GEM Detectors for the Upgrade of the CMS Muon Spectrometer

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Abstract. The Large Hadron Collider (LHC) will be upgraded in several phases to allow a significant expansion of its physics program. We are nearing the end of Long Shutdown 2 (LS2, 2019-2021), after which the LHC will initiate its third running period (Run-3) expected to last three years. In Run-3 LHC will collide protons with an instantaneous luminosity of 2-3$\times10^{34}$cm^{-2}s^{-1} exceeding its design luminosity by a factor of 2-3, allowing the CMS experiment to collect an integrated luminosity of approximately 100 fb^{-1}/year. A subsequent upgrade in 2025-27 (Long Shutdown 3 - LS3) will increase the luminosity up to 5$\times10^{34}$cm^{-2}s^{-1}. The CMS muon system must enable a physics program that maintains sensitivity for electroweak measurements and for Beyond the Standard Model searches, similar to what was achieved in Run-1 and Run-2. To cope with the corresponding increase in trigger rates and to provide additional coordinate measurements in the high background environment, the installation of additional sets of muon detectors, referred to as GE1/1, GE2/1 and ME0, that use Gas Electron Multiplier (GEM) technology, has been approved. The GE1/1 chambers have already been installed in spring-summer 2020 and are currently being commissioned and tested with cosmic rays. The construction of GE2/1 will start in 2021, while for ME0 the final R&D is in progress and construction is foreseen in 2023. We present an overview of the Muon Spectrometer upgrade using the GEM technology, the performance of the GE1/1 chambers during Quality Control tests and in cosmic ray tests, and the design of the GE2/1 and ME0 chambers.

1. Introduction

Large Hadron Collider (LHC) [1] will be upgraded in various phases in order to reach the designed energy of 14 TeV and instantaneous luminosity of about 2-3$\times10^{34}$cm^{-2}s^{-1}. The whole accelerator complex and its detectors will be reinforced and upgraded for the subsequent LHC run. In order to cope with the increased trigger rates and to ensure the redundancy of the muon system, the Compact Muon Solenoid (CMS) Experiment [2] approved installation of additional detector layers in the forward parts of the muon system [3, 4], namely ME0, GE1/1 and GE2/1, based on the Gas Electron Multiplier (GEM) technology [5] and so called improved Resistive Plate Chambers (iRPC) as shown in Figure 1 with red and purple color respectively. These GEM detectors are built using GEM foils which consists of a thin layer of insulating polymer coated on both sides with copper and chemically perforated with a high density of microscopic holes. Each GEM detector for the muon endcap upgrade relies on the triple-GEM structure with gas gap of 3/1/2/1 mm for drift gap, two transfer gaps and an induction gap respectively.

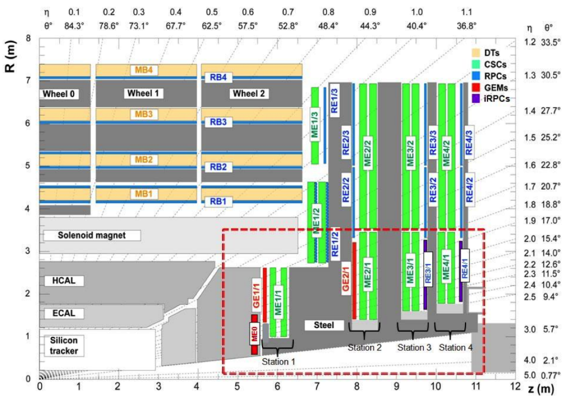

Figure 1. Transverse view of a quadrant of the CMS experiment showing future upgrades using GEM technology (shown in red).

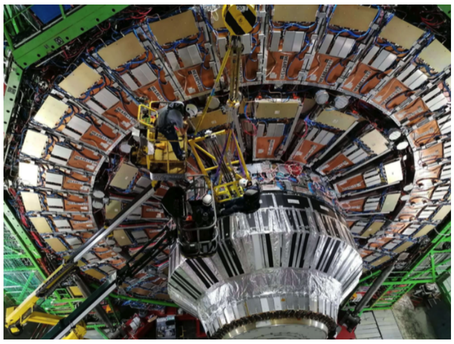

Figure 2. Installation of GE1/1 chambers during LS2.

