A TEST STAND FOR THE MUON TRIGGER DEVELOPMENT FOR THE CMS EXPERIMENT AT THE LHC

Undergraduate Research Scholars Thesis

By

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ABSTRACT

A Test Stand for the Muon Trigger Development for the CMS Experiment at the LHC.
(May 2013)

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Compact Muon Solenoid (CMS) is one of two flagship experiments in particle physics operating at the Large Hadron Collider (LHC). CMS has been built to search for signatures of Higgs bosons and other possible new phenomena. The upcoming accelerator upgrade will increase the rate of collisions and expand the physics reach of CMS, but will also push the detector systems beyond their current capabilities. One critically affected area is the CMS trigger, a system responsible for making a fast decision if a particular event is of interest and trigger the readout of the detector. While detector operations would be impossible without the trigger as saving data from every collision requires a technically unattainable bandwidth, trigger inefficiencies directly propagate into reduction of physics reach of the entire experiment. One proposal to handle the future increase in collision rates aims to combine the capabilities of the existing Cathode Strip Chambers (CSC) with the newly proposed Gaseous Electron Multiplication (GEM) detectors to improve the efficiency and discriminating power of the electronics-based muon Level-1trigger. This project focuses on development of a test-stand to emulate operational conditions of such a system, and the results of this study will present a proof of principle that building a joint GEM-CSC trigger system is feasible and it can be used to improve trigger efficiency.

DEDICATION

To my parents, Bhavna and Rahul Lakdawala, and my dearest friends who have always supported me and made me the person I am today. Thank you.

I would like to also dedicate this to everyone who has devoted their lives to unlocking the mysteries of the universe.

“A person who never made a mistake never tried anything new.” **–** Albert Einstein

ACKNOWLEDGEMENTS

I would like to acknowledge the following people; Dr. Alexei Safonov, Dr. Jason Gilmore, Dr. Vadim Khotilovich, and Aysen Tatarinov. Without their help this would not have been possible.

NOMENCLATURE

LHC	Large Hadron Collider
CSC	Cathode Strip Chambers
GEM	Gas Electron Multiplication
CMS	Compact Muon Solenoid
TMB	Trigger Mother Board
TAMU	Texas A&M University
LUT	Look Up Table
FE	Front End

CHAPTER I

INTRODUCTION

The LHC[1] is located in Geneva, Switzerland at the European Center for Nuclear Research (CERN), and has been built to conduct research in particle physics. In the LHC protons are accelerated near to the speed of light through a series of accelerators which use strong electric

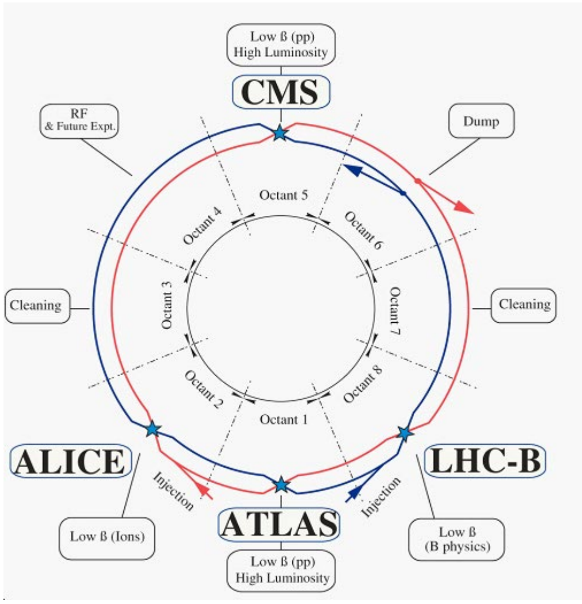

Figure 1: Illustration of the LHC layout. The LHC lies 574 feet underground and the circumference is about 17 miles. The two proton beams divided into bunches cycle in the opposite directions and are brought to collision at several interaction points with interactions happening every 25 ns. The CMS experiment is located at the collision point appearing at the top in this illustration.[5]

fields to accelerate the protons and strong magnetic fields to keep them in orbit[2]. Thousands of proton bunches (each over a billion protons) are circulated around the collider and brought into collisions at several points in the LHC tunnel, as displayed in Figure 1. During these collisions, which occur every 25 nanoseconds, the partons (constituents within the protons) collide producing abundant energy that gives rise to new particles, which subsequently decay into lighter particles that ultimately travel through the particle detectors surrounding each of the collision points. Detecting and identifying these final-state particles allows the reconstruction of the details in a collision event.

The Compact Muon Solenoid (CMS) detector at the LHC consists of several sub-systems, each responsible for detecting and measuring the properties of different types of particles produced in

