Total Ionizing Dose Testing of the ABC130 ASIC for the ATLAS Phase-II Semiconductor Tracker Upgrade

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The Large Hadron Collider's (LHC) current inner detector was not built to withstand the radiation damage from the 3000 fb^{-1} of integrated luminosity that is planned for the high luminosity LHC (HL-LHC). Therefore, the ATLAS inner detector (ID) must be completely upgraded. As a part of this upgrade, the semiconductor tracker (SCT) and transition radiation tracker (TRT) will be replaced with new silicon microstrip sensors [1]. These silicon strips will be read out by the ABC130 chip and thus the ABC130 must be able to withstand an expected 30 Mrad of radiation over 10 years. The ABC130 chip was irradiated with 70 Mrad of x-ray radiation over the course of 2 days and the results are discussed in this report.

I. INTRODUCTION

The Standard Model

The Standard Model (SM) is currently humankind's most complete and consistent theory of all known fundamental particles and their interaction via three of the four known forces of nature - electromagnetism, the weak nuclear force, and the strong nuclear force. It is a remarkably successful theory, having predicted the existence of particles such as the W, Z and Higgs boson before their discovery as well as being consistent with almost all experimental observations to date. However, there is a significant amount of experimental evidence demonstrating the incompleteness of the SM. Any truly complete description of nature should include gravity and a solution to the hierarchy problem - an explanation of why gravitation is so much weaker than the other three forces. Aside from that, the SM does not contain a dark matter candidate nor an explanation of dark energy leaving 84% of the observed matter in the universe and 95% of the energy content a mystery for now. Furthermore, the SM neutrinos are massless and thus do not undergo flavour oscillation which is inconsistent with observation. The question of how a matter antimatter asymmetry of one part per billion arose in the early universe is also unexplained by the current amount of CP violation in the SM.

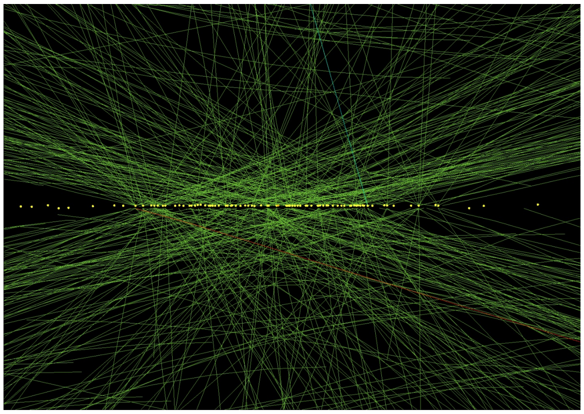
In order to make progress on the problems mentioned above, it is imperative that the SM be rigorously tested in order to uncover any subtle inconsistancies with experimental observation at the LHC. Even small deviations from SM predictions could provide valuable hints as to what physics beyond the SM might be.

The LHC and HL-LHC

The LHC accelerates protons to ultrarelativistic energies in order to produce the required TeV scale collisions to probe the SM and beyond. It is a 27 km long *pp* collider designed to run at centre of mass energy $\sqrt{s} = 14$ TeV and luminosity $\mathcal{L} = 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$. There are 1232 high field 8.3 T liquid helium cooled superconducting dipole electromagnets which are required to direct the beams around the circular path as well as 392 quadropoles to focus them. It has two ultrahigh vacuum beam pipes for opposite momentum proton beams which cross at four points along the ring. At these crossings, bunches of 10^{11} protons intersect every 25 ns which resulted in approximately 20 collisions per bunch crossing during Run 1. One of the intersection points is centered at the ATLAS detector, one of two general purpose detectors at the LHC and the largest ever built.

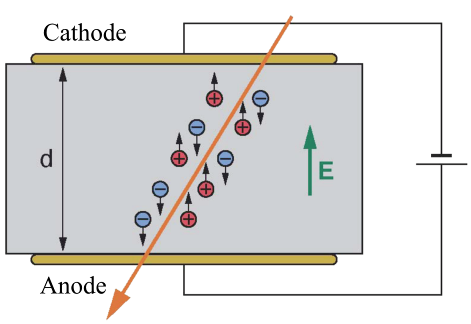
There are two ways that the LHC can continue to probe deeper into physics of the SM and beyond: the first is to increase the energy of the collisions, and the second is to increase the luminosity of the machine to yield higher statistics. An increase in luminosity, to 5×10^{34} $\text{cm}^{-2}\text{s}^{-1}$, is planned for the HL-LHC in 2025. The HL-LHC will require a full upgrade to the ATLAS detector, particularly the ID as the average number of interaction vertices per bunch crossing will go from $\langle\mu\rangle = 23$ to $\langle\mu\rangle = 140$.

