

# Radiation Effects Facilities, Dosimetry and Program at the Indiana University Cyclotron Facility

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**Abstract.** High energy protons are useful for ground based simulation of the effects of space radiation on electronic devices and systems. Present and planned facilities to support the ongoing IUCF radiation effects research program (RERP), which uses protons with energies as high as 200 MeV, are described and results of high energy proton dosimetry studies are presented.

## INTRODUCTION

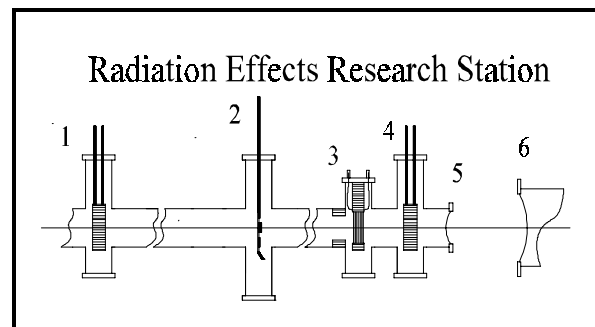
The use of accelerator produced high-energy protons to study the response of microelectronic devices and systems to simulated space radiation environments is well established[1,2]. IUCF has an active proton-based radiation effects research program, which has served many government, industrial and academic users since 1994. The facilities used to support this program are described in the proceedings of the 14<sup>th</sup> International Conference on the Application of Accelerators in Research and Industry [3]. The present paper will briefly review those facilities, report on calibration and validation studies for high-energy proton dosimetry and describe expanded radiation effects research facilities planned for the future.

IUCF is converting the 200 MeV proton cyclotron from use for nuclear physics research to a research facility for proton therapy and for radiation effects studies in biological, material and electronic systems. This conversion requires the reconstruction of the high energy beam transport system to convert it from the momentum dispersive system used for nuclear physics research to an achromatic system which is optimal for proton therapy. This reconstruction, which is in progress now and expected to be completed early in 2003, provides an opportunity to implement the improved facilities for radiation effects described in this paper. Throughout the reconstruction period, access to beam for radiation effects tests and research will be provided for an average of about two weeks out of every two months. After the reconstruction is complete, beam sharing on a fast time scale with proton therapy will allow access to beam for radiation effects studies 24 hours each day for

about 300 days each year.

## RADIATION EFFECTS RESEARCH STATION

One of the beam lines of the IUCF is configured to provide an accurately known radiation field. The configuration (the RERS) is shown schematically in Figure 1 and described in detail in reference [3]. It uses a spreading foil to initially scatter the proton beam so that a more uniform distribution of beam intensity may be obtained at the test site. This initial scattering also makes the intensity distribution less sensitive to any drift of the focus or position of the beam in the vacuum line.



**Figure 1.** The RERS. Beam goes from left to right. Number 1 is a removable stop which turns the beam on and off, #2 is a target ladder with a scintillator for beam alignment and a Cu foil to spread the beam, #3 is the defining collimator and Secondary Emission Monitor (SEM), #4 is a removable Faraday cup used to calibrate the SEM, #5 is the exit window, and #6 is the entrance to the beam dump. Test devices are placed, in air, between 5 and 6.

A 5 cm inside diameter collimator is located 216 cm downstream from the scattering foil. This collimator serves to define the beam to a 7 cm diameter beam spot at the position of the device to be tested. Immediately following the collimator is the secondary emission monitor, (SEM) consisting of 15 half mil thick Cu foils alternately biased to collect the secondary electrons produced by the proton beam as it passes through. The Faraday cup is located 20 cm downstream from the SEM. It consists of a Cu block about 9 cm by 8 cm and 5 cm thick, (more than enough to stop 200 MeV protons). Two high strength, rare earth ceramic, permanent magnets are attached to the back of the Cu block to provide a trapping field for the secondary electrons produced at the face of the Faraday cup. Also, the outer foils of the SEM are positively biased at 100 Volts to return any secondary electrons back to them so that they would not be a source of secondary electrons that might get to the Faraday cup. This method of secondary electron control works well at these proton energies because there are few secondaries produced (.022 electrons per proton per copper surface are observed) and these secondaries are of low energy [4] (about 30 eV). We routinely measure less than 2 pA Faraday cup currents without beam. These leakage currents are measured and subtracted from the several nA beams used in these dosimetry comparisons. The Faraday cup is mounted so that it can be withdrawn to allow the beam to pass through an exit window and into the region, in air, where samples can be placed for irradiation.

The SEM measures the beam current. In order to determine the flux, a beam intensity profile is measured using GAFCHROMIC™ film [1], the change in optical density of which is proportional to the dose delivered to the film. This method is used for fluxes in the range from  $10^6$  p's/sec  $\text{cm}^2$  to  $10^{11}$  p's/sec  $\text{cm}^2$ . A proton energy range from 40 to 200 MeV is provided by degrading the proton beam with Cu plates placed directly up stream of the device under test. The reduction in flux due to multiple scattering in the degraders has been measured and corrections are made [3].

