Improved Capabilities for Proton and Neutron Irradiations at TRIUMF

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***Abstract*--Improvements have been made at TRIUMF to permit higher proton intensities of up to 10^{10} cm^{-2}s^{-1} over the energy range 20-500 MeV. This improved capability enables the study of displacement damage effects that require higher fluence irradiations. In addition, a high energy neutron irradiation capability has been developed for terrestrial cosmic ray soft error rate (SER) characterization of integrated circuits. The neutron beam characteristics of this facility are similar to those currently available at the Los Alamos National Laboratory WNR test facility. SER data measured on several SRAMs using the TRIUMF neutron beam are in good agreement with the results obtained on the same devices using the WNR facility. The TRIUMF neutron beam also contains thermal neutrons that can be easily removed by a sheet of cadmium. The ability to choose whether thermal neutrons are present is a useful attribute not possible at the WNR.**

I. Introduction

THE TRIUMF Proton Irradiation Facility (PIF)[1] can provide monoenergetic proton beams from 65 to 500 MeV with energies down to 20 MeV obtained by degrading the low energy beam. Initially the facility was optimized for single event studies with proton fluxes up to 10^8 cm^{-2}s^{-1} and with uniform beams up to 7.5 cm diameter. Two proton beam lines are used to cover the full energy range with each beam line terminating in the same test area. BL2C produces protons with energies up to 120 MeV and BL1B the range from 180 to 500 MeV. This facility has been in operation since 1995 with scheduled test periods of days to weeks available about every second month, depending on demand.

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The user community is mainly from Canadian space-related companies [2,3] but a number of groups of foreign users [4] are now using the unique capabilities of PIF as it can provide such a large range of proton energies. In addition, groups from particle physics [5] and life sciences are also active users.

This paper reports on two improvements that have been implemented recently to increase the proton flux available for testing smaller devices and to develop a high flux, high-energy neutron capability.

II. Higher Proton Intensities

There has been an increasing demand for higher proton fluxes for studying displacement damage of new materials such as GaN and GaAs LEDs, and for simulating the higher doses required for testing ATLAS detector components for experiments at the Large Hadron Collider at CERN.

There are limitations on the maximum proton current that can be transported into the test area due to shielding of the neutrons that are produced, in particular at the higher proton energies. The solution has been to make more efficient use of the protons by using smaller beam spots at the test location. Typically the devices that are being tested at these high fluences are only a few mm in size so this is a viable solution. The smaller beam spots require more precise knowledge of the beam position and profile. This has been achieved by using a thin multi-wire ionization chamber, which gives a real time indication of the beam position and size in the two transverse dimensions. Each dimension is measured by 16 wires with 3 mm spacing. The device under test is placed on the same mounting plate as for the chamber so that accurate positioning can be achieved. Profiles are also measured at the start of irradiation using radiochromic film. The profile monitor can be easily switched between the two beam lines so that higher proton intensities up to 10^{10} cm^{-2}s^{-1} are now available over the entire energy range. This is an increase of a factor of 100 over the previous test capability.

A. Proton Dosimetry and Beam Size

Fig. 1 shows the layout of the BL2C equipment with typical beam sizes at the two test locations. Fig. 2 is a photograph of the front end of the beam line showing the device mounting arrangement and the beam monitoring equipment. The beam size and uniformity can be adjusted by changing the thickness or the material of a scattering foil located at the front collimator. Table I lists the proton flux and beam size for some measured beam conditions on both beam lines.

