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Status of the Triple-GEM project for the upgrade of the CMS Muon System

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ABSTRACT: The CMS GEM collaboration is performing a feasibility study to install triple-GEM detectors in the forward region of the muon system ($1.6 < |\eta| < 2.4$) of the CMS detector at the LHC. Such micro-pattern gas detectors are able to cope with the extreme particle rates that are expected in that region during the High Luminosity phase of the LHC. With their spatial resolution of order 100 micron GEMs would not only provide additional benefits in the CMS muon High Level Trigger, but also in the muon identification and track reconstruction, effectively combining tracking and triggering capabilities in one single device. The present status of the full project will be reviewed, highlighting all important steps and achievements since the start of the R&D in 2009. Several small and full-size prototypes were constructed with different geometries and techniques. The baseline design of the triple-GEM detector for CMS will be described, along with the results from extensive test measurements of all prototypes both in the lab and in test beams at the CERN SPS. The proposed on- and off-detector electronics for the final system will be presented.

KEYWORDS: Muon spectrometers; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc)

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1 Introduction

Gas Electron Multipliers (GEMs) [1] are gaseous, position sensitive devices featured by spatial resolutions of order $100\,\mu\text{m}$, time resolutions of a few ns, detection efficiencies above 98% and rate capabilities up to $10\,\text{MHz}/\text{cm}^2$ [2]. They can be operated in a stable manner in high radiation environments, at high gains exceeding 10^4 . This makes GEMs very suitable detectors for a wide range of applications in many different fields including high energy particle physics.

In the CMS experiment [3] at the CERN LHC, GEMs are under consideration for the extension of the Muon System in the forward region. Figure 1 shows a transverse section of the CMS detector as it will appear after the ongoing first LHC Long Shutdown. The CMS Muon System [4] contains three different gaseous detection systems for muon tracking and triggering, Cathode Strip Chambers (CSCs), Drift Tubes (DTs) and Resistive Plate Chambers (RPCs). At present, the forward region with $1.6 < |\eta| < 2.4$ is only instrumented with CSCs, leaving this part of the detector less robust, with low redundancy for muon tracking and reconstruction. Furthermore, in the forward region one has a relatively high track density, and track projections in the bending plane are relatively short, which hampers the muon momentum determination and makes this area the most challenging region for muon detection.

In view of the ongoing and future upgrades of the LHC, the CMS Collaboration is looking into different options to instrument the $1.6 < |\eta| < 2.4$ region with additional detectors in order to maintain the present performance level of the Muon System in terms of tracking and triggering, and to enhance also the physics reach by increasing the muon acceptance of the detector. The main

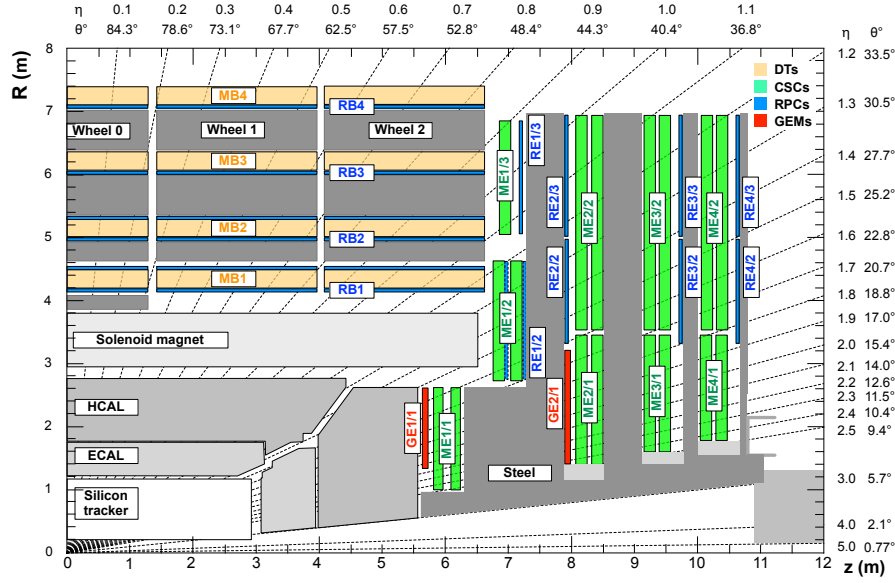


Figure 1. Transverse section of the CMS detector showing the present muon system including RPCs, DTs and CSCs. The proposed locations for the GEM detectors in the inner two endcap stations are indicated by the red boxes.

