# Radiation Tests of MC10H116 Chips

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**Abstract**

We report the results of radiation tests of MC10H116 triple line receivers, which we performed to evaluate the suitability of this COTs device for use on the Front End Boards of the ATLAS LAr readout. Samples have been exposed to high intensity proton beams in order to simultaneously evaluate their tolerance to ionizing radiation, hadrons, and possible single event effects (SEE). No SEE-induced effects were observed, and the devices were shown to be 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 (both DMILL and DSM). However, for certain functions, we plan to employ commercial off-the-shelf (COTs) components. In this paper, we present the results of our radiation tests of the commercial MC10H116 triple line receiver.

## 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 [2] 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.

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

| 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.

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.

## 2.1 Safety Factors

The MC10H116 is a bipolar COTs device which, for production, we purchase from a known homogeneous lot. Table 2 summarizes the appropriate safety factors to use for both preselection and production tests, while Table 3 lists the resultant Radiation Tolerance Criteria (RTC).

| Test Type | Preselection Tests | | | | Production Tests | | | |
|---|---|---|---|---|---|---|---|---|
| | $SF_{sim}$ | $SF_{ldr}$ | $SF_{lot}$ | Total | $SF_{sim}$ | $SF_{ldr}$ | $SF_{lot}$ | Total |
| TID | 3.5 | 5 | 2 | 35 | 3.5 | 5 | 1 | 17.5 |
| NIEL | 5 | 1 | 2 | 10 | 5 | 1 | 1 | 5 |
| SEE | 5 | 1 | 2 | 10 | 5 | 1 | 1 | 5 |

Table 2: Summary of safety factors to use in the preselection and production radiation qualification of the MC10H116, a bipolar COTs component.

| Test Type | Simulated Level | Preselection RTC | Production RTC |
|---|---|---|---|
| TID | 5 kRad | 170 kRad | 87.5 kRad |
| NIEL | $1.6 \times 10^{12}\ n/cm^2$ | $1.6 \times 10^{13}\ n/cm^2$ | $8.0 \times 10^{12}\ n/cm^2$ |
| SEE | $7.7 \times 10^{11}\ h/cm^2$ | $7.7 \times 10^{12}\ h/cm^2$ | $3.8 \times 10^{12}\ h/cm^2$ |

Table 3: Simulated radiation levels for 10 years of LHC operation, and the Radiation Tolerance Criteria (RTC) for the MC10H116 for both pre-selection and production tests.

# 3 Radiation Facility

The irradiation runs were performed at the *Harvard Cyclotron Laboratory (HCL)* [3] 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 $\approx$ 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 4 summarizes the conversion for calculating the equivalent TID from the proton fluence.

| 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 4: Fluence of protons required to accumulate 1 MRad total ionizing dose, as a function of proton energy.

# 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 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 $\mu$s. Every second, the DAQ would record to disk the average value, RMS, maximum value and minimum value of both the voltage and current.

The DAQ was programmed to record the entire history to disk if there was a significant variation of any of the values during any one second interval.

In case of an SEL occurrence, the supply current would be expected to rise dramatically. To prevent a possible fire hazard, the DAQ was programmed to switch off the power to the DUT if its supply current exceeded a pre-set limit. To see if the device would recover from a possible occurrence of SEL, the DAQ would automatically turn the power on again after 30 seconds. After 20 such power cycles, the DAQ would turn off the power permanently, and abort the run.

# 5 Device Description

The MC10H116 is an ECL triple-line receiver which we plan to use for driving the SCA address and control buses. The MC10H116 is a bipolar device fabricated by ON Semiconductor [4]. The chip does not contain any internal registers or digital logic, and therefore does not present Single Event Upset (SEU) concerns. However, in addition to sufficient TID and NIEL tolerance, we must demonstrate immunity of the device to Single Event Latchup (SEL).

The pre-selection tests were performed using MC10H116FN parts packaged in a PLCC20. For the final production boards, negotiations with ON Semiconductor and a distributor culminated in an agreement wherein we ordered the full quantity of chips required from a single existing production lot. The production chips were packaged in an SOIC-16, corresponding to part number MC10H116D. Discussions with ON Semiconductor verified that the parts are identical to the MC10H116FN, apart from the package, confirming that the pre-selection tests are still valid despite the package change.

