

COMPARISON OF INDIANA UNIVERSITY CYCLOTRON FACILITY FARADAY CUP PROTON DOSIMETRY WITH RADIOCHROMIC FILMS, A CALORIMETER, AND A CALIBRATED ION CHAMBER.

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Abstract

The accuracy and utility of the dosimetry system used for radiation effects research with high energy protons at The Indiana University Cyclotron Facility, IUCF, has been confirmed by comparison with an independently calibrated Markus ion chamber, a Shulz water calorimeter and GAFCHROMIC[™] films.

I. Introduction

Energetic proton beams are finding a wide application outside the field of basic nuclear physics. In particular, they have been used extensively in the radiation testing of electronic components and systems intended for use in the space environment. Also, there is a rapidly growing interest in the use of proton beams for radiation therapy applications due to their well defined dose-depth distributions. Both applications depend on accurate dosimetry.

Accurate comparison between two methods of dosimetry cannot be performed without equally accurate understanding of the interaction of the radiation with any and all of the materials which the radiation encounters during the comparison. The internationally accepted tables of proton stopping power and ranges are those of Janni [1] cited in report 49 of the International Commission on Radiation Units and Measurements, ICRU 49 [2].

There is an operating Faraday cup system installed on a beam line at the IUCF [3]. In addition, a Schulz [4] type water calorimeter has been constructed at the IUCF and there is a calibrated Markus [5] ion chamber available for comparison. The availability of these independent dosimetry systems provides a unique opportunity to cross compare methods of dosimetry.

II. Stopping Power Corrections

To determine the dose at any point due to proton irradiations it is necessary to know, not only the fluence, but also the proton energy and to use this to calculate the stopping power at that point. A comparison of stopping powers calculated by the beam monitoring program, "BeamMonster" [9] and those found in ICRU 49, the internationally accepted standard for proton stopping powers, was made. The BeamMonster values differed from the ICRU 49 values by less

than 1%. BeamMonster values will be used and quoted with a 1% uncertainty.

III. Method

One of the beam lines of the IUCF is configured to provide an accurately known radiation field. The configuration is shown in Figure 1. 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. A 3 cm inside diameter collimator was located 216 cm downstream from the scattering foil. This collimator served to define the beam. Immediately following the collimator was the secondary emission monitor, (SEM) consisting of 15 half mil Cu foils alternately biased to collect the secondary electrons produced by the proton beam as it passed through. The Faraday cup is 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 [9] (about 30 eV). We routinely measure less than 2 pA Faraday cup currents without beam. These leakage currents were measured and subtracted from the several nA beams used in these dosimetry comparisons. The Faraday cup was mounted so that it could be withdrawn to allow the beam to pass through an exit window and into the region where samples could be placed for irradiation.

IV. Film Calibration

The GAFCHROMIC[™] film [6,7] type HD 810 and MD 55 provides a convenient and reproducible dose sensitive material with which to tie together the other methods of dosimetry. This film was calibrated as a function of proton fluence using

Radiation Effects Research Station

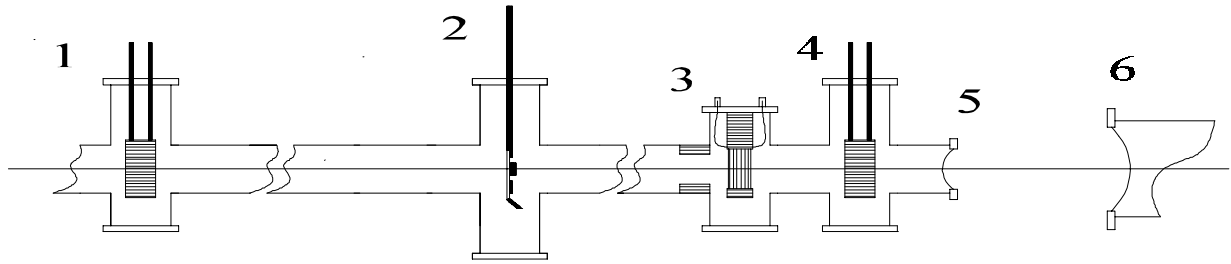


Figure 1: The Radiation Effects Research Station, RERS. Number 1 is a removable stop which turns the beam on and off, #2 is target ladder with a scintillator for beam alignment and Cu foils to spread the beam, #3 is the defining collimator and Secondary Emission Monitor, (SEM), #4 is a removable Faraday cup used to calibrate the SEM, #5 is the exit window, and #6 is the entrance to the beam dump. Devices to be tested are placed between 5 and 6.

the above described system. A standard position 18.5 cm downstream from the exit window was established where all the films were irradiated for calibration purposes.

