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GEM detectors characterisation for the upgrade of the CMS muon system

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Summary. — During its second running period (Run 2), the Large Hadron Collider (LHC) has delivered an instantaneous luminosity up to 2×10^{34} cm^{-2}s^{-1}. In the Long Shutdown 2 (LS2) the accelerator complex will be upgraded for the next Run 3 and in preparation for the High-Luminosity LHC (HL-LHC) which will operate at instantaneous luminosities of 5×10^{34} cm^{-2}s^{-1} up to 7.5×10^{34} cm^{-2}s^{-1} starting from 2025. To handle the high expected background rates and to improve the trigger capabilities keeping the trigger rate at an acceptable level, the forward muon system of the Compact Muon Solenoid (CMS) experiment will be upgraded with Gas Electron Multiplier (GEM) and Resistive Plate Chamber (RPC) detectors. In 2019 the first endcap of triple-GEM detectors has been installed in the first station of the muon detector (GE1/1), while a the second endcap is going to be installed in 2020. A second station of triple-GEM detectors named GE2/1 will be installed in 2021–2022. We will present an overview of the CMS muon detector upgrade with triple-GEM detectors: the production and quality control of the 144 triple-GEM detectors for the first station and the final validation of the GE1/1 chambers before installation.

1. – Motivations for the CMS muon system upgrade

During the next LHC running period the muon system of the CMS experiment will operate in a high-background rate environment. Muon trigger studies [1] demonstrated the need for an upgrade of the muon system to achieve acceptable trigger rates and efficiency in the high-luminosity scenario. The major challenge is to keep high performance for muon triggering and reconstruction in the very forward region of the detector, where the number of detector hits for the muon track reconstruction is not sufficient.

The integration of GEM detectors together with the existing Cathode Strip Chambers (CSC) system in the $1.6 < |\eta| < 2.4$ forward end-cap region will improve the muon trigger momentum resolution due to an increase in the lever arm for the measurement of the muon bending angle [2]. In particular, the GE1/1 station will help in reducing the level-1 (L1) muon trigger rates by providing a measurement of the muon transverse momenta p_T

based on the GEM-CSC system. This p_T measurement will make it feasible to maintain low muon momentum thresholds, which is crucial for a large variety of physics processes characterized by low-p_T muons in the final state.

2. – The triple-GEM technology

The Gas Electron Multiplier (GEM) consists of a thin polymer foil, metal coated on both sides and perforated such that the holes have a uniform diameter and a high-density pattern (typically 50–100 holes/mm). A large potential difference is applied between the two sides of the foil and creates a high electric field inside the holes. The primary ionization charges released in the drift gap move towards the GEM foil and trigger Townsend avalanches that develop in the holes. A large fraction of the secondary electrons drift towards the anode, inducing signals on the readout plane.

A widely used multi-GEM detector is the triple-GEM consisting of a stack of three cascaded GEM foils providing a high total charge multiplication factor (gain) at modest voltage values. GEM detectors were developed to achieve high-rate capability ($>$100 Mhz/cm^2) and high-accuracy localization of fast charged particles in high-energy physics experiments, in order to overcome the limitations of the traditional multi-wire proportional chambers. Moreover, high spatial resolutions ($<300\,\mu$m) have been achieved when using GEM-detectors as trackers, such as in the COMPASS experiment at CERN.

3. – The GE1/1 station

The GE1/1 chambers are trapezoidal large-sized triple-GEM detectors with 3/1/2/1 mm gaps operating with an Ar/CO_2 70:30 gas mixture, which is greenhouse gas free. 72 ten-degree triple-GEM chambers per endcap will provide full coverage in ϕ while covering the pseudorapidity region $1.55 < |\eta| < 2.18$ as sketched in fig. 1. In the GE1/1 muon system, a pair of such triple-GEM chambers is combined to form a super-chamber (SC) that provides two measurement planes for the muon hits. Each chamber is splitted into 24 readout sectors, each read out by 128 strips.

A 5-years long R&D program led to the final design of the detectors together with a standardized protocol for their production and testing. Further details on the prototyping steps and technical design of the chambers are reported in [3].

