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BEAM HANDLING

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Before we can study beam handling, we must define the parameters of the beam emerging from the proton linac. For the Yale design these are:

(a) Beam size: 1 cm radius. The distribution of protons across the beam will depend upon the output from the ion source, but is believed to be reasonably uniform, so that no hot spots or core should develop, which would lead to burn out of targets and foils.

(b) Beam energy: 750 MeV $\pm$ 0.1%, i.e., the beam spreads to a diameter of 3.81 in. at 400 ft. after magnetic deflection through 30^{o}; $\Delta\theta = 1.2 \times 10^{-3}\ \theta$.

(c) Average current 1 mA, 30 pulses/sec, 2 msec/pulse, with a superposed rf structure of 200 Mc/sec.

(d) Angular spread of the beam: 1.2×10^{-3} rad, i.e., an additional beam width of 5.8 in. at 400 ft.

(e) Power: 750 MeV x 1 mA = 750 kW spread over π cm^2.

Originally, it was thought best to have no magnetic deflection of the proton beam from the machine.(1) It would travel down the target cave approximately 80 ft., passing through various targets, then go along a pipe another 60 to 100 ft., as shown in Fig. 1, to the stopping target. The drift pipe and shielding reduce the background. It might be necessary to use quadrupoles to contain the beam in the earlier stages.

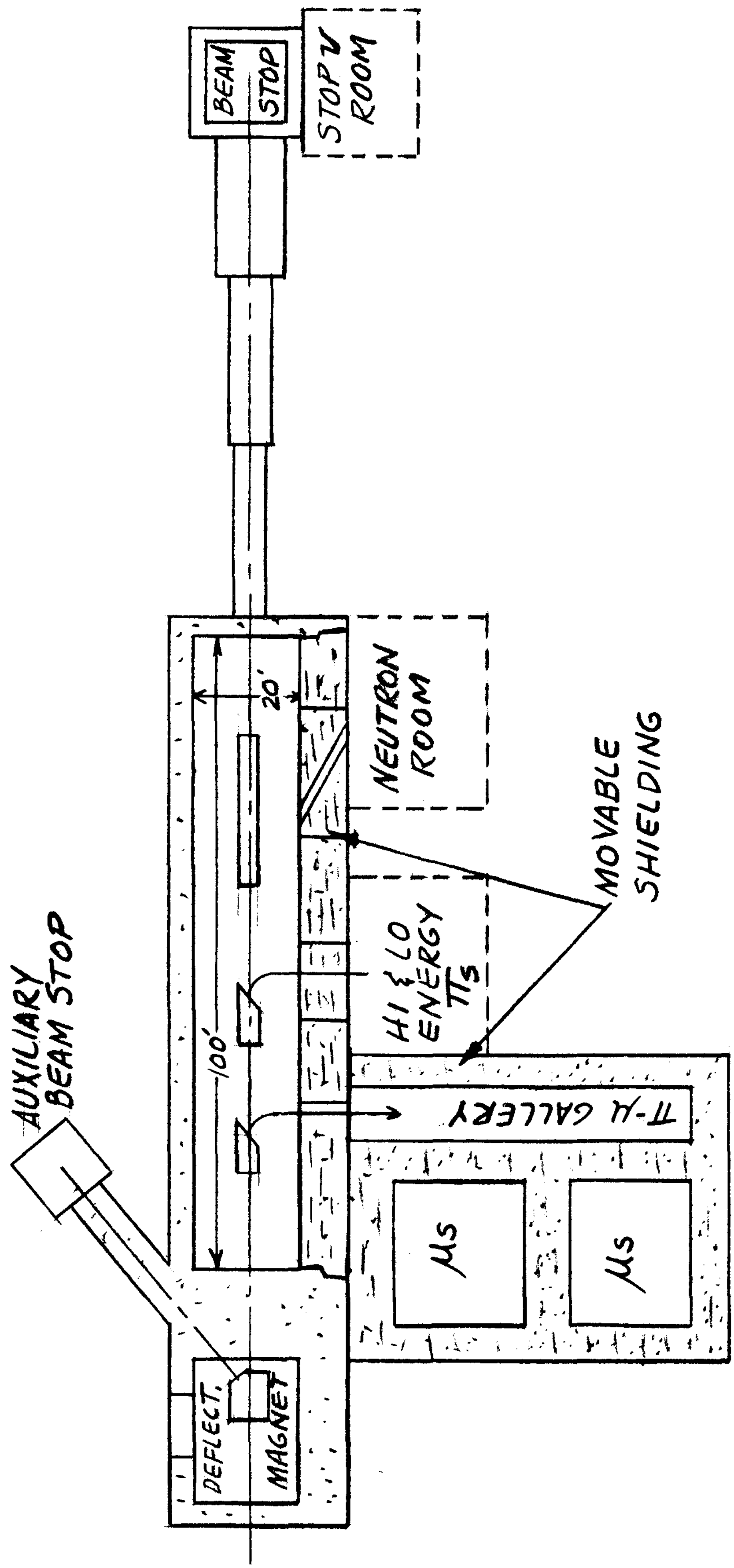

BEAM STOP
STOP ν ROOM
NEUTRON ROOM
20'
100'
MOVABLE SHIELDING
HI & LO ENERGY πs
π-μ GALLERY
μs
μs
AUXILIARY BEAM STOP
DEFLECT. MAGNET

FIG. 1

We have also considered a double target room to allow more flexibility, with the possibility of maintenance in one room while the other is in use, employing bending magnets with a radius of about 4.5 m to deflect the beam into the second chamber.

Experiments and Particle Beams

The second consideration is the type of experiment to be performed, which will in turn determine the primary target and beam characteristics.[2] The beams required for various experiments are shown in Fig. 2. These are:

(a) Proton beam.

(b) Polarized proton beam (either from scattering or a Rabi-type polarized ion source).

(c) Neutron beam.

(d) Fast π and μ beams (i) pure
(ii) poor angular and energy resolution and of wide aperture.

