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ABSTRACT

A sign-selected dichromatic neutrino beam using conventional magnets is described. The beam has a solid angle acceptance of 11.6 μsr and can focus charged hadrons up to a momentum of 170 GeV/c. The beam can be used to select either neutrinos or anti-neutrinos: when focused for neutrinos, the anti-neutrino contamination is less than .001 for neutrino momenta greater than 40 GeV/c; when the beam is focused for anti-neutrinos, the neutrino background is .01 over most of the momentum range. The beam has a provision for momentum selection which produces a dichromatic neutrino beam - a beam focused into two momentum bands.

I. INTRODUCTION

Focusing devices for neutrino beams typically have a large solid angle acceptance over a broad band of momenta and are capable of focusing most of the mesons produced at a target into a beam of small angular divergence.[1] (After focusing, this beam is allowed to drift in a long tube; the decay of mesons in this decay tube generates the neutrinos in the beam.) These focusing devices have, historically, required thin metalic sheets carrying high currents, and subsequently have required sophisticated systems for cooling, pulsing and overall operation. They have also in the past been restricted to pulsed operation and are, therefore, inadequate for operation with a slowly extracted beam. With the high proton beam energies available at NAL, however, the energetic mesons are produced at relatively small forward angles and it is possible to use conventional magnets in the focusing system for a neutrino beam. This report describes a neutrino beam with conventional magnets presently in use at NAL.

In some studies of neutrino interactions it is advantageous to know whether this interaction is produced by a neutrino or an anti-neutrino. For this purpose, a highly purified or sign-selected neutrino or anti-neutrino beam must be used. If the beam also contains momentum definition, it offers a further constraint for the experimenter. The beam described in this report is sign-selected and also dichromatic; that is, the neutrinos can be focused into two separate momentum bands. A set of dipoles is used for momentum and sign-selection, and quadrupole lenses are used to focus the beam.

II. GENERAL PROPERTIES OF THE BEAM

The typical geometry of the sign-selected dichromatic neutrino beam at NAL is shown schematically in Figure 1. The target area is a shielded enclosure that contains the target, collimators, beam stop, magnets and instrumentation for the beam. Hadrons produced at the target are focused into the evacuated decay pipe where the pions and kaons decay predominantly into muons and neutrinos. The earth shielding is of sufficient length to stop high-energy muons resulting in a relatively clean neutrino beam at the detector areas.

The crucial feature of the beam is the arrangement of the elements in the target area as shown in the insert of Figure 1. The extracted proton beam at NAL is focused at the production target. This target is made of aluminum and is twelve inches long. Its cross-sectional area is sufficiently large to guarantee that all of the incident protons interact in the target; typically, 3/8 inch wide by 1-1/2 inch high. Hadrons produced at the target are focused by the quadrupoles used here as a doublet lens; the downstream quadrupole is also used to cancel the dispersion of the dipoles. Sign-selection and momentum definition are achieved with the dipole bends and the collimators. The dipoles bend the beam vertically; the proton beam is incident on the target at an angle of 6 mrad to the horizontal; the upstream dipoles bend the beam of secondaries down 12 mrad; the downstream dipole bends the secondary beam back up 6 mrad, putting it at zero degrees to the horizontal in the decay pipe. Simultaneously, the dipoles transport the primary proton beam, after it interacts with the production target, to the beam dumps.

The beam envelope and the magnet and collimator apertures are shown in Figure 2. The secondary beam center line is coincident with the abscissa in these plots. The quadrupoles in this beam have an aperture 3 inches in diameter, the dipoles have a gap measuring 1-1/2 inches horizontally and 5 inches vertically. Because the horizontal apertures of the dipoles are severly restricting, the upstream quadrupoles are horizontally focusing to achieve a good horizontal angular acceptance. Operation of the quadrupoles as a doublet lens then requires that the downstream quadrupole focus vertically. Conveniently, this allows the downstream quadrupole to cancel the dispersion of the dipoles. Since the upstream bend is twice as strong as the downstream bend, the downstream quadrupole must focus vertically to cancel the dispersion of these bends. A summary of beam properties is given in Table I.

Special consideration must be given to dumping the primary proton beam. Figure 3 shows the proton beam center lines for various magnet currents. The secondary beam center line is assumed coincident with the abscissa in this figure. As is evident from the figure, two separate beam stops are required. The beam is stopped in the upstream dump, called the auxiliary beam dump, when the magnet polarities are set for negative particles (that is, when the beam is used as an anti-neutrino beam) or when the dipoles are turned off. Under normal operating conditions, when the beam is used for neutrinos the protons are stopped in the downstream dump called the primary beam dump. The decay products of low energy pions and kaons in the beam stop constitute a possible source of background for the sign-selected neutrino beam.

