Single Event Upset Energy Dependence
In a Buck-Converter Power Supply Design

G. Drake, Member, IEEE, P. De Lurgio, Member, IEEE, A. Gopalakrishnan, S. Mahadik, B. Mellado, J. Proudfoot, R. Reed, A. Senthilkumaran, R. Stanek, On behalf of the ATLAS Tile Calorimeter System

Abstract—We present a study of Single Event Upsets (SEU) performed on a commercial pulse-width modulator controller chip for switching power supplies. We performed tests to study the probability of an SEU occurring as a function of incident particle (hadron) energy. We discuss the performance of the circuit, and present a solution using external circuitry to effectively eliminate the effect.

I. INTRODUCTION

A new switching power supply has been designed for use in the front-end electronics of the ATLAS Tile Calorimeter (TileCal) [1] for the ATLAS experiment [2] at CERN. The new supply is a drop-in replacement for the previous version that was installed on the detector in 2007. A power supply for this application consists of eight different bricks, which together provide power to the front-end electronics in a module of the Tile Calorimeter detector. Each of the eight bricks provides power to a different set of sub-circuits in the detector module. The supplies must function in a radiation environment and in a magnetic field. There are 256 modules in the TileCal detector, or a total of 2048 bricks in the system. All units will be replaced in 2013. A description of the redesign project is given in [3-4]. A picture of a new brick is shown in Fig. 1.

One of the performance requirements for the bricks is radiation tolerance, since the power supplies must function on the detector very close to the front-end electronics. The radiation requirements for the TileCal power supplies are given in Table I [5-6]. The table shows the expected dose for 10 years of running at a luminosity of \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\), including safety factors. Our interpretation of this specification is that there should be no hard failures in irradiation up to these limits, although changes in overall performance may be acceptable depending on the severity and the ability of the overall system to continue to perform at an acceptable level.

The original version of the bricks, V6.5.4, had been tested previously as part of the design review process. No problems were found in these tests. In the redesign project, we endeavored to use as many of the same parts as possible, especially the critical active parts, and generally succeeded with the exception of one new voltage regulator. Nonetheless, we felt it important to repeat all of the tests, to confirm that the new design was as radiation tolerant as the previous one.

For our radiation tests, since the specifications were differentiated by radiation type, we chose three facilities for which there were relatively pure sources of particles. This seemed prudent in order to clearly understand the sources of radiation damage, since the mechanisms are different for each type of radiation. The three facilities that we used and their respective radiation types are shown in Table II. The testing program began in December, 2010, and continued through May, 2011. In this paper, we will focus on the results from proton irradiation.

![Fig. 1. View of the new power brick for the ATLAS TileCal detector.](image_url)

**TABLE I**

<table>
<thead>
<tr>
<th>Radiation Tolerance Limits for the TileCal Bricks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Years of Running, at (10^{34} \text{ cm}^{-2} \text{s}^{-1})</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Expected Dose</td>
</tr>
<tr>
<td>Survival Limit</td>
</tr>
<tr>
<td>Safety Factor</td>
</tr>
</tbody>
</table>

TID = Total Ionizing Dose, NIEL = Non-Ionizing Energy Loss; SEE = Single Event Effects; 1 Gray = 100 Rads. The Survival Limits include the safety factors and are the specified dose levels for testing.
II. OVERVIEW OF THE CIRCUIT

The basic topology of the brick is a transformer-coupled buck converter. Each brick receives 200 VDC at low current, and converts it using switching techniques to low voltage at moderate currents. A block diagram of the new power supply brick is shown in Fig. 2.

The heart of the design is the LT1681 controller chip [7]. It is a pulse width modulator that operates at a frequency of 300 kHz. The output duty factor can vary from a few percent up to a maximum of 45%. The pulse width is controlled by two inputs: the slow feedback path, which monitors the feedback voltage with a bandwidth of ~1 kHz, and a fast feedback path that monitors the current through the low-side transistor on the primary side. Both feedback paths must be designed properly to ensure continuous-mode operation at the nominal voltages and currents for each brick type.