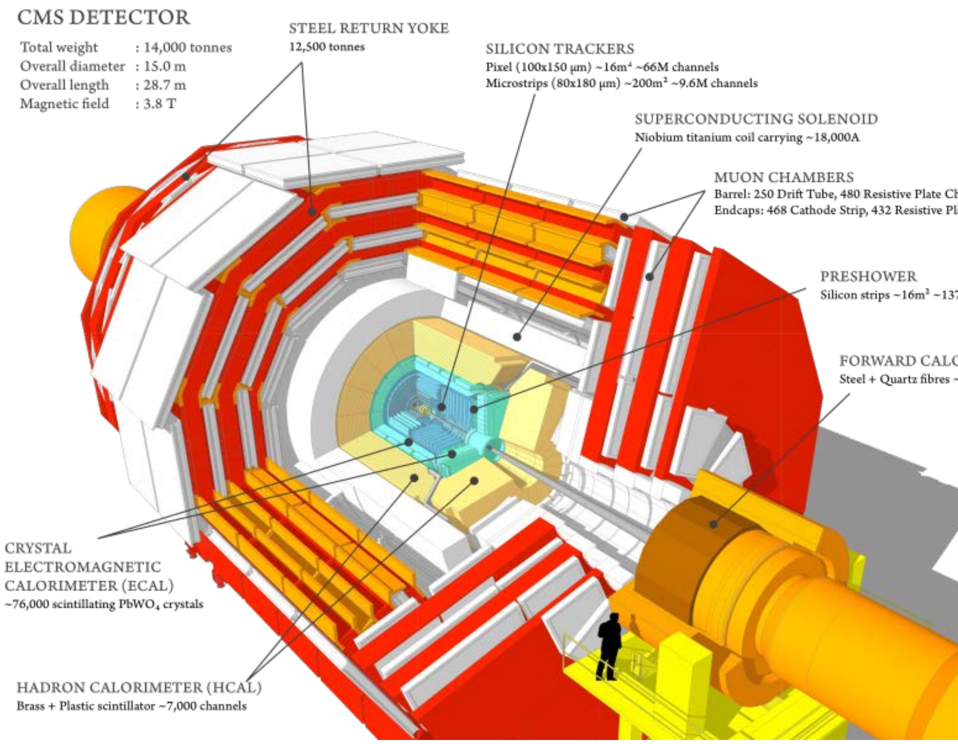

Figure 2: Schematic view of the CMS detector and its main systems. The detector is designed to track and identify particles produced at the collision point (in the center of the detector) and measure their properties (momentum, energy, location, angle and charge).[6]

a collision[3]. One key element of the CMS experiment is the muon detector, which consists of two main systems: the Drift Tubes (DT) detectors[3] are the outer layer of the CMS "barrel" region and the Cathode Strip Chamber (CSC) detectors[3] which are located in the forward regions of the detector forming the so-called end-caps, as shown in Figure 2.

This study is part of a program aimed at improving muon performance in the forward region instrumented by the CSC detector. Each CSC chamber has 6 layers; each layer consists of an array of strips about 1 cm wide running radially from the beamline (known as cathode strips), and closely spaced anode wires which run perpendicular to the strips CSCs are arranged in four stations (seen in Figure 3) such that particles originating at the interaction point pass through at least 4 CSC chambers upon reaching the endcap. Each station consists of one to three (this number is station dependent) "rings" of trapezoidal CSC chambers positioned perpendicular to the beam line, which goes through the center of each such ring. The electronics accompanying each chamber measure the position and timing of the charge deposits left by muons as they pass through and ionize the gas in the chamber. These measurements are used to determine the momentum, and charge of the particle, as well as provide a timing tag to enable differentiating between muons produced in different bunch crossings.

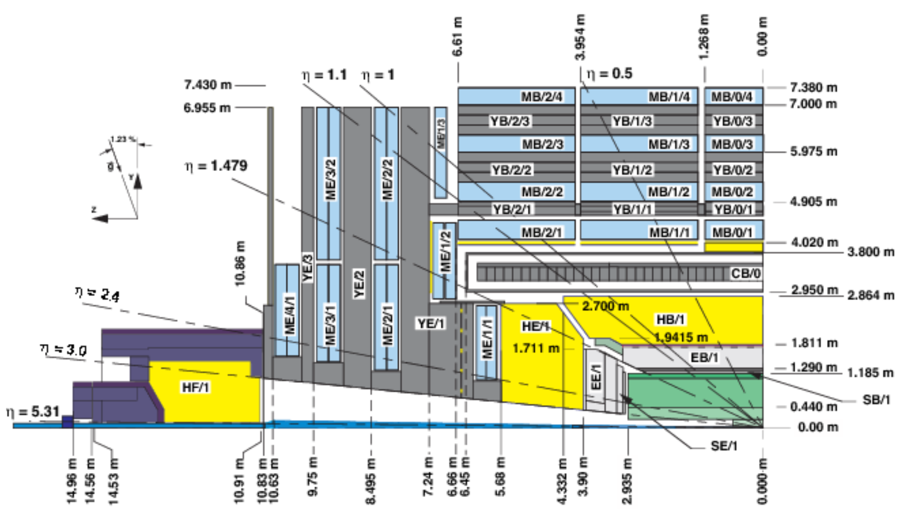

Figure 3: The cross-section of a quadrant of the CMS detector (the collision point is in the bottom right corner and the beam line goes horizontally). The GEM detector is proposed to be installed near the chambers of the CSC Station ME-1/1 (in the lower part of the drawing at z=5.68 m). The new GEM chambers will be positioned parallel to the CSC chambers but 30-50 cm closer to the interaction point providing an additional point+direction measurement of muon trajectories.[7]

As the measurements are collected, the CSC system performs a fast calculation to make a "trigger" decision, which is essentially an instruction for the electronics to perform a full readout of the data for a particular collision "event". The triggering is designed to filter out noise and background events, e.g. spurious hits in the muon stations or random coincidences of hits from different muons, in order to maintain the data rate within the available system bandwidth.

The anticipated LHC upgrades will increase the intensity of the proton beams, which will require the CMS experiment to process data at a much higher rate. The increase is substantial and will cause the present muon trigger system to acquire significant inefficiencies. One proposal to maintain acceptable efficiency under the high-rate conditions is to install a set of new chambers based on a novel technology utilizing Gaseous Electron Multiplication (GEM) detectors[3]. Installation of the new system would enhance the redundancy of the overall muon system and provide new tools to control the muon trigger rate while preserving high efficiency.

The GEM detectors are proposed to be added to station ME-1/1 of the endcap muon system, which is the inner ring of the station closest to the interaction point (the collision point of the proton bunches) as illustrated in Figure 4. GEM chambers would be placed 30-50 cm closer to the interaction point relative to the CSCs. Additional measurements provided by the GEM detector are expected to help in resolving cases where the CSC cannot unambiguously reconstruct a muon track due to the high combinatorial background (e.g. when multiple particle hits occur in the same chamber). In addition, the combination of the GEM and CSC measurements allows measuring the "bending angle" of the track, which is directly related to the particle momentum, and provides a new powerful tool for reducing the trigger rate while maintaining high efficiency.

