Single-Event Effects Test Report on IEEE 1394

(Testing conducted at Texas A&M on 10/14/01)

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I. Introduction

Radiation testing was performed on IEEE 1394 Open Host Controller Interface (OHCI) Chipsets from Texas Instruments to characterize the single-event effects response to heavy ions, including single-event upset (SEU), single-event functional interrupt (SEFI) and single-event latchup (SEL). The testing was done at Texas A&M Cyclotron Facility.

II. Devices Tested

The IEEE1394 OHCI chipset consists of two devices – Link Layer Controller (LLC) and Physical Layer (PHY). Both chips were mounted on a development board supplied by the manufacturer. Table 1 shows the part numbers, the Lot and Date Codes (LDC) and the number of the development board. In a previous report on testing 1394 OHCI, it was determined that the parts manufactured by NSC were latchup prone and therefore did not warrant further testing.

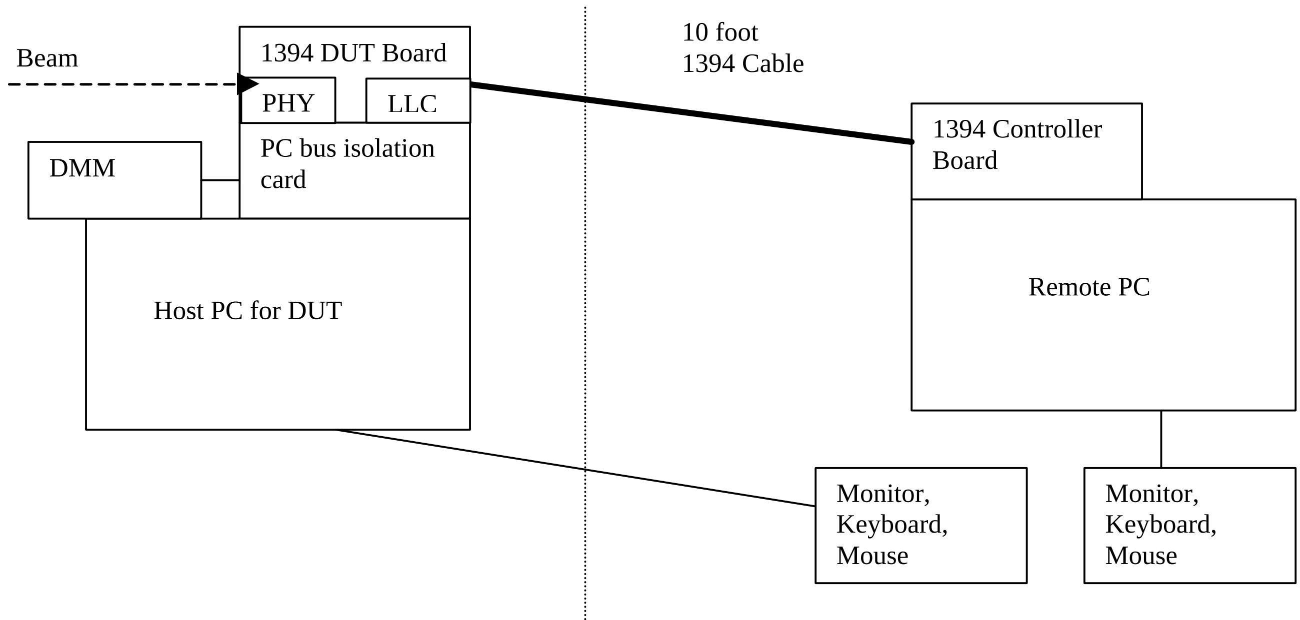
Table 1. Summary of devices tested.

Manufacturer	LLC		PHY		Development Board
	Part Number	LDC	Part Number	LDC	
TI	TSB12LV26PZT	CA-OAAO45T	TSB41AB3PFP	OCC4RTT	TSBKOHCI403

III. Test Setup

A. Hardware

Two personal computers (PCs) with PCI slots were used in the test. Each PC contained an IEEE 1394 board and was connected to the other by an IEEE 1394 cable 10 feet long. One of the PCs was positioned close to the exit port of the accelerator and the other was located outside the chamber. The IEEE 1394 board containing the two devices-under-test (DUTs) was mounted on top of its host PC case and positioned in front of the accelerator exit port for exposure to the ion beam in air. The host PC was secured to a stage that could be moved linearly in all directions and could also be rotated. Only one of the DUTs at a time was exposed to the beam. A PCI bus isolation card was placed between the DUT board and its host PC, making it possible to measure the supply current to the DUT board from the host PC via the PCI interface. A HP34401A Digital Multi-Meter (DMM) was used to read and record the current to assist in identifying SEL. A monitor, mouse and keyboard were connected to the PC hosting the DUT via a bus extender. In that way both PCs could be controlled from outside the chamber. Fig. 1 shows the hardware setup.



