UNIFORMITY OF PROTON BEAMS AVAILABLE AT THE NASA SYNCHROCYCLOTRON (SREL)

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INTRODUCTION

The National Aeronautics and Space Administration (NASA) has in operation a space radiation effects research facility that is suitably designed for radiation biology research. A 600 MeV proton synchrocyclotron, capable of simulating the space radiation environment, is the facility's major machine. Space radiation simulation is achieved by degrading either of the two primary extracted proton beams having measured energies of 595 MeV and 325 MeV. The primary extracted beams are degraded to lower energies by using copper absorbers located in the magnet hall of the facility (see figure 1). Proton beams having energies from 595 MeV to approximately 30 MeV can be obtained at the target position.

Both small and large area beams are available over a wide energy range. The final beam configuration at the target position, however, is dependent upon the optimization of some 25 magnets located in the proton beam transport system (P.B.T.S.). Because of this, an extensive proton beam characterization study was initiated and recently completed. This paper summarizes the characteristics of approximately 30 beam configurations and includes such

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parameters as proton beam energy, energy spread, intensity, intensity profile, repeatability, and area.

The results reported here are primarily related to large area beams which are of interest to experimenters studying the radiation effects of protons on animals. Uniformity of several large area beams is discussed in terms of dose rate (rads/min) in muscle.

EXPERIMENTAL METHODS

I. Monitoring Techniques

Foil activation is considered one of the best techniques for determining high energy proton beam intensities. The C^{12} (p,pn) C^{11} reaction is widely used since the cross section is known to within ± 5% over an energy range of 50 MeV to the GeV region (ref. 1). The induced C^{11} atoms decay to B^{11} by positron emission with a half-life of 20.5 minutes and a maximum energy of 0.968 MeV.

For the determination of absolute C^{11} activity induced in a polystyrene target, a gamma counting system was chosen for this experiment. The emitted positrons were stopped in an aluminum capsule surrounding the polystyrene disc. Gamma rays produced by positron annihilation were then counted with a NaI(Tl) crystal.

Horizontal and vertical profiles of the small area, high intensity beams were obtained by scanning the beams with a silicon diode (ref. 2 and 3). Figure 2 is the horizontal profile of the small area 325 MeV proton beam.

II. Calibration of Detector System

Several precision gamma standard sources with accuracies of ± 1 - 2 percent were used for calibration of the 3" x 3" NaI(Tl) crystal detector system. Nominal source-to-detector distances of 0, 5 and 10 cm were chosen depending on the source strength of each disc.

Crystal efficiency was determined for each sample size and each source-to-detector distance. Since the samples used were not point sources, corrections were made in the calibrated efficiencies and were found to be 1.5 percent for the 1" diameter samples.

From the above calibrations it was possible to determine the number of gamma rays being emitted from a source at some distance, 0, 5 or 10 cm.

III. Beam Set-Up and Irradiation

Two methods were used to obtain large area beams at the target position. The preferred technique, because of lower background radiation, employed magnet defocusing and was used for the majority of the beams. The coulomb scattering method was used for the five larger area beams in order to obtain higher intensities.

Lower energy beams were obtained by arrangements of both beam degraders in the transport system and magnet defocusing. Very tedious efforts have been spent in obtaining uniform, large area beams covering a wide energy range.

Polystyrene samples with a diameter of 1" and 1/8" thick were placed in the beam area to monitor the vertical and horizontal beam profile. These samples were irradiated for three half lives (61.5 min.) and the induced activity counted for a live time of one minute on the pulse height analyzer.

