Exploration of the IUCF 220-MeV Proton Synchrotron as a Flash Proton Source

C. C. Foster[1], M. F. Krzesniak[2], V. McAtee[2], B. J. Hamilton[1], M. S. Ball[1], J. L. Titus[2], B. von Przewoski[1], T. L. Turflinger[2], E. R. Hall[1], G. W. East[1], D. L. Friesel[1], W. T. Sloan[1], T. Rinckel[1], K. M. Murray[3], M. Savage[2], Y. D. Kim[2], and J. L. Ramsey[4]

[1] Indiana University Cyclotron Facility, 2401 Sampson Lane, Bloomington, Indiana 47408
[2] Naval Surface Warfare Center, 300 Hwy 361, Crane, Indiana 47522
[3] KM Sciences, 3138 S. Laurel Ct., Bloomington, Indiana 47401
[4] JR & A, RR2, Box 129, Odon, Indiana 47562

Abstract

A synchrotron has been constructed at the Indiana University Cyclotron Facility (IUCF) to inject 100 to 200 MeV protons into an electron cooled storage ring to perform nuclear physics experiments. The maximum synchrotron extraction is greater than 10^{10} protons in a 20-ns wide pulse with a 1-Hz pulse repetition rate. These properties make it possible to provide transient dose rates on the order of 10^{10} rad(Si)/s, in a 3 cm^2 circular spot, using high energy protons which can penetrate deeply (up to 10 cm) into semiconductor type materials. Recent tests show that noise during the pulse from electromagnetic interference is relatively small when compared to conventional e-beam sources. That is, most of the noise occurs before the protons arrive at the test location. Finally, dose rates of 2x10^{10} rad(Si)/s were measured using several different techniques.

INTRODUCTION

In the absence of the capability to perform nuclear underground testing, several national simulator facilities have been, or are being developed, to perform high-dose-rate tests of twenty-first century space and missile systems and their components to validate system performance in case of a nuclear weapons event. It has recently been recognized that the Cooler Injector Synchrotron (CIS) [1], designed and constructed at the Indiana University Cyclotron Facility (IUCF), has capabilities which may make it useful as a simulator or may lead to development of a high intensity proton synchrotron specifically designed for high dose rate radiation effects testing. First, this paper will describe the CIS and its capabilities as a high-energy (200 MwV), narrow pulse width (< 20 ns wide) and high dose rate (> 10^{10} rad(Si)/s) proton source for radiation effects studies. At these high dose rates, transient effects should mask any single event effects. Then, actual measured data are presented using high energy protons ejected from the CIS to demonstrate these capabilities. The results of noise measurements are included.

COOLER INJECTOR SYNCHROTRON

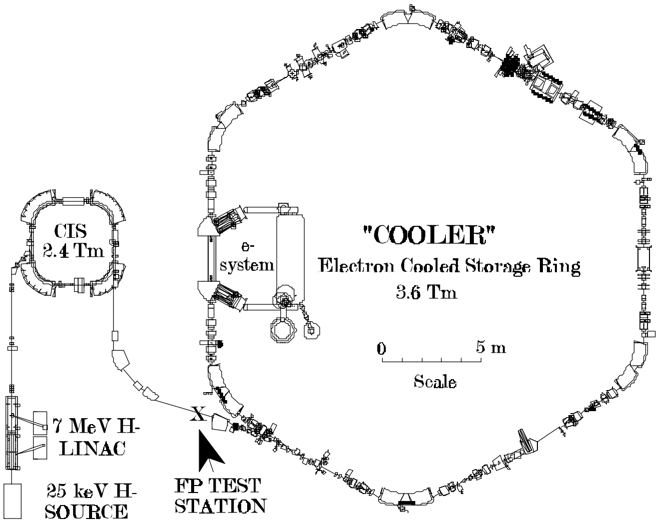

Figure 1: Layout of the IUCF accelerator research facility showing the CIS which injects high energy protons into the Cooler via a transfer beam line. The dosimetry and EMI tests were performed in air by breaking the transfer beam line at the point X just before entry into the Cooler.

