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PERSONAL DOSIMETRY IN A MIXED FIELD OF HIGH ENERGY MUONS AND NEUTRONS*

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1. Introduction

At high energy proton accelerator laboratories, radiation exposure due to muons is often quite significant. The properties of such muon fields have been studied at Fermilab using scintillation telescopes (Co83;El84). The muon intensity has been observed to be peaked in the direction of the incident high energy proton beam in a cone typically less than six degrees FWHM. The nature of the high energy physics experiments that use particle beams incident on targets at rest in the laboratory frame of reference requires that the majority of the experimental apparatus be placed in, or very near, this cone. The signal cables leading from these particle detectors to areas of significant occupancy by experimenters are often restricted in length by pulse

[†]Operated by Universities Research Association Inc. under contract with the U.S. Department of Energy.

quality and delay considerations. Since muons, which have a rest energy of 105.7 MeV, behave in matter as would electrons of such large mass, they have very long ranges (e.g., about 700 m of soil at 400 GeV). It is therefore generally impractical to use shielding to reduce dose equivalent rates in areas of high occupancy. In specialized cases, magnetic fields are effective in reducing the muon fluence by deflection, but this technique is limited by the expense of magnets sufficiently large to deflect muons with momenta typically of the order of tens of GeV/c. Thus, high occupancy areas are sometimes locations of significant muon fluence. It is therefore necessary to be able to accurately assess the dose equivalents received by individuals in muon fields having poorly known energy spectra. This note presents a comparison of the response of dosimeters in a radiation field that is a mixture of muons and neutrons.

2. Properties of the Radiation Field

Figure 1 shows the geometrical configuration at the location at which measurements were carried out. The muons arise primarily in the decay of pions formed by the interaction in two tungsten targets of 800 GeV protons from the Tevatron. Two parallel proton beams separated by a few tens of mm were used. Following each target was a channel to allow passage of the beam to a beam dump inside the electro-magnet. The simple view shown in the Fig. does not show the details of the physics experiment. The radiation field also includes neutrons from the targets, beam dump, and associated iron shielding. The dosimetry measurements were made in a plane 4.3 m above that of the beam. This location was not a high occupancy area but was chosen because the radiation field in this area, although of higher intensity, is similar in composition to that at locations typically occupied by personnel.

The characteristics of the radiation field at this location were determined from measurements performed with various detectors which were mounted in a vehicle equipped with counting electronics. The neutron fluence as a function of energy was measured by a Bonner multisphere spectrometer (Br60;Aw85). The details of this system, which consists of an 8 mm diameter by 8 mm long LiI(Eu) scintillator embedded in a 12.7 mm diameter by 12.7 mm long plastic scintillator called a phoswich (Aw73), surrounded by moderating polyethylene spheres of various diameters, has been described a number of times (Co85;El86) and will not be repeated here. For present purposes it is sufficient to point out that the peak associated with neutrons in the pulse-height spectrum is well-separated from charged particle background events even though large muon fluences are also observed (see below). In these measurements the counting electronics were gated-on during the 23 second beam spill, which occurred once during each (approximately) 60 second accelerator cycle, and a precision $^{10}BF_3$ long counter (De66) provided the relative normalization for the individual Bonner sphere measurements. A threshold set on the long counter output rendered it insensitive to muons and γ-rays.

If the energy-dependent multisphere response functions are known (Sa73), the neutron fluence as a function of energy (i.e., the neutron spectrum) can be obtained from measured Bonner sphere counting rates by unfolding methods (see, e.g., Ro85). To gain some confidence in the reasonableness of the unfolded spectrum, we have used two programs, SWIFT (OB81; Ch83; OB83), based on Monte Carlo techniques, and BUNKI (Lo84;Br84), an iterative recursion method. The unfolded spectra associated with a good fit to the data is shown in Fig. 2, plotted as fluence per unit logarithmic energy interval. The results from SWIFT, shown as the points, are an average of the 100 best-fit spectra from the approximately 7×10^6 sampled. While there are some energy bins at which the two spectra disagree, the general shape is similar for both. Of interest is the fact that while about 20% of the total fluence is associated with thermal neutrons, almost 40% arises from those with energies above 100 keV. The general shape of this spectrum is similar to that measured external to a thick iron shield (E186), a result which is not surprising given the present geometry. The fluence, absorbed dose, dose equivalent, and quality factor associated with the neutrons are shown in Table 1 for 10^{12} protons incident on the target as measured by a secondary emission monitor (SEM) in the primary beam line. The values are based on the average of the results from the two fitting programs BUNKI and SWIFT, and the errors are calculated as the standard deviation of the mean.

