FERMILAB Proposal No. 420

Scientific Spokesman: Z.G.T. Guiragossián
High Energy Physics Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California 94305
Telephone: (415) 497-0133

FERMILAB PROPOSAL

FOR

HIGH PRECISION STUDIES OF DEEP SCATTERING PHENOMENA

FROM PROTONS, PIONS, ELECTRONS AND GAMMA-RAYS ON HYDROGEN AND DEUTERIUM

Submitted by

G. Conger, J. Edighoffer, A. Grigorian,

Z.G.T. Guiragossián, R. Hofstadter and M. R. Yearian

The W. W. Hansen High Energy Physics Laboratory and Department of Physics
Stanford University, Stanford, California 94305

TO

The FERMI National Accelerator Laboratory
Batavia, Illinois 60510

May 21, 1975

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

Proposal to the Fermi National Accelerator Laboratory

for

HIGH PRECISION STUDIES OF DEEP SCATTERING PHENOMENA FROM PROTONS, PIONS, ELECTRONS AND GAMMA-RAYS ON HYDROGEN AND DEUTERIUM

Abstract

We propose to measure with high precision the cross sections of elastic and inelastic collisions in the deep scattering region, using the highest energy and intensity beams of protons, pions, electrons and gamma-rays, on hydrogen and deuterium targets. Initially, these studies will be carried out in the beam momentum region of 50 - 400 GeV/c, and thereafter in the Energy-Doubler/Saver mode, in the region of 400 - 1000 GeV/c. The cross-sections of these processes will be measured as a function of s, in the range of 95 GeV^2 to 1880 GeV^2, as a function of the invariant momentum transfer t, in the range of $t_{min} = 0.040\ (GeV/c)^2$ and $t_{max} = 3.25\ (GeV/c)^2$, and as a function of the missing-mass M, in the range of $M = m_\pi$ and $M = 40$ GeV. Beam intensities and energies to be used are: 50 - 1000 GeV; $10^{11} - 10^{12}$ p/pulse; 50 - 800 GeV, $10^9 - 10^{10}$ π^-/pulse; 50 - 700 GeV, $10^9 - 10^{10}$ $e^\pm$/pulse; 50 - 700 GeV, $\frac{1}{2}(10^9 - 10^{10})$ γ/pulse. Moreover, using high precision missing-mass techniques, searches will be made to discover new states of: heavy baryons(N^{*+} and N^{*o}) produced by protons; heavy mesons (M^{*-}), exotic mesons (M^{*--}), and charged intermediate vector bosons (W^-) produced by pions; heavy vector and scalar bosons (W^o, V^{*o}, B^{*o}, ψ^{*o}, η_c^{*o}) produced by real and virtual photons; excited leptons ($e^{*\pm}$), and heavy leptons (E^o) produced by electrons.

We propose to complete and install the HEPL 168", 2.5 GeV/c, large acceptance, high precision, focussing spectrometer at FERMILAB, at the end of the Proton-West beam line, so that it can be used initially for the benefit of these studies. Our goal is to complete fabrication of the spectrometer at HEPL in 1978, and to transport and install the spectrometer at FERMILAB in 1979. Consideration of this proposal is requested presently to permit the completion of the fabrication project.

I. INTRODUCTION

The Batavia Accelerator[1] is now operating at 400 GeV and 10^{13} protons/pulse and in the future, after implementation of the Energy-Doubler/Saver improvements, it will be able to deliver primary proton beams of up to 1000 GeV. The quality and intensity of secondary and tertiary beams dramatically improve as the energy of primary protons increases. Accordingly, with proper beam design, beams of 10^{12} protons, 10^{10} pions, 10^{9} pure electrons, and $1/2 \times 10^{9}$ pure broad-band photons can be made available at a fixed spectrometer installation. By combining such facilities, a highly competitive and desirable tool of physics is obtained if the spectrometer has sharp resolution and large acceptance. For example, elastic electron scattering at 200 GeV and at $Q^2 = 3.25\ (\mathrm{GeV}/c)^2$ can be observed at a rate of 1 event/hour, or, the production of ψ-particles from γ - p and e - p collisions can be recorded at a rate of 1 event/pulse with mass resolution of a few MeV.

Such a versatile beam is now evolving at FERMILAB, at the Proton-West Area, using entirely superconducting beam-line dipoles, quadrupoles and sextupoles. Such a high precision large acceptance focussing spectrometer[2] is being fabricated at HEPL. We propose to join together these two powerful facilities, initially for the use of the following experimental studies in which the same beam facility will be tuned to produce protons, pions, electrons and photons at a fixed and well understood instrument of physics. It is our view that only by the concurrent investigations with these particle beams, and with the same calibrated instrument, that we can be able to answer some of the fundamental questions on the constituent structure of nucleons, with high precision and statistical significance. By looking at the nucleon with hadronic, leptonic and electromagnetic probes at high energies and intensities, we hope to answer some of these exciting questions of physics: how is the constituent nature of nucleons manifested say, in large impact elastic scattering ; what are some of the relevant new states of nature, created in deep inelastic collisions from several beam probes; are there any new underlying quantum numbers which regulate nature; what are after all the fundamental constituents of nature?

We believe some of these questions can be answered experimentally by the good opportunity presented at the FERMILAB accelerator and especially during the onset of the Energy-Double regime. We propose to carry out a systematic investigation using the high intensity, and high energy beams of protons, pions, electrons and photons. At a fixed location we propose to use this beam facility together with a high resolution large acceptance focussing spectrometer by which high statistics and reliable data are collected with well understood systematics, in a relatively short period of running time and analysis time.

II. EXPERIMENTAL PROGRAM

Although the physics interest of our proposal can be separated naturally between elastic and inelastic reaction channels, experimentally in terms of running time, distinction is not required for these two reaction types. Because of the large acceptance and good resolution of our spectrometer in missing-mass, both elastic and inelastic channels will be measured concurrently and will be separated clearly.

The experimental program of this proposal makes use of the HEPL 168" focussing spectrometer in a simple configuration. In this proposal the spectrometer will be used exclusively as a single-arm "stand-alone" device, to provide new and precise knowledge on the behavior of elastic and quasi-two-body scattering processes and on the missing-mass spectra produced in deep inelastic scattering collisions from p-N, π^--N, $e^\pm$-N and γ - N interactions.

At a later time, a more complete configuration can be obtained in order to investigate details of specific reaction channels or the decay properties of new phenomena. The focussing spectrometer can be used together with a moderately large acceptance forward spectrometer arrangement consisting of superconducting dipole magnets, MWPC's, cells of threshold gas Cerenkov counters and total absorption counters made up by NaI(Tl) modules. A new capability in experimental high energy physics is derived by this complete arrangement.

It should be noted that the 168" spectrometer is capable of operating at the highest possible beam intensities of 10^{13} protons/pulse with 20 cm long LH_2/LD_2 targets. Although the spectrometer's acceptance is very large, $\Delta p/p =$ 11% (FW), $\Delta\Omega = 0.009$ sterad, all of the experimental detectors associated with the spectrometer are mounted 28 ft above the beam line in a well shielded environment.

The 2.5 GeV/c 168" spectrometer is a scaled-up version of the HEPL 1 GeV/c 72" spectrometer which was operated successfully for many years, in electron experiments with instantaneous electron beam rates of 10^{17} - 10^{18} e/sec. Therefore, at FERMILAB we do not expect to find any dangerous background at the detectors of the 168" spectrometer from use of the most intense proton beam rates of 10^{13} p/sec. Thus, it will be possible to do search type experiments for rarely occuring particles, with very good mass and momentum-transfer resolution and with very high statistics, in a relatively short period of running time. Our inherent resolution in momentum is 0.01% and in angle is 0.1 mrad.

As new or anomalous effects become observed quickly and with good confidence in a single-arm search experiment, the role of the 168" spectrometer changes from being a "search" device to becoming a "trigger" device, for utilization with a forward spectrometer configuration. In the "trigger" mode, the focussing spectrometer is tuned in angle and momentum, corresponding to the missing-mass and momentum transfer values which exhibit new or anomalous behavior. The 168" spectrometer thus acts as a trigger of new phenomena so that now, the forward spectrometer configuration is triggered very selectively to observe decay products from new effects. Ordinarily, these search and study modes in experimental high energy physics are separated in time by as much as a few years. What we mean by a new experimental capability is the compaction of this time scale, potentially to a few months.

We also believe that with our high precision techniques, we will be making studies of types of physics at FERMILAB which have never been done before anywhere. As demonstrated in Section III.2, our typical resolution in momentum transfer is $\delta t = 0.0002\ (\mathrm{GeV}/c)^2$ at $t = 1.5\ (\mathrm{GeV}/c)^2$ and our resolution in missing-mass is $\delta M = 5$ MeV at $M = 10$ GeV. The 168" focussing spectrometer and our large NaI(Tl) crystal modules constitute the components of new high precision techniques which we are proposing to bring to FERMILAB. Recent results in experimental high energy physics speak eminently well on behalf of these high precision concepts.

1. Elastic Scattering Measurements

We propose to measure the elastic scattering differential cross section $d\sigma/dt$ of the following reactions, in the momentum transfer range of $t_{min} = 0.040\ (\mathrm{GeV}/c)^2$ and $t_{max} = 3.25\ (\mathrm{GeV}/c)^2$ and with beam energies starting at 50 GeV, (π^-, $e^\pm$) or 200 GeV (p) and up to maximum available energies at FERMILAB:

$$pp \rightarrow pp \qquad (1)$$

$$\pi^- p \rightarrow p\pi^- \qquad (2)$$

$$e^- p \rightarrow pe^- \qquad (3)$$

$$e^+ p \rightarrow pe^+ \qquad (4)$$

$$ed \rightarrow de \qquad (5)$$

The $d\sigma/dt$ of these reactions will be measured with high statistics and very narrow binning in t, typically with resolution of $\delta t = 0.0002$ $(GeV/c)^2$, where t is the invariant momentum transfer between target and recoil protons. The first named of the two outgoing particles is the one which is accepted by the focussing spectrometer.

We plan to observe any fine-structure that may be present in the t distribution of reactions (1) and (2). In the t range of 0.04 $(GeV/c)^2$ - 0.5 $(GeV/c)^2$, two distinct slopes are observed[3] in $d\sigma/dt$ of reaction (1) at ISR energies. Moreover, there seems to be oscillations in the data about average fitted slope values. There may be a fine-structure superimposed on the diffraction peak, possibly related[4] with multiple Pomeron exchange phenomena which in turn could explain the observed rise of total cross sections in p-p and π-p collisions. In general, the behavior of reactions (1) and (2) as a function of s, at the first diffraction peak region, is found to be intimately related with the general behavior of $\sigma_{tot}(s)$ and on how the apparent "interaction size" of particles grow with s. Hence, a precise measurement of elastic p-p and π-p scattering at the highest possible energies is a necessary ingredient for the understanding of $\sigma_{tot}(s)$ data from FERMILAB and ISR.