Figure 1. Pileup at the HL-LHC.



The ATLAS ID is currently made of four sections. Closest to the beam pipe is the insertable b-layer (IBL) which was added during the first long shutdown. The IBL is a pixel detector which aids the original pixel detector in vertex reconstruction and b-jet tagging. Next is the original pixel detector which contributes to the same measurements as the IBL. The semiconductor tracker (SCT) is the third high resolution layer; made of silicon microstrips it provides high resolution particle tracking. The general principle behind silicon microstrip sensors is the following: semiconductors like silicon can have electron-hole pairs kicked into the conduction band by an energetic particle. Therefore, if a voltage is applied across a semiconductor and no particles are streaming through, then no current will flow because the conduction band is not populated. However, if an energetic particle interacts with the semiconductor, the conduction band will become populated and a detectable electrical signal will be generated.

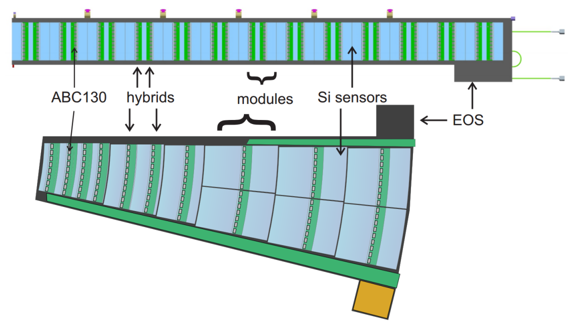
Figure 2. Principle behind a semiconductor tracker.



Finally, the transition radiation tracker (TRT) made of gas-filled straw tubes is a larger section of lower resolution sensors which also aid in electron identification. Since the HL-LHC will require the ATLAS detector to be capable of higher resolution vertex reconstruction as well as a higher readout frequency and greater radiation hardness, the ATLAS phase-II upgrade will provide an ID with more microstip sensors, replacing the current TRT [1]. This upgrade is needed because the TRT will experience near 100% occupancy at $\mathcal{L} = 5 \times 10^{34}$ cm^{-2}s^{-1}.

The ATLAS SCT is made of barrels and end caps which are situated coaxially with the LHC beam. On a smaller scale, these barrels and end caps are made of planar components called staves and petals, on which silicon microstrips and readout chips are mounted in the form of modules. For this report, the readout application specific integrated circuits (ASICs) are the ABC130 chips.

Figure 3. SCT stave and petal.



Effects of Radiaton on Electronics

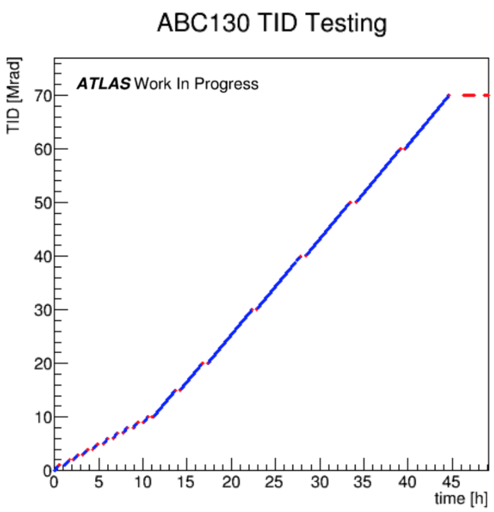
Total ionizing dose (TID) effects on electronics are the changes in operating characteristics due to cumulative radiation damage. This referes to effects that are correlated with total exposure over the lifetime of the electronic component. On the contrary, single event effects (SEE) are those which are associated with a localised interaction between a high energy particle and an electronic component. An example of an SEE is memory corruption due to a bit flip caused by an energetic particle. One possible problem attributed to TID effects is the buildup of charge in SiO_2 defect centres within a transistor. This can happen when a high energy particle liberates an electron-hole pair within the SiO_2 crystal; this pair drifts apart in an electric field. However the electron is more mobile and can quickly dissipate leaving a net possitive charge to be trapped in defect centres and accumulate in the device [2]. This charge buildup can cause changes in characteristic voltages within the device that can lead to malfunctions.

The ABC130 ASICs must not be plagued by a drastic increase in power consumption as TID increases because the cooling system for the chips isn't designed to deal with the increase in heat. Additionally, it is better to have a constant, predictable power consumption so the entire ATLAS power supply system can perform at best. Finally, if a buildup of charge occurs in the device over time, the data taking conditions would also change and therefore data quality issues could arise.

