Operational experience with the GEM detector assembly lines for the CMS forward muon upgrade


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Abstract—The CMS Collaboration has been developing large-area Triple-GEM detectors to be installed in the muon endcap regions of the CMS experiment in 2019 to maintain forward muon trigger and tracking performance at the HL-LHC. Ten pre-production detectors were built at CERN to commission the first assembly line and the quality controls. These were installed in the CMS detector in early 2017 and participated in the 2017 LHC run. The collaboration has prepared several additional assembly and quality control lines for distributed mass production of 160 GEM detectors at various sites worldwide. During 2017, these additional production sites have been optimizing construction techniques and quality control procedures and validating them against common specifications by constructing additional pre-production detectors. Using the specific experience from one production site as an example, we discuss how the quality controls make use of independent hardware and trained personnel to ensure fast and reliable production. Preliminary results on the construction status of CMS GEM detectors are presented.

1. Introduction

The High-Luminosity (HL-LHC) upgrade of the LHC, will feature an increase of the background rate, which will reach up to 1 kHz/cm$^2$ in the first station at the higher $\eta$ regions. The muon system, operational during Run 1, would not allow to achieve an acceptable L1 trigger rate for muons, without increasing the threshold on muon $p_T$ itself. In order to cope with the new HL-LHC environment, the CMS Collaboration decided to renovate the muon system, upgrading the already existing stations while installing new detectors. Among the new foreseen stations, the first one is called GE1/1 (see Fig. 1) and it will be installed in the region $1.6 < |\eta| < 2.2$ by 2020.

Fig. 1. Overview of the CMS muon system upgrade. In red the new GEM stations.

The first GE1/1 station will allow to keep the muon trigger rate below 5 kHz without increasing the muon momentum threshold. Additionally, the new station, will work in combination with the Cathode Strip Chambers (CSCs) detectors, adding redundancy in the region $1.6 < |\eta| < 2.2$ (actually covered only with CSCs) and allowing the measurement of the muon bending angle in the magnetic field, unobstructed by multiple scattering.

The selected technology for the GE1/1 station is Gas Electron Multiplier (GEM) \[2\], which consists of a 50 $\mu$m thick polymer foil coated with 5 $\mu$m copper on each side and perforated with a high density of holes. The main advantage of this technology is the separation of the drift and amplification stages: the avalanche multiplication of electrons is localized inside the holes, thus resulting in an improved rate capability (up to 100 MHz/cm$^2$) and space resolution (of the order of 100 $\mu$m).

In particular, the CMS Collaboration selected Triple-GEM that are made of a stack of three GEM foils. The full station will be composed of 36 pairs of Triple-GEM detectors (so-called GEMINI) for each CMS endcap, for a total of 144 chambers for the whole system.

2. GE1/1 Slice Test

In January 2017, a total of 10 Triple-GEM detectors (equivalent to 5 GEMINI) were installed in one of the CMS endcaps, in the positions shown in Fig. 2 with the aim of:

- Acquiring installation and commissioning expertise
- Proving operability for the system
- Demonstrating the integration into the CMS online system.

The detectors are operated in Ar/CO$_2$ 70/30 gas mixture (flux of 5-6 l/h), which allows to reach all the requested performance for the operation in the GE1/1 station (see \[3\] for more details on the R&D performed).

The readout system is based on VFAT2 front-end chips\[9\] and one optohybrid (OHv2b). A full sketch of the readout system is shown in Fig. 3. To supply it, a total of 3 LV (low voltage) channels are then needed for each detector\[10\].

All the detectors mount a cooling circuit as the one shown in Fig. 4. It consists of a main copper pipe and several copper pads, welded to the pipe and in thermal contact with the optohybrid and the VFATs. Water coming from the main CMS cooling system is circulated through the pipe: this in turns cools down the pads and the components in contact with them.

A. The vertical superchambers

The four GEMINI mounted in Slot 1 (see Fig. 2) are powered by a single channel HV system, with the voltages distributed to the foils through a ceramic divider.

