RADIATION HARDNESS ASSESSMENT FOR MUON SYSTEM ELECTRONICS INSTALLED IN THE 2020 CMS UPGRADE

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

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Over the next few years, CERN is taking its LHC (Large Hadron Collider) particle accelerator into a series of long-term shutdowns, during which the devices rate of producing interesting particle interactions will be increased dramatically. At the moment, the CSC (Cathode Strip Chamber) trigger hardware and firmware at the CMS (Compact Muon Solenoid) has a near perfect efficiency in handling muon events in the CMS endcap, but considering the increase in luminosity (intensity) these systems will suffer a reduction in efficiency(3). Therefore new hardware and firmware are being devised to for high luminosity with the critical requirement that these components be tested to withstand the harsh radiation environment in the region of the CMS end-caps. The results of testing are detailed below, along with the relevant methods used to obtain said results. Building upon previous 2005 electronics equipment for the muon system, new digital components for the upgrade project will replace the copper connections within the CMS's detectors with optical fiber connections. Some replacements for analog components which have become obsolete (regulators, oscillators, etc) will be upgraded as well.

CHAPTER I

INTRODUCTION

A series of LHC shutdowns over the next several years will build the way to a five-fold increase in luminosity (collision intensity). This is the ideal situation for improving statistics on rare particle interactions but creates an enormous data acquisition and triggering strain on the CSC's (Cathode Strip Chamber) system and would decrease trigger efficiency from ~100 to 98% at 1 bunch collision for every 50 ns or from 63 to 59% at 25 ns (3). In order to maintain high muon trigger efficiency with increased LHC luminosity, the CSC trigger firmware and hardware must be improved, and its new constituent pieces rad-tested.

The COTS (commercial off-the-shelf) devices tested in this study are meant to be implemented in the endcap muon system electronics for CMS, the Compact Muon Solenoid Experiment, one of the four experiments at the LHC. CMS is composed of a central barrel section and two symmetric endcaps. The end-caps are flat disks of CSC detectors, aligned perpendicularly to the beam (as shown in Figure 1). Furthermore, because the endcaps are closest to the beam pipe, they experience the highest radiation levels (1).

