

RADIATION EFFECTS RESEARCH AND TEST FACILITIES AT THE INDIANA UNIVERSITY CYCLOTRON FACILITY

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ABSTRACT

Two nearly identical beam line end stations and a dedicated counting room have been installed and fully instrumented at the Indiana University Cyclotron Facility (IUCF) for the performance of radiation effects tests and studies with high energy protons (up to 200 MeV) on semiconductor and other micro- and opto-electronic devices to be used in space and other radiation environments. These facilities are flexible and easy to use and take advantage of the unique fast beam splitting and beam intensity modulation systems developed at IUCF to increase user access to beam and reduce the costs of tests. Irradiations have been carried out using fluxes as low as $1E2 \text{ p's/cm}^2/\text{sec}$ and as high as $1E11 \text{ p's/cm}^2/\text{sec}$, energies as low as 20 MeV and as high as 200 MeV, exposure times as short as 1 second and as long as 12 hours, and beam spot sizes from 2 cm in diameter to 7 cm in diameter. Present facilities will be described, plans for radiation effects facilities at IUCF in the future presented, and a conceptual design for a large area facility using non-linear expansion of the proton beam by multipole magnetic fields outlined.

INTRODUCTION

Measurements with accelerator-produced proton and heavy ion beams have provided data which are important for understanding and predicting the behavior of microelectronic devices and systems in space and other radiation environments. Characterization of single event and/or total dose responses of devices and device types to radiation exposure is the goal of most studies, including those of commercial-off-the-shelf (COTS) parts. Advantages of using entire COTS systems in space has led to ground based studies to measure directly the response of complete systems to radiation doses that simulate expected mission exposures.

A space mission exposes on-board components to a complex distribution of protons and heavier ions. Protons and heavy ions cause effects in semiconductor and optical devices through different, but related, interaction mechanisms. Recent work has shown that characterization of the single event response of a device or system to accelerator produced protons with energies above 100 MeV can be used to predict the single event response to heavy ion exposures of devices [1] and determine a firm upper bound to the on-orbit heavy ion upset rate and failure risk [2].

These new results together with the high cost of high energy heavy ion testing, 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 the fact that, for protons, good rate prediction depends principally on accurate high energy asymptotic cross section data [1] lead to an increased demand for testing with high energy protons.

In cooperation with KM Sciences, the IUCF cyclotron program has developed a test station, the Radiation Effects Research Station (RERS), for exposure of devices and systems up to 7 cm diameter to protons in the energy range from 40 to 200 MeV. The RERS has been duplicated in a second beam line so that radiation effects research may be carried out essentially simultaneously for two experiments with independent control of exposure times and proton fluxes through the use of the fast (milli-second) beam sharing and beam intensity modulation systems developed at IUCF.

The IUCF cyclotron program is changing from a National Science Foundation supported laboratory for basic research in nuclear physics to a fee base supported facility for clinical treatment and research in proton therapy and radiation effects in material and biological systems. This transition will limit access to beam for radiation effects studies to about 10 days every two months during the planned three year transition phase. It also provides the opportunity to construct improved facilities for radiation effects research and testing which will incorporate recent trends in radiation effects research and exploit advances in beam transport technology.

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 (2) and the exit of the evacuated beam pipe just before the device under test (DUT) with a 5 mm x 5 mm

