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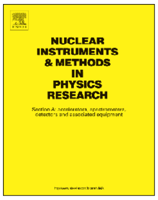

Status report of the upgrade of the CMS muon system with Triple-GEM detectors

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ABSTRACT

For the High Luminosity LHC CMS is planning to install new large size Triple-GEM detectors, equipped with a new readout system in the forward region of its muon system ($1.5<|\eta|<2.2$). In this note we report on the status of the project, the main achievements regarding the detectors as well as the electronics and readout system.

1. Introduction

For the High Luminosity LHC (HL-LHC), the CMS collaboration aims for the installation during the second LHC long shutdown (2018–2019) of an entire ring of Triple-GEMs [1], referred to as GE1/1, in the first endcap station of the CMS forward muon spectrometer, as shown in Fig. 1. The Triple-GEM system will re-establish the redundancy of the muon spectrometer which, in the region $1.5<|\eta|<2.2$, is only equipped with Cathode Strip Chambers (CSC).

This note summarizes the status of the GE1/1 project, underlining some of the main achievements regarding the detector as well as the electronics and the new readout system. The GE1/1 project schedule and the plans for additional CMS upgrades with Triple-GEMs are also briefly described.

2. Requirements on GE1/1 detector performance and design

To be installed inside the first station of the CMS forward muon spectrometer, the new detectors have to fulfil numerous requirements related to detection performance as well as mechanic and electronic constraints since these detectors have to be integrated inside an existing infrastructure.

- The new detectors should provide the largest geometric acceptance within the given available envelope to improve as much as possible the physics yield. Fig. 2 shows a picture of a ~ 120 cm long GE1/1 Triple-GEM. The maximum thickness available in CMS is 9.9 cm which allows to install back-to-back two Triple-GEMs, forming a so-called superchamber. Each superchamber spans 10° in ϕ.
- With a 97.0% detection efficiency per Triple-GEM, a superchamber will have an efficiency above 99.9% when the signals from the two Triple-GEMs are 'ORed'.
- Simulations have shown that for the CMS muon trigger an azimuthal resolution of 300 μrad is sufficient. For a binary readout, this corresponds to a resolution of 0.8 mm at the outer radius (2.6 m) of the GE1/1 detectors.
- A time resolution of 10 ns or better per individual chamber, combined with the timing provided by the CSC located just behind, is sufficient to unambiguously match the muon to the correct LHC bunch crossing.
- The maximum expected hit rate within the GE1/1 acceptance is about a few kHz/cm^2 for HL-LHC running at 14 TeV and 5×10^{34} cm^{-2} s^{-1}.
- Finally the Triple-GEM detector response should be uniform within 10–15% and the detectors must be able to tolerate an accumulated ionization charge of 200 mC/cm^2 to remain operational over 20 years of HL-LHC.

3. Detector developments

Over 5 years of intensive R&D, the GE1/1 project introduced 6 generations of large-area Triple-GEM detectors; each generation built on the experience from the previous ones and bringing new improvements. In this note we will only review a couple of the main achievements.

In 2010 we introduced the first 1 m-class Triple-GEM detector ever constructed and operated [2]. The various components were glued and spacers were used to keep the GEM foils apart. The third generation, which is shown in Fig. 2, was the first detector in which the foils were stretched purely mechanically against the outer detector frame, but glue was still used to hold the different pieces of the frame and to glue it to the drift board [3]. In the fourth generation, both readout and drift boards were bolted to the outer frames and sealed with O-rings making this generation, the first large-area GEM detector produced without gluing any components. Consequently the assembly time could be reduced to a few hours. In the fifth generation the assembly technique has been improved by tensioning the foils against independent "pull-out" pieces, onto which both readout and drift boards are bolted. The outer frame is made from a single piece and only serves to close the gas volume. It is sealed against readout and drift boards with O-rings. The last generation presents only minor modifications with respect to the fifth generation, mainly details to optimize the geometric acceptance within the CMS envelope. Note