III. THE SIGN-SELECTED BEAM

Sign-selection is determined by the upstream dipoles in the beam. As an example, consider a beam of 300 GeV/c protons incident on the target, with the beam tuned for positive particles of 150 GeV/c momentum. The primary proton beam in this case will exit the upstream bend at 0° to the horizontal (see the insert to Figure 1). Positive secondaries are bent down and into the beam, while negative particles are swept up and out of the beam. In particular, negative particles with a momentum of 150 GeV/c will on average be directed upward at 18 mrad to the horizontal. Since the bend points are about 100 feet apart, particles of momentum 150 GeV/c of opposite sign would be separated by 21.6 inches at the second bend, and the negative particles are therefore well out of the beam.

If the same beam is tuned for negative particles with a momentum of 150 GeV/c, the primary proton beam exits the first bend at an upward angle of 12 mrad and positive particles of lower momentum are diverted upward at even larger angles. Particles of opposite charge are therefore well separated at the downstream bend and sign-selection is maintained.

To estimate the neutrino flux for the sign-selected beam the computer program NUADA was used.[2] The thermodynamic model was used for pion and kaon production.[3] The calculations were done for a beam of 300 GeV/c protons on target, and the secondary beam tuned to 150 GeV/c. The momentum and angle defining slits were assumed opened to full aperture. Figure 4 gives the neutrino flux, based on these calculations, for this beam as compared to a bare target beam - a beam that contains no focusing elements. Also shown are the flux of anti-neutrinos from two sources of background: (1) upstream decays of negative pions and kaons that have not been effectively swept from the beam and (2) the decays of negative pions and kaons in the beam stop. Figure 5 gives the corresponding curves for a beam tuned to anti-neutrinos.

As can be seen from these figures, the sign-selection for the neutrino beam is excellent especially at high neutrino energies. For the anti-neutrino beam the sign-selection is considerably worse because of the less desirable production spectra of negative pions and kaons. The ratio of negative to positive pions or kaons decreases drastically with increasing secondary particle energy. Nevertheless, the sign-selection is still quite good, the ratio of anti-neutrino to neutrino is greater than 100 over most of the neutrino energy range.

IV. SOURCES OF BACKGROUND

Two sources of background were mentioned in Section III; upstream decays and the decay of particles in the beam dump. To minimize the effects of upstream decays, particles produced at very large angles must be stopped as near to the target as possible. Figure 2 shows a one inch collimator just downstream of the target which serves this purpose. The calculations show that this collimator improves the sign-selection of the beam by about a factor of ten.

Since the primary proton beam tends to be aimed directly at the experimenter's detectors when it hits the beam stop, the decays of secondaries in the beam dump can be an important source of background. To minimize the effect the primary beam dump has 8 inches of tungsten on its front face. The rest of this beam stop and all of the auxiliary beam dump are made of aluminum.

Another source of background is from the interactions of the secondary beam in the decay pipe. To minimize the effect the decay pipe is evacuated to a pressure of 100 μm. The interaction of the beam with this residual air will generate only a negligible background. However, the beam must be well centered in the pipe to avoid interactions with the walls of the pipe. The beam position is monitored during operation to avoid backgrounds from this source.

Similarly, the proton beam transport from the accelerator must be carefully monitored to avoid generating backgrounds from decays upstream of the target. Beam loss monitors are used along the entire length of the proton beam to minimize scrapping and beam halo. When the proton beam is well centered in the transport system it should contribute only a negligible background to the neutrino beam.

A further background is the fraction of electron neutrinos in the beam. These are unimportant for experiments that require the identification of an energetic muon in the final state of the interaction, but is of considerable importance in experiments that search for muonless neutrino interactions. The primary source of this background is Ke_3 decays. Since the branching ratio for this decay is about 5%, the background of electron neutrinos will be at about this level. The background should be largest for high energy neutrinos which come primarily from kaon decays. Low energy neutrinos are mainly of pion parentage, and therefore, the ν_e background should be small at lower energies. A detailed calculation of the distribution of ν_e in the beam has not yet been completed.