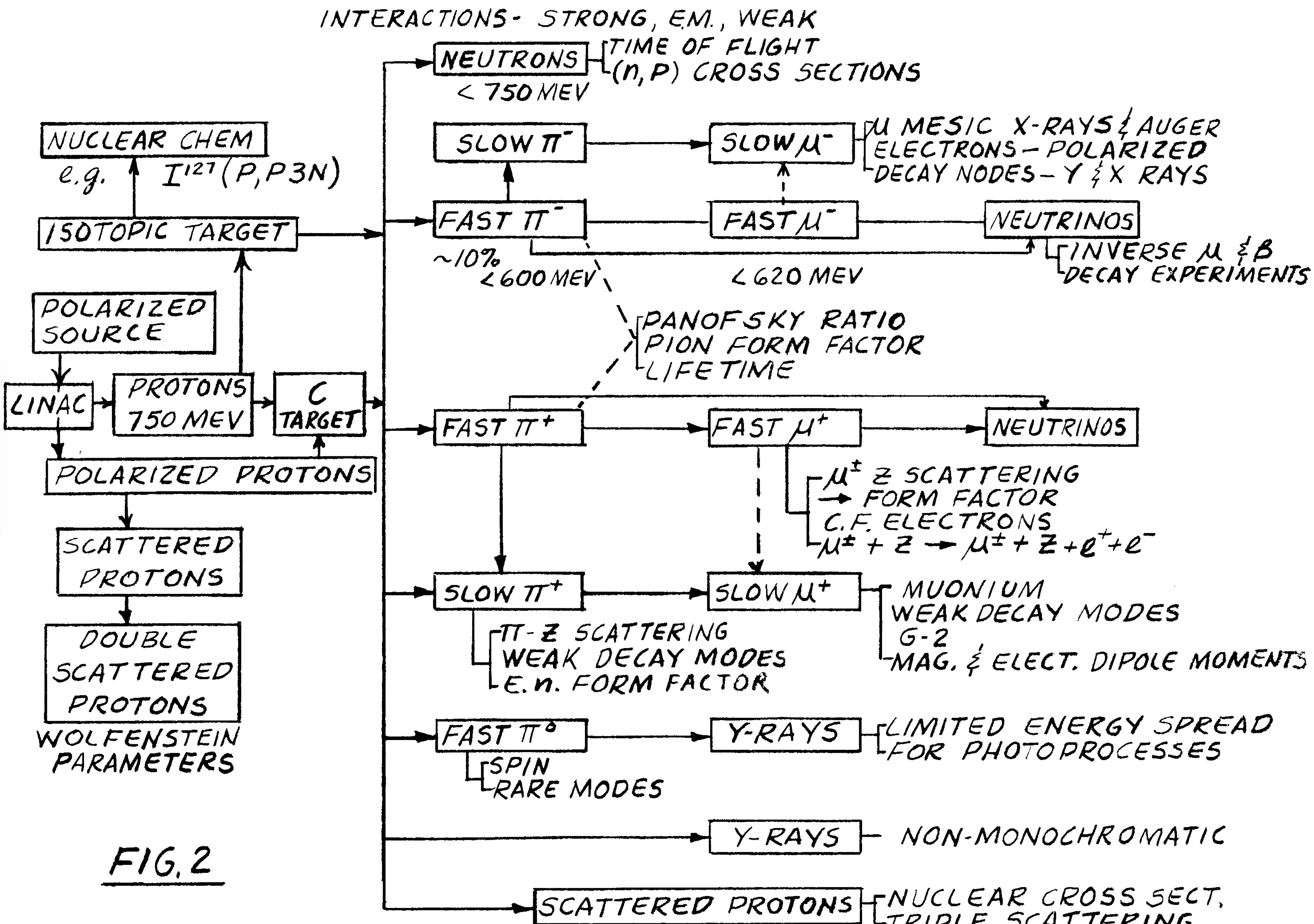
(e) Slow π and μ beams for stopping π and μ experiments.

(f) Neutrinos (i) energetic
(ii) from the stopped beam.

(g) Gamma rays (from π^o decay).

Proton Beam: The handling of the primary proton beam is described above. Direct proton scattering experiments will be performed in the target cave, where high intensity is required, or outside if only low intensity is needed.

Polarized Proton Beam: The polarized beam will be handled as above if it is obtained using a Rabi-type polarized ion



INTERACTIONS - STRONG, E.M., WEAK
NEUTRONS
TIME OF FLIGHT
(n, P) CROSS SECTIONS
< 750 MEV
NUCLEAR CHEM
e.g. $I^{127}(P, P3N)$
ISOTOPIC TARGET
SLOW π⁻
SLOW μ⁻
μ MESIC X-RAYS & AUGER
ELECTRONS – POLARIZED
DECAY NODES – γ & X RAYS
FAST π⁻
FAST μ⁻
NEUTRINOS
~10%
∠600 MEV
∠620 MEV
INVERSE μ & β
DECAY EXPERIMENTS
POLARIZED SOURCE
PANOFSKY RATIO
PION FORM FACTOR
LIFETIME
LINAC
PROTONS 750 MEV
C TARGET
FAST π⁺
FAST μ⁺
NEUTRINOS
POLARIZED PROTONS
μ± Z SCATTERING
→ FORM FACTOR
C.F. ELECTRONS
μ± + Z → μ± + Z + e⁺ + e⁻
SCATTERED PROTONS
SLOW π⁺
SLOW μ⁺
MUONIUM
WEAK DECAY MODES
G-2
MAG. & ELECT. DIPOLE MOMENTS
DOUBLE SCATTERED PROTONS
π - Z SCATTERING
WEAK DECAY MODES
E.n. FORM FACTOR
WOLFENSTEIN PARAMETERS
FAST π⁰
γ-RAYS
LIMITED ENERGY SPREAD
FOR PHOTOPROCESSES
SPIN
RARE MODES
γ-RAYS
NON-MONOCHROMATIC
SCATTERED PROTONS
NUCLEAR CROSS SECT.
TRIPLE SCATTERING

FIG. 2

source. However, polarization by scattering will require a beam transport system to bring the beam from the target chamber to the experimental room. A triplet lens system may be used to perform a momentum analysis on the scattered beam, but it is likely to be preceded by strong focussing quadrupoles to increase the acceptance angle. It should be noted that we cannot increase the phase space of the beam, so that ultimately we shall have a beam of small solid angle but large diameter, or small diameter and large solid angle, xx'yy' being a constant of the motion. Both large x or x' (or y, y') for the incident beam are, of course, bad for angular distribution experiments.

Neutron Beam: The neutron beam is transported using a series of collimating stops. In particular, if a thick target is used to produce neutrons, the collimator should be aligned with the target. Approximately 12 ft. of iron and 6 ft. of concrete should be sufficient to shield the experimental room. The collimator itself should be tapered with its apex toward the target, to reduce internal scattering, and have a magnet system at the end to clean up the neutron beam. The experimental room should preferably be 40 x 40 ft. with a neutron pit in the floor approximately 8 ft. deep to reduce backscattering. Sufficient space for time-of-flight work must be provided, since this will be a most important feature, employing the rf beam structure to give short pulses. It is necessary to deflect the proton beam immediately after it strikes the neutron-producing target, to allow the collimator to be set at sufficiently small angles.

