Development of the data acquisition system for the Triple-GEM detectors for the upgrade of the CMS forward muon spectrometer

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ABSTRACT: In this contribution we will report on the progress of the design of the readout and data acquisition system being developed for triple-GEM detectors which will be installed in the forward region ($1.5 < |\eta| < 2.2$) of the CMS muon spectrometer during the 2nd long shutdown of the LHC, expected in the period 2017–2018. The system will be designed to take full advantage of current generic developments introduced for the LHC upgrades. The current design is based on the use of CERN GLIB boards hosted in micro-TCA crates for the off-detector electronics and the Versatile Link with the GBT chipset to link the front-end electronics to the GLIB boards. In this contribution we will describe the physics goals, the hardware architectures and report on the expected performance of the CMS GEM readout system, including preliminary timing resolution simulations.

KEYWORDS: Electronic detector readout concepts (gas, liquid); Data acquisition circuits

Contents

## 1   Introduction

The CMS GEM collaboration [1] is performing a feasibility study to install triple-GEM [2] detectors in the forward muon spectrometer of the CMS [3] experiment at the LHC, to enhance the muon tracking and the triggering capabilities in the region $1.5 < |\eta| < 2.2$. The triple-GEMs are Micro Pattern Gaseous Detectors (MPGD) able to sustain very high particle rates up to $10\,\text{MHz/cm}^2$, featuring a spatial resolution of the order of $100\,\mu\text{m}$, a time resolution of a few ns and detection efficiencies above 98%. They can be operated in a stable manner in high radiation environments at high gains, exceeding 10^4. Their performance makes the triple-GEM technology, a very good candidate to be used in the forward muon spectrometer of the CMS experiment for the LHC high luminosity phase, when one expects particle rates of several kHz/cm^2. The CMS GEM collaboration aims for the installation during the second LHC long shutdown (2017–2018) of an entire ring of triple-GEMs, referred to as GE1/1, in the first endcap station of the CMS forward muon spectrometer, as shown in figure 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). The installation of triple-GEM detectors in the second endcap stations (labeled GE2/1) could be done during the third LHC long shutdown scheduled beyond 2020 and will not be discussed further in this note.