The LT1681 provides an output clock to the transistor driver, IR2110 [8]. This device has sufficient current and voltage output capability to drive the high-side and low-side power Field Effect Transistors (FETs), which perform the switching on the primary side. The design uses synchronous switching, i.e. both the high-side and low-side transistors turn on and conduct for the duration that the output clock is in the high state, and both are in the off state when the clock is low. When the FETs conduct, current flows through the primary windings of the transformer, which transfers energy to the secondary windings. The transformer is a custom planar design made specially for this application.

The buck converter is implemented on the secondary side of the transformer. The output side also contains an additional LC stage for noise filtering. Voltage feedback for controlling the output voltage is provided by the Avago opto-isolators HCPL-7800 [9]. The design also incorporates a shunt resistor for measuring the output current, the voltage for which is fed back using an opto-isolator. The secondary side is completely floating with respect to the primary side, to facilitate grounding isolation of the front-end electronics with respect to the primary side of the power distribution system.

The value of the output voltage is controlled by a reference voltage that comes from the central controller in the power supply box. The feedback circuit uses LM6142 operational amplifiers [10].

III. DESCRIPTION OF THE TEST APPARATUS

The radiation testing was performed on the individual bricks, rather than as a complete power supply box. The bricks were operated under light load rather than full load to reduce the need for cooling. Each brick has 6 analog outputs that are part of the monitoring of the brick, as shown in Table II. When the bricks are mounted into the power supply box, these voltages are sent to the control interface board in the box where they are digitized and the data then read through the interface to the monitoring system of the experiment [11]. The connection between the brick and the control board is normally done via a 20 cm flat cable, a relatively short distance requiring very little drive of the signals. Since the box was not tested as a whole, there needed to be a way to digitize these voltages in order to monitor the performance of the bricks during irradiation. However, care was needed so that the external digitizer did not become irradiated itself. Furthermore, the output voltages of the bricks do not have good drive capability, so the transmission path must be kept short. The solution to this problem was to use buffer boards, one for each brick, separated from the bricks by approximately 0.8 m. This allowed the devices under test to be placed directly in the radiation environment, but have the buffers out of the direct radiation flux to reduce the damage that the buffer boards might receive. In some cases, it was also possible to add additional shielding around the buffers. The buffers were then configured to differentially drive 16 m long shielded twisted-pair cables. This allowed the digitizer and data acquisition computer to be far away from the radiation sources, to help reduce radiation effects there, in particular the corruption of the computer memories. A graphical representation of the data acquisition scheme is shown in Fig. 3.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Radiation Type</th>
<th>Radiation Source &amp; Test Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massachusetts General Hospital</td>
<td>Boston, MA</td>
<td>20-200 MeV Protons</td>
<td>Cyclotron for cancer therapy; Test for SEE</td>
</tr>
<tr>
<td>University of Massachusetts – Lowell</td>
<td>Lowell, MA</td>
<td>1 MeV (equiv) Neutrons</td>
<td>Neutrons from decay of $^{235}$U in a research nuclear reactor; Test for NIEL</td>
</tr>
<tr>
<td>Brookhaven National Laboratory</td>
<td>Upton, NY</td>
<td>1 MeV Gammas</td>
<td>Decays from a $^{60}$Co source; Test for TID</td>
</tr>
</tbody>
</table>

TABLE II
RADIATION FACILITIES USED IN THE TESTING PROGRAM

<table>
<thead>
<tr>
<th>Brick Monitor Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Input Voltage</td>
</tr>
<tr>
<td>2 Input Current</td>
</tr>
<tr>
<td>3 Output Voltage</td>
</tr>
<tr>
<td>4 Output Current</td>
</tr>
<tr>
<td>5 Temperature 1</td>
</tr>
<tr>
<td>6 Temperature 2</td>
</tr>
</tbody>
</table>

