COMMISSIONING OF THE GEM-CSC INTEGRATED LOCAL TRIGGER FOR RUN-3 OF THE CMS EXPERIMENT AT THE LARGE HADRON COLLIDER

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

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CMS Experiment at the Large Hadron Collider

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The high luminosity upgrade to the Large Hadron Collider (LHC), means a significant increase in data, which the existing muon trigger system's bandwidth is inadequate to process. The solution for enabling the muon system to handle this increase in data is the installation of thin Gas Electron Multiplier (GEM) detectors in front of the existing Cathode Strip Chambers (CSC), where the magnetic field is strong allowing for best measurement of the transverse momentum (p_T). Combining the data from the new GE1/1 system with ME1/1 will improve the p_T resolution of the Level one (L1) trigger, allowing it to filter out many soft muons which otherwise would have been incorrectly reconstructed by the ME1/1 system alone, thus reducing the load on the higher level triggering system to catch these poor quality muons. In order to successfully implement this combined triggering system in time for the scheduled run-3, there must be an efficient means of commission the combined trigger system. This thesis describes the software and hardware developed to verify proper operation of this combined triggering system. This will vastly speed up the process of commissioning the combined Integrated Local Trigger (ILT), which will reduce the time wasted during installation, optimizing the amount of useful data collected by the CMS experiment.

NOMENCLATURE

CERN	Conseil Europeen pour la Recherche Nucleaire (French) [European Council for Nuclear Research]
TAMU	Texas A&M University
LHC	Large Hadron Collider
CMS	Compact Muon Solenoid
GEM	Gas Electron Multiplier
p_T	Transverse Momentum
ILT	Integrated Local Trigger
L1	Level One
LS2	Long Shutdown Two
RPC	Resistive Plate Chamber
OTMB	Trigger Mother Board
FPGA	Field Programmable Gate Array
ROM	Read Only Memory
RAM	Random Access Memory
BX	Bunch Crossing
CSC	Cathode Strip Chamber
CLCT	Cathode Local Charged Track
GUI	Graphical User Interface
LUT	Lookup Table

CHAPTER I

INTRODUCTION

The standard model of particle physics summarizes what is currently known about the fundamental particles and forces which comprise the known universe. In recent decades the Standard Model has successfully predicted the existence of the top quark and Higgs boson, nevertheless it remains clearly incomplete. Observed phenomena such as gravity, dark matter/energy and baryon asymmetry fail to be accounted for by the model, thus experiments are necessary if there is any hope to unravel these phenomena. The Large Hadron Collider (LHC) at CERN is one such an experiment that aims to study these mysteries. By colliding beams protons travelling at near light speeds [1], the LHC creates perfect conditions for studying the fundamental particles of the universe. There are four distinct collision points located along the 27 km circumference of the LHC, each allocated for independently designed and operated physics experiments. Among these experiments is the Compact Muon Solenoid (CMS Fig. 1) for which this research has been conducted.