V. MOMENTUM DEFINITION

Momentum selection is accomplished by using the angle and momentum defining slits shown in Figure 2. The vertical phase space acceptance of the beam, for several slit apertures, is given in Figure 6. As is shown in the figure, because the momentum slit is located in a dispersion free region of the beam the momentum definition of the slit is a strong function of the production angle. To block out a well defined region of place space, the angle slit must be used in addition to the momentum slit.

When the angle slit is fully open, the momentum acceptance of the beam is sufficiently large to transmit diffracted protons into the decay pipe. These particles can be a source of backgrounds in the beam if they interact with the walls of the decay pipe. Also, their flux can be sufficiently large to confuse the beam monitoring. To eliminate diffracted protons from the beam, the lower jaw of the angle slit is closed to 0.5 inches: the beam transmits 300 GeV/c protons, when tuned to 150 GeV/c, for production angles from 1.7 to 2.8 mrad.

The beam can be operated as a dichromatic neutrino beam when the angle and momentum slits are used to select a beam of hadrons of well-defined momentum in the decay pipe. The neutrino spectrum for such a beam is shown in Figure 7. The dichromatic nature of the beam is evident; the low energy peak contains neutrinos of pion parentage, while the high energy peak comes from kaon decays. The crucial feature of this spectrum is the suppression of neutrinos between the two peaks of two orders of magnitude, which is essential for neutrino experiments that use a dichromatic beam.

Three body, K_{l_3}, decays can comprise a background for the dichromatic beam and weaken the resolution between the momentum peaks. We have not made detailed calculations of this background, but estimates[4] indicate that it should not be serious.

VI. CONCLUSIONS

The beam described here has been in use for several months at NAL. It has been routinely operated with the momentum slits open; therefore, the flux curves shown in Figures 4 and 5 were pertinent for these runs. (Only the lower jaw of the angle slits were closed slightly to eliminate diffracted protons from the beam, and the upstream collimator was absent so that backgrounds from upstream decays were greater.) This mode of operation is relevant to experiments that search for new processes where momentum definition is of lesser importance than obtaining the highest possible neutrino flux. A group of physicists from the Cal. Inst. of Tech., and NAL have done an experiment of this type to search for a heavy lepton[4]. The beam has also been used as the front end of a muon beam, the properties of which are described elsewhere.[5]

The dichromatic properties of the beam have not been fully exploited to date. These should be useful for neutrino total cross-section measurements and an experiment of this type has been proposed and approved.[4]

VII. ACKNOWLEDGMENTS

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[1]Neutrino Focusing Systems -- Past, Present and Future; F. A. Nezrick et al., International Conference on Instrumentation for High Energy Physics, Dubna, 1970, Proceedings; Vol II, pp 826. See also, for example, Focusing Devices for a Neutrino Beam at NAL, Palmer R.B. (TID 25874, pp 381-9) (Brookhaven Lab, Upton, N.Y.) 1970.

[2]The computer program NUADA has been developed and modified by Dr. D.C.Carey at NAL.

[3]Particle Spectra; Grote, Hagedorn, and Ranft; CERN-Service d'Information Scientifique; December, 1970.

[4]NAL proposal E21; F. Sciulli et al., June 10, 1972.

[5]Neutrino Area Design Report - Muon Beam N1; P. Limon et al., NAL, TM429, June 1973.

TABLE I

SUMMARY OF BEAM PROPERTIES

Momentum Range of Quadrupoles for Point to Parallel Focus:		
Minimum	0	GeV/c
Maximum	170	GeV/c
Production angle	0	mr
Solid angle acceptance	11.63	μster
Angular Acceptance:		
Horizontal	±3.04	mr
Vertical	±1.22	mr
Momentum bite	Defined by collimators (see Figure 6)	
Beam Properties at End of Decay Pipe for $\Delta P/P = \pm 5\%$:		
Beam width	±8.4	Inch
Horizontal divergence	±0.55	mrad
Beam height	±3.3	Inch
Vertical divergence	±0.16	mrad
Spot Size at Target:		
Horizontal	0.070	Inch
Vertical	0.118	Inch
Beam length from target to end of decay pipe	1326.9	Feet
Magnetic Fields at 150 GeV/c:		
Dipoles	9.9	K gauss
Upstream quadrupoles	4.5	K gauss/Inch
Downstream quadrupoles	3.3	K gauss/Inch

FIGURE CAPTIONS

Figure 1 Schematic drawing of the neutrino area geometry at NAL. The insert shows the arrangement of beam elements in the target area.

Figure 2 Horizontal and vertical secondary beam envelopes. The target is at the origin of the curves. The boxes represent the apertures of the elements in the beam.