It is also important to have precise data of reactions (1) and (2) in the large impact elastic scattering region of $t = 1 - 3.3$ $(GeV/c)^2$. At ISR a minimum in $d\sigma/dt$ is observed[5] in reaction (1) at $t \simeq 1.4$ $(GeV/c)^2$. We plan to observe changes in the behavior of $d\sigma/dt$ at this interesting region, as a function of s, for reactions (1) and (2). We believe, comparison of data from π^-- p and p-p elastic scattering from this region may exhibit differences which could be a consequence of the interaction of constituents in the particle structure of nucleons (qqq) and mesons ($\bar{q}$q).

A new opportunity is made available at FERMILAB, to carry out for the first time electron physics experiments in the 50 GeV - 800 GeV energy region typically with 10^9 electrons/pulse where the electron beam at experimental targets is absolutely pure.(6) Measurements of elastic electron-proton and positron-proton scattering at very high energies (50 - 800 GeV) and up to Q^2 values of 3.3 $(GeV/c)^2$ may provide new answers in the behavior of nucleon structure functions, since the electromagnetic form factor of protons will be measured in an as yet unexplored energy domain. We are proposing to extend the pioneering work of Hofstadter and co-workers in this field to a new energy region at FERMILAB, using proven and successful techniques.

Comparison of data from reactions (1) - (5) could give significant new knowledge in relating the hadronic and electromagnetic parts of the nucleon's form factor. With measurements of $e^{\pm}$-p elastic scattering differential cross sections $d\sigma/d\Omega$ (E), we are interested in finding experimental answers to some of the following questions:

(a) Is the nucleon's electromagnetic form factor $G(Q^2)$, dependent only on Q^2, or is it dependent on an as yet undiscovered scaling variable in which the energy dependence in s enters weakly ? Strictly Q^2 dependence is found in nucleon form factors between data at $s = 3$ GeV^2

(Mark III at HEPL) and $s = 35\ GeV^2$ (SLAC). Will this behavior persist to be true at $s = 375\ GeV^2$ to $s = 1500\ GeV^2$, at FERMILAB? One can think of several scaling variables in which s could enter, moderated by some size parameter M where M is some large characteristic mass, say $M \sim 30$ GeV. Such behavior can be detected only at large s regions.

(b) Does the Rosenbluth formula, with the assumption of "scaling law" relating electric and magnetic nucleon form factors, remain valid at high energies to describe elastic $e^{\pm}$-p scattering?

(c) Is there a simple connection between hadronic and electromagnetic form factors of the nucleon, at small or large Q^2 regions? How is the charge distribution of protons related with the distribution of constituent matter in protons? Is there shrinkage in $d\sigma_{ep}/dQ^2$ with s?

Answers to some of these questions require not only high statistics and precise data from reactions (1) - (5), but also, data that are obtained under the same experimental conditions, both in beam and apparatus, so that systematic effects do not obscure some of these significant comparisons.

Event Rates

As discussed in Section III.1, typically 20 cm long LH_2/LD_2 targets will be used with the 168" focussing spectrometer. Thus, as an example, the event luminosity for an incident beam of 10^9 particles/pulse will be $0.853 \times 10^{33}\ cm^{-2}$/pulse.

For p-p elastic scattering, specific event rates of interest are obtained by using cross section figures of $d\sigma/dt$ from the ISR measurements, at the interesting "second diffraction peak" region.[5] We take the lowest possible cross section value to be in the dip structure region at $t \simeq 1.4\ (\mathrm{GeV}/c)^2$ or beyond the peak at $t \simeq 3.3\ (\mathrm{GeV}/c)^2$. This is:

$$d\sigma/dt \simeq 1.7 \times 10^{-32}\ \mathrm{cm}^2/(\mathrm{GeV}/c)^2 \ .$$

As demonstrated in Section III.2 from Table IV, the acceptance range of the 168" spectrometer in t , including the effective azimuthal acceptance, is $\Delta t = 0.011\ (\mathrm{GeV}/c)^2$ at $t \simeq 1.6\ (\mathrm{GeV}/c)^2$ and $\Delta t = 0.024\ (\mathrm{GeV}/c)^2$ at $t \simeq 3.3\ (\mathrm{GeV}/c)^2$. So that, in reaction (1) $\Delta \sigma_{accept} = 1.9 \times 10^{-34}\ \mathrm{cm}^2$, is the smallest possible accepted cross section to be measured by the spectrometer in this experiment.

Thus, with 10^{11} incident protons/pulse, the lowest event rate is:

$$0.85 \times 10^{35}\ \mathrm{cm}^{-2}/\mathrm{pulse} \cdot 1.9 \times 10^{-34}\ \mathrm{cm}^2 = 16\ \mathrm{events/pulse}$$

at $t \simeq 1.4\ (\mathrm{GeV}/c)^2$, where the resolution is $\delta t = 0.0002\ (\mathrm{GeV}/c)^2$. In comparison, the event rate in the equivalent ISR experiment,[5] at the dip region, is estimated to be a few events/hour, for a t bin of $0.05\ (\mathrm{GeV}/c)^2$. Therefore, it is evident, at FERMILAB the 168" spectrometer will produce $d\sigma/dt$ spectra with high statistics and extremely good precision from this reaction in the large impact region of $t = 1.0 - 3.3\ (\mathrm{GeV}/c)^2$. At smaller t regions the event rate is limited only electronically by the event acquisition rates of $\sim$ 1000 events/pulse.

For π^--p elastic scattering, typical event rates of interest are obtained by assuming that the π^--p differential cross sections have distributions similar to the $d\sigma/dt$ distributions of p-p elastic scattering. In this case, $d\sigma/dt$ values from p-p scattering should be scaled down by the factor of $[\sigma_{tot}(\pi\text{-p})/\sigma_{tot}(pp)]^2 \simeq 0.4$, to have an estimate of $d\sigma/dt$ figures for π-p scattering at the large impact regions. Hence, we estimate, the smallest cross section in π-p could be:

$$d\sigma/dt \simeq 0.7 \times 10^{-32} \text{ cm}^2/(\text{GeV}/c)^2$$

somewhere in the t range of 1.3 - 3.3 $(\text{GeV}/c)^2$. So that, in reaction (2) $\Delta\,\sigma_{accept} = 10^{-34}\text{ cm}^2$, could be the smallest possible aceepted cross section to be measured by the spectrometer.

Thus, with 10^9 incident pions/pulse, the lowest anticipated event rate is 0.1 event/pulse, presumably at a dip structure region.

For $e^\pm$-p elastic scattering, event rates are calculated in a fairly expectant way by use of the Rosenbluth formula

$$\frac{d\sigma}{d\Omega_e} = \frac{\alpha^2}{Q^2} \cdot \left(\frac{E'}{E_o}\right)^2 \cdot \left(\frac{\tau G_M^2 + G_E^2}{1+\tau} \cdot \cot^2(\theta_e/2) + 2\tau G_M^2\right)$$

$$\frac{d\sigma}{dQ^2} \approx 4\pi\,\alpha^2 \cdot \left(\frac{E'}{E_o}\right)^2 \cdot \cos^2(\theta_e/2) \cdot \frac{G_E^2}{Q^4}\left[\frac{1+\tau\mu^2}{1+\tau}\right]$$

where $\tau = Q^2/4M^2$, G_E and G_M are the electric and magnetic form factors of the proton, E_o and E' are the incident and scattered electron energy, and θ_e is the scattered electron angle.

A "scaling law" is used to relate $G_M = \mu_p G_E$ where $\mu_p = 2.793$ is the magnetic moment of the proton. This "law" is shown to be valid up to SLAC energies. The form of $G_E(Q^2)$ is well described by Hofstadter's 1957 "dipole fit" which surprisingly remains valid today with a few percent deviations. G_E is given as: $G_E(Q^2) = (1 + Q^2/0.71)^{-2}$.

The expected differential cross-section $d\sigma(ep)/dQ^2$ is almost independent of electron beam energy. With good event rates we will determine if there exists any shrinkage in $d\sigma(ep \rightarrow pe)/dQ^2$, similar to the behavior found in $d\sigma(pp \rightarrow pp)/dt$ at FERMILAB and ISR energies. With recoil protons detected in the 168" spectrometer, from interactions produced by 10^9 incident electrons/pulse on a 20 cm LH_2/LD_2 target, the event rates are:

P_3 GeV/c	Q^2 $(GeV/c)^2$	$d\sigma/dQ^2$ $\times 10^{-33} cm^2/GeV^2$	ΔQ^2_{accept} $(GeV/c)^2$	$\Delta\sigma$ accept $\times 10^{-33} cm^2$	Events/hour (500 Pulses/hour)
0.50	0.23	2158	0.0027	5.83	2500
1.00	0.81	42.5	0.0063	0.27	114
1.50	1.56	3.2	0.0110	0.04	15
2.00	2.38	0.48	0.0171	0.008	4
2.50	3.25	0.11	0.0244	0.003	1

where in ΔQ^2_{accept} the effective azimuthal acceptance of the spectrometer is also included.

Radiative Effects

In e-p elastic scattering the electron beam energy is degraded by a well known behavior due to the bremsstrahlung of electrons in the target before scattering and the radiative tail induced during scattering. The bremsstrahlung of electrons in the target after scattering which is the dominant radiative correction in e-p elastic or inelastic scattering processes, is not relevant in our experimental method. Because the spectrometer will detect recoil protons the effect of scattered electrons with radiation after scattering is measured directly. In this manner radiative corrections are greatly simplified. We need to consider only the electron beam energy degradation due to radiation at scattering and bremsstrahlung before scattering. The energy spectrum of a monochromatic electron beam is modified by these radiative effects and is described[7] by:

$$dN/dE_o = I_{brem}(E_o, E_o - \Delta, t) = \frac{1}{\Gamma(bt)} \cdot \frac{1}{E_o} \cdot \left(\frac{\Delta}{E_o}\right)^{bt-1} \qquad (6)$$

in which according to the peaking approximation:

$$bt = \frac{t}{2} + t_r$$

$$t_r = \frac{1}{b} \cdot \frac{\alpha}{\pi} \cdot \left[\ell n\, (Q^2/m_c{}^2) - 1\right]$$

$$b \approx \frac{4}{3}$$

where t is the target length in units of (electron's) radiation lengths and t_r is the equivalent radiator for internal bremsstrahlung.

In practice, equation (6) will be modified by the convolution integral of a gaussian-like function which represents the energy spectrum of beam electrons, prior to their entrance in the target. In the range of $E_o = 50 - 200$ GeV the radiation degraded electron beam energy spectrum is very sharp. For example, typical spectral values in the tail as given by equation (6) are:

dN/dE_o	$= 0.031\ \text{GeV}^{-1}$	at	Δ	$= 1.0$	GeV
	$= 0.016\ \text{GeV}^{-1}$	at		$= 2.0$	GeV
	$= 0.007\ \text{GeV}^{-1}$	at		$= 5.0$	GeV

and so, most of the spectrum is concentrated below 0.7 GeV in spread.