Monitor quantities from the brick were processed as voltage signals, and were used to monitor the performance of the bricks through the irradiation studies.
In performing radiation tests, the ideal case is to have uniform flux on the face of each brick. In most cases, the solid angle of the beam source was relatively small. The radiation sources were generally sufficient to irradiate the entire surface of a single brick to within 10% uniformity, but they were not sufficient to irradiate a structure in which the bricks would be tiled. Because irradiation time was sometimes expensive, and because it was deemed important to test multiple bricks at a time (we chose five at a time for most studies), a fixture was designed so that the bricks were stacked laterally, one behind the other, as shown in Fig. 3. For the tests with the proton beam, the particle flux was perpendicular to the front face of the stack. Each buffer board was read out using a 32-conductor cable consisting of shielded twisted pairs. This cable had digital signals for turning on and off the bricks and to detect trips, and also provided power for the buffer boards. The 200V needed to operate the bricks was sent on a separate single 16 m coax cable to the buffer boards, and then daisy-chained from buffer board to buffer board. Each buffer board in turn sent the 200V to the brick that it was connected to. The ADC was part of a data acquisition module from National Instruments, Model NI-DAQ M series 6221 [12]. It contained a 12-bit ADC, with a multiplexer capable of digitizing 40 differential channels. Thus, this module could read out up to six buffer boards, with each buffer board supplying 6 voltages. Generally, each test session used 5 boards, although in some cases a sixth buffer board was used.

The interface of the NI digitizer module to the computer was done via USB. National Instruments supplies drivers to allow end users to write their own data acquisition programs. We wrote a program using VC++ that would read out the voltages from the buffer boards continuously, so that trips and changes in monitor voltages could be monitored during the course of irradiation. The program was designed to detect changes in values, and would record the values in a data file if they became outside of a preset tolerance. Generally, the program worked as follows. Approximately every 80 ms the entire 40 channels were read four times and then averaged. The averages were then compared to baseline means and
RMS values measured before the start of each test session. If any channel was outside of predefined limits, the entire event was written to a file. If no deviation from the baseline was seen, then the event was ignored. At every 10 second interval, the readings were written to the file independent of their tolerances.

The data acquisition program evolved over the course of the different radiation studies. At first the bricks were run continuously. If a trip was detected, the program attempted to restart the brick, retrying up to 10 times before giving up if the restart was not successful. Subsequently a procedure was added where the bricks were stopped and started every 30 minutes in order to verify that the starting of a brick did not fail. This flexibility in program control allowed us to adapt to different conditions and issues as our tests progressed. This became especially important in the tests with protons, as will be described in Section IV.

Before beginning each test session, the apparatus was set up at the test facility but outside of the radiation area. The bricks that were to be tested were run overnight, reading and recording data, to establish a baseline, and to ensure that all of our devices to be tested were good. Each radiation test session used new bricks so that the results were not skewed. Generally this approach worked well, but there were some problems in time as the testing program proceeded. One was the concern that despite the use of light loads, there was still a need for cooling. In later sessions fans were added to help cool the fixture. This was sufficient to keep the temperature under control, even for the neutron tests. Another issue was in trip detection and recovery. Generally, trips were detected by the program when the output voltage went to zero volts. In cases where there was high flux, such as was possible in the proton tests, it became difficult to reset the bricks remotely during the tests. Eventually this problem was overcome with a combination of hardware and software changes.

Some of the testing was done with a combination of new bricks, V7, and original bricks, V6.5.4. During the first proton testing session, significant tripping was observed. It was decided to include at least one of the old bricks as a reference. Since the new design used almost all of the same parts as were used in the old design, this provided a good reference in the testing program. It was also decided to test some of the active components used in the brick on a separate test board. This board, called the Components Board in the following, was designed so that the parts could operate as stand-alone circuits, operating approximately as they do in the brick, and arranged to read out voltages from these parts through the buffer boards, the same way that the bricks were read out. This was intended to provide an indication of how the individual chips performed independently of the feedback circuit of the brick. As will be described in the next section, these two additions to the testing program and apparatus helped us understand and solve some of the problems that we encountered in earlier sessions, and were key in isolating a previously unknown mechanism for Single Event Upset in the controller chip.