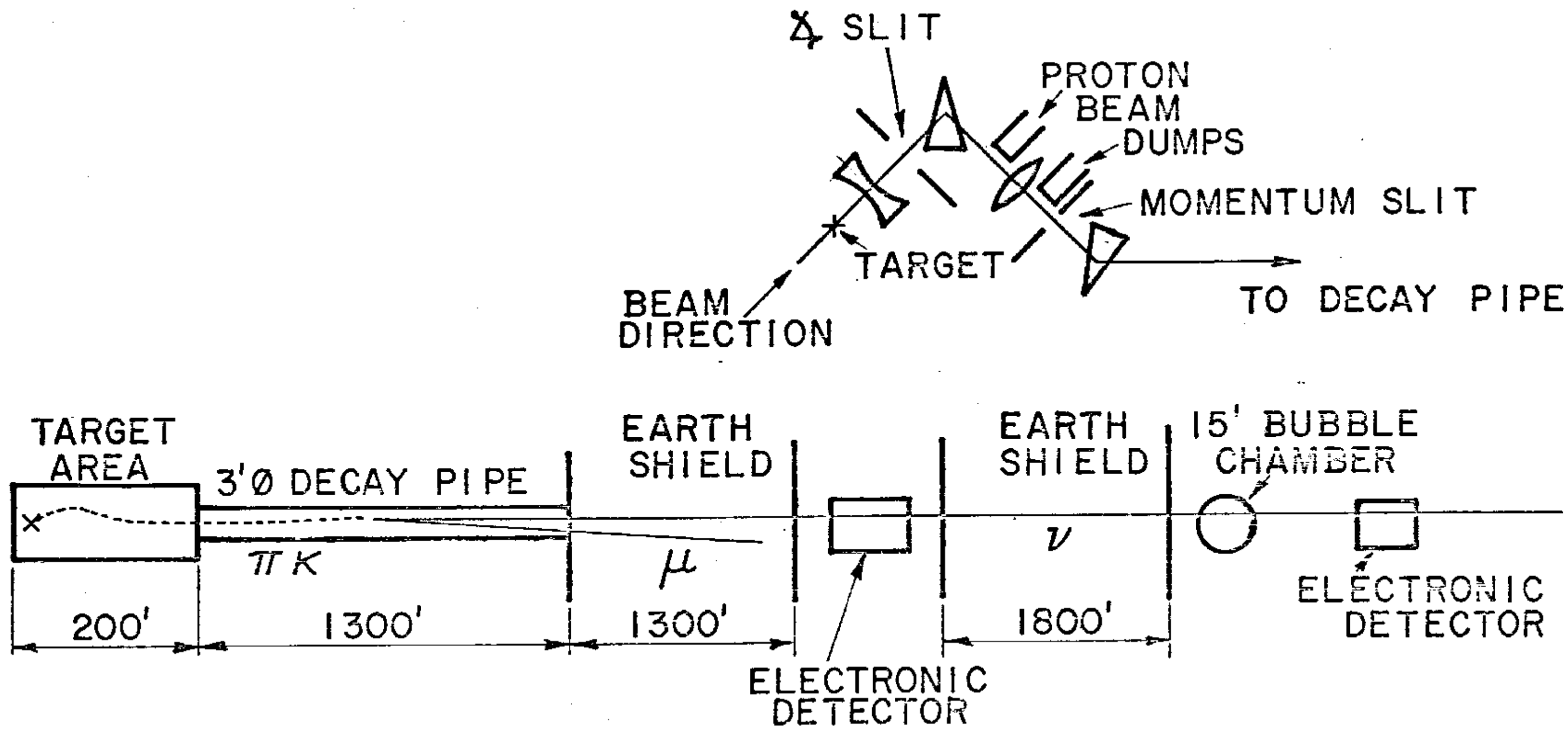
Figure 3 The trajectories of the primary proton beam for various beam tunes.

Figure 4 Neutrino flux estimates for the beam tuned to select positive particles. A bare target flux is shown for comparison. Anti-neutrino backgrounds from the upstream decays and from decays in the beam dump are also shown.

Figure 5 Anti-neutrino flux estimates for the beam tuned to select negative particles compared with the flux from a bare target. The flux of background neutrinos is also shown.

