Radiation Tests of Configuration Controller Chips

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Abstract

We report the results of radiation tests of DMILL Configuration Controller chips, an ASIC which was designed for use on the Front End Boards of the ATLAS LAr readout. Samples have been exposed to high intensity 158 MeV proton beams in order to simultaneously evaluate their tolerance to ionizing radiation, hadrons, and possible single event effects. The results obtained demonstrate that the devices are sufficiently radiation tolerant to be suitable for our application.

1 Introduction

Radiation hardening the design of the ATLAS LAr Front End Boards (FEB) [1] has required the development of several custom ASICs using radiation-hard processes. The DMILL-based Configuration Controller (Config) [2] was designed to provide the interface between the "SPAC" serial control bus and the various devices which require configuration or control on the FEB. The devices to which the Config interfaces include voltage regulators, custom BiCMOS shaper chips, and several varieties of both DMILL and DSM digital ASICs. In this paper, we present the results of our radiation tests of DMILL Config samples.

2 Radiation Tolerance Requirements

Simulations of the ATLAS detector have been performed to estimate the radiation levels to which the electronics will be exposed over 10 years of LHC operation. Separate levels are provided for Total Ionizing Dose (TID in kRad), neutron-induced damage (NIEL, in 1 MeV equivalent neutrons/cm^2), and for single event effects (SEE, calculated for the total fluence of hadrons of momentum greater than 20 MeV).

The FEBs will be installed in the ATLAS detector in crates mounted directly on the signal feedthroughs of the barrel and endcap cryostats. The expected radiation levels [3] to which the FEBs will be exposed in the EM barrel are summarized in Table 1. Since the expected levels in the endcaps are approximately ten times lower than in the barrel, the qualification procedure concentrates on the case of the EM barrel.

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Type of Radiation	Simulated Level
TID	5 kRad
NIEL	$1.6 \times 10^{12}\ n/cm^2$
SEE	$7.7 \times 10^{11}\ h/cm^2$

Table 1: Expected radiation levels for the FEBs mounted in the EM barrel crates, integrated for 10 years of LHC operation.

The ATLAS radiation qualification criteria require irradiation of electronics to the expected levels multiplied by the product of "safety factors" (SF) which account for uncertainties in the simulation of the expected radiation levels (SF_{sim}), in possible low dose rate effects (SF_{ldr}), and in possible lot-to-lot variations (SF_{lot}). The safety factors to be used depend on the type of component and type of test being performed.

3 Radiation Facility

The irradiation runs were performed at the *Harvard Cyclotron Laboratory (HCL)* [4] in Cambridge, Massachusetts. The HCL, which was de-commissioned on June 2, 2002, used a proton synchrocyclotron to generate proton beams, primarily for radiation therapy. The facility could be used during the weekends for other purposes, including radiation qualification of electronics.

The HCL proton beam had a maximum energy of 158 MeV on target; irradiation at lower proton energies could be achieved by insertion in the beamline of lucite absorbers of varying thicknesses. The beam energy resolution was typically 2 - 5 MeV for energies above 100 MeV, and about 10 MeV for lower energies.

The HCL high-intensity beamline delivered a maximum flux of $\approx 3.5\times10^{10}$ protons/cm^2/s. The uniformity of the flux was within $\approx \pm20\%$ over the beamspot of ≈ 1 cm diameter. The proton fluence was measured online using a calibrated ion chamber positioned in the proton beam, the signal from which was integrated and used to generated "Monitoring Pulses" (MON) after given increments of integrated proton fluence. The MON were used by the cyclotron control room to monitor the operation of the machine.

Using a 20 - 160 MeV proton beam allows us to simultaneously accumulate total ionizing dose (TID), 1 MeV-equivalent neutron fluence, and hadrons with sufficient energy to potentially cause SEE. The conversion factors are energy-dependent. For protons in this energy range, the 1 MeV-equivalent neutron fluence is somewhat higher than the actual proton fluence, though we assume a conversion factor of unity in order to be conservative. Table 2 summarizes the conversion for calculating the equivalent TID from the proton fluence.