Under this proposal, the GEM and CSC Front End (FE) electronics for adjacent CSC and GEM chambers will send the information to a common signal processing unit that will be responsible for constructing "tracklets" using data provided by both systems. A cost effective solution under consideration is to utilize an already existing electronics component, the CSC Trigger MotherBoards (TMBs), where each TMB is currently responsible for reconstructing muon tracklets using data within a single CSC chamber. However, it has yet to be proven that the TMB has sufficient capabilities to perform necessary reconstruction steps within the time limits imposed by CMS global trigger system.

This study aims at building an electronics test stand to provide a realistic emulation of the proposed CSC and GEM electronics configuration and operating conditions during actual data taking. The test-stand will be used to study and evaluate the feasibility of utilizing the existing TMB board in the role of processing the joint CSC-GEM data, and to identify potential limitations of the proposed schema. Eventually the test-stand will be used as a test-bed for design and development of the final production firmware to be used in the combined trigger system.

CHAPTER II

METHODS

Evaluating the feasibility of the proposed two-detector system requires the test stand to emulate the operational conditions of the electronics in the first station of the muon endcap. The test

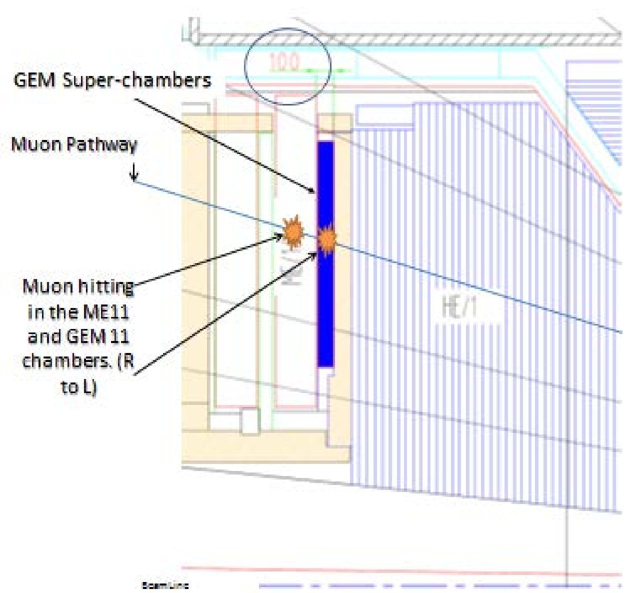

Figure 4: A Mechanical drawing showing positions of the CSC and GEM chambers. As an illustration, a path of a hypothetical muon produced in an LHC collision is shown along with the hits such muon would generate in the two overlapping chambers

stand should realistically emulate the data being sent by the CSC and GEM (FE) electronics boards which are on located on the detectors themselves. This data must contain correlations in the locations of the hits between the two systems as if a real muon went through, and must realistically represent the distribution of the incoming data including differences in the arrival time and location of the signals from the two systems. The test stand is therefore an electronics device capable of emulating CSC and GEM data being sent by the FE electronics of each system to the TMB. The test-stand should utilize the same data formats and correlations as those expected in real operations.

To meet these goals we need to accomplish three related tasks:

1. Develop an algorithm to realistically emulate the CSC and GEM data, taking into account correlations of the positions of the hits produced by the same muon traversing through both detectors.
2. Build an actual electronics setup with a programmable logic device capable of emulating the CSC and GEM data and transmitting it via optical fibers to the CSC TMB at a desired rate.
3. Implement an algorithm in programmable logic that generates the “data” and sends it to the CSC TMB via optical fibers.

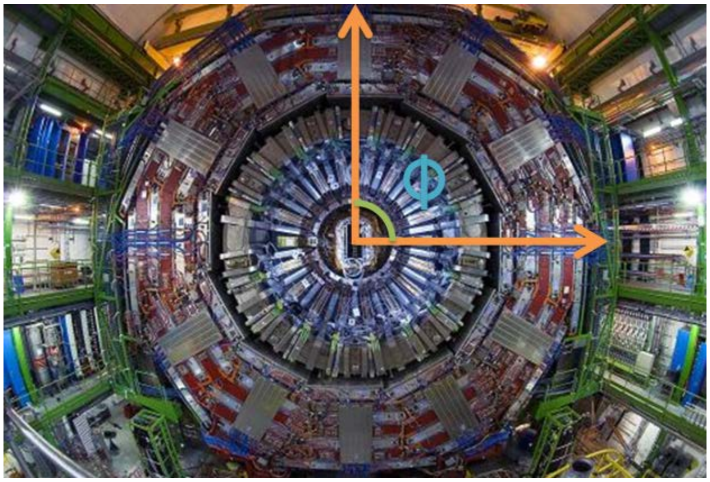

Figure 5: A view of the opened CMS detector. The global ϕ coordinate is measured in counter-clockwise direction from the x-axis (shown as horizontal axis).[7]

Correlations in the CSC and GEM hit positions

Once the GEM system is implemented in the real CMS detector its job is to work in conjunction with the CSC trigger system to determine whether a particle of interest (typically, a muon candidate with momentum above a pre-determined threshold) has traveled through the region instrumented by the two systems. An illustration of this situation is displayed in Figure 4, where an energetic muon has traveled through a pair of the GEM and CSC chambers. In order for the combined CSC-GEM system to determine whether a particle of interest has traveled through, an algorithm (implemented in the programmable logic of the electronics) that converts the hit location from each detector into a common coordinate system to enable direct comparisions of the measured positions. If the hit positions match a pre-defined correlation pattern (which could