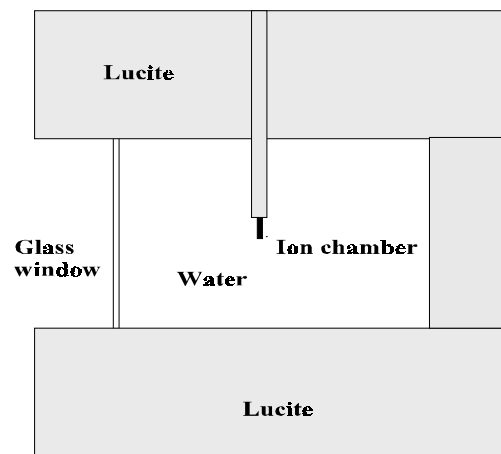
To confirm the accuracy of this Faraday cup/SEM dosimetry system, a careful comparison [5] was made with an independently calibrated Markus ion chamber [6] and a Shultz type [7] water calorimeter. The results of this comparison is presented later in this paper.

The need for extending the lower limit of the flux range to below  $10^2$  p's/sec  $\text{cm}^2$  to serve some users, required the use of direct counting of the protons in the beam using a small scintillator and a high count rate photo-multiplier system. The highest fluxes measurable

with such a scintillator system are limited by the onset of pulse pile up and sag in the gain of the photo-multiplier tube. The lower limit (about  $3 \times 10^6$  p's/sec  $\text{cm}^2$ ) of the fluxes measurable by the Faraday cup/SEM system, which has a gain of about 1.4, is due to the noise current of the system (about 2 pA). In order to compare the scintillator and the SEM systems in an overlapping range, operation of the SEM in air (as a parallel plate ion chamber with a gain of about 360) was explored. The results of this study also follows.

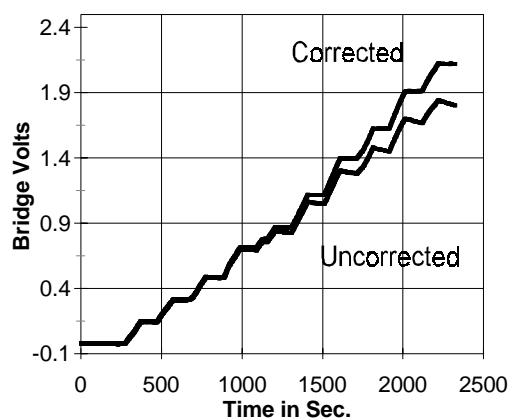
## ION CHAMBER AND CALORIMETER COMPARISON

The calorimeter was placed in the beam 18.5 cm downstream of the exit window. The central part of the calorimeter is a cylinder of water 10 cm in diameter and 10 cm long in the beam direction with temperature sensors placed at the center, 5 cm deep. An acrylic phantom was constructed with dimensions similar to the Calorimeter. It is shown in Figure 2. It was designed with an insert in which an ion chamber could be placed such that it would see the same flux of protons as seen by the temperature probes of the Shultz type calorimeter.



**Figure 2.** The phantom chamber which was identical to the calorimeter except that the ion chamber was located at the position of the thermistors of the calorimeter. Films were placed at the front face of the calorimeter and also just ahead of the ion chamber to measure the change in fluence due to 5 cm of water.

Films were placed just in front of the calorimeter and just in front of the phantom calorimeter. A small film was also placed just ahead of the ion chamber. The



**Figure 3.** Bridge voltage versus time for the thermistors during a calorimeter measurement. The lower curve is the raw calorimeter response and the upper curve is the calorimeter response with the “cooling” removed.

ratio of the fluences at the two locations in the phantom determined from the film doses and the appropriate proton energies provided a factor to correct for the change in fluence of the proton beam while passing through 5 cm of water. It was assumed that this factor for the real calorimeter was identical to that for the phantom.

The calorimeter, being surrounded by a constant temperature water jacket at 4 degrees Celsius, does not make an adiabatic measurement. Heat is continually flowing in or out of the instrument. The Voltage across the probes, a quantity which is proportional to the temperature of the probes [5,7], was measured at one second intervals and digitally recorded throughout the calorimeter run. In order to determine the heating due to the protons, runs were made consisting of 12 to 15 cycles of beam on and beam off, using an “on” time of 5 minutes followed by an “off” time of 5 minutes. The “off” time temperatures were then fitted with a third order polynomial to provide a “cooling” function. This “cooling” function was then used to correct all the data to get the “true” heating due to the protons. The effect of this correction is evident from the fact that the slope of the corrected curve during the beam “off” times is zero. Similar run cycles were used when exposing the phantom to get the ion chamber responses. Figure 3 shows the raw calorimeter response together with the heating curve with the cooling removed.