issue with respect to muon triggering in this region is the high background rate stemming from low- p_T tracks that are misidentified as high- p_T muons. Adding more detection layers with high granularity at high $|\eta|$ will yield additional space points for track reconstruction to be combined with the information from the CSCs. This will improve both the muon momentum resolution and the background rejection at the trigger level, especially in the inner endcap stations where the muon track bending angle due to the magnetic field from the CMS solenoid is largest.

For the high-luminosity phase of the LHC, one expects particle rates of several kHz/cm² in the $|\eta| > 1.6$ region of the Muon System, which imposes severe restrictions on the technology that can be used. The presently installed Bakelite-based RPCs in the $|\eta| < 1.6$ region are for example not able to sustain such rates. Instead, the CMS GEM Collaboration aims at installing several layers of triple-GEMs in the $1.5 < |\eta| < 2.4$ region of the Muon System. Pairs of triple-GEM chambers combined together to form super-chambers, would be installed in the two inner endcap stations of the Muon System, as indicated in figure 1. In the presently proposed schedule, the inner endcap stations would be equipped with GEMs (labeled GE1/1) during the second LHC Long Shutdown in 2017–2018, while the installation in the second endcap stations (labeled GE2/1) would be done during the third LHC Long Shutdown scheduled beyond 2020.

2 Detector description

2.1 Overall layout of the system

The overall layout of the GEM chambers follows closely the design of the existing RPCs in the endcap disks. In each of the 4 endcap stations ($x = 1 \dots 4$), the latter detectors are arranged in two concentric rings (RE x /2 and RE x /3) of 36 chambers each around the beamline, covering the

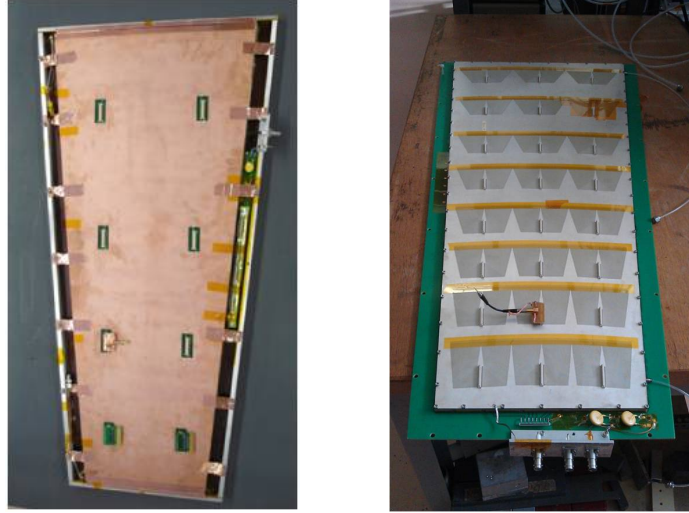


Figure 2. (Left) The first GE1/1 prototype built in 2010. (Right) The latest version of the GE1/1 prototype as built in 2013 (without cover box).

region in $|\eta|$ up to 1.6 roughly, while the $|\eta| > 1.6$ zone of the disks remains empty and can accommodate the GEM chambers. The GE1/1 chambers are designed to match the presently vacant insertion slots for the $1.6 < |\eta| < 2.1$ region of the first endcap stations. Each chamber covers a 10° azimuthal sector, yielding a total of 36 chambers per station. A GEM super-chamber is then composed of a double layer of chambers, mounted face-to-face and separated by 20 mm. Thus, every super-chamber in principle yields 2 space points for the muon track reconstruction.

2.2 Detector construction aspects

Since the start of this project in 2009, many studies were performed with small ($10 \times 10 \text{ cm}^2$) GEM detectors [5] before full-size GE1/1 detectors were constructed. The presently envisaged project for CMS would require about 500 m^2 of GEM foils, for the production of a few hundred detector units. For such quantities, the production time and cost becomes a real issue and needs to be optimized. As a result, the present GE1/1 chamber design and construction procedure has evolved quite a bit since the first prototype was built in 2010 [6, 7].