We conclude that at FERMILAB energies the radiation degradation of electron beams is a minor modification of the incident electron beam energy spectrum which will be chosen to be $\Delta E_o/E_o = \pm 2\%$. This value is consistent with our resolution requirements and provides us with maximum possible electron beam intensities. In this case, in e-p elastic scattering the error in missing mass will be dominated by the resolution of recoil proton scattering angles. As demonstrated in Section III the total uncertainty in missing mass, from a ± 2% defined 200 GeV electron beam and the measurement of recoil proton momentum and angle in the 168" spectrometer, is $\Delta(M^2) = 0.09\ \text{GeV}^2$, for the Q^2 region of $0.8 - 3.3\ (\text{GeV}/c)^2$ in e-p elastic scattering.

2. Deep Inelastic Scattering Measurements

In the past, missing-mass search type experiments have been very productive in discovering new states of heavy baryons and mesons. Good resolution in missing-mass is crucial, because usually such states are observed in the presence of a large background continuum.

Moreover, recent discoveries of ψ particles with narrow line-widths in the 100 KeV range proved that it is an essential experimental requirement to use high precision techniques, otherwise such discoveries would be missed entirely.

We propose to use the 168" focussing spectrometer at a fixed installation as a high precision and large acceptance missing-mass detector that can also cover the deep scattering region for the production of new particles and the observation of new phenomena. For example, the mass region of 10 GeV will be observed within a mass acceptance of 2.6 GeV and with a mass precision of 5 MeV in the t region of 3.3 $(GeV/c)^2$. As a versatile setup, we propose to bring to this fixed installation, incident beams of primary protons, secondary pions, tertiary pure electrons and broad-band pure photons, initially for the benefit of implementing the following physics in the deep inelastic scattering region.

We propose to measure the double-differential cross sections, $(d^2\sigma/d\Omega_3 dp_3)$ or the invariant cross sections $(E_3 d\,\sigma/d^3p_3)$ of the following reactions, as a function of missing-mass M, in the range of M between threshold and 40 GeV, and also, as a function of invariant momentum transfer t, between $t_{min}(M)$ and 3.3 $(GeV/c)^2$. (The subscript 3 is for the particle accepted by the spectrometer.)

a) With primary proton beams of 200 GeV - 1000 GeV:

$$p\ p \rightarrow p + \text{anything} \qquad (N^{*+}) \tag{8}$$

$$p\ n \rightarrow p + \text{anything} \qquad (N^{*o}) \tag{9}$$

to search for heavy baryons N^{*+}, N^{*o} produced in hadronic interactions.

b) With secondary pion beams of 200 GeV - 800 GeV:

$$\pi^- p \rightarrow p + \text{anything} \qquad (M^{*-}, W^-) \tag{10}$$

$$\pi^- n \rightarrow p + \text{anything} \qquad (M^{*--}) \tag{11}$$

to search for heavy charged mesons M^{*-}, produced in hadronic interactions; charged intermediate vector bosons W^-, produced in semi-weak interactions; and exotic mesons M^{*--}, produced via some new mechanism.

c) With tertiary pure electron and positron beams of 50 GeV - 700 GeV :

$$e^- p \rightarrow p + \text{anything} \qquad (e^{*-}) \tag{12}$$

$$e^- p \rightarrow p\ e' + \text{anything} \qquad (V^o,\ Z^o,\ B^o,\ \psi^o,\ \eta_c^o) \tag{13}$$

$$e^- n \rightarrow p\ e' + \text{anything} \qquad (W^-) \tag{14}$$

$$e^+ p \rightarrow p + \text{anything} \qquad (e^{*+}) \tag{15}$$

$$e^+ n \rightarrow p + \text{anything} \qquad (E^o) \tag{16}$$

to search for heavy excited leptons, e^{*-}, e^{*+} produced in leptonic interactions;vector mesons V^o, heavy photons B^o, ψ^o-particles, heavy pseudo-scalar mesons η_c^o produced in electromagnetic interactions by space-like virtual photons ; neutral intermediate vector (W^o) or scalar (Z^o) bosons produced in semi-leptonic interactions; and the direct leptonic production of heavy leptons (E^o).

d) With broad-band pure photon beams of 50 GeV - 700 GeV:

$$\gamma p \to p + \text{anything } (V^o, Z^o, B^o, \psi^o, \eta_c^o) \quad (17)$$

$$\gamma n \to p + \text{anything } \quad (W^-) \quad (18)$$

to search for charged intermediate vector bosons, W^-, and neutral intermediate vector (W^o) or scalar (Z^o) bosons, produced in semi-weak interactions and the production of V^o, B^o, ψ^o, η_c^o particles in electromagnetic interactions by real photons.

In all of the above reactions the recoil proton is detected by the 168" focussing spectrometer in the range of recoil proton momenta, between 200 MeV/c and 2500 MeV/c and recoil proton angles between 28^o and close to 90^o . For the electron reactions (13) and (14), scattered electrons will be detected by a segmented NaI(Tl) crystal assembly, located some 50 ft downstream from the LH_2/LD_2 target, to intercept scattered electrons at angles between 10-50 mrad. The NaI(Tl) assembly will identify scattered electrons with great certainty and measure their energy and production angle with good precision in a manner which is demonstrated elsewhere.[8] This assembly acts as a tagging system of the space-like virtual photons mediating reactions (13) and (14). In the case of reactions (17) and (18), in which broad-band pure photon beams are used, the missing-mass will be deduced by the well known bremsstrahlung subtraction technique for the continuum region in missing-mass. Or, in the photoproduction case of states having discrete mass or narrow resonance width, the well established technique of deriving the differential yield curve from the integral yield, at a fixed t bin, will be used.

The <u>proton reactions</u> will be done with better resolution in t and M, than in experiments carried out at the CØ internal target area of FERMILAB. Moreover, reactions (8) and (9) will be studied with extremely high luminosity, reaching 10^{35} cm^{-2}/pulse, and covering wide dynamic range in t [0.004 - 3.3 $(GeV/c)^2$] and in M (M_{min}-40 GeV). Reactions (10) - (18) can only be done at the proposed secondary beam area.

In reactions (9), (11), (16) and (18) a 20 cm long LD_2 target will be used specifically to observe interactions on neutrons. The missing-mass resolution in these reactions will be essentially the same as with proton-targets. The beam momentum or the forward going missing-mass momentum will have an additional effective spread of about 70 MeV/c due to the Fermi motion of spectator nucleons. We believe that measurement of these neutron target reactions is very meaningful because it allows us to make significant comparisons between proton and neutron targets for the proposed search studies, especially since well-defined charge states can only be observed by use of neutron targets with these practical beams.

In the <u>electron reactions</u> the spectrum of missing-mass will be examined under two well-defined conditions. In the simpler case, such as in reactions (12), (15) and (16), the missing-mass will have definite leptonic content so that searches for massive excited leptons ($e^{*\pm}$)

and heavy leptons (E^o) can be carried out with excellent precision. It is anticipated that such states of leptons could exist. In the proposed reactions they would appear as extremely narrow line shapes in the missing-mass spectrum. Good resolution in t (target nucleon-to-recoil nucleon momentum transfer) is essential because these leptonic interactions would be produced with characteristically small t values. In reactions (13) and (14) the leptonic content is removed from the missing-mass spectrum by the observation of scattered electrons in coincidence with the observation of recoil protons. Measurement of energy and angle of scattered electrons together with information from beam electrons define the properties of γ_v, where γ_v is the virtual beam of space-like photons interacting with target nucleons. In this manner the electroproduction of heavy vector mesons will be studied to search for massive vector particles in a wide dynamic range of M and t. In particular, the studied reactions are of the type:

$$\gamma_v \; p \rightarrow p + \text{anything} \; (V^o, Z^o, B^o, \psi^o, \eta_c^o) \qquad (19)$$

in which the missing-mass M and momentum transfer t are measured with fine resolution and also cross-sections are obtained as a function of Q^2, where Q^2 is the space-like mass of γ_v, $Q^2 = 4E_o E' \times \sin^2 (\theta_{ee'}/2)$, and as a function of t.

In the <u>photon reactions</u> (17) and (18) the photoproduction of neutral vector mesons and pseudo-scalar mesons will be studied.

Searches for massive vector mesons will be made using a high intensity $Q^2 = 0$ pure photon beam having a bremsstrahlung energy spectrum. The high precision qualitiees of the 168" spectrometer is used in this case to provide a great advantage by making it possible to trace integral photoproduction yield curves at fixed t values, where the production of states having discrete mass values or narrow resonance line shapes is exhibited as steps on the integral yield curves. A high precision spectrometer is required to detect these steps and to unravel a differential yield curve for each t bin. This technique has been used in several successful photo-production experiments at electron accelerators. We propose to extend these studies at FERMILAB and carry out a systematic search of massive particles which are preferentially coupled to $Q^2 = 0$ real photons or large Q^2 virtual photons. These searches will be made in a wide mass range which extend up to 35 GeV in mass value and also in a wide momentum transfer range which extend up to 3.3 $(GeV/c)^2$ in the deep scattering region.

Finally, in all of the above reaction channels the inclusive invariant cross section in the continuum of missing-mass values will be measured as a function of t, between values of t_{min} and 3.3 $(GeV/c)^2$.

Event Rates

In all of the above reactions, (8) - (19), the recoil protons accepted by the 168" spectrometer are in the kinematical region described in terms of the Feynman scaling variables $P_{\perp}$ and x, where $x = 2p_{\parallel}^{*}/\sqrt{s}$, such that $p_{\perp}$ is between 0.0 and 1.8 GeV/c and x is between - 1.0 and - 0.1 . For the proton and pion reactions, we estimate event rates based on some typically small cross sections in the continuum of missing-mass, say in the extreme case where $p_{\perp}$ = 1.8 GeV/c and x = -1.0 . The smallest possible hadronic interaction cross-section in this region is estimated to be approximately:

$$\frac{d^2\sigma}{d\Omega_3 dp_3} \sim 0.1 \;\; \text{mb}/(\text{sr} - \text{GeV}/c)$$

where the average cross-section might be some 100 times larger than this extreme value. The total accepted cross section measured by the spectrometer is given by the acceptance factor:

$$\begin{aligned} \Delta\Omega \cdot (\Delta p/p) \cdot p &= 0.00853\,(\text{sr}) \times 0.112 \times 2.5(\text{GeV}/c) \\ &= 0.24 \times 10^{-2}\;(\text{sr} - \text{GeV}/c) \end{aligned}$$

for the case of $p_3 = 2.5$ GeV/c and $\theta_3 = 45^{\circ}$. We find that the smallest accepted cross section due to deep inelastic hadronic interactions is $\Delta\sigma_{accept} = 0.2 \times 10^{-30}\ \text{cm}^2$ and with a π^- beam intensity of 10^9 pions/pulse on a 20 cm long LH_2 target, corresponding to an event luminosity of $0.853 \times 10^{33}\ \text{cm}^{-2}$/pulse, the event rate is 200 events/pulse. In the case of a proton beam, 10^{10} protons/pulse appears to be sufficient to saturate maximum data collection rates from these inelastic hadronic interactions. We see that these reactions will be studied with good statistics.