IV. Dose Determination

The total activity from an irradiated disc is given by:

$$A_T = N_o \sigma \Phi(t) (1 - e^{-\lambda t})$$

where N_o = number of C^{12} atoms/cm^2

σ = cross section for C^{12} (p,pn) C^{11} reaction

$\Phi(t)$ = protons/sec

$\lambda = \frac{0.693}{T\ 1/2} = 0.0338\ min.^{-1}$ (T 1/2 = 20.5 min.)

t = duration of irradiation in minutes

By integrating the peak associated with the 0.511 MeV gamma rays and using the calibration data, one can easily determine A_T for each disc. The only unknown quantity is therefore $\Phi(t)$ which is calculated from knowing all of the other parameters. After $\Phi(t)$ is determined, it is then possible to determine the flux per unit area per unit time, $\frac{d\Phi}{dt} = \frac{p}{cm^2\ sec}$. Therefore, dose rate can be calculated by using the following relation (ref. 4):

$$\frac{dD}{dt} = 1.6 \times 10^{-8} \times \frac{d\Phi}{dt} \times \left(\frac{1}{\rho}\frac{dE}{dx}\right)_E \quad \text{rads/sec}$$

where 1.6×10^{-8} rad $= \frac{1\ MeV}{gm}$

$\frac{d\Phi}{dt} = \frac{protons}{cm^2 \cdot sec}$

$\left(\frac{1}{\rho}\frac{dE}{dx}\right)_E$ = mass stopping power for the absorbing material, in $\frac{MeV \cdot cm^2}{gm}$, for protons of energy E (MeV).

Dose rates in muscle were calculated in this manner for all of the beams considered and are discussed in detail.

V. Discussion of Errors

The largest error involved in the aforementioned technique for proton beam monitoring is in the uncertainty of the value of cross section for the C^{12} (p,pn) C^{11} reaction. This error is reported to be approximately ± 5 percent over the energy range considered (ref. 1).

Several investigators (ref. 5, 6) have reported a loss of activity in this technique due to the diffusion process of C^{11} atoms in a gaseous form. As much as a 15 percent loss has been reported for very thin samples. However, the loss of activity for the thick samples used in this experiment was found to be less than ± 0.5 percent.

All standard γ-sources were calibrated to an accuracy of ± 2 percent or better.

Although care was taken in evaluating the 0.511 MeV peak, a ± 3 percent error was assigned for counting and evaluating the area of the peak.

A ± 2 percent error was involved because of absorption of the 0.511 MeV gamma ray in the polystyrene disc and aluminum capsule.

The proton beam intensity fluctuation was measured to be ± 2 percent during the irradiation of the discs. This was checked by monitoring the beam with a secondary emission chamber during the irradiation.

Other errors such as inaccuracy in the number of C^{12} atoms/cm^2, time measurements, etc. were estimated to be ± 2 percent. Therefore, the overall error was calculated to be ± 8 - 10 percent.

The contribution of the C^{12} (n, 2n) C^{11} reaction to the total sample activity was found to be negligible for the energies considered.

DISCUSSION OF RESULTS

I. Large Area Beams Obtained by Magnet Defocusing

Most of the large area beams were obtained by degrading the 325 MeV beam in beam degrader #1 (BD-1) and blowing up the lower energy beam by defocusing the last pair of quadrupoles in the transport system. Figure 2 shows a horizontal scan of the 325 MeV beam taken in the combined target area (C.T.A.) at the target position 10 feet from beam monitor #4 (BM-4) exit window. Incidently, both proton and electron beams are available in the C.T.A. The scan was made with a silicon diode. Since the profile of this initial beam is approximately Gaussian, it would seem that the profiles of any larger area beams obtained with this beam would be Gaussian. This was found to be the case for all of the large area beams.

Figure 2 shows a horizontal profile of two 225 MeV large area beams taken at 10 feet and 25 feet from BM-4 exit window in the C.T.A. Experimental points are represented by the black dots and a ± 10 percent in dose rate is shown with vertical error bars. Calculations showed that the error in the dose measurements for large dose rates was ± 8 - 10 percent. Therefore the ± 10 percent error in dose rate, as indicated by the vertical error bars, was used for convenience in the calculation and plotting of all data points. However, in reality the errors are greater for the lower dose rates, because of the low counting rates. The horizontal error bars represent the width of the polystyrene disc, which in most cases was one inch. A best fit Gaussian curve was determined for each large area beam and the equations are given on each figure in terms of dose rate as a function of position in the proton beam. Only horizontal profiles are shown since the vertical profiles were similar. Since the vertical and horizontal profiles were similar, it is possible to calculate, using the available equations, dose rate for a given size target, if the position relative to the beam pipe center is known.