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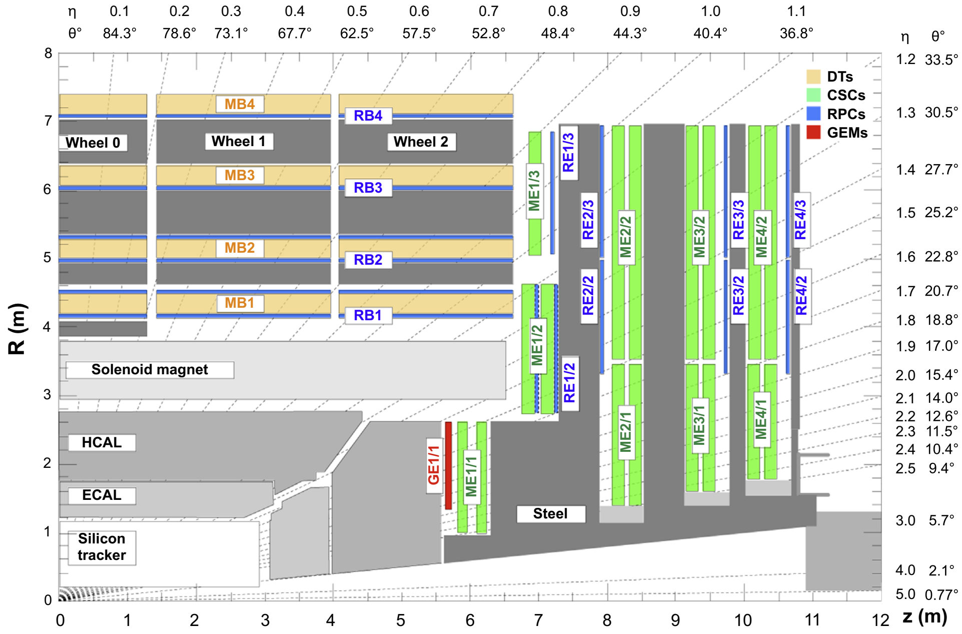

Fig. 1. A quadrant of the *R*–*z* cross-section of the CMS detector, highlighting in red the location of the proposed GE1/1 detector within the CMS muon system.

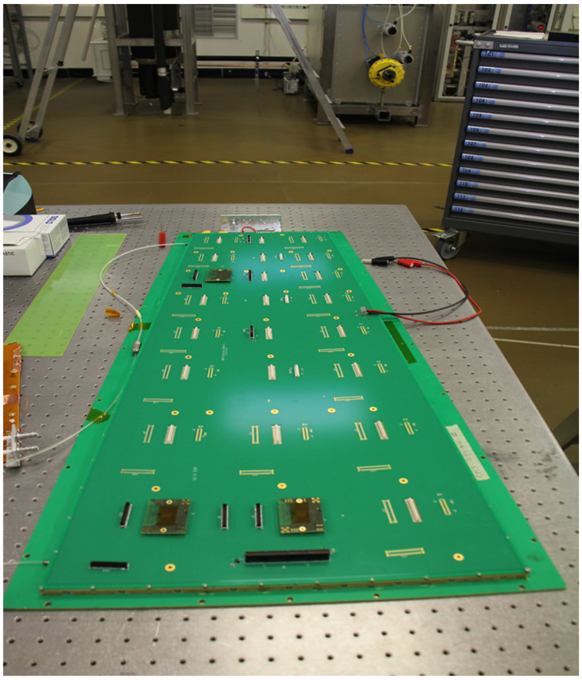

Fig. 2. A CMS GE1/1 Triple-GEM detector equipped with the GEB PCB.

that although no glue is used in the assembly, every component in contact with the gas will be tested for ageing and/or outgassing.

4. Performance

The performance of the different GE1/1 prototypes have been studied thoroughly in laboratories as well as in a series of beam tests at CERN [2–4] and at Fermilab [5]. Only a few results are presented here. Most of the measurements are performed with the $Ar/CO_2/CF_4$ 45:15:40 and Ar/CO_2 70:30 gas mixtures. While for the GE1/1 project a new front-end chip, the VFAT3 is being developed (see Section 5), the prototypes are most of the time read out with the binary VFAT2 [6] chips.

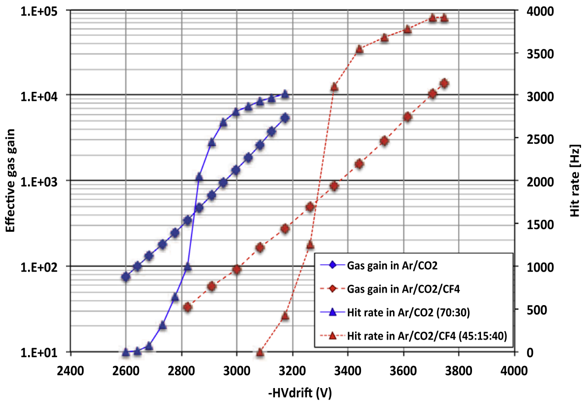

Fig. 3. GE1/1 Triple-GEM gain as a function of the high voltage applied to the drift electrode for both $Ar/CO_2/CF_4$ 45:15:40 and Ar/CO_2 70:30 gas mixtures. The counting rate is also shown for a fixed rate of incident X-rays.