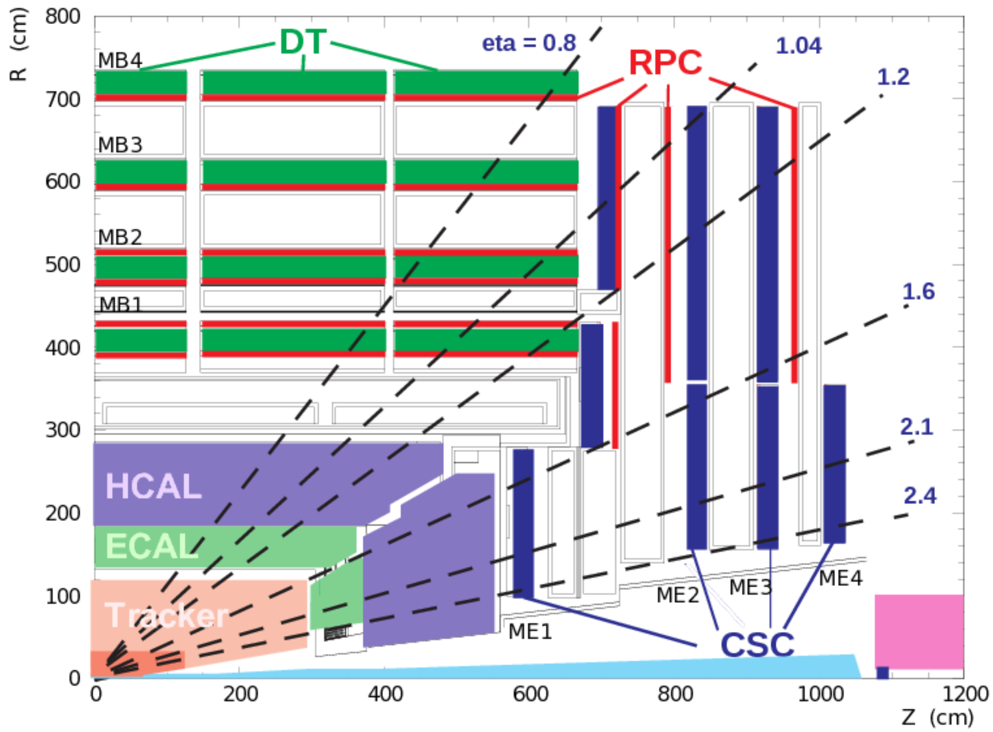

Figure 1: LHC Endcap (dark blue) separated by large Iron buffers (white) (7).

Each CSC reads out summaries of all charge deposits picked up by the CSC and feeds this information to a Trigger Motherboard (TMB). This makes the instantaneous decision on whether the interaction had an interesting muon candidate, and if so the Data Motherboards (DMB) will record the data. The electronic devices used on all of these boards require radiation tolerance studies to be sure they will operate reliably in the CMS endcap environment.

The current PCB (printed circuit board) (Figure 2) for tests contains a central FPGA atop the mezzanine board to perform logical commands, and the optical transceivers (circled in red) which are the subject of the tests. In the 2013 upgrade cycle, the board design had to be backwards compatible. That meant that dedicated space on the TMB was allocated for devices which communicated with copper cables. In the new upgrades, the CSC front-end boards are going to communicate with the TMB entirely through optical fibers. On account of this a new optical transceiver in place of the copper connections will be tested.

Figure 2: Test Board for last series of radiation tests w/ tested components

The inner-most layer of CSC detectors experiences the highest degree of radiation. With the new luminosity the HL-LHC (high luminosity LHC) will experience 1 MeV neutron fluence as high as 10^{12} n cm^{-2} and about 10 krad total dose over 10 years (1). This puts a constraint on the COTS devices: they must be able to perform reliably despite SEUs (single event upsets), transient errors in digital circuits caused by incident neutron collisions within the silicon of a chip, and they must also have sufficiently high TID (total ionizing dose) tolerance to withstand 10 krad of total dose (1). In previous studies of muon system electronics design, 2012 and earlier, this baseline target has been tripled (1) to provide an extra safety factor, which has the dual advantage of making certain that the devices do not fail and that they may last longer than expected.

SEUs in silicon-based electronics become significant with neutrons of energy higher than 20 MeV (1). Neutrons of this energy level are still common in the CMS endcap, with over 100 cm^{-2} fluence per second. This is evident from the neutron fluence spectrum shown in Figure 3, where neutron fluence only drops off after 100 MeV.

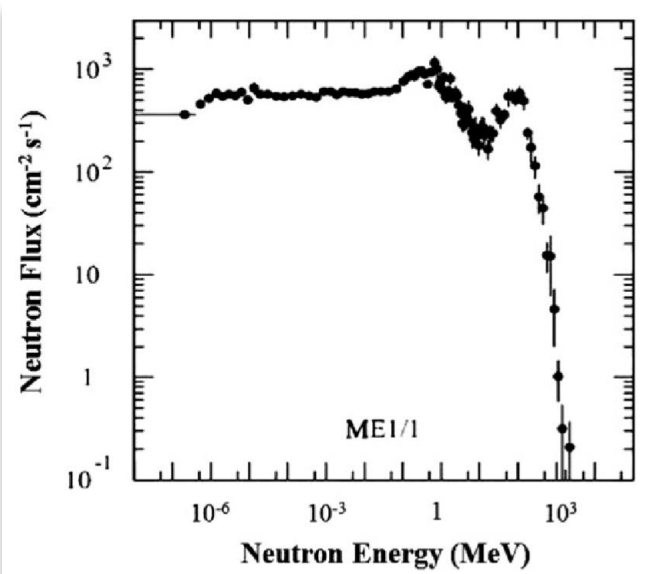

Figure 3: Energy Spectrum of Neutrons in the highest radiation area of the CMS endcap (1)

For performing SEU studies, the Texas A&M University Cyclotron Institute can provide proton beams with energy up to 45 MeV(4), and above 30 MeV the SEU response in silicon is equivalent for neutrons and protons which makes it useful for our neutron studies. Over a few hours of high-intensity testing we may see a high rate of SEUs for a given digital component, but this may translate to only a couple per month in the CSC electronics during normal operations at LHC. We will only need mitigation factors, like sending redundant signals, etc., for those components that will see multiple SEUs per day.