The GEM foils used so far for the detector prototypes were produced in the Surface Treatment Workshop at CERN, using a photolithographic hole etching procedure. Given the relatively large active area of the foils required by CMS, i.e. about 0.5 m^2 for the smallest size chambers, the use of a single-mask technique [8] is mandatory to overcome any mask alignment issues that one encounters during the hole etching procedure with double-mask techniques. The validity of this single-mask technique was demonstrated with small prototypes, where no major differences in performance were observed between detectors produced with single and double-mask GEM foils [5].

An important step in the detector production is the foil stretching and mounting. For the construction of the first GE1/1 prototype shown in figure 2 (left), the GEM foils were thermally stretched during 24 hours at 37° in a special oven [6]. Fiberglass spacer frames were then glued onto the foils in order to fix them and to keep them separated at the correct distance in the triple-GEM configuration. This procedure was both labor-intensive and time-consuming, and therefore

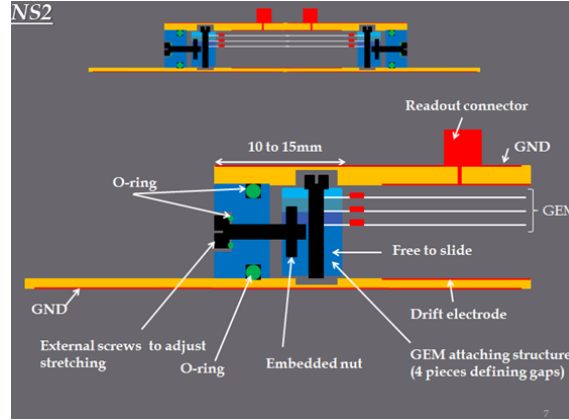


Figure 3. Transverse section of a GE1/1 detector constructed with the self-stretching technique.

not well suited for mass production. A first attempt to avoid the need of foil stretching and to speed up the assembly procedure using honeycomb structures as spacers did not yield satisfying results [5]. However, an alternative method to stretch GEM foils using infrared heating lamps was successfully tested [9]. Nevertheless, a major improvement in the detector assembly procedure was introduced in 2011 with the so-called self-stretching technique [7] in which the GEM foils are mechanically stretched and the detector is constructed without the need for any spacers frames or glueing. This new technique was initially tested on small size prototypes and later on used to produce several GE1/1 chambers [10].

2.3 Current GE1/1 design

The latest version of the GE1/1 prototype is shown in figure 2 (right). The triple-GEMs have a trapezoidal-shaped active area of $990 \times (220 - 455) \text{ mm}^2$ with a 3/1/2/1 mm drift/transfer-1/transfer-2/induction field gap configuration. The detector is assembled using the self-stretching technique, as illustrated in figure 3: outside the active area, the edges of the GEM foils contain a pattern of holes which is used to attach each of the 3 foils with nylon pins to an inner frame structure; this inner frame defines the gap sizes and is placed inside an outer frame; by tightening screws passing through the outer frame and fitting into nuts inside the inner frame, the 3 foils are mechanically stretched. The outer frame is designed to withstand the tension of the foils. With this technique a GE1/1 detector can be assembled in a few hours time, in contrast to the old thermal stretching and glueing method which took several days. At the bottom of the assembly is the Drift Board (see figure 4), which is a printed circuit board holding the drift electrode. The board contains a high voltage filter and a ceramic voltage divider, with spring contacts to connect the GEM foils to the high voltage, i.e. 4 contacts per GEM foil, with 1 for the top side, 1 for the bottom side and 2 spare contacts. On top of the assembly, the Readout Board (see figure 5) is screwed onto the outer frame. The inner side of the board contains a pattern of readout strips oriented radially along the long side of the detector. The strip pattern is segmented in 8×3 partitions in (η, ϕ) , with a strip pitch varying between 0.6 mm at the short end of the detector and 1.2 mm at the wide end. The strips are connected through metalized vias to the outer side of the board, where 3 128-channel Panasonic connectors per η partition are soldered for the signal transfer to the front-end electronics. The gas



Figure 4. (Left) A GE1/1 Drift Board with a GEM foil in the inner and outer frame. (Right) Close-up view of a closed chamber, showing the voltage divider, high voltage filter and power connections mounted on the Drift Board.