4 DAQ and Test Procedure

The radiation test setup utilizes the portable DAQ we developed for a variety of electronics testing and radiation qualification purposes. The DAQ is driven by a portable PC equipped with two National Instruments DAQ boards, one for digital I/O and the other for analog

Proton Energy (MeV)	Proton Fluence per MRad TID (10^{13} p/cm^2)
158	1.47
100	1.06
50	0.67
20	0.31

Table 2: Fluence of protons required to accumulate 1 MRad total ionizing dose, as a function of proton energy.

I/O and power connections.

A cable from the cyclotron control room provided a pulse for every MON unit. The pulses were counted using a general-purpose counter on the analog I/O board and read by the DAQ PC in order to provide online measurements of the integrated exposure.

Each DAQ I/O board is connected via its own 50-pin 75-foot twisted-pair cable to a "Sample Driver" board. The Sample Driver contains voltage regulators for providing power to the Device-Under-Test (DUT) fixture; the power supply currents and voltages can be measured through the analog I/O. In addition, four analog inputs and two DAC outputs are available to the DUT fixture. The digital I/O implements two 8-bit TTL ports, with strong TTL drivers and terminations on both ends of the cable.

For typical runs, the supply voltage and current of the DUT were monitored during the irradiation with a time resolution of 200 μs. Every second, the DAQ would record to disk the average value, RMS, maximum value and minimum value of both the voltage and current.

5 Device Description

The Config is a purely CMOS digital ASIC realized in the radiation-hard DMILL process. The Config provides the interface between the SPAC and the large variety of devices requiring configuration on the FEB. The Config is clocked on the FEB with a 5 MHz clock.

The Config design was submitted for prototyping as part of Europractice MPW Run 511 submitted in September 2000. In February 2001, shortly before the chips were scheduled to be delivered, the foundry announced that they had detected a processing error which resulted in a substantial via misalignment in this MPW run. We decided to accept delivery of the chips anyway, hoping that the error might not be so serious as to prevent us from testing and verifying the design. This did in fact turn out to be the case. This initial set of 20 packaged chips was received in March 2001. In the meantime, the foundry processed an additional set of wafers, and delivered a new set of 20 chips, without the via problem, in May 2001.

5.1 Radiation Levels and Safety Factors

The Config is a DMILL ASIC which, for production, we will purchase from a known homogeneous lot. Table 3 summarizes the appropriate safety factors to use, and lists the resultant Radiation Tolerance Criteria (RTC).

Test Type	Simulated Level	Preselection Safety Factors				Preselection RTC
		SF_{sim}	SF_{ldr}	SF_{lot}	Total	
TID	5 kRad	3.5	1.5	2	10.5	52.5 kRad
NIEL	$1.6 \times 10^{12}\ n/cm^2$	5	1	2	10	$1.6 \times 10^{13}\ n/cm^2$
SEE	$7.7 \times 10^{11}\ h/cm^2$	5	1	2	10	$7.7 \times 10^{12}\ h/cm^2$

Table 3: Summary of safety factors and resultant RTC to use in the preselection radiation qualification of the DMILL Config ASIC.

6 Radiation Test Procedure

Due to the long cables required to remove the PC from the radiation environment, the DAQ PC did not directly verify the correct operation of the Config. Instead, the real-time control of the Config DUT was driven by an Altera FPGA mounted on an "FPGA testjig" connected to the DUT testjig via short cables ($\approx$ 20 cm, long enough to allow the FPGA to be sufficiently shielded from the proton beam). All I/O pins of the Config were connected in this way to the FPGA, which could therefore monitor all Config activity in real time.

During the irradiation, the chips were powered and clocked at their nominal frequency of 5 MHz. Each of the major functional blocks of the Config (for more details of the Config design, see reference [2]) was tested during the irradiation. These tests can be divided into several classes:

- serial port tests - each of the 4 Config serial ports was tested with broadcast Write commands, individual Write commands, and individual Read commands,
- shaper tests - it was verified that the Config can write and read from each of the shaper switch setting addresses,
- voltage regulator tests - all 8 Inhibit lines were tested, as were the over-current sense lines,
- flag tests - it was verified that all 4 flags could be set properly
- passive test - during a time when no SPAC activity was present, the Config was monitored to see if it generated spurious SPAC activity or exhibited any change in its state as a result of SEU.

During the irradiation, the test ran in an infinite loop. Every second iteration, the serial port tests were performed. Every 16th iteration, the shaper tests were performed. The regulator and flag tests were performed every 31st iteration. At the end of each loop, a wait period of one second was inserted before re-starting. The passive test was run each loop to look for spurious signals or changes.