One of the exciting fields of physics that has recently developed is the search for massive Ψ-particle-like states. The 168" focussing spectrometer is ideally matched for such a quest because it provides extremely good resolution in missing-mass. The missing-msss search mode for Ψ-particle types is also an ideal way of discovering such states because in this manner the search becomes independent of decay branching ratios, as all decay modes participate in the missing-mass technique. Reaction types (13), (17) and (19) are the best candidates for these searches.

We estimate the cross-section for the production of Ψ-particles in these reactions by considering recent results from FERMILAB experiment E-87 in which Ψ-photoproduction cross-sections were measured(9) using a broad-band photon beam at the Proton-East area and detecting Ψ-particles in the decay mode of $\Psi \to \mu^+\mu^-$. Correcting for the use of LH_2 target, instead of Beryllium, and for total decay modes, instead of only di-muons, the differential cross-section in the diffraction region is

$$\frac{d\sigma}{dt}\left(\gamma + p \to p + \Psi\ (3095)\right) = 1.5 \times 10^{-30}\ \frac{cm^2}{(GeV/c)^2} \cdot e^{-40t} \quad .$$

We assume that in the region of t between t_{min} and $t = 0.25\ (GeV/c)^2$ the measured diffractive cross-section mostly represents the cross-section of Ψ production in the two-body final states. Accordingly, the smallest cross-section for reaction (17) or (19) could be at $t = 0.25\ (\mathrm{GeV}/c)^2$ where acceptance in the 168" spectrometer (including the effective azimuthal acceptance) is given by $\Delta t_{accept} = 0.003\ (\mathrm{GeV}/c)^2$. We find that the smaller accepted cross-section to be measured by the spectrometer is:

$$\Delta \sigma_{accept}\ (\gamma + p \rightarrow p + \Psi) = 1.7 \times 10^{-33}\ \mathrm{cm}^2,$$
$$\text{at} \quad t = 0.25\ (\mathrm{GeV}/c)^2 \ .$$

In Section IV it is demonstrated that a beam of pure photons with energy say, between 50 GeV and 200 GeV and intensity of $\frac{1}{2} \times 10^9$ γ/pulse is obtained in the Proton-West area. Using a 20 cm long LH_2 target, the corresponding event luminosity is $0.43 \times 10^{33}\ \mathrm{cm}^{-2}$/pulse, and so 0.8 events/pulse is the event rate.

We conclude this section by stating that we consider inelastic event rates of interest to be about 0.02 events/pulse at the lowest, corresponding to 1 event in 10 minutes, and about 1000 events/pulse at the highest. We define a detection sensitivity in terms of the double-differential cross section $d^2\sigma/dMdt$ for any one of the above reactions. In the deep scattering region, say in the t range of 1.5 - 3.3 $(\mathrm{GeV}/c)^2$, $\Delta t_{accept} \simeq 0.02\ (\mathrm{GeV}/c)^2$ (including the effective azimuthal acceptance of the 168" spectrometer) and $\Delta M_{accept} \simeq 4$ GeV. Assuming a typical event luminosity of $10^{33}\ \mathrm{cm}^{-2}$/pulse, our sensitivity figure is based on the detection of 100 events in a 100 hour run, at 500 pulses/hour in 500 GeV accelerator operations:

$$100 \text{ events} = \frac{d^2\sigma}{dM\,dt} \cdot 4(\text{GeV}) \cdot 0.02\,(\text{GeV/c})^2 \cdot 10^{33}\,\frac{\text{cm}^{-2}}{\text{pulse}} \cdot 500\,\frac{\text{pulses}}{\text{hour}}$$

$$\cdot\ 100 \text{ hour}$$

Thus, $\frac{d^2\sigma}{dM\,dt} = 2.5 \times 10^{-35}\ \text{cm}^2/\text{GeV}^3$.

Compared with other search type experiments our method is very competitive. It provides high statistics and high precision so that acquired data can be distributed in a meaningful fashion in very fine binning, both in missing-mass M and momentum transfer t distributions, from experimental runs which could be as short as a few days.

Other potential physics research programs that could be implemented at FERMILAB with the use of the HEPL 168" focussing spectrometer are discussed in a recent study.(10)

The beam quality requirements for the proposed experimental studies are discussed in Section III.4 and IV.

III. EXPERIMENTAL METHOD

In this section we describe the 168" focussing spectrometer, give realistic resolution and acceptance figures for elastic and inelastic reactions and present the experimental instrumentation which is needed in order to implement the proposed physics program.

1. The HEPL 168" Focussing Spectrometer

The 2.5 GeV/c 168" focussing spectrometer is designed as a scaled-up version of the HEPL 1.0 GeV/c 72" spectrometer which was the main instrument for many years in a highly successful series of electron scattering experiments at the Mark III electron linear accelerator. The optics of the 168" spectrometer has been designed to provide an inherent momentum resolution of $\Delta p/p = \pm 0.01\,\%$ and inherent angular resolution of $\Delta\theta = \pm 0.1$ mrad. The magnet's bending angle α is 180° vertically and the radius of curvature of the central ray R is 168".

Throughout the 180° aperture the magnet has slightly slanted flat pole faces, where each pole face is sloping by 0.85°. In this manner focussing action is introduced by field constants n and β where $n = -(\rho_o/B_o)\,\partial B/\partial\rho$ is the field gradient index and $\beta = 1/2\,(\rho_o^2/B_o)\,\partial^2 B/\partial\rho^2$ is the second order coefficient in the field expansion:

$$B_y = B_o\left(1 - n\left(x/\rho_o\right) + \beta(x/\rho_o)^2 + \gamma\,(x/\rho_o)^3 \ldots\right)$$

with $\beta = n^2,\ \gamma = -n^3$.

Thus, in addition to the main dipole element, distributed along the entire magnetic length a quadrupole element exists, as a consequence of having a non-zero n value and superimposed, a distributed sextupole element exists, due to having a non-zero β term. The transverse imaging forces along y (in the non-bending plane) are proportional to $\sqrt{n}$, and the radial imaging forces (in the bending plane) are proportional to $\sqrt{1-n}$, so that by choosing a field gradient index of $n = 1/2$ a point-to-point double focussing spectrometer is obtained. The 168" spectrometer is designed to have $n = 0.5$ and $\beta = 0.25$. This is produced by machining flat pole faces at a slope of 0.85^{o} for this magnet. The magnet has a nominal gap of 10 inches and the magnet width along the orbit is 60 inches.

The spectrometer is always held focussed on the experimental target. The distance D, between target and magnet entrance aperture is held fixed by the rotation arm of the spectrometer, where D is given by:

$$D = \left[\sqrt{1-n} \cdot \tan(\sqrt{1-n} \;\; \alpha/2)\right]^{-1} \cdot R = 117.74''$$

for $R = 168''$, $\alpha = 180^{o}$ and $n = 1/2$. Point-to-point focussing at unit optical magnification is achieved by also locating detectors at the momentum focal plane, situated a distance $D = 117.74''$ away from the exit aperture of the magnet. At the momentum focal plane the target is imaged by one of the coordinates and momentum is resolved by the other. Moreover, at this location, the momentum focal plane is tilted away from the normal to the optical axis by an angle Ψ, whereby second-order aberrations are minimized, and, momentum and vertical scattering angle become uncorrelated. In this manner a pure momentum focus is obtained. Using standard TRANSPORT notation, the tilt angle Ψ is given by:

$$\Psi = \tan^{-1}\left[- \frac{(x;\ \theta_o\ \delta)}{(\theta;\ \theta_o) \cdot (x;\ \delta)}\right] = 54.74^{o}$$

where the terms are evaluated at the untilted focal plane. The 168" spectrometer achieves a large dispersion in momentum, given by:

$$d = 2(1 + |M|)\ R/100\% = 4\ R/100\% = 6.72''/\%$$

so that a distance of 1.7 mm on the tilted focal plane corresponds to 10^{-4} in $\delta p/p$. Hence, track momenta and target exit coordinates are measured (with an inherent resolution of $\delta p/p = \pm 0.01\%$) by a multi-wire proportional counter positioned 117.74" away from the magnet exit aperture and tilted by 54.74^{o} from the vertical plane. Vertical and horizontal scattering angles θ and φ are measured by MWPC's located ahead and behind the tilted focal plane, with lever arm of 25 ft. Inherent angular resolution including higher order aberrations is ± 0.1 mrad.

The target length acceptance of the spectrometer has a trapezoidal distribution shape with a flat-top about 5" long for scattering angles near 90^{o} ; at other scattering angles much longer targets can be accepted by the spectrometer. All event rate estimates however, are based on the use of a nominally 20 cm long LH_2/LD_2 targets.

The magnet rotates about the target and can be set at scattering angles between 28^o and 152^o without obstructing the passage of beams at upstream or downstream ends.

A vacuum chamber extends out of the magnet by a length of 70" facing the target, to eliminate multiple Coulomb scattering in the focal distance. The same vacuum chamber continues throughout the magnet and extends 30" out of the magnet at the top, allowing for detectors to be placed ahead of, at, and beyond the (tilted) momentum focal plane. At the entrance, p, θ, φ acceptance defining slits are placed.

The principal performance characteristics of the 168" spectrometer are listed in Table I. Figure 1(a) is the photograph of a model, depicting the 168" spectrometer with the bridge-construction type of support structure which allows for full rotation about the target, supported on four circular rails. Figure 1(b) is a photograph of the magnet coils in their present location, at the End Station area of HEPL's superconducting cavity electron accelerator. As shown, the fabricated coils are fastened in their own coil forms. The coil forms are left in place so that the magnet coils can be transported in a safe manner. All electrical tests on these coils have been made with very good results. The total weight of 2 magnet coils and coil forms is 76 tons. Work on machining and sizing of magnet return-flux iron plates has been done at HEPL using our own facilities. There are

152 iron plate pieces with total weight of 949 tons. The magnet pole pieces are being fabricated and will be delivered at the end of 1975. There are 8 pole-face sections with total weight of 196 tons. Thus, total weight in transportation will be 1221 tons. Figure 2 is a photograph showing one of the magnet coils in the process of being received at HEPL.

A floor space area of about 70' × 70' is needed to accomodate this spectrometer arrangement. Figure 3 shows the top view of such a facility at FERMILAB and Figure 4 displays various elevation views of the 168" focussing spectrometer and superstructure. The required beam height is 6 1/2' and if necessary this could be made to be 6.0'. All experimental detectors are housed in a well shielded area at the top of the support structure. The detectors are located 28' above being height and the detectors hut ceiling is 46' from the floor. The shielded detectors hut extends out, over the bridge-type superstructure, providing a distance of 29' beyond the momentum focal plane. This length is needed to accomodate the placement of several experimental detectors as discussed in Section III.3.

2. Experimental Acceptances and Resolutions

Since the 168" spectrometer has excellent resolution in momentum and in scattering angle, sufficient care must be given in the design of targets and windows so that inherent resolutions are not degraded by multiple scattering effects.

