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A micro-TCA based data acquisition system for the Triple-GEM detectors for the upgrade of the CMS forward muon spectrometer

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Abstract

We will present the electronic and DAQ system being developed for TripleGEM detectors which will be installed in the CMS muon spectrometer. The microTCA system uses an Advanced Mezzanine Card equipped with an FPGA and the Versatile Link with the GBT chipset to link the front and back-end. On the detector an FPGA mezzanine board, the OptoHybrid, has to collect the data from the detector readout chips to transmit them optically to the microTCA boards using the GBT protocol. We will describe the hardware architecture, report on the status of the developments, and present results obtained with the system.In this contribution we will report on the progress of the design of the electronic readout and data acquisition (DAQ) 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, planed for the period 2018-2019. The architecture of the Triple-GEM readout system is based on the use of the microTCA standard hosting FPGA-based Advanced Mezzanine Card (AMC) and of the Versatile Link with the GBT chipset to link the front-end electronics to the micro-TCA boards. For the on-detector electronics a new front-end ASIC, called VFAT3, is being developed for the CMS Triple-GEM system. Its architecture is based on the TOTEM VFAT2 chip which is currently used to test the CMS Triple-GEM prototypes and the new data acquisition system. On detector, a Xilinx Virtex-6 FPGA mezzanine board, called the OptoHybrid, has to collect the data from 24 front-end chips and to transmit the data optically to the off-detector micro-TCA electronics as well as to transmit the trigger data at 40 MHz to the CMS Cathode Strip Chamber (CSC) trigger. Two versions of this OptoHybrid have already been designed. They are used to readout the CMS Triple-GEM prototypes equipped with VFAT2 chips and both have been tested with beam at CERN. The microTCA electronics provides the interfaces from the detector (and front-end electronics) to the CMS DAQ, TTC (Timing, Trigger and Control) and Trigger systems. Each micro-TCA crate can house 12 AMC boards. Currently the GLIB board designed by CERN is used for the system developments. For the final system more powerful boards based on the Virtex-7 or Kintex-7 Xilinx FPGA are envisaged. During the LHC yearly extended technical stop of winter 2016-2017, 8 Triple-GEM detectors will be installed inside CMS. They will be read-out with the existing VFAT2 chip and with the data acquisition system described above. To prepare this installation, called slice-test, a dedicated test bench has been set-up at CERN to integrate the GEM with the CSC electronics. This work also includes the development of the DAQ software based on xDAQ and of the detector control system.In this contribution we will describe the hardware architecture and expected performance, report on the status of the developments of the various electronic components and present preliminary results obtained with the microTCA-based readout system developed for the slice-test.

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A micro-TCA Based Data Acquisition System for the Triple-GEM Detectors for the Upgrade of the CMS Forward Muon Spectrometer

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ABSTRACT: The Gas Electron Multiplier (GEM) upgrade project aims at improving the performance of the muon spectrometer of the Compact Muon Solenoid (CMS) experiment which will suffer from the increase in luminosity of the Large Hadron Collider (LHC). After a long technical stop in 2019-2020, the LHC will restart and run at a luminosity of 2×10^{34} cm^{-2} s^{-1}, twice its nominal value. This will in turn increase the rate of particles to which detectors in CMS will be exposed and affect their performance. The muon spectrometers in particular will suffer from a degraded detection efficiency due to the lack of redundancy in its most forward region. To solve this issue, the GEM collaboration proposes to instrument the first muon station with Triple-GEM detectors, a technology which has proven to be resistant to high fluxes of particles. The architecture of the readout system is based on the use of the microTCA standard hosting FPGA-based Advanced Mezzanine Card (AMC) and of the Versatile Link with the GBT chipset to link the on-detector electronics to the micro-TCA boards. For the front-end electronics a new ASIC, called VFAT3, is being developed. On the detector, a Xilinx Virtex-6 FPGA mezzanine board, called the OptoHybrid, has to collect the data from 24 VFAT3s and to transmit the data optically to the off-detector micro-TCA electronics, as well as to transmit the trigger data at 40 MHz to the CMS Cathode Strip Chamber (CSC) trigger. The microTCA electronics provides the interfaces from the detector (and front-end electronics) to the CMS DAQ, TTC (Timing, Trigger and Control) and Trigger systems. In this paper, we will describe the DAQ system of the Triple-GEM project and provide results from the latest test beam campaigns done at CERN.