All MC10H116D production parts came from lot code 0035. As a first stage in the procurement process, we received 50 samples from this reserved lot for radiation testing. The agreement stipulated that, in the (unlikely) event that the devices did not pass our radiation-tolerance requirements, we could cancel the order without penalty. Once the radiation tests described here were successfully completed, we proceeded with the complete order and have purchased and received all of the production parts.

## 5.1 MC10H116 Use in Other ATLAS Applications

Various institutions have expressed interest in using MC10H116 chips in other ATLAS applications, namely in the LAr Controller Board and in the CSC readout. We have agreed to purchase sufficient MC10H116 chips from our production lot for these applications as well, and to perform the radiation qualification of the production lot such that it satisfies the requirements of all three applications.

The LAr Controller resides in the same crates as the LAr FEBs, and therefore has identical radiation tolerance criteria. However, the expected neutron level in the worst case position of the CSC readout, with a value of $\mathrm{RTC}_{NIEL} = 2.7 \times 10^{13}\ n/cm^2$, is a factor $\approx 3.4$ higher than for the LAr readout. As described later, we irradiated a subset of the production chips to these higher levels in order to satisfy this criterion.

# 6 Pre-Selection Tests

For the pre-selection tests, the chips were powered during irradiation and the supply voltage and current were continuously measured and recorded. However, no online AC tests were performed. Instead, the non-inverting inputs were tied to ground, and the inverting inputs were tied to $V_{BB}$.

A total of six samples were prepared for the first round of pre-selection tests. Five of the samples were irradiated with the final sample kept as a control. These first tests on October 15, 2000 used the lower-flux aerospace beamline at HCL, and were therefore limited in the total fluence which could be achieved. To overcome the fluence limitation, a second set of tests was performed on November 5 and 11, 2000, with the samples installed in the high intensity beamline directly in the cyclotron vault. A total of an additional 13 devices were irradiated.

Table 5 summarizes the MC10H116 chips irradiated during the two sets of pre-selection tests The 13 devices of the second set of tests were irradiated to proton fluences which exceed the LAr pre-selection $\mathrm{RTC}_{NIEL}$ of $1.6 \times 10^{13}$ $n/cm^2$ by factors of typically 1.5 to 3 (by which point they exceed the required TID and SEE levels by very large factors).

| Test Date | Number of Samples | Total Fluence ($p/cm^2/s$) | TID (kRad) |
|---|---|---|---|
| Oct. 15, 2000 | 3 | $1.1 \times 10^{12}$ | 75 |
| | 1 | $4.4 \times 10^{12}$ | 299 |
| | 1 | $8.5 \times 10^{11}$ | 58 |
| | 1 | 0 | 0 |
| Nov. 5+11, 2000 | 8 | $2.5 \times 10^{13}$ | 1700 |
| | 5 | $5.0 \times 10^{13}$ | 3400 |

Table 5: Summary of pre-selection radiation tests of the MC10H116.

The voltages and currents of all samples were stable during irradiation, and there were no instances where variations during any one second interval exceeded the pre-set thresholds ($10\,\mathrm{mA}, 100\,\mathrm{mV}$ for max − min, and $5\,\mathrm{mA}, 50\,\mathrm{mV}$ for the RMS). The current limit of the power supply was set to 1 A, in order to deliver sufficient current for a real-life latchup condition. However, no occurrences of latchup were observed.

Based on these results, we consider the MC10H116 to have passed the pre-selection radiation qualification criteria.

# 7 Production Tests

For the production tests, we had to design a new DUT test jig due to our decision to move to the SOIC package (part number MC10H116D). The new jig was designed to allow AC measurements during irradiation, in addition to online current and voltage measurements. All three of the line receivers of the DUT could be driven with a differential clock signal, and one of three differential outputs could be observed. The input and output differential signals were transmitted over $\approx 50$ m coax cables installed between the control room and the cyclotron vault.

During irradiation, we used an external pulse generator to send a 40 MHz differential clock signal of $\approx$ 400 mV amplitude to the MC10H116 inputs. The MC10H116 output signal was recorded using a digital oscilloscope which displayed the received signal and also measured the voltage levels and rise and fall times.