A schematic of the present IUCF nuclear research accelerator facility, consisting of the new CIS booster synchrotron and the electron cooled storage ring, "Cooler", (the storage ring is not used during our tests) is shown in Figure 1. A 25-keVbeam of negatively charged ions (H$^-$) is matched to the acceptance of a commercial 7-MeV H$^-$ linear accelerator (Linac), a pre-accelerator, consisting of a 3-MeV radio frequency quadrupole (RFQ) coupled to a 4-MeV drift tube Linac [2,3]. Both operate at 425 MHz. The 7-MeV H$^-$ beam is strip injected into the synchrotron, protons are accumulated, RF captured, accelerated to 210 MeV and single turn fast extracted for bucket-to-bucket transfer into the Cooler storage ring for accumulation, electron cooling and subsequent acceleration.

Design, construction, and commission of the CIS was carried out between August, 1994 and April, 1998 at a cost of about $5M. With a circumference of 17.36 m, the CIS is possibly the smallest and least expensive example of this proton accelerator type. Table 1 gives a summary of potential proton beam properties generated by the CIS. The CIS was designed specifically to provide polarized proton beams which match the small acceptance of the Cooler at the lowest cost. Preliminary designs of "CIS like" synchrotrons with larger beam spots and intensities have already been made. Potentially, such synchrotrons could provide dose rates that exceed 10^{10} rad(Si)/s with a 10-cm diameter beam spot.

CIS OPERATION

A 2.0 mA (peak) pulsed, 25-keV H$^-$ beam from the source is focused at the entrance of the PL-7 Linac. A double einsel lens focuses the beam into the 2.5 mm diameter RFQ entrance aperture. Beam transmission through the Linac is 80%.

Table1. CIS Proton Parameters

Source	25-keV H^-
Linac Pre-accelerator	7 -MeV H^-
Strip Injection Foil	4.5 μgm/cm^2 (Carbon)
Fast Extraction	50- to 220-MeV protons
Pulse Width	20-ns FWHM
Extracted Intensity	$\geq 10^{10}$ p/pulse (variable)
Rep. Rate	.05 to 1 Hz (variable)
Spot size	>1 to 7 cm diameter (variable)
Maximum computed dose rate in a 1 cm^2 beam spot	
(A.) 200-MeV protons	(A.) 3.0 x 10^{10} rad(Si)/s
(B.) 160-MeV protons	(B.) 3.4 x 10^{10} rad(Si)/s
(C.) 120-MeV protons	(C.) 4.2 x 10^{10} rad(Si)/s
(D.) 60-MeV protons	(D.) 6.0 x 10^{10} rad(Si)/s
Maximum computed dose per burst for 1 cm^2 beam	
(A.) 200-MeV protons	(A.) 589 rad(Si)
(B.) 160-MeV protons	(B.) 681 rad(Si)
(C.) 120-MeV protons	(C.) 830 rad(Si)
(D.) 60-MeV protons	(D.) 1180 rad(Si)

The Linac delivers a 200-μs long, 2.0-mA (peak) 7-MeV H^- beam pulse at 4 Hz into a 9 meter transfer beam line to match it to the acceptance of the CIS. The beam is strip injected through a 6 mm x 25 mm x 3.0 μgm/cm^2 carbon foil. Two injection bumpers displace the circulating beam orbit 25 mm onto the foil for coasting beam accumulation. In practice, an intensity gain of 80 is routinely achieved after 175 μs, corresponding to an initial coasting beam accumulation of 8 x 10^{10} protons. One source of beam loss is the emittance growth of the circulating 7-MeV proton beam in the 0.1 μTorr average ring vacuum. Another source of beam loss at injection is the slow fall time (0.2 ms) of the bumper magnets after accumulation. Both effects can produce emittance growths nearly equal to that of the foil during injection. Vertical emittance growth during strip accumulation is the intensity limiting mechanism in the CIS.