Digital components are the only components which require testing for SEUs, because SEUs can flip a logical signal (e.g. from a one to a zero) and cause data corruption or cause dysfunction in a control or decision system. For TID studies, we need to test both digital and analog components with the low energy neutron radiation provided in the Texas A&M University Nuclear Science Center's TRIGA reactor. This reactor can supply exposure to the DUT (device under test) within 2 to 3 hours that is equivalent to decades in CMS end-caps.

CHAPTER II

METHODS

The tests required by each device type fall into two classes: Those devices which only require TID studies, and those which require SEU testing in addition with concurrent TID testing. The SEU testing with concurrent TID testing was performed at the Texas A&M University's cyclotron facility using a proton beam. The TID-only studies were conducted with gamma rays and neutrons in the Texas A&M University Nuclear Science Center's TRIGA reactor.

TID-Only Studies

Some of the devices needed for CMS experiment are not handling logic, and the only testing required for them is to verify they will continue to operate properly in the radiation environment of the CMS endcap.-The metric for operational failure is different for each type of device; for some devices only require maintaining a fixed voltage output, while others have a output wave signal with shape and amplitude that must be maintained. The analog DUT (Devices Under Testing) are therefore separated in the following categories which will expand on the purpose of each device and be tested.

The first category contains the devices which must maintain only a constant output voltage. These include the level translators and LDO (low dropout) voltage regulators. On the CSC TMB (trigger motherboard), the onboard electronics requires a few different voltage power supplies to operate reliably (ranging from 1.0 to 2.5 V). The LDO regulators step-down the DC input voltage to a lower level, suitable for the device it powers. The level translators also step down voltages; but these devices are specifically used for any incoming signals that require a different level to communicate with devices like the FPGA, and not for supplying power.

LP38853s-adj (from National Semiconductor), MIC49500WR, and MIC69502WR (both from Micrel) are the LDO linear regulators that were evaluated during this study. These were the only commercial regulators that met the current rating requirements for the muon electronics upgrade. These regulator devices have selectable output voltage that is defined by application of specific resistance networks outside of the chip. If any of these devices demonstrate a deviation from set power output more than 5 percent in magnitude during exposure, then such devices have the potential to damage the connected electronics. This paper will detail the device types and methods used for linear regulators; level translator tests are similar in nature.

In the March 2017 electronics TID tests (4), there were 2 (Figure 4) or more instances of each device tested to increase the significance of the results. Some devices had more copies installed because the design specs required some LDO devices more than others. The devices were taken to the Nuclear Science Centers' TRIGA reactor. The idea of the test is to measure incident voltage over each LDO device~~s~~ before and after exposure to neutron and gamma radiation as an indication of how it would perform in CMS conditions. All tests were done with at-least 100 mA of current going through the chip during testing.

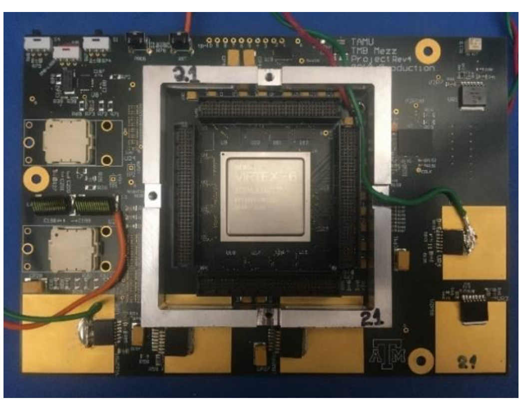

Figure 4. March 2017 Test Board for LDO devices. The devices sit on copper cooling pad.

