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SOURCE FUNCTIONS AND TRANSPORT LOSSES FOR A 28-GeV EXTERNAL PROTON BEAM†

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Dose and flux measurements along the axis of a practical external beam transport system are reported for various target configurations. Source functions are derived and normal transport beam losses are found by extrapolation. In addition, inside the shield, we have measured the ratio of dose measured by β and γ sensitive film to the 'neutron' dose measured by NTA film, as well as the ratio of total dose to secondary flux density using ^{11}C activation.

1. INTRODUCTION

In designing an economical radiation shield for a beam transport system some of the questions to be considered are:

1. What fraction of the beam will be lost?
2. What is the distribution of beam loss?
3. What radiation level will be produced?

Some of this information is available for accelerators, which are characterized by a very dense lattice compared to an external beam transport. This paper describes the results of an investigation of beam loss, and resulting dose and flux from a practical external beam transport system at 28 GeV.

2. EXPERIMENTAL PROCEDURE

These studies were conducted in the external beam to target 'C' (Fig. 1 is a schematic of the layout). Thin (0.006 in.) aluminum vacuum 'windows' were installed approximately 83 ft upstream of the C target position. An air space of 10 in. between the windows allowed targets to be inserted into the beam at that location. Detector packages consisting of 'pocket' (ionization chamber) dosimeters, film badges and polyethylene foils were placed along the vacuum chamber at a typical interval of 10 ft; the detectors were located approximately 8 in. from the beam axis. The beam intensity for all runs was monitored by activation of Carbon-eleven in poly foils placed in the beam between the vacuum windows (position 0), and at target position C.

Flux was measured by normalizing the activity from ^{11}C decay in the foils placed along the beam line to the activity in the monitor foils placed directly in the beam; thus we assume the same cross section for ^{11}C activation by secondary particles as by the 28 GeV primary protons, 25.9 mb.[1] Dose was determined from standard personnel monitoring film badges containing film sensitive to the β and γ components of the spectrum, and NTA film sensitive to neutrons and protons. Dose was also measured using quartz fiber pocket dosimeters. Correction for extraneous exposure of the film badges was determined from unexposed 'controls' which constituted ~ 10 per cent of the number exposed.

The question of transport loss is difficult to answer directly since beam loss in a practical external beam line is less than 1 per cent. The method we used was to measure the radiation produced from the normal, evacuated transport, and the radiation when it contains a long target of long, known, interaction length, e.g., air. Knowing the fraction of the beam lost in the second case, the loss for the normal transport system is found by extrapolation.

3. RESULTS

After tuning the beam extraction and transport elements for minimum loss three runs were made with target conditions as shown below:

Run	*Target*
I	1 inch thick A1 target at position 0
II	Target out (background)
III	83 ft of air at STP from position 0 to the 'C' target location

† Work done under the auspices of the US Atomic Energy Commission.