Optimal adiabatic capture of the accumulated beam requires a 2-ms ramp of the RF cavity to 150 V. The captured beam energy is 6.987 MeV. Beam acceleration is initiated within a few milliseconds of RF capture, by which time lifetime losses reduce the stored beam to 2x10^{10} protons. This intensity is also consistent with the calculated 7 MeV circulating beam space charge limit of 5x10^{10} protons, although this has yet to be identified as a CIS intensity limit. Work is continuing to improve the ring vacuum and to reduce the injection bumper fall time to increase the stored beam intensity.

The accumulated proton beam is accelerated from 7 MeV to as high as 240 MeV by simultaneously ramping the magnetic fields in the ring dipole magnets and the frequency of the accelerator RF cavity, which is under computer control. To date, protons have been accelerated to a wide range of energies from 50 to 240 MeV with ramp transmissions of 75% and flattop intensities over 1.5x10^{10} protons. All intensity losses occur in the first 200 ms during a one-second ramp-up and are caused by gas scattering losses in the 0.1 μTorr ring vacuum. The 1/e lifetime of a 225-MeV proton beam in the CIS is 573 seconds.

While higher energy and faster repetition rate development is planned, 200 MeV at 1 Hz is an ideal beam for Cooler injection. A 0.8-Hz, 200-MeV proton ramp cycle consisting of a 0.5 s ramp-up and down, a 50 ms flattop for extraction, and a 200-ms reset and fill period is routinely used for this purpose. A special cycle will be used for the tests described in this paper, which provides a 20-ns wide beam pulsed every few seconds.

A fast ferromagnetic kicker and Lambertson septum extraction dipole are used to extract the circulating beam from the CIS and direct it to the transfer beam line to the Cooler. The Lambertson extraction channel horizontal width is 16 mm. The diameter of a 10π mm mradian, 200-MeV proton beam is about 11 mm, hence a careful alignment of the Lambertson dipole with the extraction orbit is required. Over 1.4x10^{10} protons have been extracted from the CIS at 150, 200 and 210 MeV. Extraction efficiency is typically 75%, and has been as high as 86%. The rise time and width of the 55-kV kicker pulse are 35 and 300 ns.

DOSIMETRY MEASUREMENTS

The CIS beam was tuned using a removable copper Faraday stop mounted in air just upstream from the test site (Figure 2). The Faraday stop could be moved in and out of the beam remotely from the data acquisition area. The pulse repetition rate was set up to provide a pulse every 20 seconds. A wall gap monitor (capacitive pickup) located just upstream from the test site in the evacuated portion of the transfer line was used to monitor the quality and time structure of the beam pulses. Beam positioning monitors located upstream were used to monitor the beam position and profile. Quadrupole magnets in

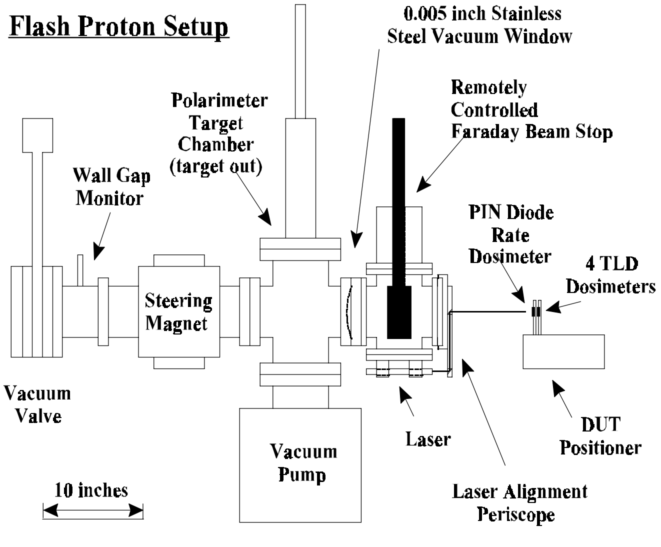

Figure 2: Schematic of the set up in the transfer beam line between CIS and the Cooler used for the dosimetry measurements. The proton beam went from left to right.