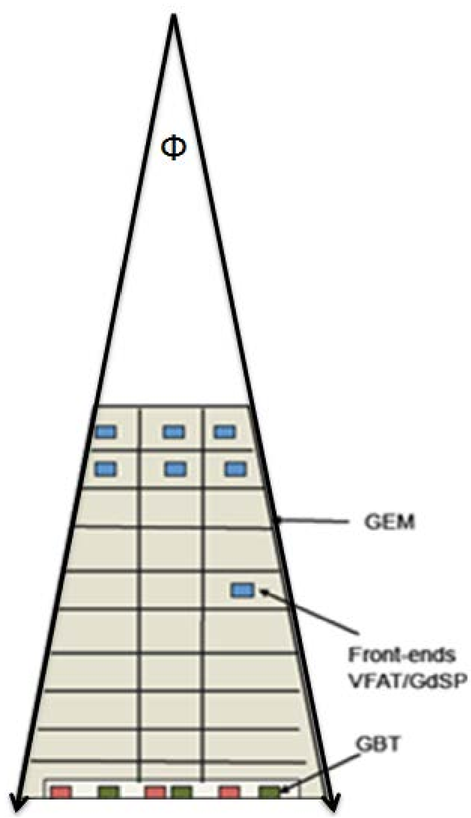

Figure 6: Schematic view of the GEM chamber showing the electronics readout elements. The horizontal rows represent GEM chamber "partitions", each partition being served by 3 VFAT chips, each reading out 128 strips. GEM pads are defined as combinations of groups of strips, which in this study have been taken as 16 strips per pad. Therefore, each GEM chamber partition is divided into 24 pads.

be programmed as a lookup table), the system will report that a particle of interest has been detected. Alternatively, if the positions do not match any of the expected patterns, the system will consider the data to be noise and the data processing will be terminated.

The first step is to understand the geometry and coordinate systems of both the GEM and the CSC. As mentioned previously, the CSC is a 6-layer chamber where each layer contains an array of cathode strips which run radially, and anode wires which run perpendicular to them. For this stage in the project we will focus on the cathode strips of the CSC as strip measurements determine the muon momentum measurement. Emulation of anode wire data is less critical and its implementation has been planned for later stages of the test stand development.

The GEM chamber has 10 rows with 24 pads per row in the global ϕ, see Figure 6 showing the layout of the front end readout electronics on the GEM chamber.

Each CSC chamber covers 10.945 degrees in global ϕ coordinate, whereas the GEM chambers are slightly narrower covering only 10.150 degrees (the definition of global ϕ is shown in Figure 5). For both systems, each "ring" in a station contains 36 chambers, which provides the full 360 degrees coverage while also having small overlaps of the chambers to avoid gaps in the coverage. Knowledge of the corresponding geometries allows developing an algorithm to perform a cross-correlation of the hit positions in the CSC and GEM chambers.

Electronics setup

The purpose of the electronics test stand is to emulate the actual operating conditions of the TMB electronics during data taking in CMS. Figure 7 illustrates the flow of the GEM and data from the front-end electronics of each of the detectors to the CSC TMB in the final system configuration. The FE electronics from both systems will transmit locations of particle hits in a 25 ns period to the CSC TMB. The CSC TMB will then process the data encoding hit locations from both systems and make a determination whether a muon of interest has been found or not.

It has been determined that an earlier TMB prototype board, seen in Figure 10, can be modified to simulate the data sent by the FE electronics of the GEM and CSC systems. This modified TMB will be known as the table-top TMB and its function will be to emulate the behavior of the components shown in the box on the left side of Figure 7. In the emulation, for a particular GEM pad being "hit", the table-top TMB will generate the selected GEM pad ID, this hit location can be communicated to the board through, e.g. the use of a manual switch, and calculate the position and ID of a corresponding CSC half-strip where a matching hit would be expected.

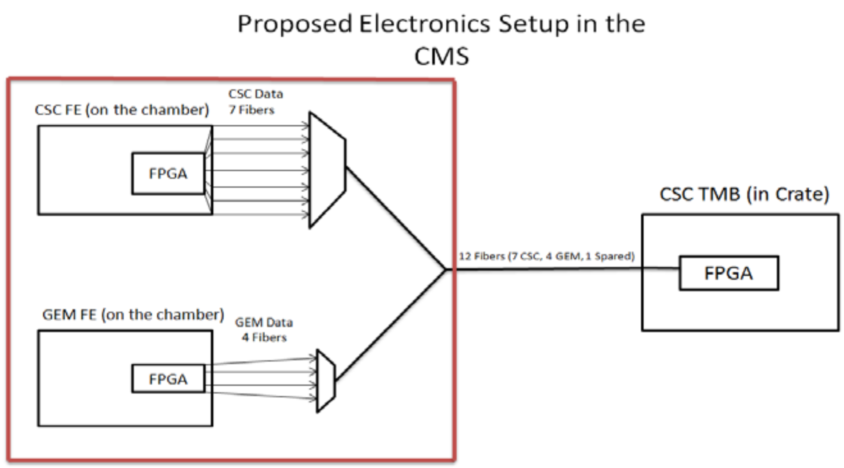

Figure 7: Depiction of the electronics communications of the CSC and GEM electronics proposed to be built at CMS.

The emulation algorithm will use a look up table (LUT) programmed into the firmware of the FPGA (the processing unit of the TMB). The LUT allows for an easy conversion (or translation) of the position associated with a specific GEM pad ID number to the equivalent-position associated with a CSC half-strip number. As the selected GEM pad location and the calculated CSC half-strip position form a geometric match, the data reporting positions of such hypothetical "hits" would represent a signature for a high energy muon traversing the two chambers. The data containing the generated pad number and the CSC half-strip coordinates will be transmitted via

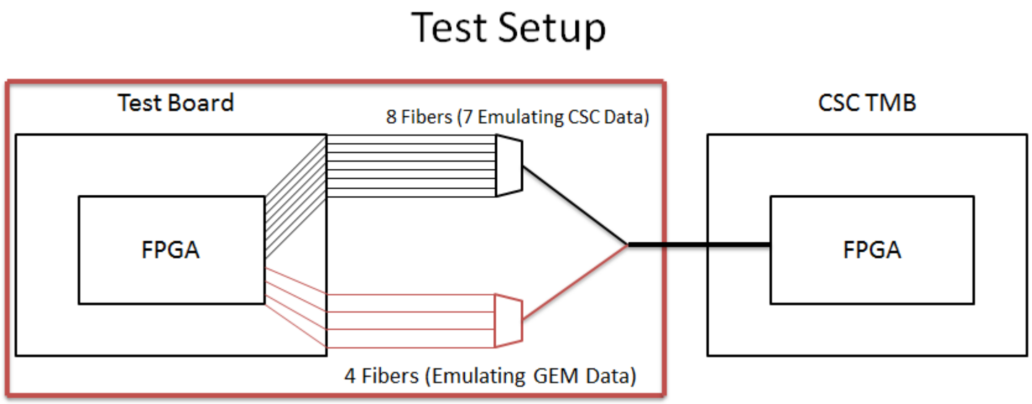

Figure 8: Proposed test-stand electronics setup designed to emulate the conditions in which the CSC TMB will operate at the LHC.

fiber optic links to the CSC TMB in the crate. Out of the 12 fibers that link the two boards, 7 fibers will be used to transmit the emulated CSC data, 4 will be used to transmit the emulated GEM data, and the remaining one will be used as a spare.