Fast π and μ Beams: The fast π and μ beams differ in that the π separation channel should be as short as possible to reduce the chance of π decay, and the μ channel as long as possible to allow most of the π's to decay to μ's.

The nature of the π production target is determined by the experimental characteristics of (p,π) reactions.[2] These indicate that a light element should be chosen, since the π production cross section is largely a nuclear surface phenomenon. The most suitable solid light elements appear to be C or Be. However, there are many advantages to a hydrogenous liquid target, which can be used as its own coolant, so water or oil might well be used. The $p + p \rightarrow \pi^+ + d$ reaction has a sharp peak in cross section for 300 MeV π^+ mesons in the forward direction, with 750 MeV protons incident, which is of great value for experiments requiring a small momentum spread. This cross section is shown in Fig. 3.. Otherwise, the cross section shows a maximum in π yield at approximately 250 MeV.[3]

The difficulty of obtaining a suitable fast π beam from the target remains a big problem. Since the yield falls to half-value at approximately 30^o,[4] the phase space occupied by the π beam is very large, and we can only make use of a small portion of it.[5] The first part of the problem is to determine the optimum target thickness for π yield. Attenuation of the π-beam prevents the use of thick targets. Carbon targets of thickness 5 and 25 cm would attenuate a 300 MeV π beam by 20 MeV and 107 MeV, respectively.

For the high-quality π beam, only a small part of the total meson output would be employed, since resolution

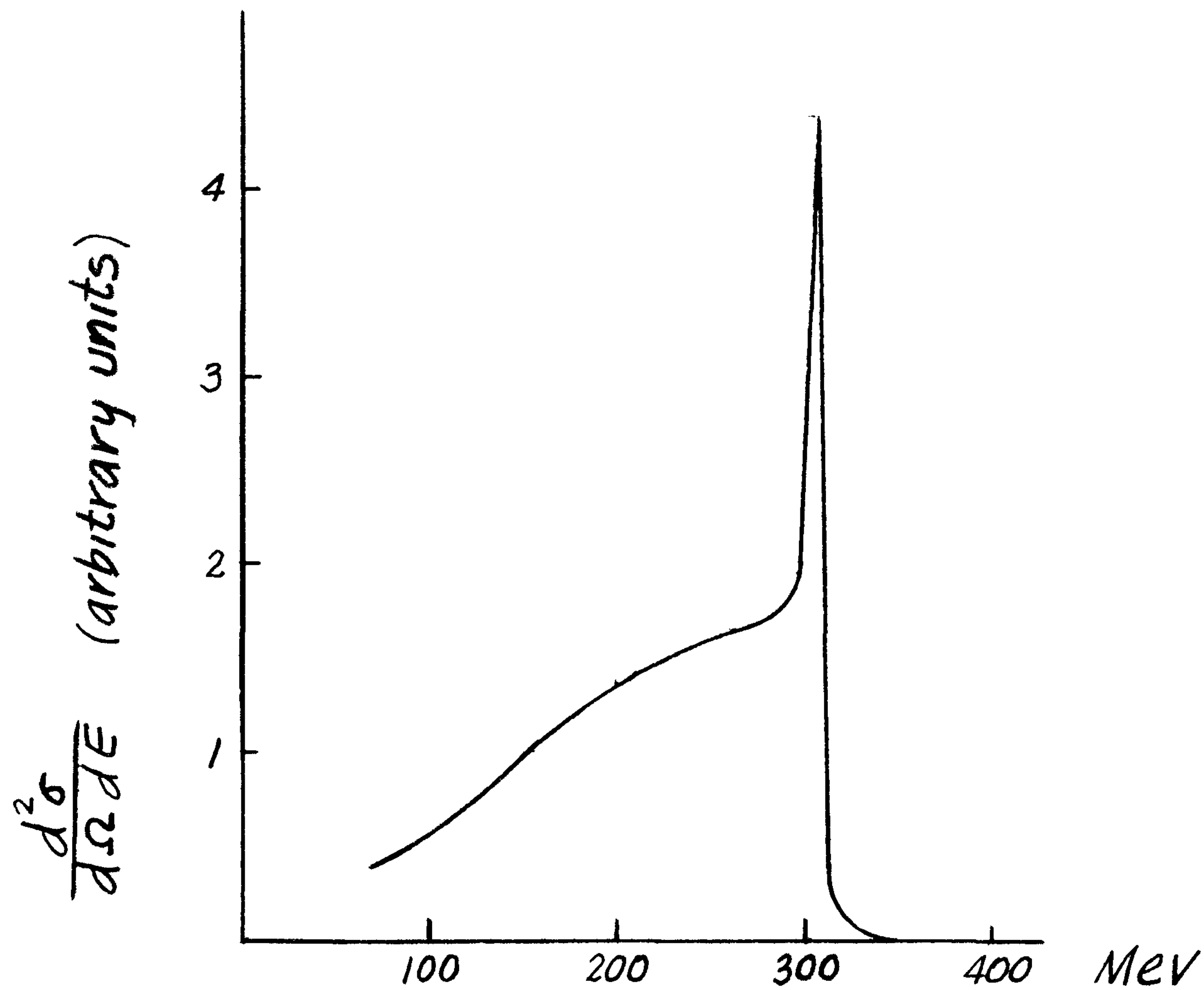


FIG.3 - ENERGY SPECTRUM OF THE POSITIVE PIONS FROM $P+P \rightarrow n+P+\pi^+$ AT AN ANGLE OF 24° IN THE LAB SYSTEM, & FOR AN INCIDENT PROTON ENERGY = 657 MEV

in both energy and angle would be required. For energies which are not too high, the ($p + p \rightarrow \pi^+ + d$) reaction, giving a high yield over a narrow energy range, would be profitable. Thus Crowe[6] et al. maximized their 310 MeV π beam at 0^o, using the 740 MeV Berkeley synchrocyclotron, by employing a 50 cm thick polyethylene target. The momentum and angular resolution of the beam are obtained by using a conventional achromatic magnetic triplet.[7-9]

Target thicknesses may be increased, if the π beam can be drawn off at a small angle, thus reducing the attenuation of π energy in the target, as shown in Fig. 4.

The low quality π beam would be produced in the same way. Quadrupoles of large aperture might be employed to draw off the beam, if a very large density of low quality π's is required. A diagram of such a device, similar to an orange spectrometer, using a toroid of aluminum with steel disks, is shown in Fig. 5. The particles intersecting the toroid are brought to a very broad focus at some point on the axis, where they enter a quadrupole of large aperture. These magnet systems should be shielded from the target to avoid radiation deterioration of the windings.