To control and read-out this new CMS sub-detector we propose the electronics system shown in figure 2. The architecture is composed of two regions: the "on-detector" region and the "off-detector" region, the latter being located in the counting room. All electronics located "on-detector" typically require custom made electronics components which have to be resistant to the radiation. The "off-detector" electronics can be designed using relatively inexpensive and available "off the shelf" components. The communication between the two regions will be done via optical fibers which also require to be resistant to radiation.
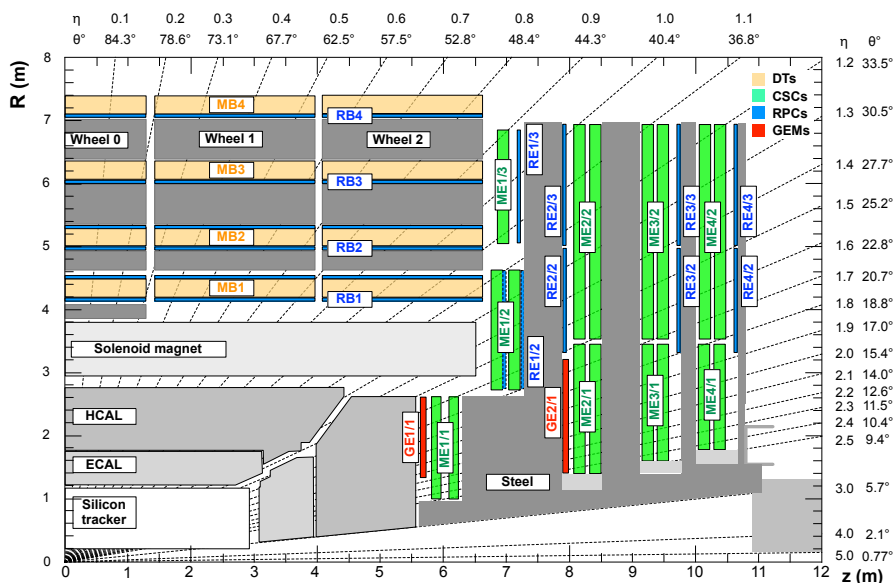
Figure 1. Transverse section of one quadrant of the CMS detector showing the present muon system and the proposed locations for the triple-GEM detectors.
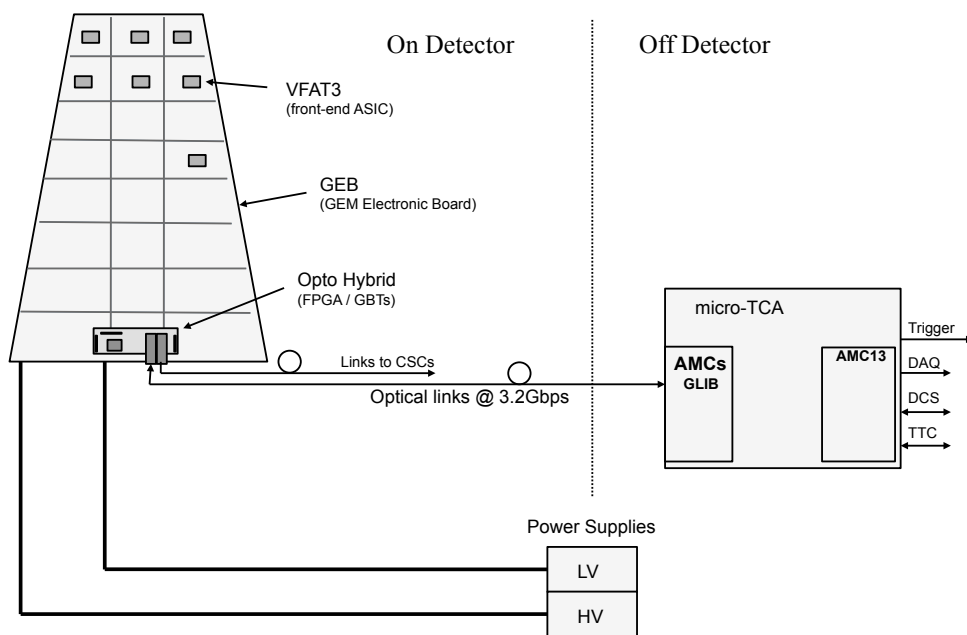
Figure 2. Electronics and data acquisition system architecture proposed for the CMS GE1/1 sub-detector.

The proposed architecture for the readout system is very similar to other LHC experiment upgrades and hence common needs exist between sub-detector systems. Common areas are typically the power regulation and the optic data transmission link. At CERN, generic developments, such as the Gigabit Transceiver (GBT) [4], the Versatile Link [5] and DC/DC converters [6] projects have
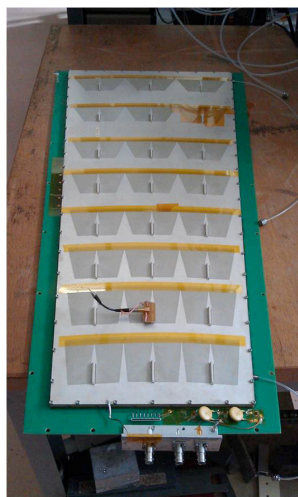
Figure 3. Latest version of the CMS GE1/1 triple-GEM prototypes.

been put in place since several years already to satisfy the "on-detector" common needs. In addition the Gigabit Link Interface Board (GLIB) project [7] addresses common off-detector needs. The CMS GEM electronics system intends to make full use of these generic developments as far as possible, in order to minimize duplication effort and to ensure that design resources within the project are focused on the project specific designs needed.

2 The "on-detector" electronics

In this section we will first review the design of the CMS triple-GEM detector, in particular its readout properties, and then examine the requirements as well as the design specifications of the front-end electronics

2.1 The CMS triple-GEM detector

The latest version of the CMS GE1/1 prototypes is shown in figure 3. The triple-GEMs have a trapezoidal-shaped active area of $990 \times (220\text{–}455)$ mm^2 with a 3/1/2/1 mm drift/transfer-1/transfer-2/induction gap configuration. The side of the detector seen in figure 3 is the readout board. Its inner side 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 $\eta - \phi$, with a strip pitch varying from 0.6 mm at the short end (at high η in CMS) to 1.2 mm at the wide end (at low η in CMS). The strips are connected through metalized vias to the outer side of the board where 128-channel connectors are soldered for the signal transfer to the front-end electronics.