the transfer line may be used to adjust the beam spot size, but were not adjusted for this test. GafChromic^{TM} films were exposed to physically locate the beam position, to determine a spot size, and to ascertain a dose profile. A laser alignment tool was then used to position the PIN diode and thermoluminescence dosimeters (TLDs) to the approximate beam center. The PIN diodes and TLDs used are similar to the dosimeters used to monitor and measure pulses and dose from electrons at the Naval Surface Warfare Center Crane Linac test facility (see Appendix A). Figure 3 shows a schematic of the PIN diode circuitry and Table 2 provides information about the PIN diodes as well as the TLDs which were used.

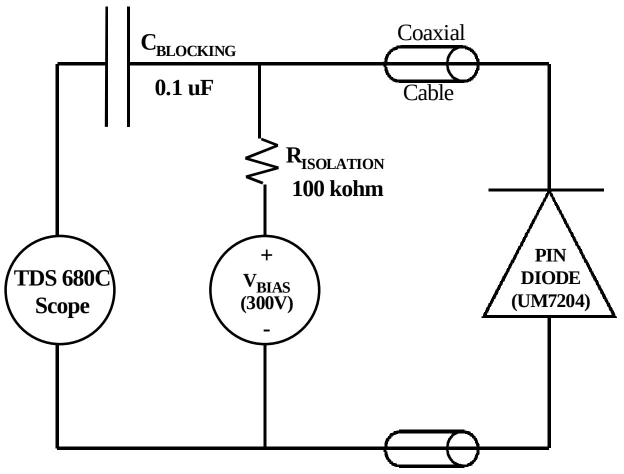

Figure 3: Schematic of PIN diode circuitry. TLDs are placed directly behind the PIN diode and are used to determine accumulated dose.

Table 2. Dosimeter parameters.

DOSIMETER	TYPE	CONDITIONS
TLD	CaF$_2$ Mn doped chip	Chip Size: 1/8" x 1/8" x 1/32" (2 chips x 2 chips array)
PIN Diode	UM7204	BV: 400 Volts In situ bias: 300 Volts

Measurements of dose rate and dose were made at four different beam energies of about 200, 160, 120, and 60 MeV. These beam energies were readily achieved by placing 0.0, 0.5, 1.0, and 1.5 inch copper degraders in front of the PIN diode and TLD. A summary of the observed doses, pulse widths, and dose rates are given in Table 3.

Table 3. Summary of Dosimetry Measurements.

Energy[MeV]	200	160	120	60
Dose [rad(Si)]	324	259	167	398
PW (FWHM)	16 ns	13 ns	13 ns	18 ns
Dose Rate [rad(Si)/s]	2.0x10^{10}	2.0x10^{10}	1.5x10^{10}	2.2x10^{10}

Figure 4 shows three responses of the PIN diode when exposed to a 200-MeV proton pulse (top curve), a 60-MeV proton pulse (middle curve), and a 50-MeV electron pulse. Remember that the 60-MeV flash protons were obtained by placing a 1.5 inch copper degrader in front of the 200-MeV flash protons. These observed responses due to protons are very similar to the observed responses that are obtained with a 20-ns electron beam.

