# Production, Quality Control and Performance of GE1/1 Detectors for the CMS Upgrade

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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. After the long shutdown in 2019 (LS2) the accelerator luminosity will be increased to  $2-3 \times 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup> for Run 3 and later up to  $5 \times 10^{34}$  $cm^{-2}s^{-1}$  for Phase 2 (HL-LHC). The physics program of the LHC experiments will benefit from the augmented luminosity; the sensitivity of the CMS experiment to new physics and to the Standard Model will be fully exploited, providing that a suitable upgrade will enable the CMS detector to cope with future data-taking conditions. Among the upgrades, the installation of new muon stations based on Gas Electron Multiplier (GEM) technology in the endcap will start in early 2019 (GE1/1 station), followed by the installation of two additional stations (GE2/1 and ME0) in 2023. The CMS Muon Collaboration produced the 144 GEM detectors to be installed in the GE1/1 station, sharing the assembly and testing of the detectors among several production sites spread all over the world. A detailed common assembly protocol and quality control procedure (QC) has been deployed, with the ambitious goal to ensure standardization of the performance of the detectors produced by the different sites. The same procedure has been successfully adopted to test the first prototypes of the GE2/1 detectors. In this contribution, we present the final results of the QC tests performed on the GE1/1 chambers, assembled by all the production sites following the common specification parameters.

#### 1. Introduction

The Muon System of the CMS experiment installed at the CERN Large Hadron Collider exploits three different gaseous detector technologies: Resistive Plate Chambers in both barrel and endcaps, Cathode Strip Chambers in the endcaps and Drift Tubes in the barrel, according to the background rates expected in each region. The system provides information simultaneously for muon triggering, reconstruction and identification with excellent performance during the whole Run I and Run II data-taking [1][2]. After the upgrade of the LHC injector chain during the second Long Shutdown, which is currently ongoing, the instantaneous luminosity of the colliding beams will approach  $2 \times 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>, twice the design luminosity [3]. Under these conditions up to 50 pile-up interactions (PU) per event are foreseen, together with an increase of the integrated radiation dose that will lead to the degradation of the present detector performance. In this scenario, the muon reconstruction in the forward region of the CMS Muon system will become particularly challenging, especially at the first trigger level (L1): in addition to the existing reduced track bending in the magnetic field surrounding the detectors placed behind the return yoke, the increased background rates will not be compensated by adequate redundancy in the region  $|\eta| \geq 1.6$  (this region being instrumented just by CSC detectors). These factors lead

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to muon momentum mis-measurements at L1 trigger, and as a consequence, the contribution to the trigger rate coming from the forward region is particularly high. This effect will be increased in the HL-LHC scenario, where 200 PU interactions per bunch-crossing are foreseen. As a consequence, a general upgrade of the present muon system has been carefully designed and planned [4]. This contribution will focus on a new station based on triple-GEM detector technology [5], that will be installed before the beginning of the Run 3 in the endcap of the CMS Muon System (GE1/1) [6] in front of the first CSC station (ME1/1), as it is sketched in Fig. 1. It has been shown by simulation studies that the new station will improve the muon reconstruction performance in the forward region, keeping the L1 trigger rates under control even in the harsh Run 3 environment [6].



**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 .

#### 2. The GE1/1 station

The GE1/1 station will provide full coverage in  $\phi$  while instrumenting the pseudorapidity region  $1.55 < |\eta| < 2.18$  as sketched in Fig. 1. The choice of the triple-GEM technology was driven by the excellent performance of those detectors (rate capability  $\sim O(10 \text{ kHz/cm}^2)$ ), time resolution  $\sim 5$ ns, spatial resolution  $\sim O(200\mu\text{m})$ ), that make them suitable for the purposes of the CMS upgrade. In the GE1/1 station, a pair of triple-GEM chambers is combined to form a superchamber (SC) that provides two measurements of the muon hit position. Each super-chamber covers a  $\sim 10^{\circ}$  sector, so 36 super-chambers will be installed in each endcap. Short and long chambers will be alternated to maximize the pseudorapidity coverage within the constraint of space. Thus 144 triple-GEM detectors have been prepared and are ready to be installed.

An exploded view of a GE1/1 detector is shown in Fig. 2 (left). Three copper-clad kapton foils perforated with a high density of holes (with 140  $\mu$ m pitch and 70  $\mu$ m hole diameter), produced with the single-mask photolithographic technique are sandwiched between drift and readout electrodes.

The electric signal produced by the particles that hit the detector is picked up by the anode readout board segmented in 384 truly radial readout strips, divided into 3 main sectors along the azimuthal coordinate and 8 sectors along the  $\eta$  coordinate, thus resulting in a total of 24 readout sectors. While operating in CMS, each sector will be read out by one VFAT chip [7]. The voltage to the GEM foils is provided through the drift board, a single drift cathode that routes a total of seven potentials (drift electrode plus two sides of each of the three GEM foils) to the various GEM electrodes and to the drift cathode. During the production and test phase of the detectors, a simple ceramic voltage divider, directly soldered on the board has been used to divide the voltage from one HV input line.

