Integration Studies for the CMS Gas Electron Multiplier Upgrade

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This report gives a brief description of the work I preformed within the CMS GEM group during the 2022 CERN Summer Student Programme. The report begins with an overview of the CMS Muon System upgrade as well as the basic working principles of Gas Electron Multiplier detectors. This is followed by descriptions of a selection of integration studies I contributed to - such as quality control, assembly, and performance testing of GE-2/1 chambers - including motivations, specific contributions, and next steps where applicable, for each project.

I. INTRODUCTION

The Compact Muon Solenoid (CMS) detector is a general purpose detector located on the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). The High Luminosity LHC upgrade scheduled to be installed during Long Shutdown 3 will increase proton-proton collision rates by more than 250%. In preparation for this upgrade, the CMS Muon System is undergoing a three-phase upgrade to expand range into higher pseudorapidity sectors and increase redundancy in the system, improving efficiency and resolution through the installation of Gas Electron Multiplier (GEM) detectors in the GE-1/1, GE-2/1, and ME-0 sectors of the CMS detector. GEMs are chosen for this upgrade due to their high efficiency, rate capability, and thin profile that permits them to fit into existing space in the CMS detector. The GEM detector at GE-1/1 was installed during Long Shutdown 2, with installations for the detectors at GE2/1 and ME-0 planned for the Extended Year End Technical Stop in 2024 and Long Shutdown 3 in 2026, respectively. My work this summer has been focused on electronics testing and preparation for the mass production of GEM modules for the GE-2/1 site.

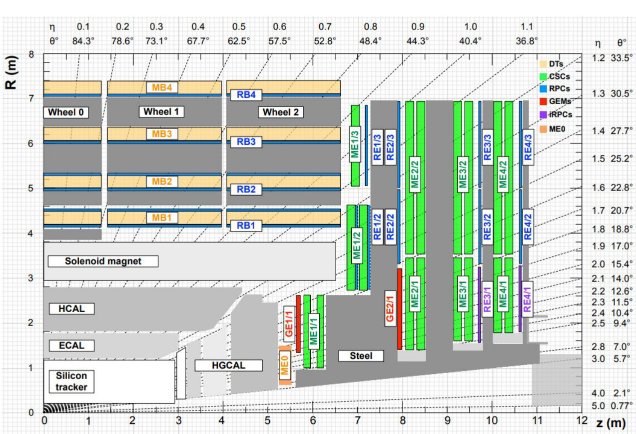


FIG. 1: Cross-section of CMS detector, showing GE-2/1 and ME-0 locations[1]

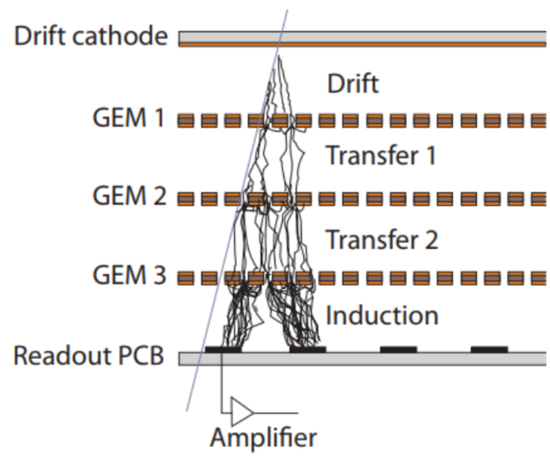


FIG. 2: Depiction of electron avalanche in triple GEM detector[2]

II. WHAT ARE GEMS?

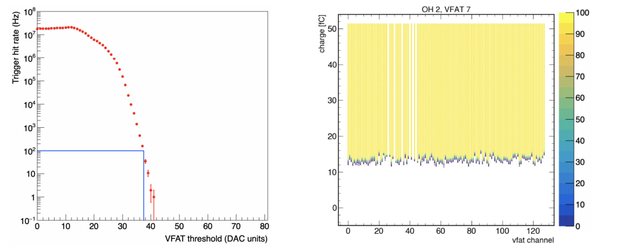
The working principle of GEM detectors is that incoming charged particles ionize gaseous particles in the chamber, triggering an electron avalanche as the primary electrons pass through regions of high electric fields. A primary component of the GEM detectors in development for the CMS Muon System upgrade are the GEM foils, which consist of thin layers of copper affixed to both sides of a thin polyimide sheet. High voltage is applied to these copper layers to produce electric fields of ∼80 kV/cm within the GEM foils. Holes of diameter 50 µm and pitch 140 µm are photochemically etched into the foil for electrons to pass through towards the readout electronics. Muons entering the detector ionize the gaseous argon particles in the chamber, and the resulting electrons are accelerated through the high electric field in the GEM foil to produce an electron avalanche. A single GEM chamber consists of three layers of GEM foils, leading to a signal gain of order 10^5. Three GEM foils are utilized instead of a single GEM foil with a higher electric field or greater separation distance to mitigate the risk of electric discharges that could permanently damage the foil. Similarly, the gas in the chamber is not pure argon, but instead rather a mixture of 70% argon and 30% CO2 to control ionization, reduce pileup, and mitigate discharge risk. Finally, the electron cascade is deposited onto the readout strips, with pitch 952 µrad or 909 µrad for the GE-2/1 or ME-0 detectors, respectively, connected to electronics that convert the analog signal from the readout trips to digital hits with high spatial resolution. Electronic components of particular importance are the front end chips known as VFATs, each of which attaches to 128 strips and allows experimenters to set the charge threshold at which an incoming signal is interpreted as a hit or disregarded as noise.