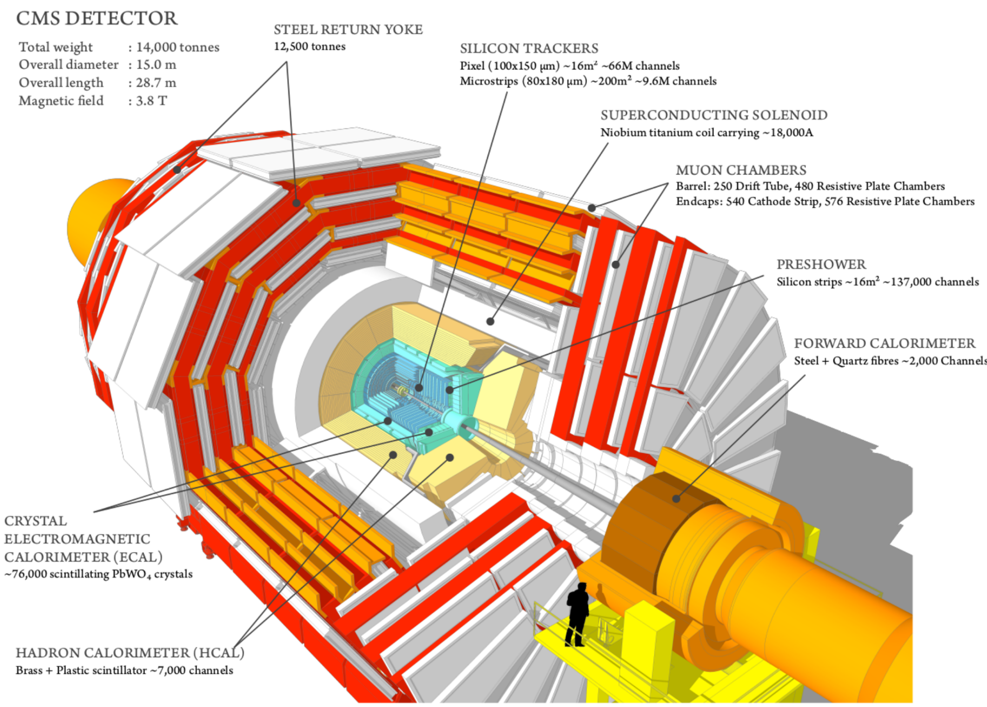

Figure 1: A diagram of the CMS experiment [2]

The CMS experiment is a general purpose detector, meaning that it is designed to observe all types of events occurring from the proton-proton collisions and consists of an ensemble of smaller detectors operating together as one. As a general purpose detector the CMS aims to search for new physics along with performing high precision measurements of the recently discovered Higgs boson (officially discovered by the CMS and ATLAS in 2012). Each sub-detector system of the CMS is critical for reconstructing the events of interest, but the focus of this project is on the muon system located in the endcap regions. The muon system composes the outermost shell of detectors in the CMS, and is used to measure the transverse momentum ($\mathrm{p_T}$) of muons by recording their trajectory then calculating the curvature induced by the CMS magnetic field.

Although the probability of a true high p_T muons being produced by the proton-proton collisions is small, the probability of secondary muons, produced by kaon and pion decays especially in the cascading decays that occur in the calorimeter, is not so small. Considering that the rate of inelastic collisions during Run-2 was approximately 1 GHz [3], the probability to observe a number of these undesirable secondary muons per bunch crossing is large. Since recording all data observed by the detectors would be physically impossible, a triggering system is implemented to filter out much of the unwanted data. Texas A&M University (TAMU) is responsible for developing the algorithm and hardware, Optical Trigger Mother Board (OTMB), which implement the local trigger for the CSC chambers. Since this trigger is a critical step in the data acquisition system, it is important to thoroughly understand the decisions it makes.

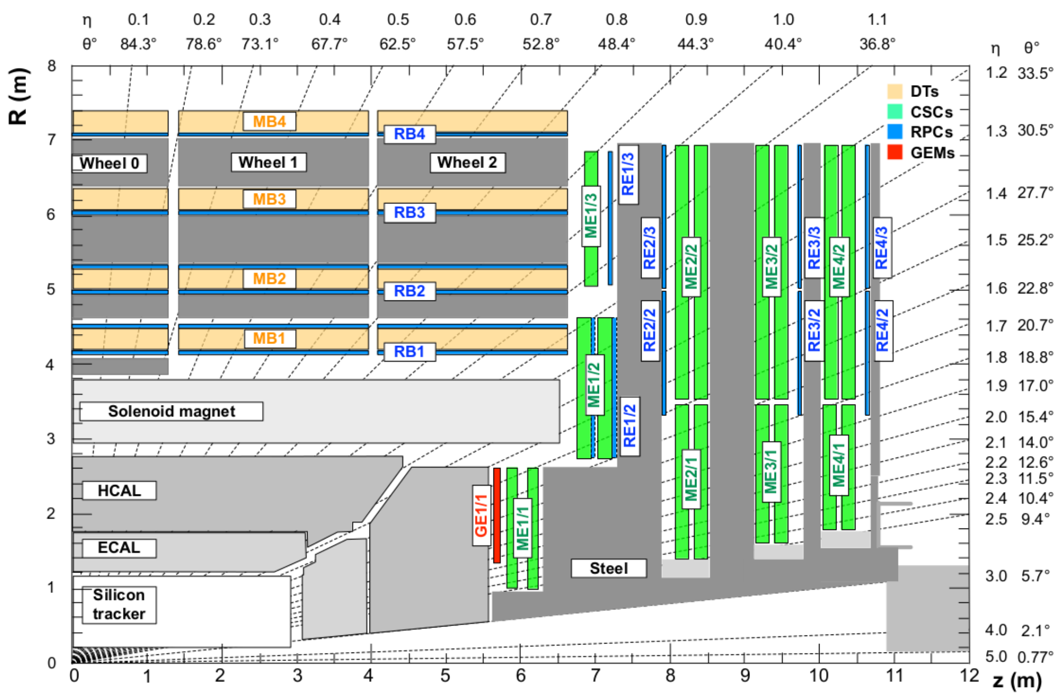

Figure 2: A diagram displaying the relevant quadrant slice of the CMS detector system [4]