Table 6 summarizes the MC10H116 chips irradiated during the production tests. As a first step, 16 devices were irradiated on March 9/10, 2002 to proton fluences of $9.2 \times 10^{12}$ $n/cm^2$ (15% above the LAr production $\mathrm{RTC}_{NIEL}$ of $8.0 \times 10^{12}$ $n/cm^2$, by which point they exceed the reqiured TID and SEE levels by very large factors). Due to the higher $\mathrm{RTC}_{NIEL}$ of $2.7 \times 10^{13}$ $n/cm^2$ for the CSC readout, an additional 12 devices were irradiated on May 7 and 16, 2002 to fluences which meet or slightly exceed this level.

| Test Date | Number of Samples | Total Fluence ($p/cm^2/s$) | TID (kRad) |
|---|---|---|---|
| March 9/10, 2002 | 16 | $9.2 \times 10^{12}$ | 626 |
| May 7, 2002 | 8 | $2.7 \times 10^{13}$ | 1837 |
| March 16, 2002 | 4 | $2.8 \times 10^{13}$ | 1905 |

Table 6: Summary of production radiation tests of the MC10H116.

No occurrences of latchup were observed. The stability of the power consumption is demonstrated by Figure 1, which displays the measured supply currents versus integrated proton fluence for the irradiated production MC10H116D samples. The devices, powered with a 5 V supply, have a typical current before irradiation of $\approx$ 82 mA. A slight change in the current with fluence is observed, amounting to less than 1 mA. This very small effect is of no consequence for operation in ATLAS. The small spikes which are seen are artifacts of the DAQ and likely result from pickup in the long cables connecting the DUT in the cyclotron vault to the external DAQ setup.

No significant variations were observed in the voltage levels or rise and fall times of the MC10H116D output signal. As an example, Figure 2 displays the pulseshape accumulated during irradiation of one production MC10H116D sample with the oscilloscope configured to infinite persistence.

# 8 Discussion of Results

The MC10H116D samples from the production lot passed the production NIEL and TID radiation qualification criteria for both LAr applications (FEB and Controller) and for the CSC readout.

No occurrences of latch-up were observed, during a total proton fluence (summed over the 28 production devices listed in Table 6 which were irradiated) of $4.75 \times 10^{14}$ $p/cm^2$. The statistical sensitivity of the data, therefore, allows one to set an upper limit on the SEL cross-section of $< 4.84 \times 10^{-15}$ $cm^{-2}$ (90% CL). Including the pre-selection samples in the total proton fluence would reduce this upper limit by a factor of about 2, but we consider only the production samples in order to have a conservative limit.

To evaluate the implications for operation in ATLAS, we must consider that each FEB uses 8 MC10H116 chips. A total of 1524 FEBs are to be installed in ATLAS. Of these, 896 FEBs, or 7168 MC10H116 chips, are used to read out the EM Barrel calorimeter, for