2.2 The front-end electronics

The functional requirements on the readout system (and therefore on its front-end ASIC) are to provide both triggering and tracking information. These are similar basic requirements to that needed for the TOTEM experiment [8] that uses the VFAT2 [9] chip to read-out both silicon and GEM detectors. Consequently the VFAT2 architecture is the baseline for the new front-end ASIC,

the VFAT3, being currently developed for the CMS triple-GEM system. The features of the new ASIC are listed below:

- Operation at high particle rate using large GEM detectors;

- Provide trigger data at 40 MHz as well as precise tracking data upon Level-1 Accept (L1A) signal;

- Large detector capacitance 20–60 pF;

- Relatively long signal charge collection ~ 80 ns;

- Programmable shaping time: 25, 50, 100, 250, 500 ns;

- Interface required: slvds elinks to GBT at 320 Mbps;

- Level-1 latency up to $20\,\mu$s;

- Integrated calibration, bias and monitoring functions.

Similarly to VFAT2 it will have 128 channels of preamplifier, shaper and comparator. The shaping time and gain will be programmable in order to optimize the signal charge collection from the GEM detector whilst maintaining excellent timing resolution (~ 4.5 ns rms for VFAT2). A longer shaping time will result in improved signal to noise ratio when used with GEM detectors due to reduced ballistic deficit. However increased shaping times come at the cost of degrading time-resolution due to increased time-walk. As discussed in section 4, we are studying techniques to compensate for time walk and restore the original time resolution.

Both trigger and tracking data are sent to the off-detector electronics located in the CMS service cavern via the new Versatile Link. 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 to be connected directly to the GBT chipset. The trigger data will be sent in parallel to the Cathode Strip Chamber (CSC) Trigger Mother Board (TMB) to be combined with the CSC data and to improve the Level-1 trigger efficiency of the CSC system.

To send the trigger data to the CSC TMB we will use existing optical fibers located along the CSC detectors inside CMS. These fibers cannot sustain the GBT protocol. Consequently an FPGA will be placed on-detector to concentrate the trigger signals from the 24 VFAT3, to perform zero-suppression and transmit the data to the CSC as well as to the micro-TCA off-detector electronics. About 400 I/Os will be required to connect the FPGA to the 24 VFAT3 chips. This FPGA will be mounted on a board called "opto-hybrid" which will host in addition the GBT chipsets as well as the optical connectors. Initially a Xilinx Virtex 6 was considered to equip the opto-hybrid board because it is the type of FPGA used on the CFEB boards located on the CMS CSC detectors. In addition radiation studies described in ref. [10] show that the FPGA Block RAMs would encounter ~ 9 SEU/day at high LHC luminosities. Mitigation processes are being investigated. Given the little space (240×225 mm$^2 \times 11$ mm in height) left on-detector for the opto-hybrid and to reduce the heat, a smaller FPGA like the Xilinx Artix7 is now under study.
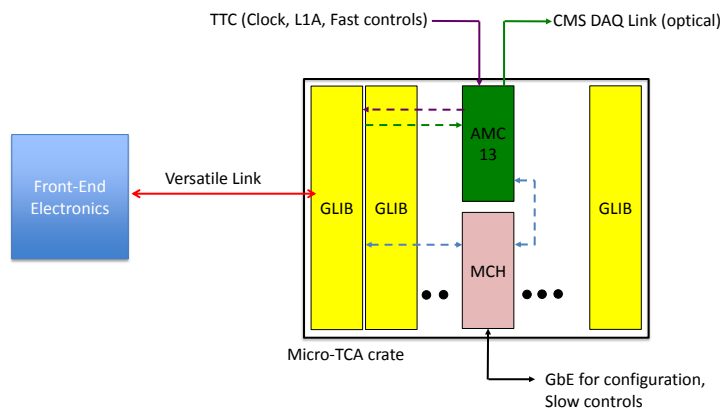
Figure 4. Layout of the "off-detector" electronics for the CMS triple-GEM system.

