

# RADIATION EFFECTS TEST FACILITY AT THE INDIANA UNIVERSITY CYCLOTRON FACILITY

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The beam line end station, associated instrumentation and dosimetry used at the Indiana University Cyclotron Facility for radiation effects research and testing with up to 200 MeV protons are described. Access to beam for radiation effects studies is greatly enhanced by the capability to share beam with other users on a millisecond time scale. Use of shared beam mandates that the beam energy be changed through the use of degraders. Beams degraded by the use of copper degraders are characterized at several locations downstream of the degraders where devices may be placed for study.

## INTRODUCTION

Ground based measurements with accelerator produced neutron, proton and heavy ion beams have provided data which are important for understanding and predicting the behavior of microelectronic devices and systems in the space and other radiation environments [1,2]. Possible cost savings, increased speed and density, and the availability of a large variety of offerings with different product functions, speed selections, package styles etc. make the use of commercial-off-the-shelf (COTS) devices attractive for use in space applications [3]. However, since these devices were not, in general, intended to perform in a radiation environment, it may be difficult to predict the effects of space radiation upon their performance and the functioning of systems of which they are a component. Accelerator based ground measurements are then used as part of the process of developing and qualifying reliable systems using COTS devices in space.

There is increased interest in studies of device and system performance with high energy proton beams for several reasons. Among these reasons are the convenience of testing in air without the need to remove device lids, the relatively small angular spread due to multiple scattering in passing through several layers of components, and of the fact that, for protons, good rate prediction depends principally on accurate high energy asymptotic cross section data [2].

IUCF, in cooperation with KM Sciences, has developed a test station, the Radiation Effects Research Station (RERS) for exposure of micro- and opto-electronic devices and systems, up to 7 cm diameter, to protons in the energy range from 40 to 200 MeV. Protons with an energy of 200 MeV will penetrate the equivalent of more than 4 inches of aluminum. This paper will describe the RERS, its instrumentation and its operation.

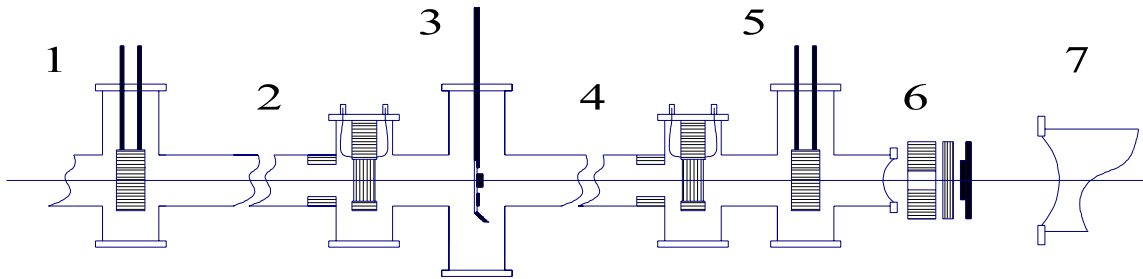
The RERS has been used in the last year by groups from the NASA Johnson Space Center, the NASA Goddard Space

Flight Center, the Jet Propulsion Laboratory, the Naval Research Laboratory, Sandia National Laboratories, the Lockheed Martin Corporation and Honeywell Corporation. Systems and devices studied have included IBM Thinkpad computers, atomic clock oscillators, DC/DC converters, micro processors, a PCMCIA-256 megabyte hard disk, photo diodes, optical couplers, a global positioning system-inertial guidance system and the control and power unit for the SAFER emergency back pack rocket for astronauts.

## RADIATION EFFECTS RESEARCH STATION

Figure 1., which is a schematic view of the RERS, is referred to in this section. The proton beam is prepared for irradiating devices by adjusting beam line quadrupole and dipole magnets until the beam is centered on scintillating viewers located at the spreader target (3) and the exit of the evacuated beam pipe just before the device under test (DUT) with a 5 mm x 5 mm spot on the spreader target scintillator. Use of the upstream secondary electron monitor (SEM) (2) facilitates this process and provides a sensitive beam intensity monitor for the cyclotron operator. A copper foil inserted into the beam at position (3) spreads the beam by multiple scattering. Typically, the thickness of the copper foil is chosen, for the incident proton energy being used, so that about 65% of the spread beam passes through a 6 cm diameter collimator in front of the dosimetry SEM (4). This produces a 7 cm beam spot at the location of the DUT (6) as determined by exposure of GAFCHROMIC™ films at that location.