Fig. 2. Overview of the Slice test chambers installed in the CMS endcap
In addition, one long vertical GEMINI mounts alignment sensors based on Fiber Bragg Grating (FBG) displacement sensors [4]. The sensors are made by a strain sensor combined with a temperature sensor, to cover a measurement range of 0-10 mm, with a resolution lower than 10 µm. The aim of the system is to locate the strips of the readout boards in the CMS coordinate system and monitor their movements. In particular, in the complete system, the internal alignment is performed measuring the distance between adjacent chambers, with 2 sensors for the \( \phi \) coordinate and one for the \( R \) coordinate, as shown in Fig. 5. In this case however, the \( R \) coordinate sensor was not mounted, while two additional FBGs without spring (i.e. without strain measurement) were inserted on the other side of the long superchamber, on the right in picture 5, to obtain a reference measurement.

Preliminary results show no creeping effect and strain changes were observed by the spring-equipped sensors. In general, effects related to the magnet were observed on the chamber position, as expected.

The other long vertical GEMINI is instead equipped with a Radiation Monitoring (RadMon) sensor. RadMons have been developed at CERN for monitoring of irradiation facilities and equipment and include RadFETs for Total Ionising Dose (TID) measurements, silicon p-i-n diodes for the 1-MeV equivalent neutron fluence, and SRAM memories for the high energy hadron and thermal neutron fluence [5]. In the interested slice test chamber, the RadMon is mounted on the cooling circuit plate as shown in Fig. 4.

### B. The horizontal chamber

The horizontal chamber in Slot 2 is powered by a new multichannel HV system, with seven HV channels for each detector, developed on purpose for Triple-GEM detectors and adopted as final solution for the full GE1/1 station. The operation of these chambers is then essential for the whole GE1/1 project, as it is offers a unique test bench for the powering system in the final operative conditions. The results of the first stability tests performed on this GEMINI are shown in Section 2-C, while an intensive stability and discharge probability study is actually ongoing with the full 2017 dataset.

Moreover, the horizontal GEMINI mounts a full set of FBG sensors aimed at monitoring the temperature of system [6]. Six sensors are installed on the readout board of each Triple-GEM (for a total of twelve sensors). The analysis of the data coming from these sensors will give us fundamental information regarding operational conditions of the detectors, the effectiveness of the cooling system and will allow us to identify main heating source of the system. So far preliminary correlations between the temperature and the LV system status have been observed while more results will be available in the next months.

### C. System stability

One of the main goals of the slice test was to prove the stability of the system and study the operational conditions of the detectors. For this reason, stability tests have been performed specifically without beam and during LHC runs with collisions.

Fig. 6 shows the results of a stability test performed without beam, while Figs. 7 and 8 show the results of the same study carried out during LHC collisions run, with the single channel and the multichannel HV system respectively: in all the configurations the system reaches a stability within \( 10^{-3} \) during several hours of operation (several days in the case of the operation without beam). In general, an overall stability of the order of 1 % or less has been observed with/without collisions. Similar results have been obtained also for the LV system shown in Fig. 9. In this plot, two operational conditions can be observed: the current drawn by the VFAT chips is stable around 2 A when the system is in idle state, i.e. it is configured by it is not actually taking data. The current then rises up to 6.5-7 A during the actual data taking periods.
Fig. 6. Voltage and divider current vs time (≈ 10 days) for one Triple-GEM chamber installed for the GE1/1 station slice test. In this period no beam was provided by LHC, so reported data are taken without collisions in CMS. Blue trend represents the voltage applied to the chamber, while red trend shows the current going through the high voltage divider, used to distribute the power to the different foils. The plot shows overall stability of the chamber over a 7 hours period, with variations of the order of 0.3% for the voltage and 0.1% for the divider current. Errors are estimated from the resolution of the A1526N CAEN HV power module: ± 1 V and ± 0.1 µA for the voltage and current respectively.

Fig. 7. Voltage and divider current vs time (≈ 7 hours) during LHC collisions, for one Triple-GEM chamber installed for the GE1/1 station slice test. Blue trend represents the voltage applied to the chamber, while red trend shows the current going through the high voltage divider, used to distribute the power to the different foils. The plot shows overall stability of the chamber over a 7 hours period, with variations of the order of 0.3% for the voltage and 0.1% for the divider current. Errors are estimated from the resolution of the A1526N CAEN HV power module: ± 1 V and ± 0.1 µA for the voltage and current respectively.