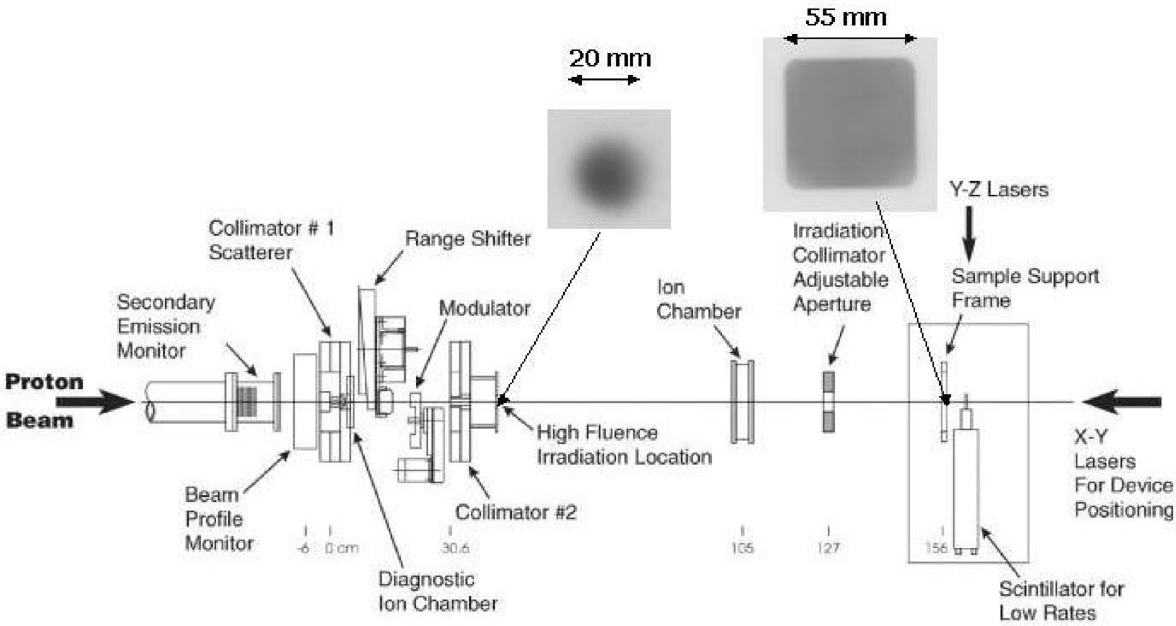

Fig. 1. Layout of the irradiation equipment at the end of beam line 2C showing typical beam sizes.

TABLE I
PROTON FLUX AND BEAM SIZE MEASUREMENTS

Beam line Energy MeV	I_{max} nA	Test energy MeV	Range shifter or absorber thickness mm	Scatterer material thickness mm	Proton flux per nA $cm^{-2}s^{-1}$ x 10^8	Beam size 80% uniform X mm	Y mm
BL2C							
70	10	63	0	0.8 Pb	1.4	25	25
		52	15.5*	0	24	7.3	7.3
		50	15.5*	0.3 Cu	6.0	10	10
		50	780	0.8 Pb	1.1	28	28
116	6	115	0	0	41	5.4	4.4
		115	0	0.3 Cu	20	6.4	6.4
		111	0	0.8 Pb	6.2	16	16
		105	0	2.4 Pb	1.6	27	27
		85.5	2000	2.4 Pb	1.3	>27	>27
		67	3800	2.4 Pb	1.1	>27	>27
BL1B							
200	4	198	0	0.63 Pb	3.5	19	19
354	3	352	0	1.3 Pb	3.5	25	25
493	2	491	0	1.3 Pb	5.0	19	19

*Lucite absorber placed directly in front of test point

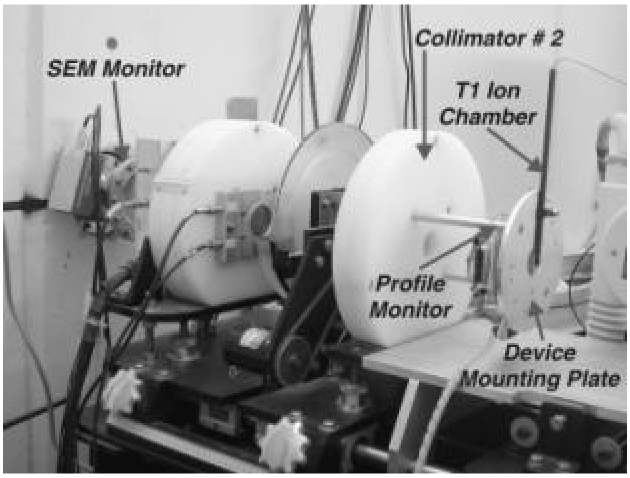

Fig. 2. Photograph of the front end of BL2C showing the high intensity test arrangement.