The assembly and sealing of the detector are entirely mechanical. No glue is applied during assembly, which makes it possible to open a detector again for repairs if needed. The three GEM foils are sandwiched at their edges between four thin frames. As depicted in Fig. 2 (right), additional square stainless steel nuts are embedded into the frames every few centimeters to host stainless steel screws that are inserted into small brass posts, so-called pull-outs, which are located within the gas volume.



**Figure 2.** Exploded view of the mechanical design of a Triple-GEM chamber (left) and transversal section of a GE1/1 detector that illustrate the mechanism employed to stretch the GEM foils in GE1/1 chambers (right).

When the pull-out screws are tightened manually, the GEM foils in the stack are tensioned as the inner frame is being stretched. A large outer glass-epoxy frame is placed around the tensioned GEM stack and the brass pull-outs providing the confines of the gas volume [8]. The standard gas mixture for operating a triple-GEM CMS detector consists of Argon (70%) and  $CO_2$  (30%).

## 3. The Quality Control Process and Performance of GE1/1 detectors

Several institutions from six countries spread all over the world participated in the assembly and test process of the GE1/1 detectors, 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). An additional satellite site at University of Aachen performed tests on the chambers produced in the different production sites. In order to ensure proper and robust operation of the chamber when installed in CMS and standard detector performance, a detailed procedure for the Quality Controls (QC) has been deployed to all the production sites, equipped with the very same necessary infrastructure. This protocol aims to carefully assess the detector performance; if measurements are found that are incompatible with pre-defined standard thresholds (set to ensure stable and proper operation in CMS), the detector undergoes further adjustment until it fulfills those requirements.

A first group of test is performed on the components before the assembly. A second one is completed on a single chamber, while the third set of test is performed after the SC assembly. Single chamber assembly and validation are done by the different production sites, while the

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assembly and the QC tests on the SC are performed at CERN exclusively. The detailed stepby-step description of the QC process performed by each production site, is given below.

## 3.1. Measurement of the detector tightness

The detector tightness is crucial to avoid gas leaks and to reduce the possibility of contamination by external pollutants. This can deteriorate the effective gas gain, thus affecting the detector efficiency and time resolution during operation. Given the layout of the GE1/1 detectors, where a large number of screws are employed, this is the first test performed after the assembly. It aims to quantify the gas leak rate of a GE1/1 detector by monitoring the drop of the internal overpressure as a function of the time. A pressure sensor connected to a micro controller (i.e. a commercial Arduino-Mega board) allows monitoring of the over-pressure inside of the detector and the gas system. The pressure drop is modeled by the function  $P(t) = e^{A-\frac{t}{\tau}}$  where A is a constant that takes into account the initial overpressure of the detector P<sub>0</sub> (set to P<sub>0</sub>=25 mbar for all the production sites and for each detector) and  $\tau$  quantifies how fast the overpressure inside the detector decreases as a function of the time. Values of  $\tau \geq 3$  hours guarantee a maximum leak rate ~ 0.02 l/h, less than 0.5% of the gas influx during the operation. As shown in Fig. 3 (left), all the GE1/1 detectors are found to be gas tight except two built with a pre-series internal frame, that will not be installed in CMS.

## 3.2. HV and Linearity Test

This test determines the voltage vs. current curve of a GE1/1 detector and identifies possible malfunctions in the HV circuit that is responsible for the proper configuration of the drift, transfer and induction electric fields. The chamber is flushed with pure  $CO_2$  and ramped up to 4.9 kV in steps of 100 V; for each step, the current through the circuit that powers the detector is recorded. The detector is accepted if the I-V curve shows a linear behavior, quantified as the deviation of the nominal resistance of the powering circuit with respect to its measured value. All the GE1/1 detectors show good linearity (Fig. 3, right). Moreover the number of spurious



Figure 3. Gas leak constant of all the GE1/1 detectors (left). Deviation of the nominal resistance of the powering circuit with respect to its measured value (right). The thresholds for the acceptance are also shown.

pulses, read from the bottom of the third GEM foil, is measured. The detector is accepted if

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this rate is below  $10^{-2}$  Hz/cm<sup>2</sup>, a negligible value with respect to the 4.5 kHz/cm<sup>2</sup> background rate expected in CMS in standard operating conditions [6].

