these has been validated up to QC5. The status can be visualized in Figure 5.
Figure 4. Production and test steps of the GE1/1 chambers. Each of the QC tests lasts around 1 – 2 days.

Figure 5. GE1/1 production status (mid-September 2018).

6. Assembly of a GEM chamber
Starting with single foils that are tested to not have shorts, the triple GEM stack is composed on plexiglass supporting plates with spacing frames (3/1/2/1 mm) and held together by means of screws. The stack is then moved from the plexiglass plate to the drift PCB, where it is kept in place and stretched by screws inserted into metallic pull-outs. After the stretching, performed applying a torque of 8.5 cNm to each of the screws, the outer frame is positioned and finally the chamber is closed with the readout PCB. The foils are then tested again for shorts and contacts with the other electrodes.

The GEM chamber assembly is condensed in pictures in Figure 6.

Figure 6. Assembly of a GEM chamber.

7. Single chamber QC tests
In Figure 7 is shown a summary of the results of the tests done on the single chambers produced.

The gas leakage test (QC3) is performed by setting the chamber to an overpressure of 25 mbar with pure CO2, closing gas inlet and outlet and monitoring the pressure. If the pressure drop rate is less than 5 mbar/h, the test is passed.

The HV integrity test (QC4) is performed by operating the chamber with pure CO2 and installing a resistive voltage divider on the HV distribution pads. The input voltage to the divider
is then increased up to 4.9 kV; both the current and the spurious signal rate are monitored to check the linearity of HV vs current and the rate has to be $O(100\text{Hz})$ or lower.

The gas gain is checked for two main aspects. First, its absolute value in one of the 24 sectors; second, its uniformity across the area of the chamber. Since the amplification in each of the foils is around 20, the target value for the gain is $O(10^4)$.

### Figure 7.
Summary results of QC tests on single chambers. The ones pointed by arrows were tested in the Aachen test site.

8. **Slice test**

In parallel with the production and the quality control tests, a major test is performed at CERN: the slice test. It consists in 5 GE1/1 detectors installed in one of the two endcaps of CMS. The installations slots can be visualized in figure 8, left. The detector in ‘slot 2’ is equipped with the final version of the HV power supply and readout electronics. Even with only a small portion of installed chambers, GEM is taking part to the global operations of CMS as a regular subdetector. Since the CMS experiment is complex and already fully operational, the participation in the Detector Control System (DCS) and the Data Acquisition System (DAQ) is challenging, but it has proved to be successful. In figure 8 (right), one real event in proton-proton collision is depicted with a muon track extrapolated to GE1/1 and the corresponding hits in the GEM detector.

The slice test is essential for the future installation and integration all the 72 GE1/1 detectors in CMS DCS and DAQ systems.

### Figure 8.
GEM Slice Test. Left: Slice test detector slots. Right: Event display with muon track confirmed by GEM.
9. Conclusions
The GEM technology and the GE1/1 designed have been described, together with the production and the quality control tests. The status of the chamber production is aligned with the schedule and the chambers have demonstrated to have very good performance. Both quality control and slice tests have proved to give excellent results, which are important steps towards the integration of the GEM detectors in CMS during the LS2.

References
[1] CMS collaboration 2008 JINST 3 S08004
[2] Colaleo A et al. 2015 Preprint CERN-LHCC-2015-012 CMS-TDR-013
[3] CMS collaboration 2017 Preprint CERN-LHCC-2017-012 CMS-TDR-016,
[4] Sauli F 2016 Nucl. Instrum. Methods Phys. Res. A 805 2–24
[5] https://twiki.cern.ch/twiki/bin/view/CMSPublic/GEMDPGPublic#Public_Results_2018