KEYWORDS: Micropattern gaseous detectors, Data acquisition circuits, Detector control systems, Modular electronics

Contents

1 Introduction

The Large Hadron Collider (LHC) [1], operated since 2008 by the European Organization for Nuclear Research (CERN), is state-of-the-art in the field of particle accelerators and colliders. Providing collisions at an energy of 13 TeV in the center of mass reference frame and a luminosity of 10^{34} cm^{-2} s^{-1}, it enables scientists to study particle physics at scales never reached before. The data collected by the experiments recording the collisions of the LHC, among which the Compact Muon Solenoid (CMS) [2], is used to test and refine the current models used to describe our universe. To improve the performance of the LHC and increase the recorded statistics, an upgrade of the machine is foreseen for 2019-2020, during the so-called Long Shutdown 2 (LS2). After this upgrade, the LHC will restart with a luminosity of 2×10^{34} cm^{-2} s^{-1}, twice its nominal value. This will in turn impact the detectors as the number of proton-proton interactions occurring during each collision will increase.

The increase in luminosity of the LHC will greatly affect the forward region of the muon spectrometer of CMS where particle rates can reach several kHz cm^{-2}. While most of the muon spectrometer is equipped with two technologies of detectors, either Drift Tubes (DTs) or Cathode Strip Chambers (CSCs) combined with Resistive Plate Chambers (RPCs), the forward region only instruments CSCs. Due to concerns regarding the rate capability of RPCs, the space foreseen to equip these detectors was left vacant, thus relying solely on CSCs to perform measurements. If left as is, CMS will experience of loss of efficiency in the triggering and reconstruction of tracks after LS2.

To tackle this issue, new detectors relying on the Gas Electron Multiplier (GEM) [3] technology are under development. Studies led by the CMS GEM collaboration, on the so-called GE1/1 project, have proven that GEM detectors maintain an efficiency above 98% at particle fluxes of several MHz cm^{-2}. Additionally, they provide a spatial resolution of the order of 150 μm and a time resolution

