CMS phase-II upgrade with GEM detector

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Abstract. The Large Hadron Collider (LHC) will be upgraded in several phases that will allow significant expansion of its physics program. The final luminosity of the accelerator is expected to exceed $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, 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 similar to what was achieved up to now. 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 GE2/1 and ME0, has been planned. The installation and commissioning of the GE2/1 chambers is scheduled in 2022, and for ME0 detectors are expected to be installed between 2022 to 2024. We present an overview of the Muon Spectrometer upgrade using GEM technology, a detailed description of the GE2/1 and ME0 upgrade in terms of design, pre-production chambers, mechanics, installation services etc. We will focus in particular on the novel solutions adopted for realization of the latter project, with a summary of the ongoing R&D activities.

1. Introduction

The Compact muon solenoid (CMS) is a general purpose detector used for measuring proton-proton and heavy-ions collisions at the large hadron collider (LHC)\cite{1} at CERN. It has already produced many excellent scientific results and to increase the extent of the new physics searches, a major upgrade of the LHC has been decided which is known as High Luminosity LHC (HL-LHC). As a consequence the integrated luminosity$^2$ will increase ten times with respect to designed value. The projected evolution of instantaneous and integrated luminosity$^3$ is shown in Figure 1-2.

The proton-proton collision centre of mass energy is expected to increase from 13 TeV to 14 TeV. After finishing the data taking of phase-I in 2023, which will be followed by the long shutdown for HL-LHC\cite{4} upgrade ending in 2026 and the high luminosity data taking period with the upgraded LHC is called "Phase-II" is expected to end in 2038. The upgrade program helps in exploiting the physics potential of the LHC, allowing to improve the sensitivity of channels limited in statistics. The muon detectors play a central role in CMS. The most sensitive signatures of the production of new particles often include one or more muons. Therefore, CMS was built with several complementary sub-detectors to identify muons, already at trigger level, and to measure their momentum and charge over a broad range of kinematics. To cope with the increase in background rates and trigger requirements, the GE2/1 and ME0\cite{5} Gas Electron Multiplier (GEM) detectors will be installed in the CMS muon spectrometer.
Figure 1. The LHC schedule and designed values for instantaneous and integrated luminosity.

Figure 2. The ultimate values for instantaneous and integrated luminosity.

2. GEM detectors GE2/1

Many particle physics experiments like COMPASS[6] and LHCb[7] are using the GEM technology and it has operated reliably at hit rates of the order of a few MHz/cm$^2$. No aging[8] problem has been reported so far. A gas amplification by a factor of typically 20-25 is achieved by the high electric field between two copper layers coated on both faces of thin polyimide foils, which are perforated by conical holes. By combining three foils to a triple-GEM chamber the gas gain reaches a value of the order of $10^4$ as shown in Figure 3. Finally the electrical signals are read out by a PCB with electrodes in the form of strips.

Figure 3. Equipotential field lines and triple GEM detector.

The GE2/1 detector consists of 20-degree trapezoidal shape triple-GEM chambers arranged in two layers in each of the CMS end-caps. The GE2/1 system provides a second ring of GEM muon detectors in the end-cap region next to the ME2/1 chambers. The GE2/1 detectors will cover the pseudo-rapidity range $1.62 < \eta < 2.43$ having total active readout area of 1.45m$^2$. The eta range of GE2/1 partially overlaps with that of GE1/1 and extends coverage to the range $2.1 < \eta < 2.43$. The two layers of the GE2/1 system consist of front chambers, closer to the interaction point, and back layers. For convenience, a pair of GE2/1 chambers covering the same eta and phi region is referred to as a super-chamber although each chamber is completely independent of the other, including independent installation. Each GE2/1 chamber consists of four modules M1-M4, each being a single CMS triple-GEM detector. The full system consists of 72 GE2/1 chambers (36 per endcap), which corresponds to 288 basic GE2/1 modules. Each module is assembled from a drift and a readout PCB, external and internal frames, and set of GEM foils specific for each module. The assembly and qualification of the modules can be done independently from the other chamber components. Each single module is segmented into four partitions along the \( \eta \)-direction and 1,536 strips along the \( \Phi \)-direction. Strips that belong to the same \( \eta \)-partition are routed to the readout connectors in groups of 128 strips to match the granularity of the front-end electronics. The modules differ from each other only with respect to their dimensions; number and type of components are very similar for all eight module types.
The unavoidable non-active gap between two adjacent modules in one GE2/1 chamber is 35.5 mm wide in this design. To avoid an overlap between the gaps of two chamber layers within the superchamber, the front and back chambers are staggered by making them of different size, as shown in Figure 4.

![Figure 4](image-url)  
**Figure 4.** GE2/1 module numbering and overlap of active area between front and back layer.

The staggered module design, adopted to preserve full coverage, generates two different "families" of support structures, one for the front chambers and one for the back chambers. For example, the copper-pipe cooling system for the electronics will be slightly different for the front and back chambers.