B. Software

Custom software was developed using C++ under a Windows/NT environment. It is essentially a ping-pong program that enables communication between two PCs via IEEE1394 connection. The speed of the communication was 100 Mbps. Two operating modes were tested – isochronous and asynchronous. During the test, register values were continuously checked and any errors were sent via an asynchronous or isochronous (depending on the test mode) block packet to the remote PC for error analysis. Register errors that did not cause communication failure were classified as “soft” errors. After a “soft” error was detected and recorded, the registers were scrubbed and the test continued. The software did not allow for identifying “soft” errors in the PHY registers. . Those errors that did cause a failure in communications were assigned to the “hard” error category. By “hard” we do not mean that there was any permanent damage, only that either software or hardware, or both, had to be rebooted in order to re-establish communications. Only hard errors were detected when the PHY was irradiated, regardless of whether it was operating in the isochronous or asynchronous mode.

IV. Test Procedure

Both high-energy (55 MeV/amu) and low-energy (15.2 MeV/amu) ions were used for the single-event effects testing. Table II shows the ions, their energies, angles of incidence and effective LETs. The LETs were corrected for the energy loss in the widow material (25.4 μm of Aramica) and in 4.5 cm of air between the window and the DUT.

Table II. Ions used for SEE testing.

Ion	Energy (MeV/amu)	Angle (Degrees)	Effective LET (MeV.cm^2/mg)
Argon	55	0	3
Argon	55	45	4.2
Argon	15.2	0	8.39
Argon	15.2	45	11.9
Krypton	15.3	0	27.7
Krypton	15.3	45	39.2
Xenon	15.2	0	51.5
Xenon	15.2	30	59.6
Xenon	15.2	45	73

A low ion flux (~1000 particles/cm^2/sec) was used for testing with low-energy (high LET) ions because of the high SEE cross-section. Before starting the test, each computer was first booted, then the bus software was started, and finally communication between the two computers was established. During this pre-irradiation period a few "soft" errors occurred as a result of the startup procedure. They were ignored. Once these non-radiation induced "soft" errors had been cleared out of the system, the beam was turned on and irradiation commenced. The parts were exposed to the beam and the beam was turned off when communications halted or when the fluence reached 1.0E+06 particles/cm^2.

Following a SEFI, a series of steps was taken to restart the system. SEFIs were categorized according to what steps were necessary to re-establish communications. Some SEFIs required only that communication be re-established via software, whereas others required a complete reboot of both PCs as well as all the software. Table II gives the series of steps taken to re-establish communications following a SEFI. Step 1 required less than a minute, whereas step 12 required approximately 10 minutes to complete.

Table II. List of steps taken following a SEFI to re-establish communications.

Step	Action
1	SEU test loop is restarted on the controller i.e. a packet is sent to DUT requesting register information
2	Software bus reset. Force root (R bit), set IBR (initiate bus reset) in the PHY, Reset node on the LLC (HCCC register, set bit 16 –Soft Reset) This restores OHCI registers and flushed FIFOs. Set bus Ops, IRMC, CMC, ISC, configuration ROM, Enable Rx (receive) and Tx(transmit).
3	Reload Software application. This refreshes the lockdown memory region shared between the software and hardware.
4	Step 2 followed by step 3.
5	Able to verify that the controller is sending register data solicit packets to the DUT. Able to verify that the DUT receives the register data solicit packet. Able to verify that the DUT sends register data packet response to the controller. Able to verify that the controller cannot see the register data response packet. Power cycle the controller.
6	Disconnect/reconnect the 1394 cable. Causes hard bus reset, tree ID process.
7	Step 6 followed by steps 3, 2, and 1.
8	Step 6 followed by cold rebooting DUT followed by steps 3, 2, and 1.
9	Cold reboot DUT followed by steps 3, 2 and 1.
10	Step 6 followed by step 9
11	Reboot controller, followed by steps 3, 2 and 1.
12	Reboot both controller and DUT PCs, followed by steps 3, 2 and 1.