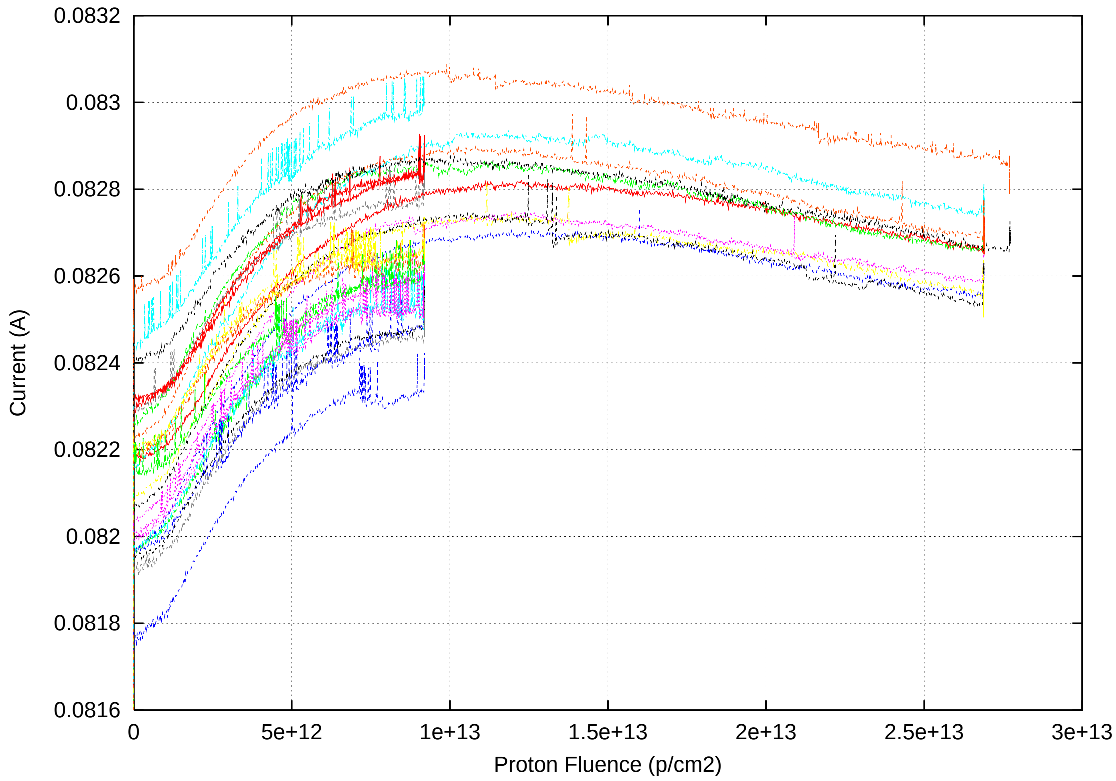


Figure 1: Measured test jig supply current versus integrated proton fluence for a number of production MC10H116D chips.

which $\mathrm{RTC}_{SEE} = 3.8 \times 10^{12}\ h/cm^2$ including the required safety factor of 5 (see Tables 2 and 3). The SEL cross-section upper limit yields, therefore, a 90% CL upper limit of about 130 SEL occurrences in the entire EM Barrel over 10 years of LHC operation (and a factor of about 10 lower in the LAr Endcaps); assuming $10^7$ s of operation each year, this limit would correspond to an average of one SEL in the EM Barrel every 8.8 days of operation. While no SEL occurrences are expected, such a rate would not cause any significant operational difficulties in ATLAS. The use of current-limiting voltage regulators on the FEBs also provides added protection against fire hazards.

In conclusion, the MC10H116D devices have passed the radiation qualification process for both the LAr applications (FEB and Controller) and for the CSC readout. We have, therefore, completed the purchase of the entire set of 18200 devices needed (14600 for the LAr FEB, 2700 for the LAr Controller, and 900 for the CSC readout).

# 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`.

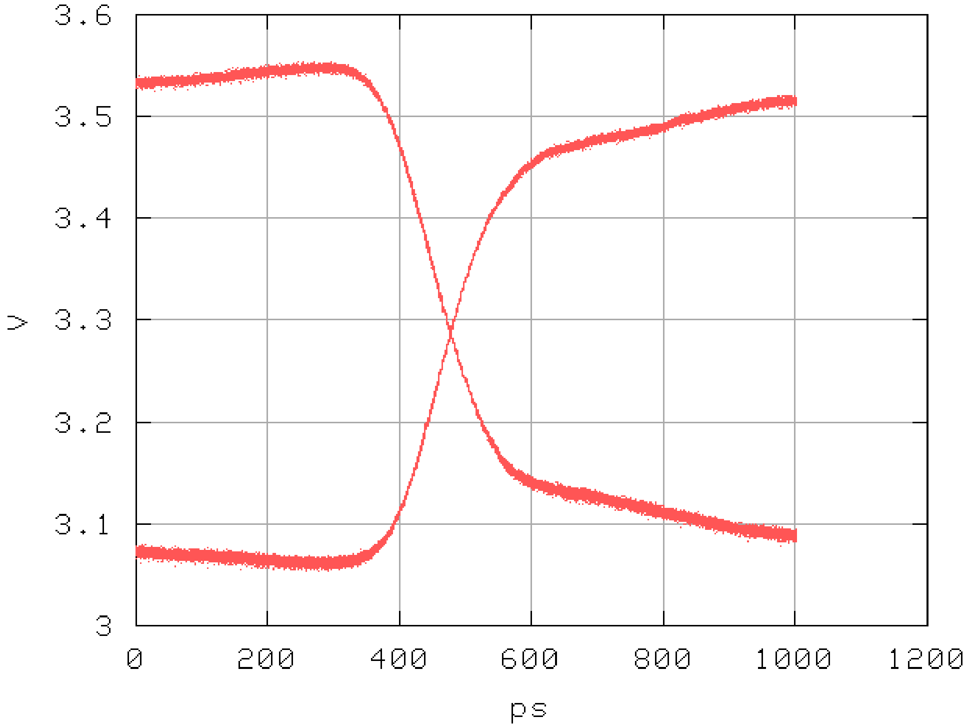


Figure 2: Measured output pulse shape accumulated during irradiation of a MC10H116D production sample.

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

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

[4] The datasheet for the MC10H116 can be obtained from `http://www.onsemi.com`.