A liquid hydrogen or deuterium target will be used, in the form of a cylindrical tube 3 mm in diameter and 20 cm long. The beam spot will be prepared to occupy 2 mm in diameter, as required also by other imaging considerations (see Section III.4). On one side facing the spectrometer, along the 20 cm length, thin windows will be placed on the liquid target container and the vacuum jacket. Both of these windows will be made of 1 mil thick high strength Beryllium alloy sheets.[11] Also, thin windows of the magnet's vacuum chamber and those on the first three MWPC's will be made of 1 mil thick Beryllium alloy sheets. This is a new commercially available material and the technology of making special flanges for windows using this material is known. In this manner, the principal multiple scattering effects will be due entirely to the liquid hydrogen or deuterium by itself.

The rms uncertainty in scattering angles from traversal of track in 1.5 mm of LH_2 is:

$$\Delta \theta_{ms} = 0.195 \text{ (MeV/c)}/p \beta \quad . \tag{20}$$

The rms uncertainty in recoil momenta due to momentum loss correction uncertainty from 1 mm of LH_2 is:

$$(\Delta p/p)_{ms} = (dE/dx) \cdot (0.1 \text{ cm})/p\beta \tag{21}$$

where p in MeV/c is the measured recoil particle momentum and β is its relative velocity; dE/dx in MeV/cm is the ionization energy loss of the recoil particle having momentum p .

Spectrometer Acceptances

The 168" spectrometer's nominal acceptances are obtained by well known magnetic optics design relations.[12] Once the spectrometer is calibrated at FERMILAB, ray tracing programs will be used to arrive at more precise and detailed acceptance parameters. The vertical angular acceptance (in the bending plane) is given by:

$$\Delta\theta = (W/R) \cdot \sqrt{1 - n} \cdot \sin\left(\sqrt{1 - n}\ \alpha/2\right) = 226.3 \text{ mrad}$$

for magnet width $W = 60''$, $R = 168''$, $n = 0.5$, and $\alpha = 180^\circ$. The horizontal angular acceptance (in the non-bending plane is obtained by:

$$\Delta\varphi = (G/R) \cdot \sqrt{n} \cdot \sin\left(\sqrt{n}\ \alpha/2\right) = 37.7 \text{ mrad} \quad \text{where} \quad G = 10''$$

is the magnet gap. The momentum acceptance is deduced by:

$$\Delta p/p(FW) = (W/R) \cdot (1-n) \cdot \left[1-\cos\left(\sqrt{1-n}\ \alpha\right)\right]^{-1} = 11.12\ \%,$$

and the solid angle acceptance is $\Delta\Omega = \Delta\theta\Delta\varphi = 8.534$ msterad.

Resolution in Missing-Mass and Momentum Transfer

The inherent momentum resolution of $\pm 0.01\%$ and the scattering angle resolution of ± 0.1 mrad from the 168" focussing spectrometer are modified by multiple scattering effects as given in equations (20) and (21). Typically, the spectrometer's inherent resolution are maintained in the range of recoil momenta 1.0 - 2.5 GeV/c .

The missing-mass resolution depends on the uncertainties in beam momentum, p_1 , in recoil particle momentum, p_3 , and recoil particle angle, θ_3 . We use the notation: $p_1 + p_2 \rightarrow p_3 + P$ for momenta, and, $m_1 + m_2 \rightarrow m_3 + M$ for masses. The following equations define the contributions of the various uncertainties to the missing-mass resolution:

$$(\Delta M)_{p_1} = p_1[p_3 \cos\theta_3 - (E_3 - m_2)\beta_1]/M \cdot (\Delta p_1/p_1) = f_{p_1} \cdot (\Delta p_1/p_1)$$

$$\left\{\begin{array}{l} (\Delta M)_{p_1} = [M^2 - m_1^2 - |t| + 2m_1^2(E_3 - m_2)/E_1]/(2M) \cdot (\Delta p_1/p_1) \\ \\ (\Delta M^2)_{p_1} \approx [M^2 - m_1^2 - |t|] \cdot (\Delta p_1/p_1) \ . \end{array}\right. \qquad (22)$$

$$\left\{\begin{array}{l} (\Delta M)_{p_3} = p_3[p_1 \cos\theta_3 - (E_1 + m_2)\beta_3]/M \cdot (\Delta p_3/p_3) = f_{p_3} \cdot (\Delta p_3/p_3) \\ \\ (\Delta M^2)_{p_3} \approx 2\, p_1 p_3 [\cos\theta_3 - \beta_3] \cdot (\Delta p_3/p_3) \end{array}\right. \qquad (23)$$

$$\left\{\begin{array}{l} (\Delta M)_{\theta_3} = p_1 p_3 \sin\theta_3/M \cdot (\Delta\theta_3) = f_{\theta_3} \cdot (\Delta\theta_3) \\ \\ (\Delta M^2)_{\theta_3} = 2p_1 p_3 \sin\theta_3 \cdot (\Delta\theta_3) \end{array}\right. \qquad (24)$$

where the invariant momentum transfer between target nucleon p_2 and recoil particle p_3 is

$$Q^2 = -|t| = 2m_2 E_3 - m_2^2 - m_3^2 \qquad (25)$$

and the missing-mass is evaluated by the kinematical (θ_3, p_3) correlation:

$$\cos\theta_3 = M^2 - m_3^{\,2} - s + 2\,E_3\,(E_1 + m_2)/(2p_1p_3) \qquad (26)$$

with $s = m_1^{\,2} + m_2^{\,3} + 2m_2\,E_1$. In the above, $\Delta p_1/p_1$, $\Delta p_3/p_3$ and $\Delta\theta_3$ are the total uncertainties of these variables.

The overall missing-mass uncertainty is the quadratic sum of the three terms given by equations (22), (23) and (24). At high energies, the kinematical factors in these equations obtain values such that f_{p_1} is about 200 times smaller than f_{p_3} , and f_{p_3} is 2 - 3 times smaller than f_{θ_3} . Essentially, at high energies, as seen in equation (22-c) , the missing-mass resolution due to uncertainties in beam momentum is independent of p_1 . This means that a $\pm$ 1% or $\pm$ 2% beam momentum definition is more than sufficient to match with the $\pm$ 0.01% definition of the recoil particle momentum. Therefore, the contribution from equation (22) is negligible and the dominant term is from equation (24). Typical values of the resolution factors f_{p_1} , f_{p_3} , and f_{θ_3} are entered in Tables II and III for elastic and inelastic scattering processes of interest to this proposal.

In Table II missing-mass resolution values are given for the cases of 300 GeV/c and 900 GeV/c p-p elastic scattering at representative t points. The corresponding multiple scattering uncertainties from equations (20) and (21) are entered together with measuring errors in p_3 and θ_3 , and it is assumed that measurements of reaction (1) will be carried out with a proton beam having about ± 1% momentum bite. For example, at 300 GeV/c and at momentum transfer values of $t = 1.0 - 3.3\ (GeV/c)^2$ the missing-mass resolution is 60 MeV, where also the missing-mass acceptance is a few GeV wide. Here, elastic events can be selected with extremely good precision while measurements are being made simultaneously on quasi-two-body reactions to study the production of excited baryons.

In the case of e-p elastic scattering at 200 GeV with an electon beam momentum bite of ± 2% , the missing-mass resolution is $\Delta(M^2) \simeq 0.09\ GeV^2$ in the region of $Q^2 = 0.8 - 3.3\ (GeV/c)^2$.

Distinction of e-p and π-p elastic collisions from other inelastic reactions, especially at the interesting inelastic threshold regions in missing-mass, will be made also by the use of a simple veto counter arrangement. This is explained in Section III.3. The veto counter assembly, together with the high resolution kinematical separations made by the 168" spectrometer, guarantees that a clear and confident separation of elastic and inelastic events will be made with pion beam intensities of up to 10^9 π/pulse and electron beam intensities of up to 10^{11} e/pulse, due to the excellent beam duty cycle at FERMILAB.

In Table III we demonstrate values of missing-mass resolution for the case of 300 GeV/c deep inelastic π^--p collisions. As an example, the mass region of 10 GeV will be studied with a mass acceptance of about 2 GeV (FW) and with unsurpassed mass resolution of 5 MeV; this is in the t region of 1.0 - 3.3 $(\text{GeV/c})^2$ where the resolution in t is $\sim 3 \times 10^{-4}$ $(\text{GeV/c})^2$ and the acceptance in t is typically 0.35 $(\text{GeV/c})^2$ (FW). In these examples the missing-mass spectrum will be studied with a ± 1% or ± 2% momentum defined π^- beam and only with the use of the 168" spectrometer as a stand-alone apparatus, to unravel states of heavy bosons.

Finally, in Table IV we present the acceptance and resolution of the momentum transfer variable t, between target and recoil nucleons. From equation (25) the resolution in t is given as:

$$\delta t = 2m_2 p_3^{\,2}/E_3 \cdot (\delta p_3/p_3) \qquad (27)$$

As seen, the resolution in t is in most cases at the level of 10^{-4} $(\text{GeV/c})^2$.

The (FW) acceptance in t is obtained by equation (27) with the use of $\Delta p_3/p_3 = 0.1112$ as the (FW) momentum acceptance of the 168" spectrometer. For practical calculations of event rates, the acceptance in t, including the effective azimuthal acceptance of the spectrometer, is obtained by:

$$\Delta t_{\substack{\text{azimuth}\\ \text{accept}}} = (dt/d\Omega) \cdot \Delta\Omega_{\text{accept}} \; ; \quad \Delta\Omega = 0.00853 \text{ sterad}$$

where the dependence of $dt/d\Omega$ on the measured variables p_3 and θ_3 is:

$$\frac{dt}{d\Omega} = 2m_2 p_1 p_3{}^3/\pi \cdot \left[(M^2-m_3{}^2-s)\ E_3 + 2m_3{}^2\ (E_1 + m_2)\right]^{-1} \qquad (28)$$

and the missing-mass M is deduced from equation (26).

Similarly, the (FW) acceptance in M is estimated by the quadratic sum of equations (22), (23) and (24) in which for $\Delta p_1/p_1$, $\Delta p_3/p_3$ and $\Delta\theta_3$, (FW) acceptance values are entered.

Moreover, in Figure (5) we demonstrate the accepted kinematical region in terms of the Feynman scaling variables $p_\perp$ and x. The top figure is for the case where recoil protons are accepted in the spectrometer and similarly, the bottom figure is where recoil pions are accepted from deep inelastic collisions generated by 200 GeV proton or pion beams. In each figure, the phase space region in $p_\perp$ and x covered by the spectrometer's momentum and scattering angle capabilities is indicated by the shaded boundaries.

3. Experimental Detectors and Instrumentation of the 168" Spectrometer

In Figure (4) the general layout of experimental detectors is shown. Detector types separate into two specific functions: (a) those measuring scattering angles (θ,φ), momentum and target exit coordinate; and (b), those serving as particle identifiers, to distinguish the identity of e, μ, π, K, p, d and α particles in the momentum range of 0.2 - 2.5 GeV/c.