# Radiation Effects Research Station



**FIGURE 1.** Schematic view of the RERS. The proton beam goes from left to right. Shown are the movable upstream beam stop (1), upstream secondary electron monitor (2), beam spreader target ladder (3), dosimetry secondary electron monitor (4), movable dosimetry beam stop (5), air gap with external collimator, energy degrader and device under test (6), and entrance to a well-shielded Faraday cup beam dump (7). Drawing is not to scale. The distance from (3) to (6) is about 10 feet and the beam pipe is 4 inches in diameter.

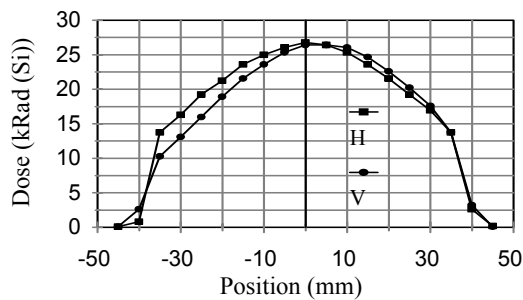
Beam intensity profiles obtained by scanning exposed films with a photometer, show an intensity fall off of less than 50% from the center to the edge of the beam spot as seen in Fig. 2 which shows a plot of a typical beam profile.

The stability of the beam profile is indicated by the small errors seen in Table 1, which contains the ratios of the average flux at the center of the beam, the 1 cm radius and the 2 cm radius to the integral of the proton current over the

Profile Ratio	Value
Center	$0.03489 \pm 0.00054$
1 cm radius	$0.03223 \pm 0.00045$
2 cm radius	$0.02644 \pm 0.00028$

## Beam Profile

196 MeV Protons



**FIGURE 2.** Typical beam profile for 196 MeV proton beam at position of DUT. Horizontal and vertical scans of the beam are shown.

total area of the beam, averaged for 5 typical profiles taken during the March to August, 1996 period. Such profile ratios and the current from the calibrated dosimetry SEM (4) are used by a dosimetry/control computer to determine the fluence of protons on the DUT (6). The dosimetry SEM (4) is calibrated before each exposure by measuring the ratio of current from the movable dosimetry beam stop (5) to the current from the dosimetry SEM (4). Permanent magnets are mounted to the movable dosimetry beam stop to suppress the emission of secondary electrons from the stop. Currents from the SEM's and the dosimetry beam stop are measured with computer controlled picoammeters.

When the dosimetry stop (5) is out of the beam, protons may pass out of the evacuated pipe through a .5 mil thick Kapton foil into an 18 inch long air gap (6) and back through another Kapton foil into the vacuum of a well-shielded Faraday cup beam dump (7). A DUT may be clamped in a universal mount, which allows rotation of the device about a vertical axis and which may be translated precisely in the horizontal and vertical directions. Alignment of the DUT is accomplished with the aid of a laser alignment tool and the xz translator. If it is desired to mask a portion of the 7 cm beam spot, an external 2 inch thick copper collimator may be inserted in air between the upstream exit window and the DUT. The beam energy may be degraded to a chosen energy at the location of the DUT by insertion of a copper plate of the proper thickness at this location as well. Degrading the beam energy, in this way, from 200 MeV to 100, or 40 MeV, causes a calculated energy spread of 3.6, or 4 MeV, full width at half maximum, respectively.

Exposure of a DUT is accomplished entirely under computer control with the user friendly program IUCFMON provided by KM Sciences. Beam stops (1) and (5) are remotely controlled in the proper sequence to calibrate the dosimetry SEM (4) before each exposure and to provide the desired fluence on the DUT. Dosimetry data is stored to disk and also immediately printed.

Adequate space and clean electrical power is provided just outside of the shielded vault which houses the RERS. The cable run from the DUT to the instrumentation area is less than 75 feet. Inside the vault there is an area shielded

from neutrons for test head electronics which requires a 14 foot cable run.

Table 2 summarizes the proton capabilities of the IUCF Radiation Effects Research Station. A low dose rate beam monitoring capability using a 1 cm<sup>2</sup> by 1 cm thick plastic scintillator detector has been developed. This is useful for proton fluxes less than 10<sup>4</sup> protons/cm<sup>2</sup> sec. Alpha particle beams with energies in the range from 40 to 200 MeV are available from the cyclotron but have not been used for radiation effects studies.

Table 2. Proton Capabilities of the RERS	
Energy Range:	40 to 200 MeV*
Flux:	10 <sup>4</sup> to > 10 <sup>11</sup> p's/sec cm <sup>2</sup> **
Areas:	< 2 cm to 7 cm diameter
Uniformity:	< 50% variation over area
Absolute Dosimetry:	Better than 10% routinely.
Exposure Durations:	> 5 seconds routinely available.
Overhead duration: (For energy changes and device positioning)	3 minutes per exposure (Due to delayed room entry and room clear requirement of radiation safety system.)