IV. PROTON IRRADIATION STUDIES

We performed four sessions of proton irradiation tests on the bricks with protons using the Francis H. Burr Proton Therapy Center [13] at Massachusetts General Hospital (MGH), which is normally used for cancer therapy. The tests on the bricks were designed to measure susceptibility to Single Event Effects (SEE). One particular type of SEE is Single Event Upset (SEU), in which a memory or digital state is changed as a result of a high-energy massive particle interacting with circuitry inside of an integrated circuit. Another type of SEE is latch-up, in which parasitic NPN-PNP transistors inside an integrated circuit begin to conduct between the power supply and the substrate. Since there are several integrated circuits in the design, and two circuits that have digital logic, this test was appropriate. The net effect of susceptibility to SEU in the operation of the bricks would be to observe abnormal tripping.

It is known that there is a threshold for SEU occurrence as a function of incident hadron energy, which is also dependent on the feature size and technology of the device [14]. Certain technologies can have thresholds at ~50 MeV or lower. The cyclotron at MGH delivers protons up to about 200 MeV, so this is a good choice for SEE measurements. A realistic dose rate was not possible in a finite period of time, since the calculated yearly dose for the bricks installed on the detector (200 days at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$) is $6.7 \times 10^{8}$ hadrons/cm$^{2}$, which would result in 10k p/cm$^{2}$·S beam flux. An active measurement of the response of the bricks and Component Boards under irradiation was desired, thus a reasonable time period to search for any detrimental effects was chosen to be several hours. To first order, the SEE effects should be independent of rate. However, proton irradiation also produces ionizing radiation, and the devices can become damaged from TID radiation if care is not taken in the dose rate. We will discuss this more below.

A picture of our setup at MGH is shown in Fig. 4. The beam port is the round gold object just above the center of the photo on the left. The bricks were placed so that the front face of the first brick in the fixture was at a distance of 157.5 cm from the beam port, with the boards situated to be perpendicular to beam. Although not shown in this photo, the buffer boards were well shielded by lead bricks to minimize SEE effects. Alignment was done with a laser and mirrors and the intensity normalized with a Faraday cup. Beam intensity was controlled by us in a remote section of the hospital. The proton beam energy was 188 MeV for most tests, and the beam spot was uniform to 90% within a 10 cm diameter. At this energy, $dE/dx$ for protons is 7 MeV/g·cm$^{2}$. We estimated that the beam energy would degrade by approximately 25% as the protons went through the stack, given the density of the materials, although as will be described, the radiation effects were seen approximately uniformly for all bricks in the stack. The readout computer was located 16 meters away in a room outside of the radiation area. The monitor voltages of the bricks under test were measured continuously during the runs, as described previously.
The first test session with protons occurred on Dec 4, 2010. At the time, the loads on the bricks were light (510 ohms for the 15V bricks, 22 ohms for the 5V bricks,) and there was no auxiliary cooling. The beam energy was 188 MeV. The measurements were begun at a very low rate, 1.6x10⁷ protons/cm²/s. When the beam was turned on, we observed bricks trip off almost immediately, approximately once every minute (once every ~1x10⁹ protons delivered.) As the beam rate increased, the rate of tripping increased. Since the parts used in the V7 bricks were the same as used in the old design, there was concern that there was something wrong with the test apparatus. Since debugging in place was not possible, and since we lacked remote diagnostic capabilities at the time, we decided to abort the test prematurely, after only 8.7x10ⁱ⁰ protons/cm² exposure, or about 5% of our target dose.

The next session with protons occurred on Feb 27, 2011. The beam energy was again 188 MeV. Some changes in the apparatus were made: (1) the addition of a fan, to provide better cooling for the bricks; (2) a V6.5.4 brick was included as a control standard, since those bricks had been tested for SEE susceptibility before; (3) two Component Boards as described in Section III were added to the fixture; and (4) a feature was added to the DAQ program to automatically restart a brick if a trip was detected. The test was run over a period of 3.5 hours, accumulating a total dose of 1.5x10¹² p/cm². The output voltages and currents were monitored continuously through this period. After about 102 minutes, the TID limit of 37 kRad was reached. Note that in order to achieve the proton fluency specification of 1.5x10¹² p/cm², the protons with energy 188 MeV also delivered an ionizing dose of 88 kRads – over a factor of two above the testing limit for TID. Indeed, toward the end of the testing session, several of the bricks stopped functioning altogether, and the others were clearly wounded. Nonetheless, this test revealed two important clues: 1) All bricks exhibited tripping, V6.5.4 and V7 alike; 2) All components on the Component Board functioned perfectly except the LT1681 controller chip. From these measurements, it became clear that there was a problem with Single Event Upset in the controller chip. The V6.5.4 brick that we used as a standard tripped with the same frequency as the V7 bricks. Furthermore, the measurement of the clock output of the controller chip on the Component Boards showed the clock stopping at the same rate as that which the bricks were tripping. This study uncovered a significant susceptibility for the brick to trip off due to SEU, one that is not only inherent in the design but existing deep in the heart of the controller chip for the brick.