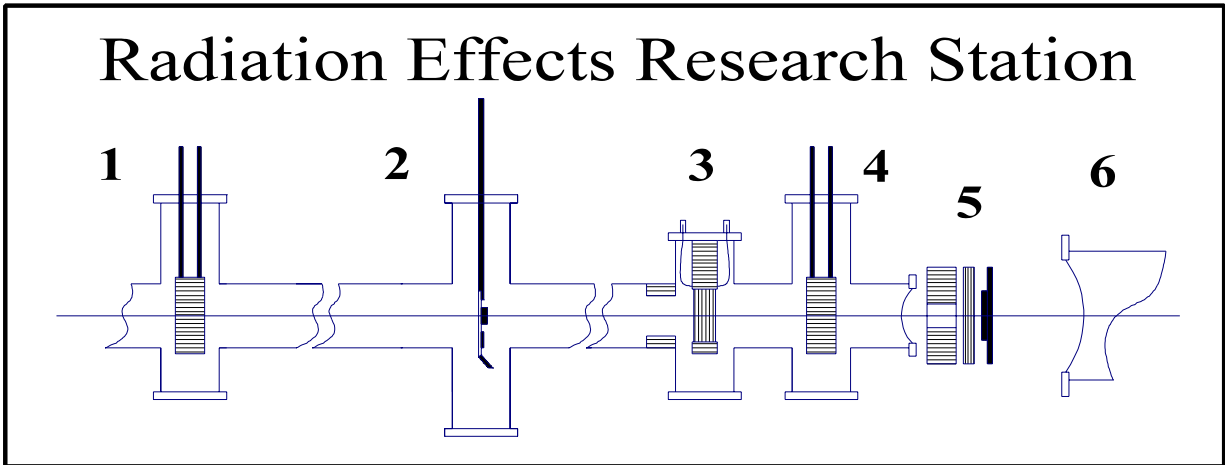


Figure 1. Schematic view of the RERS. The proton beam goes from left to right. Shown are the movable upstream beam stop (1), beam spreader target ladder (2), dosimetry secondary electron monitor (3), movable dosimetry beam stop (4), air gap with external collimator, energy degrader and device under test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

spot on the spreader target scintillator. A copper foil inserted into the beam at position (2) 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 (3). This produces a 7 cm beam spot at the location of the DUT (5) as determined by exposure of GAFCHROMIC™ films at that location.

from the SEM's and the dosimetry beam stop are measured with computer controlled picoammeters.

When the dosimetry stop (4) 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 (5) and back through another Kapton foil into the vacuum of a Faraday cup beam dump (6). 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 vignetting 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. Exposure of a DUT is accomplished entirely under computer control with the user friendly program IUCFMON provided by KM Sciences. Beam stops (1) and (4) are remotely controlled in the proper sequence to calibrate the dosimetry SEM (3) before each exposure and to provide the desired fluence on the DUT. Dosimetry data is stored to disk and also immediately printed.

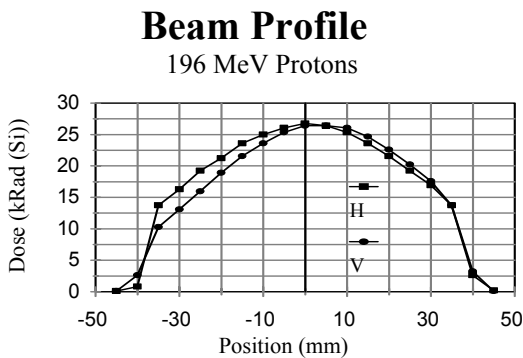


FIGURE 2. Typical beam profile for 196 MeV proton beam at position of DUT. Horizontal and vertical scans of the beam are shown.

Beam intensity profiles obtained by scanning exposed films with a densitometer, show an intensity fall off of less than 50% from the center to the edge of the beam spot as seen in Figure 2. Such dose profiles and the current from the calibrated dosimetry SEM (3) are used by a dosimetry/control computer to determine the fluence of protons on the DUT (5). The dosimetry SEM (3) is calibrated before each exposure by measuring the ratio of current from the movable dosimetry beam stop (4) to the current from the dosimetry SEM (3). Permanent magnets attached to the movable dosimetry beam stop suppress the emission of secondary electrons. Currents

A dedicated counting room with an adequate supply of clean electrical power is provided just outside of the shielded vaults which house the two RERS. The cable run from the DUT to the instrumentation area is less than 75 feet for either RERS. Inside the vaults are areas shielded from neutrons for test head electronics which require a 14 foot cable runs. There is ample space outside of the counting room for unpacking and off line checking of users' test setups.

Table 1. Proton Capabilities of the RERS	
Energy Range:	40 to 200 MeV*
Flux:	10^4 to 10^{11} p's/sec cm ^{2**}
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 the 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 10^6 p's/sec cm² special techniques are required.

Table 1 summarizes the proton capabilities of the IUCF Radiation Effects Research Station. For fluxes less than 10^4 protons/cm² sec, a beam monitoring capability using a 1 cm² by 1 cm thick plastic scintillator detector has been developed.

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 research without significant impact on other users of the proton beam.