The muon fluence at this location was determined from measurements with a pair of 6.4 mm thick plastic scintillator paddles of transverse dimensions 0.2032 m by 0.2032 m, separated by about 0.15 m with a 25.4 mm thick aluminum plate located in the gap. Standard electronics modules were used to record on scalers both singles and coincidence events. As before, the scalers were gated-on during both beam-on (23 second spill period) and beam-off time periods in synchronization with the accelerator cycle. Coincidence rates were about 75% of the singles rates; this reflects the reduced coincidence efficiency for detection of muons that are incident at angles other than 90° to the surface of the plates (Co81; El84). The muon fluence based on singles counting rates for 10^{12} incident protons is shown in row 2 of Table 1. Also shown are muon absorbed dose and dose equivalent obtained from the measured fluence by use of the conversion factor of 40 fSv-m^2 and an assumed muon quality factor of unity (St83). The table lists the fractions of the total fluence, absorbed dose and dose equivalent of the radiation field that are due to the neutrons and muons.

The quality factor (QF) of the mixed neutron and muon radiation field was measured by use of a recombination chamber. The procedure has been described previously (Co84; Co85; El86). Briefly, the response (current or charge, I, Measured at the anode) of a special high pressure ion chamber* is measured over its operating potential range (20-1200 volts), and is fit to the equation $I = kV^N$, where k is a constant dependent upon the chamber and the absorbed dose. Fig. 3 shows the measured response and the resultant fit. As noted previously

*Model REM-2 Chamber, Radiation Dosimetry Instrument Division, ZZUJ, "Polan," Bydgoszcz, Poland.

(Co84; Co85), the value of N from the fit is correlated with the QF. For the value of N shown, the QF based upon the power law fit in Fig. 6 of (Co85) is 1.05 ± 0.26. This can be compared to the average value of 1.42 ± 0.15 based upon the individual neutron and muon QF's shown in Table 1, weighted by the appropriate absorbed dose fractions.

3. Dosimeter and Film Badge Mesurements

The responses of self-reading pocket dosimeters[†] and the film badges[††] were determined in this radiation field, and compared to the total (both neutron and muon) absorbed dose measured with a tissue equivalent ion chamber of Fermilab design and calibration (Aw72). These chambers have a digital readout calibrated with a ^{137}Cs source to produce one logic pulse per exposure of 6.45×10^{-9} C kg^{-1} (25μR) in air. Similarly, the self-reading pocket dosimeters read out in the traditional

[†]Model 862 0-200mR Gamma and x-ray Dosimeter, Dosimeter Corporation of America, P.O. Box 42377, Cincinnati, OH 45242, USA.

[††]Model P1 Dosimeter, R.S. Landauer, Jr. & Co., 2 Science Road, Glenwood, IL 60425 USA

units of mR (1 mR = 2.58E-07 C kg^{-1} in air) and are calibrated with photons up to ^{60}Co energies for their designed use in photon radiation fields. According to Cember (Ce83), a photon exposure of one Roentgen, which corresponds to 87.6 ergs/gram in air, results in an absorbed dose of 95 ergs/gram or 9.5×10^{-3} Gy in tissue. Thus a fluence of muons producing an apparent reading of one Roentgen in the tissue equivalent ion chamber represents a tissue absorbed dose of 9.5×10^{-3} Gy. Further, since the ratio of muon stopping power in tissue (St83) to that in air (nitrogen) (Lo85) for energies between one and 800 Gev is 1.07 ± 0.05, an apparent reading of one Roentgen on the self-reading pocket dosimeter corresponds to a tissue absorbed dose of $\approx 9.5 \times 10^{-3}$ Gy as well.