IV. Test Results

Tables III, IV, V and VI show the results for both "soft" and "hard" errors for the PHY and LLC running in either isochronous or asynchronous modes. The tables show that there are three different kinds of "soft" errors and fourteen different kinds of "hard" errors. The hard errors are categorized according to what happened and what was required to restore proper operation., according to the steps detailed in Table II. Because a considerable amount of time was required to reboot the PCs and reset the software following a "crash", the statistics for these kinds of errors are poor. Better statistics were obtained by treating all "hard" errors as one kind of error and all "soft" errors as another kind. A "0" in a cell indicates that no errors of that kind were observed. An "x" in a cell indicates that testing was not done for that particular condition due to time constraints.

The increase in current from 18 mA to 44 mA does not necessarily indicate latchup even though the system "crashed" and power had to be cycled, a standard indication of latchup. In most cases we believe that the increase in current was caused by a single-event functional interrupt (SEFI) although the exact cause is unknown. There were two occasions on which the system stopped functioning and the current increased; in one case it jumped from 18 mA to 104 mA during irradiation with ions having an LET of 51.6 MeV.cm^2/mg, and in the other case to 450 mA when irradiated with ions having an LET of 8.9 MeV.cm2/mg.. These may have been latchups but they did not lead to chip damage.

Table III. Cross-sections (cm^2/device) for both soft and hard errors as a function of ion LET ($MeV.cm^2/mg$) for LLC running in Isochronous Mode.

	ERRORS IN *LLC* RUNNING *ISOCHRONOUS* MODE	**3**	**4.2**	**8.39**	**11.9**	**27.7**	**39.2**	**51.6**	**59.6**	**73**
	"Soft" Errors									
1	No errors observed but curent jumped from 18mA->44mA	0	1.0E-06	0	0	0	0	0	x	x
2	Register error, self-corrected and no change in current	9.1E-07	3.0E-06	1.2E-05	2.6E-05	4.9E-05	7.8E-06	7.4E-05	x	x
3	Register error, self-corrected, current jumped 18mA->44mA	0	0	0	0	0	0	0	x	x
	"Hard" Errors									
4	Restart communications from Controller.	0	0	5.2E-06	0	0	0	0	x	x
5	Software bus reset current jumped from 18mA to 44mA.	0	0	0	0	1.6E-06	3.7E-06	4.8E-06	x	x
6	Reset Controller and/or DUT software		0	0	9.1E-07	3.2E-06	0	0	x	x
7	Software bus reset and reset software on DUT and controller	4.5E-08	0	4.8E-08	1.4E-06	0	0	0	x	x
8	Controller sends packet, does not listen Cold reboot controller	0	0	0	0	0	0	0	x	x
9	Disconnect/reconnect cable (Hard bus reset).	0	0	0	0	0	0	0	x	x
10	Disconnect/reconnect cable, reload bus and DUT software.	0	0	0	0	0	0	0	x	x
11	Reset cable and then cold reboot DUT	0	0	0	4.5E-07	0	0	4.8E-06	x	x
12	Cold reboot DUT after lockup, but no change in current	0	0	4.8E-07	9.1E-07	3.2E-06	1.9E-06	7.1E-06	x	x
13	Cold reboot DUT after lockup, current jump 18mA to 44mA	0	0	9.5E-07	2.3E-06	3.2E-06	5.6E-06	0	x	x
14	Discont/recon cable, reboot DUT and software delta I =0	0	1.0E-06	0	0	0	0	0	x	x
15	Discon/recon cable, reboot DUT & software I: 18 -> 44 mA	0	0	0	0	0	0	0	x	x
16	Reboot controller, reset software on bus, controller and DUT	0	0	0	0	0	0	0	x	x
17	Reboot both computers, reset all software	4.5E-07	2.0E-06	4.8E-07	0	0	0	0	x	x

Table IV. Cross-sections (cm^2/device) for both soft and hard errors as a function of ion LET ($MeV.cm^2/mg$) for LLC running in Asynchronous Mode.