The full width at half maximum (FWHM) is seen to be 4.5" for the 225 MeV beam at the 10-foot position and 7.1" at the 25-foot position. Knowing these two values one may estimate the FWHM, and dose rate available, for distances between 10 and 25 feet. The dose rate per unit area is seen to be higher at the 10-foot position than it is at the 25-foot position. This is expected, however, because of beam spreading.

Figure 4 shows horizontal profiles of a 75 MeV large area beam taken 10 feet and 25 feet from BM-4 exit window. The FWHM is 5.8" for the 10-foot position and 15.6" at the 25-foot position. Both beams show very uniform characteristics and are fitted with Gaussian equations.

II. Large Area Beams Obtained by Coulomb Scattering

Five large area beams were obtained by two methods of Coulomb scattering. Figure 5 shows two large area beams obtained by Coulomb scattering. Curve 1 shows a horizontal profile of a 142 MeV beam which was obtained by degrading the 325 MeV beam in BD-1 to an energy of 225 MeV. The 225 MeV beam was then transported to the copper absorbers placed on the exit window of BM-4 and Coulomb scattered to a large area. Curve 2 shows a 146 MeV Coulomb scattered beam obtained by degrading the full energy 325 MeV beam using copper absorbers placed on exit window of BM-4. Curve 3 shows a 155 MeV large area beam obtained by magnet defocusing of a 155 MeV beam leaving BD-1. These three beams are approximately the same energy and are compared to point out that

Coulomb scattered beams in the C.T.A. give higher dose rates, are more uniform and are larger in area than the beams obtained by magnet defocusing. Note also that each of these beams are Gaussian and equations are given in terms of dose rate.

Table I is a summary of all large area beams obtained at SREL.

III. Repeatability

Since there are many parameters associated with a given beam condition, it was necessary to determine if the optimum conditions obtained were repeatable. Profiles were determined for several large area beams and then repeated again for comparison. A time period of several days between runs was sufficient for repeatability studies. Pictures of the beams were also taken. The entire system was found to be remarkably repeatable (within experimental accuracy) in terms of beam area and dose rate.

CONCLUSIONS

The NASA Space Radiation Effects Laboratory (SREL) has a unique capability in producing both small and large area beams having energies from 595 MeV - 30 MeV. Dose rates are available over a wide energy spectrum to meet the requirements for radiation biology experiments. All of the large area beams are uniform and repeatable.

Several investigators have used the available large area beams to irradiate mice, rabbits and monkeys.

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TABLE I.- A SUMMARY OF THE PROTON MEASUREMENTS MADE ON THE SREL SYNCHROCYCLOTRON

PROTON ENERGY (MeV)	ENERGY SPREAD (MeV)	FWHM OF HORIZONTAL PROFILE (INCHES)			SMALL BEAM INTENSITY (PROTONS/SEC)
		SMALL BEAM (10 FEET)[a]	LARGE BEAM (10 FEET)[a]	LARGE BEAM (25 FEET)[a]	
325	1.3	1.5	—	—	3×10^{10}
225	2.7	3.5	4.8	7.1	6.2×10^{9}
194[b]	2.8	—	9.0	—	—
155	4.1	3.0	6.5	15.0	3.5×10^{9}
146[b]	3.9	—	21.0	—	—
142[b]	4.0	—	16.0	—	—
95	4.1	3.3	9.0	17.0	1.5×10^{9}
90[b]	4.5	—	23.0	—	—
75	4.8	4.0	6.0	14.0	1.3×10^{9}
50	4.8	3.5	16.0	—	7.8×10^{8}
40	6.1	14.0	—	—	6.8×10^{8}
31[b]	6.2	—	35.0	—	—

a. DISTANCE FROM BM-4 EXIT WINDOW
b. COULOMB SCATTERED IN C.T.A.