A second requirement is for accurate calibration of dose and fluence at the higher intensities, where the normal calibration technique using a miniature ion chamber may suffer from saturation or size effects. The chamber used is an Exradin T1 ion chamber, which has a sensitive volume of 0.056 cm^3, transverse dimensions of 3-4 mm and a nominal calibration of 60 cGy/nC. The maximum incoming proton current ranges from 10 nA at 70 MeV to 2 nA at 500 MeV.

A Faraday cup capable of measuring the proton current up to 225 MeV has been designed and fabricated. A low leakage current of less than 0.6 pA under operating bias conditions has been achieved and there is good agreement between the Faraday cup measurements and ion chamber calibrations as indicated in Fig. 3. The difference on the calibration at low proton energies is due to the energy loss in the walls of the T1 ion chamber, which has not been taken into account.

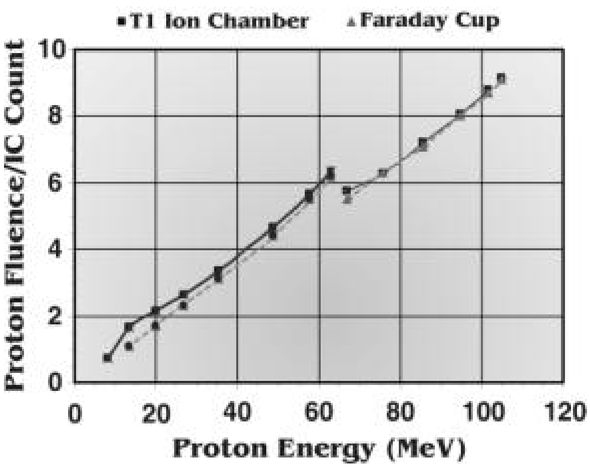

Fig. 3. Comparison of proton beam calibrations using the Faraday Cup and miniature ion chamber.

III. TRIUMF NEUTRON FACILITY

In the PIF area, neutron irradiations have been carried out by stopping 70-500 MeV protons in a lead or steel absorber and placing the samples to be irradiated in the resulting neutron beam 1-2 m downstream of the absorber. The neutron energy spectrum from 116 MeV protons stopping in a 20 mm lead absorber has been accurately measured using Bonner spheres and carbon activation and used in a number of experiments related to neutron single event effects and dosimetry. The 1 MeV equivalent neutron flux is 2 x 10^5 $cm^{-2}s^{-1}$ at a distance of 1.4 m from the proton beam stop.

A request for a significantly higher flux of 1 MeV and higher energy neutrons resulted in a study of the neutron beam produced in one of the neutron channels located at the high power beam dump on BL1A [6]. At this dump typically 100-150 uA of 450-500 MeV protons is stopped after passing through meson and isotope production targets and this operation is scheduled for about 3000 hours per year.

The protons are stopped in an aluminum plate beam dump 20 cm in diameter and 57 cm long, with the aluminum divided into a number of plates separated by 2 mm water channels. The target is immersed in a cylindrical water tank 73 cm in diameter. In the original design of the TRIUMF neutron facility (TNF), four horizontal beam channels 20 cm wide by 9 cm deep were created in the steel shielding surrounding the water tank (see Fig 4). These channels are offset vertically from the proton beam so that they look at the water moderator below the beam stop. One of these channels has a vertical access aperture in the shielding at a distance of 2.6 m from the beam stop, which emerges 5 m above the channel.

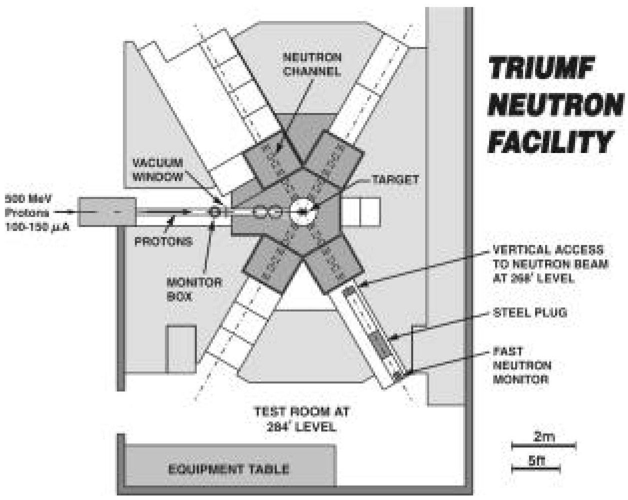

Fig. 4. Plan view of the TNF showing the neutron channel and test location.