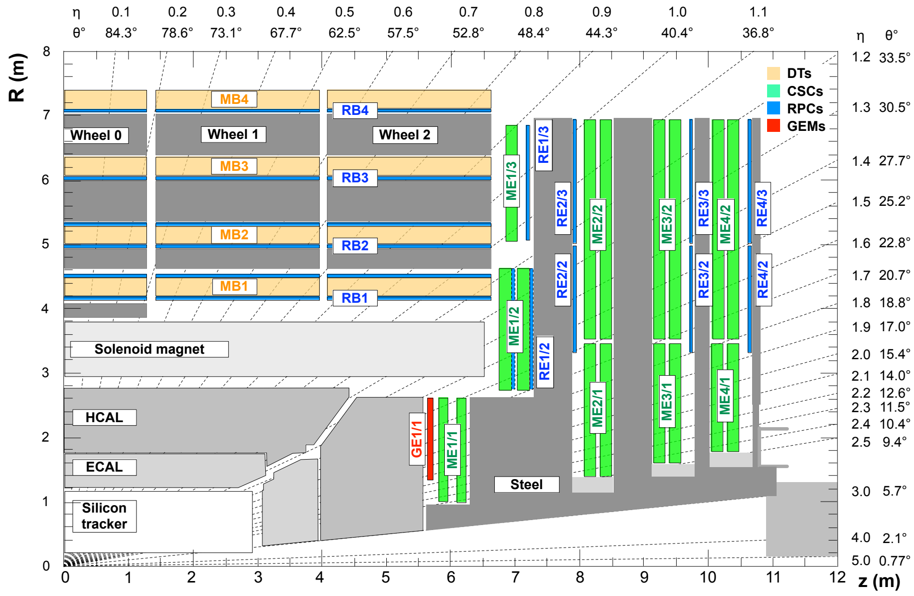

Figure 1. Longitudinal view of a quadrant of CMS highlighting the location of the GE1/1 detectors colored in red within the muon spectrometer. DTs are represented in yellow, CSCs in green, and RPCs in blue [3]

better than 5 ns with a gas mixture of $ArCO_2CF_4$. Figure 1 is a longitudinal view of a quadrant of CMS highlighting the location where the GE1/1 detectors, colored in red, will be installed within the muon spectrometer. Through simulations, it was shown that the instrumentation of a layer of GEM detectors in the forward region of the muon spectrometer, coupled with the CSCs, would improve the triggering and reconstruction efficiency of CMS. These results led to the approval of the installation of a full ring of detectors in both endcaps of CMS during LS2. In preparation of the LS2 installation, a small scale test with the near final electronics, called the slice test, will take place starting in March 2017.

Within the GEM collaboration, the Data Acquisition (DAQ) subgroup is in charge of the development of the electronics and software of the DAQ system. The readout and digitization of the GEM detectors is performed by the VFAT3 analog front-end chip coupled to the OptoHybrid board. The latter concentrates the data from the 24 VFAT3s placed on the detector and forwards it, over optical links, to the off-detector electronics composed of the CTP7. The latter runs within a Micro Telecommunications Computing Architecture (microTCA) crate, standard adopted throughout CMS, and is the gateway to the central DAQ system of CMS.

2 The GE1/1 Data Acquisition System

The architecture of the GE1/1 DAQ system is represented in Figure 2. It is divided into two sectors: the on-detector electronics, on the left, in charge of the management of the detector, and the off-detector electronics, on the right, responsible for the data handling and the connection to the cen-

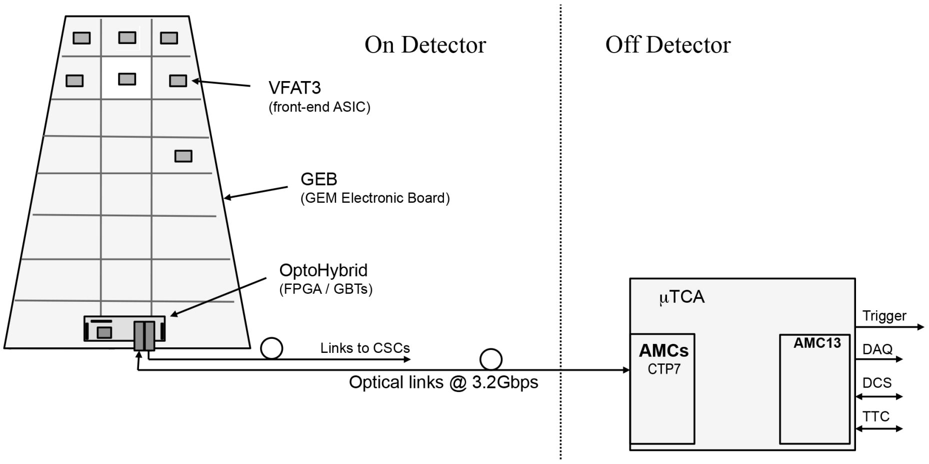

Figure 2. Architecture of the GE1/1 DAQ system divided into two sectors: the on-detector electronics composed of the VFAT3 ASICs, GEB, and OptoHybrid, and the off-detector electronics with CTP7 and AMC13 mezzanines located in a microTCA crate [3].

tral DAQ. The two sectors are separated by a few dozen meters and connected through optical fibers.