3 The "off-detector" electronics

The off-detector electronics provides the interfaces from the detector (and front-end electronics) to the CMS DAQ, TTC and Trigger systems. The design foreseen for the CMS GEM off- detector electronics is based on FPGAs and Multi-GBit/s links that adhere to the micro-TCA (μTCA) standard [11]. Micro-TCA is a recent standard that has been introduced for the Telecom industry and aims at high data throughput (2 Tbit/s) and high availability (the proportion of time the device is actually operating correctly compared with the planned time of operation $=$ 99.999%). It is compact, hot swappable and has a high speed serial backplane. The μTCA is now a common standard for all the CMS upgrades and will replace the VME electronics.

The CMS GEM "off-detector" electronics, shown in figure 4, will be composed of the preferred CMS μTCA crate, the VadaTech VT892 [12], which supports 12 double-width, full-height AMC cards and two μTCA Carrier Hub (MCH) slots. The MCH1 slot houses a commercial MCH module, used for gigabit Ethernet communication and IPMI control. The MCH2 slot houses a custom AMC developed by Boston University and called AMC13 [13]. The AMC13 became the standard module within CMS to interface the μTCA crates to the CMS data acquisition system and to provide the CMS Trigger Timing and Control (TTC) signals downlink.

Each μTCA crate will house 12 GLIB AMC boards as the GEM trigger and tracking data receiver. The GLIB AMC is based on a Xilinx Virtex-6 FPGA with Multi-Gigabit Transceivers (MGT) operating at rates of up to 6.5 Gb/s. In addition the GLIB board features two high-pin count (HPC) FMC Mezzanine Card (FMC) sockets that can be used to extend the I/O connectivity of the GLIB AMC. Consequently each GLIB could accommodate up to 8 GBT high-speed data links and read-out a $10°$ ϕ-sector of triple-GEMs. In total 6 μTCA crates are needed to read-out the entire GE1/1 system tracking data and 2 crates for the trigger data.

4 Time resolution studies

An important parameter of the CMS GEM system is to provide a time resolution better than 8 ns to unambiguously identify the LHC bunch crossings. Measurements performed in beam tests have shown that a time resolution of the order of 5 ns is achievable with triple-GEM detectors oper-
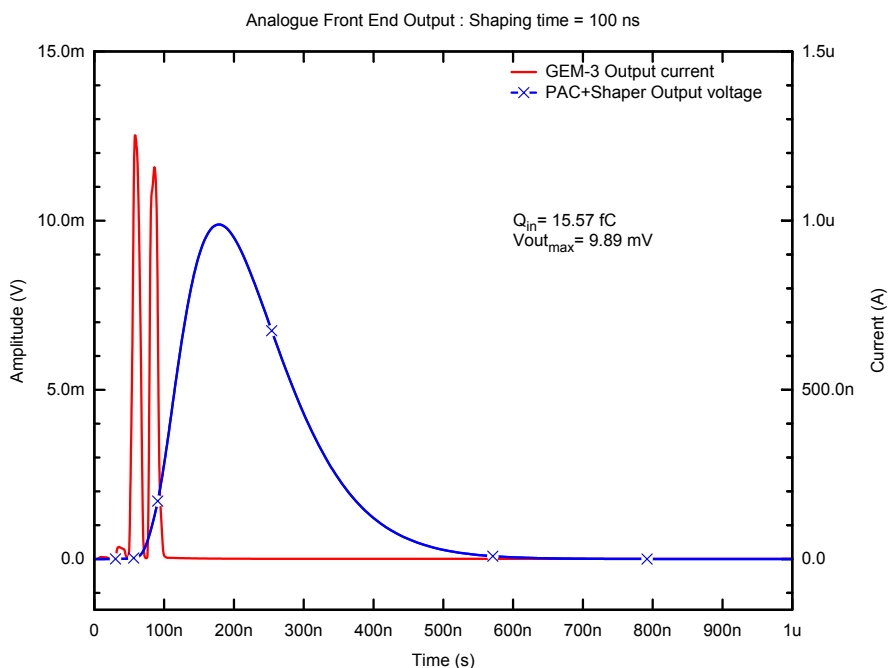
Figure 5. Example of a simulated CMS triple-GEM detector signal. The induced signal on the anodes is represented in red and the corresponding VFAT3 output in blue, with a shaping time of 100 ns.