II. METHODS & RESULTS

In order to test the TID effects of radiation on the ABC130, the chip was exposed to 70 Mrad of x-ray radiation over the course of two days, more than twice the expected total dose the ABC130 will endure in the HL-LHC. The dose rate was 2 Mrad/h and periodically the exposure was stopped for 30 minutes to perform calibrations and scans. In steps of 1 Mrad, the TID was increased from 0-10 Mrad, then in steps of 5 Mrad from 10-20 Mrad, and finally in steps of 10 Mrad from 20-70 Mrad. This exposure scheme is depicted in the following plot.

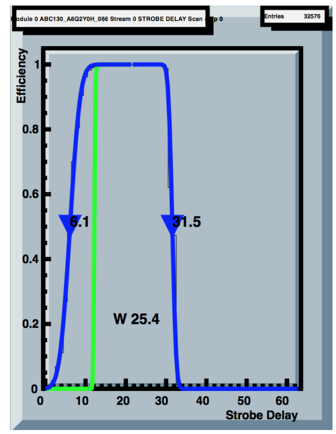
Figure 4. TID delivery scheme.



The procedure was performed with no cooling system for the ABC130 because it was not available at the time. In order to simulate a more realistic environment, the chip was exercised during irradiation by reading and writing to registers on the ABC130 as well as simulating hits. During the entire experiment, both current and voltage supplied to digital and analog components of the chip as well as the voltages across the chip were plotted online as well as recorded for offline analysis.

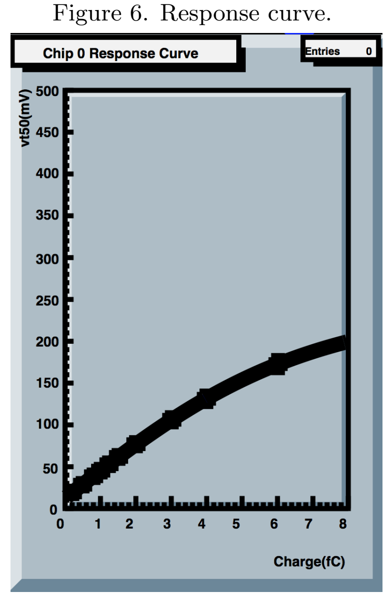
During the 30 minute pauses, the strobe delay was calibrated and a scan was performed in order to plot the response curve. The strobe delay is the time between injecting a charge into a channel of the ABC130 and reading out the result of whether it was registered as a hit or not.

Figure 5. Strobe delay [ns].



Secondly, the response curve is an average over all channels of the 50% threshold voltage (vt50) as a function of injected charge, where vt50 is the voltage across a channel for which 50% of hits are registered. The slope of this curve is the gain in mV/fC.

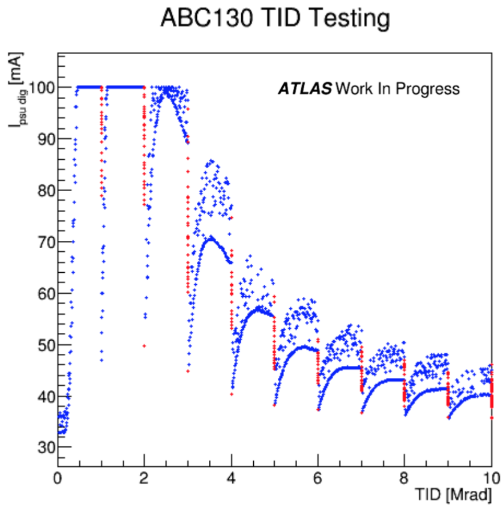
Figure 6. Response curve.



The goal of the TID tests was to detect any TID effects on the ABC130 by measuring the change in power supply characteristics as well as the change in gain and noise as a function of radiation dose. However, it is important to discriminate between true TID effects and dose rate effects.

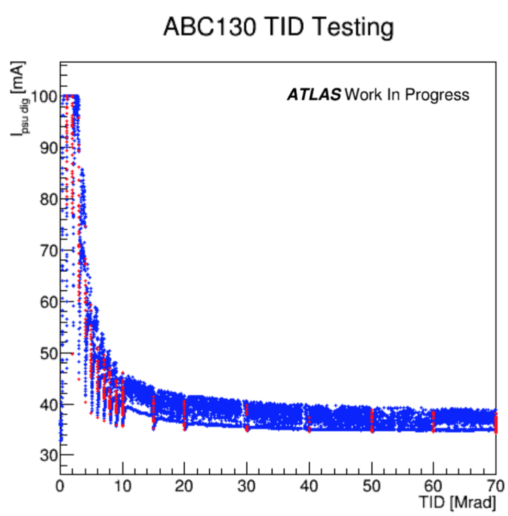
An initial spike in current supplied to the digital end of the ABC130 was observed which was limited by the current limit set at 100 mA on the power supply; this is hypothesized to be a result of the high dose rate but further testing is required to verify such a claim.