The on-detector electronics focuses on the control and readout of the VFAT3 Application Specific Integrated Circuit (ASIC) [4] which digitizes the signals formed on the readout strips of the detector. The GEM Electronic Board (GEB), on which the VFAT3s are plugged in, then routes the data to the OptoHybrid which acts as concentrator board and communication relay for the 24 VFAT3s. The communication with the off-detector system is performed through the GigaBit Transceiver (GBT) [5] chipset and the Versatile Link [6] components installed on the OptoHybrid. Both projects are led by CERN and provide radiation hard tools for LHC experiments.

On the off-detector side, the Micro Telecommunications Computing Architecture (microTCA, MTCA, or μTCA) crate standard is used to power and monitor the Advanced Mezzanine Cards (AMCs) which provide the resources to communicate with the on-detector electronics. Links from 12 OptoHybrids are concentrated on one CTP7 AMC [**?**] which formats the data and transfers it to the CMS AMC13 mezzanine [7]. The AMC13 is the link between the microTCA crate and the central DAQ of CMS which provides the clocking, trigger, and control over the system. The control of the DAQ chain is performed through software using the IPBus protocol over Ethernet. A total of six CTP7s are required to readout one endcap of GEM detectors.

2.1 The VFAT3 ASIC

The VFAT3 ASIC is a binary front-end chip optimized for gaseous detectors which function is to digitize the analog signals coming from the detector and provide fast trigger and tracking data. The trigger data is sent at the LHC clock frequency over a fixed latency path and then used in the algorithms of the L1 trigger to accept or reject events. The tracking data holds the full granularity information of the events that have been accepted and follows a variable latency path. The logic diagram of the chip is shown in Figure 3. It is made of an analog front-end which amplifies, shapes,

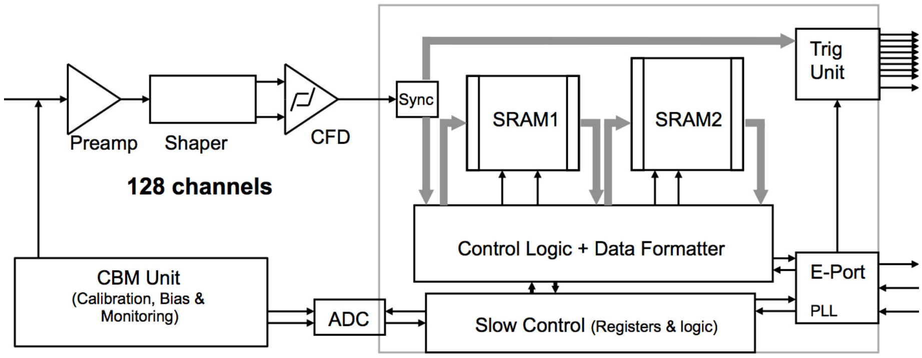

Figure 3. Schematic diagram of the VFAT3 showing the analog front-end on the left and the digital control and readout system on the right [3].

and digitizes the signal from the GEM strips, and of a digital back-end for slow control, fast control, and data readout.

The analog front-end is further optimized for the readout of GEMs in particular. It is composed of 128 channels which amplify and shape the analog signals from the strips with programmable shaping times to allow for various integration lengths of the signal. According to the gas mixture, signal charge from the GEM can last for approximately 60 ns. Increasing the shaping time to fully integrate the charge will result in a higher signal to noise ratio. Simulations performed on the analog front-end show that a time resolution of 7 ns can be achieved by using a Constant Fraction Discriminator (CFD) with a shaping time of 50 ns. After shaping, the amplitude of the analog signal is compared against a programmable threshold by a comparator to yield a binary output flag for each channel.