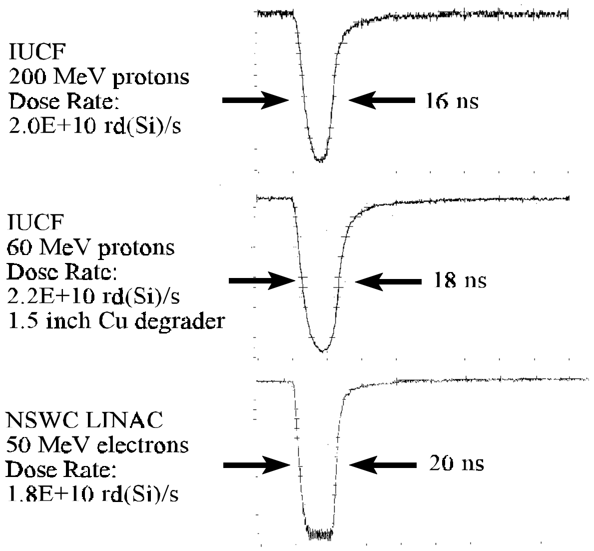

Figure 4: Response of UM7204 PIN diode to pulsed proton beam, 200 MeV (top), 60 MeV (middle) and 50 MeV electrons (bottom).

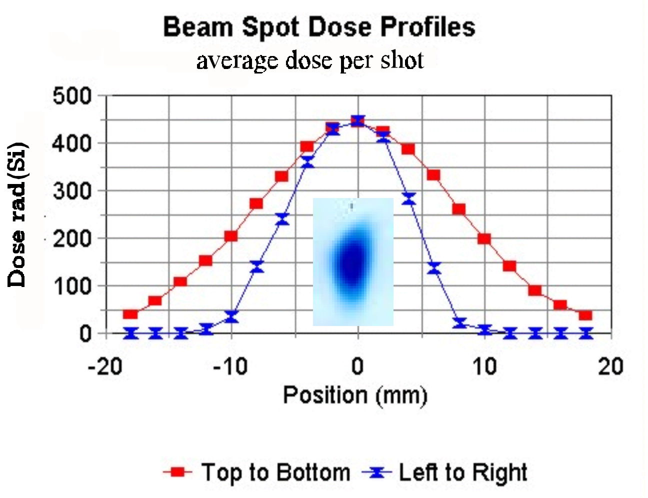

Figure 5: Vertical and horizontal dose profiles through beam center of 202.6 MeV proton beam. The PIN diode and TLDs were placed at beam center (0,0) using a laser pointer. Dose distributions were obtained from the change in optical density of MD55 GafChromic film, seen in the inset (not to scale), which wass exposed to the beam for ten pulses.

Figure 5 shows the dose profile of the beam measured with MD55 GafChromic film. The beam spot is oval in shape (no effort was made to optimize the beam spot characteristics) with a peak center dose of approximately 440 rad(Si)/pulse. The beam spot dimensions based upon the FWHM dose is 1.8 cm vertically and 1.2 cm horizontally. These results clearly demonstrate that CIS can produce dose rates as high as 2.2x10^{10} rad(Si)/s provided in approximately a 20-ns pulsewidth.

EMI MEASUREMENTS

Many of the present simulation facilities are troubled by EMI as a result of the large fast surges of power required to produce the desired dose rates. The nature of the CIS acceleration process is such that EMI during the actual pulsed beam is expected to be small. That is, the noise pulse from the 7-MeV Linac occurs more than 0.5 second before the beam pulse arrives at the test site. To determine the amplitude, nature, and time distribution of the noise that might possibly interfere with signals from test devices, measurements were made using a wide-band antenna located near the test site. The signals from the antenna were stored on a fast oscilloscope. A representative plot of the noise, the capacitive pickup monitor, and the Faraday cup is shown in Figure 6, which shows the time structure and amplitude of the amplified EMI noise (~37dB) before, during, and after the pulsed beam. Clearly, EMI during the actual pulse at the test site is small.