The fast μ beam will be provided by a quadrupole channel similar to the one at CERN[11] or the University of Chicago. The principle of the CERN device is shown in Fig. 6. The μ momentum ranges from 0.555 to 1.01 of the π momentum for 400 MeV/c π mesons, and has a maximum angle of emission of approximately 5.67^o. The system is divided into three parts. An analyzing magnet is used to select a π momentum range, and to compress as many π's corresponding

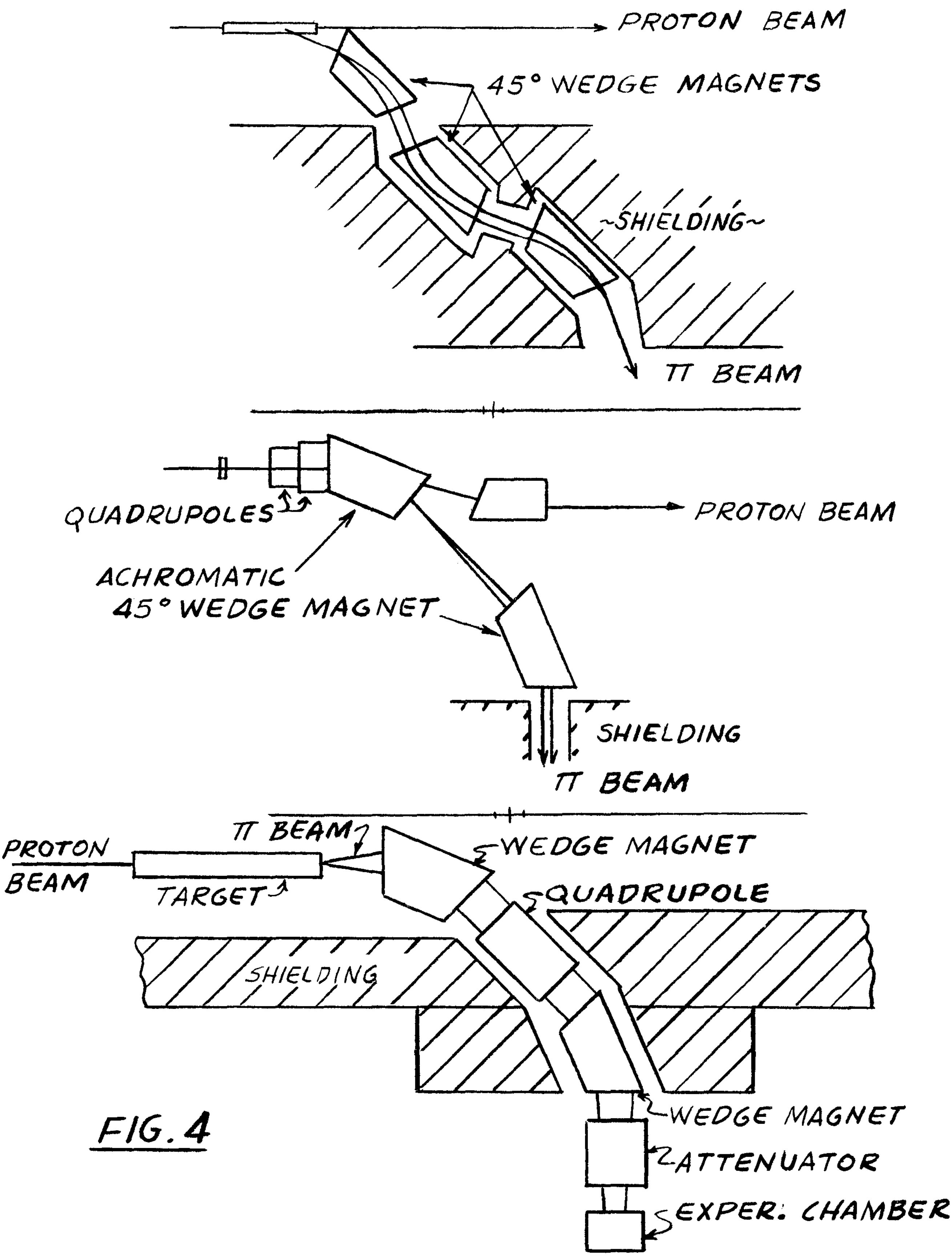

PROTON BEAM
45° WEDGE MAGNETS
~SHIELDING~
π BEAM
QUADRUPOLES
PROTON BEAM
ACHROMATIC
45° WEDGE MAGNET
SHIELDING
π BEAM
π BEAM
PROTON
BEAM
TARGET
WEDGE MAGNET
QUADRUPOLE
SHIELDING
WEDGE MAGNET
ATTENUATOR
EXPER. CHAMBER