The first function is fulfilled by the use of five multi-wire proportional chambers. Each chamber has amplifier per wire instrumentation where readout wires are oriented along three directions:

60°, 90°, and 120° , so that x-y coordinates are defined at each chamber location, without having reconstruction ambiguities. With wire spacing of 1.9 mm, the rms uncertainty in the vertical coordinate is $\delta x = \pm 0.55$ mm and in the horizontal coordinate is $\delta y = \pm 0.78$ mm .

We define a longitudinal coordinate z, at the detectors hut, starting from the edge of the spectrometer's magnet exit aperture. Allowing space for the placement of 3 feet thick concrete shielding walls on all five sides, the detectors hut on the superstructure is a 39 ft long shielded room; 14 ft high and 6 ft wide where these are centered about the optical axis. This space is necessary to accommodate the following list of detectors. The magnet's vacuum chamber extends out to z = 30" and the (tilted) momentum focal plane is located at z = 117.74".

We list the location, orientation and active surface area of the five track measuring MWPC's. These and other counter dimensions are designed to intercept tracks in all extreme values in the p, θ, φ acceptances of the 168" spectrometer.

MWPC	Active Area in x and y (inches)	Location in z (inches)	Orientation	Measuring Function
1	68 × 12	42	vertical	θ, φ
2	140 × 16	117.74	54.74° wrt normal	p, y_{target}
3	88 × 18	195	vertical	θ, φ
4	98 × 22	280	vertical	θ, φ
5	112 × 26	335	vertical	θ, φ

There are no other detectors about the first three MWPC's. Interleaved about MWPC 4 and 5 there are other light-material detectors and behind MWPC 5 are located the heavy-material absorption detectors. Thus, using MWPC's 1,3,4 and 5 the reconstructed scattering angles will have rms uncertainties of $\delta\theta = \pm 0.07$ mrad (vertically) and $\delta\varphi = \pm 0.1$ mrad (horizontally). Momentum will be defined with an uncertainty of ± 0.01% by MWPC 2, where also an image of y_{target}, the accepted track's exit coordinate at the target, is given. With the latter information, a more precise correction will be made of dE/dx losses at the target.

The second detectors function in particle identification is fulfilled by a combination of detectors: a) ionization loss pulse-height measuring counters (plastic scintillators S_1, S_2 and S_3), b) time-of-flight counters with a useful flight-path of 5 meters, c) threshold Cerenkov counters, (C_1 for $\beta > 0.990$, gas counter; and C_2 for $\beta > 0.940$, liquid counter), d) electromagnetic shower total absorption NaI counters, and lastly e) muon range counters sandwiched between muon stopping iron plates.

dE/dx Counters: These are plastic scintillator counters, S_1, S_2 and S_3 located at $z = 195''$ behind MWPC 3. The counters have a sensitive area of 90" in height and 18" in width. Each counter is made up by 5 18" × 18" tiles which are viewed independently through adiabatic light guides. These counters participate in the formation of event trigger gates and also in initiating time-of-flight measurements. They serve the function of measuring a composite pulse-height due to the ionization energy loss of accepted traversing particles.

Threshold Čerenkov Counters: At $z = 210''$, the first gas threshold Čerenhov counter, C_1, is located producing Čerenkov light from traversing particles with $\beta > 0.990$. All traversing electrons, and muons and pions having momenta greater than 1 GeV/c will produce C_1 signals. Other heavier particles, K, p, d, α, having momenta in the range of 0.200 - 2.5 GeV/c will not produce C_1 signals. Therefore, the role of C_1 is to do π-K separation beginning at a momentum range where the time-of-flight technique loses resolution. Conservatively, we assume a time-of-flight resolution of 1.5 nsec which for a flight-path of 5 meters provides a good π-K separation in the momentum range of 0.200 - 1.1 GeV/c and it also yields a good K-p (TOF) separation in the momentum range of 0.200 - 1.7 GeV/c. The C_1 counter is 36" long and has an active surface which is 110" high and 22" wide. The counter is made up of 5 22" $\times$ 22" cells. Light is focussed to one side by a spherical thin reflector and each cell is viewed independently by a photomultiplier.

The second threshold Čerenkov counter, C_2, is a liquid counter positioned at $z = 295''$. C_2 is active with $\beta > 0.940$. C_2 will produce signals from all traversing e, μ, π particles and, from kaons having momenta greater than 1.5 GeV/c. Other heavier particles, p, d, α, having momenta in the range of 0.200 - 2.5 GeV/c will not yield signals from C_2; these will be separated by the time-of-flight technique. The C_2 counter is 12" long, 125" high and 25" wide. It also is made up by 5 cells, each with dimensions 25" $\times$ 25" and each cell is viewed independently on one side where light is collected by a thin spherical reflector.

Electron Total Absorption Shower Counters: An unambiguous electron identifier is required to either reject or form event triggers on accepted electrons. A modular arrangement of (polysin-type) NaI(Tl) crystals will be used in the form of 5" × 5" × 20" blocks. The TASC assembly is made up by 182 blocks which are stacked to provide a detector surface area, 130" high and 35" wide, located at z = 345", behind the last MWPC.

Muon Range Telescope: Muons produced at the target and accepted by the spectrometer or muons from the decay of accepted pions and K-mesons must be identified. The most reliable method of identifying muons in the momentum interval of 0.200 - 2.5 GeV/c is by a muon range telescope made by iron degraders interleaved with plastic scintillators. The last detector assembly in the detector hut is this telescope located at z = 385". Iron plates which are 156" high and 40" wide will be used to assemble the following muon range detector:

Layer	Iron Thickness (inches)	Plastic Scintil. Area Behind Fe height × width (inches)	Plastic Scintil. Tiles height × width (inches)
1	12	S_6: 132.5 × 36	5: 26.5 × 36
2	24	S_7: 140.0 × 38	5: 28.0 × 28
3	18	S_8: 145.0 × 40	5: 29.0 × 40
4	12	S_9: 150.0 × 40	5: 30.0 × 40
5	6	S_{10}: 155.0 × 40	5: 31.0 × 40
		S_{11}: 155.0 × 40	5: 31.0 × 40

Each layer of plastic scintillator behind respective iron plates is made up of 5 tiles where each tile is viewed independently through adiabatic light guides. The counters behind the last iron layer function as veto counters in event triggers.

Time-Of-Flight and Trigger Counters: Together with the S_1, S_2, S_3, dE/dx counters the following plastic scintillator planes will be used to form fast master-triggers of events and to measure the time-of-flight of accepted particles. S_4 and S_5 are located behind MWPC 4 and 5, respectively.

Location at z (inches)	Plastic Scintil. Area height × width (inches)	Plastic Scintil. Tiles height × width (inches)
280	S_4: 98 × 22	5: 20 × 22
340	S_5: 125 × 25	5: 25 × 25

Timing from the TASC assembly and from the first muon-range counter S_6 will also participate in time-of-flight measurements.

The weight of iron in the muon-range telescope is 86 tons. The weight of concrete shielding 3 ft thick walls forming the detector hut is 510 tons. The 168" spectrometer superstructure is designed to carry a weight of 1000 tons.

Forward Inelastic Events Veto Counter: A simple veto counter assembly will be used located some 15 ft downstream from the experimental target. The use of this counter will be helpful in providing an additional distinction to e-p and π-p elastic collisions from other inelastic processes. In addition to the high resolution kinematical separation made by the 168" spectrometer, the use of this counter will be especially helpful in making measurements at the interesting inelastic mass-threshold regions.

The counter will cover an active circular area, 3 ft in diameter, with a 6" in diameter hole at the center to pass through beam and all forward elastically scattered particles within a 1° cone. The veto counter assembly will be made up by 12 symmetrically arranged segments forming the circular area. Each segment will consist of four layers of plastic scintillators interspersed by four layers of Pb sheets, viewed radially by a dual set of photomultipliers. In each segment, the first and third layer are viewed by one and, the second and fourth layer are viewed by the other photomultiplier. Signals from both photomultipliers will be used in coincidence so that dark noise effects are suppressed. In this manner, each segment is sensitive to the passage of charged particles and energetic gamma-rays. The mixed sum-signals from all segments will be discriminated at some high level to remove the effect of random veto-signals which could be present, due to a potentially high background of beam-associated muons.

Downstream Detector for Inelastically Scattered Electrons:

In the studies of electron reactions (13) and (14) a detector is required to measure the energy and scattering angle of scattered electrons so that the variable Q^2 can be defined in these measurements. These scattered electrons will be detected by a segmented

NaI(Tl) crystal assembly interleaved by MWPC planes having delay line readout. This assembly will identify scattered electrons with high precision and measure their energy and production angle with good certainty. Details of this detector assembly are given elsewhere.[8]

4. Beam Quality Requirements for the 168" Spectrometer

The following beam and spot size qualities are required at the experimental target, so that the inherent resolution of the 168" spectrometer is preserved:

a) beam angular definitions: $\Delta\theta = \Delta\phi \leq \pm\ 0.2$ mrad

b) horizontal spot size: $\Delta x = \pm 1$ mm

c) vertical spot size: $\Delta y = \pm 1$ mm

d) beam momentum definition: $\Delta p/p = \pm 1\%$ to $\pm 2\%$.

The Proton-West secondary beam,[13] as presently planned, readily fulfills these requirements. B. C. Cox has designed this beam using superconducting beam-line elements where higher order aberrations are corrected by sextupoles. The Proton-West beam's large acceptance and the method of correcting aberrations by sextupoles make it possible to have the above beam spot definitions together with the intensities of designated secondary particle beams. Especially it will be more so true at the second corrected focus in the P-West area.

The required optical properties of the beam, in conjunction with the use of the 168" spectrometer, are determined from the following considerations:

1) Although the inherent angular resolution of the spectrometer is ± 0.1 mrad, as seen from equation (20), multiple scattering of recoil particles in the LH_2/LD_2 targets degrades this resolution to a typical value of ± 0.2 mrad for momenta near 1 GeV/c. So that the beam angular divergence must be comparable with or smaller than, the measurement uncertainty caused by the multiple scattering effect. The required beam divergence in (a) can be accomplished with the use of aperture stops placed at appropriate locations upstream, along the secondary beam line.

2) The horizontal spot size of the beam determines the amount of uncertainty in the energy-loss correction, for slow recoil particles exiting from LH_2/LD_2 targets, according to values obtained from equation (21). A spot size of ± 1 mm horizontally, corresponds to maintaining the spectrometer's inherent momentum resolution of $\Delta p/p = \pm 0.01\%$ above 0.85 GeV/c.

3) Because the spectrometer bends vertically, the vertical spot size of the beam is imaged at the momentum focal plane which is tilted by 54.74° away from the normal to the optical axis. A distance of 1.7 mm in this plane corresponds to 0.01% in momentum. Accordingly, a vertical beam spot size of ± 1 mm is needed to preserve the inherent momentum resolution of the spectrometer.

4) The required beam momentum bite is given by the tolerance in missing-mass uncertainties due to the uncertainty in beam momentum definition. We choose a beam momentum bite such that this uncertainty is typically 1/3 as large as the uncertainty from other contributions.