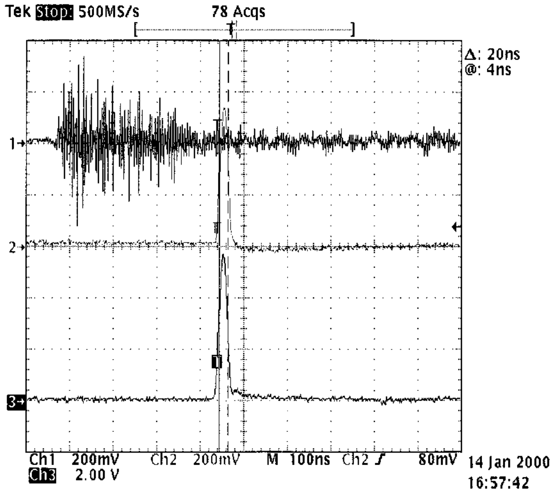

Figure 6: Comparison of amplified (~ 37 dB) EMI noise (upper trace) with the beam pulse signal from the capacitive pickup monitor (middle trace) and from the Faraday cup (bottom trace).

Features of High Energy Protons

High energy protons are minimally ionizing. That means that they produce relatively few secondary electrons. Approximately one secondary electron is produced for every thirty protons that strikes a copper surface. High energy protons also have a long range. It takes a nearly 2-inch thick copper degrader to stop a 200-MeV proton. In addition, as these protons traverse through a material multiple scattering causes the number of particles/cm^2/s (flux) to decrease while the stopping power increases as the protons lose energy. This means that the dose rate, which is proportional to the product of the stopping power and the flux, changes slowly as the proton penetrates a material. This effect continues until the proton energy falls below about 80 MeV. Then, the stopping power begins to change more rapidly. These properties make high energy protons well suited for characterizing the response of integrated systems which can have numerous layers of material to traverse (like stacked boards).

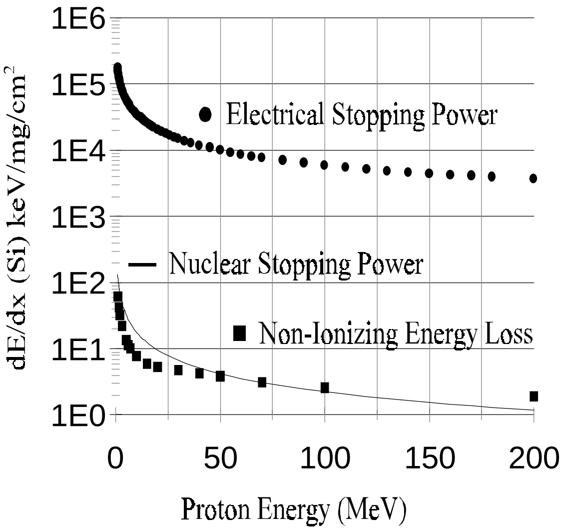

Figure 7: Plot of electrical and nuclear stopping powers and non-ionizing energy loss versus proton energy showing protons are primarily an ionizing radiation.

Figure 7 is a plot of the electrical (ionizing) stopping power for protons in silicon, the stopping power due to nuclear processes caused by the interaction of protons in silicon and the non-ionizing energy loss (NIEL) of protons in silicon. The stopping powers were calculated using the program SRIM [4] and the NIEL from reference [5]. Protons are shown to be primarily an ionizing radiation. Displacement damage which is associated with NIEL is seen to be nearly three orders of magnitude lower than effects due to ionization.

A 200-MeV proton is expected to cause nearly the same displacement damage as a 1-MeV neutron and about ten times more displacement damage than a 40-MeV electron (see figures 4.7 and 4.8 on pages 299 and 300 of reference [6]).

Conclusions

This paper reports the first measurements of a feasibility study using flash protons at high energy (200 MeV) from a synchrotron to simulate radiation effects produced by a nuclear event [7]. It has been demonstrated, through PIN diode, TLD and radiochromic film dosimetry that the IUCF synchrotron, CIS, can produce 20 ns pulses of 200 MeV protons in a > 2 cm^2 area with a dose rate of about 2 x 10^{10} rad(Si)/s. It has also been shown that the dose rate remains nearly constant as the beam is lowered in energy from 200 MeV to 60 MeV by pasage through copper plates. This makes high energy protons useful for tests of multilayered systems. EMI was shown to be negligibly small.

Protons are shown to be essentially an ionizing source with relative displacement effects (NIEL) at the 10^{-3} level. CIS has been shown to be a useful high dose rate flash proton source.