The fixed latency path is used to provide a fast hit information to the trigger system of CMS at a frequency equal to the LHC clock of 40 MHz. The trigger unit inside the VFAT3 formats the output of the 128 comparators and transmits it over 8 differential pairs at a rate of 64 bits per BX. The variable latency path is activated upon reception of an L1A to transmit the full granularity information on an event that has been accepted by the trigger system.

2.2 The GEM Electronic Board

The limited space in which the GEM detectors will be installed constrains the design of the system by making it impossible to run flat cables for the 24 VFAT3s. Therefore, the GEB, a 1-m-long multilayer Printed Circuit Board (PCB) of the same dimension as the GEM detector, was designed to route the signals of the front-end chips to the OptoHybrid located on the large side of the detector, furthest away from the beam pipe. Figure 4 is a photograph of the GEB. The functions of the GEB are to host the VFAT3 ASICs connected to the 24 sectors of the GEM readout board, route their signals to the OptoHybrid, distribute power to the chips, and provide electric shielding to the detector. The VFAT3s are mounted on small PCBs, called the VFAT Hybrids, attached to the GEB and connected to the GEM readout board. The control and data signals from the chips are routed

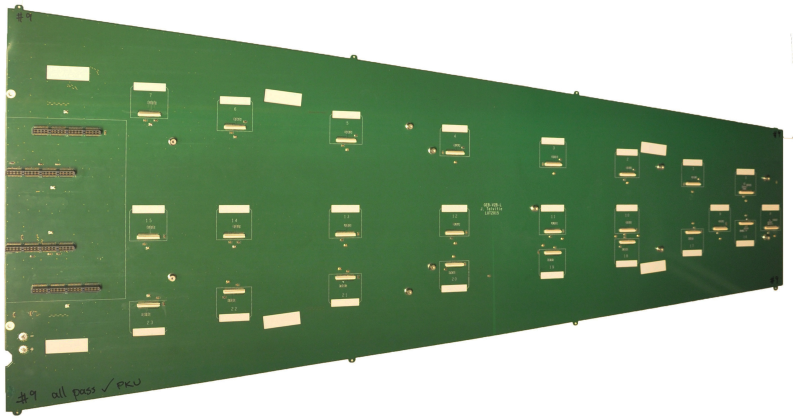

Figure 4. Photograph of the GEB, a 1-m-long multilayer PCB, designed to route the signals of the front-end chips to the OptoHybrid.

on the PCB towards four connectors located on the large side of the detector which connect to the OptoHybrid. The power for the VFAT3s and the OptoHybrid is distributed by the GEB using radiation hard DC/DC converters developed by CERN, which convert the incoming low voltage to the required voltages.

2.3 The OptoHybrid

The OptoHybrid is the interface between the VFAT3 ASICs and the off-detector system. It is a 10 cm × 20 cm board mounted on the GEB equipped with a Field Programmable Gate Array (FPGA) and Integrated Circuits (ICs) dedicated to the operation of the optical links. The FPGA solely handles the trigger data by applying zero suppression algorithms, formatting the data, and sending it to the CSC and the GEM trigger system separately over two optical links. Each of these links uses one VTTx, the dual radiation-hard transmitter module of the Versatile Link project. The other functions of the VFAT3s are directly connected to the three GBT chipsets installed on the OptoHybrid. Each GBT chipset is capable of handling one column of eight VFAT3s and is connected to a VTRx, the radiation-hard transceiver of the Versatile Link project. Figure 5 is a photograph of a near-final version of the OptoHybrid which uses one GBT chipset. This version is used to control the VFAT2 [8] front-end electronics, the predecessor of the VFAT3.

2.4 The CTP7 Advanced Mezzanine Card

The AMC board used as back-end electronics is the CTP7 developed by the University of Wisconsin. It is equipped with a large Virtex-7 FPGA (XC7VX690T) providing extensive computational power along with a Zynq FPGA (XC7Z045) able to run a Linux operating system for monitoring. The optical interface with the on-detector electronics is done through 36 transmitters and 48 receivers: 36 tranceiver GBT-FPGA cores (an implementation of the GBT chipset on the FPGA) for the tracking data and slow control, and 12 receivers for the trigger data. Using one CTP7, six superchambers can be readout thus requiring a total of six CTP7s per endcap for the GE1/1 project.