4.1. Gas gain

Fig. 3 shows the gain of a 4th generation GE1/1 Triple-GEM as a function of the high voltage applied to the drift electrode for both $Ar/CO_2/CF_4$ 45:15:40 and Ar/CO_2 70:30 gas mixtures. The counting rate is also shown for a fixed rate of incident X-rays, featuring the beginning of rate plateaus which indicates that the chamber starts operating with full efficiency. The Triple-GEM starts to be efficient at a gas gain of several thousands. At this gain, the individual GEM foils are operated with a potential difference around $\sim$400 V, providing a comfortable safety margin [7].

4.2. Detection efficiency and spatial resolution

Several detection efficiency measurements have also been performed with various prototypes showing that the GE1/1 Triple-GEMs can reach efficiency plateaus of 97–98% with both gas mixtures [5]. In Ref. [5] a detailed study on the spatial resolution also shows that the GE1/1 Triple-GEMs have a spatial resolution of $\sim 137\,\mu\text{m}$ at a radius of 1.88 m, which is consistent with the expected resolution for binary readout of $\sim 131\,\mu\text{m}$.

4.3. *Time resolution*

The timing performance first measured with $10 \times 10\,\text{cm}^2$ prototypes has showed that using the 3/1/2/1 mm drift/transfer-1/transfer-2/induction gap configuration and Ar/CO_2/CF_4 45:15:40 the Triple-GEM could reach time resolutions as good as 4 ns. Since then the measurements have been confirmed with the full-size GE1/1 prototype [3]. It is important to note that even with the slower but environmentally friendly Ar/CO_2 70:30 gas mixture, an overall time resolution of 8 ns for a superchamber can be obtained, which is sufficient for the CMS trigger application.

5. Readout system

To control and read-out this new CMS sub-detector we propose the electronics system shown in Fig. 4.

5.1. *The on-detector electronics*

The functional requirements on the readout system (and therefore on its front-end electronics) are to provide both triggering and tracking information. Similar functionalities are provided by the VFAT2. Therefore the VFAT2 architecture is the baseline for the new front-end ASIC, the VFAT3. The features of this new ASIC are listed below:

- provide trigger data at 40 MHz as well as precise tracking data upon Level-1 Accept (L1A) signal;
- relatively long signal charge collection ~ 80 ns;
- programmable shaping time: 25, 50, 100, 250, 500 ns;
- interface required: slvds elinks to GBT [8] at 320 Mbps;
- level-1 latency up to 20 μs;
- integrated calibration, bias and monitoring functions.

Similar to VFAT2 it will have 128 channels of preamplifier, shaper and comparator. Both trigger and tracking data are sent to the off-detector electronics located in the CMS service cavern via the new Versatile Link [9]. The Versatile Link is bi-directional and operates at a rate of 4.8 Gbps. On-detector the GBT radiation hard chipset will transmit the data from the detector through the Versatile Link. The VFAT3 chip will embed an e-Port [10] to be connected directly to the GBT chipset. In addition the trigger data will be sent to the CSC trigger electronics to be combined with the CSC data to improve the Level-1 trigger efficiency of the CSC system.

The readout strips are oriented radially along the long side of the detector. The strip pattern is segmented into 8×3 partitions in η–ϕ. The strips are connected through metallized vias to the outer side of the readout board where 128-channel connectors are soldered for the signal transfer to the VFAT3. To avoid long cables running along the detector the VFAT3 signals are transmitted through the GEM Electronics Board (GEB) [11]. The GEB is a 1 mm thick 6-layer PCB of the size of the detector. Actually it is the green side of the detector seen in Fig. 2. Electrical measurements have been done to characterize the signal integrity at 40 MHz and the functionality of the GEB with the VFAT2 chips has been tested successfully. Using pulse generators, the signal integrity has also been checked at 160 MHz and work is now on-going to reach 320 MHz.

The last on-detector electronics component is the opto-hybrid which consists in a mezzanine board mounted along the large side of the GEB , with typical dimensions of $10.0\,\text{cm} \times 20.0\,\text{cm} \times 1.1\,\text{cm}$. The tasks of the opto-hybrid board are to synchronize the data sent by the VFAT3 chips, zero-suppress the trigger data, encode the data and send them via optical links to the trigger electronics. The opto-hybrid is composed of a Virtex-6 FPGA, 3 GBT chipsets and 12 optical connectors of type SFP+ (small form factor pluggable).