Future Directions

Preliminary studies show that the combination of CIS and the electron cooled storage ring (Cooler) presently in operation at IUCF may be used, if properly modified, to provide a 20 ns wide pulse of >2 x 10^{10} rad(Si)/s of 200 MeV protons followed by a 400 ns wide pulse of > 5 x 10^{9} rad(Si)/s of 200 MeV protons. The time between pulses could be varied from 10 microseconds to more that several seconds. Such a double pulse weapons simulation capability does not presently exist anywhere, but a conceptual design study is planned.

ACKNOWLEDGEMENTS

This work was supported in part by NSWC under contract DTRA-MIPR-99-2020 and in part by the National Science Foundation.

APPENDIX. DOSIMETRY SYSTEM

A PIN diode is a semiconductor device which uses a heavily doped p-type region and n-type region separated by a thin intrinsic region [8]. PIN diodes are used to monitor the pulse response and the thermoluminescence dosimeters (TLDs) are used to measure the dose. The dosimetry is based upon a cobalt-60 source, traceble to NIST [9,10]. The TLD material is a calcium-fluoride, manganese doped (CaF_2:Mn) ribbon with dimensions of 1/8" X 1/8" X 0.035". Four ribbons are placed in each TLD package which are then wrapped in a thin, (~0.001") aluminum foil. The average reading is used to determine the dose. The TLD package is placed directly behind the PIN diode. The PIN diode is used to provide an approximate dose and dose rate during the radiation event. The dose is determined by integrating the diode response area above 10% of the peak response. This area is then entered into the Equation 1 where the variables, C1 and C2, are calibration constants.

$$\text{Dose} = 10^{C1}(\text{Area})^{C2} \qquad (1)$$

REFERENCES

[1] D. L. Friesel, Initial Performance of the IUCF Cooler Injector Synchrotron, PAC'99.

[2] D. L. Friesel et al, PAC'97, IEEE 97CH36167, 2811 (1997).

[3] D. L. Friesel et al, Proc. Linac'98, Chicago, IL Aug 23-28,1998, to be published.

[4] "The Stopping and Range of Ions in Solids", by J. F. Ziegler, J. P. Biersack and U. Littmark, Pergamon Press, New York, 1985.

[5] G. P. Summers, E. A. Burke, C. J. Dale, E. A. Wolicki, P. W. Marshall and M. A. Gehlhausen, "Correlation of Particle Induced Displacement Damage in Silicon," IEEE Trans. In Nucl. Sci., 34, 1134-1134 (1987).

[6] R. L. Pease, A. H. Johnston and J. L. Azarewicz, "Radiation Testing of Semiconductors for Space Electronics," IEEE Nuclear and Space Radiation Effects Short Course, 253-357, July, 1990.

[7] L. W. Ricketts, *Fundamentals of Nuclear Hardening of Electronic Equipment*, John Wiley & Sons, Inc, 1972.

[8] K. G. Kerris, "Practical Dosimetry for Radiation Hardness Testing," IEEE Nuclear and Space Radiation Effects Short Course, July, 1992.

[9] ASTM Standard E170, "Standard Terminology Relating to Radiation Measurements and Dosimetry," in **Annual Book of ASTM Standards, volume 12.02:Nuclear(II), Solar, and Geothermal Energy**, American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103-1187, USA, (215) 299-5400 (published annually).

[10] ASTM Standard E668, "Standard Practice for the Application of Thermoluminscence-Dosimetry(TLD) Systems for Determining Absorbed Dose in Radiation Hardness Testing of Electronic Devices," in **Annual Book of ASTM Standards, volume 12.02:Nuclear(II), Solar, and Geothermal Energy,** American Society for Testing and Materials, 1916 Race St., Philadelphia, PA 19103-1187, USA, (215) 299-5400 (published annually).

"GAFCHROMIC™" is a trademark of GAF Chemicals Corp.