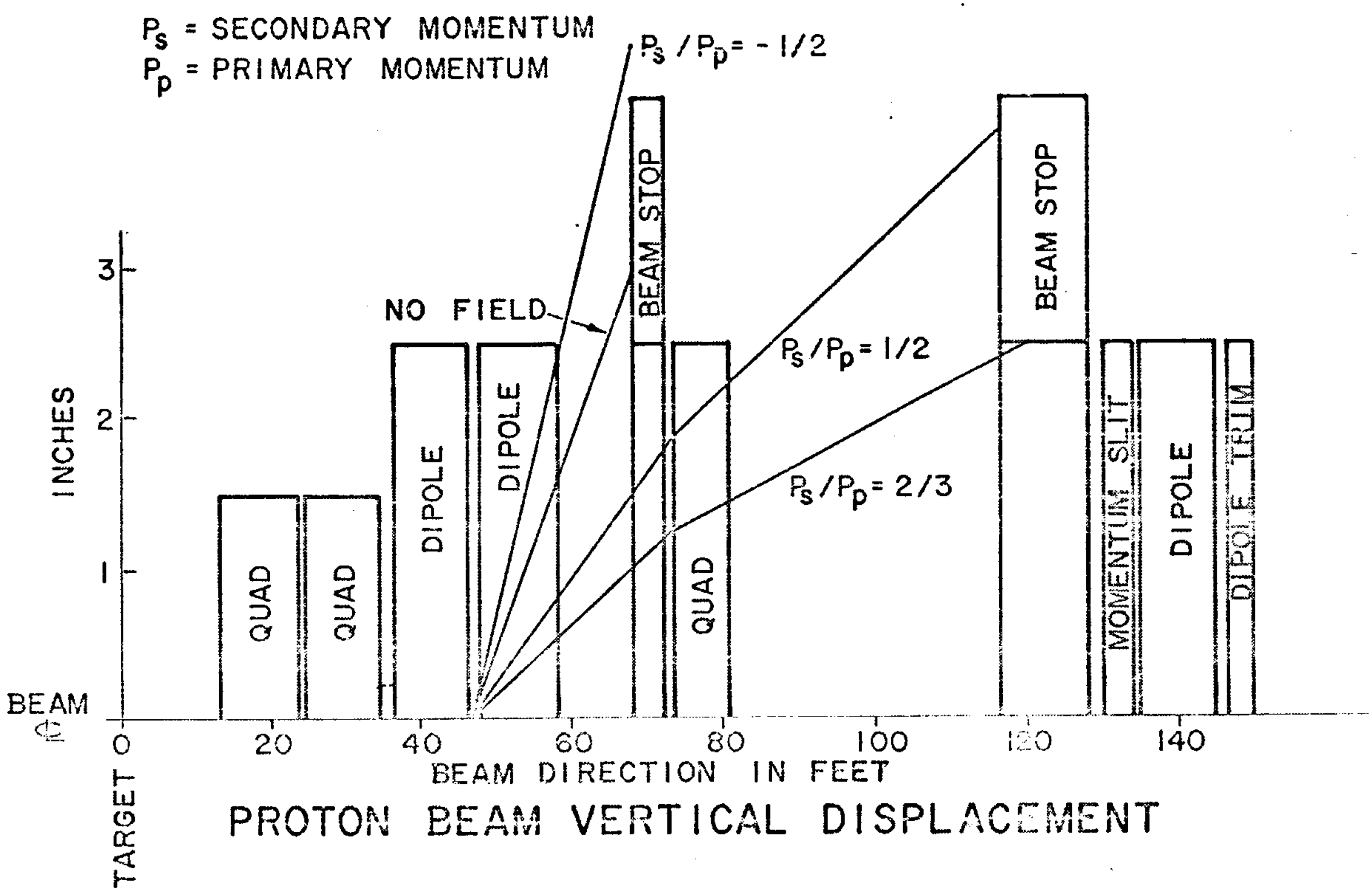
Figure 6 Phase space acceptance for charged particles transported to the end of the decay pipe for various slit apertures.

Figure 7 Neutrino flux estimate for the beam tuned as a dichromatic beam.