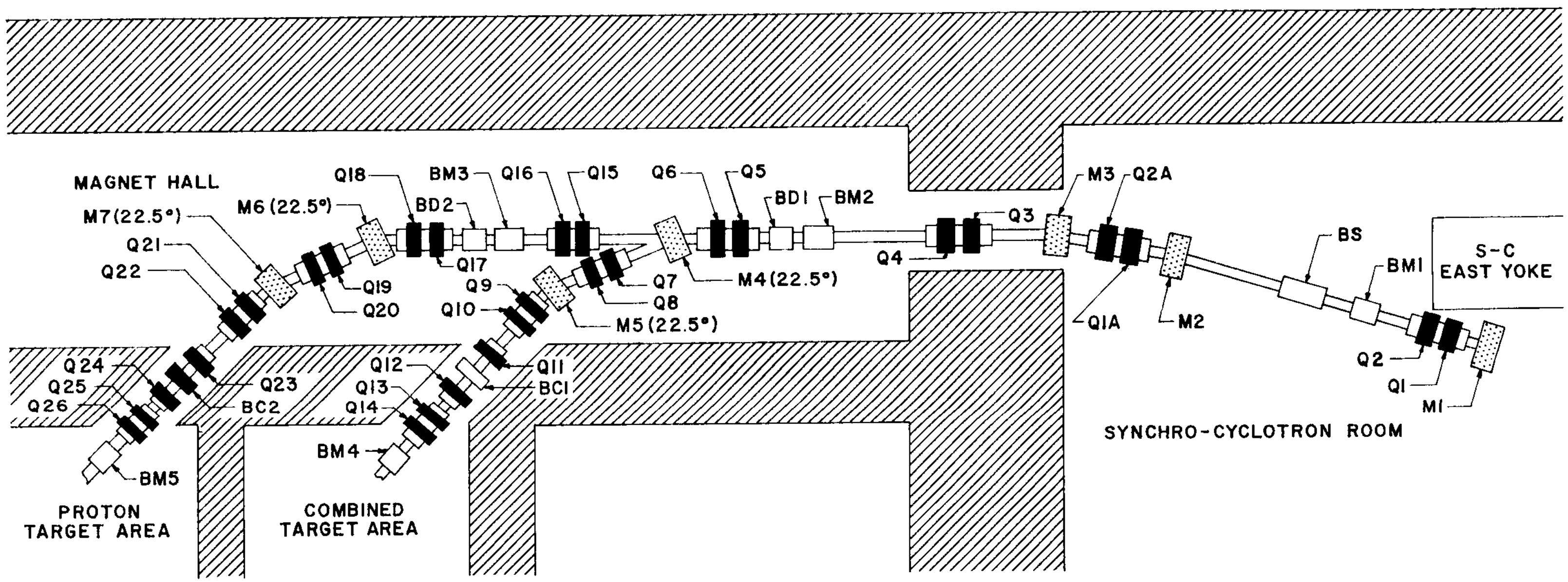

Figure 1.- Schematic diagram of the proton beam transport system (PBTS) at SREL.