\* Lower energies readily available via degraders. For special needs, machine energy may be tuned to any energy with in the range. \*\* Below 10<sup>6</sup> p's/sec cm<sup>2</sup> special techniques are required.

At the IUCF, a particle beam may be delivered to some pairs of research stations nearly simultaneously by redirecting the beam on a millisecond time scale. The availability of such "shared beam" is important for radiation effects studies because it allows beam to be provided for this applied research without significant impact on the basic research mission of the laboratory. At present, IUCF makes available about 60 days of split beam and 10 days of "sole use beam", when the radiation effects user is the only user, each year for radiation effects research distributed somewhat randomly in clusters of several days throughout the year. It is recognized that users may need rapid access for proton tests. The laboratory makes efforts to accommodate such requests.

### ENERGY SELECTION

Since it is not convenient to change the energy of the primary beam of the IUCF, one usually introduces various thicknesses of copper plates just upstream of the DUT to degrade the energy to the desired value. Although this is convenient, it introduces uncertainties as to the amount of straggling and geometric spreading of the protons. The following shows the results of some measurements of these effects. Figure 3 shows the calculated energy after degrading as a function of degrader thickness for a range of thicknesses of copper together with the calculated FWHM

as a function of degraded energy. Measurements of the proton energy and the FWHM were made with a large NaI detector. The results of these measurements are consistent with values depicted in Fig. 3.

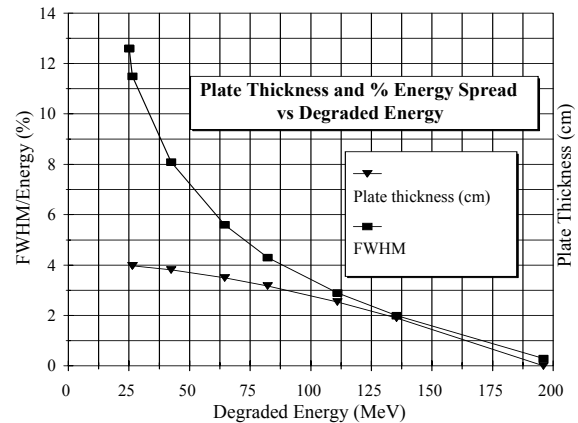


FIGURE 3. Plot of copper plate thicknesses required to degrade a 200 MeV proton beam to various energies and of the calculated energy spread at each energy.

As protons pass through the degrader they scatter somewhat and a certain fraction are lost. Measurements were made using GAFCHROMIC™ film immediately before and after the copper degrader plate for several thicknesses. Since the dose predicted by the IUCFMON dosimetry program assumes no protons are lost, the ratio of measured to predicted dose at each energy was calculated (Table 3). It is not always possible to place the DUT close behind the degrader. Since the beam is spreading after the degrader, it is necessary to measure how the intensity of the radiation field falls off in the space behind the degrader.

### RADIATION FIELD MAPPING

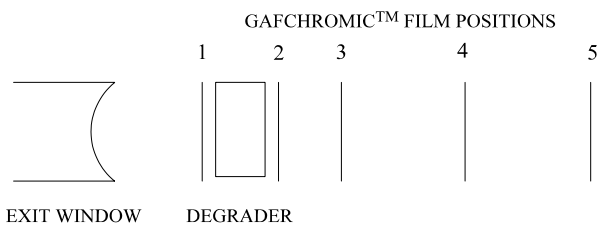


FIGURE 4. Schematic view of the positions at which films were exposed to proton beams to measure the effect of copper degraders on the center dose.

Figure 4 depicts the arrangement for mapping the radiation field behind various degraders. GAFCHROMIC™ film was placed at positions 2 through 5 with various thicknesses of Cu degraders to map the field at a variety of degraded energies. This was done both for the case of a vignetting collimator of 3 cm ID placed just after the exit window and for no collimator. The dosimetry program, IUCFMON, predicts the dose at position 2 assuming that no protons are lost in the degrader. Table 3 shows the ratio of the dose measured at position 2 to that predicted by IUCFMON.