Fig. 8. Voltage vs time (≈ 12 hours), for one Triple-GEM GE1/1 slice test detector during LHC collisions run. This particular detector is powered by a multichannel power supply, through 7 channels represented by the 7 data series called Drift, G1Top, G1Bot, G2Top, G2Bot, G3Top, G3Bot. Absolute values of voltage are not shown, whereas each series represents voltage difference with respect to the previous one.

Fig. 9. The plot shows the behavior of the voltage and current of the GEB and VFATs of one of the Triple-GEM chamber installed for the GE1/1 slice test in the period 10th-20th of April 2017. The blue data series represents the voltage applied, while the red one is the current drawn by the GEB and the VFATs. For the current, two typical ranges can be observed: the current is around 2 A when the VFATs are in sleep mode, while during the runs, the current reaches about 6.5 A. During the period considered the LV remained always on, with moment of operation alternating to period of standby, except for a short moment on the 14th of April (when the two data series go to zero). During both the periods of operation and standby, the system results to be overall stable.

D. Local calibration of the system

Initially, in order to be able to take meaningful data and to include GEM detectors into the CMS data acquisition, we focused our work on the local calibration of the detectors and electronics system. The local calibration mainly concerns three steps:

1) Threshold scan: used to study the noise of all channels as function of set threshold.
2) S-curve: measures the response of the channels to an injected pulse calibrated to a given charge (at a given threshold).
3) Latency scan: shows the amount of recorded events,

Data are recorded (not by regular sampling but every time one value changes) in the GEM Detector Control System (DCS) database.
Fig. 10. VFAT2 front-end chip response to the injection of internal calibration pulses. The size and the quantity of the injected pulses are configurable by a programmable memory (VCal DAC). The size and the quantity of the injected pulses are configurable by a programmable memory (VCal DAC). This plot shows the response after adjusting the individual channel registers to trim the 50% response point to the same VCal value.

per different latency value, over the total number of events. The latency value is defined as the time difference between the time of arrival of a L1Accept (L1A), i.e. an event accepted by the Level 1 trigger, and the time at which the related event is stored [10].

Fig. 10 and Fig. 11 show the results of an s-curve performed with one VFAT installed on one slice test chamber: while the first plot shows the raw results of the procedure, in the second one instead the result is obtained after the so-called *trimming* procedure, which consists in adjusting the individual channel registers to trim the 50% response point to the same VCal value. From this s-curve it is then possible to understand at which amplitude of the calibration pulse a signal becomes visible, i.e. a conversion between the threshold and the charge, to evaluate the equivalent noise charge of the system.

Fig. 12 instead shows the results of a latency scan taken during an CMS cosmics run. It shows that the observed delay is of the order of 175 bunch crossings (BX), compatible with the expectation for CMS cosmic ray muon data.

**E. Integration into the CMS system**

The integration in CMS basically foresees the integration of two elements: the DAQ and the DCS. Currently, the basic elements of the local DAQ system of the GEM slice tests have been deployed and are being tested. A series of stress tests at high-rate is actually on-going to fully qualify the GEM DAQ system for the full inclusion in CMS.

The DCS is the system that allows the remote control and monitoring of the detectors from the control room. In order to be integrated with the central system, the GEM DCS must include two important elements: the protection system and the automation system. The protection system is designed to move the system (applying HV, LV) into a safe condition during the most delicate phases of operation, i.e. beam injection and the magnet ramp, in order to prevent potentially dangerous situations. The automation system instead, following a predetermined action matrix, takes care of powering ON the detectors to ensure a reliable data-taking in stable beam mode.

Both the GEM protection system and the GEM automation system have been developed and are under test. A fully featured and operational DCS has been then pushed into the CMS integrated system at the end of 2017.

**3. GEM Construction**

Given the complexity of GEM detectors [7] and the quantity needed to instrument the endcap station, several assembly lines have been established to perform a mass production using a progressive assembly approach. In accordance with this approach, the GE1/1 design relies on interchangeable parts added in sequence until the final assembly. The entire assembly takes place in a class 1000 clean room fully equipped with all the necessary tooling and assembly devices.