	ERRORS IN *LLC* RUNNING *ASYNCHRONOUS* MODE	**3**	**4.2**	**8.39**	**11.9**	**27.7**	**39.2**	**51.6**	**59.6**	**73**
	"Soft" Errors									
1	No errors observed but curent jumped from 18mA->44mA	0	0	0	0	0	0	0	0	x
2	Register error, self-corrected and no change in current	1.3E-04	1.0E-05	4.6E-05	2.5E-05	8.8E-05	3.1E-04	2.4E-04	1.3E-04	x
3	Register error, self-corrected, current jumped 18mA->44mA	0	0	0	0	0	0	0	0	x
	"Hard" Errors									
4	Restart communications from Controller.	0	0	0	8.3E-07	0	0	6.8E-06	0	x
5	Software bus reset current jumped from 18mA to 44mA.	0	0	0	0	0	2.6E-05	0	0	x
6	Reset Controller and/or DUT software	0	0	4.3E-06	8.3E-07	2.3E-06	0	0	0	x
7	Software bus reset and reset software on DUT and controller	0	0	4.3E-06	4.2E-06	0	1.3E-05	0	0	x
8	Controller sends packet, does not listen Cold reboot controller	0	0	0	0	2.3E-06	0	0	0	x
9	Disconnect/reconnect cable (Hard bus reset).	0	0	0	0	0	0	0	0	x
10	Disconnect/reconnect cable, reload bus and DUT software.	0	0	0	0	0	0	6.8E-06	0	x
11	Reset cable and then cold reboot DUT	0	0	0	0	2.3E-06	0	0	5.7E-05	x
12	Cold reboot DUT after lockup, but no change in current	0	0	0	8.3E-07	4.5E-06	2.6E-05	1.4E-05	0	x
13	Cold reboot DUT after lockup, current jump 18mA to 44mA	0	0	2.2E-06	1.7E-06	4.5E-06	0	1.4E-05	0	x
14	Discont/recon cable, reboot DUT and software delta I =0	0	0	0	0	0	0	0	0	x
15	Discon/recon cable, reboot DUT & software I: 18 -> 44 mA	0	0	0	0	0	0	0	0	x
16	Reboot controller, reset software on bus, controller and DUT	0	0	0	0	0	0	0	0	x
17	Reboot both computers, reset all software	0	0	4.3E-06	0	0	0	6.8E-06	0	x

Table V. Cross-sections (cm^2/device) for both soft and hard errors as a function of ion LET (MeV.cm^2/mg) for PHY running in Isochronous Mode.

	ERRORS IN *PHY* RUNNING *ISOCHRONOUS* MODE	**3**	**4.2**	**8.39**	**11.9**	**27.7**	**39.2**	**51.6**	**59.6**	**73**
	"Soft" Errors									
1	No errors observed but curent jumped from 18mA->44mA	0	0	0	x	X	x	x	0	0
2	Register error, self-corrected and no change in current	0	0	0	x	X	x	x	0	0
3	Register error, self-corrected, current jumped 18mA->44mA	0	0	0	x	X	x	x	0	0
	"Hard" Errors									
4	Restart communications from Controller.	0	0	0	x	X	x	x	0	0
5	Software bus reset current jumped from 18mA to 44mA.	0	0	0	x	X	x	x	0	0
6	Reset Controller and/or DUT software	0	0	0	x	X	x	x	0	0
7	Software bus reset and reset software on DUT and controller	0	1.5E-06	0	x	X	x	x	0	0
8	Controller sends packet, does not listen Cold reboot controller	0	0	7.4E-07	x	X	x	x	0	0
9	Disconnect/reconnect cable (Hard bus reset).	0	0	0	x	X	x	x	0	0
10	Disconnect/reconnect cable, reload bus and DUT software.	5.5E-06	4.5E-06	2.2E-06	x	X	x	x	0	0
11	Reset cable and then cold reboot DUT	0	0	0	x	X	x	x	0	0
12	Cold reboot DUT after lockup, but no change in current	0	0	0	x	X	x	x	0	0
13	Cold reboot DUT after lockup, current jump 18mA to 44mA	0	0	0	x	X	x	x	0	0
14	Discont/recon cable, reboot DUT and software delta I =0	0	0	0	x	X	x	x	0	0
15	Discon/recon cable, reboot DUT & software I: 18 -> 44 mA	0	0	0	x	X	x	x	0	0
16	Reboot controller, reset software on bus, controller and DUT	0	0	0	x	X	x	x	0	0
17	Reboot both computers, reset all software	0	0	3.7E-07	x	X	x	x	4.5E-04	4.7E-04

Table VI. Cross-sections (cm^2/device) for both soft and hard errors as a function of ion LET ($MeV.cm^2/mg$) for PHY running in Asynchronous Mode.