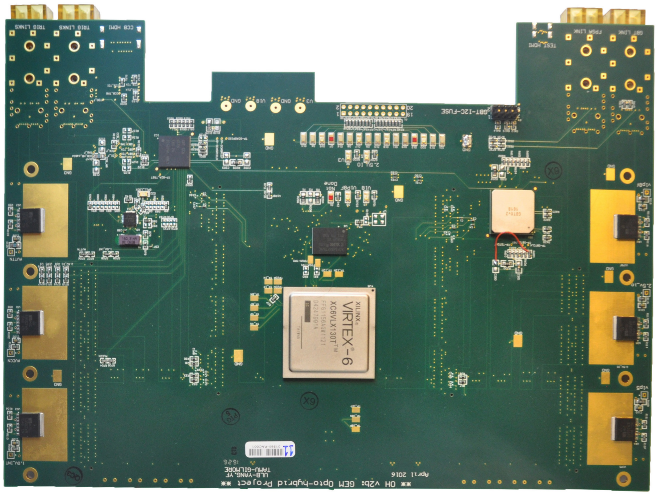

Figure 5. Picture of the near-final OptoHybrid with a Virtex-6 FPGA (middle), one GBT chipset (middle-right), two VTTx (top-left), and two VTRx (top-right).

The function of the CTP7 is triple: handle slow control requests for the subsystems, interpret TTC (Timing, Trigger and Control) signals, and readout the trigger and tracking data from the OptoHybrids. The CTP7 is the interface between the control and monitoring software and the detector electronics. It recieves IPBus requests over TCP/IP on the Zynq and forwards them to the Virtex-7 over a dedicated AXI bus connecting the two chips. The Virtex-7 interprets the requests and forwards them to the appropriate subsystem: either itself or over the optical link to the OptoHybrids and VFAT3s. The CTP7 also receives the TTC commands through the backplane of the microTCA and must forward them to the subsystems along with the LHC clock. Finally, when the VFAT3s or the OptoHybrids push data upwards to the CTP7, the latter must format the data before sending it on the backplane to a dedicated DAQ AMC.

3 Test Beam Results

The test beam campaign took place at CERN in November 2015 using pion and muon beams at 150 GeV. Two GE1/1 (generation V) detectors were used to collect data and were connected to a gas system providing a mixture of Ar/CO_2/CF_4 at 45%, 15%, and 40% respectively. Each detector was equipped with 12 VFAT2 Hybrids (the predecessor of the VFAT3) mounted in the central four rows. The remaining slots, too far away from the beam spot, were covered with grounding equipment. Each GEM was mounted with a GEB and a OptoHybrid. Both OptoHybrids were connected to the same back-end electronics. The GE1/1 detectors were inserted in the beam path and adjusted so that only one VFAT2 in the middle column would be exposed to the beam spot. Four scintillators, three placed in front of the detector and visible in the picture, and one placed in the back of the detector were used to provide triggers to the system.

The evolution of the noise (green) and efficiency (orange) of the system as a function of the high-voltage with muons is shown on the left in Figure 6. The results show an increase in efficiency