V. CIRCUIT ANALYSIS

The block diagram for the LT1681 controller chip is shown in Fig. 5. There are two areas of the circuit that contain flip-flops. One is in the clock section, but this flip-flop is reset at 300 kHz. The worst that can happen in this circuit is that the brick would miss a clock cycle. From previous studies it is known that this will not cause a trip. The other circuit area that has a flip-flop is the soft-start circuit. The chip has several built-in features that can cause it to stop clocking, including over temperature, under voltage, and over current. When any of these occur, the chip automatically initiates a soft-restart sequence, which begins by setting this flip-flop. When the flip-flop is set, an external timing capacitor is quickly discharged. After discharging, the flip-flop is reset, and an internal current source recharges the external timing capacitor. When the voltage on the capacitor reaches ~1.5 V, the clocking restarts. The clock has low duty cycle at first but gradually reaches the full cycle depending on the value of the timing capacitor.

The basic philosophy of the soft start feature is to provide a gradual start-up sequence, either from a cold start or in the case of an abnormal condition. As long as the energy stored in the primary side does not go away or dissipates away, the brick would restart. Note that this feature was designed for short delays, of order a few tens of milliseconds. Note also that it is intrinsic in the chip. It is part of the basic operation, and even contributes to how the brick starts up from a cold start. There is no way to disable the operation inside the chip.
For this brick design, the primary feature that the soft-start provides is the slow ramp-up of the output voltage of the brick when starting. This prevents an overshoot of the output voltage, and also prevents tripping from either over-current or over-voltage. The soft-restart feature of the controller chip is not used in this power system. If a brick has an abnormal condition, it trips off, and must be manually restarted. In the V6.5.4 bricks, the timing capacitors were large, with the delay set to between 0.1 s – 0.8 s, where different bricks have different delays to implement startup sequencing. For the V7 bricks, the start-up sequencing is done a different way, and the delays were set to 30 ms uniformly for all brick types, where it was determined that this gave acceptable performance. We have measured that after about 10 ms of no clocking, the stored energy on the primary side has dissipated to the point that it cannot restart without sending a start pulse from the control system. This is why both the V7 bricks and the V6.5.4 bricks trip off if this flip-flop is subject to SEU. We also saw that the controller chip on the Component Board tripped off as well, as indicated by the drop in output voltage associated with the output clock of the chip, but because the Component Board always had power, it restarted after the 30 ms delay set by the external timing capacitor. This was the primary indicator that this SEU problem was related to the soft-start feature of the controller chip.

After this discovery, we worked on a solution to the problem. The fix that we came up with is shown in Fig. 6. The addition of the diode allows the soft-start circuit to function normally during a cold start, where the ramp rate of the output voltage is important. If the chip is hit by an SEU during operation, the diode becomes back-biased and holds the capacitor voltage. The soft-start circuit then only has to charge a parasitic capacitor, which happens within one or two clock cycles. The scheme was tested at MGH on Dec. 11, 2011, using the three V7 bricks without the modification and two V7 bricks with the SEU fix. We ran at 216 MeV, and accumulated $9.3 \times 10^{10}$ p/cm$^2$. The three unmodified bricks tripped a total of $\sim$100 times during this run, while the modified bricks did not trip at all. We regarded this as validation of the fix to this problem, which was subsequently incorporated into the final design before production.