2. GE1/1 Upgrade

During Long Shutdown 2 (LS2), the CMS experiment upgraded its muon endcap system by installing GEM detectors (figure 2) in high eta region ($1.55 < |\eta| < 2.2$), also known as GE1/1 upgrade [3]. A typical GE1/1 chamber is a trapezoidal chamber with 22.5 cm base and radial length of 128.5 cm for Long and 113.5 cm for Short chamber; each covering a 10° sector, requiring 36 chambers (18 Long and 18 Short) for each endcap. A super-chamber (SC) is a combination of two GE1/1 chambers exhibiting approximately the same gain at a given voltage, thus a total of 144 GE1/1 chambers were required. The chambers operate with an Ar/CO_2 (70/30) gas mixture, with gas gain of about 1.5×10^4.

Table 1. Summary of the Quality Control steps followed.

Location	QC Process	Description
CERN	QC1/QC2	Material inspection & GEM foil test
Production sites	Assembly	GEM chamber construction
Production sites	QC2	Single GEM foils HV test
Production sites	QC3	Gas leak test
Production sites	QC4	HV test
Production sites	QC5	Gain calibration
CERN	QC6	Assembly for SC and HV stability test
CERN	QC7	Electronics connectivity test
CERN	QC8	Cosmic ray test

2.1. Quality Control and Early Commissioning

A well-defined Quality Control (QC) path has been established by the CMS Muon group, both on the single chambers components and on the assembled SCs [6]. Table 1 summarizes the stepwise information about the assembly and various QCs performed at CERN and various production sites. Material inspection and preliminary GEM foil testing was performed at CERN as a part of QC1/QC2 before dispatching the material at various production sites for assembly. In QC2, leakage current is measured by applying voltage across each of the GEM foils which allows a current flow from top to bottom due to the surface conductivity of the polyimide (Kapton). For QC3, all the GE1/1 chambers were tested against gas leaks to assure the detector tightness after its assembly; a detector is said to be gas tight if the over-pressure in its volume remains constant with time. QC4 is performed under the high voltage (HV) environment to check the behavior of the HV distribution circuit of the detector and related spurious signals.

Gain is defined as the ratio of the output current to the input current. The current and rate were measured across the $(i\eta,\ i\phi) = (4,\ 2)$ readout sector under the radiation of X-rays as a part of the QC5 measurement. Effective gains for few GE1/1 detectors assembled at CERN are shown in figure 3 which are normalized to a pre-defined pressure and temperature values, to account for differences in the environmental conditions across all the different production sites. The next part of QC5 involves the gain uniformity measurement where the drift electrode was illuminated with the X-ray beam and the amplified charge, collected by readout strips, was acquired by data acquisition based on the Scalable Read-out System (SRS) through the analog APV25 readout chips. The gain uniformity for 132 detectors for a fixed high voltage is shown in figure 4 and and all the GE1/1 detectors produced gain variations below 30%.

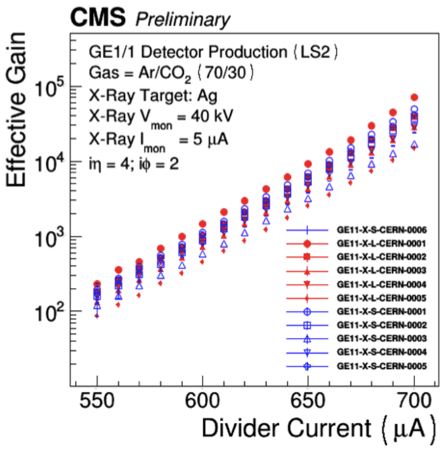

Figure 3. Effective gain for GE1/1 detectors.