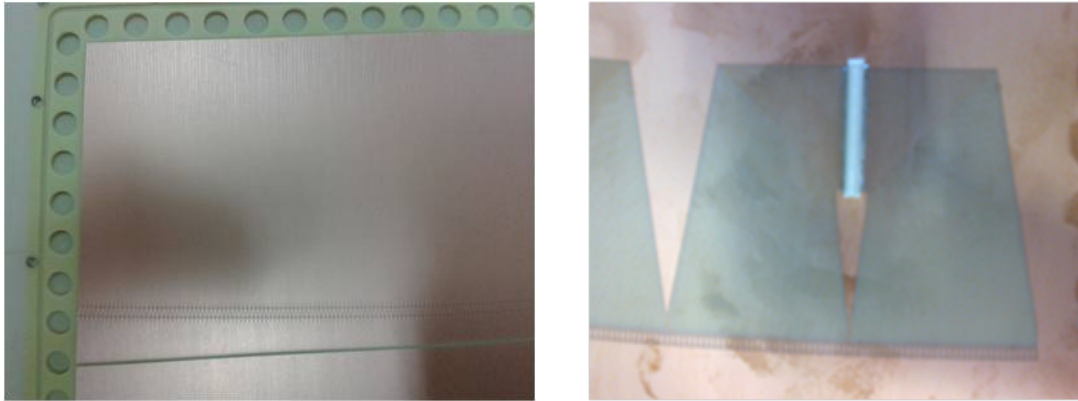


Figure 5. Close-up view of a GE1/1 Readout Board: inner side with the radial strip pattern (left) and outer side with the Panasonic connectors (right).

volume of the assembly is sealed off using 2 large O-rings embedded in grooves in the outer frame. The entire assembly is embedded in an aluminum cover box for protection and mechanical support. A cooling system made of Cu strips and water pipes (see figure 6) is foreseen for the cooling of the front-end electronics mounted on the detector.

3 Detector performance

3.1 Test beam measurements

During the past years, the performance of the CMS triple-GEMs has been evaluated both in the RD51 lab at CERN with x-ray sources and in many test beam campaigns at the CERN SPS [5, 7, 11]. The detectors were operated mainly with a Ar:CO₂:CF₄ 45:15:40 gas mixture. The readout was performed either using digital TURBO/VFAT2-based front-end electronics [12] or with the Scalable Readout System (SRS) [13] as developed by the RD51 Collaboration, with an analog front-end based on APV25 hybrids.

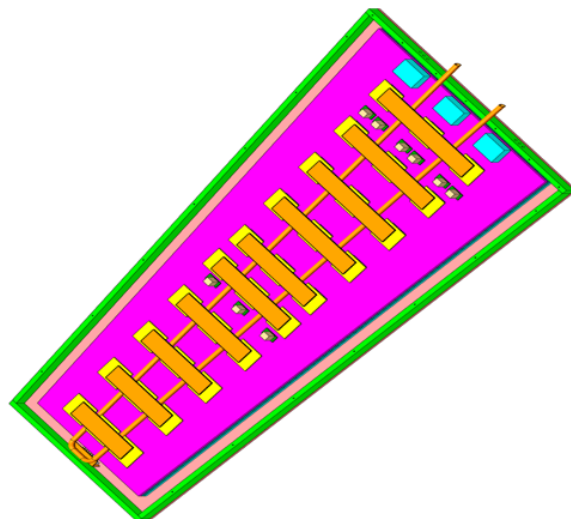


Figure 6. Top view of a closed GE1/1 chamber, showing the Cu cooling circuit (brown) for the front-end chips.

It was demonstrated that the detectors exhibit a broad efficiency plateau with maximum efficiency above 98%. A time resolution of 4 ns was obtained during drift and induction field scans. Spatial resolution on the order of $270\ \mu\text{m}$ were measured with a digital readout, compatible with the values one expects from the strip pitch; using analog readout, spatial resolutions below $110\ \mu\text{m}$ were found. Furthermore, it was shown that the detector performance was not affected significantly when operating inside a magnetic field similar to the one expected inside the CMS detector.