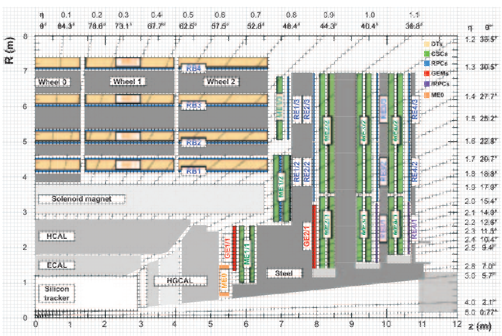


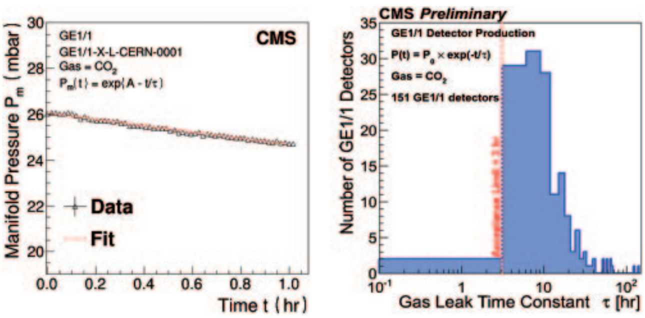
Fig. 1. – A quadrant of the muon system, showing DT chambers (yellow), RPC (light blue), and CSC (green).

4. – Production and quality controls of the GE1/1 detectors

In order to create a community of GEM experts and to share the effort of producing such a large number of detectors, the CMS Collaboration decided to spread the production of the GE1/1 detectors over several institutes from six different countries. During the long R&D phase which led to the detector design, standardized Quality Control (QC) and Quality Assurance (QA) procedures have been established to ensure high detector performance and uniform production quality. The assembly and production procedure is divided into three major steps: the component production and quality control, the assembly and commissioning of single GE1/1 chambers at production sites and the assembly and commissioning of superchambers at CERN before installation. The production of the 144 chambers needed for the GE1/1 station has been completed in December 2018 together with their validation up to the QC5 step. Here we report a summary of the results from the quality controls performed on the full production together with the description of the most important quality controls.

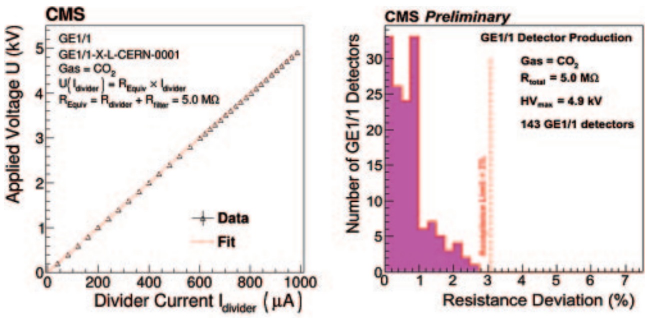
4˙1. *QC3: gas leak test.* – The QC3 gas leak test is the first quality control test performed on a newly assembled GE1/1 detector. It aims to identify possible gas leaks and eventually measure the gas leak rate by monitoring the drop of the internal over-pressure as a function of time. The chamber is filled with CO_2 until an over-pressure $P_0 = 25\,\text{mbar}$ is reached; the detector over-pressure is then monitored over 1 hour. The detector under test is validated if the pressure drop in the detector does not exceed 7 mbar per hour. The pressure drop is modelled by the function $P(t) = P_0 \exp(-t/\tau)$, where the time constant τ qualifies the gas tightness of the chamber; the detector is validated if τ is below 3 hours. Typical results from the QC3 gas leak test can be seen in fig. 2(a), while the gas leak time constant values for all the GE1/1 chambers are reported in fig. 2(b).

4˙2. *QC4: HV test in pure CO_2.* – The identification of possible defects in the HV circuit and the measurement of the intrinsic noise rate is addressed by the QC4 HV test. The current-voltage characteristic of the detector under test is measured in pure CO_2 by ramping up the high voltage (HV) and measuring the current drawn. The GEM electrodes are powered through a resistive voltage divider by a single channel power supply and the total equivalent resistance of the HV circuit (R_{equiv}) is extracted from



(a) Typical QC3 output. (b) QC3 summary plot.