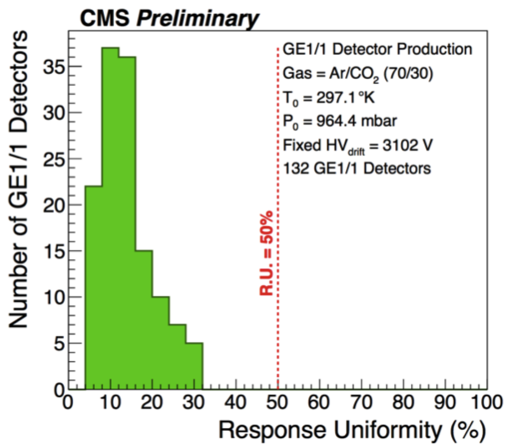

Figure 4. Gain uniformity for 132 GE1/1 detectors.

After passing all the QC steps, detectors were shipped back to CERN by various production sites and were further assembled into a SC. GE1/1 chambers were then instrumented with the final digital electronic, VFAT3 and the front-end noise was evaluated by measuring the equivalent noise charge (ENC) which was extracted from the s-curves (sigma of the fit of the s-curves). ENC measurement taken from QC7 (chamber-electronic integration) and QC8 (cosmic ray test) were compared with the measurements in the CMS experimental cavern (Point 5) after the installation and the results are shown in figure 5 for each VFAT3 chip and figure 6 for each readout channel. The mean value for ENC (in fC) at P5 is always lower as compared with the ENC measurement during QC7 and QC8.

3. GE2/1 Upgrade

Extended Year End Technical Stop (EYETS) is planned in the winter 2023/2024 during which two additional layers, named GE2/1, will be installed. Each GE2/1 detector will cover an angle of 20° of the CMS endcap and the pseudo-rapidity range $1.62 < |\eta| < 2.43$ with a total length of

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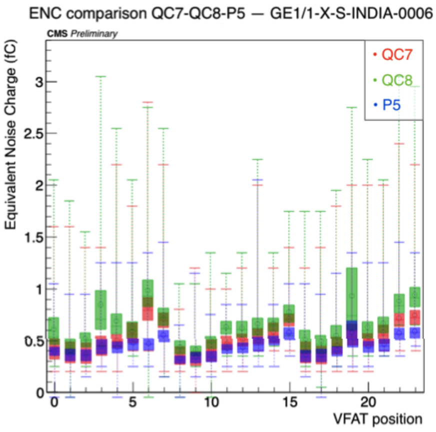

Figure 5. ENC per VFAT.

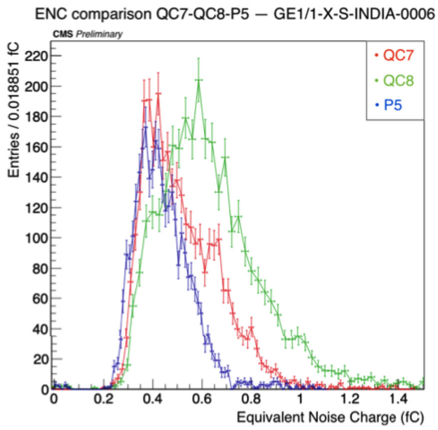

Figure 6. ENC per readout channel.

183.3 cm. Two layers of the GE2/1 system consist of back chambers (with modules M1-M4), far from the interaction point and front chambers (with modules M5-M8) closer to the interaction point (shown in figure 7), each being a single CMS triple-GEM detector. It consists of 72 GE2/1 chambers which corresponds to 288 basic GE2/1 modules. The non-active gap between two adjacent modules in one GE2/1 chamber is 35.5 mm wide which is avoided by choosing slightly different sizes of modules in second layer. Figure 8 shows the effective gain as a function of divider current (normalized to pressure and temperature) for various prototype modules of GE2/1 chambers. A complete GE2/1 chamber has been built and tested for the basic quality controls as well as on chamber electronics prototyping and testing have been performed.