III. OVERVIEW OF PROJECT INVOLVEMENT

A. Electronics Quality Control and Production Preparation

My first project upon arrival at CERN was assisting with the electronics quality control process for GEM chambers; ensuring proper connections and communications of the electronic components of fully assembled GE-2/1 modules. The primary steps of this process are running trigger rate scans and threshold scans. The trigger rate scan, depicted in Figure 3(a), is conducted by recording the trigger rates while iterating over all 256 possible threshold values of each VFAT. The trigger rate of a properly functioning VFAT decreases smoothly as threshold increases, so deviation from this norm is a clear signal that the VFAT is not well connected, the connection has dust or other impurities impeding it, or that the VFAT itself may be damaged. Another important scan that is performed is the threshold scan shown in Figure 3(b), where charges of varying magnitude are injected onto each strip of each VFAT and the number of hits per channel are recorded at a given threshold. This scan is used to measure the noise in a channel, which is characterized by the Equivalent Noise Charge (ENC) given by the standard deviation of a channel's sigmoid curve. Additionally, the threshold scan is useful for the identification of dead channels in a VFAT. In aggregate, the analysis of these scans allow for the identification of faulty electrical and fiber optic connections, as well as performance issues in the voltage converters, VFATs, and digital-to-optical converters resulting from damage or manufacturing defects. Following this quality control stage, GE-2/1 GEM detectors are fully assembled and sent to the final stage of quality control.

In addition to testing the electronics for GEM modules, we performed the first full test assembly of a GE-2/1 GEM Chamber, which consists of 4 GEM modules, a cooling plate, and a protective chimney. As part of this test assembly, we established a standardized routing for all gas lines, low and high voltage lines, and fiber optic cables, designed to ensure the longevity and reliability of the system through the end of LHC Run 5 in 2038. The primary constraints of this routing are that;



(a) (b)

FIG. 3: Examples of (a) a trigger rate scan, with a selected noise threshold of 100 Hz for a VFAT [3] and (b) a threshold scan showing efficiency in each channel of a VFAT with respect to pulse injection magnitude. In this example, there are 5 dead channels clearly visible

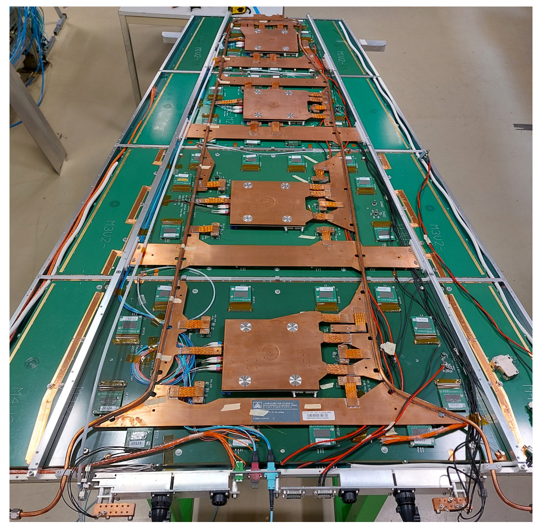


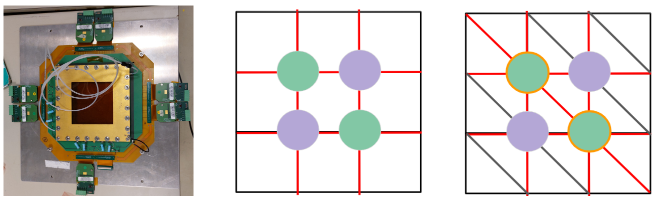
FIG. 4: Assembled GE-2/1 module with cooling plate

- gas lines must be kept away from sharp components of the detector
- optical fibers are quite fragile, and thus must avoid any points of high curvature or pressure from other components that may cause fractures
- stress and tension must be minimized while ensuring that all components fit within the tight spatial constraints of the cooling apparatus and chimney.