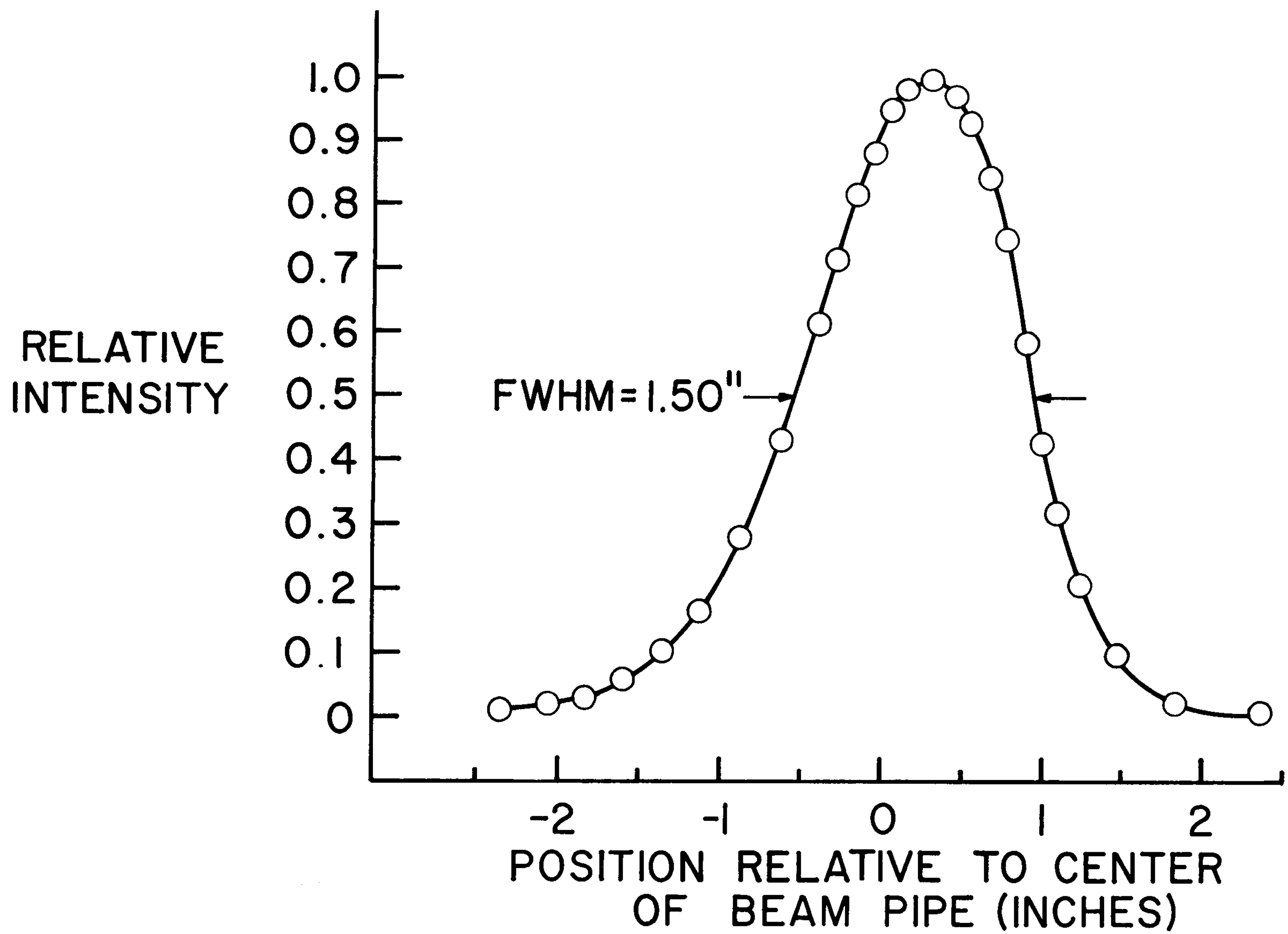

Figure 2.- Relative intensity profile of a horizontal scan of the 325-MeV proton beam taken 10 feet from BM-4 exit window.