Two separate dosimeter tests were conducted. For both cases eight self-reading dosimeters supported vertically (as they typically would be worn by a person) in an aluminum holder 80 mm by 140 mm were placed directly upstream of the tissue equivalent ion chamber. Film badges (three in the first test, five in the second) were attached to the same holder. The film badge package contained both x-ray, beta, gamma film and Kodak NTA emulsion wrapped together so both muon and neutron absorbed doses were determined individually. The expectation being tested is that the "gamma" film accurately records the muon absorbed dose. The dimensions of the aluminum holder are very similar to that of the ion chamber. The spatial nonuniformity of the radiation field is insignificant over these dimensions. The pocket dosimeters were read out immediately, while the film badges were sent to the vendor for prompt processing (within two weeks of the exposure) to avoid possible fading of the NTA emulsion.

The results of the tests are summarized in Table 2. Errors assigned to the pocket dosimeter and film badge values are standard deviations. Neutron absorbed doses were derived from the dose equivalents reported by the vendor by removing a quality factor of eight appropriate to the Am-Be neutron field used in the calibration of the NTA emulsion.

As seen in the Table, both the self-reading dosimeters and the film badges designed for the measurement of photon doses give reasonable results for muons. The results based on the NTA film, on the other hand, suggest that the neutron component of the total absorbed dose is a factor of 1.3 to 1.8 times larger than was determined by measurements shown in Table 1. This occurs in spite of the fact that the film should not record absorbed dose from the considerable fluence of neutrons with energies below the approximate 1 MeV threshold of NTA emulsion.

4. Conclusion

It is seen that self-reading pocket dosimeters and ordinary film badges provide an adequately accurate record of absorbed dose and dose equivalent in a muon radiation field even where the energy spectrum is not well known. Any neutron contamination of such a field, however, will complicate the dosimetry considerably. Future work on the subject of muon dosimetry should be done. At Fermilab, a beam of monoenergetic muons has recently been built and the authors hope to exploit it in extensions of this work.

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List of Table Captions

TABLE 1

Type	Fluence $m^{-2} \times 10^7$	Fluence Fraction	Absorbed Dose μGy	Absorbed Dose Fraction	Dose Equivalent μSv	Dose Equivalent Fraction	QF
Neutrons	9.12±.38	0.62	0.19±.06	0.08±.03	1.16±.31	0.34±.26	6.24±.18
Muons[a)]	5.62	0.38	2.25	0.92	2.25	0.66	1

[a)] Fluence based on singles counting rates. For fluence based upon coincidence rates, multiply by 0.75.