The unscattered beam was aligned to be centered on scintillator plates placed at the spreading foil location, and just outside the exit window. The upstream scintillator was replaced with a 0.239 cm, (0.094 inch) thick Cu scattering foil. With the Faraday cup in place, the ratio of the Faraday cup current to the SEM current was recorded so that the SEM current could be used as a direct measure of the beam current. This Faraday cup to SEM ratio was quite stable, varying by less than 0.1%. Next, an image of the beam was made using the GAFCHROMIC[™] film placed at the 18.5 cm position. This provided a determination of the intensity distribution of the beam without depending on any calibration. Three beam profiles were taken during the calibration of the film. An average of these beam profiles is shown in Figure 2. The ratio plotted in this figure is the average number of protons in a square centimeter area at a radius, r , from the beam center

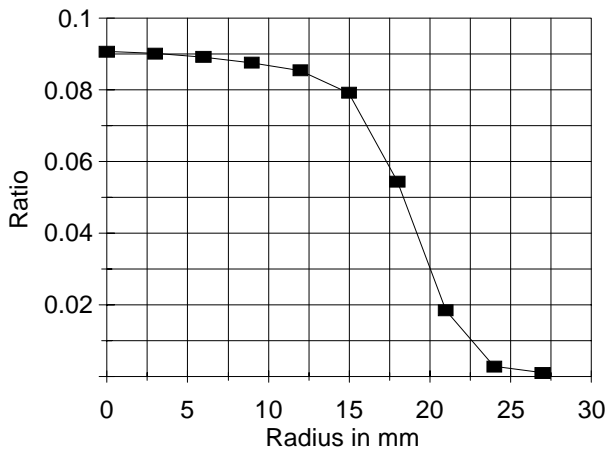


Figure 2: Average profile for the calibration runs. This is the ratio of the beam intensity at any radius to the total number of beam protons.

divided by the total number of protons in the beam as determined by the integral of the measured fluence over the area of the beam. The average ratio of the intensity at the center of the beam to the total beam was 0.09072 +/- .0008. This method allowed the determination of the fluence at the center of the beam at 18.5 cm from the exit window with a 1% uncertainty.

One inch square samples of the GAFCHROMIC[™] film, (both type 810 and type 55), were irradiated at the 18.5 cm position. They were wrapped in a layer of aluminum foil to facilitate handling. They were irradiated at varying fluences to produce doses (H_2O) from less than 1 Gray to 6 kiloGray. Temperature conditions were monitored and remained at 22 +/- 2 degrees C. The optical density of the GAFCHROMIC[™] film increases with time reaching saturation less than 24 hours after irradiation. (Note: the type 55 film was observed to continue darkening somewhat after 24 hours.) Hence, a standard reading time of 24 hours was adopted for this calibration [7]. The change in optical density of the films was measured using a Tobias model TBX densitometer with an interference filter whose band pass was 10% centered at 600 nanometers. Unexposed samples of the type 810 and type 55 film were used to provide a base optical density which was subtracted from the measured optical densities of the irradiated films to give the change in optical density.

Figure 3 shows a plot of change in optical density versus dose (film). Dose film was calculated from the fluences determined by the Faraday cup system using software by Ziegler et. al [8]. The composition of the active material in the GAFCHROMIC[™] film was taken from manufacturer's data as 50% H, 30% C, and 20% O, with a material density of 1.20 g per cm^3 .

The type 810 film had been calibrated by a similar method with 62.5 MeV protons at U. C. Davis 10 years earlier [9]. This data is in excellent agreement with the current measurement at 193 MeV showing only a small difference in saturation characteristics above one kiloGray. This high dose

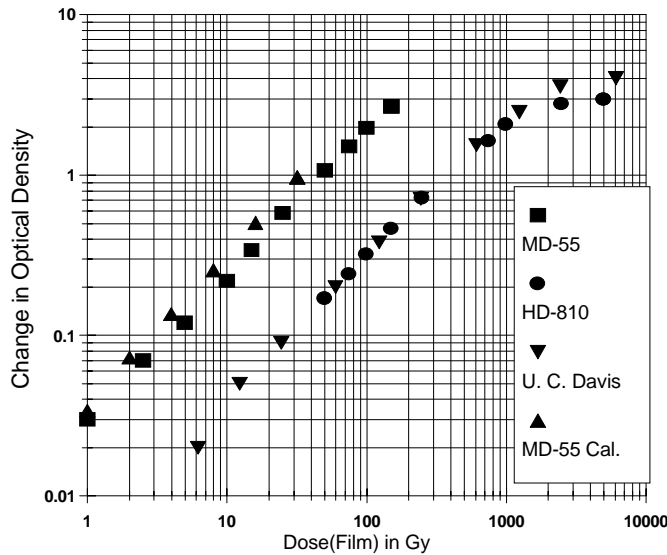


Figure 3: Optical density versus dose(film) for MD-55 and HD-810 GAFCHROMIC™ film.