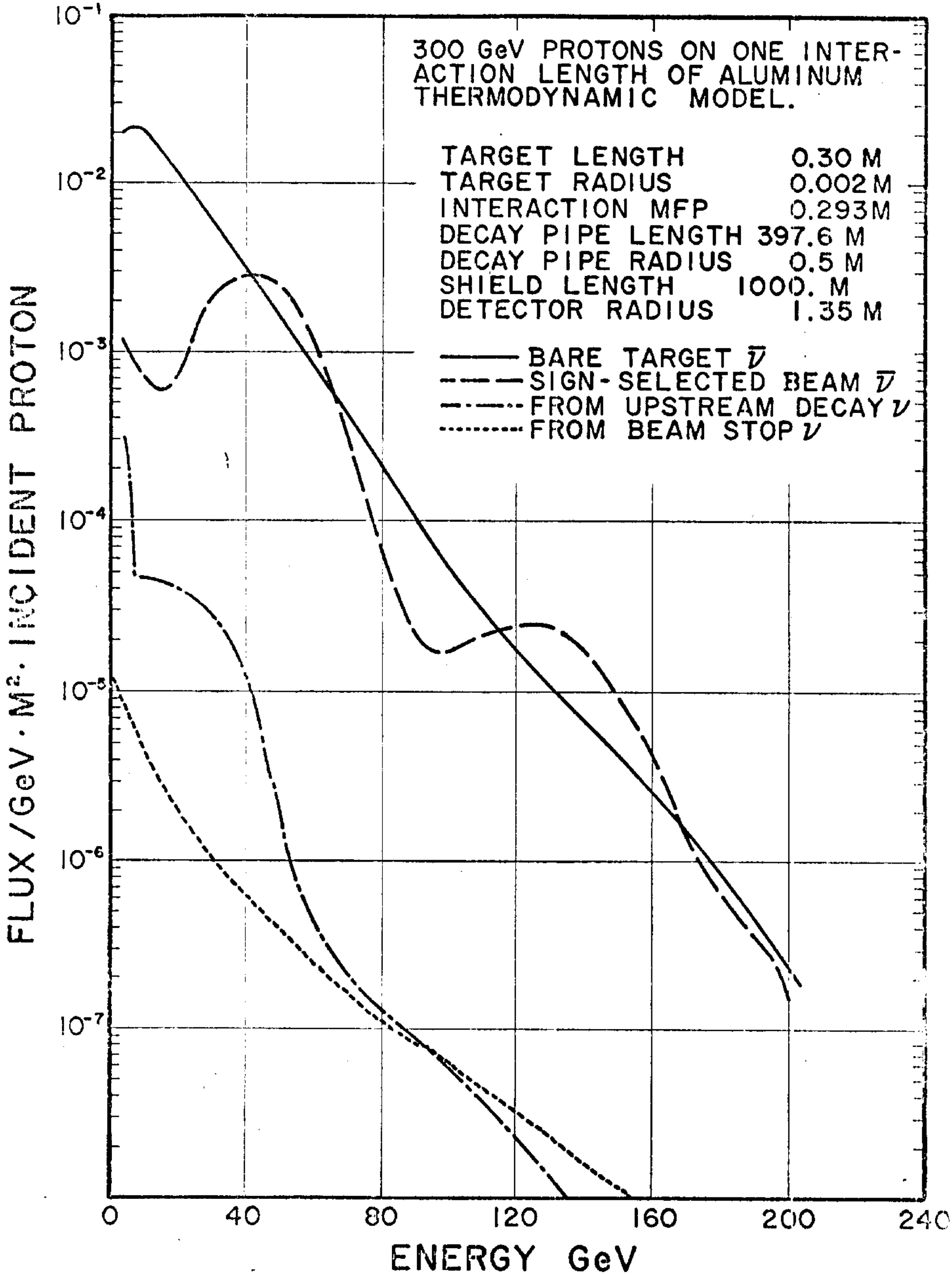
SLIT
PROTON
BEAM
DUMPS
MOMENTUM SLIT
TARGET
BEAM
DIRECTION
TO DECAY PIPE
TARGET
AREA
3'Ø DECAY PIPE
EARTH
SHIELD
EARTH
SHIELD
15' BUBBLE
CHAMBER
π K
μ
ν
200'
1300'
1300'
1800'
ELECTRONIC
DETECTOR
ELECTRONIC
DETECTOR