VI. STUDY OF TRIPS AS A FUNCTION OF INCIDENT ENERGY

After the discovery of the SEU sensitivity, it was curious that the SEU problem had not been seen in measurements on the original version of the bricks. Those measurements were made using a 60 MeV proton beam, whereas we used a 188 MeV proton beam. The physics of linear energy transfer (LET) is well known in the space instrumentation community [15-16], which predicts how SEUs are a function of energy and physical layout of the circuit. What follows is a study that we performed on this device to confirm that the two sets of measurements just happened to fall between the cut-off in the LET threshold.

A. Measurements

The DC cyclotron at MGH delivers protons from $\sim$20 MeV up to about 216 MeV, making it an excellent facility for SEU studies. In the experimental beam line at MGH, energy degraders are used to reduce the energy of the proton beam. We returned to the hospital in April, 2011, with four of the final bricks, without the SEU fix described in the previous section. We requested six energies between $\sim$20 MeV and the maximum. This was achieved by delivering primary beam at 102.2, 171.1 and 228.9 MeV and subsequently using degraders resulting in delivered energies of 59.9, 100.5, 140.5, 178.9 and 216 MeV protons. At the entrance to our apparatus, the beam spot was measured to be 10 cm diameter and uniform to 90%. A typical beam flux was $\sim$2 x $10^8$ p/cm$^2$/s. Beam divergence was typically 35 mrad and only slightly energy dependent.

In this set of measurements, we implemented a modification to the DAQ system that corrected for dead-time by turning off the beam when there was a trip and turning it back on when the trip was reset. An SEU was defined if the output voltage of any brick fell near zero. In such a case, the beam was disabled to allow the software to log the trip and to reset the tripped brick. After the reset, beam was enabled and dead-time was corrected for. A laser from the beamline port set the alignment of our apparatus. The laser was centered on the upstream LT1681 chip, and a mirror placed on the fixture reflected light back to the source to ensure the other bricks’
LT1681 chips were in line. The beam current at our apparatus was measured with an ion chamber at each energy, normalized to a scaler which counted what was known as “monitor units” which is proportional to the cyclotron intensity. From these measurements, the fluence per monitor unit was calculated, as well as dE/dx. The ion chamber measurements were performed both upstream and downstream of the stack, and this provided us with an estimate of the energy loss in each brick. Cyclotron intensity was controlled by us in a remote section of the hospital and we recorded the total monitor units for each run.

The results of the measurement are shown in Fig. 7. The measurements have been corrected for dE/dx energy loss for each brick using an estimate of the density of the stack. The energy for each point is the mean of the ensemble, with the uncertainties shown. As can be seen, the reduction in SEUs is more than an order of magnitude between 200 and 100 MeV. Note that no trips were observed at the 59.9 MeV run, and this point was not plotted in Fig. 7.

**B. Discussion**

There are two primary mechanisms for generating SEUs in semiconductor devices. The first is direct ionization. As a heavy particle passes through a sensitive node in the circuit, electron-hole pairs are created along the trajectory as it deposits energy. The particle travels a certain range before losing all its energy and coming to rest. The energy deposited per unit length is called the linear energy transfer (LET) and is measured in MeV·cm²/mg. The value is normalized to the density so it can be quoted independently of the target. The LET can be related to the charge deposited [17]. An initial ion strike creates electron-hole pairs in the wake, followed by the drift collection, and finally the diffusion collection. The three stages lead to a build up of charge. This charge produces a current pulse at the junction of the transistor. If sufficient charge is collected by a node the data state may change. This charge limit is called the critical charge \( Q_c \). Since charge deposition can be calculated from the LET, the value corresponding to \( Q_c \) is called the linear energy transfer threshold (LET\(_{th}\)). If the energy deposition is larger than this value then it can cause a transistor to change state. If the sensitive volume (the region where upsets can occur) of the device and the density of the material are known, then the threshold energy (\( E_{th} \)) can be calculated.