Studies using an alternative readout structure with zigzag strips, with a larger pitch than the presently used straight strips, are ongoing and yield promising results [11]. Such a zigzag structure would allow to reduce the total amount of strips and readout channels, and would thus ultimately reduce the overall cost of the system.

3.2 Detector gain and uniformity measurements

Given the large area of the CMS GEM chambers, the uniformity of the detector response across its surface should be assessed. A basic quantity to verify here is the detector gain. Gain measurements have been performed regularly in the RD51 lab at CERN, using a Cu target x-ray gun. Measuring, as a function of the applied high voltage, the event rate and the detector output current with a correction for dark current, one can derive the detector gain curve. Figure 7 shows gain curves for one of the latest GE1/1 chambers, measured on different sectors of the detector. For a total voltage between 3.20 kV and 3.55 kV supplied to the detector, the drift/transfer-1/transfer-2/induction field varied between about 2.3/2.6/2.6/3.8 kV/cm and 2.5/2.9/2.9/4.2 kV/cm, while the voltage across the GEM-1/GEM-2/GEM-3 foil ranged from about 340/330/315 V to 375/370/350 V. No significant difference between the different sectors can be seen.

A dedicated setup was built to measure the gain uniformity across the entire surface of a GE1/1 chamber. Such a setup can be used for quality control of the chambers in case of a mass production for CMS, and also allows to study gain variations with time or as a function of external parameters. In the setup, the entire chamber is illuminated at once by an x-ray gun placed at a

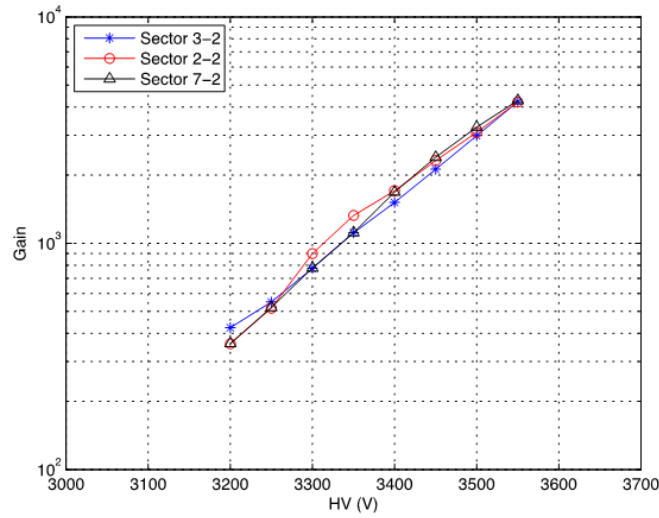


Figure 7. Examples of GE1/1 gain curves, determined for several sectors of a chamber.

distance of about 1 m. The full detector is readout with an SRS/APV25 data-acquisition, where a signal coming from the bottom side of the lowest GEM foil is used to generate a trigger for the APV25 hybrids. First, a run is done with the x-ray gun off, allowing to determine the noise level and pedestal of all detector channels; second, a run is performed with x-rays on, yielding the charge (ADC) spectrum of the source everywhere on the detector. To assess the detector gain uniformity, the measurement is analyzed sector by sector. For a given sector, the peak position (in ADC counts) of the pedestal corrected charge distribution is determined for each readout channel, revealing detector gain variations along the η sector. Figure 8 shows an example charge spectrum for one η sector, where the peak position of the charge distribution is determined for groups of about 30 adjacent strips. Combining the data from each of the η sectors, the observed relative variation of this peak position can then be used to judge the gain uniformity of the chamber as shown in figure 8. In this way, gain variations up to about 15% along the chamber were measured for the GE1/1 prototypes.

4 Electronics and data-acquisition system

The data-acquisition system and front-end electronics for the GEMs should be able to provide the necessary input information to the CMS muon triggering and tracking system. Triggering requires the electronics to provide fast logical OR trigger information, possibly with a granularity of 2 or more channels, to be sent locally to the CSC trigger system. Tracking requires the electronics to provide full granularity spatial hit information for every triggered event in CMS. Figure 9 shows the proposed electronic readout scheme for the GEMs at CMS. The system is divided into two main parts, i.e. the on-detector electronics which are on or close to the detector, and the off-detector part which is to be installed in the CMS counting room.