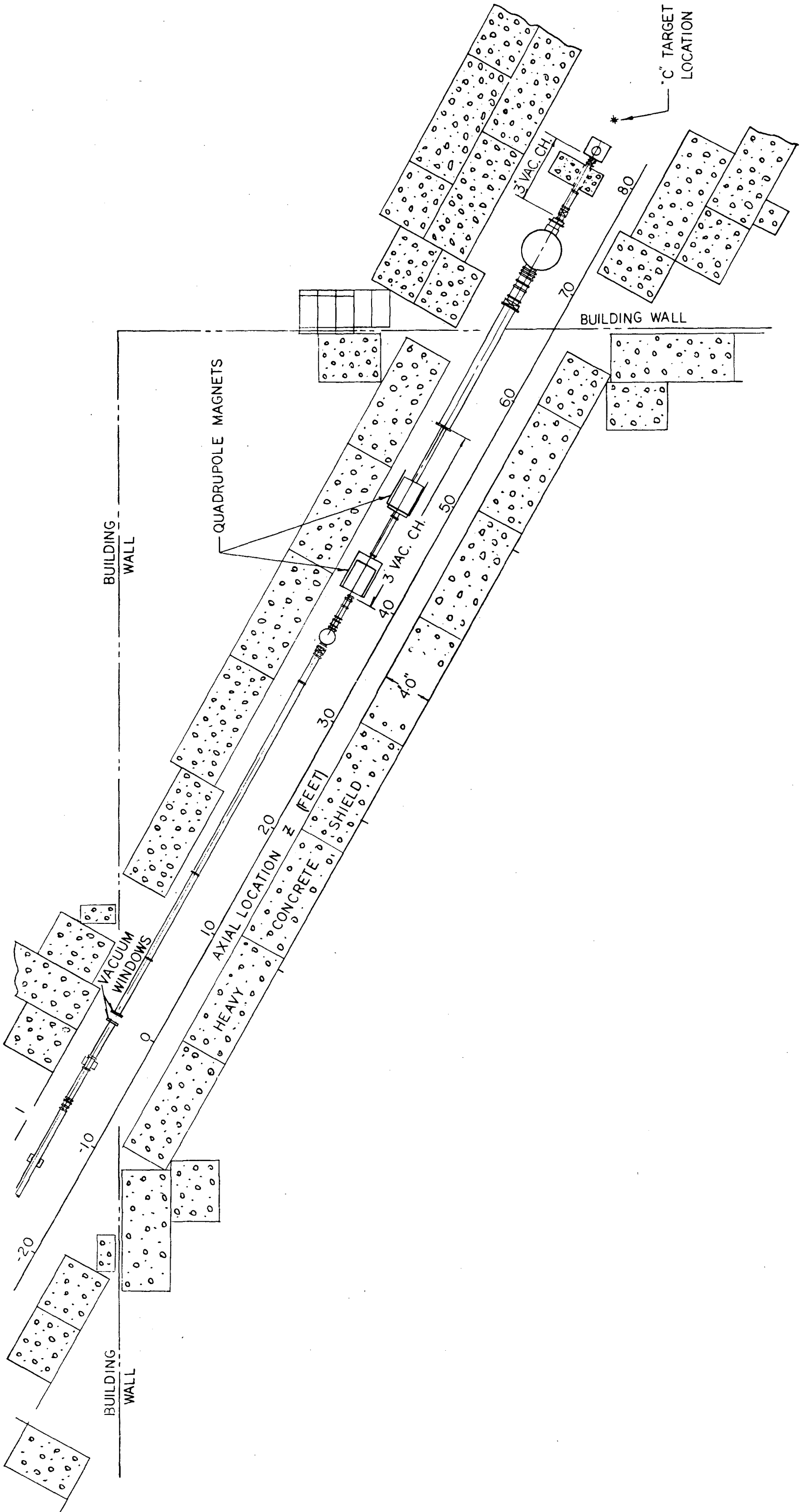

FIG. 1. External beam layout upstream of target 'C' showing thin shield and detector locations.

The data for these runs are included in the Appendix. Figures 2 to 5 display the radiation distribution along the beam pipe normalized to the beam intensity. The curves are derived by averaging and 'smoothing' the data, i.e.,

$$D_{i+1/2}=\tfrac{1}{2}(D_i+D_{i+1})$$

where D_i is the dose or flux value at location i. The main features of the distribution for the 'point' aluminum target (Figs. 2 and 3) are a very steep exponential rise upstream of the target ($D \sim e^{Z/\lambda_b}$), and a slower exponential decline of the flux and dose on the downstream side ($D \sim e^{-Z/\lambda_f}$). The departures from these main features are also evident for runs II and III (Figs. 4 and 5) and are due to the quadrupole magnets where the vacuum chamber is reduced in diameter from 6 to 3 in.; another 3 in. pipe section is just upstream of target C.

Note that the dose measurements in the figures reflect only the $\beta\gamma$ film badge data. The NTA film data were incomplete. For those positions where the neutron dose was determined the mean ratio of NTA film dose to $\beta\gamma$ film dose was 5.1 : 1, where for the $\beta\gamma$ film a quality factor of 1 is assumed (1R = 1 rem) and for the NTA film 1 rem = 100 tracks per 25 (microscope) fields.

4. SOURCE FUNCTIONS

It is useful to compare the axial distributions we have measured for the external beam with those determined for accelerators. The National Accelerator Laboratory Design Report[2] offers a generalized source function for the CERN machine with a point target:

$$Y(Z)=K\{[\exp(-Z/\lambda_b)+C\exp(Z/\lambda_f)]^{-1}+D\},$$

where Y is defined as the dose measured along the beam direction at a fixed distance from the vacuum chamber.