Ideally testing is performed after the nuclear reactor has been inert for a while, otherwise residual gamma radiation during startup will distort the actual dose received by the DUT. In this study we account for the radiation dose before, during and after the reactor is critical.

The moveable reactor core (Figure 5) was situated away from the testing cell before testing, and allowed to place a borated plate before exposure. This borated plate is installed to block neutrons below 100 keV. This was desirable for the tests because while those neutrons would certainly increase the dosage on each device the resulting spectrum would be inconsistent with what is expected in the CMS environment.

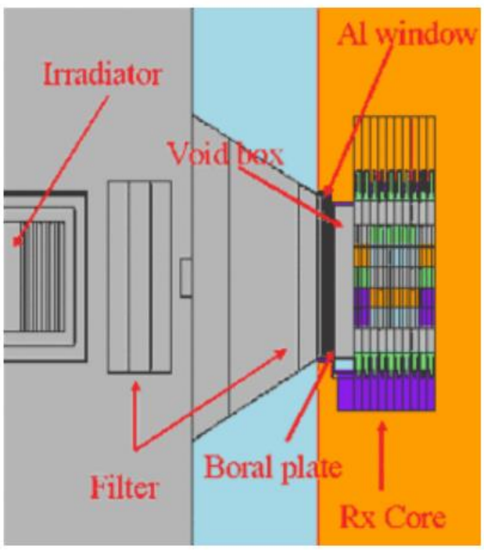

Figure. 5. Testing Cell Cross Section (6)

The LDO devices were under power during the tests, and the testing board was connected to a power supply and ammeter outside the main cell to ensure the connections in the device did not come loose while testing. Another device monitored the incident radiation inside the testing cell over time; the device was supplied by the technicians at the NSC. It was the means by which we know how much exposure (krad) the device experienced in the duration of the test. After an interval of 7 krad, the testing board was quarantined for a 2 week cooldown period. Then it was tested for its output voltage levels and prepared for another round of reactor exposure immediately afterwards. This series of exposures was performed up to 21 krad as this test was done parasitically in parallel with a different experiment. In order that their long-term behavior could be analyzed, another test with two instances of MIC49500WR and MIC69502WR on the board was performed, and the voltage output over each device was measured after 40 krad of exposure.

The next category of devices under TID analysis simple logical devices, where not only the amount of the output must be tested but also the shape of their output. These were the SN74AUP1GDCK inverter and the SN74VC1G34DCK OR gate tested in March 2018. These devices were not tested in intervals, but rather the entire expected lifetime dosage was supplied to them during one 3 hour interval at the NSC. After waiting two-weeks for the radiation cool-down, voltages were supplied to the gate's inputs, and if they performed as expected, then the devices would pass the test.

SEU-focused Studies

Transient errors induced by SEUs in a DUT can cause small data transmission errors, but most of the time will not affect CMS efficiency. However persistent errors which require a reset of the control system can impact efficiency. This can be understood in terms of the number of resets that are required to mitigate persistent SEUs during a period of time, and the length of time which the reset operations take, which leads to deadtime relative to the CMS total runtime. The aim of these next tests is to determine the rate of SEUs which are inherently transient (and don't require resets) as well as the rate of SEUs which persist over thousands of consecutive calculations until a reset is issued. Both events are undesirable and are measured in these studies. In these tests, each device under test (in this case optical transceivers) are tested up to the three times safety margin for decade-long exposure in the CMS environment, and the neutron fluence vs SEU count is used to calculate an equivalent SEU cross section for said device (2).

The Samtec Firefly ECUO-R12-14-030 it is an optical receiver which would replace devices in the upcoming upgrade which are no longer available. The testing board had only one input and required manual changes to test multiple instances of the device. The image below (figure 6) is the new mezzanine 2019 prototype board, which shows the arrangement of parts on the board as used in the radiation studies. Also included in Figure 7 is an image of the older board for comparison.