High and low voltage is delivered to the chambers through electrical cables. DC/DC regulators mounted on the chamber provide the voltage levels needed by the on-detector electronics.

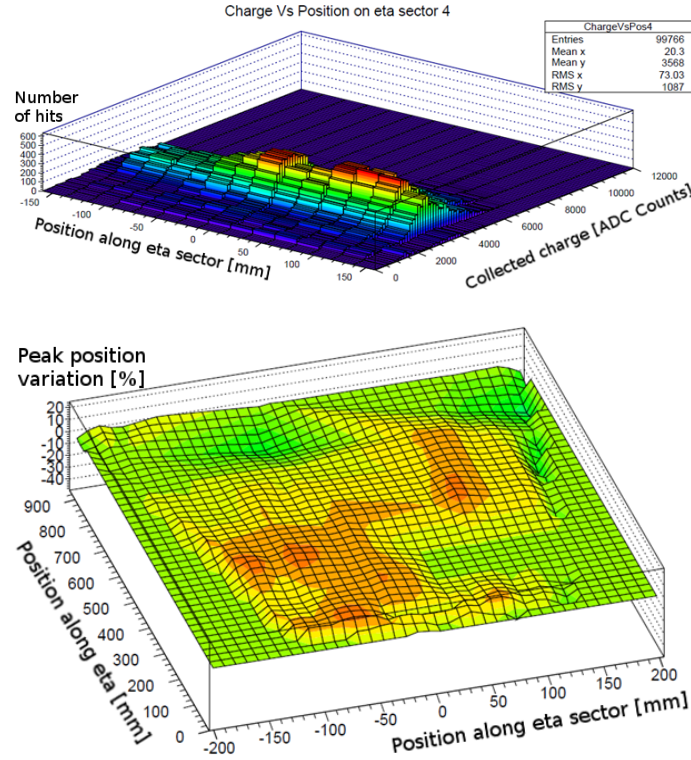


Figure 8. Illustration of the GE1/1 gain uniformity measurement: the detector response plotted for one single sector (top); 2D map of the detector response uniformity (bottom).

The on-detector electronics have to be radiation resistant and are therefore mainly custom made. The final GE1/1 detector will be segmented in (η, ϕ) , with 3 segments in ϕ and up to 10 in η . Every (η, ϕ) segment contains 128 channels and is readout by one single front-end ASIC. This means that a basic detector unit has up to 3840 channels, readout by up to 30 front-end chips. The communication between the on-detector and off-detector electronics is done via GBT-GLIB-based optical links [14]. Electrical links (e-links) connect all front-end chips in the same column in ϕ to one single GBT chipset mounted on the detector. The GBT chipsets are linked via optical fibers, 3 in total per chamber, to the GLIB-based off-detector electronics housed in μ TCA crates. The latter contain dedicated units to interface to the CMS trigger, data-acquisition and control systems.

Two possibilities are pursued for the front-end chips [15], a digital readout based on the VFAT3 ASIC and an analog one based on the GdSP ASIC. Block diagrams of these 128 channel chips are displayed in figure 10. The VFAT3 chip, the successor of the VFAT2, has a programmable shaping time and gain in order to optimize the charge collection from the GEM detector while keeping an excellent timing resolution; it is designed for high rates, and interfaces directly to the GBT chipset. The GdSP chip is quite similar to the VFAT3, except that this one instead of a comparator incorporates an ADC to digitize samples from the preamplifier and signal shaper. This kind of chip with one ADC per channel for a total of 128 channels became only recently feasible thanks to the low power consumption below 4 mW per channel. From the CMS trigger point of view, the digital VFAT3 chip would provide sufficient information for now, for the GE1/1 detector to be installed during the second LHC Long Shutdown. During the third LHC Long Shutdown one could imagine replacing the VFAT3 with the GdSP, when also the GE2/1 detector would be installed.