### 3.3. Measurement of the Effective Gas Gain

The Effective Gas Gain of a GE1/1 detector is determined by a two-step procedure. In the first step this parameter is measured in one reference readout sector, while in the second step the detector response uniformity is assessed with the goal to extrapolate the effective gas gain from the reference sector to the whole detector. The two measurements are performed with the same set-up as described below. In the first step, the effective gain is measured in the central readout sector ( $\eta = 4$  and  $\phi = 2$ , following the detector local coordinate system) as a function of the current through the divider with a X-ray tube with Ag target and beam energy that peaks at 22.5 and 25 keV. The photons are absorbed by the copper atoms of the drift electrode that emits 8 keV photons by fluorescence. They are then converted by photo-electric effect in the gas volume. The effective gas gain is defined as  $G = \frac{I_{RO}}{R \cdot q_{el} \cdot N_p}$ , where:  $I_{RO}$  is the current induced on the readout electrode, measured with a pico-ammeter; R is the rate of electrons converted by photoelectric effect by the incident photons in the drift gap, measured as the rate of pulses recorded by the readout electrode;  $q_{el}$  is the elementary electron charge;  $N_p$  is the number of primary electrons produced by the incident photoelectron in the  $Ar/CO_2$  (70/30) gas mixture, extracted, in a separate measurement, with a calibration procedure from the X-ray source spectrum recorded by a triple GEM detector. In order to account for the difference in the environmental conditions across all the different production sites, the gain measurements are then normalized to pre-defined reference pressure and temperature value, that correspond to the average values observed in the nominal GE1/1 station position in CMS over one year.

## 3.4. Response Uniformity

The gain measurement, performed in the central readout sector of each GE1/1 detector, has to be correlated to the detector response uniformity to evaluate the overall detector performance. In order to measure the uniformity of the detector response across the whole detector, the drift electrode is illuminated with the X-ray beam mentioned above and the amplified charge is collected by readout strips and transferred to ADC units by APV25 analogue readout chips [9]. The GE1/1 detector is ideally divided into 768 slices, each slice consisting of 4 strips. The cluster charge ADC spectrum recorded from each slice is fit to extract the position of the copper fluorescence photopeak. Fig. 4 (left) shows an example of the cluster charge ADC spectrum, taken for a given slice of a GE1/1 detector. The distribution of the cluster charge corresponding to the copper fluorescence photopeak mean position, across the different slices of the detector, is fit to extract the mean ( $\mu$ ) and the standard deviation ( $\sigma$ ) of the distribution. The Response Uniformity of a GE1/1 detector is defined as  $\frac{\sigma}{\mu} \cdot 100\%$  and it characterizes to the gain variation across the whole detector surface. We estimated that gain fluctuation across the same detector and between different detectors, can be induced by

- the bending of drift and readout electrodes that affect the drift and induction electric fields, thus modifying the transparency of the GEM foils
- the thickness of the GEM foils and the variation of GEM hole diameter that would affect the intrinsic gain [5] of each amplification stage.

Combining those effects, up to 40% gain variations are expected. Nevertheless, as can be seen from Fig. 4, all the GE1/1 detectors exhibit gain variations below 30%. This value is well below the threshold (50%) that would degrade the detector efficiency and time resolution.

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**Figure 4.** Left: copper fluorescence spectrum recorded by a slice of a GE1/1 detector in ADC units. Right: response uniformity of all GE1/1 detectors produced so far by all the different sites.

#### 4. Choice of the operational working point

Combining the detector response uniformity and the gain measurement in the reference readout sector it is possible to infer the gas gain of each detector slice, at each operating HV point. The average detector gain, defined as the mean across the 768 values, is shown in Fig. 5 in yellow, for short and long GE1/1 detectors at a fixed HV applied to the drift electrode. It is crucial to



Figure 5. Average effective gas gain distribution for short and long GE1/1 detectors, flushed with Ar/CO2 (70/30) gas mixture, before (yellow) and after (blue) the procedure of detector pairing for a SC. The 50% contours represent the fluctuations of the gain before (orange) and after (azure) the pairing procedure. The gain is normalized to the pressure and temperature expected in CMS.

emphasize here that during the standard operation in CMS, the detectors in the SC are powered together with the same power supply, so it's really important to choose the optimal HV point

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that guarantees a uniform behavior of the SC, in terms of gain and thus efficiency and time resolution. The operating HV point is chosen by sorting the detectors by increasing value of the gain, then iteratively choosing the pair of detectors with similar gain. Finally the intermediate HV point that ensures a super-chamber gain around  $10^4$  is computed. The corresponding gas gain distributions, obtained after the optimization procedure, are showed in blue in Fig. 5 for short and long detectors.

## 5. Summary, Conclusions and Perspectives

Currently all the 160 (144 to be installed in the GE1/1 station plus 16 spares) GE1/1 detectors have been assembled and fully validated following the quality control process described above. A further validation step is ongoing at CERN, where the super-chambers are equipped with the final readout electronics in order to measure the efficiency at the operating point with cosmic muons before the final installation in CMS. The QC procedure described ensures robust performance and comparable results for detectors assembled and tested in different production sites, thus fulfilling the criteria required by a successful operation in the CMS experiment, even in the HL-LHC era. This is a great success of the distributed sites production model, that at the same time allowed the creation of wide community of GEM technology experts now ready for the production of the modules for two additional muon stations based on GEM technology: GE2/1 and ME0, that will be installed in CMS in 2023 to enhance the Muon System during the Run 4 and 5 data taking [4].

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