FIG. 4

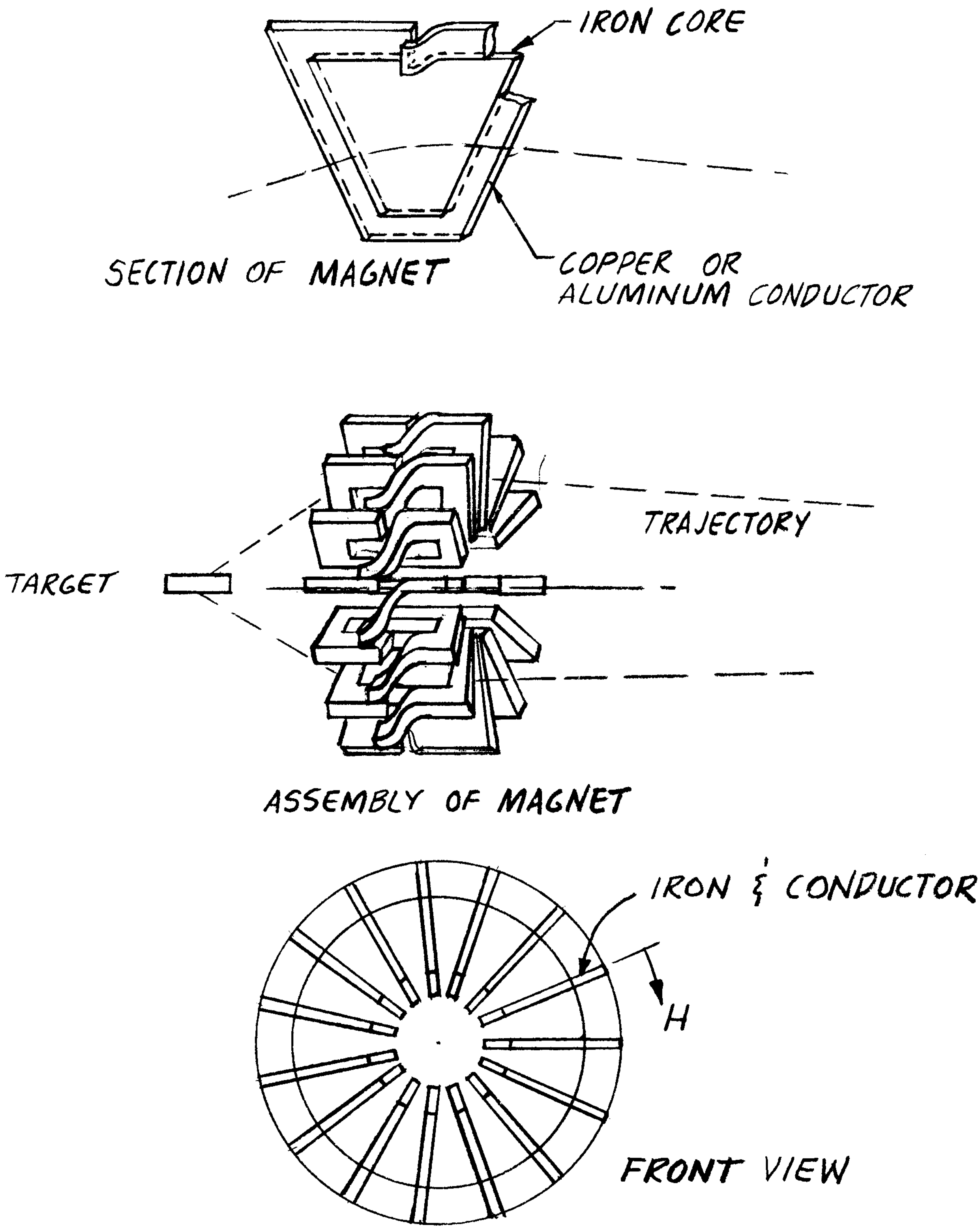
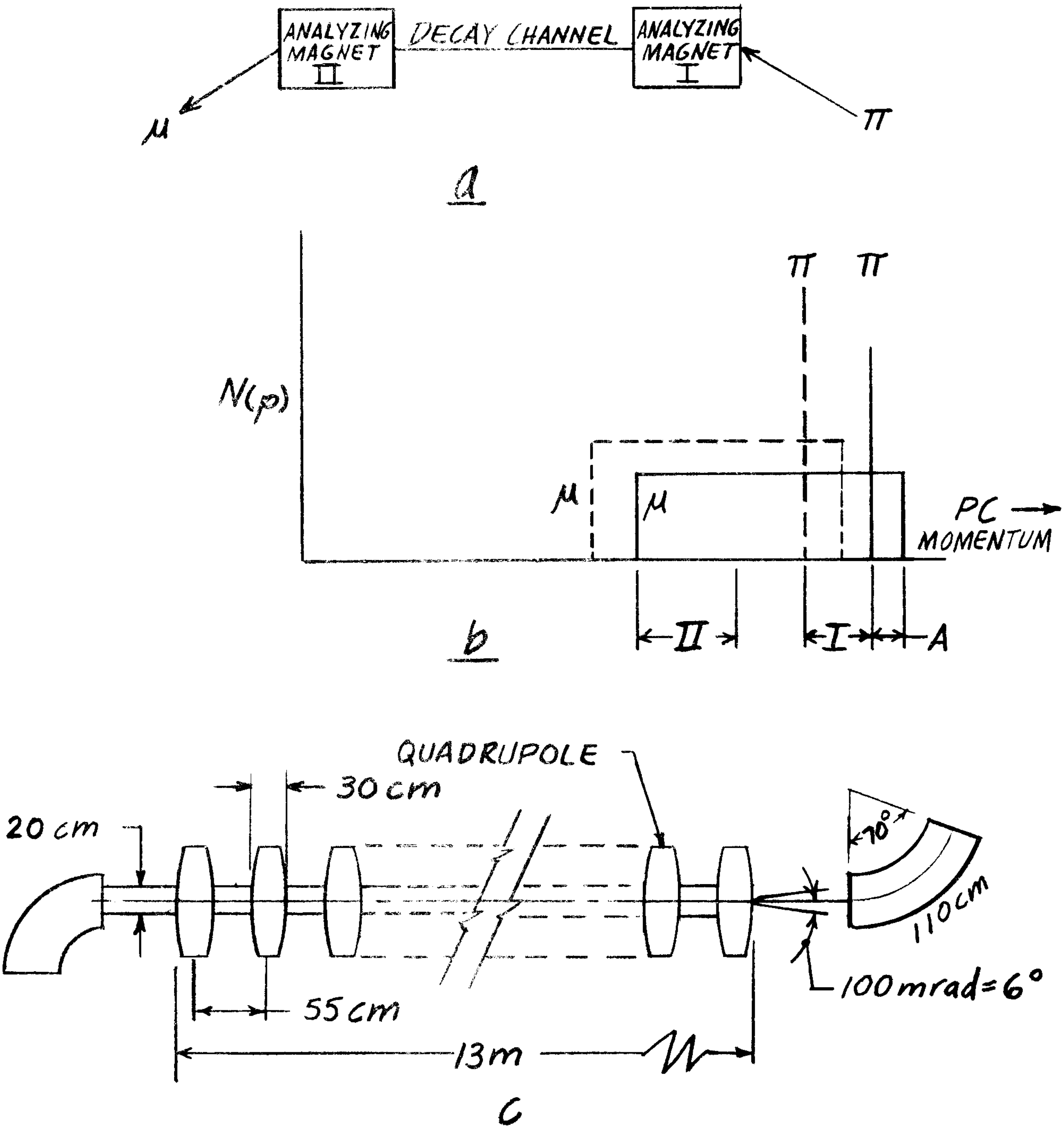


FIG. 5 - LARGE ANGLE, LOW QUALITY, FOCUSSING DEVICE (DIAGRAMMATIC)

to Range I (Fig. 6b) into the quadrupole channel, which consists of closely spaced (55 cm) quadrupoles, having a maximum gradient of 1 kG/cm, and an aperture radius of 10 cm, being about 65 ft. long in all. This is designed to accept a large proportion of the μ's into which the π's decay, and, on emerging from the channel, a second analyzing magnet separates the μ's of low energy (Range II of Fig. 6b), as shown. With these will be mixed some scattered π's. Since the object of this device is a pure μ beam, this contamination is unwanted, but can only be eliminated by separating the high energy μ's (region A), into which only a very few π's decay. The length of the channel is designed for 400 MeV/c μ's. It could not profitably be increased more than 25 to 30%. If there is no objection to a contaminated beam, a gain in intensity can be obtained by sacrificing the analyzing magnets.