The Test-Stand firmware development

For the test stand to have the desired functionality, the logic needs to be implemented in the firmware running in the FPGA[9]of the test stand electronics. In addition to implementing the CSC and GEM emulation algorithm, the firmware of the table-top TMB needs to perform data formatting to enable transmission over the optical connection using a suitable protocol. Similarly, the firmware for the CSC TMB will enable the board to receive the data and determine whether there was a muon passing through the two systems or if the signal received was just noise.

The algorithm for the test stand (implemented in the firmware operating the table-top TMB) has to take the selected GEM pad ID from the switch and convert it through the use of the developed

LUT. The GEM pad ID will be converted into a position in the CSC coordinate system in terms of a CSC half-strip that corresponds to the geometrical position of the expected CSC hit. The algorithm assumes that a muon of interest passing through the two chambers is very energetic, and therefore has very little bending in the magnetic field.

The initial LUT parameters are obtained using the Microsoft Excel spreadsheet by correlating a GEM pad number to a half-strip number in the CSC, using the knowledge of the CSC-GEM geometries. After the LUT is created, it is compiled and loaded into the firmware of the table-top TMB. With this firmware operating in the test stand, anytime a GEM pad ID is selected, the corresponding half-strip ID is displayed on the LEDs of the board and along with the GEM pad ID is transmitted via optical fibers to the CSC TMB.

The algorithm operating the CSC TMB must determine whether the hits from the CSC and the GEM systems are consistent with those produced by an energetic muon. The CSC TMB will compare the hit position reported by the GEM, which is essentially a particular pad ID number, with the position of the reported cathode half-strip in the CSC. If the two hits are correlated then the data will be passed to the next level of the trigger system. If the hits are not correlated then it will be treated as noise and the data processing will stop for this event.

CHAPTER III

RESULTS

Setup & functionality of electronics

The purpose of this study is to build an electronics test-stand that can provide a realistic emulation of the FE electronics of the GEM and CSC systems. The first step is to develop a physical interface that allows the user to designate a hypothetical hit or pattern of hits in the GEM chamber. To create a physical user interface, a device which has 8 switches (shown in Figure 9) has been developed and installed on to the table-top TMB. This set of switches allows the user to select any value from 0 to 255 in binary code to designate a particular GEM pad ID. The second step is to convert the GEM pad ID number into a CSC half-strip number using the

Figure 9: GEM pad ID selection switches, which attach to the table-top TMB. The blue device allows the user to input a GEM pad ID number in binary.

LUT that is now programmed into the table-top TMB’s FPGA. When the conversion is complete the half-strip number is displayed on the LEDs located on the right side of the board, as shown in Figure 10.