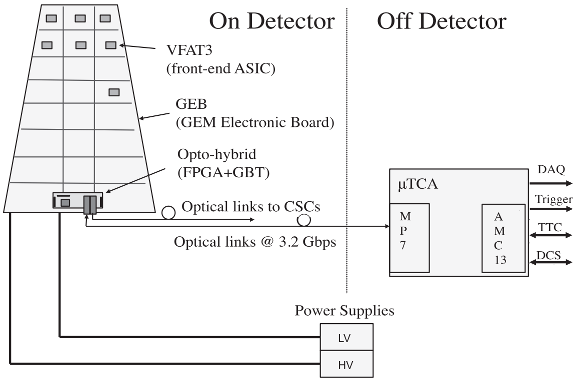

Fig. 4. Readout architecture of the CMS GE1/1 system.

5.2. *The off-detector electronics*

The off-detector electronics provides the interfaces from the detector (and front-end electronics) to the CMS data acquisition (DAQ), the CMS Trigger Timing and Control (TTC) and the Trigger systems. The design foreseen for the CMS GEM off-detector electronics is based on FPGAs boards with Multi-GBit/s links that adhere to the micro-TCA (μTCA) standard. In CMS μTCA is now a common standard for all the CMS upgrades and will replace the VME electronics. The GE1/1 project benefits from μTCA boards developed by other CMS upgrades (trigger and HCAL).

5.3. *Schedule and conclusions*

In December 2014, for the first time, a GE1/1 Triple-GEM detector equipped with the VFAT2 chips and with the new electronics architecture, as described above, has been tested with particle beams at CERN. The aims of these tests were to validate the system architecture and to test as many electronic functionalities as possible. Performance measurements like noise measurements and cluster size have been performed and showed similar behaviour with the former readout system.

In 2015, the developments are focusing on finalizing the various components for the readout of the VFAT2 chips, with the objectives to install in CMS four GE1/1 superchambers during the LHC extended yearly technical stop of 2016–2017. The first two final GE1/1 detectors have been produced and the first GE1/1 superchamber is being assembled at the time of this writing.

Once the VFAT3 and the GBT chipsets will be available by the end of 2015, the developments will then focus on the final system: 72 GE1/1 superchambers will be installed in CMS during the second LHC long shutdown (2018–2019).

For the longer term, CMS plans to install in 2022–2023, a second station of Triple-GEM detectors, called GE2/1. The architecture of GE2/1 will be very similar than GE1/1 but with even larger detectors, spanning 20° in ϕ. R&D is currently on-going to design such large chambers. Finally, with the CMS plans to redesign the calorimeter endcap, there would be space to add a new muon tagging station, called ME0, in the region $2.0 < |\eta| < 3.0$ to enhance the far forward muon coverage. A possibility which is under study is to use stacks of six GE1/1-like Triple-GEM detectors to reduce the neutron background.

Acknowledgments

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References

[1] F. Sauli, Nuclear Instruments and Methods in Physics Research A386 (1997) 531.
[2] D. Abbaneo, et al., IEEE Nuclear Science Symposium and Medical Imaging Conference Records, 2010, pp. 1416–1422.
[3] D. Abbaneo, et al., IEEE Nuclear Science Symposium and Medical Imaging Conference Record, 2012, pp. 1172–1176.
[4] D. Abbaneo, et al., IEEE Nuclear Science Symposium and Medical Imaging Conference Record, 2011, pp. 1806–1810.
[5] D. Abbaneo, et al., IEEE Nuclear Science Symposium and Medical Imaging Conference Record, 2014.
[6] P. Aspell, et al., VFAT2: a front-end system on chip providing fast trigger information, digitized data storage and formatting for the charge sensitive readout of multi-channel silicon and gas particle detectors, in: Topical Workshop on Electronics for Particle Physics, Prague, Czech Republic, 03-07 September, 2007, pp. 292–296.
[7] F. Sauli, Nuclear Instruments and Methods in Physics Research A 424 (1999) 321.
[8] P. Moreira, et al., Journal of Instrumentation 5 (2010) C11016.
[9] J. Troska, et al., Journal of Instrumentation 6 (2011) C01089.
[10] P. Aspell, et al., Journal of Instrumentation 10 (03) (2015) C03019.
[11] P. Aspell, et al., Journal of Instrumentation 9 (12) (2014) C12030.