ated with $Ar/CO_2/CF_4$ (45/15/40) gas mixture and the VFAT2 front-end electronics [14]. While the VFAT3 design is ongoing, detailed simulations of the CMS triple-GEM detector response to 1 GeV/c momentum muons have been performed. A detection cell has been simulated in 3D with the GARFIELD [15] software using electric field maps computed by the finite element (FEM) software Ansys [16]. Using the response function of the pre-amplifier of the current VFAT3 design we have studied the time resolution with two different methods that could be implemented on the front-end chip: the Time-Over-Threshold (TOT) and the Constant Fraction Discriminator (CFD).

Figure 5 shows an example of a simulated triple-GEM induced signal on the anodes (red) and the corresponding amplified and shaped signal obtained with a shaping time of 100 ns (blue). The two peaks observed in the induced signal are due to the spread of the primary ionization along the muon track in the 3 mm-long drift gap. Figure 6 shows the evolution of the time resolution as a function of the shaping time for the two methods, TOT and CFD. With both methods a time resolution better than 5 ns can be achieved for shaping times above 50 ns with the $Ar/CO_2/CF_4$ (45/15/40) gas mixture.

5 Summary

The installation of a new sub-detector in the CMS forward muon spectrometer is essential for enhancing both the muon tracking and triggering capabilities, ensuring a highly performing muon system during the LHC High Luminosity phase. Triple-GEM detectors have shown to have the requested performance to achieve these goals. In this paper we reviewed the status of the electronics system for this CMS upgrade, to be installed during the second LHC long shutdown. The
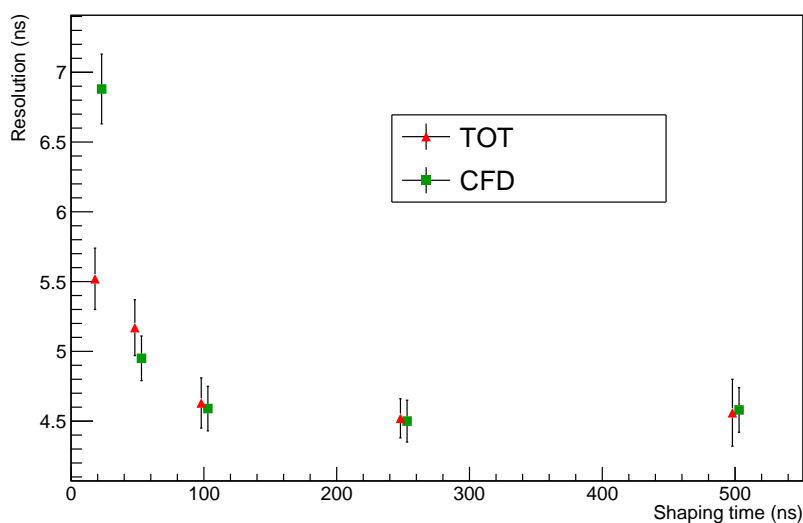
Figure 6. Time resolution as a function of the shaping time for the TOT and CFD methods.

system requires the design of a new front-end chip, the VFAT3, with similar functionalities that the TOTEM VFAT2 chip. In addition to make full use of generic projects and to minimize duplication efforts, the system will use the Versatile Link, the GBT chipset and the GLIB boards that will be hosted in the "CMS standard μTCA crate", the VadaTech VT892. The "CMS standard AMC13 board" will be used to interface the μTCA crates to the CMS data acquisition system. Nevertheless an FPGA opto-hybrid board located on the detector is necessary to transmit the GEM trigger data to the new CSC trigger boards through existing optical fibers.

Finally we present preliminary studies on the time resolution that could be achieved with the VFAT3 chip under design with two methods: the TOT and the CFD. In both cases a time resolution better than 5 ns can be achieved for shaping times above 50 ns with the Ar/CO$_2$/CF$_4$ (45/15/40) gas mixture.

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