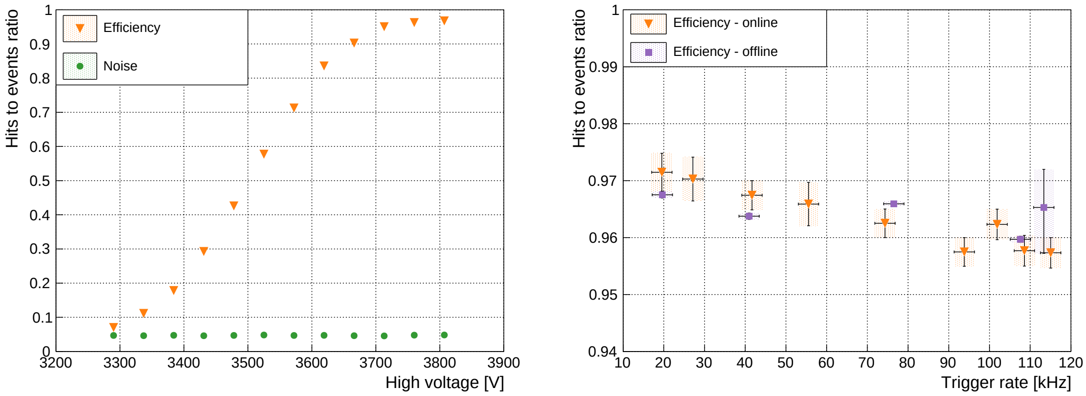

Figure 6. Left: plot of the noise (green) and efficiency (orange) as a function of the high-voltage with muons. Right: plot of the online efficiency (orange) and offline efficiency (purple) as a function of the trigger rates with pions.

with the high-voltage, reaching a plateau above 97%. This is caused by the higher gain at which the GEM foils start to operate which in turn amplifies the signals and allows it to be detected by the VFAT2 ASIC. The noise on the otherhand is constant with the high-voltage and remains at 4%. Later developments have allowed to cancel the noise under normal operating conditions of the front-end VFAT2s and thus function at lower threshold for the digitization of the analog signals. This in turn increased the efficiency of the system above 98%.

Similarly to the measurements performed for the high-voltage, the effect of trigger rate on the efficiency was measured. Focus is given on the latter as the noise levels are not influenced by the increase in rate and remain at 4%. The plot on the right in Figure 6 depicts the online efficiency (orange) and offline efficiency (purple) as a function of the trigger rates with pions. The offline efficiency combines the measurements of the two chambers to reconstruct tracks. Control over the trigger rates were done using collimaters in front of the beam setup. These results support the fact that the DAQ system can sustain rates up to several tens of kilohertz. When going from 20 kHz to 120 kHz, a drop in efficiency of 1% is observed. In CMS, the trigger rate will be of 100 kHz for the LHC Phase I. It is important to emphasize that these results show the performance of the whole system: the efficiency of the detector and the performance of the DAQ system. Furthermore, the improvements on the noise have allowed to increase the efficiency by 1% to 2%.

4 Conclusion

The GEM upgrade aims at improving the triggering and reconstruction performances of CMS after the increase in luminosity of the LHC foreseen for 2019-2020. Through the installation of a ring of GEM detectors in both endcaps of CMS, the CMS GEM collaboration proposes to increase the redundancy of the muon spectrometer and combine the results of the GEMs and the CSCs. Before the full installation, at the end of 2016, during the an extended shutdown of the LHC, five superchambers (an assembly of two GEM detectors) equipped with a near-final DAQ system will be installed in CMS and connected to the central DAQ of CMS. This small scale test is called the slice test and will demonstrate the integration of the GEMs with the CSCs.

In this article, we have presented the multiple components of the DAQ system of the GE1/1 detectors: the on-detector electronics, composed of 24 VFAT3s connected to the OptoHybrid concentrator board through the GEB, on one side, and microTCA back-end, integrating the CTP7 and AMC13 AMCs, on the other side. The two are linked through optical fibres using the GBT and Versatile Link projects. A near-final DAQ system was tested during two test beam campaigns organized at CERN and using the SPS proton beam to produce muons and pions. These have shown that the system is operational and functions reliably, providing all required functionalities to read out, control, and monitor the systems. It yields an efficiency above 97% and a strong resistence to high rates of triggers.

Acknowledgments

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