The LHC is currently in a period dubbed the long shutdown two (LS2), in which many upgrades are being made all around the accelerator complex. Perhaps most relevant is the upgrade to the injector chain, as this will increase the instantaneous luminosity beyond $2 \times 10^{34} (cm^{-2}s^{-1})$ [4], which will exceed the processing capability of the existing muon system of the CMS. The solution, currently being implemented, is the installation of a new set of detectors GE1/1. These detectors utilize Gas Electron Multiplier (GEM) technology and as a result are very thin, allowing them to occupy the thin gap in front of the existing ME1/1 system Fig. 2, originally intended for a Resistive Plate Chamber (RPC) which was scrapped due to its poor performance at such high rates [3]. The GE1/1 sits in front of the ME1/1, making it the closest detectors to the interaction point, where the Magnetic Field is strongest, giving it the optimal conditions for improving the transverse momentum (p_T) measurements of muons.

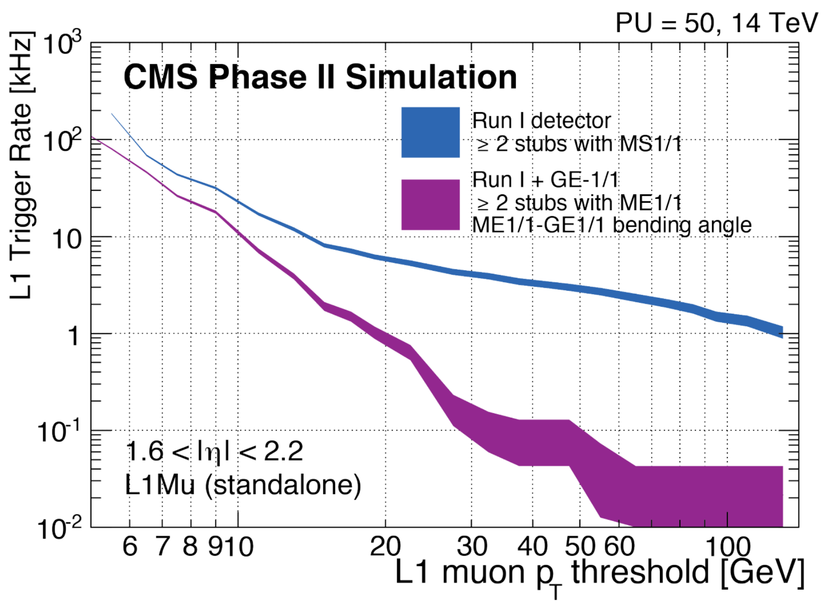

Figure 3: The effects of the GEM addition on the local muon trigger rate [4]

One of the primary advantages to the implementation of the new GE1/1 system is the combination of it's data with that of the existing ME1/1 system in the level one (L1) trigger will have an improved p_T resolution, increasing sensitivity to soft muons, by reducing the overall trigger rate to one which can be handled by the system's finite bandwidth (Fig. 3). With the added resolution the trigger can make more informed decisions, more efficiently differentiating interesting data from background noise. This increased efficiency will allow the CMS experiment to study physics in the Higgs sector while simultaneously studying higher energy physics [4]. The goal of this study is to design and implement an emulation system for use in the development and commissioning of the L1 Trigger in preparation for Run-3.

CHAPTER II

METHODS

In the TAMU lab oTMB test-stand has been extended with the addition of an Emulation System, capable of verifying the performance of the oTMB triggering algorithm. The Emulation Hardware was created by re-purposing a circuit board equipped with a high grade FPGA, enough RAM to store 500 Bx of chamber output data and optical transceivers capable of delivering the data at LHC clock speed (40 MHz).