Whenever the ALTERA operating the test detected a result different than that expected, it would provide the relevant information to the DAQ PC in order to monitor occurrences of SEU-induced errors.

7 Config Radiation Test Results

As summarized in Table 4, two rounds of irradiation tests of Config chips were performed using 158 MeV protons. First, four Config ASICs from the initial delivery (ie. including the via misalignment problem). were irradiated during the weekend of May 12/13, 2001. Given the limited statistical sample, we were able to irradiate these devices to proton fluences which far exceed our requirements. In the second step, 8 Config chips from the final delivery (ie. without the via problem) were irradiated on the weekend of May 7/8, 2002.

Test Date	Sample	Total Fluence (p/cm^2)	TID (MRad)
May 12/13, 2001	A1	3.4×10^{13}	2.3
	A2	6.7×10^{13}	4.6
	A3	14.2×10^{13}	9.7
	A4	22.5×10^{13}	15.3
May 7/8, 2002	B1	1.65×10^{13}	1.12
	B2	1.65×10^{13}	1.12
	B3	1.74×10^{13}	1.18
	B4	1.74×10^{13}	1.18
	B5	1.74×10^{13}	1.18
	B6	1.74×10^{13}	1.18
	B7	1.76×10^{13}	1.20
	B8	1.76×10^{13}	1.20

Table 4: Summary of radiation tests of the DMILL Config. All tests were performed with 158 MeV protons.

7.1 Current Monitoring Results

The supply currents of all samples were monitored during irradiation. No occurrences of latchup were observed.

The supply current versus proton fluence is shown in figure 1 (2) for the first (second) set of devices irradiated. The devices do demonstrate an increase in supply current with irradiation, reaching in the worst case an increase of ≈ 50 mA for one sample (A4 in Table 4) irradiated to a total fluence more than an order of magnitude higher than the RTC. For the final set of 8 samples irradiated to the RTC, the increase was in the range $\approx 2 - 8$ mA (see figure 2).

Similar behavior was seen in irradiation tests of DMILL Gain Selector chips produced as part of the same MPW run, where increases in the range of several mA were observed for irradiations corresponding to the RTC. Since the total Gain Selector current is much larger than for the Config, but the absolute increase is similar, it is believed the increase is most probably in the differential receiver cells, of which the Config has four and the Gain Selector five. The same receiver cells are used in the DMILL SCA, where no such increase has been observed. It is possible, therefore, that the increase results from some feature of the processing of MPW 511, and will not be observed in the production run. In any case, the