The establishment of this standardized assembly will serve as a reference for CERN's technicians involved in the mass production of the GE-2/1 chambers, and the consistent and organized layout will ease maintenance or repairs in the CMS cavern if needed.

B. Tracker Mapping and Hit Reconstruction

Throughout the R&D process of GEM detectors, 10cm x 10cm GEM trackers are often used to get information about incoming particle fluxes with high spatial resolution. The readout strips of these trackers have traditionally been a grid of perpendicularly oriented strips forming a Cartesian xy plane. However, this leads to ambiguity in identifying the spatial coordinates of hits when there are multiple particles hitting the detector within the same event trigger, as illustrated in Figure 5(b)(c). A proposed improvement to this tracker technology involves the addition of a layer of readout strips oriented diagonally. In support of this project, I created the mapping between physical strips and raw output data that will allow for accurate hit reconstructions with the added layer of diagonal strips.



(a) (b) (c)

FIG. 5: (a) Image of a 10cm x 10cm tracker. (b) Diagram of xy grid of strips that demonstrates the ambiguity of particle location when multiple strips fire simultaneously; if the red strips record a signal, that could be a result of particles interacting at the locations indicated in green or purple. (c) The addition of diagonal strips removes this ambiguity and confirms that two particles passed through the tracker at the locations marked in green.

Similarly, I have developed a program that reconstructs hits for GE-2/1 modules, which assigns a physical coordinate (r and ϕ) to each unique muon that hits the detector in a given event. As illustrated in Figure 2, the electron avalanches produced in the GEM chamber can have width, and thus multiple strips may fire for a single muon event. My program identifies clusters corresponding to each muon in an event, determines the mean position of each, and writes a ROOT file with each reconstructed hit along with information about its position, cluster size, and the corresponding event trigger. This program was used in the cross talk study discussed in Section III D.

C. Efficiency

To estimate the efficiency of the detector, scintillators were installed above and below a GE-2/1 module mounted to the test stand shown in Figure 6. Muons from cosmic rays produce a coincident signal in both scintillators, which serves as the trigger for the GEM module. The ratio of events with recorded hits from the GEM detector in the region covered by the scintillators to the total number of coincident scintillator triggers is used in this estimation of efficiency. With this methodology, the efficiency of a GE-2/1 module operating at 700 μA was measured to be $97.3 \pm .6\%$ with $N \sim 3,200$ and $\alpha = .05$, which is within the expected range of the detector.

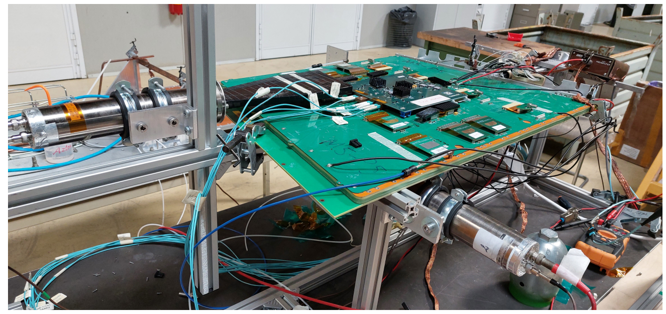


FIG. 6: Test stand with overlapping scintillators on either side of GE-2/1 module used for efficiency and crosstalk studies

D. Crosstalk

Latency scans from studies in the test beam showed that there appeared to be a signal consistently appearing approximately 250ns after the initial pulse. A similar time delay signature has been recorded in past observations of crosstalk in GEMs, so we performed a study to determine the extent to which crosstalk signals may be impacting the performance of our apparatus [4]. To perform the study, we affixed a Cd109 source to a small hole in the PCB beneath the strips read by VFAT0; if hit rates increased in channels measured by VFATs other than VFAT0 after the introduction of the Cd109 source, that would support the hypothesis that the delayed signal present in the latency scans is the result of crosstalk signals. However, as shown in Figure 7, no discernable increase in hit rate outside of VFAT0 is recorded, and thus the lab is turning its attention to other potential causes for this time delay, such as problems with triggering and data acquisition.