Table I shows the results of these comparisons of the calorimeter and ion chamber to the Faraday cup.

**TABLE 1. Comparison Results.**

Test No.	Energy at the thermistor and ion chamber.	Average ratio of the calorimeter dose to Faraday Cup dose.	Average ratio of the ion chamber dose to Faraday cup dose.
69	154 MeV	0.987 +/-0.014	0.984 +/-0.002
76	165 MeV	0.987 +/-0.009	1.005 +/-0.005
78	163 MeV	0.996 +/-0.019	0.990 +/-0.005
81	131 MeV	0.997 +/-0.010	0.993 +/-0.012

In this table each figure is an average of 12 to 15 measurements together with their standard deviations. Measurements were made on each of 4 different days and at different energies.

The Markus ion chamber has a documented calibration [8] which can be traced to the National Institute of Standards. The Faraday cup system together with it’s software, BeamMonster, was found to indicate a higher dose than the ion chamber by 0.7% with a standard deviation of 1.2%. The Faraday cup system also indicated a higher dose than the calorimeter data by 0.8% although it has a standard deviation of 1.9%. Hence, all three systems, the ion chamber, the calorimeter, and the Faraday cup system are in agreement to within 1% with an experimental uncertainty of about 2%.

## LOW FLUX DOSIMETRY

In order to explore the use of the SEM in air, 5 mil thick kapton windows were inserted just upstream and just downstream of the SEM and the vacuum plumbing modified to allow operation of the SEM in air (as an “Air-SEM”) while maintaining vacuum in the beam line and Faraday cup (see Figure 1). After aligning the beam and measuring the beam profile with the SEM in vacuum to verify that the system was operating normally, the SEM was operated in air and the average beam current, as measured on the Faraday cup, varied. The ratio of the charge measured by the Faraday cup to that measured by the SEM for a standard time interval was determined. The ratio was found to be constant (0.00270) to within +/-1% in the range of beam currents from 0.1 to 1.0 nA. For beam currents above 1.0 nA, the Air-SEM saturates because the 100 V bias is too low to collect all the charge. The ratio of the FC/SEM ratios

for the Air-SEM to the vacuum SEM gives a gain of 530 +/-10, which makes the Air-SEM effective at low fluxes.

For fluxes in the range below about  $10^5$  p's/sec  $\text{cm}^2$ , a small scintillator (1/4"x1" and 1/2" thick) had been used for several experiments. This scintillator was placed just downstream of the exit window (Figure 1) and 1.2 cm away from the center of the beam profile. The fluence at the center of the beam profile was then calculated from the counts for a given time recorded by the scintillator/photo-multiplier system divided by the area of the scintillator (1.613  $\text{cm}^2$ ) and corrected for the offset from the center of the profile. This procedure was checked by direct comparison with the Air-SEM using the FC/Air-SEM ratio of 0.0027 +/-0.0003 and found to be accurate to within +/- 2%. This indicated that losses of counts in the scintillator due to edge effects was small. It was, therefore, decided to calibrate against the Air-SEM a scintillator of small enough area to overlap the flux range of usefulness of the vacuum SEM. This scintillator, which had an area of 0.4  $\text{cm}^2$  (1/4"x1/4" and 1/2" thick), was calibrated in the same manner and found to be accurate within +/- 2% as well. This work has shown that the combination of the vacuum SEM and the small scintillator provides accurate, convenient and continuous dosimetry over the entire range of fluxes from  $10$  to  $10^{11}$  p's/sec  $\text{cm}^2$ .

## FUTURE FACILITIES

The new beam line configuration being built at IUCF for proton therapy will incorporate several features of use for radiation effects studies. These are: an achromatic high energy proton beam, beam sharing and beam intensity modulation on a millisecond time scale, momentum analyzed energy degraders on the beam line to each end station, and the possibility of providing beams with a uniform beam profile through the use of non-linear magnetic fields. The technical basis of these features and their advantages for radiation effects are described in reference [9]. It is planned to build two beam line end stations for radiation effects research. One will be to the west and the other to the east of the main trunk line at the north end of the accelerator building. The end station on the east line will be identical to the present RERS and will not have a momentum analyzed energy degrader system. The end station to the west will have a new large area beam profile (up to 40 cm x 40 cm) either through the use of non-linear expansion of the beam or through multiple scattering in a foil and a large drift distance. This large area radiation effects research

station will make available high energy proton fluxes as high as  $10^9$  p's/sec  $\text{cm}^2$ . This will be useful for radiation effects tests of entire commercial-off-the-shelf (COTS) systems [10]. Both the east and west end stations will exploit fast beam sharing and intensity modulation. It is planned to have the east station operational in the late summer of 2001 and the west station operational early in 2003.

## CONCLUSION

The radiation effects research program at IUCF is an active program which is based on convenient access to high energy protons and careful dosimetry. The present facilities were described as were validating dosimetry studies. Planned facility development to support the program well into the future were outlined.

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