A track with a pulley system was installed in the vertical channel to allow measurement instrumentation to be lowered to neutron beam level. Devices to be tested or activation foils are mounted on a trolley plate, which can be accurately placed in the beam. The maximum transverse size that can be accommodated is 15 cm wide by 5 cm thick.

A. Neutron Flux Studies

The neutron flux and energy spectrum have been measured by irradiating activation foils of gold, indium, nickel, aluminum and carbon to cover neutron energy ranges from thermal to above 20 MeV. Using a number of different materials allows different energy ranges to be investigated as indicated in Table II. However some knowledge of the neutron energy spectrum is required and this has been determined by simulating the neutron production using the FLUKA [7] code. Fig. 5 shows the results of this calculation and two fits to this calculation, one proportional to $1/E^{.94}$ and the second a cubic function in log-log space.

The cross sections for the different activation reactions have to be folded into this energy spectrum, with the neutron flux normalization calculated from the resulting activity. The test method followed ASTM E264-92 [8].

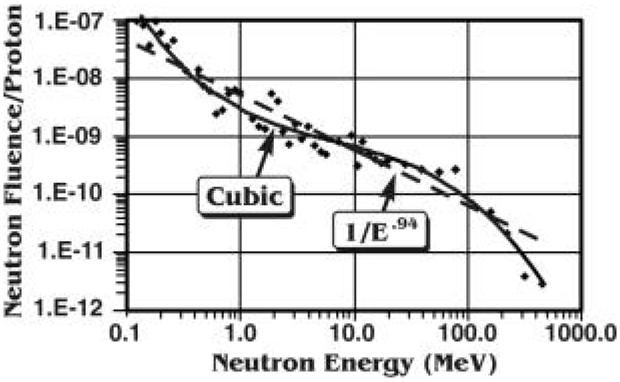

Fig. 5. FLUKA calculation of the neutron energy spectrum with the solid lines showing two fits to the calculation.

TABLE II
NEUTRON ACTIVATION FOILS

Foil	Reaction	Half-life	Energy Range MeV	Cross Section* Barns
Gold	^{197}Au(n,?)^{198}Au	64.7 hour	Thermal	98.8
Indium	^{115}In(n,?)^{116}In	54 min	Thermal	161
Nickel	^{58}Ni(n,p)^{58}Co	70.8 day	2-25	0.628
Aluminum	^{27}Al(n,a)^{24}Na	15.0 hour	6-30	0.125
Carbon	^{12}C(n,2n)^{11}C	20.5 min	>20	0.018

*peak cross section.

Table III summarizes the results of a series of activation measurements, using the cubic function for the neutron spectrum shape. The results are normalized to 140 µA extracted down BL1A. The thermal flux was obtained from the difference in activity between a bare gold foil and a second gold foil covered with cadmium. The equivalent 1 MeV neutron flux for displacement damage measurements has been calculated using the method of ASTM E722-94 [9] and is listed in Table III, based on the nickel activation normalization.

TABLE III
NEUTRON FLUX MEASUREMENTS

Activation Foil	Energy Range MeV	Neutron Flux* $cm^{-2}s^{-1}$	Total Neutron Flux* $cm^{-2}s^{-1}$ 1-400 MeV
Nickel	1-30	3.6×10^5	4.5×10^6
Aluminum	1-30	4.2×10^5	5.2×10^6
Carbon	>24	1.9×10^5	3.4×10^6
Gold	thermal	1.0×10^6	-
ASTM E722-94	1	-	9.3×10^6**

* normalized to 140 µA on BL1A
** 1 MeV equivalent flux

A PC based program has been written to integrate the proton beam current and provide a real-time display of the beam current, integrated current and beam hours, as well as a graph of this information. Typical exposure times for the activation measurements are 2-100 hours, with the shorter time for the carbon activation and the longer for nickel irradiations. The activity/µA-hour is constant to ±5% for different measurements with the same foil and location. The deviations in the measurements for the different materials is likely due to errors in the cross sections, where the data is not well known above 20 MeV for nickel and aluminum, and in the assumed shape of the energy spectrum. However the agreement is reasonable and it is presently estimated that the absolute flux above 1 MeV is known to about 20%.