	ERRORS IN *PHY* RUNNING *ASYNCHRONOUS* MODE	**3**	**4.2**	**8.39**	**11.9**	**27.7**	**39.2**	**51.6**	**59.6**	**73**
	"Soft" Errors									
1	No errors observed but curent jumped from 18mA->44mA	0	0	x	0	0	0	0	x	x
2	Register error, self-corrected and no change in current	0	0	x	0	0	0	0	x	x
3	Register error, self-corrected, current jumped 18mA->44mA	0	0	x	0	0	0	0	x	x
	"Hard" Errors									
4	Restart communications from Controller.	0	0	x	0	0	0	0	x	x
5	Software bus reset current jumped from 18mA to 44mA.	0	0	x	0	0	1.0E-04	6.4E-05	x	x
6	Reset Controller and/or DUT software	0	0	x	0	9.1E-06	0	0	x	x
7	Software bus reset and reset software on DUT and controller	0	0	x	0	0	0	0	x	x
8	Controller sends packet, does not listen Cold reboot controller	0	0	x	0	0	0	0	x	x
9	Disconnect/reconnect cable (Hard bus reset).	9.1E-08	0	x	8.3E-07	0	0	0	x	x
10	Disconnect/reconnect cable, reload bus and DUT software.	0	0	x	3.3E-06	0	0	0	x	x
11	Reset cable and then cold reboot DUT	0	0	x	0	0	0	0	x	x
12	Cold reboot DUT after lockup, but no change in current	0	0	x	0	0	2.0E-04	0	x	x
13	Cold reboot DUT after lockup, current jump 18mA to 44mA	0	0	x	0	0	0	0	x	x
14	Discont/recon cable, reboot DUT and software delta I =0	0	0	x	0	0	0	0	x	x
15	Discon/recon cable, reboot DUT & software I: 18 -> 44 mA	0	0	x	0	0	0	0	x	x
16	Reboot controller, reset software on bus, controller and DUT	0	0	x	0	0	0	0	x	x
17	Reboot both computers, reset all software	0	0	x	2.5E-06	3.6E-05	2.0E-04	2.6E-04	x	x

"Hard" and "soft" error cross-sections as a function of ion LET were plotted for the PHY and LLC operating in the isochronous and asynchronous modes. The results are shown in Figs 2, 3 and 4. It appears from figures 2 and 3 that both hard errors and soft error are more prevalent in the LLC for the asynchronous mode than for the isochronous mode. There were no soft errors observable when the PHY was irradiated, and it was assumed that the mode of operation, i.e., asynchronous or isochronous, did not matter as far as SEFI cross-section was concerned. Hence, the data from the two modes were combined into a single plot.

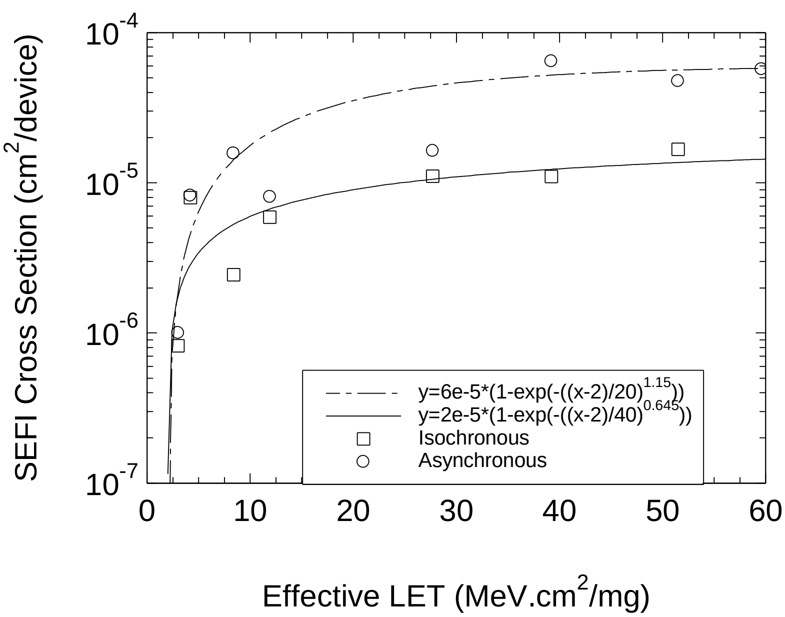


Fig. 2. Cross-section per device for "hard" errors as a function of ion LET for the LLC.