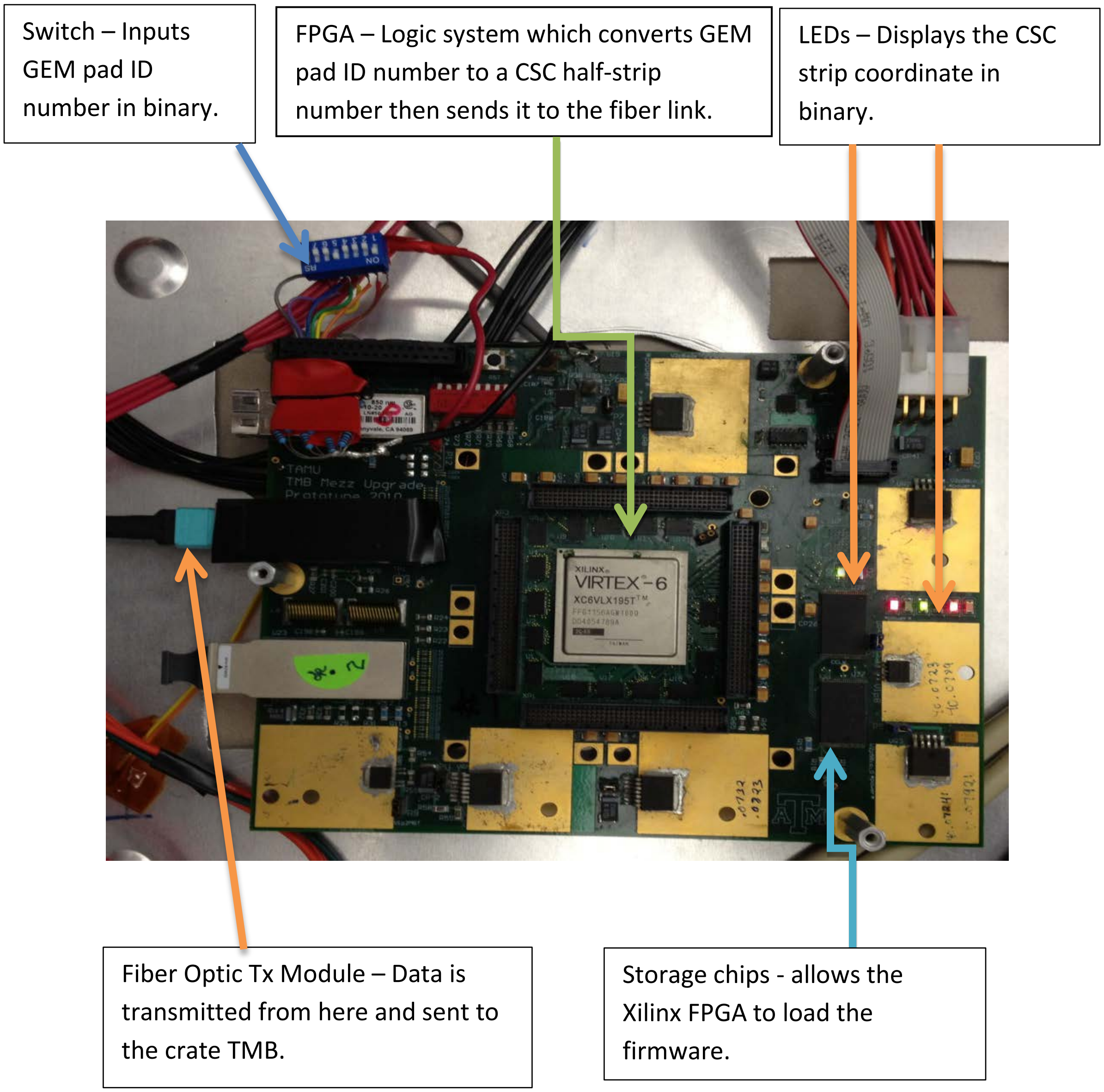

Figure 10: Table-Top TMB which will simulate both the CSC and GEM data.

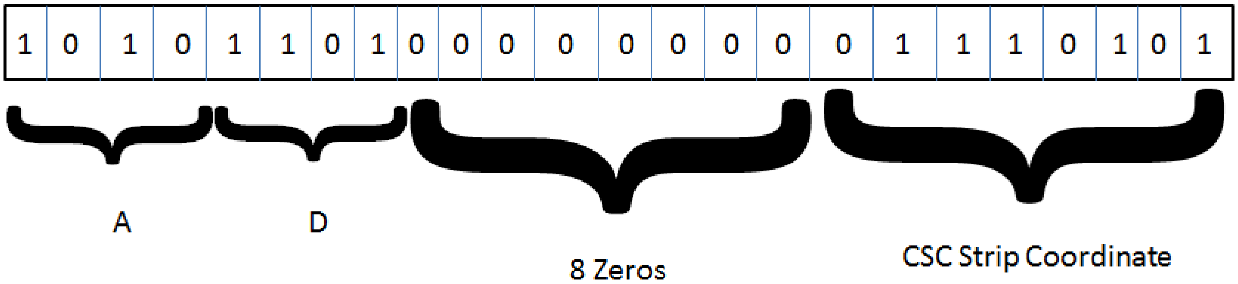

Figure 11: The bit sequence sent between the Table-Top TMB and the CSC TMB. The first 8 bits represent the 'AD' character, the second 8 bits are zeros and the last 8 are the CSC strip coordinate.

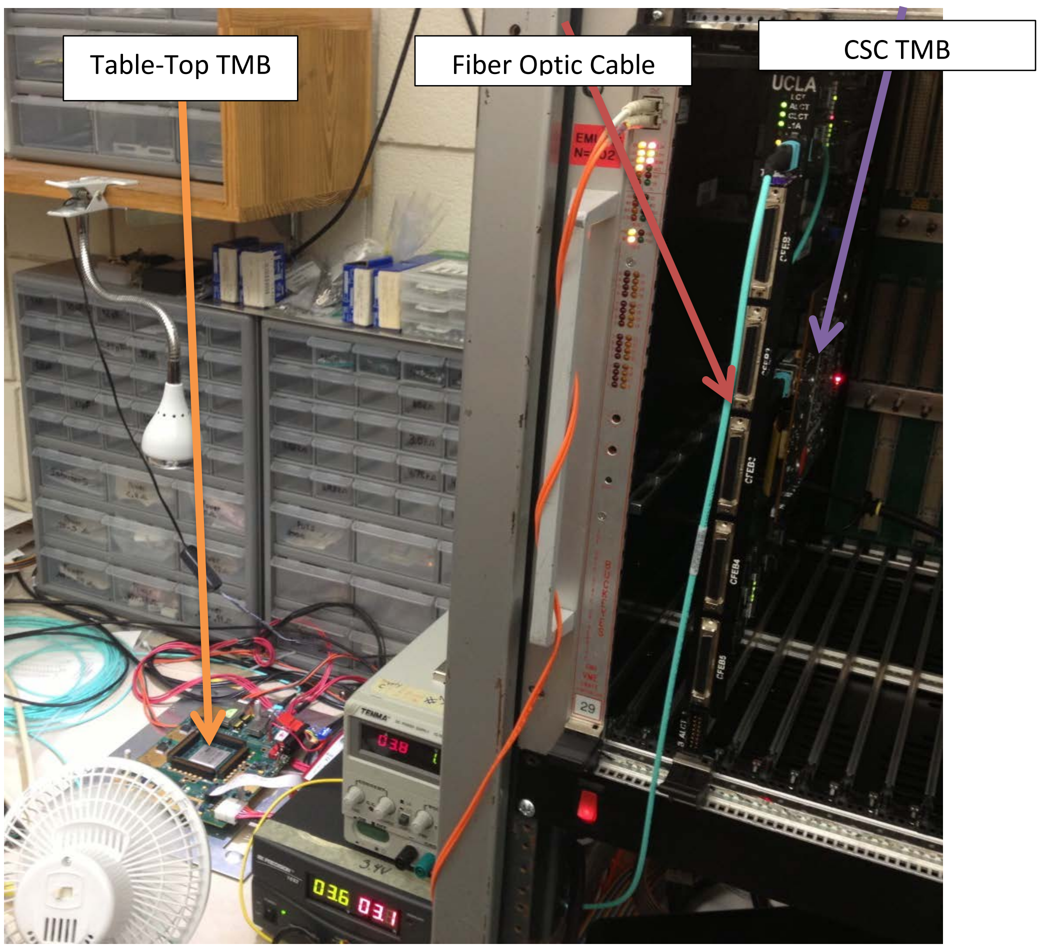

Figure 12: The test stand setup in the TAMU laboratory with the Table-Top TMB and the CSC TMB connected via fiber optic links.