FIGURE 1



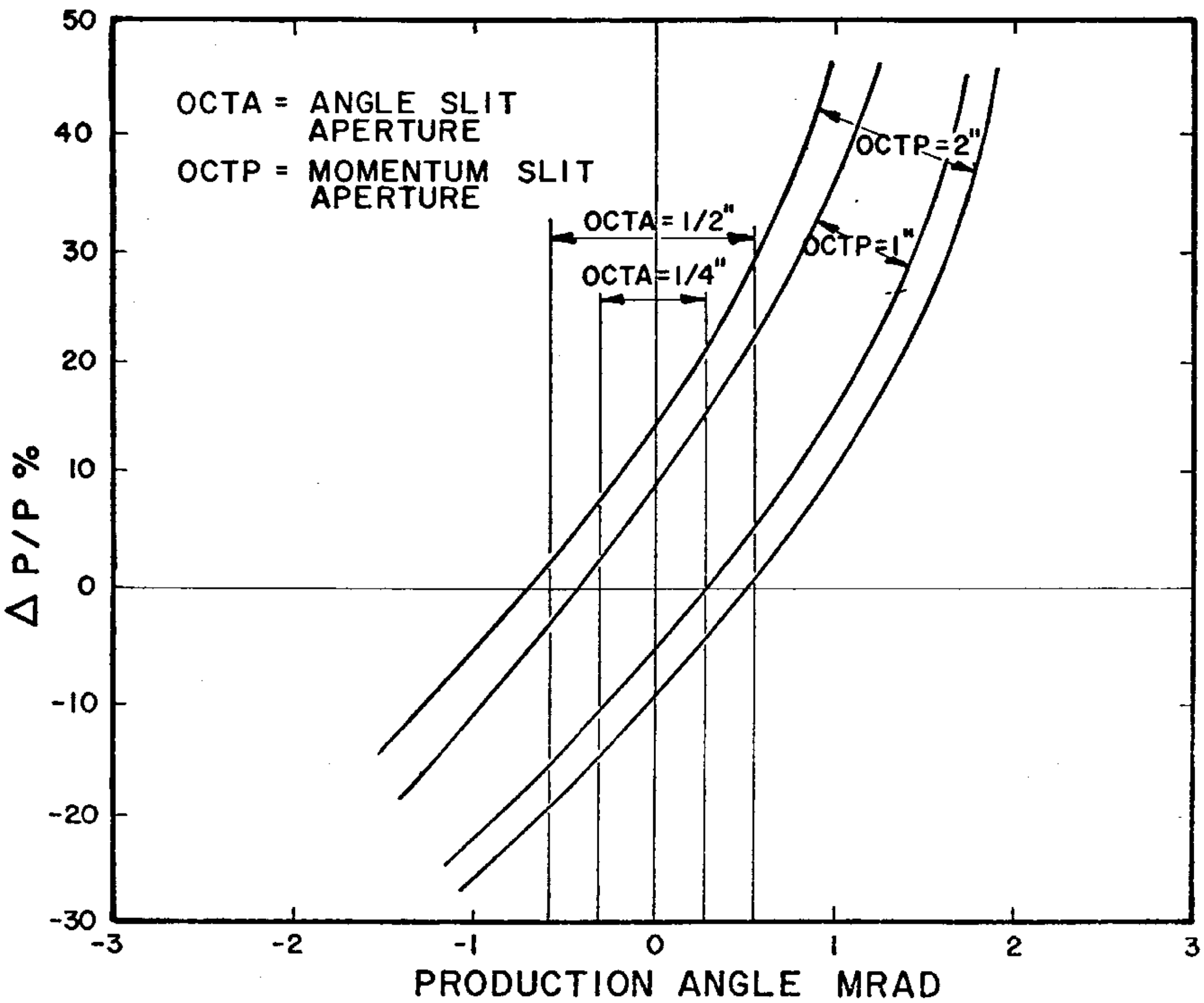
PROTON BEAM VERTICAL DISPLACEMENT

FIGURE 3



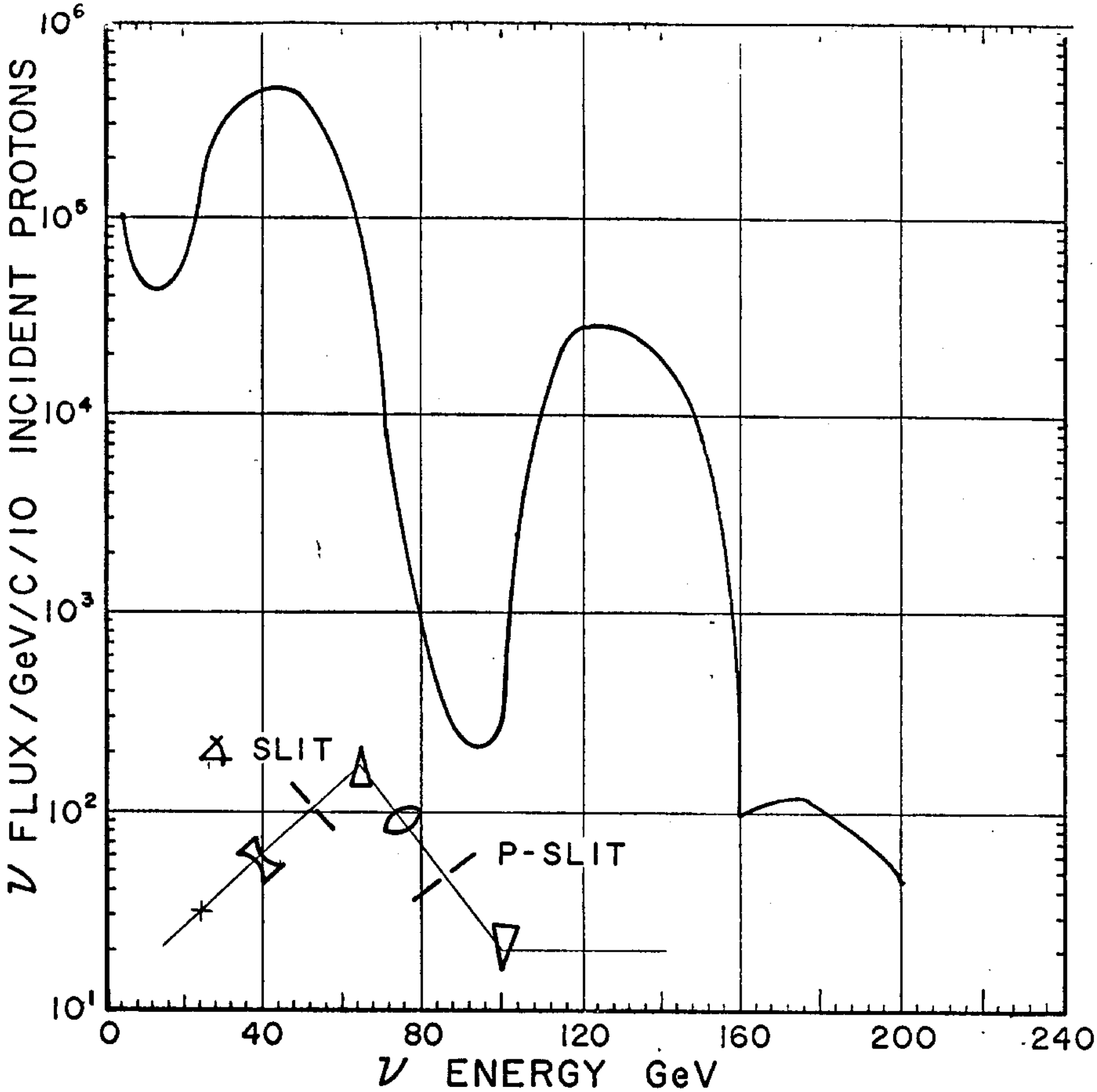
300 GeV PROTONS ON ONE INTERACTION LENGTH OF ALUMINUM THERMODYNAMIC MODEL.
TARGET LENGTH 0.30 M
TARGET RADIUS 0.002 M
INTERACTION MFP 0.293 M
DECAY PIPE LENGTH 397.6 M
DECAY PIPE RADIUS 0.5 M
SHIELD LENGTH 1000. M
DETECTOR RADIUS 1.35 M
BARE TARGET $\bar{\nu}$
SIGN-SELECTED BEAM $\bar{\nu}$
FROM UPSTREAM DECAY ν
FROM BEAM STOP ν
FLUX / GeV · M². INCIDENT PROTON
ENERGY GeV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
40
80
120
160
200
240

FIGURE 5



OCTA = ANGLE SLIT APERTURE
OCTP = MOMENTUM SLIT APERTURE
OCTA = 1/2"
OCTA = 1/4"
OCTP = 2"
OCTP = 1"
Δ P/P %
PRODUCTION ANGLE MRAD
50
40
30
20
10
0
-10
-20
-30
-3
-2
-1
0
1
2
3

FIGURE 6



300 GeV INTERACTING PROTONS HAGEDORN-RANFT PRODUCTION MODEL. BEAM TUNED TO 150 GeV

TARGET: LENGTH	.3M	DECAY PIPE: LENGTH	397.6M
INTERACTION MFP	.293M	RADIUS	.5M
FRONT RADIUS	.002M	SHIELD:	1000.0M
COLLIMATOR APERTURES:		DETECTOR RADIUS	1.35M
ANGLE SLIT	.25 IN.		
MOMENTUM SLIT	2.50 IN.		

ν_e BACKGROUND NOT INCLUDED

FIGURE 7