Although light particles generally do not cause sufficient ionization and resulting charge build-up to reach the critical level for generating an SEU, they can deposit energy via other mechanisms [18]. There are numerous nuclear reactions that can take place. There can be elastic collisions (producing a recoiling Si atom), the production of alpha or gamma particles and spallation reactions where the target is broken down into fragments [19]. Each particle produced can itself produce charge build-up through the processes described before. Eq. (1) shows a typical example where a neutron interacts with the boron-10 (commonly used as a p-type dopant for junction formation in IC packages).

\[
^{10}\text{B} + n \rightarrow ^{7}\text{Li} + ^{4}\text{He} + \gamma
\]

The energy deposited by the products of this reaction can cause charge build-up as described above, and an SEU can result if it is over the critical level. This mechanism has been recently found to be the dominant form of soft errors in 0.25 and 0.18 micron SRAM [17]. In the case of incident protons there are numerous nuclear reactions that can occur between the proton and silicon [19].

**C. Analysis**

The energy threshold for causing an SEU can be expressed as:

\[
E_{th} = LET\_th \times d \times \rho
\]

where \( LET\_th \) is the linear energy transfer threshold measured in MeV·cm²/mg, \( \rho \) is the density of the material measured in mg/cm³, and \( d \) is the distance travelled by the particle in the sensitive volume measured in cm. For silicon, the density can be taken as 2.33 g/cm³. Generally, the distance travelled through the sensitive volume is not known, but can be estimated from the fabrication technology parameters.

The expression for the critical charge is given by:

\[
Q_c = \frac{E_{sh} \times e}{E_{ehp}} = \frac{LET\_th \times d \times \rho \times e}{E_{ehp}}
\]

where \( E_{sh} \) is the energy threshold in MeV, \( e \) is the charge of an electron, and \( E_{ehp} \) is the energy required to create an electron-hole pair, for which a value of 3.6 eV will be used. The energy threshold for SEUs can be estimated from the physical parameters of the device if the material composition, fabrication technology, and physical layout are known. Since these parameters are generally not known by experimenters or end users, semi-empirical models have been developed to predict SEUs. One model is the Bendel equation [20], which has been shown to be useful in estimating the energy.
threshold from measured data. The general form of the Bendel equation is given as:

\[ \sigma = \sigma_\infty \left[ 1 - e^{\Delta E/kT} \right]^n \]  

(4)

Where \( h, m, \) and \( n \) are constants. The quantity \( \sigma_\infty \) is the saturation upset rate as the energy tends to infinity. \( Y \) is a linear function of energy, which goes to zero when the energy is equal to the critical energy \( E_0 \). A variation of this function called the two-parameter Bendel equation [21] is given as:

\[ \sigma = \left( \frac{B}{E_0} \right)^4 \left[ 1 - e^{-0.18Y} \right] \]  

(5)

To calculate the energy threshold, we look to our measurements. The data from MGH is summarized in Table IV, including the statistical uncertainties. The values shown for incident energy and SEUs is the average of the ensemble at a particular energy setting. This data was then fit to the two-parameter Bendel model given in (5) using a \( \chi^2 \) fitting algorithm. The result is shown in Fig. 8. The \( \chi^2 \) value is small, indicating a good fit for the values of \( \sigma_\infty \) and \( E_0 \) in spite of having only four data points. The value of 64 MeV for the energy threshold explains why no SEUs were observed in the original design using 60 MeV protons. We also measured 0 trips for the 59.9 MeV energy run.

VII. CONCLUSIONS

We have performed a comprehensive set of radiation tolerance measurements to qualify a new switching power supply for the ATLAS TileCal front-end electronics. We discovered a sensitivity to single event upsets. This was surprising since the previous design had been measured for SEU tolerance and found to be satisfactory, and since we used mostly the same parts in the new design. Our studies over the course of a year identified the cause being a flip flop in the controller chip. Fortunately, we were able to find a fix for this in the design before going into production. We also showed that there is an energy dependence of SEUs in this design. This study underscores the importance of specifying the energy range of interest for SEU tolerance, which will be dependent on the environment.

ACKNOWLEDGMENT

We would like to thank the contributions from the Tile Calorimeter physics community for the many hours of data taking, testing, and analysis that contributed to this work. We thank the technical staff of the Argonne Electronics Support Group for the expertise in assembling and testing the instrumentation used in this study. We especially thank the graduate students from Madison and Johannesburg who we had the pleasure to work with on this project. Finally, we thank Ethan Cascio of Massachusetts General Hospital for the use of the facilities in making these measurements and the many hours of interesting discussions on SEU phenomena.

REFERENCES