Fig. 2. – Left: typical QC3 output. The pressure drop is modelled by the function $P(t) = P_0 \exp(-t/\tau)$. Right: QC3 summary plot showing the distribution of the gas leak time constant values τ measured during the GE1/1 QC3 test for the 151 GE1/1 detectors tested so far.



(a) Typical QC4 output. (b) QC4 summary plot.

Fig. 3. – Left: typical $I(V)$ curve obtained performing the QC4 test on a GE1/1 detector. Right: QC4 production summary plot showing the distribution of the deviation between the expected resistance and the resistance measured with the $I(V)$ curve for 143 GE1/1 detectors.

the V-I curve. Deviations of R_{equiv} from the value directly measured using a multimeter indicate loss of linearity. The detector under test is validated if the percentage resistance deviation does not exceed 2%. Typical results from the QC4 HV test can be seen in fig. 3(a), while fig. 3(b) shows the distribution of the percentage resistance deviation for most of the GE1/1 chambers produced so far.

4·2.1. QC5: effective gain measurement and uniformity test. The first step of the QC5 test consists in measuring the effective gas gain in Ar/CO_2 70:30 gas mixture as a function of the voltage applied on the resistive high voltage divider. The detector is irradiated with a ∼23 keV X-ray beam. 8 keV photons are produced by copper fluorescence, which are then converted by photo-electric effect in the gas volume. The effective gas gain is defined as: $G = \frac{I_{RO}}{R \cdot q_e \cdot N_p}$, where: I_{RO} is the current induced on the readout electrode, measured with a pico-amperometer; R is the number of electrons converted by photoelectric effect by the incident photons per minute; q_e is the elementary electron charge; N_p is the average number of electrons produced by the incident photo-electron (∼346 in Ar/CO_2 70:30). The gain is measured in one central readout sector as a function of the current drawn by the divider (I_{divider}), *i.e.*, the HV working point. The measured gain is then normalized to defined reference pressure and temperature values. A typical effective gain curve is shown in fig. 4. The second step of the QC5 test is to evaluate the detector response uniformity, which correlates to the gain measurement to describe the overall detector performance. The drift electrode is uniformly illuminated with a 23 keV X-ray beam and the signal acquisition is done with APV25 analog readout chips, which can record the cluster charge ADC spectrum in each group of 4 strips. Each spectrum is separately fitted to extract the position of the copper fluorescence photo-peak and the distribution of this variable across the different slices of the detector is fitted with a Gaussian function to extract the mean (μ) and the standard deviation (σ). The Response Uniformity (RU) of a GE1/1 detector is then defined as: RU $=\frac{\sigma}{\mu} \cdot 100\%$; the detector is validated if the measured RU is below 40%.

4·3. *SC pairing*. – The orange distribution in fig. 5 shows the effective gas gain of the short and long GE1/1 chambers at $I_{\text{divider}} = 660\,\mu$A, corresponding to a voltage between the drift electrode and the readout of $V_{\text{drift}} = 3102$ V. As showed in fig. 5, the

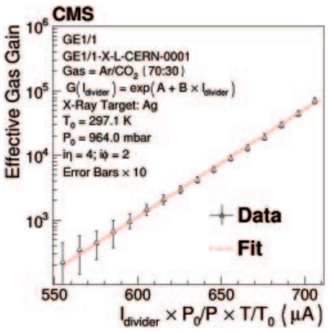
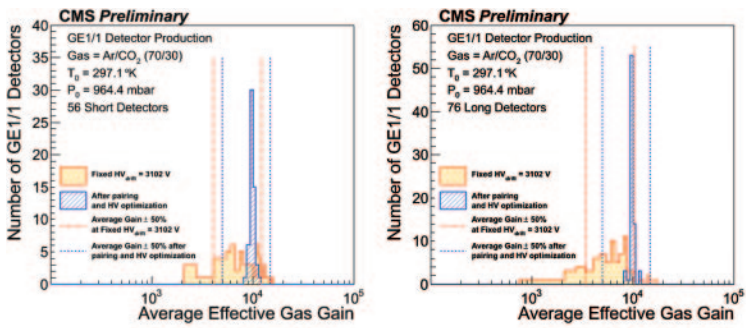


Fig. 4. – Typical effective gain curve obtained during the GE1/1 quality control. I_{divider} is the current flowing through the HV resistive divider that provide potential to the detector electrodes. P_0 and T_0 corrections parameter are determined by averaging the temperature and pressure conditions in the P5 cavern.