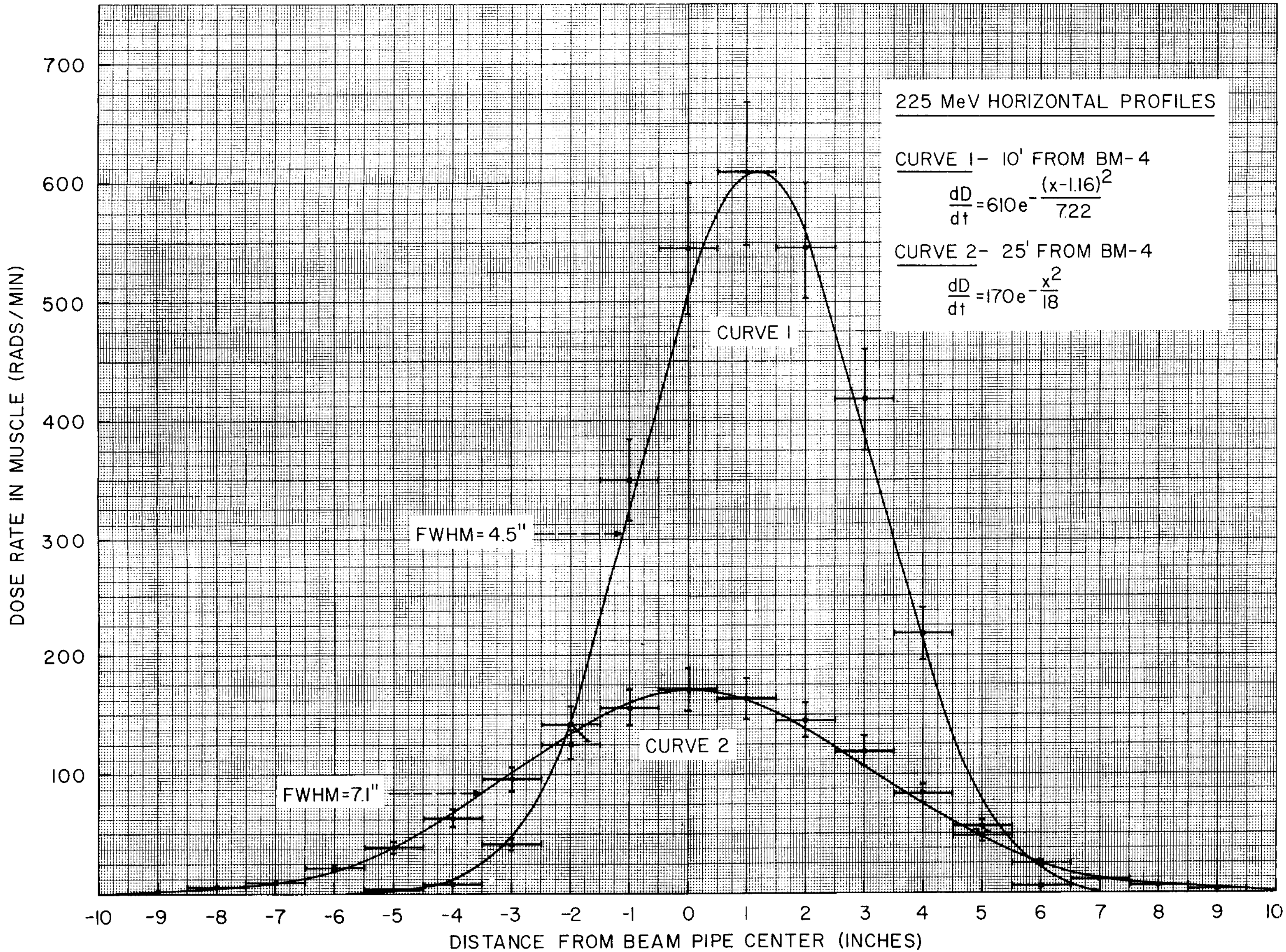

Figure 3.- Horizontal profiles of a 225-MeV large area beam taken 10 feet and 25 feet from BM-4 exit window.