Stopping π's: A stopping π intensity can be obtained by degrading the fast π beam with a block of suitable attenuator. However, here quite a different phase space problem exists. We do not require the maximum number of π's in a given interval of momentum or angle, but maximum π density stopping in a given volume of the detector. The same is true for the stopping μ beam. Hence, we have to consider the straggling in the energy degrader, as well as beam spread. It is not clear what the best system would be, but it may be preferable to transport π's at energies of 100 MeV or more because of π decay-in-transit, and because of the large number of π's produced at this energy. A comparatively thick proton target can be used and a suitable quadrupole and sector magnet system employed to



ANALYZING MAGNET II
DECAY CHANNEL
ANALYZING MAGNET I
μ
π
a
N(p)
π π
μ
μ
PC →
MOMENTUM
II
I
A
b
QUADRUPOLE
30 cm
20 cm
70°
110 cm
100 mrad = 6°
55 cm
13 m
c

FIG. 6

transport and focus the π's onto the detector with its accompanying attenuator (Fig. 4).

Density is the criterion for the stopping μ's, and this involves transporting them at approximately 40 MeV. Either a quadrupole or solenoid channel may be used at these low energies, followed by an analyzing magnet and energy attenuating material to reduce the μ energy to the point where mesons stop in the experimental chamber.

Neutrino Beam: The neutrinos from the fast π mesons from the target are emitted in a forward cone. For 200 MeV π mesons, 50% of the neutrinos lie within a cone with approximately a 30° half angle from the direction of the π mesons, and the angular intensity for emission of π mesons from the proton target falls to half value at about 30°. The π meson beam may be concentrated by a neutrino horn, either of the form used by CERN, shown in Fig. 7, or of the form shown in Fig. 5. However, the neutrinos cannot be deflected, so the average angle of emission will never be much less than 35°. Hence, detectors of large area would be experimentally most suitable. The energy distribution of neutrinos against π energy is also shown in Fig. 7.

When the proton beam is stopped, neutrinos arise from the following reactions:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \ , \ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \ , \ \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

$$\mu^- \text{ nuclear capture} \rightarrow \nu_\mu .$$

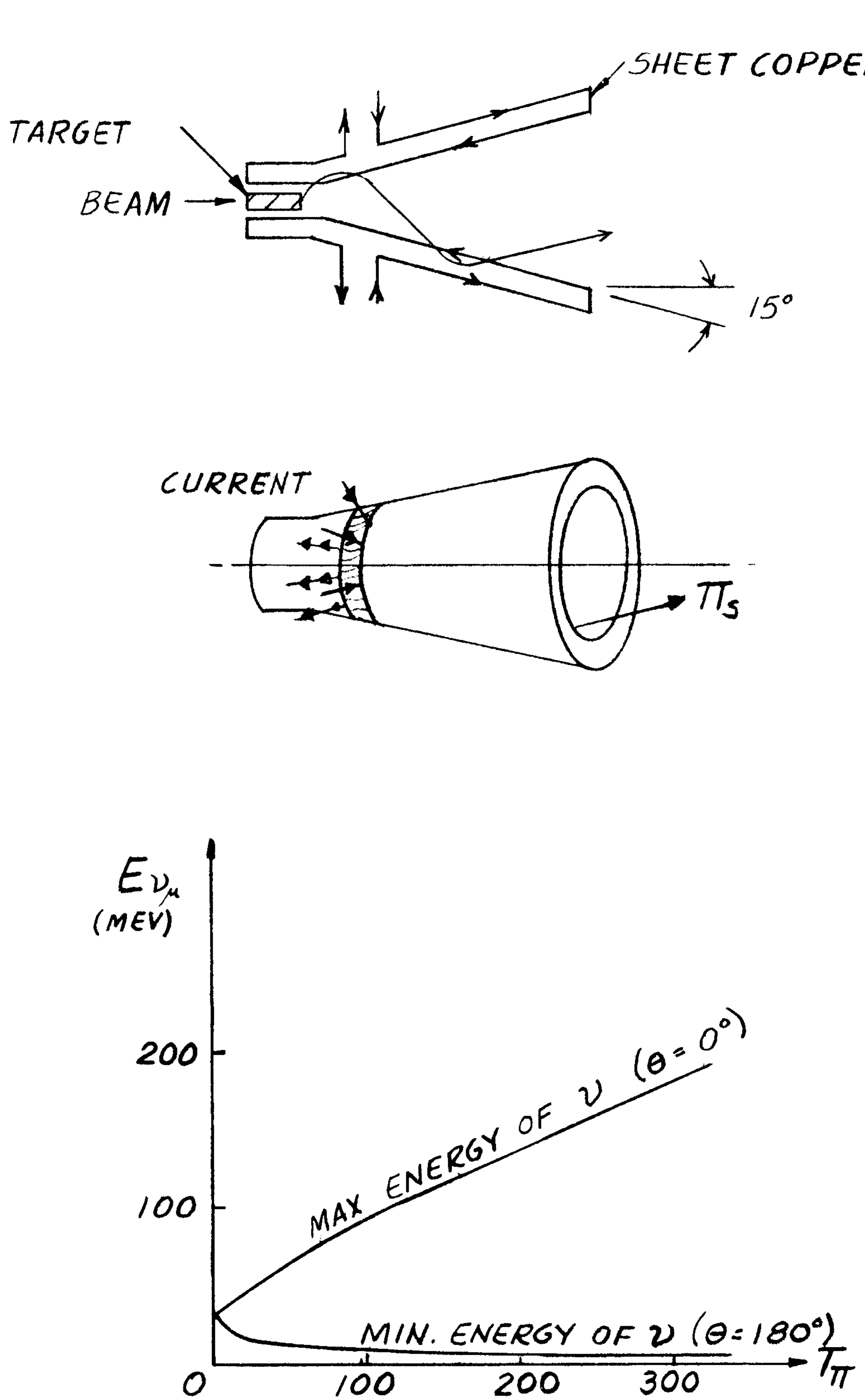

SHEET COPPER
TARGET
BEAM
15°
CURRENT
π_s
E_{ν_μ} (MEV)
200
100
MAX ENERGY OF ν (θ = 0°)
MIN. ENERGY OF ν (θ = 180°)
0
100
200
300
T_π

FIG. 7

The stopped proton-neutrino distribution has been given by Uberall.[12] His curves are normalized so that the area under each is the same. Very few slow μ^- mesons are produced because of the strong interaction of the π^- with the nucleus. The angular distribution is roughly isotropic.

If use is to be made of this neutrino yield, a dense stopping target might be employed with the experimental apparatus outside the shielding wall.

The π_o decays into two gamma rays in 10^{-16} sec ($\sim 10^{-6}$ in.). By selecting a suitable angle, it is possible to obtain a gamma ray beam which has fractional energy spread of the same order as that of the π^o's. Such a beam would be of value for photonuclear processes.