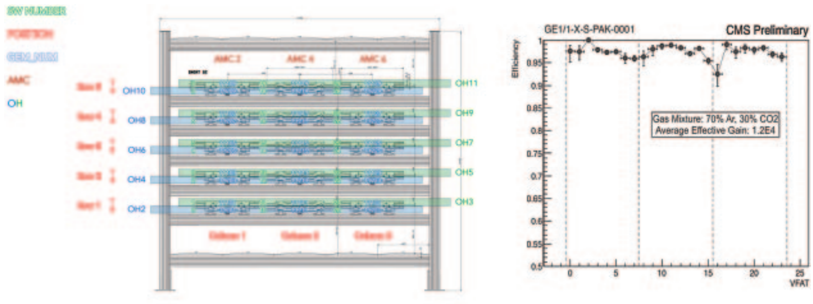
effective gain at given high voltage (HV) setting varies among the chambers, so that the HV settings providing an effective gain of 10^4 are spread across a wide range. The two triple-GEM detectors composing each superchamber are powered with the same HV power supply, so it is necessary to pair detectors with similar HV setting. This procedure is done looking at the average effective gain (G_{avg}) as measured by the QC5 test. An optimal HV setting providing $G_{\text{avg}} = 10^4$ is set for each superchamber as the mean voltage value among the two chambers. The blue distributions in fig. 5 show the G_{avg} of the single chambers at the optimal HV settings.

4·4. *GE1/1 final validation before installation.* – Before being paired to form a superchamber (SC), the GE1/1 detectors are equipped with a final HV circuitry and they are tested for long-term HV stability in Ar/CO_2 70:30 (QC6 test). Afterwards the readout electronics is installed, based on the VFAT3 front-end [4], and the front-end calibration and communication capability is verified using the full back-end system as used in CMS (QC7 test). The final validation of the SCs together with their final electronics is then



(a) (b)

Fig. 5. – Distribution of the average effective gas gain of the short (left) and long (right) GE1/1 detectors before (orange) and after (blue) pairing detectors into super-chambers at the optimum HV set point. The vertical dotted lines represent the theoretical standard deviation (37%) calculated from the uncertainty on the dimensions of the detector components.



(a) (b)

Fig. 6. – Left: geometry of the QC8 cosmic ray stand. Right: efficiency of GE1/1-X-S-PAK-0001, one of the detectors that has already been installed in CMS as part of GE1/1, as obtained from QC8 measurements.

performed at the cosmic stand (QC8 test), which can host up to 15 SCs as shown in fig. 6(a); cosmic muons are detected by two layers of plastic scintillators used for triggering and all SCs participate to the data acquisition. For each event, the muon track reconstruction is then performed offline; one of the detectors is used as "test chamber" and it is excluded from the track reconstruction, done using the reconstructed hits in the top and bottom layers of the stand as seeds. The track is extrapolated to the test chamber and the efficiency is computed looking for any matching hit. A typical efficiency plot is shown in fig. 6(b). 72 GE1/1 detectors paired in 36 SCs have been validated by measuring the efficiency as a function of the HV and have been installed in the negative endcap of the CMS muon system.

5. – Conclusions

The production of the GE1/1 chambers has been completed in December 2018 and the superchambers needed for the first endcap have been validated together with their readout electronics. The quality control procedures for the GE1/1 chambers proved to ensure robust performance and comparable results for detectors assembled and tested in different sites, thus fulfilling the prerequisite for a successful operation of the GE1/1 station. The final validation of the detectors for the second endcap is presently ongoing and their installation is foreseen for April 2020.

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