E. VFAT Rate Capability

The electron avalanches produced in the GEM detector impacts the magnitude of the electric field present between GEM foils by reducing the potential difference between plates. This phenomenon reduces the gain and efficiency of the detector, and is addressed via an overvoltage compensation, where a larger potential difference is applied between plates to maintain nominal field strengths. A study at the Gamma Irradiation Facility (GIF++) appears to indicate that although the voltage difference is being effectively compensated for, the efficiency of the detector is not recovering as expected. To investigate this phenomenon further, we are performing studies to better understand the VFAT's rate capability. An effi-

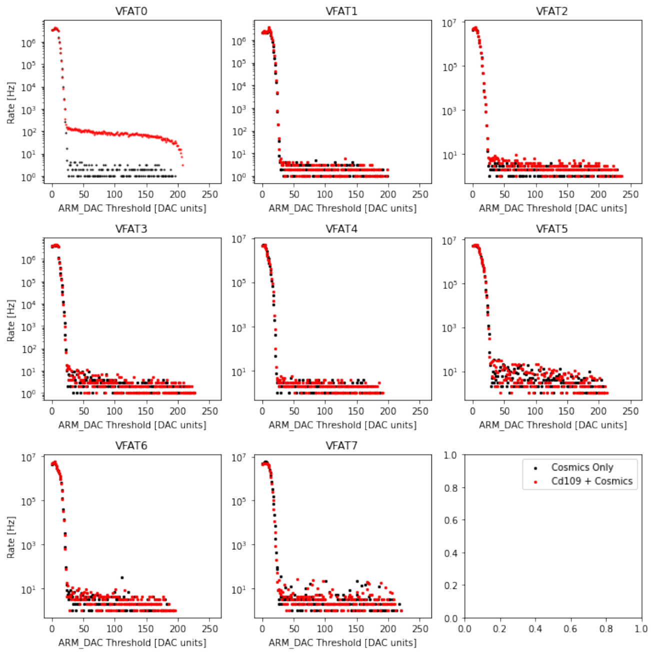


FIG. 7: Trigger Rate Scan for all VFATs with and without Cd109 source, with cosmic muons as background

ciency scan is performed by injecting charge onto every strip of every VFAT at all 256 thresholds, and recording the ratio of how many times the strip fired to the number of charge pulses sent to the strip. Iterative tests were performed by taking efficiency scans with different pulse durations, pulse rates, and charge magnitudes to get a more complete understanding of the VFAT's operating capabilities. In addition to this charge injection work, which will continue after my departure, studies will be performed with high rate x-ray irradiation of a GEM module to see if there is efficiency loss resulting from VFAT saturation. These rate capability studies are particularly impactful for determining whether VFATs are an adequate plug-in card for the ME-0 detector, which must handle significantly higher muon hit rates than the existing GEM detectors in CMS.

F. Channel Loss and Aging Studies

Channel loss in the VFATs has been observed during the July 2022 study at the Gamma Irradiation Facility (GIF++) and in test modules at the production laboratory at CERN's Prévessin site. Channel loss may have considerable implications to the long term performance of GEM detectors, and thus identifying mitigation techniques are a high priority in the lab. It is expected that discharges within the GEM chamber is a cause of this channel loss, so the upcoming longevity studies will involve operating a GEM chamber at high voltage with an alpha source to induce discharges with improved high voltage monitoring. Periodic threshold scans will automatically be taken and new channel loss will be identified using code I contributed. This study will improve the collaboration's understanding of the relationship between dead channel propagation and discharges in GEM foils.

IV. CONCLUSION

As part of the 2022 CERN Summer Student Programme, I have had the unique opportunity to be involved in a wide range of projects within the CMS GEM group, including quality control, assembly, integration, electronics testing, and data analysis. In addition to the detector development experience gained in the GEM laboratory, I also attended the extensive, 5-week lecture series organized by the CERN Summer Student Programme and CERN OpenLab on covering topics in physics, detector development, and computing.

V. ACKNOWLEDGEMENTS

I would like to thank the CMS GEM group for the welcoming and supportive environment, and in particular I would like to thank Dr. Pieter Everaerts, Francesco Ivone, and Antonello Pellecchia for their guidance, advice, and support throughout the program. Additionally, the logistical support and developmental programming provided by Dr. Myron Campbell, Dr. Junjie Zhu, and Dr. Steven Campbell through the UMich-CERN REU Program has been an incredibly valuable component of this experience. I also thank the CERN Summer Student Lecture Programme committee and the invited lecturers for organizing and delivering more than 70 engaging lectures this summer. Finally, this work was funded through the National Science Foundation's Research Experience for Undergraduates Program under grant PHY-1949923.

[1] *The Phase-2 Upgrade of the CMS Muon Detectors*, Tech. Rep. (CERN, Geneva, 2017) this is the final version, approved by the LHCC.
[2] Brendan Regnary and Giovanni Mocellin, Gas electron multipliers for the cms experiment, `indico.cern.ch/event/1177048` (2022).
[3] G. Mocellin, Performance of the GE1/1 detectors for the upgrade of the CMS muon forward system (2021), presented 19 Jul 2021.
[4] Jeremie A. Merlin, Validation of the new gem design for discharge and crosstalk mitigation, `indico.cern.ch/event/1171045` (2020).