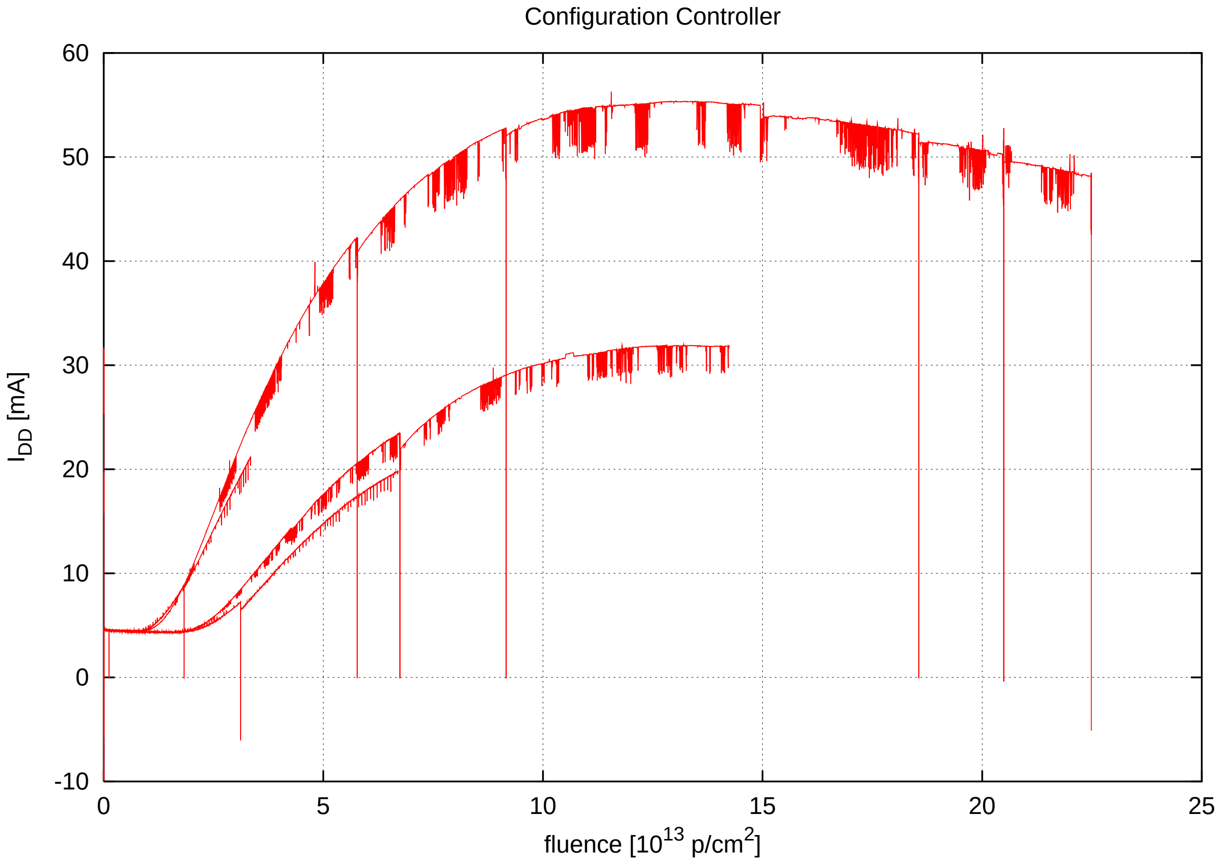

Figure 1: Measured supply current as a function of proton fluence for the first set of irradiation tests of Config chips.

effect is so small that it would have a negligible impact on operation in ATLAS and poses no concern.

7.2 SEU Results

During the first set of tests, a 3.3V oscillator was used to provide clocks to the Altera test controller. The Altera, however, formally required a 5V clock signal. While the tests did operate, the setup was not very robust, and we observed a significant number of instances when the DAQ detected errors during operation. It is believed that many of these errors did not result from SEU-induced errors in the Config but from the poor quality of the clock signal to the Altera. As a result, SEU rates cannot be reliably determined for the four Config chips irradiated during the first set of tests.

The oscillator problem was repaired before the second set of tests, providing robust operation of the test jig and DAQ. As sumarized in Table 5, a total of 9 SEU-induced errors were observed during irradiation of the 8 chips tested in the second round of tests.

The results correspond to an SEU cross-section of 6.5×10^{-14} cm^2. A total of 896 FEBs are required to instrument the full EM Barrel and each FEB contains 1 Config chip. The measured SEU cross-section implies a total of ≈ 450 SEU errors per 10 years of LHC