Estimates of the various yields are given in Table I.

Stopping Target: The design of the stopping target presents several problems[2] (Fig. 8). The radiation in the neighborhood of the target will amount to several hundred roentgens per hour, and 750 kW must be dissipated. The natural angular spread of the beam, together with Coulomb scattering in the stopping target will spread the beam to about 18 in. In order to provide for Coulomb scattering in previous targets, the stopping target should be a water tank at least 3 ft. in diameter and 7 ft. long i.e., 380 gallons. To accommodate diffraction scattering by previous targets, which would have an angular spread of a few degrees, an even wider stopping target might be employed. The container walls will probably be of aluminum, to avoid long period activity (such as, for example, is induced in stainless steel) and surrounded by a large water bath, to absorb neutrons with a minimum of extraneous activity. The water

TABLE I

Beam	Intensity No./Sec	No. Per r.f. Pulse	Time Spread To Go 10 m(ns)
Primary p	6×10^{15}	6×10^{7}	0.1
Gamma ray			
Fast π^{+} (quality)	$6\text{-}12 \times 10^{7}$	.6 - 1.2	0.1
Fast π^{-} (quality)	$8\text{-}16 \times 10^{6}$	.08 - .16	0.1
Fast π^{+} (low quality)	$2\text{-}5 \times 10^{10}$	200 - 500	0.48
Fast π^{-} (low quality)	$3\text{-}5 \times 10^{9}$	30 - 50	0.48
Fast μ^{+} (pure)	$1\text{-}5 \times 10^{8}$	1 - 5	0.19
Fast μ^{-}	$2\text{-}7 \times 10^{7}$	.2 - .7	0.19
Very fast μ^{+}	4×10^{7}	.4	
Very fast μ^{-}	5×10^{6}	.05	
Stopped π^{+}	4×10^{8}	4	
Stopped π^{-}	7×10^{7}	.7	
Stopped μ^{+}	5×10^{7}	.5	
Stopped μ^{-}	6×10^{6}	.06	
Scattered polarized protons	6×10^{12}	6×10^{4}	
Neutrons	1×10^{9}	10	
High Energy ν_{μ}	$\sim 10^{11}$	$\sim 10^{3}$	
$\bar{\nu}_{\mu}$	$\sim 10^{10}$	~ 100	
Low Energy ν_{μ} $\bar{\nu}_{\mu}$ ν_{e}	$\sim 10^{12}$ each	$\sim 10^{4}$	

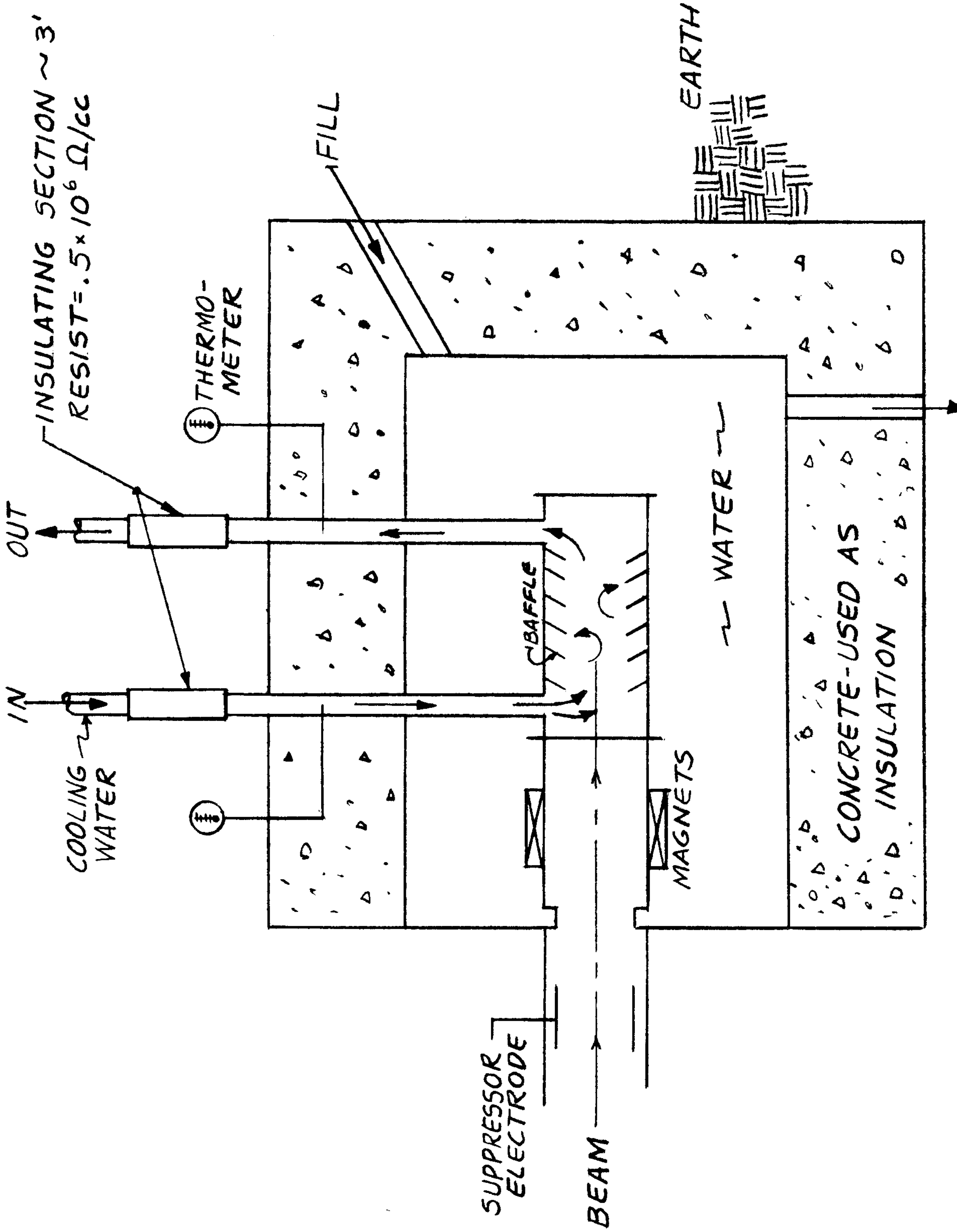


FIG. 8 - STOPPING TARGET

may easily be drained off for purification or replenishment. Outside this, a shield of approximately 40 ft. of concrete (or its earth equivalent) will be required. The stopping target should be capable of being used as a Faraday cup. The difficulty here is that of insulation, since the high radiation field would cause insulators to deteriorate rapidly.