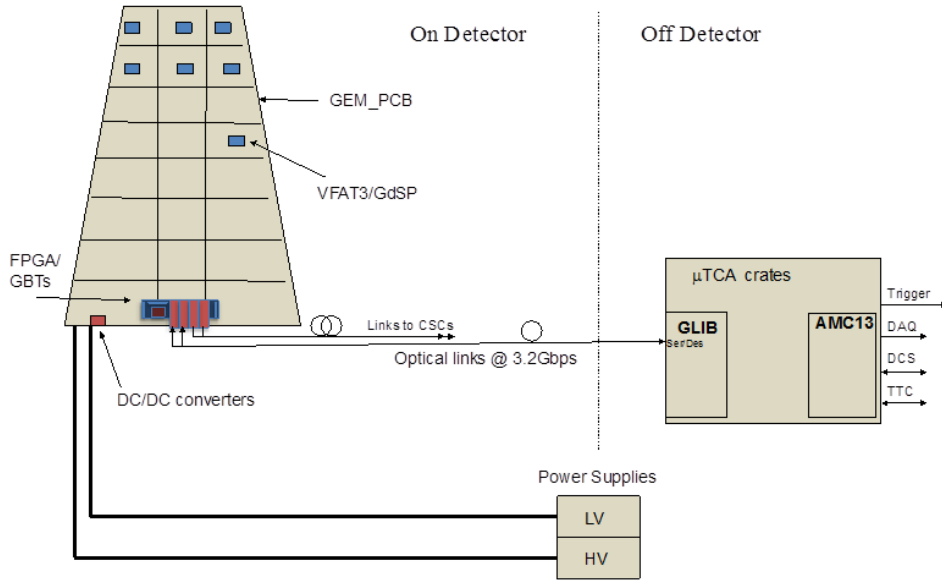


Figure 9. Diagram of the proposed electronic readout system for the GEMs at CMS.

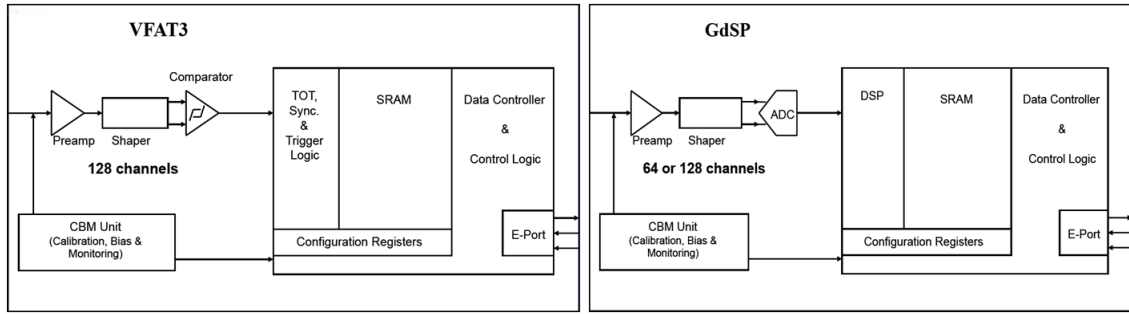


Figure 10. Block diagrams of the two proposed front-end ASICs for the GEMs at CMS: the VFAT3 (left) and the GdSP (right) chip.

5 Integration into the CMS detector

The final layout of the basic chamber units has to take into account any issues related to the integration of the GEM super-chambers into the CMS endcap stations. The space available for the super-chambers inside CMS is quite limited (about 100 mm) and the forward GE1/1 region is densely packed in terms of detector cabling and services. Apart from verifying the dimensions of the chambers and the detector insertion procedure itself, one should also make sure the positions of the connections for gas, cooling, electronics and detector powering are optimal.

In order to perform a test installation, 3 super-chamber dummies were produced as shown in figure 11. The units did not contain any detectors, nor any electronics, however, the weight and dimensions were similar to the real super-chambers. Earlier this year during the LHC Long Shutdown, the 3 dummy chambers were successfully inserted into the nose of the first endcap station as shown in figure 12. During the insertion, one makes use of rails with T-grooves, visible in the figure, to slide and rotate the chambers into their final position.