B. Neutron Dose Studies

A moderated BF3 counter has been placed at the end of the neutron channel, behind 50 cm of steel shielding to reduce the dose and harden the spectrum. This neutron dose rate has been monitored against the proton rate on the beam dump and the variation over several months is 5%. The neutron dose was measured at the test point using BD100R bubble detectors and ALOKA PDM 303 neutron dosimeters. The beta/gamma dose was also measured. The dose rate in Sv/hr can also be calculated from the neutron flux using the ICRP-74 neutron fluence to dose conversion [10]. The dose information is given in Table IV. The quality factor averaged over the energy spectrum from 0.1 to 400

MeV is about 8. Therefore the absorbed neutron dose rate at 140 µA is about 1 Gy/hr or 100 rad/hr. The bubble detectors are calibrated with an Am-Be source and are known to underestimate the dose if there are high-energy neutrons present. The ALOKA neutron dosimeters overestimate the dose by factors 3-5.

TABLE IV
NEUTRON DOSE MEASUREMENTS

Technique	Neutron Dose* Sv/hr	β-? Dose* Sv/hr
Dose from neutron spectrum – calculated	5.9 > 1 MeV 7.2 > .1 MeV	
BD-100R bubble detector	4.6-5.2	
Aloka PDM 303 neutron	22-24	
Aloka PDM 203 gamma		0.36
Rados RAD-404 gamma		0.42-0.60

* normalized to 140 µA on BL1A.

Fig. 6 shows the neutron beam profile obtained with radiochromic film at the test position. This profile has been checked with a series of aluminum foil activations. The 80% uniform region is about 5 cm high by 12 cm wide.

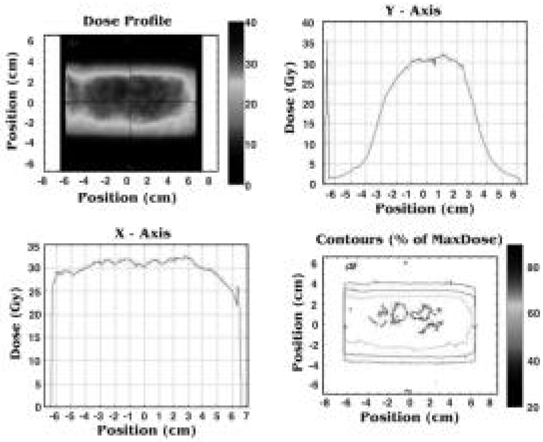

Fig. 6. The neutron beam profile at the TRIUMF Neutron Facility obtained by exposing GafChromic film at the test location.

C. *SEU Testing in the Neutron Beam*

To confirm the suitability of the TRIUMF neutron irradiation facility for terrestrial cosmic ray soft error rate (SER) characterization, 5 different SRAM types were irradiated. These devices had previously been characterized at the Los Alamos National Laboratory Weapons Neutron Research (WNR) facility [11,12]. Accelerated SER testing was performed following the JEDEC test standard for soft errors induced by terrestrial cosmic rays [13]. The terrestrial SER can then be determined for a given altitude and location using the procedures outlined in [13]. In this work SER is reported in FIT/Mbit at sea level in New York City, where 1 FIT (failure in time) = 1 error per 10^9 device-hours. SER in the SRAMs was measured as a function of power supply voltage, and latchup was detected using current monitoring. The SRAMs tested included full CMOS 6-transistor (6T) cell designs, thin film transistor (TFT) loaded 6T cells, and polysilicon resistor loaded 4T cells.

Fig. 7 shows the measured SER in 6T CMOS 1-Mbit SRAMs from manufacturer A's 0.16-µm process as a function of power supply voltage. For this SRAM the memory field is split into 3.3-V and 1.5-V halves (with dual gate oxide thicknesses). Data from both halves are combined in this figure, and the results of testing at both WNR and TRIUMF are shown. Error bars indicate the standard deviation in measurements from multiple parts. In both cases the neutron flux above 10 MeV is used in the comparison. The TRIUMF data are in reasonably good agreement with previous WNR tests, but appear to be systematically 10-30% lower than the SER calculated from the WNR data. Fig. 8 shows similar data for 3.3-V and 5-V 4-Mbit SRAMs from manufacturer B. Here, the agreement between WNR and TRIUMF data is somewhat better, with much of the data falling within the part-to-part variation. In general, however, the TRIUMF data again fall below the WNR data, suggesting a systematic error of about 25% in the neutron flux calibration between the two facilities.