During 2015-2016, we established and agreed upon a number of sequential operation to be performed in order to ensure standardization among construction sites. In early 2017, the collaboration released detailed technical manuals to accomplish all required operations and maximize compatibility and overall quality of the detectors. During 2017, CERN purchased all raw materials to be shipped to assembly sites in order to actually perform the mass production. Following a progressive
assembly approach, we split the detector construction into 5 major steps, documented with dedicated technical manuals:

Step 1: Drift and readout PCB Preparation
Step 2: GEM stack foil assembly
Step 3: Deployment of GEM stack onto the Drift
Step 4: GEM stack tensioning
Step 5: Detector Closure

The required total time to complete the assembly of a module, is approximately one working day.

A. Step 1

The active area of the detector, the Triple-GEM stack, is fully contained in a sealed chamber where the bottom panel works as a drift PCB while the top panel is the readout PCB. Both drift and readout PCB have to be prepared before to work on the Triple-GEM stack. The drift PCB (Fig. 13) has to be equipped with spring-loaded HV pins to power the Triple-GEM stack foil and with vertical pull-out mountings, to sustain the GEM foil tensioning (see also step 4). In addition, the readout PCB has to be equipped with gas connectors and both PCBs have to be carefully cleaned from dust.

B. Step 2

The GEM stack is assembled on top of a plexiglass supporting plate similar to the drift PCB. Thanks to dedicated alignment pins, all three GEM foils can be correctly positioned. The gaps in-between the foils are established using 3/1/2/1 mm internal frames. The stack assembly begins by arranging the 3 mm frames on the plexiglass plate (Fig. 14). After that the first foil (GEM1) is placed onto the 3 mm frames. Similarly, another frame (1 mm) is placed on the GEM1 and another foil (GEM2) is installed. Again a 2 mm frame, on top of GEM2, provides support for GEM3, the last foil. The last 1 mm frame completes the GEM stack, ready to be installed on the drift PCB.

C. Step 3

The GEM stack is moved from the plexiglass supporting plate onto the drift (Fig. 15).

D. Step 4

By means of stretching screws (installed in correspondence with pull-out posts mounted on the drift), the GEM stack is
tensioned via a torque screwdriver set to 0.07 Nm.

E. Step 5

The readout PCB is screwed into the pull-out posts to close the detector; a grooved external frame with O-rings on both sides then seals the detector.

4. IMPLEMENTED QUALITY CONTROLS AND PRELIMINARY RESULTS OF THE DETECTOR CONSTRUCTION AT ASSEMBLY SITES

Any industrial mass production implies the adoption of several Quality Control (QC) processes in order to check the manufacturing output against the requirements set by the specification. Following this principle, the GE1/1 detectors will also be systematically subjected to tests, measurements or comparison with standard values in order to prevent any mechanical or electrical issues that might affect the detector performance.

The GEM detector mass production will be carried out by several research institutes and universities, led by CERN which is the headquarters of the production collaboration. Among the assembly sites, CERN implemented the most exhaustive QC tests, since the production headquarters takes care of both raw material and integration of the detectors. As for the raw materials, CERN is the only assembly site that deals with detector components and their specifications: all other assembly sites receive only components within the specification. For the integration of the detectors, CERN, being the final recipient of the manufactured detectors (built externally at all assembly sites), implemented additional QCs to verify and test the performance of received detectors. After this final check, detectors are eligible to be equipped with the latest CMS electronics and get installed in the CMS experimental cavern. In summary, the list of QC tests, is as follow:

QC 1: Component Reception
QC 2: GEM foils: leakage current/spark test
QC 3: GE1/1 chamber: gas leak test
QC 4: GE1/1 chamber: HV test
QC 5: GE1/1 chamber: gain calibration
QC 6: GE1/1 chamber: HV stability test
QC 7: GE1/1 chamber: connectivity test
QC 8: GE1/1 super-chamber: cosmic ray test

While QC1-8 are implemented at CERN, only QC2-5 are implemented at assembly sites, which are in charge of delivering detectors.

A. QC1

A number of visual inspections are performed in order to validate detector raw components. This is a common practice in industrial production to use all of raw human senses and non-specialized inspection equipment to discard visibly faulty components.

B. QC2

This test, performed on GEM foils, validates their performance by measuring the leakage current across the two foil sides. The experimental setup comprises a plastic support frame where a GEM foil is attached and a custom made clip to electrically connect the GEM foil HV pads on both foil sides to the Multi Giga-ohmmeter module used to apply voltage across the two faces of the foil. Although the GEM foils are shipped to assembly site using a sealed box, the test takes place in a cleanroom after a careful cleaning of the foil.