Figure 7. Current supplied to the digital end of the ABC130.



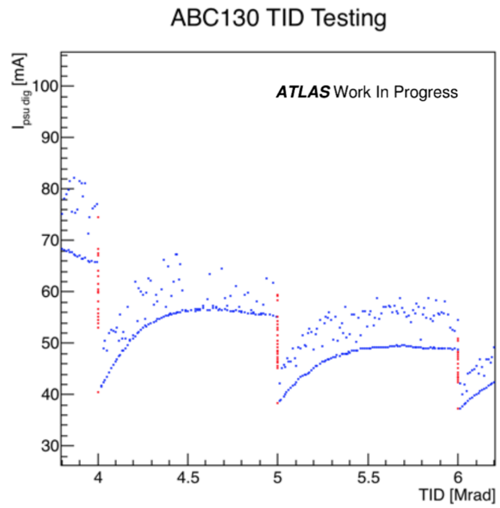
After 3 Mrad, the current dropped below the limit of 100 mA and decayed back towards the nominal value of 33 mA which was approached asymptotically as the testing progressed [Figure 8].

Figure 8. Current supplied to the digital end of the ABC130.



On a shorter time scale, over a smaller dose range, it can be seen that each period of irradiation causes a steady increase in current followed by a plateau and what looks to be the beginning of a recovery phase. This effect is not completely understood yet.

Figure 9. Current changes over radiation cycle.

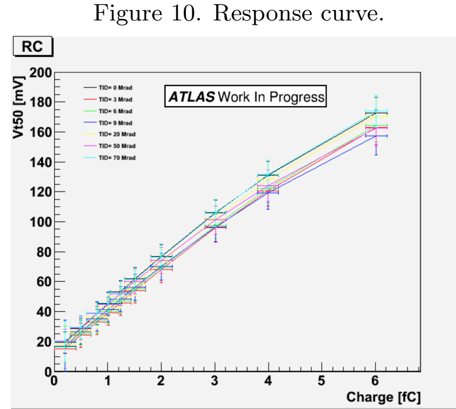


Other characteristics of the power supply and chip voltages oscillated with the periodic exposure to radiation but on a much smaller amplitude and so these effects are not a concern from the perspective of searching for TID effects.

Another place to look for TID effects of radiation from the ABC130 tests is in the behaviour of the readout characteristics displayed in the response curve, gain, and noise. The response curve, as stated above, is the channel averaged 50% threshold voltage as a function of injected charge. The gain, is related to the slope of the response curve, and the noise refers to the spread in 50% threshold voltage over channels as a function of charge injected. The following plots show the changes, if any exist, that occured in each of these quantities during the TID tests.

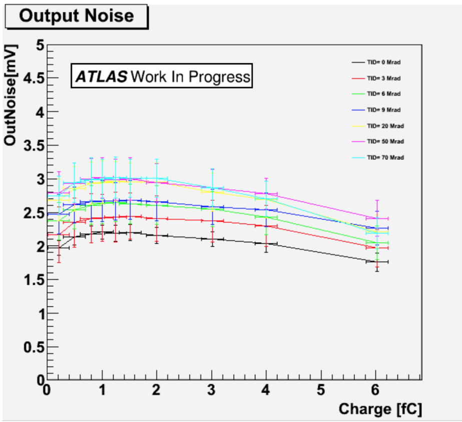
The gain and response curve over the course of the irradiation have no clear trend; they varied only a small amount during testing.

Figure 10. Response curve.



However, the noise, or spread of the threshold voltage across channels increased significantly with TID.

Figure 11. Noise.



III. DISCUSSION & CONCLUSIONS

The most important conclusion to draw from the TID tests detailed in this report, is that more testing is required in order to properly understand how the ABC130 responds to TID effects. Room temperature testing is not realistic, nor is a dose rate of 2 Mrad/h; these tests were a preliminary study and are a good start to a series of TID tests. Therefore, testing is required at a lower dose rate and with a realistic, temperature controlled environment for the ABC130. The drastic effects of radiation on the current supplied to the digital end of the chip is not yet understood; however it may be a dose rate effect, which will be determined in future tests. Furthermore, a strong conclusion can be drawn that the ABC130 chip can withstand large amounts of radiation dose, on the order of 30 Mrads while still operating well. Finally, it was shown that the noise of the readout channels increased significantly with TID. These effects should be studied in more realistic situations in order to determine their dependence on other variables like dose rate and temperature.

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[1] ATLAS Letter of Intent of Phase-II Upgrade, CERN-2012-022 LHCC-I-023 December, 2012

[2] F. Faccio, "Radiation effects in the electronics for CMS "