A least squares fit to the axial $\beta\gamma$ dose distribution for the aluminum target is obtained with the NAL formula using $K = 1.94\times10^{-12}$ rem/beam proton $\lambda_b = 0.31$ ft, $\lambda_f = 27.5$ ft, $C = 0.49$, $D = 2.94\times10^{-3}$. Not surprisingly, the distribution of flux differs in form from the dose distribution. The characteristic length in the backward direction is not well enough defined by the present flux measurements but the

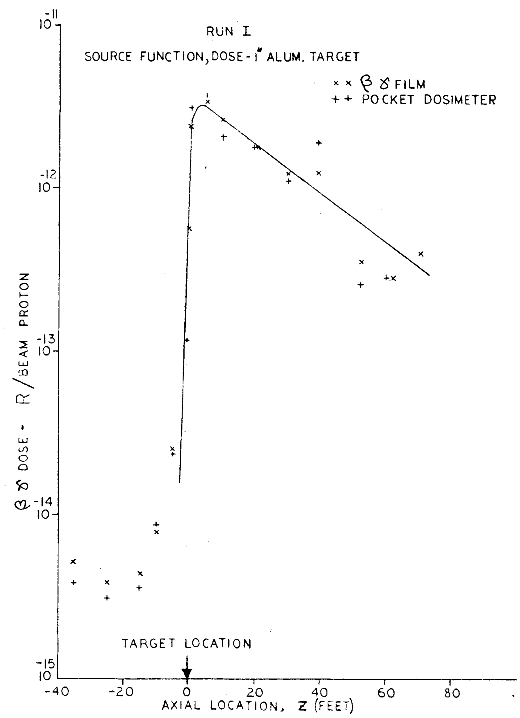

FIG. 2. Axial $\beta\gamma$ dose distribution for 1 in. aluminum target.

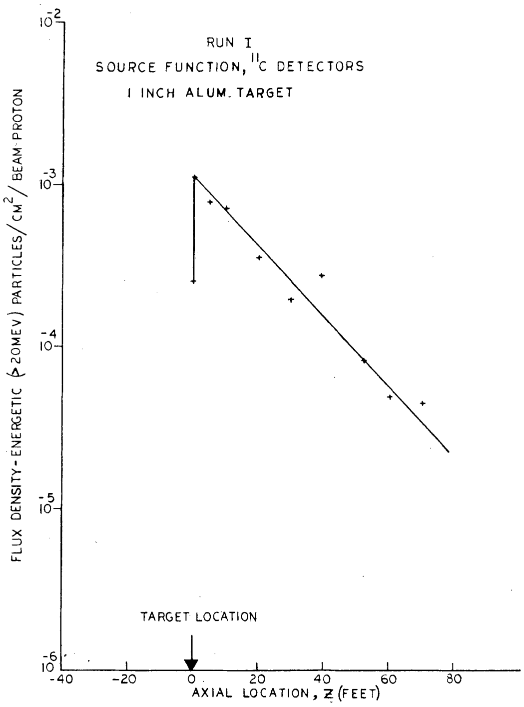

FIG. 3. Axial ^{11}C flux distribution for 1 in. aluminum target.

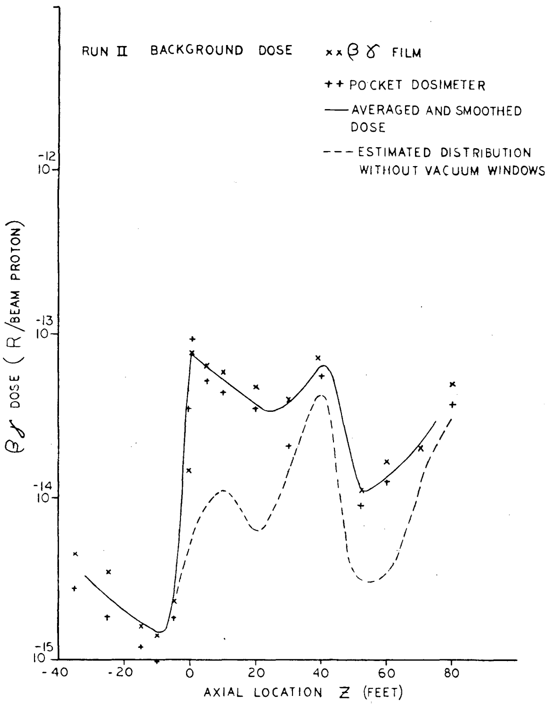

FIG. 4. Axial $\beta\gamma$ dose distribution, background run.