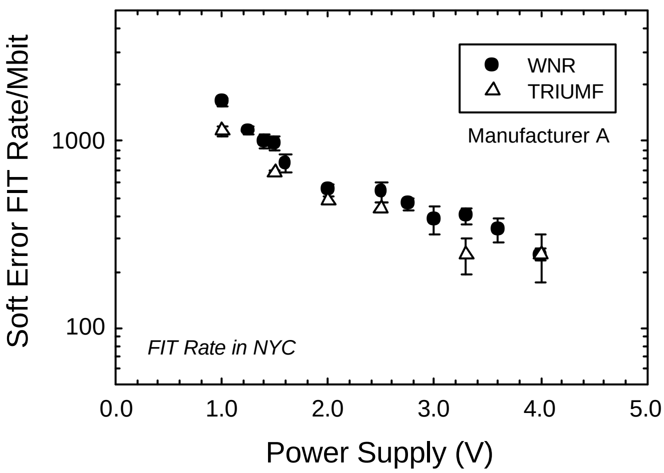

Fig. 7. Neutron-induced SER in 1.5/3.3-V 6T full CMOS 1-Mbit SRAMs from Manufacturer A's 0.16-µm process as a function of power supply voltage. Ground-level FIT rates are shown for New York City.

In contrast to the WNR neutron spectrum, the continuous neutron spectrum in the TNF includes a contribution from thermal neutrons as indicated in Table III. It has previously been shown that some ICs are sensitive to thermal neutrons, especially those whose construction incorporates boron-10 [14]. In Fig. 9, the neutron-induced SER in a 5-V 4-Mbit SRAM from a third manufacturer is plotted as a function of power supply voltage. Previous experiments have shown that this SRAM is sensitive to thermal neutrons [11]. In this figure, the SER calculated from WNR experiments has been multiplied by 0.75 to account for the apparent discrepancy in neutron flux between the two facilities. Data were taken at TRIUMF using both the unmoderated spectrum, and with a sheet of cadmium covering the SRAMs. The sheet of cadmium effectively removes all thermal neutrons from the neutron beam. At low supply voltages, the unmoderated TRIUMF data led to a calculated SER about a factor of two higher than with the cadmium sheet, indicating a significant enhancement in SER due to thermal neutrons at these voltages.

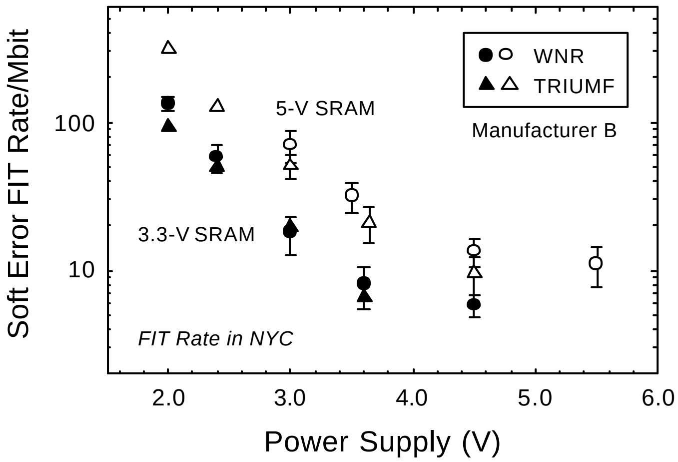

Fig. 8. Neutron-induced SER vs. power supply voltage in 3.3-V and 5-V polysilicon resistor-load 4-Mbit SRAMs from Manufacturer B. Good agreement is obtained between data taken at WNR and at TRIUMF.