Figure 6. Circuit Board Used For Future SEU Testing of Optical Devices.

The spacing between parts in this board design allow for testing individual parts during the radiation experiment. The beam from Texas A&M University's cyclotron facility can be collimated to a 1.5 cm diameter (4) to illuminate one specific device at a time. In this way we knew exactly what device registered an SEU at any given period. This board was suspended directly in-front of the K150 beam and the board was manually positioned in front of the collimator (Figure. 7). The red cross hairs indicate where the beam was focused.

Figure 7. The K150 beam pipe, arranged facing the testing board.

The K150 beam was set to expose the board to a stream of 45 MeV protons (4) at a fluence of $12.69*10^{10}$ up to $14*10^{10}$ p cm^{-2}, which reached the desired exposure after 45-90 minutes. The amount of time depended on the flux which was used during the test; a higher rate of incident particles meant that the test was shorter.

During the proton exposure, an onboard FPGA was programmed to send a random 16 bit sequence through the optical transmitter. This was then looped back into the optical receiver and compared to the original signal by the FPGA. Whenever a discrepancy was discovered, the FPGA would add that to the SEU counter, and if the software monitoring system determined the SEU persisted for more than 3 consecutive checks, a manual reset would be performed.

CHAPTER III

RESULTS

Below is a graph detailing percentage of change in output voltage versus the amount of exposure for the three types of LDO regulators (Figure 8):

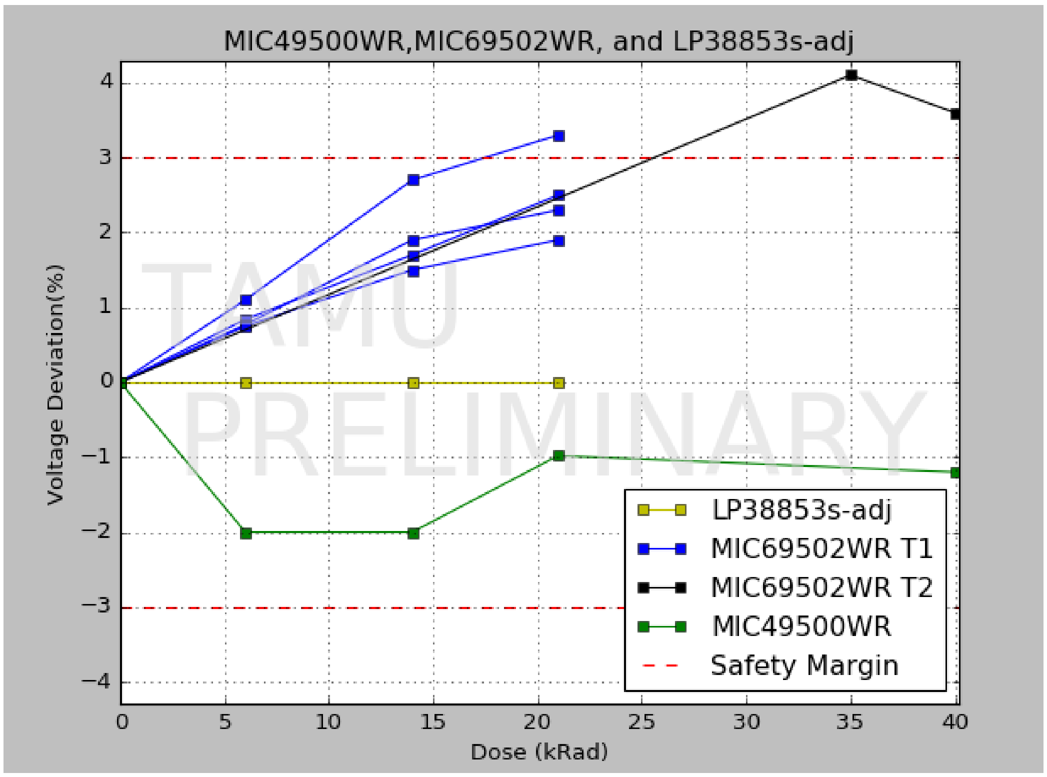

Figure 8: LDO Regulator Results

The cyan-colored points of Figure 8 plotted at 40 krad exposure, were done with different devices of the same type at a separate time. The three blue lines represent three different copies of MIC69502WR, the only regulator of the three to tread past the safety margin at one measurement of dose. The LP38853s-adj never demonstrated any change in incident voltage, its percentage change was zero.