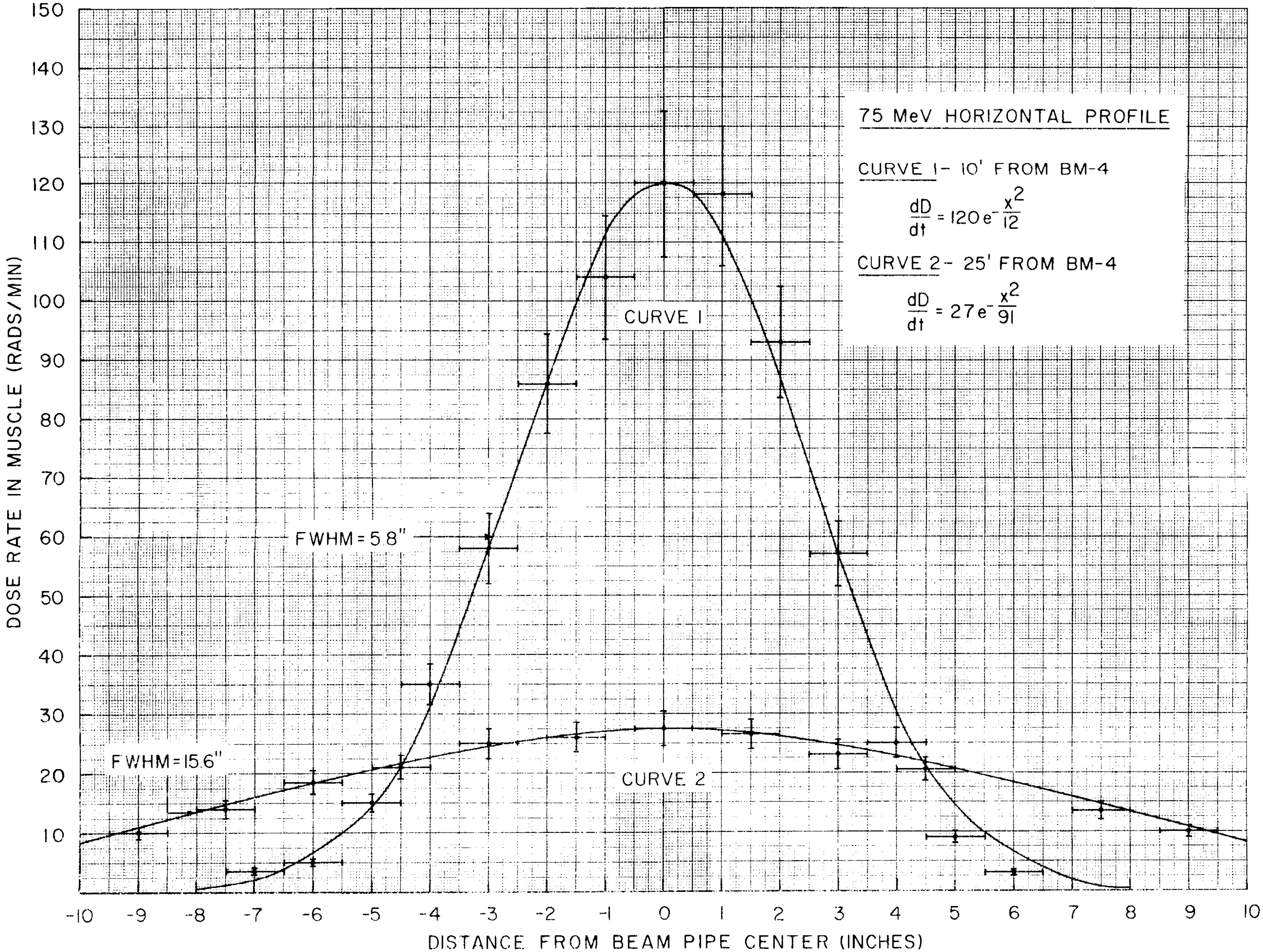

Figure 4.- Horizontal profiles of a 75-MeV large area beam taken 10 feet and 25 feet from BM-4 exit window.