saturation effect was not explored during the work reported in this paper. The MD-55 calibration data shows a higher optical density for a given dose because it was made using a laser photometer operating at a wavelength nearer the peak of the absorption spectrum. The rest of the data shown in figure three was taken using an optical densitometer with a 10% band-width interference filter centered at 600 nanometers. This relatively broad band system is much less sensitive to small shifts in the wavelength of the absorption band caused by temperature changes.

V. Ion Chamber and Calorimeter Comparison

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 4. 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 Shulz type calorimeter. 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 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 [4], 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

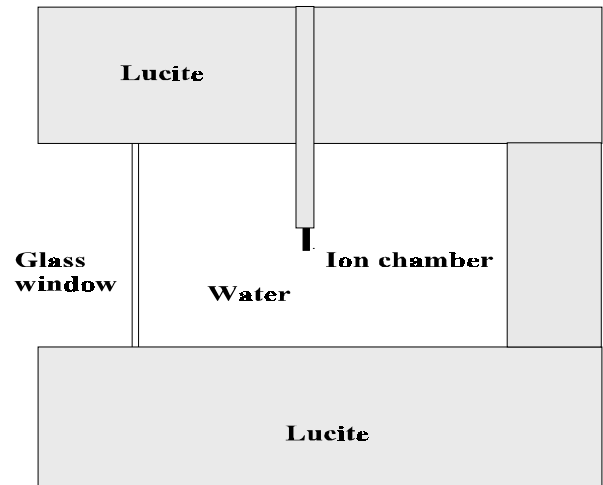


Figure 4: The phantom calorimeter. Films were placed at the front face of the calorimeter and also just ahead of the ion chamber to measure the change in fluence due to 5 cm of water.

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

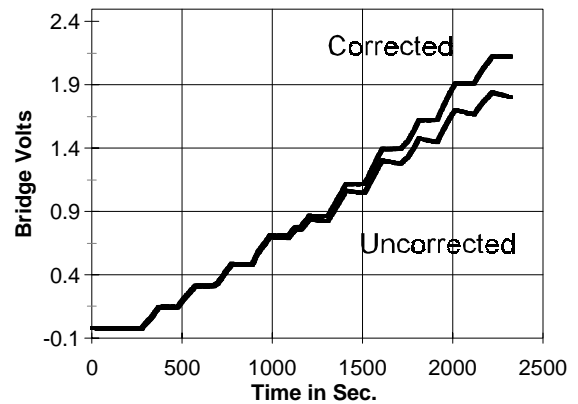


Figure 5: Bridge voltage versus time for a calorimeter measurement. Lower curve is the raw calorimeter response and the upper curve is the calorimeter response with the “cooling” removed.

phantom to get the Ion chamber responses. Figure 5 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. and energy at the temperature probe/ Ion chamber.	Average ratio of the calorimeter dose to Faraday Cup dose	Average ratio of the ion chamber dose to Faraday cup dose
Test 69 154 MeV	0.987 +/- 0.014	0.984 +/- 0.002
Test 76 165 MeV	0.987 +/- 0.009	1.005 +/- 0.005
Test 78 163 MeV	0.996 +/- 0.019	0.990 +/- 0.005
Test 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.

VI. Conclusions

The Markus ion chamber has a documented calibration [10] which can be traced to the National Institute of Standards. The Faraday cup system together with its 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%. It must be pointed out that these quoted standard deviations represent the observed scatter of about 50 different determinations of dose by each of these above described methods. Hence, while the average ratio of doses determined above only differ by less than a percent, any individual determination of dose may differ by two percent from any other determination. The observed fact that the average doses determined by the Faraday cup system are consistently

higher than the other systems may be interpreted as indicating a 1% systematic error. However, the 2% standard deviation of the observations clearly does *not* allow any such 1% conclusion as being determined. The results presented herein demonstrate that, when all factors are properly taken into account, the IUCF RERS Faraday Cup dosimetry is consistent with accepted standards of dosimetry. The usefulness of GAFCHROMIC™ film, both as a dosimeter and as an indicator of relative dose for high energy protons is also demonstrated.

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