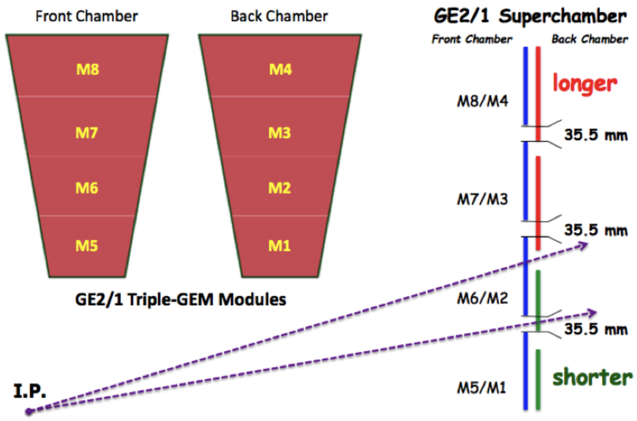

Figure 7. Design for GE2/1 chambers.

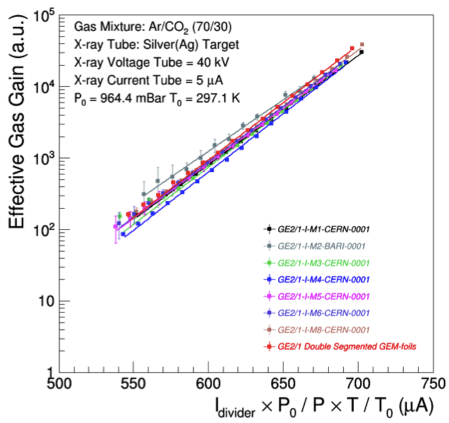

Figure 8. Effective gain of GE2/1 prototype modules.

4. ME0 Upgrade

Installation of additional six layers, named ME0, is foreseen during the Third Long Shutdown (LS3) which is expected to take place in 2025-2027. The ME0 system will cover $2.03 < |\eta| < 2.8$, with an internal layout similar to the GE1/1 and GE2/1 chambers (i.e. 3/1/2/1 mm). The active volume will have a length of 78.8 cm and width varying from 23.6 cm to 51.4 cm.

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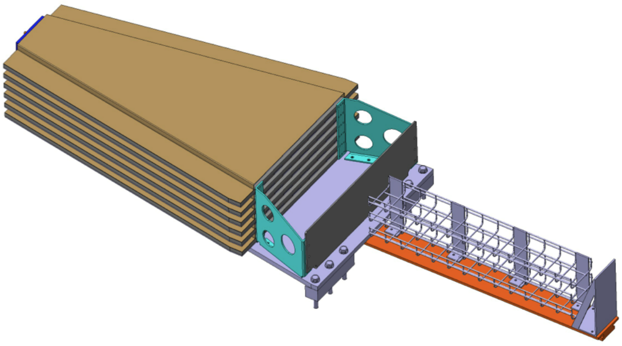

Figure 9. Design for ME0 stack.

The ME0 detector station comprises of 36 module stacks (18 per endcap), each composed of six ME0 modules. Each stack is mounted on a 15 mm thick aluminum plate which mechanically supports the system as shown in figure 9, creating a complete independent working unit. The ME0 chamber and stack prototype mechanical design is complete and so far five prototype modules have been produced and qualified.

5. Summary

The production and QC of GE1/1 chambers have been successfully completed. After passing the required quality control tests, GE1/1 chambers have already been installed in 2020 and are currently being commissioned and tested with cosmic rays. The design of the GE2/1 has been completed, validated and approved through an official CMS Engineering Design Review (EDR) and the construction of GE2/1 chambers will start during 2021. A prototype of a GE2/1 chamber has been built and tested for the basic quality controls and required electronics. For the ME0 chamber, the stack prototype mechanical design is completed with the final R&D in progress and its construction is expected to occur in 2023.

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