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. Figure 3 shows the

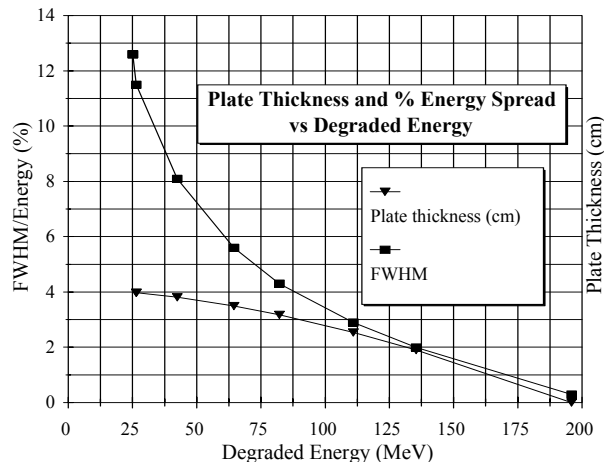


FIGURE 3. Plot of copper plate thicknesses required to degrade a 200 MeV proton beam to various energies and of the calculated energy spread at each energy.

calculated energy after degrading as a function of degrader thickness for a range of thicknesses of copper together with the calculated full-width-at-half-maximum, FWHM, as a function of degraded energy. Results of measurements of the proton energy and the FWHM made with a large NaI detector are consistent with values depicted in Fig. 3.

As protons pass through a degrader they scatter somewhat and a certain fraction is lost. Dose measurements were made using GAFCHROMIC™ film just before, immediately after and at several distances downstream of the copper degrader plate for several thicknesses of copper plates. Using doses predicted by the IUCFMON dosimetry program under the assumption of no lost protons and no beam spreading by multiple scattering, the ratio of measured to predicted dose at each energy and position was calculated to be used as correction factors. These correction factors have been incorporated into IUCFMON.

BEAM SHARING AND INTENSITY MODULATION

Through use of a fast ferrite kicker magnet and a Lambertson magnet [3], the proton beam from the cyclotron may be directed to any of several pairs of beam line end stations including one or both of the RERS. A Lambertson magnet is a magnet designed to have a high field region separated by a small distance (a millimeter or so) from a very low field region. The kicker magnet deflects the proton beam from the low field region to the high field region to direct it from one beam line to another. A typical sharing setup would, on a 100 milli-second cycle, provide 10 milli-seconds of beam to end station "A" and 90 milli-seconds of beam to end station "B". With a typical 500 nanoamp proton beam current, this would provide a flux of about $1E10$ protons/cm²/sec to "A" and of about $1E11$ protons/cm²/sec to "B" if a 7 cm diameter beam spot is assumed. The fraction of beam delivered to an end station is continuously variable by selecting the fraction of time beam is delivered to each end station.

The beam intensity modulation system [3] is used to vary the current (flux) to each end station. It does this by rapidly varying (on a milli-second scale) the voltages on electrostatic quadrupole elements in the low energy beam line between the ion source and the injector cyclotron to focus and defocus the proton beam incident on a set of slits which are adjusted to limit the acceptance of the injector cyclotron. By setting these slits appropriately, a suitable maximum beam intensity on target is established, by selecting the fraction of time beam is delivered to each end station, maximum intensities for each station are determined, and by adjusting the beam focus on the acceptance slits, the fraction of the maximum beam for each station is chosen. This allows continuous and convenient selection of fluxes at the locations of the DUTs in each area over wide ranges.

FUTURE OF RADIATION EFFECTS AT IUCF

Essentially all of the beam lines and experimental equipment north of the main cyclotron will be replaced over the next 3