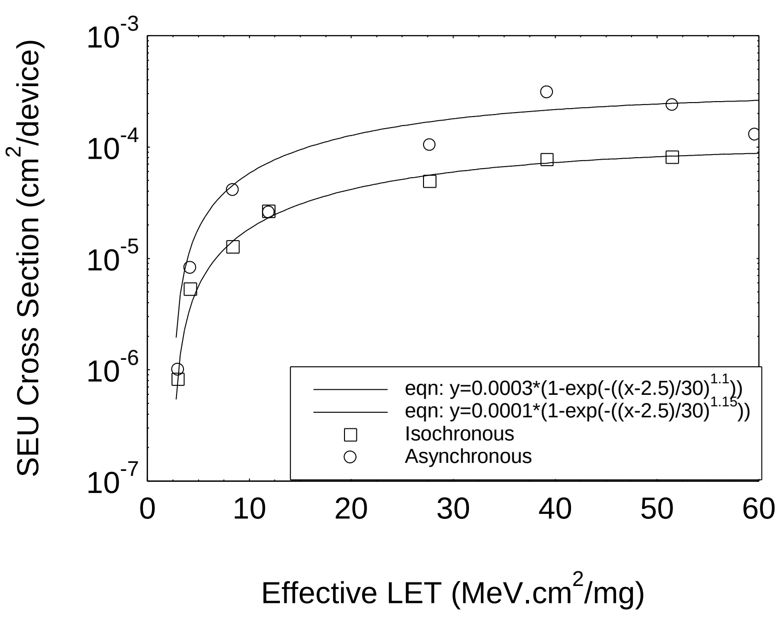


Fig. 3. Cross-section per device for "soft" errors as a function of ion LET for the LLC. Included are Weibull fits to the data.

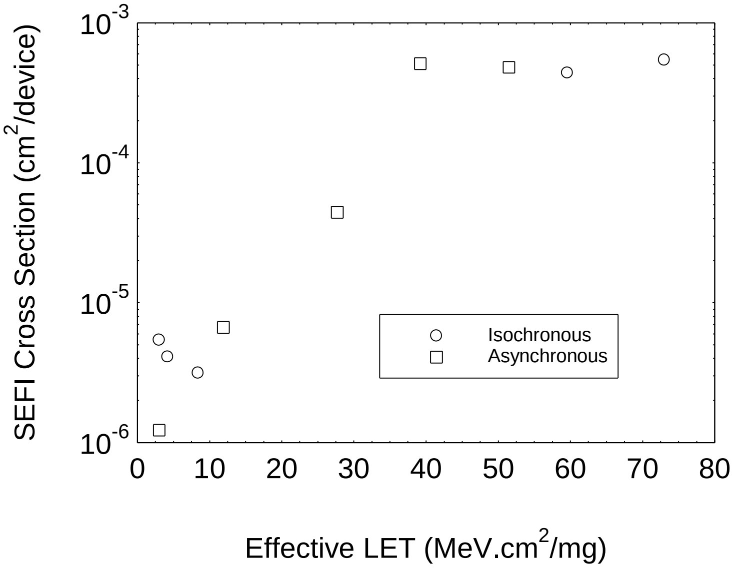


Fig. 4. Cross-section per device for “hard” errors for the PHY. The data for isochronous and asynchronous modes were combined because the mode of operation does not have any effect on the hard errors.

V. Conclusions

The IEEE1394 serial bus implementation by TI exhibits a complex and varied set of failures as a result of exposure to heavy ions. Errors were classified as “soft” if they changed information in a register without affecting communications. They were classified as “hard” if they caused an interruption in communications that necessitated a reboot of either hardware or software. “Hard” errors did not cause any physical damage. On two occasions large increases in current were observed that could be attributed to SEL. In the case of “hard” errors in the PHY, there are rather large error bars due to the small number of SEFIs recorded as a result of the excessive amount of time required to reboot the system following a SEFI.