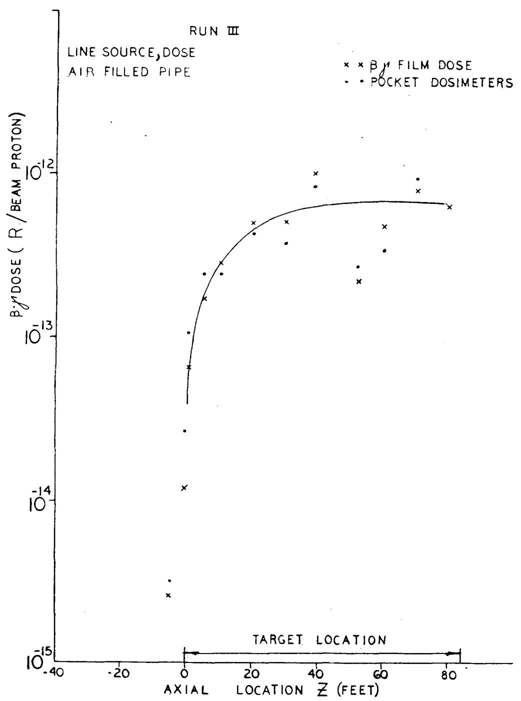

FIG. 5. Axial $\beta\gamma$ dose distribution, air-filled vacuum chamber.

forward relaxation length, λ_f, is found to be 20 ft from these flux data for the one inch aluminum target.

The CERN–LRL–RHEL collaboration[3] reported forward relaxation lengths (λ_f), of 20 to 26 ft for a variety of detectors for distances up to 130 ft (40 m) from the target. It is noteworthy that the distribution of radiation from a target is so similar for the case of an accelerator with a high density of magnetic elements and well defined betatron wavelength, and an external beam line with a low density of elements and aperiodic focusing. This suggests that the axial distribution is primarily determined by the angular distribution of secondaries from the target.

The continuous air target presents a line source, a continuum of point targets. Assume that any of these infinitesimal targets has a source function of the form

$$s(z) = 0 \quad \text{for} \quad z < Z'$$

$$s(z) = e^{-z/\lambda} \quad \text{for} \quad z \geqq Z'$$

then the line source that results has the form

$$s_L(z) \alpha (1 - e^{-z/\lambda}).$$

This is exhibited for the air target (Fig. 5) where, far enough downstream of the beginning of the air-filled pipe, the source function asymptotically approaches the value 7×10^{-13} rem per proton in the transport, as measured by the $\beta\gamma$ film and ionization chamber dosimeters.

5. TRANSPORT LOSS

Using 87 g/cm^2 (2.4×10^3 ft) for the interaction length in air at atmospheric pressure, the fraction of the beam which interacts in 83 ft of air is 3.5 per cent. In Fig. 6 the ratio of dose for run III (air target) to dose for run II (background) is plotted *vs* axial location. The asymptote for the ratio is $\cong 40$. Thus if the air target generates 40 times the dose of the transport system in the absence of a target, the actual transport loss fraction for the evacuated pipe is 0.035/40 per 83 ft or 10^{-5} protons lost per proton transported per foot. This is to be considered a conservative value since the vacuum windows are not normally present. However, this value for the transport loss depends on the asymptote of the ratio of dose for air targets and background, and the asymptote is reached quite far downstream of the vacuum windows so they affect the result there only to second order. This result is an upper limit for this beam transport since further improvements in optics, collimation, etc., have significantly reduced transport losses.

6. FLUX TO DOSE CONVERSION

The data for the aluminum target allow a comparison of the secondary particle flux density, determined from Carbon-eleven activation, to the total dose as detected by $\beta\gamma$ and NTA film dosimetry. The average ratio is 3×10^{-8} rem per secondary particle ($E > 20$ MeV) per square centimeter, for a distance up to 70 ft downstream of the target. This agrees within a factor of about 2 with calculations of Wright *et al.*[4] for dose from high energy neutrons and protons. NTA film is a dosimeter sensitive to low energy nucleons ($\lesssim 15$ MeV) but is a standard in wide use, particularly for personnel monitoring. The calculated ratios of dose equivalent per particle referred to are relatively insensitive to energy, varying from 6.8×10^{-8} rem/unit fluence at 2 GeV to 4×10^{-8} rem/unit fluence at 600 MeV for isotropically incident protons. Goebel and Ranft[5] use 8.3×10^{-8} rem per energetic particle per square centimeter.