Pattern Generation

When a muon interacts with a Cathode Strip Chamber, it ionizes the gas within leaving free charges in its wake. This charge then builds up on the cathode strips, inducing a voltage across the strips in a manner similar to a capacitor. The strips are continuously monitored by voltage comparators, which can identify the muon Hits (single layer interactions) with half strip resolution Fig. 4. Each CSC is subdivided into 16-strip sections, each monitored by a dedicated Cathode Front End Board (CFEB) which communicates directly with the oTMB. Each CFEB is responsible for reporting on all 6 layers of strips in its section simultaneously. To optimally use the available bandwidth, the data is encoded in a custom format known as a Triad. The Triad encodes hit locations using only 3 bits transmitted over 3 Bx (bunch crossings) using only 1 Byte per Bx. The first bunch crossing of data is a decoded enumeration of the Di-strip (pair of strips) on which the hit occurred, this bit also signifies beginning a Triad. On the second bunch crossing, the strip location is encoded using the same bit address as the Di-strip, now the bit level encodes the left(0) or right(1) strip of the pair. And in an identical fashion the next bit encodes the half-strip location using the same bit location, concluding the triad.

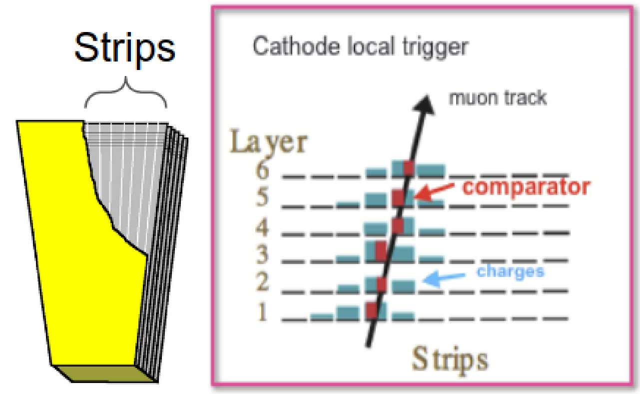

Figure 4: CSC cut away (left), muon charge track and comparator operation (right)

Triad data is directly received by the OTMB, which has logic for processing and identifying collections of these hits as multi-layer tracks, picking the best to record and send upstream to the higher level trigger. These multi-layer tracks are encoded in a more abstract form called CLCT, specified with the fields detailed in Table 1.

Table 1: CLCT composition

Field	Proper Term	Description
PID	Pattern ID	Specifies the shape of the track
KEY	Key Half strip	Half strip location which the track is centered
NHIT	Number of Hits	Number of active layers determines track quality
BX	Bunch Crossing	Time of occurrence

The trigger algorithm uses the lookup table (LUT) in Fig. 5 to classify the shape and quality of CLCTs. The pattern generation software also uses this LUT as a stencil for generating the set of hits corresponding to a given CLCT. For an individual pattern file a list of input CLCTs gets converted to a list of hits, which are written to the file in triad format. Triad format pattern files can be completely completely recovered from a list of hits, so CLCT data combined with the specific Hit data are the format used to archive patterns.

```
Hit pattern LUTs for 1 layer: - = don’t care, xx= one hit or the other or both
Pattern        id=2        id=3        id=4        id=5        id=6        id=7        id=8        id=9        idA
Bend dir       bd=0        bd=1        bd=0        bd=1        bd=0        bd=1        bd=0        bd=1        bd=0
|           |           |           |           |           |           |           |           |
ly0       --------xxx xxx-------- -------xxx- -xxx------- ------xxx-- --xxx------ -----xxx--- ---xxx----- ----xxx----
ly1       ------xx--- ---xx------ ------xx--- ---xx------ -----xx---- ----xx----- -----xx---- ----xx----- -----x-----
ly2 key   -----x----- -----x----- -----x----- -----x----- -----x----- -----x----- -----x----- -----x----- -----x-----
ly3       ---xxx----- -----xxx--- ---xx------ ------xx--- ----xx----- -----xx---- ----xx----- -----xx---- -----x-----
ly4       -xxx------- -------xxx- -xxx------- -------xxx- ---xx------ ------xx--- ---xxx----- -----xxx--- ----xxx----
ly5       xxx-------- --------xxx -xxx------- -------xxx- --xxx------ ------xxx-- ---xxx----- -----xxx--- ----xxx----
|           |           |           |           |           |           |           |           |
// Extent   0123456789A 0123456789A 0123456789A 0123456789A 0123456789A 0123456789A 0123456789A 0123456789A 0123456789A
// Avg.bend - 8.0 hs    + 8.0 hs    -6.0 hs     +6.0 hs     -4.0 hs     +4.0 hs     -2.0 hs     +2.0 hs      0.0 hs
// Min.bend -10.0 hs    + 6.0 hs    -8.0 hs     +4.0 hs     -6.0 hs     +2.0 hs     -4.0 hs      0.0 hs     -1.0 hs
// Max.bend - 6.0 hs    +10.0 hs    -4.0 hs     +8.0 hs     -2.0 hs     +6.0 hs      0.0 hs     +4.0 hs     +1.0 hs
```