At high energies it is possible to have a relatively large beam momentum bite while maintaining this condition. Typically, a beam momentum definition of ± 1% or ± 2% will be appropriate. This is accomplished by the use of a combination of aperture stops and momentum slits which is chosen to provide all of the above requirements in a manner which also optimizes secondary beam intensities.

IV. HIGH ENERGY AND HIGH INTENSITY PROTON, PION, ELECTRON AND GAMMA-RAY BEAMS AT P-WEST AREA

We propose to install the 168" focussing spectrometer at the end of the Proton-West beam line, that is at the planned second corrected focus. It is anticipated that construction of the second experimental area in this beam-line might start soon after the completion of the first experimental area. The time scale for completion and installation of our spectrometer meets well with the anticipated time scale of activating this new area. We believe that approval of this proposal at an early time is needed so that plans for the second corrected focus in P-West could be made, consistent with the plant facility requirements discussed in Section V. An early approval of this proposal is also needed to permit us to complete the fabrication of this spectrometer at HEPL.

Recently, it became evident[6] that the Proton-West secondary beam at FERMILAB has extremely powerful versatility which resulted from the use of superconducting beam line magnets and the excellent work in optical beam design.[13] We demonstrated[6] that when this beam is tuned in a prescribed manner, at the first corrected focus, 10^9 electrons/pulse are obtained with absolutely no contamination in electron beam spot, that is a pure electron beam, over electron beam energy dynamic range of 25 GeV to 800 GeV, whereby contamination pions are separated by more than three times the electron spot size and eliminated. The principal mechanism producing this spectacular effect is based on careful consideration of the synchrotron radiation energy loss of electrons as the electron beam traverses superconducting beamline dipoles. A tuning scheme is devised such that electrons remain on optical axis and other contaminating particles are separated off optical axis, until all surviving background particles are focussed a distance of three spot sizes away from the electron spot itself. The additional advantage found over the above at the second corrected focus is that, a required 2 mm in diameter spot size will be obtained at minimal sacrifice in secondary beam intensities because now, higher order aberrations in the beam optics will be fully corrected by sextupoles in two dimensions, both in x and y, successively.

Figure 6 shows the expected intensities of electrons produced by the Proton-West beam, with 400 GeV incident protons and with momentum acceptance of $\pm 5\%$. The electron beam yield curves in this and in the following figures are from our earlier calculations.[6] The curves are now renormalized to agree with a recent measurement of electron yields performed in the Proton-East tagged-photon area, produced by 300 GeV incident protons. In Figure 7, the electron beam yield produced by 500 GeV incident protons is presented. Also, in the domain of the Energy-Doubler/Saver, we present the expected electron beam yield at the Proton-West Area, produced by 1000 GeV incident protons. This is demonstrated in Figure 8. At the second corrected focus in P-West, it is expected that by use of optimal combination of aperture stops, momentum slits and quadrupoles tuned to form a long waist at the experimental target, it will be possible to produce required beam qualities at a cost of a factor of 5 in beam intensities over what is shown in Figures 6-8. Therefore, in the range of 50-700 GeV in electron beam energies, and depending on the energy of incident protons, 10^9 - 10^{10} pure electrons or positrons per pulse (per 10^{13} incident protons) will be available for use with the 168" focussing spectrometer.

Similarly, it is demonstrated(13) that 10^9 - $10^{10}\pi^-$/pulse beams can be made available in the energy range of 50 - 800 GeV, with beam qualities fulfilling the requirements of the 168" focussing spectrometer.

From the pure electron beam with intensity of 10^9 $e^{\pm}$/pulse, a broad-band high intensity pure gamma-ray beam is produced where the energy spectrum of photons is predictable and is well understood. The The pure photon beam is produced by inserting a 1/3 radiation-length Pb radiator placed some 20 ft ahead of the second corrected focus, allowing for a sufficient distance for bending of the electrons into a beam dump. The pure photon beam will have bremsstrahlung energy spectrum with intensity given by:

$$N_\gamma \simeq N_e \; \frac{t}{X_o} \int_{k_{min}}^{k_{max}} dk/k \;=\; N_e \cdot 1/3 \cdot \ell n \left(\frac{E_e}{k_{min}}\right)$$

For example, from a 200 GeV 10^9 e/pulse beam, the number of photons in the range of 50 GeV to 200 GeV is:

$$N_\gamma \, (50\text{-}200 \text{ GeV}) \;=\; 1/3 \cdot 10^9 \; \ell n \, (200/50) \;=\; 1/2 \cdot 10^9 \gamma/10^{13} \text{protons/pulse.}$$

We compare this yield of pure gamma-rays to that found in the Proton-East broad-band 0^o neutral beam where also a long LD_2 filter is needed to filter out the neutral hadronic contamination in the beam. A measurement in that beam gives 2×10^7 $\gamma/10^{13}$ protons/pulse in the range of 50 GeV to 200 GeV, from 300 GeV protons. We conclude that the Proton-West pion/electron beam will produce a pure photon beam with substantially higher intensity and with excellent purity, satisfying also the beam quality requirements of the 168" focussing spectrometer.

Conversion of the secondary beam line from a pion beam to a pure electron beam is accomplished by a simple procedure - it requires the removal of a remotely activated radiator at the front end of the beam, with a retuning of beam line and beam dump magnets which are under computer control.

V. SUMMARY OF PROPOSAL REQUIREMENTS

The major requirements for the implementation of this proposal are the following: a) completion of fabrication at HEPL, installation and assembly at FERMILAB, of the 168" 2.5 GeV/c focussing spectrometer, and b) construction of a plant facility servicing this spectrometer at the proposed location, that is at the second corrected focus of the Proton-West Area. We present key elements in both of these requirements together with cost estimates.

1. Completion of Fabrication of the 168" Spectrometer at HEPL

As of the present, a) magnet coils are fabricated and electrically tested, b) magnet return-flux iron plates are machined and sized to fit in an assembly consisting of 152 pieces with a total weight of 949 tons, and c) work on magnet pole faces is committed with anticipated delivery in December 1975 (8 pole-face pieces with a total weight of 196 tons). The total expenditure made for engineering, materials and fabrication of the above is $ 1.1 M. To complete the remaining fabrication tasks at HEPL the equivalent effort of 3 man-years is needed in drilling of plates for assembly bolts, and in the fabrication of a vacuum chamber and assembly tie rods. The estimated completion time of this task is Fall 1977, if approval is obtained sometime in 1975.

2. Transportation of the 168" Magnet to FERMILAB

The total shipping weight of the above equipment is 1230 tons, consisting of a) magnet coils and coil forms, b) magnet return-flux iron plates, c) magnet pole-faces, and d) magnet vacuum chamber.

The cost of transporting this equipment from HEPL to FERMILAB is estimated to be \$ 190 K. (The route is: HEPL to Redwood City port by truck, to Joliet on sea-going barge, via the Panama Canal to Baton Rouge and on to the Mississippi and Chicago rivers on the same vessel, thereafter to FERMILAB by truck.) The proposed transportation schedule is in Spring 1978.

3. <u>Plant Facility and Installation of the 168" Spectrometer System at FERMILAB</u>

A stable 4 ft thick reinforced concrete foundation is required, resting on eight 10 ft long posts which can support a weight of 2000 tons, over a surface area of 70 ft × 70 ft, at the second corrected focus of the Proton-West beam. A beam height of 6'6" is required over this foundation and a ceiling height of 50 ft is needed. Since all of the physics instrumentation will be inside the well-shielded detectors hut, a very simple shelter is needed around the spectrometer. Assembly of the magnet and, <u>fabrication</u> and assembly of the support structure will be done at this sheltered area. The estimated cost for the reinforced foundation is \$ 100 K, and the estimated cost of the installed support structure is \$ 350 K (\$ 170 K in labor and \$ 180 K in materials costs). The use of a 60 tons in capacity mobile crane for a period of one year will be required in these efforts. The estimated completion time of this task is Spring 1979. If the beam and other services could be made ready, experimental checkout work can start in Summer 1979.

4. Required Services for the 168" Spectrometer

Figure 9 shows the electrical power consumption of the 168" focussing spectrometer as a function of momentum. At 2 GeV/c the power is 2 MW and at 2.5 GeV/c it is 3.7 MW. In actual experimental running conditions power consumption should average at the 2 MW level. The supplied power should be scaled conveniently in current and voltage. The magnet is designed to carry a maximum current of 5200 A at 760 v. Current monitoring and regulation must be made at the level of 1 part in 50,000 . The effect of fast ripples in power lines will be damped by the total inductance of the magnet where $L_{tot} = 3$ H.

Recirculated cooling water is required where the maximum needed flow rate is 437 GPM at the 4 MW level. The pressure drop across the magnet coils will be 50.2 psi. The desired water pressure is 60 psi, however, higher pressures of up to 150 psi can be used. Clean water is needed having a resistivity of more than 0.015 ohm-cm. Cost estimates for these services are made at FERMILAB. We anticipate that existing power supplies could be shared during the operation of the 168" spectrometer.

5. Operating Instrumentation of the 168" Spectrometer

A central umbilical arrangement is used to carry signal and high voltage cables from the detectors hut, water piping and hoses from the magnet together with dc power supply flexible cables, such that the spectrometer can rotate freely between scattering angles of 28^{o} and 152^{o} . The cost estimate for all components of this arrangement is \$ 60 K.

As shown in Figures (3) and (4), the spectrometer rotates on wheels resting on four circular rails which are embedded in the supporting foundation. A driving mechanism with controls permits the setting of the focussing spectrometer at any desired scattering angular orientation. A high precision angle readout system is used to register the orientation of the spectrometer in experimental operations. The cost estimate for rails, wheels, drives, controls and angle readouts, totals to \$ 130 K.

No special operators are needed in the operational usage of the 168" spectrometer facility.

6. Manpower Needs for the Installation of the Proposed Spectrometer Facility

During the phase of on-site facility installation between Spring 1978 and Summer 1979, HEPL is prepared to provide the following manpower at FERMILAB:

18	man-months of physicists
8	man-months of mechanical engineers
4	man-months of electrical engineers
8	man-months of technicians
12	man-months of welders

We request the following manpower help from FERMILAB during that period of time:

4	man-months of electrical engineers
24	man-months of assembly technicians
2	man-months of structural engineers
5	months time of a rigging-crew distributed over a 12 months period
12	months rental of a 60 ton in capacity mobile crane.

7. Implementation of Experimental Physics Program

a) This experiment requires the use of an external proton beam of at least 5×10^{12} protons/pulse at the highest possible energy, incident on a 40 cm long Be target for the production of designated secondary beams.

b) The experimental target will be 20 cm long LH_2/LD_2. We are prepared to fabricate this target with 1 mil Beryllium windows and match it with a FERMILAB standard LH_2/LD_2 targeting system.

c) 900 hours of running time are required to complete the physics planned for this proposal. An additional 200 hours of equivalent beam time is estimated for the purposesof (a) optical calibration of the 168" focussing spectrometer, (b) calibration and checkout of the experimental apparatus in the detectors hut and (c) overall systems checkout work, distributed over a period of 6 months.

d) To accomplish the proposed goals, the group of experimenters making this proposal will be augmented by three post-doctoral physicists and several graduate students. Also we expect no difficulty in finding other collaborators once this proposal is approved and we welcome the interest of other colleagues at this time.

e) The experimental physics equipment designated in this proposal, together with the matched use of an on-line computer system, requires a preparation time of a minimum of 24 months. We have already accomplished all developmental efforts in terms of hardware and electronics prototype units.

f) Approval of this proposal is needed at this time so that the goal of implementing the proposed physics program could begin in Summer 1979.