After the data has been processed by the table-top TMB, the data is sent through fiber optic links to the CSC TMB located in the crate, as seen in Figure 12. The function of the CSC TMB is to receive the data from the fiber links and display the received CSC half-strip number on its LEDs, allowing immediate visual verification of the transmission. The transmission protocol uses a 24 bit sequence where the first 8 bits designates a two character hexadecimal constant ‘AD’ used as a data frame marker. The second 8 bits are a set of zeros (reserved for future use) data. An example of this binary sequence is shown in Figure 11. The CSC TMB gathers the data from the fiber optic cable and looks for the ‘AD’ to determine where to start reading the binary code.

Developing the Look Up Table (LUT)

In order to develop the LUT the geometries of the two chambers need to be examined closely. A single CSC chamber covers 10.945 degrees in the global ϕ whereas a single GEM detector

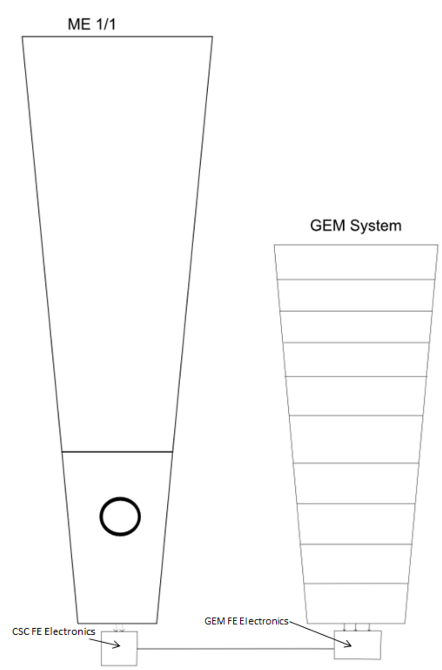

Figure 13: As seen in this diagram, the ME 1/1 (CSC Detector) is longer than the GEM system. Also it covers a greater span in the global ϕ.

covers 10.150 degrees, so the GEM chamber is narrower by .795 degrees. This means it is necessary to determine the extent of the overlap of the two detectors, and specify which half-strips correlate to the edges of the GEM chamber in terms of CSC coordinates.

For calculation purposes we orient the GEM detector directly on top of and center-aligned with the CSC system, such that there is 0.3975 degrees of a gap on each side of the CSC chamber. Therefore, the overlap with the CSC would begin at 0.3975 degrees and end at 10.5475 degrees. After the value of the phi-angle, at which the overlap begins is determined, one can calculate the ID of the CSC half-strip that correlates to the first GEM pad. To determine this correlation, the value of angle subtended by a CSC (10.945 degrees) is divided by the number of half-strips (128) to determine the angular coverage associated with a single half-strip. Similarly, for the GEM the angular coverage of a chamber (10.15 degrees) is divided by 24 (the number of pads across global ϕ). This equates to each half-strip being 0.0855 degrees wide and each pad being 0.4229 degrees wide. Based on this data, the half-strip number, where the overlap begins can be calculated as $Half\ Strip\ Number = \left| \frac{\varphi_0 - Gap\ Angle}{\varphi^{Device\ Angle}} \right|$, where φ_0 is the initial angle. It was concluded that the CSC-GEM overlap begins on half-strip number 6 and ends on half-strip number 123 on the CSC.

The next step was to correlate the GEM pad number with the CSC half-strip number. The equation relating the two is: $N_{pad}^{GEM} = Ceil(\frac{\varphi\left(\mathrm{N}_{\mathrm{Strip}}^{\mathrm{CSC}}\right) - \varphi_o}{\Delta\varphi_{pad}^{GEM}})$, where N represents the number of the CSC or GEM readout element (strip or pad), and φ is the value of the angle corresponding to the element. The half-strip number formula and the GEM pad ID equation were programmed into the Excel to obtain the corresponding table which is shown in Table 1. The mapping has been used to form a LUT, which can be implemented in the firmware.

Table 1: The calculated correlation between CSC half-strip locations and GEM pad ID numbers, which was used in development of the LUT. The table shows the correlation between the CSC Half-Strips and GEM Pads as well as the phi-locations of the CSC Half-Strips.

CSC Half-Strip #	Phi-Location of the CSC Half-Strip	GEM Pad #
6	0.4703	1
7	0.5558	1
8	0.6413	1
9	0.7268	1
10	0.8123	1
11	0.8978	2
12	0.9833	2
13	1.0688	2
14	1.1544	2
15	1.2399	2
16	1.3254	3
17	1.4109	3
…	…	…
117	9.9617	23
118	10.0472	23
119	10.1327	24
120	10.2182	24
121	10.3037	24
122	10.3892	24
123	10.4747	24

Firmware implementation

After defining the LUT that correlates a CSC half-strip to a GEM pad number the next step was to code this mapping scheme into the firmware of the table-top TMB. The FPGA is manufactured by Xilinx; we chose this particular processor for its processing capability and the ability to withstand the radiation it will be exposed to in the CMS experiment cavern. Xilinx has its own design software for firmware development called "ISE Design Suite 14.3", and Verilog programming language.

The testing procedure begins with adjusting the 'Pattern Selector Switch' to select a hit in a particular GEM pad ID. With the help of the LUT, the value of the pad number is used to calculate the ID of the CSC half-strip, which would form a match with the selected pad. The firmware has been programmed to use the half-strip number to set signals on the FPGA pins connect to the LEDs on the table-top TMB and another copy of the calculated half-strip ID is transmitted to the CSC TMB via fiber optic links. This is demonstrated in functional flow chart of Figure 14.