Figure 5: OTMB trigger algorithm uses these patterns of hits to classify CLCTs [5]

Emulator System

The emulation system (Fig. 6) consists of a dedicated emulation board, described previously, connected via specialized transceivers to an OTMB loaded with the trigger algorithm under test, where both are controlled by a lab computer (PC) via ethernet protocol. The emulation proceedure is as follows:

1. The PC Generates traid pattern files and loads them to the Emulator
2. The Emulator injects the data stored in RAM to the oTMB.
3. The PC probes registers in OTMB to retrieve the trigger decision

The OTMB trigger decision can be probed by reading two registers which store the two most recently identified CLCTs, along with the the two corresponding LCT counters which track the number of positive trigger decisions.

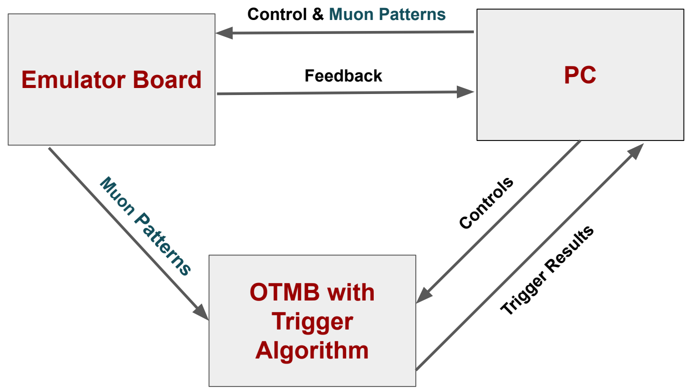

Figure 6: Block diagram overview of the emulator system

Automation Tools

One significant limitation of the emulator system previously described is the fact that a human operator needs to specify, generate and send the patterns to the emulator board, as well as recording the trigger results of the OTMB. This process will quickly become cumbersome and unmanageable if we are investigating any significantly sized set of patterns, so the emulator system has functionality to automatically facilitate the test procedure, and log the results. The graphical user interface (Fig. 7) allows the developer to efficiently study the trigger response for a range of patterns.

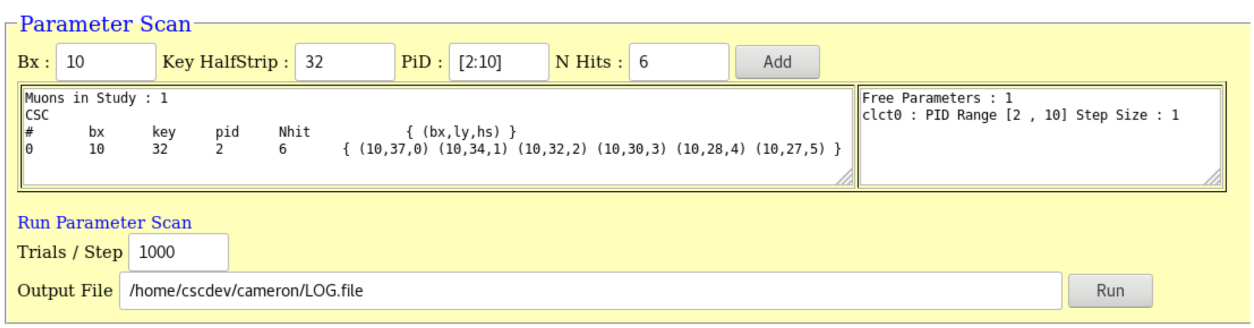

Figure 7: Screenshot of the automation software GUI, in this example the CLCT field "PiD" is set as a free variable to be iterated from 2 up to 10

The automation tool makes it possible to sweep through a set a similarly structured patterns with minimal effort. This operation is achieved by maintaining the pattern set in CLCT form, generating the triad files on each step of the sweep. Stable memory usage is achieved by overwriting the previously used triad pattern file.