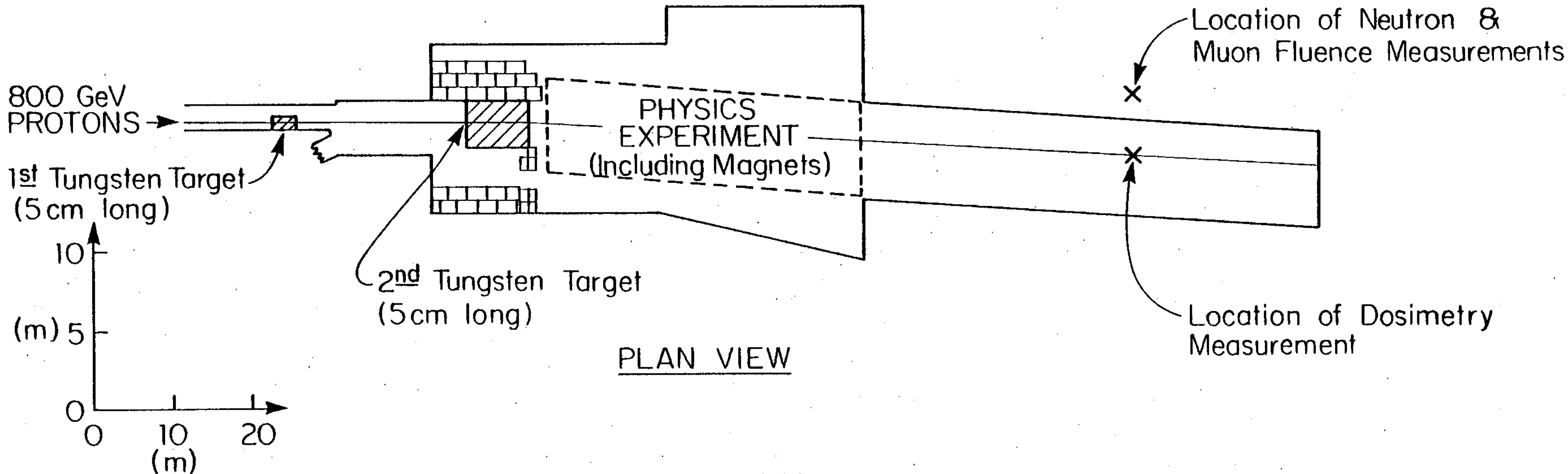
TABLE 2

	Absorbed Dose (μGy)			Normalized Absorbed Dose[a)]	
	Total	Muon	Neutron	Muon	Neutron
TEST ONE					
Ion Chamber	696	638±17[b)]	56±17[b)]	1.00	1.00
Pocket Dosimeters (8)		734±16		1.15±0.05	----
Film Badges (3)		600±100	100±38	0.94±0.16	1.72±0.90
TEST TWO					
Ion Chamber	704	644±18[b)]	56±18[b)]	1.00	1.00
Pocket Dosimeters (8)		748±20		1.16±0.05	----
Film Badges (5)		600±100	75±13	0.93±0.16	1.27±0.50

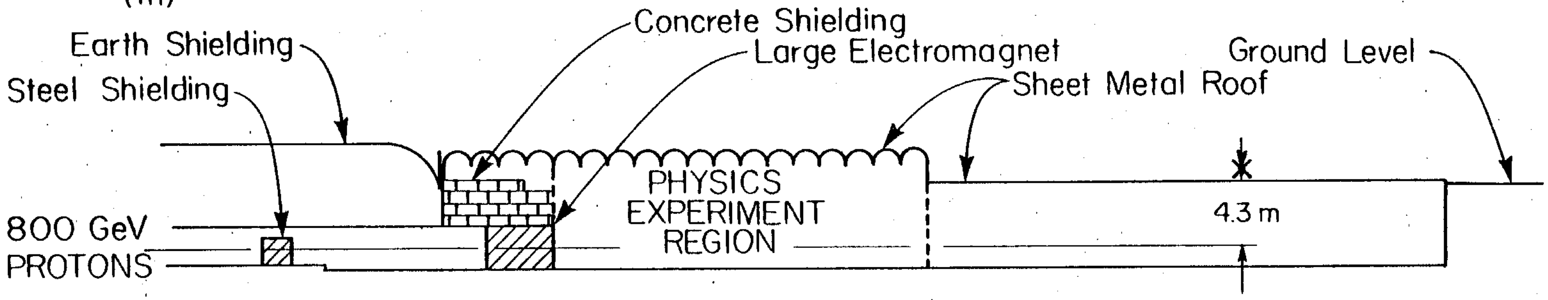
[a)]Normalized to ion-chamber values

[b)]Obtained from total obsorbed dose by use of the fractions indicated in Table 1.