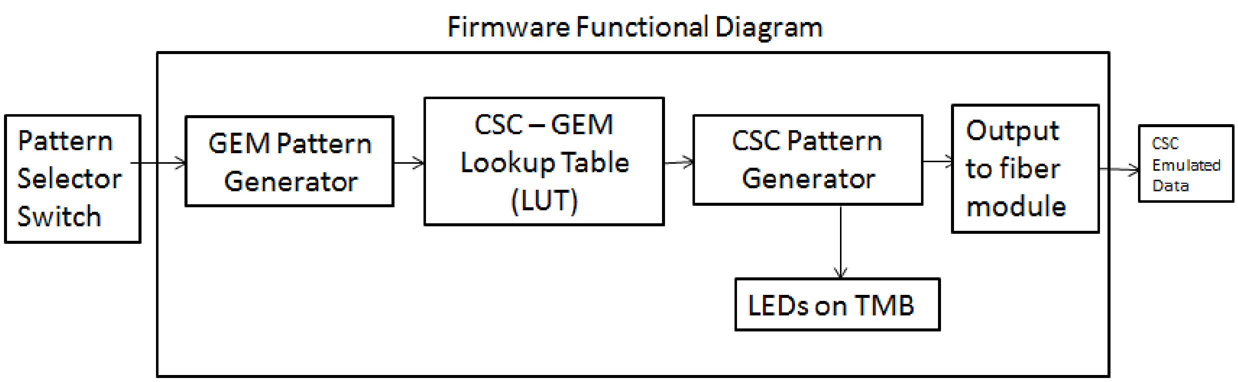

Figure 14: Functional Flow Chart of the test operations performed using the emulator board.

After the firmware code is written and compiled, it is then loaded into the non-volatile memory chips on the table-top TMB. This is done using of the Xilinx download tool (shown in Figure 15) that has a USB connection on one end for linking to a PC, and a special parallel connection on the TMB end. Once the computer and the TMB are connected to the device, the Xilinx software is used to control the download.

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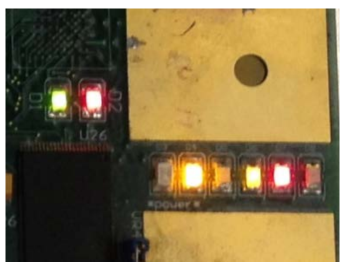
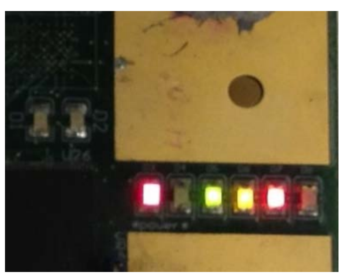
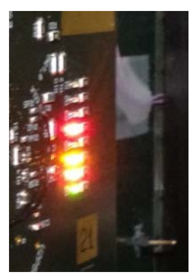
Testing and validation

After the firmware is downloaded onto the TMB there needs to be confirmation that the program is working as designed, and a few debugging tests are implemented in the firmware to achieve this. For example, when a GEM pad ID is selected the LEDs should display the correct CSC half-strip number. Another check is to verify that the same sequence of LEDs is lit up on the CSC TMB indicating that it is receiving the data properly from the table-top TMB via the fiber optic links.

Figure 15: Xilinx downloader tool, on the left is the USB connection to the PC and on the right is the cable to the TMB.

We tested three GEM pad ID numbers initially to check that the firmware was functioning as designed. The pattern switch selector was set to a GEM pad ID and the LEDs on both the table-top and CSC TMBs showed the correct correlated CSC half-strip number as specified in the LUT. To confirm that the signal was being sent, an oscilloscope was set up on the CSC TMB to determine the frequency and duration of the transmission signal. We needed to make sure that the signal was sent for exactly 25 ns and not longer otherwise it would interrupt the data coming in from the next collision. Several values were tested and showed a good match; these results are displayed in Table 2.

Table 2: This table demonstrates the proper operation of the emulation algorithm. A GEM pad ID that is selected on the manual switch is translated into a CSC half-strip number. The result is displayed in binary on the table-top TMB's LED, which can also be observed on the CSC TMB LEDs. A lit LED signifies a binary 1; when off it signifies a 0. Only 7 bits are used to display the CSC half-strip number, so the 8th LED is always off. The last column confirms that the signal was sent from the table-top TMB to the CSC TMB.

Selected GEM Pad ID	Expected Half-Strip Value	Table-Top TMB LEDs	CSC TMB LEDs	Digital Signal Confirmation
1000100	1110101			
1010100	1101011			
1110100	0010111			

Further testing over all the patterns in the LUT proves that the data is successfully registered by the emulator logic using the LUT, and then sent via fiber optic links to the CSC TMB where it is successfully received.

CHAPTER IV

CONCLUSION

As the work on enhancing the CMS experiment capabilities for the upcoming luminosity upgrades of the LHC is gaining momentum, the analysis of available options and technical feasibility of implementation scenarios is becoming particularly important. One such upgrade is the addition of a new GEM system to the existing detector, which has the potential of allowing to maintain the current high efficiency and discriminating power of the electronics-based muon Level-1 trigger.

The project described in this paper has been focusing on building a complete electronics test-stand necessary for studying the technical implementation options as well as development of the production system related to the combined GEM-CSC level-1 muon trigger. The result of this work is an electronics system implemented in a multi-layer custom electronics board with a Virtex-6 FPGA capable of realistically emulating the operational conditions in the data taking regime. The new system is being already used to evaluate whether the existing CSC TMB electronics board has sufficient resources to be used as the main unit responsible for trigger primitive creation of the integrated GEM-CSC trigger.

As a byproduct, several other important findings have been made. First, it has been concluded that the fiber optic links from the FE of the CSC and GEM systems can transmit the data encoding the hit locations in the two chambers to the CSC TMB using the standard CSC communication protocol. Second, it has been determined that the CSC TMB has sufficient available resources for a new LUT to be implemented in the programmable logic of the board. This is an important step in proving that the new electronics GEM-CSC trigger system is feasible and can be implemented in CMS to work seamlessly with the current CSC trigger framework.

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