On each step the current CLCT is encoded and loaded to the emulator board, then the PC repetitively performs steps 2 and 3 of the described emulation process. Between each emulation process the program calculates the change in the LCL counters, corresponding to the number of positive tracks due to the injection process. Each OTMB response is then characterized by the data of the CLCT registers and the counter increments.

As the automation program sweeps through the parameter space, a list of unique observed OTMB response with the count of occurrences. Upon each injection process, the data retrieved from the OTMB is compared against each entry of the response vector, incrementing the counter when identically matched, otherwise appending itself as a new observation. Upon completion of the repeated emulation loop, the results of the experiment (the response vector) along the the experimental set up (CLCTs with Hit vectors) are recorded to a specified file on the PC. Thus all pattern studies performed are recorded and easily reproducible. The desired output file is determined by entering the full file path in the "Output File" field shown in the GUI of Fig. 7.

Trigger Verification

The procedure for determining expected versus unexpected trigger behavior is outlined in the block diagram of Fig. 8.

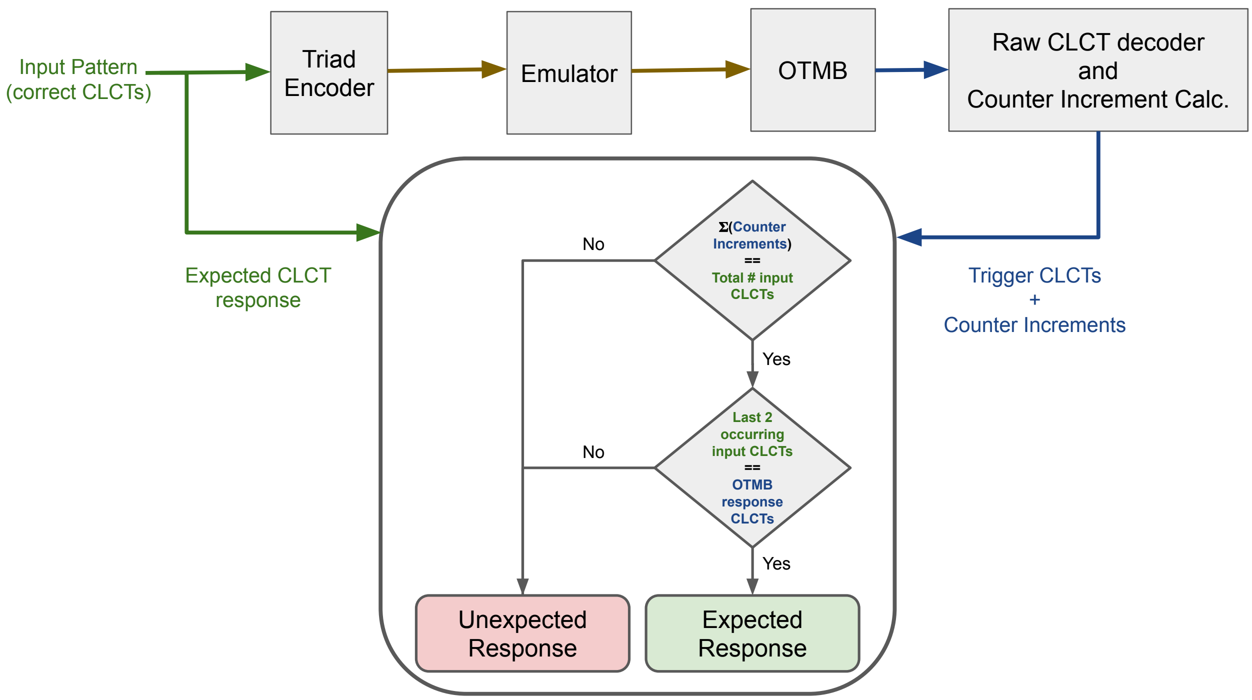

Figure 8: Block diagram depicting the procedure for trigger verification

Input data may take the form of a list of CLCTs each paired with a list of Hits, or a simple list of CLCTs from which a set of hits may be generated. Either way the input data must contain the desired OTMB trigger decision, thus the output data may be compared against the input to verify proper triggering. In order to conduct tests with more than two muons present the sum of LCT counter increments is compared against the number of input CLCTs, since the OTMB only stores the two most recent tracks. Expected trigger response occurs when the counter increments equal the number of input muons, and the final two occurring CLCTs of the pattern exactly match those stored in the OTMB.