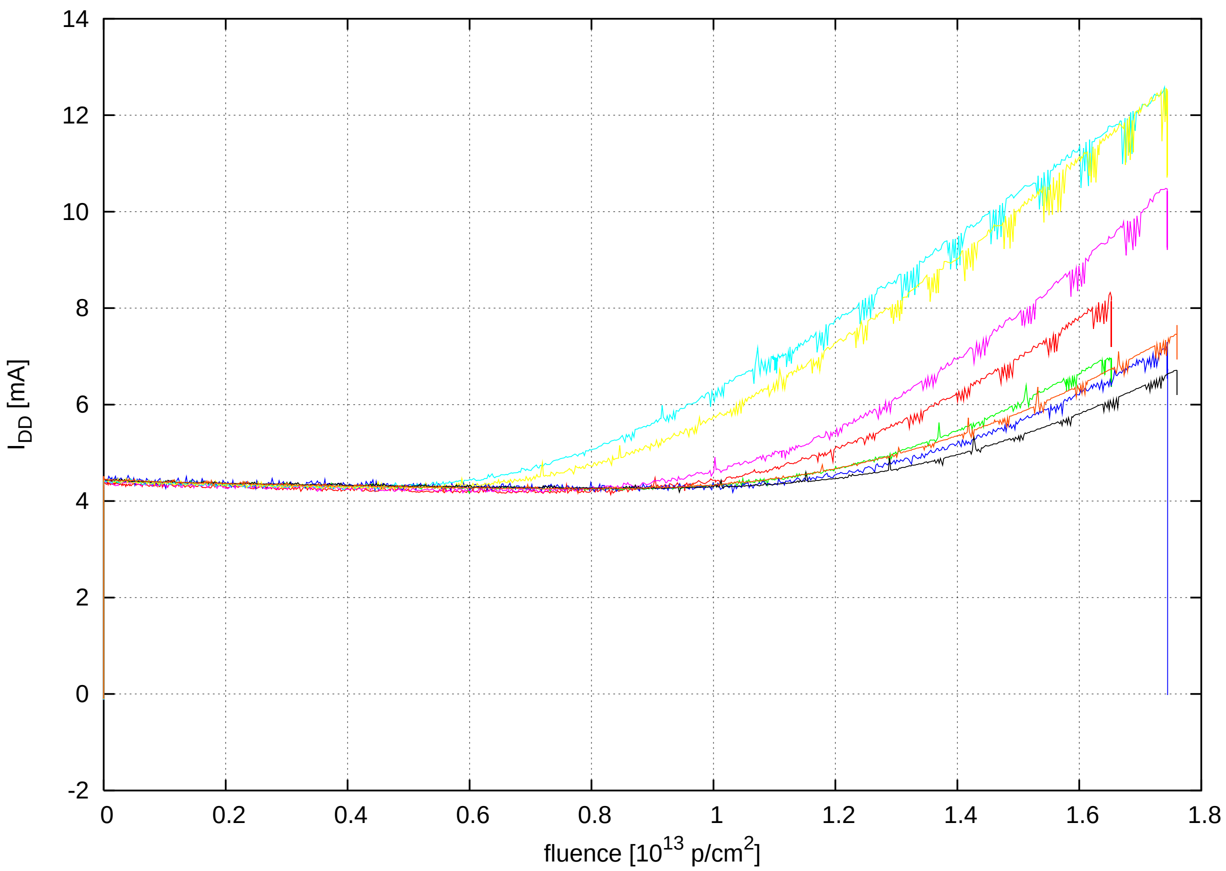

Figure 2: Measured supply current as a function of proton fluence for the second set of irradiation tests of Config chips.

operation at design luminosity, including a safety factor of 10. Assuming 10^7 s of LHC operation per year, this corresponds to an SEU-induced error in the EM Barrel readout every 2.6 days. Even this very low rate is a conservative estimate, since during physics running the SPAC system, and therefore the Config, is idle most of the time.

8 Discussion of Results

A total of 12 DMILL Config chips were irradiated using 158 MeV proton beams. The power supply increase of < 10 mA which was observed for fluences corresponding to the RTC is of no concern for operation in ATLAS. The measured SEU cross-section of 6.5×10^{-14} cm^2 implies a negligible error rate for operation of the ATLAS calorimeter readout.

In summary, the tests demonstrate the DMILL Config is sufficiently radiation tolerant for use on the ATLAS LAr FEBs.

Test Date	Sample	Total Fluence (p/cm^2)	Number of SEU Errors
May 7/8, 2002	B1	1.65×10^{13}	0
	B2	1.65×10^{13}	2
	B3	1.74×10^{13}	1
	B4	1.74×10^{13}	2
	B5	1.74×10^{13}	1
	B6	1.74×10^{13}	1
	B7	1.76×10^{13}	1
	B8	1.76×10^{13}	1
	Total	13.78×10^{13}	9

Table 5: Summary of occurrences of SEU-induced errors observed during the second set of Config irradiation tests.

References

[1] J. Ban, S. Negroni, J. Parsons, S. Simion, and B. Sippach, "Design and Implementation of the ATLAS LAr Front End Board"; available at `http://www.nevis.columbia.edu/~atlas/electronics/ATLASFEB/FEBnote.pdf`.

[2] P. Cros, M. Bouchel, J. Parsons, B. Sippach, and S. Böttcher, "The Configuration Controller", available at `http://www.nevis.columbia.edu/~atlas/electronics/asics/conf_ctrl.pdf`.

[3] These levels are based on the November 18, 2000 baseline and are available at `http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm`.

[4] For more information on the Harvard Cyclotron Laboratory, see `http://neurosurgery.mgh.harvard.edu/hcl/flyer.htm`.