However, the present results show that the dose and flux distributions have different relaxation lengths (λ_f) and thus the ratio of flux to dose must change with distance from the target.

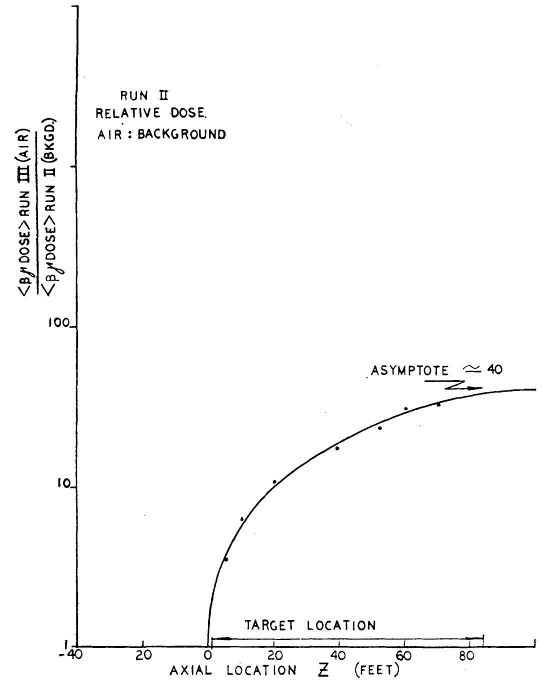

FIG. 6. Ratio of dose (air-filled pipe) to dose (background) *vs* axial location.

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APPENDIX

RUN I—1 in. Al Target

Total Beam Protons = 8.44×10^{13}

Axial Location (ft)	$\beta\gamma$ Film (rem)	NTA Film† (tracks/ 25 fields)	Pocket Dosimeters (rem)	^{11}C Flux n_z/cm^2/ beam proton
−35	0.435	109	0.32	—
−25	0.325	122	0.26	—
−15	0.375	206	0.30	—
−10	0.670	322	0.73	—
−5	2.15	§	2.0	—
−1/2	48‡	§	100	2.5×10^{-4}
+1/2	210‡	§	265	1.12×10^{-3}
5	290‡	§	305	7.7×10^{-4}
10	220‡	§	175	7.1×10^{-4}
20	190‡	§	150	3.5×10^{-4}
30	102‡	§	95	1.9×10^{-4}
39	104‡	§	160	2.7×10^{-4}
52	30‡	§	22	8.2×10^{-5}
60	24‡	§	24	4.8×10^{-5}
70	34‡	§	—	4.4×10^{-5}
80	10.7‡	§	—	—

† 1 rem = 100 tracks/25 fields.
‡ Emulsions required scraping.
§ Track density off scale (> 25 tracks/field, i.e., > 6.25 rem).

RUN II—Target Out

Total Beam Protons = 9.70×10^{13}

Axial Location (ft)	$\beta\gamma$ Film (rem)	NTA Film† (tracks/25 fields)	Pocket Dosimeters (rem)
−35	0.44		0.27
−25	0.34	113	0.18
−15	0.16	105	0.12
−10	0.14	71	0.09
−5	0.22	168	0.18
−1/2	1.4	1340	3.4
+1/2	7.4	‡	9.0
5	6.2	‡	5.0
10	5.7	‡	4.3
20	4.6	‡	3.4
30	3.8	‡	2.0
39	6.9	‡	5.4
52	1.1	760	0.90
60	1.6	585	1.2
70	2.0	450	2.0
80	4.8	1585	3.6

† 1 rem = 100 tracks per 25 fields.
‡ off scale (> 25 tracks/field).

RUN III—83 ft Air at STP

Total Beam Protons = 1.88×10^{13}

Axial Location (ft)	$\beta\gamma$ Film (rem)	NTA Film† (tracks/25 fields)	Pocket Dosimeters (rem)
−35			
−25			
−15			
−10			
−5	0.05	48	0.06
−1/2	0.23	650	0.51
+1/2	1.23	‡	2.0
5	3.3	‡	4.6
10	5.3	‡	4.6
20	9.4	‡	8.1
30	9.6	‡	7.0
39	19.0	‡	15.8
52	4.2	‡	5.1
60	9.0	‡	6.4
70	15.0	‡	17.6
80	12.0	‡	14.5

† 1 rem = 100 tracks per 25 fields.
‡ off scale (> 25 tracks/field).

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