Despite one of the MIC69502WR passing the safety margin at 21 krad, all three devices have been classified as reliable for use in upgrades. This is because, on average, that device was below the margin, and well below the other typical failure standard of 5 percent (1). It may be worthwhile to put MIC49500WR through more tests simply because of its irregular behavior.

The two Samtec Firefly optical receivers were tested at TAMU Cyclotron facility, to 22.3 krad and 24.6 krad exposure respectively as well as $12.69*10^{10}$ and $14.00*10^{10}$ protons/cm^2 cross section (Table 1). During these exposures both devices experienced 33 SEU.

Table 1: SEU Count for devices exposed to protons over 45 MeV in a cyclotron beam.

Optical Reciever SEU Results

	Samtec Firefly 2	Samtec Firefly 3	SN-R12-C01001-23 1	SN-R12-C01001-23 2
Exposure (kRad)	22.3	24.6	25	23
Proton Fluence (p/cm^2)	$14.00*10^{10}$	$12.69*10^{10}$	$18.2*10^{10}$	$16.3*10^{10}$
SEU Count	33	33	128	161.8

We can convert that to the daily experienced SEUs in the following manner:

$$DailyRate = \left(1.577 * 10^8 \frac{cm^2}{day}\right) * \frac{SEU\ COUNT}{FLUENCE}$$

The SEUs over the total fluence gives us the cross section of an SEU event (the likelihood such an event will occur), which has units of area. The linear factor giving us daily rate from cross section is a calculated value from the CMS environment (2). Using this value, the two firefly receivers will experience one event every 30 days (for device 2) and one event every 40 (for device 3).

The two Snap12 Rx tests were performed at the UC Davis Nuclear Research Center cyclotron (5), rather than at the TAMU Cyclotron Institute. The Snap 12 results for the two receivers correspond to 1 event every ten days for device 1 and every 8 for device 2. The Snap12 Rx results were verified independently (5) at the TAMU Cyclotron Institute, where they were calculated to have around 1.2 SEU per day in normal CMS operations at LHC (worse than the Firefly but not bad).

Another optical device tested, the Avago optical receiver, began experiencing persistent SEUs when under the proton beam, and would not recover its performance after a manual reset. This device was the only optical model among the body of devices to fail, as under CMS conditions it would experience several thousand SEU from charge deposit daily. This demonstrates the importance of SEU testing, despite the transient nature of charge deposits: the CMS Experiment simply couldn’t arrive at the same high degree of efficiency if it had to compensate for poor electronics with frequent resets.

CHAPTER IV

CONCLUSION

Most of the components tested at each of the three facilities can perform in a high radiation without SEUs and up to 30 k Rad. This is enough for their inclusion in any device in future upgrades. Most tests performed on LDO-devices do not examine their performance versus increasing exposure; the relationship between decreasing performance and increased TID was verified on account of this unique aspect of the most recent tests. Furthermore, because devices of the same type, but from different batches, demonstrated similar trend in the exposure vs performance tracks it is certain that the supply of off the shelf devices was not corrupted. The safety margin implemented for these devices will likely see them outperform their required decade long lifespans, and not need further intervention unless additional upgrades are proposed in the future. As for the optical devices, there are two commercial models that were proven to work well for the electronics upgrade project. It will be important to retest some of these devices in the future as their production techniques may change, but the methods outline for analog and digital devices in this paper will assist in securing well made components in CMS electronics upgrades.

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