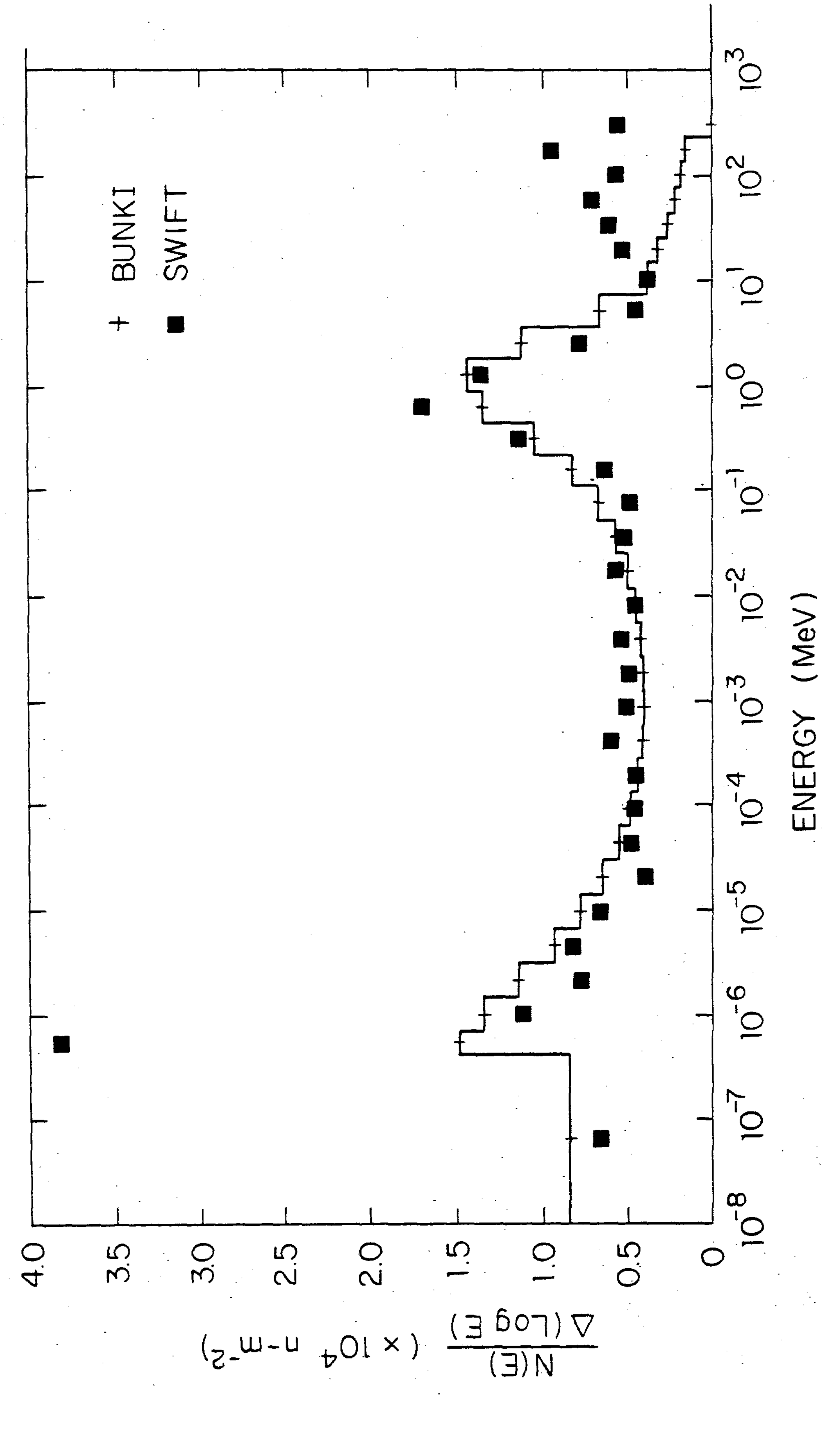
List of Figure Captions



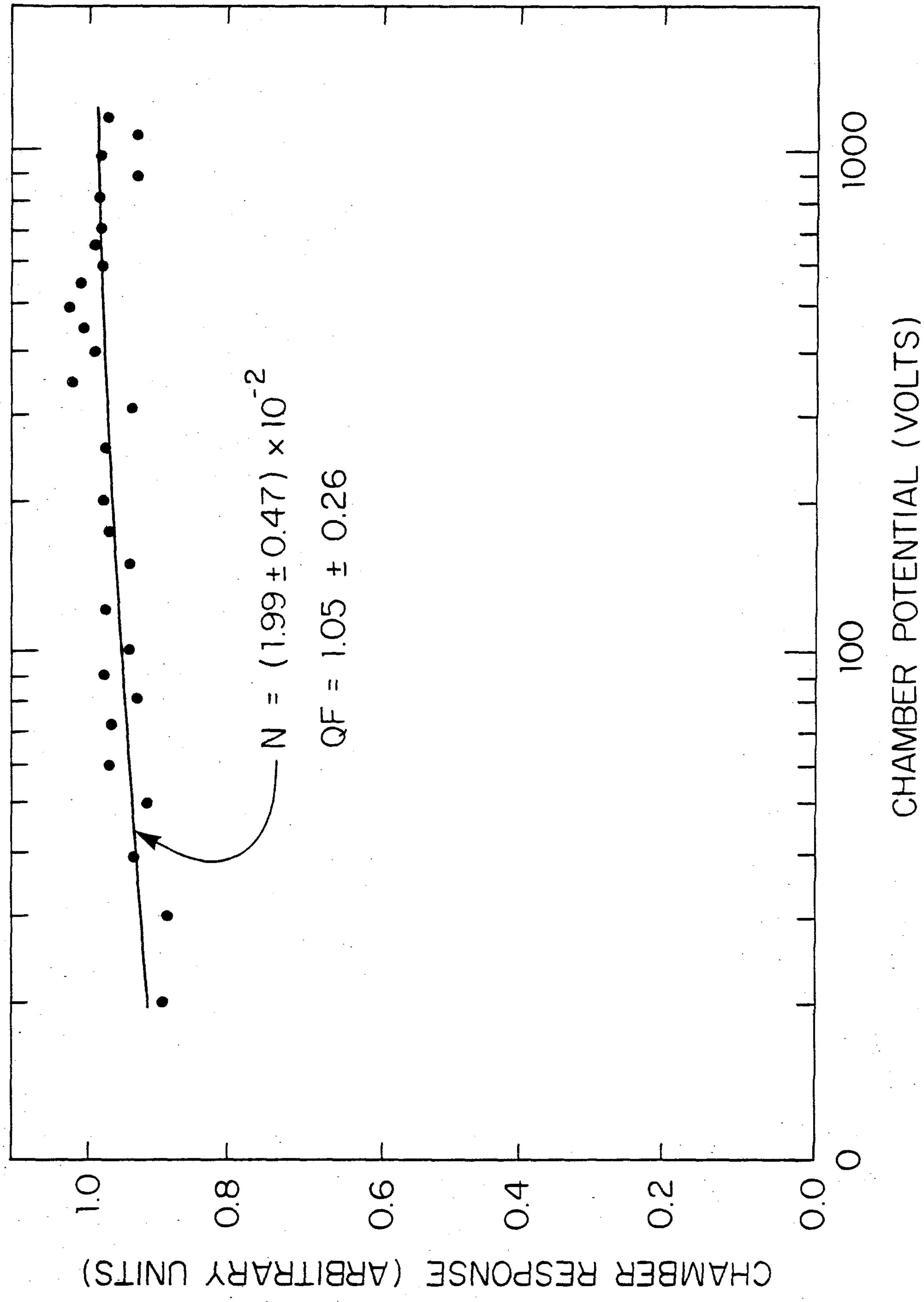
PLAN VIEW



ELEVATION VIEW IN THE PLANE OF THE BEAM



+ BUNKI
■ SWIFT
ENERGY (MeV)
N(E) / Δ(Log E) (x 10^4 n-m^-2)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3



CHAMBER RESPONSE (ARBITRARY UNITS)
0.0
0.2
0.4
0.6
0.8
1.0
0
100
1000
CHAMBER POTENTIAL (VOLTS)
N = (1.99 ± 0.47) × 10^-2
QF = 1.05 ± 0.26