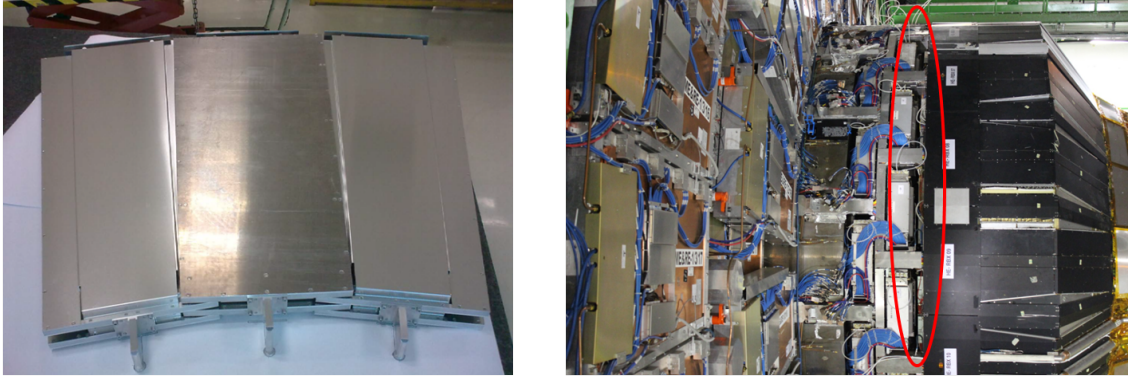


Figure 11. (Left) Photograph of the GE1/1 super-chamber dummies used for trial insertion into one of the first CMS endcap stations. (Right) Photograph of the actual situation in the nose of one of the first endcap stations; the location foreseen for the super-chamber installation is indicated by the red oval shape.

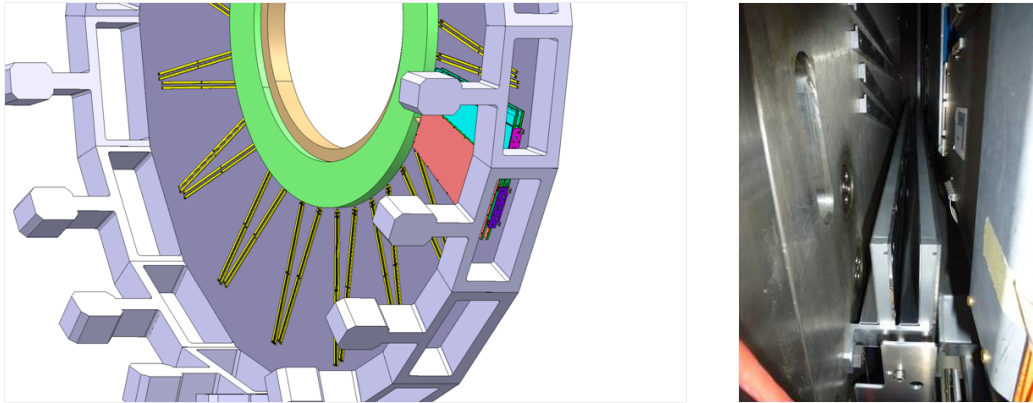


Figure 12. (Left) Drawing of the GEM insertion slots in the first endcap station, including two super-chambers. (Right) Photograph of the insertion slots, with one super-chamber dummy installed.

6 Summary and outlook

After over 4 years of R&D, the design and characterization is close to being finalized of triple-GEM chambers suitable for the extension of the CMS Muon System in the forward region. These chambers would enhance both the muon tracking and triggering capabilities, ensuring a highly performing muon system during the LHC High Luminosity phase. Several full-size detector prototypes have been produced and were successfully operated in test beams. The integration of the chambers into the CMS detector is being prepared. A CMS GEM data-acquisition system based on VFAT3 front-end chips and the GBT-GLIB optical link system is under development.

The CMS Collaboration recently approved the installation during the 2016 LHC Year End Technical Stop of a demonstrator system, i.e. two GE1/1 super-chambers covering a 20° sector of one inner endcap station at $1.5 < |\eta| < 2.1$. The configuration of the demonstrator will be close to the final system proposed for installation in CMS during the second LHC Long Shutdown. It will allow to perform a validation of the system in-situ, to gain operational experience and to reduce the integration time and effort for the final system later on.

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