196 MeV (undegraded)	1.000
157.6 MeV	1.000
135.8 MeV	1.000
112.3 MeV	0.935
85.3 MeV	0.849
65.9 MeV	0.784
44.6 MeV	0.753

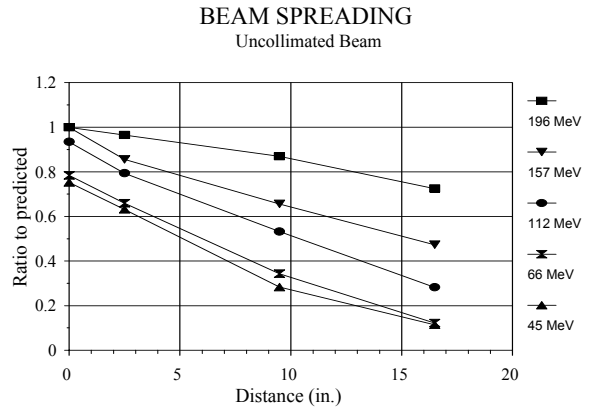
Beam profile scans for the beam at position 1, 2 and a point about 5 inches behind a degrader which degraded the beam to 98 MeV show that, although the intensity of the beam drops off behind the degrader, the shape near the center does not change significantly. One can, therefore, learn much about the radiation field after the degrader by studying the intensity on axis. Such measurements were made at positions 2 through 5 (Fig. 4), and the ratio of the intensity measured at positions, 3 through 5, to the intensity measured at position 2 were calculated for a number of different degraded energies. Figures 5 and 6 are plots of these ratios. Fig. 5 is for an uncollimated beam and Fig. 6 is for a beam which has a 3 cm ID vignetting collimator placed just after the exit window of the beam line vacuum plumbing. For the uncollimated beam the fall-off is quite linear indicating the "near field" of a distributed source. The slopes are essentially the same for all energies except the undegraded one of 196 MeV. The average slope turns out to be  $-.0373 / \text{inch} \pm 0.0016$ . Even the slopes for the 2 inch position of the collimated beam falls within this value, indicating that that point also is in the "near field". These data indicate that, for the IUCF facility, one can predict the radiation field on axis behind degraders out to a foot or more for the uncollimated beam or for a couple of inches for a beam collimated to 3 cm. in diameter by the following linear relationship.

$$D(x) = D_c ( C_c - .037 x ) ,$$

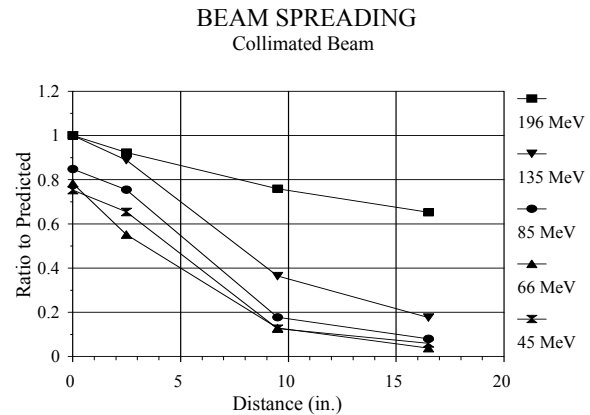
where  $D(x)$  is the dose at  $x$  inches behind the degrader,  $D_c$  is the calculated dose after the degrader, and  $C_c$  is the measured effect of the degrader (column 2 of Table 3).

### CONCLUSIONS

A capability has been developed at the Indiana University Cyclotron Facility for radiation effects studies. The 200 MeV proton beam is uniquely suited to system testing due to its penetrating nature. The use of beam shared with another user mandates changing the beam energy by the introduction of degraders. The results above indicate that one can predict within about a 10% uncertainty the radiation



**FIGURE 5.** Dose correction factor (ratio of the measured center dose to the calculated center dose) for no vignetting collimator as a function of the distance from the downstream surface of the copper degrader.



**FIGURE 6.** Dose correction factors (ratio of the measured center dose to the calculated center dose) for a 3 cm inside diameter vignetting collimator as a function of distance from the downstream surface of the copper degrader.

field at any energy from that of the primary beam (196 MeV), down to a degraded energy of 45 MeV on axis and within a distance of 1 1/2 feet behind the degrader at the Radiation Effects Research Station of the IUCF. The energy FWHM of the beam will, in the lowest energy case, be less than 20%.

### REFERENCES

- [1] W. Stapor, "Single Event Effects (SEE) Qualification," IEEE Nuclear and Space Effects Conference Short Course, page II-1, July, 1995.
  - [2] E. Normand, "Single-Event Effects in Systems Using Commercial Electronics in Harsh Environments," IEEE Nuclear and Space Effects Conference Short Course, page V-1, July, 1994.
  - [3] N. Haddad and T. Scott, "Adapting Commercial Electronics to the Naturally Occurring Radiation Environment," IEEE Nuclear and Space Radiation Effects Conference Short Course, page IV-1, July, 1994.
- "GAFCHROMIC™ is a trademark of GAF Chemicals Corp.