### 2.1. GE2/1 Pre-production Chambers

Eight GE2/1 modules have been assembled and tested at the CERN 904 lab facility. After the assembly of the modules, basic quality controls tests QC2-QC5[9, 10] have been performed.

![Figure 5](image-url)  
**Figure 5.** Gas leak test for GE2/1 modules.

![Figure 6](image-url)  
**Figure 6.** High voltage test for GE2/1 modules.

To test the gas tightness after assembling a detector, it is first pressurized under the safe limit of 25 mbar. The input and output valves are then closed to detect any gas leak in case the overpressure in this volume drops to zero with a time scale which depends on the leak rate and
on the initial overpressure, as shown in Figure 5. Then an HV test (QC4) is performed to check the behaviour of the high voltage distribution circuit of the detector as shown in Figure 6. The effective gain is the central parameter of the detector which depends on the geometrical and electrical properties of the detector. This test is performed with Ar:CO$_2$/70:30 gas composition as shown in Figure 7. The gain uniformity of the modules is shown in Figure 8 which gives the variation in gain over the active area of the detector[11].

2.2. GE2/1 Electronics, integration and commissioning

The main components used to readout a single GE2/1 chamber are shown in Figure 9. The front-end readout chips (VFAT3) for each module are mounted on a GEM Electronics Board (GEB). Communication to the off-detector electronics is provided by Opto-Hybrid (OH) boards, one for each module. The VFAT3 chips designed for GE1/1 will also be used for the GE2/1. Each detector will require 48 VFAT3 chips.

The GE2/1 chambers will be installed after Long Shutdown 2 (LS2), during End-Year technical stops (EYTS). The chambers for one endcap will be installed in EYTS 2021-2022 and those for the other endcap in EYTS 2022-2023. The services needed for a single GE2/1
detector are shown in Figure 10. There are pipes for gas and cooling, four low-voltage cables for the electronics, four HV cables for the detector, and eight optical fibers for readout and control. Four fibers run from the OH to the service cavern (USC55) and four fibers run from the OH to the ME2/1 Optical Trigger Mother Board (OTMB).

3. GEM detectors ME0

The ME0 system will cover $2.03 < |\eta| < 2.8$ using six layers of triple-GEM detectors as shown in Figure 11. The six layers provide good pattern recognition and background rejection. The ME0 system provides unique coverage in the range $2.4 < |\eta| < 2.8$ and strengthens the coverage provided by the CSCs, RPCs and GE2/1 in the range $2.03 < |\eta| < 2.4$. Based on simulation, the muon identification efficiency is estimated to be approximately 95% for transverse momentum as low as 3 GeV.

![Figure 11. Layout of ME0 stack with six triple-GEM layers including cable trays.](image1)

![Figure 12. 3D drawing of the insertion of two adjacent stacks of six ME0 modules into the end-cap nose.](image2)

The ME0 system is composed of 18 super-chambers per end-cap. Each super-chamber is mounted on a 15 mm thick aluminum plate to give mechanical strength as shown in Figure 12. Each detector layer is 33.4 mm thick and the 6-layer super chamber is 224.4 mm thick, including shielding. The area of ME0 chamber is same as GE1/1 detector. The readout segmentation of an individual chamber layer is 8 sectors in $\eta$ and 3 sectors in $\Phi$; each sector $\Phi$ contains 128 radial strips.

3.1. ME0 Electronics, integration and commissioning

The electronics architecture is the same for all the three upgrades, also the DAQ layout will be a copy of GE2/1. Each module uses a single GEB PCB board. The module readout plane consists of 24 sectors 3 columns in $\Phi$ and 8 partitions in $\eta$, each containing 128 strips. The signal is readout by the VFAT3 chips and in total 24 chips are placed on a single GEB board per module. Finally the signal is routed to the single Optohybrid board as shown in Figure 13.

ME0 installation schedule has been designed to avoid conflict with the HGC installation schedule, in particular with the HGC services installation as shown in Figure 14. ME0 installation will proceed in bursts of 3 stacks (60 deg) at a time, with HGC following right behind ME0 installation and covering ME0 with HGC services. Three low voltage (LV) cable with two LV channels per cable are required to power and run the single ME0 stack. Three high voltage (HV) cables to power the six triple-GEM detector, pipes for the gas and cooling supply and return lines.

4. Conclusion

The HL-LHC phase requires the upgrade of the CMS muon system. Specific chambers, GE2/1 and ME0, have been designed and are being produced. A complete chamber (stack) of eight
GE2/1 modules have been built and have passed the basic quality controls (QC2-QC5). On chamber electronics prototyping and testing are completed for GE2/1. For ME0, the chamber (stack) prototype mechanical design as well as the on-chamber and off-chamber electronics design has been completed. Also an aging test for triple-GEM chambers is on going at GIF++/904 lab. No aging has been observed up to 1.5C/cm$^2$.

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