Beam Monitoring

Of the absolute methods, the Faraday cup and calorimetric methods require mention. The difference between high energy and low energy Faraday cups lies in the size, which must be large enough to stop the beam and charged secondaries, and also in that the insulation must be such that it is unaffected by ionization from escaping gamma rays or neutrons.[13] The other points to be considered are the same for both low and high energy beams. The cup must be strongly re-entrant to prevent backscatter, a potential bias must be provided to prevent low energy electrons escaping, and a magnet is required to bend back the high energy secondaries.

The calorimetric method measures the rise in temperature of the cooling water. With such a large volume and rapid circulation of the water in our system this method might well prove the most accurate, since the heat would remain in the water, and not be lost by conduction or radiation.

Foils may be activated by the beam. Carbon is often used employing the reaction C^{12} (p, pn) C^{11} (half life 20.5 min.). Provided the foils are counted by some absolute counting method, and we assume the value of the reaction cross section, which is well known, this is as accurate as an absolute method of beam measurement. The proton energy must be known reasonably accurately for this method, but the method is commended by its simplicity.

The secondary electron emission monitor is an accurate relative method which has been developed at Stanford for use with intense electron beams. This consists of two interleaved sets of ten aluminum foils, 1.7 mg/cm^2, one set at ground potential and the other held at a few hundred volts. The secondary electrons produced by a charged particle beam passing through the foils gives rise to a measurable current, which is independent of beam energy from a few MeV upward.

Beam induction electrodes are very useful in steering the beam. The electrodes act as plates in a capacitor on which the beam, passing close to the surface, induces an alternating charge. The system is strongly sensitive to beam position and can be used to determine where to steer the beam.

Induction monitors are in common use with electron linacs. The beam passes through a ferrite ring which acts as the core of a transformer. The ac voltage across the secondary wound on the ring is a measure of the beam current. This method is independent of beam position. As with all similar beam detectors, radiation protection for the instrument is required.

For the low-intensity meson beams coming from the target, it may be profitable to use integrating Čerenkov or phosphor-photomultiplier setups. Such devices are not affected by the rf beam structure as would be particle counters of short resolving time. Great care must be taken to collect all the light from the phosphor.

Single Pulse Beam Deflection

For injection into circular accelerators, or bubble and cloud chambers, one pulse of protons every one or two seconds may be required. To provide this, a pulsed magnet must be used which will remove one proton pulse per second, and allow the remainder to go by for other experiments (see Fig. 9). Since most of the energy required for the pulse goes into the field, a laminated steel magnet must be used, where the field energy is located in the space between the pole tips. For the Yale design linac, the magnet must rise to its peak field in about 15 msec, remain flat for anything from a few microseconds to 2 msec, then decay in 15 msec.

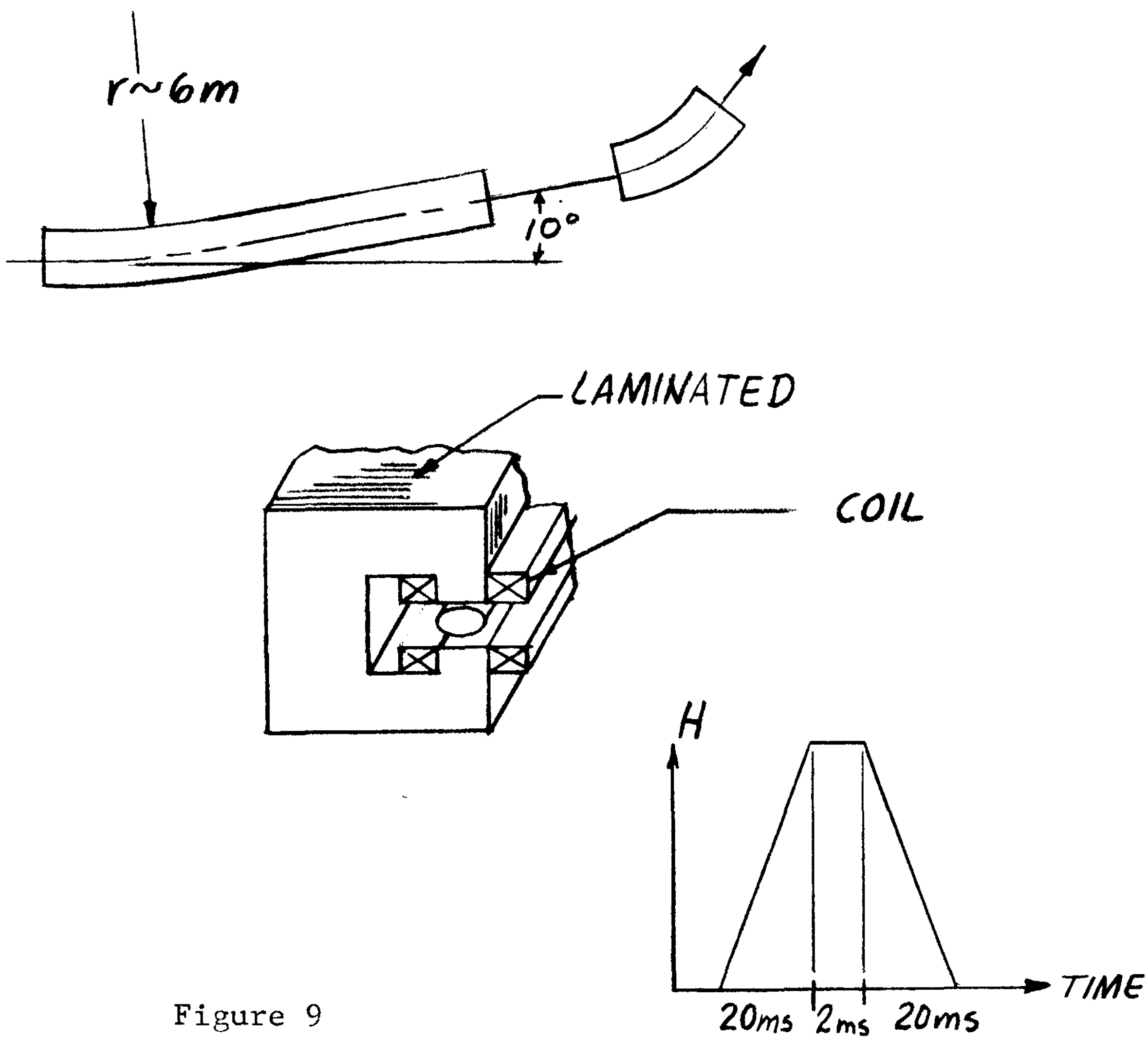


Figure 9

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