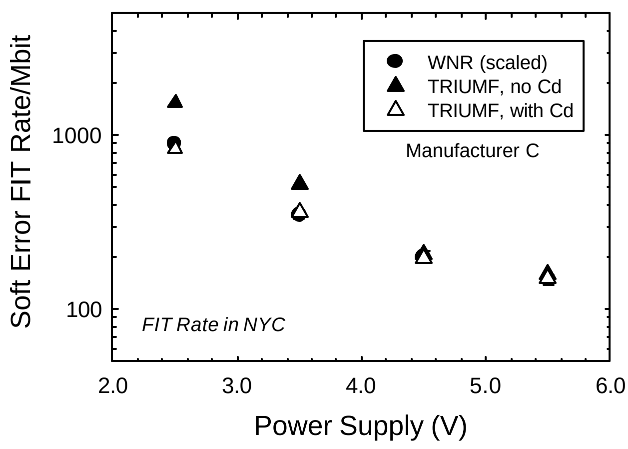

Fig. 9. Neutron-induced SER vs. power supply voltage in 5-V 6T TFT-load 4-Mbit SRAMs from Manufacturer C. The WNR data were multiplied by 0.75 to match the TRIUMF data. Note increased SER at low power supply due to thermal neutron contribution in un-moderated TRIUMF spectrum.

In contrast, data taken with the cadmium sheet in place match the scaled WNR data at all voltages, indicating successful removal of the thermal neutron flux. Note that the JEDEC method for calculating neutron-induced SER assumes no thermal neutron sensitivity is present. To properly calculate the terrestrial SER for this SRAM would require a more in-depth characterization of its thermal neutron sensitivity and the thermal neutron flux in the location of interest. Nonetheless, the ability to choose whether thermal neutrons are present in the TNF is a useful attribute not possible at WNR because it allows one to determine whether ICs being tested are indeed sensitive to thermal neutrons and thus require further characterization.

It has recently been experimentally demonstrated that terrestrial neutrons can induce latchup in some technologies [12]. In some SRAMs, neutron-induced latchup rates greater than 500 FIT/Mbit at worst-case conditions of maximum voltage and maximum temperature have been measured. Fig. 10 shows a comparison between room-temperature neutron-induced latchup rates measured at WNR and TRIUMF. Similar characteristics are seen at both facilities, but once again the latchup FIT calculated from TRIUMF data is consistently lower than from the WNR data.

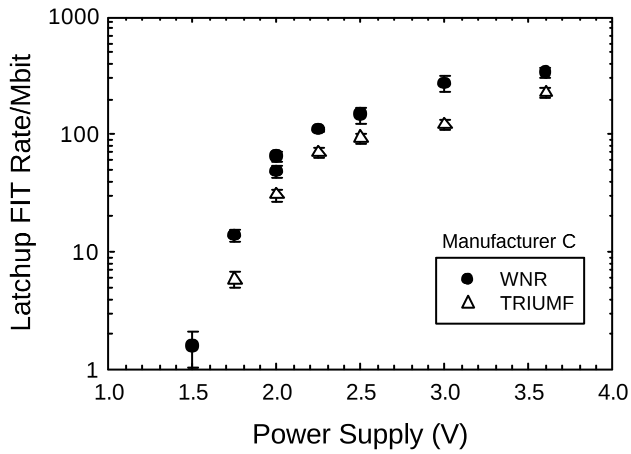

Fig. 10. Neutron-induced latchup rate in 3.3-V 6T full CMOS 4-Mbit SRAMs from Manufacturer C as a function of power supply voltage.

IV. CONCLUSION

The increased flux capability of the TRIUMF proton facility has been used for several series of displacement damage studies. The beam size and position could be controlled to better than 0.5 mm using the improved diagnostics.

The TNF neutron beam has been characterized by activation measurements that, together with a FLUKA calculation of the neutron energy spectrum, yields a flux calibration based on SER measurements that is within 25% of the WNR neutron facility. The SER comparison is based on the estimated neutron flux above an energy of 10 MeV at the two facilities. It should be pointed out that the WNR spectrum extends to higher neutron energies than TRIUMF. The TRIUMF results are within the experimental error for this stage of development of the facility and further work is required to measure the neutron energy spectrum directly. The ratio of neutron flux to proton current is stable and reproducible to 5%, enabling reliable relative measurements to be made.

V. Acknowledgment

L. Moritz from TRIUMF carried out the FLUKA calculation of the neutron spectrum. M. Mouat and the TRIUMF Controls Group provided the software support for the proton current integration. G. Hash provided software and hardware test support for the integrated circuit irradiations at TRIUMF.

VI. References

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