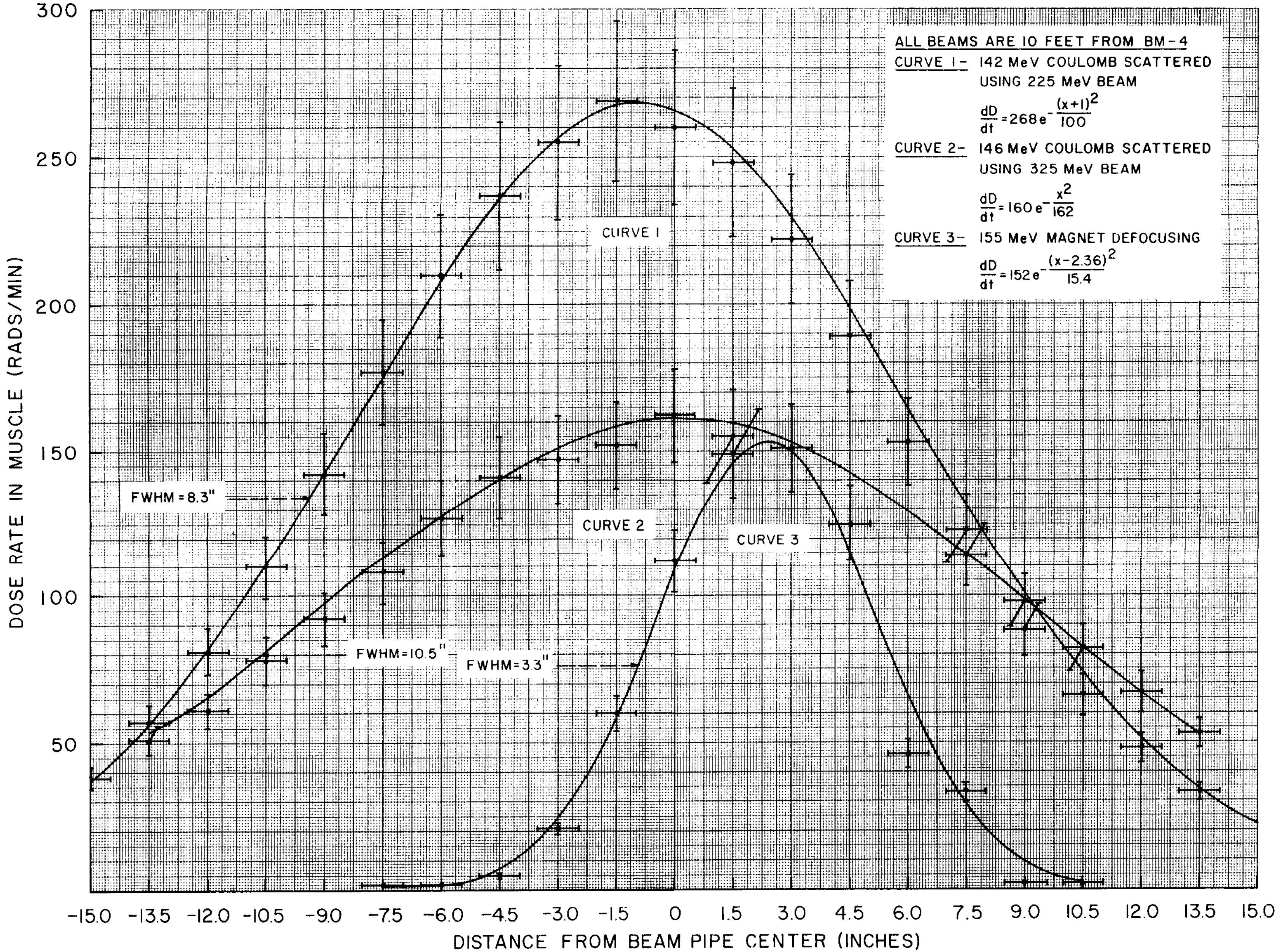

Figure 5.- A comparison of two coulomb scattered, large area beams (142 and 146 MeV) with a large area beam (155 MeV) obtained by magnet defocusing. All three beams were measured 10 feet from BM-4 exit window.