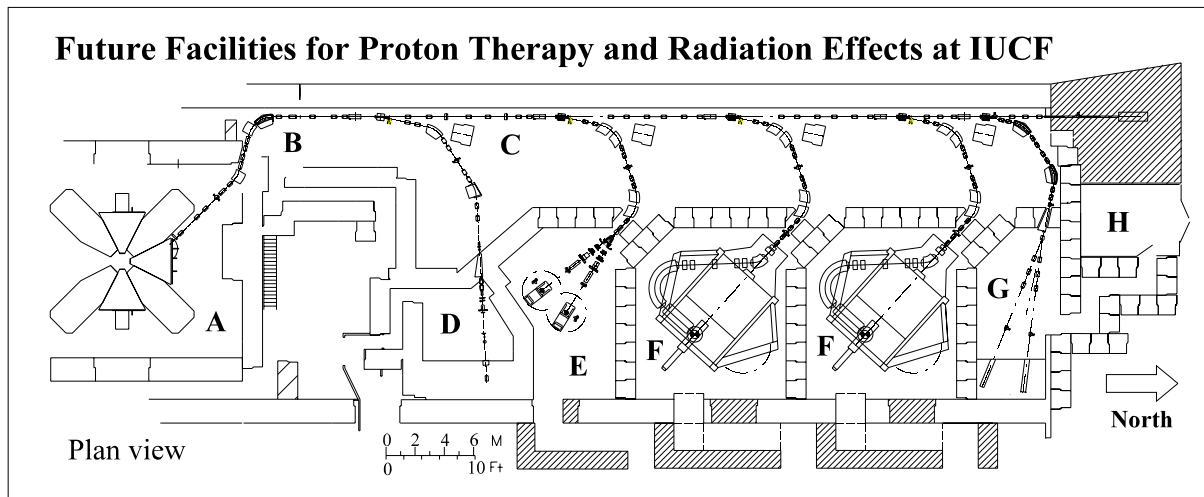


Figure 4. Schematic view of planned proton and radiation effects facilities for IUCF. A: Main cyclotron and beam line, B: Magnets to make achromatic beam, C: Non-linear expansion elements, D: Eye treatment end station, E: Horizontal proton treatment lines, F: Proton Therapy Gantries, G: Radiation effects beam lines, H: Radiation effects counting area.

years as the IUCF cyclotron makes a transition from basic research in nuclear physics to a proton therapy center and research facility in radiation effects of micro-electronic and biological systems. The present plan for the final configuration of the beam lines and end stations is shown in Figure 4. In this figure A is the main cyclotron which will be modified to provide reliably a 1 microampere beam of protons at the single energy of 210 MeV. B is the location of the magnetic dipoles needed to change the beam properties from dispersive to achromatic, C contains multipole magnets for non-linear expansion of the beam, D, E, and F are horizontal and gantry beam delivery systems for proton therapy; G is the radiation effects area which houses end stations for biological and micro-/opto-electronic studies. Lambertson magnets and ferrite kickers will be installed at each branch position to implement beam sharing for all end stations. In each branch degraders will provide momentum analyzed 70 to 200 MeV protons to each area. These degraded beams will have reduced intensities suitable for single event effect studies. The proton energies can be degraded further by plates just in front of the DUT if desired.

While reconstructing the beam lines will limit access to beam during the transition phase, it offers the opportunity to design and construct a new radiation effects end station which exploits a novel magnetic non-linear expansion technique [4] to make a beam spot as large as 45 cm x 45 cm with a flat profile with negligible loss of flux and proton energy. The proton beam with a flat intensity profile produced by multipole magnets in region C (Figure 4) is small enough to be transported to the radiation effects area where it is expanded in size by a set of quadrupole magnets. By adjusting the current in the quadrupole magnets, the size of the beam spot at the location of a DUT can be varied rapidly and conveniently while maintaining the flat beam profile. This capability will enable efficient tests of large systems, enhanced low dose

studies by simultaneous irradiation of a large planar array of parts and retain, with improvements, all the capabilities described above for the present RERS. Enhanced beam sharing capabilities will be provided which will make it possible for radiation effects studies to be conducted at the same time as medical irradiations. The location of the radiation effects counting room at the north end of the facility is chosen to separate radiation effects activities from clinical functions of the facility.

CONCLUSIONS

During the transition of the IUCF cyclotrons from nuclear physics research, IUCF plans to provide beam and support services for radiation effects research on a schedule of about 10 days every two months. IUCF also plans to build as part of the transition a new large area radiation effects research station incorporating magnetic beam spreading of the 200 MeV proton beam and providing narrow-energy-spread proton beams for single event and total dose studies over a wide range of fluxes, spot sizes and energies.

REFERENCES

- [1] E.L. Petersen, "The SEU Figure of Merit and Proton Upset Rate Calculations," to be published in IEEE Trans. Nuc. Sci., Dec 1998.
 - [2] P.M. O'Neill, G.D. Badhwar, and W.X. Culpepper, "Internuclear Cascade - Evaporation Model for LET Spectra of 200 MeV Protons Used for Parts Testing," to be published in IEEE Trans. Nuc. Sci., Dec 1998.
 - [3] D.L. Friesel, T. Ellison and T. Sloan, "Beam Splitting Development," 1986 IUCF Scientific and Technical Report, p. 143
 - [4] E. Kashy and B. Sherrill, "A Method for the Uniform Charged Particle Irradiation of Large Targets," Nucl. Instr. and Meth., B26 (1987) 610. A.J. Jason, B. Blind and K. Halbach, "Beam Expansion with Specified Final Distributions," 1997 Particle Accelerator Conference, Vancouver, BC, Canada, May, 1997.
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