CHAPTER III

RESULTS

In order to demonstrate the proper functionality of the Pattern Generation software, single CLCT patterns were generated and tested against an oTMB algorithm known to work on a basic level. The CLCTs in this test were generated by placing the key half strip in the center of each CFEB, and scanning through all possible pattern shapes (PiD) for each location. The results for the ME1/1 algorithm are tabulated below Table 2.

Since the trigger response returned the original CLCT values used to generate each pattern file, it is evident that the pattern generation software works successfully. Similar tests have been conducted to ensure proper pattern generation functionality on both ME1/1 and MEX/1 geometries, as well as on both end caps.

Table 2: Results of testing the pattern generation software throughout the ME1/1 chamber. The number of trials per pattern was $N_{trial} = 1000$, and the values of each table entry represents the number of trigger responses matching the input CLCT values

PID	KEY=16	KEY=48	KEY=80	KEY=112	KEY=144	KEY=176	KEY=208
2	1000	1000	1000	1000	1000	1000	1000
3	1000	1000	1000	1000	1000	1000	1000
4	1000	1000	1000	1000	1000	1000	1000
5	1000	1000	1000	1000	1000	1000	1000
6	1000	1000	1000	1000	1000	1000	1000
7	1000	1000	1000	1000	1000	1000	1000
8	1000	1000	1000	1000	1000	1000	1000
9	1000	1000	1000	1000	1000	1000	1000
10	1000	1000	1000	1000	1000	1000	1000

The automation software has been validated by performing various parameter scans such as that specified in Fig. 7. A sample of data of the results for a single pattern is included below.

Table 3: Logged results of the automation tests using CLCT :(KeyHalfStrip = 32, Pid = 2, NHit = 6), The columns CLCT0 and CLCT1 are the coded hexadecimal data stored in the OTMB registers, when decoded this correspods to observing a single CLCT matching the parameters specified. The columns Δ_{LCT0} and Δ_{LCT1} represent the change of OTMB LCT counters as of the most recent pattern dump from the emulator. Note that the sum of $N_{total} = 1,000$ which wass the total number of pattern injections conducted

Response	CLCT0	CLCT1	Δ_{LCT0}	Δ_{LCT0}	N_{occur}
0	d202d	d0000	1	0	273
1	f202d	f0000	1	0	229
2	c202d	c0000	1	0	251
3	e202d	e0000	1	0	247

The results of Table 3 demonstrate some key artifacts of automated response logging. First it may be noted that there are four unique responses for a single pattern. This is due to the way the oTMB records data within its memory, after identifying a CLCT the TMB stores the data on the track it identifies along with appending a timestamp header. The first byte in both the CLCT0 and CLCT1 columns matches for every entry, and the values alternate between values (d,f,c,e). These values correspond to the bunch crossing of occurence with respect to the the oTMB's internal timing. Since the automation software requires interactions from the PC, ethernet protocol used to control emulator and read the results, between each pattern dump there becomes an unpredictable mismatch in timing as the oTMB sits idle during this period, hence the four unique entries.

Another key result of the automation software is the speed of operation. After running a variety pattern scans, on different dimensions, it has been observed that the bottleneck on the speed is the latency between tests, and that the time for the PC spent writing binary files is negligible. It can be estimated from these experiments that in a span of 20 minutes the automation system can perform roughly 100,000 pattern test, whereas only about 50 could be done in similar time by hand. This leads to conclude the automation software outperforms human capability by a factor of about 200,000. This enhanced speed will allow gathering and study of trigger behavior not just for specific CLCT combinations, but also gather statistical data on the trigger response for related CLCT combinations.

CHAPTER IV

CONCLUSION

With customized boards emulating the GEM and CSC chamber response to proton-proton collisions at the LHC, the automated emulation system has greatly improved the OTMB test-stand at TAMU. Implementation of the automated emulation system has resulted in the introduction of several new algorithms to the existing test-stand. While the scope of the pattern generation software may be limited to the study of OTMB trigger decisions, the algorithms composing the automation system can serve as a generic framework for facilitating hardware tests which utilise the emulator board. These tools will be vital in commissioning the L1 Trigger for Run-3.

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