The test is performed at 550 V while monitoring the impedance of the foil and counting the number of sparks per minute over a period of ten minutes. A GEM foil passes the QC2 test if its impedance is above 10 GOhm and the spark rate is lower than 2 Hz after ten minutes.

C. QC3

This is the first test performed on a newly assembled detector and aims at measuring its gas leakage (Fig. 16). This is measured by pressurizing the foil to 25 mbar while recording the internal pressure with a dedicated digital pressure transducer, along with environmental variables. A proper gas sealing ensures that the detector can run in the CMS Experiment without affecting other detectors and with a minimal amount of gas.

D. QC4

The objective of this test is to acquire the characteristic IV curve (Fig. 17) of the detector under high voltage and the spurious signal rate recorded while operating the detector with pure CO\textsubscript{2}. The IV curve (0 - 5 kV) is obtained by powering on the detector while recording the HV divider current. To get the spurious signal rate (Fig. 18), a chain of charge sensitive preamplifier, amplifier, discriminator is connected to the GEM3 foil that faces the readout PCB via RC circuit to decouple the DC component of the GEM foil. The rate of spurious pulses is measured and should not exceed ∼30 Hz. In addition to the spurious rate this test aims also at validating the HV divider and the electric circuitry itself to ensure a safe and reliable powering system.
Fig. 16. Measured pressure drop of all detectors built by the collaboration in 2017.

**E. QC5**

This is the last test to be performed at assembly sites before shipping a detector back to CERN. The first part of the QC is a measurement of the gas gain of the detector as a function of the HV in one central ($i_\eta=4$, $i_\phi=2$), readout sector (Fig. 19). The second part is a measurement of the full detector response strip-by-strip using the Scalable Readout System (SRS[8]) together with the APV25 front-end chip. Both parts of the test are carried out using an X-ray gun with large emission angle.

Given the large area of the CMS GEM chambers, the uniformity of the detector response across the surface should be assured. At a gas gain of $\approx 600$, using Ar/CO2 (70:30), we measure the response uniformity recording the pulse height of every readout strip, such response uniformity is expected to be within 15% (Fig. 20).

Fig. 17. Summary IV curve of all the detectors built during 2017.

**F. QC6**

This test is the first test performed at CERN after the detectors are shipped back from the assembly sites. This test is a measurement of the IV curve before and after the HV connector is replaced to be compliant with the standard cable installed at CMS.

**G. QC7**

A GEM Electronics Board (GEB) is mounted onto the detector and fully tested, along with an optoHybrid to provide fiber-optic data output featuring compatibility with the new VFAT3 chip designed specifically for CMS GEMs.

Fig. 18. Summary of the measured spurious signal rate of all detectors built during 2017.

Fig. 19. Measured effective gain of all detectors built during 2017.
**H. QC8**

Before the installation at CMS, the detector performance is tested in a dedicated cosmic ray stand. This test aims at measuring the efficiency and time resolution of detector and electronics system.

5. **CONCLUSIONS**

The slice test has been a unique opportunity to gain installation and operational experience with new GEMs at CMS. The GEM detectors showed stable performance, while the software integration will be completed by the end of 2017. The experience gained during 2016-2017 will be fundamental in 2019-2020 when 144 additional detectors, currently being assembled, will be installed in the CMS endcaps.

The GE1/1 project is progressing towards a successful implementation: the intense R&D program has led to the development of detectors with excellent performance while the assembly and quality control (QC) procedures have been fully defined. Preliminary results of the first 10 detectors built show uniform production and performance within specifications. In particular all the QC1-5, performed in production centers, aims at establishing a coherent and uniform production in the several assembly lines that have been planned around the world. Ensuring the proper detector gas sealing, the stable performance of the HV power system circuit and the correct gas gain across the large active area allow to validate a detector to be shipped to CERN for integration and installation into the CMS Endcap. QC6-8 are performed at CERN after detector reception, new electronics installation and final cosmic test commissioning where we aims at measuring a detector efficiency close to the maximum using the CMS front-end digital electronics.

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