* * *

We are grateful to the Directorate of FERMILAB for their interest and their encouragement in the development of a physics proposal with use of the 168" high precision focussing spectrometer. A site visit to HEPL by Dr. A. L. Read was made possible and we are pleased to acknowledge for several stimulating discussions which were helpful in formulating this proposal.

TABLE I

CHARACTERISTICS OF THE 168" HEPL 2.5 GeV/c HIGH RESOLUTION LARGE ACCEPTANCE SPECTROMETER

Optics	point-to point double focussing, $n = 1/2$ magnet, unit magnification at $\theta = 90°$
Target length	13 cm target acceptance (flat-top of distribution); 39 cm acceptance full length (at base of distribution).
Maximum momentum	2.5 GeV/c
Solid angle acceptance	8.53×10^{-3} strad.
Horizontal angular acceptance	37.7 mrad.
Vertical angular acceptance	226.3 mrad.
Momentum acceptance	11.12% (FW)
Momentum resolution	10^{-4}
MWPC spatial resolution required to match momentum resolution	$\pm$ 1.7 mm
MWPC spatial resolution actually available	$\pm$ 0.6 mm
Production angular resolution	$\pm$ 0.1 mrad
Power requirement (See graph)	2 MW at p_{max} = 2 GeV/c 3.7 MW at p_{max} = 2.5 GeV/c
Total spectrometer turning radius	32'6" ; 9.9 m
Beam line height from supporting floor	6'6" ; 1.98 m
Total spectrometer height from supporting floor	46' ; 14 m
Magnet weight	1100 tons; 1010 metric tons
Magnet superstructure weight	300 tons; 272 metric tons

TABLE II

300 GeV/c pp Elastic

p_3 (MeV/c)	θ_3 (deg)	t (GeV^2)	f_{p_1} (GeV) $\Delta M/\Delta p_1/p_1$	f_{p_3} (GeV) $\Delta M/\Delta p_3/p_3$	rms Momentum error $\Delta p_3/p_3 \cdot 10^{-4}$	f_{θ_3} (GeV) $\Delta M/\Delta\theta_3$	rms Angle error $\Delta\theta_3 \cdot 10^{-4}$	(MeV) $\Delta M)_{p_3}$	(MeV) $\Delta M)_{\theta_3}$	(MeV) ΔM
536	74.55	0.267	0.1428	39.630	3.190	165.210	8.293	12.642	137.009	137.6
1486	56.44	1.537	0.8217	140.280	1.000	395.880	1.533	14.280	60.688	62.3
2404	46.74	3.084	1.6476	191.520	1.000	559.800	1.000	19.152	55.980	59.2

900 GeV/c pp Elastic

p_3 (MeV/c)	θ_3 (deg)	t (GeV^2)	f_{p_1} (GeV) $\Delta M/\Delta p_1/p_1$	f_{p_3} (GeV) $\Delta M/\Delta p_3/p_3$	f_{θ_3} (GeV) $\Delta M/\Delta\theta_3$	(MeV) $\Delta M)_{p_3}$	(MeV) $\Delta M)_{\theta_3}$	(MeV) ΔM
559	74.00	.289	0.1542	127.080	515.700	40.539	427.67	429.6
1509	56.20	1.573	0.8394	425.160	1202.670	42.516	184.37	189.2
2477	46.27	3.210	1.7124	581.850	1716.930	58.185	171.69	181.3

TABLE III

300 GeV/c $\pi p \rightarrow p$ + anything

MM = 5 GeV			(GeV)	(GeV)	(MeV)	(MeV)	(MeV)	(GeV)	$(GeV)^2$
MeV/c	p_3	θ_3	$\Delta m/\Delta p_3/p_3$	$\Delta m/\Delta \theta_3$	$\Delta M)_{p_3}$	$\Delta M)_{\theta_3}$	ΔM	ΔM_{accept}	$(dt/d\Omega)\ \Delta\Omega_{accept}$
	500	70.54°	4.157	28.286	1.326	23.458	23.5	1.33	0.0043
	1500	54.32°	24.046	73.106	2.405	11.207	11.5	4.18	0.0121
	2500	44.64°	34.202	105.398	3.420	10.540	11.1	6.00	0.0262
MM = 10 GeV			(GeV)	(GeV)	(MeV)	(MeV)	(MeV)	(GeV)	$(GeV)^2$
MeV/c	p_3	θ_3	$\Delta m/\Delta p_3/p_3$	$\Delta m/\Delta \theta_3$	$\Delta M)_{p_3}$	$\Delta M)_{\theta_3}$	ΔM	ΔM_{accept}	$(dt/d\Omega)\ \Delta\Omega_{accept}$
	500	54.32°	1.672	12.184	0.533	10.104	10.1	0.57	0.0054
	1500	48.19°	8.274	33.541	0.827	5.142	5.2	1.7	0.0177
	2500	40.40°	13.326	48.609	1.333	4.861	5.0	2.6	0.0336
MM = 15 GeV			(GeV)	(GeV)	(MeV)	(MeV)	(MeV)	(GeV)	$(GeV)^2$
MeV/c	p_3	θ_3	$\Delta m/\Delta p_3/p_3$	$\Delta m/\Delta \theta_3$	$\Delta M)_{p_3}$	$\Delta M)_{\theta_3}$	ΔM	ΔM_{accept}	$(dt/d\Omega)\ \Delta\Omega_{accept}$
	1500	36.34°	1.349	17.777	0.135	2.725	2.73	0.80	0.0721
	2500	32.35°	4.718	26.755	0.472	2.676	2.72	1.29	0.0632

$(\Delta \theta_3)_{accept}$ = 0.0377 rad; $\Delta\Omega_{accept}$ = 0.00853 sr; $(\Delta p_3/p_3)_{accept}$ = 0.1112

TABLE IV

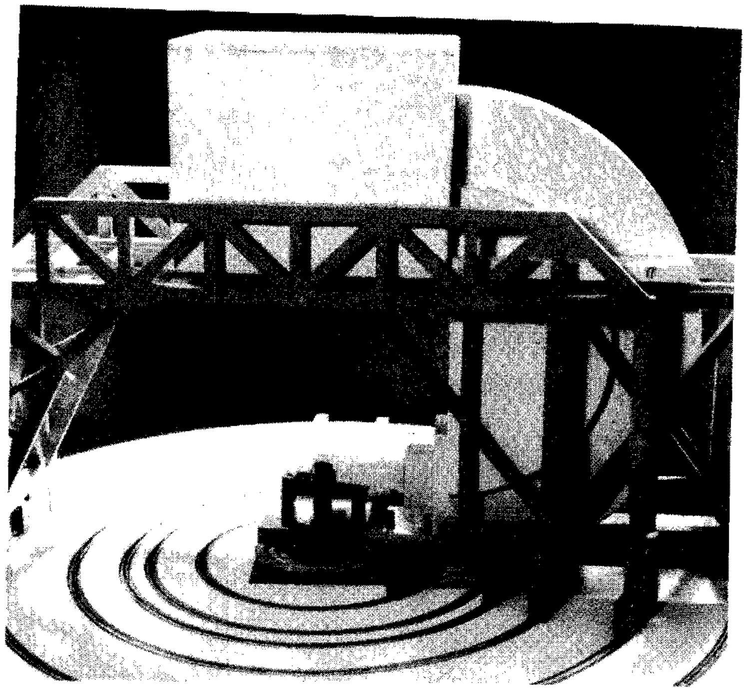
MOMENTUM TRANSFER RESOLUTION AND ACCEPTANCE IN

$pp \rightarrow pp$ AND $\pi p \rightarrow p\pi$

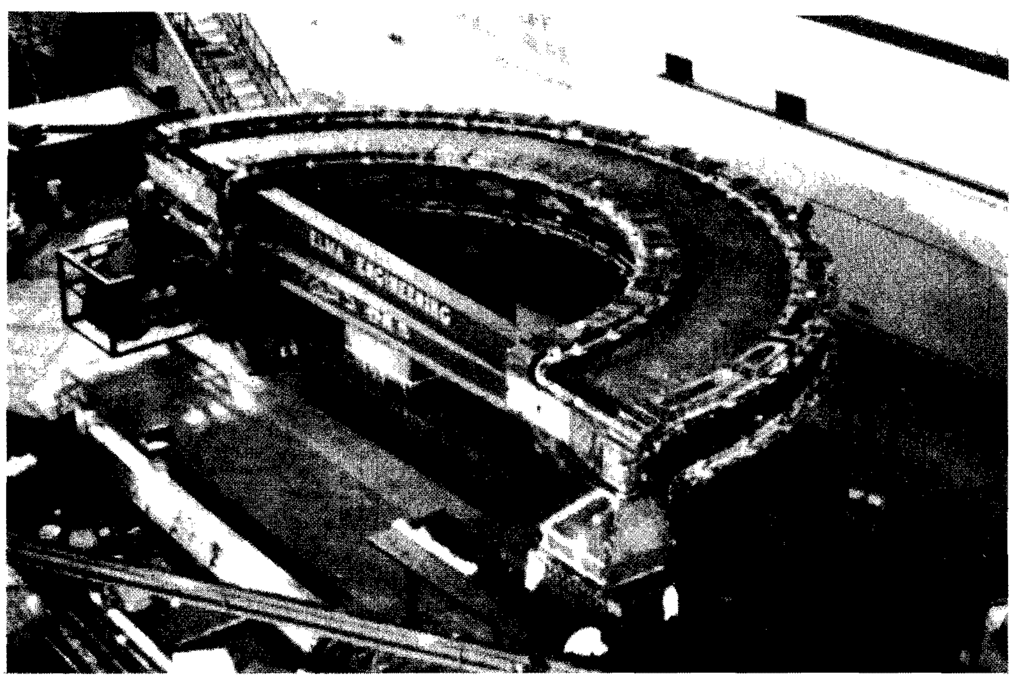
GeV/c p_3	GeV^2 t	GeV^2 δt	GeV^2 $\Delta t(FW)_{accept}$	GeV^2 Δt $azimuth_{accept} = (dt/d\Omega)\Delta\Omega_{accept}$
0.200	0.0396	0.00062	0.0088	0.0010
0.500	0.2344	0.00014	0.0494	0.0027
1.000	0.8125	0.00014	0.1533	0.0063
1.500	1.5594	0.00024	0.2673	0.0110
2.000	2.3849	0.00034	0.3806	0.0171
2.500	3.2502	0.00044	0.4919	0.0244

$\Delta\Omega$ = 0.00853 sterad

See Table II for rms $\delta p_3/p_3$

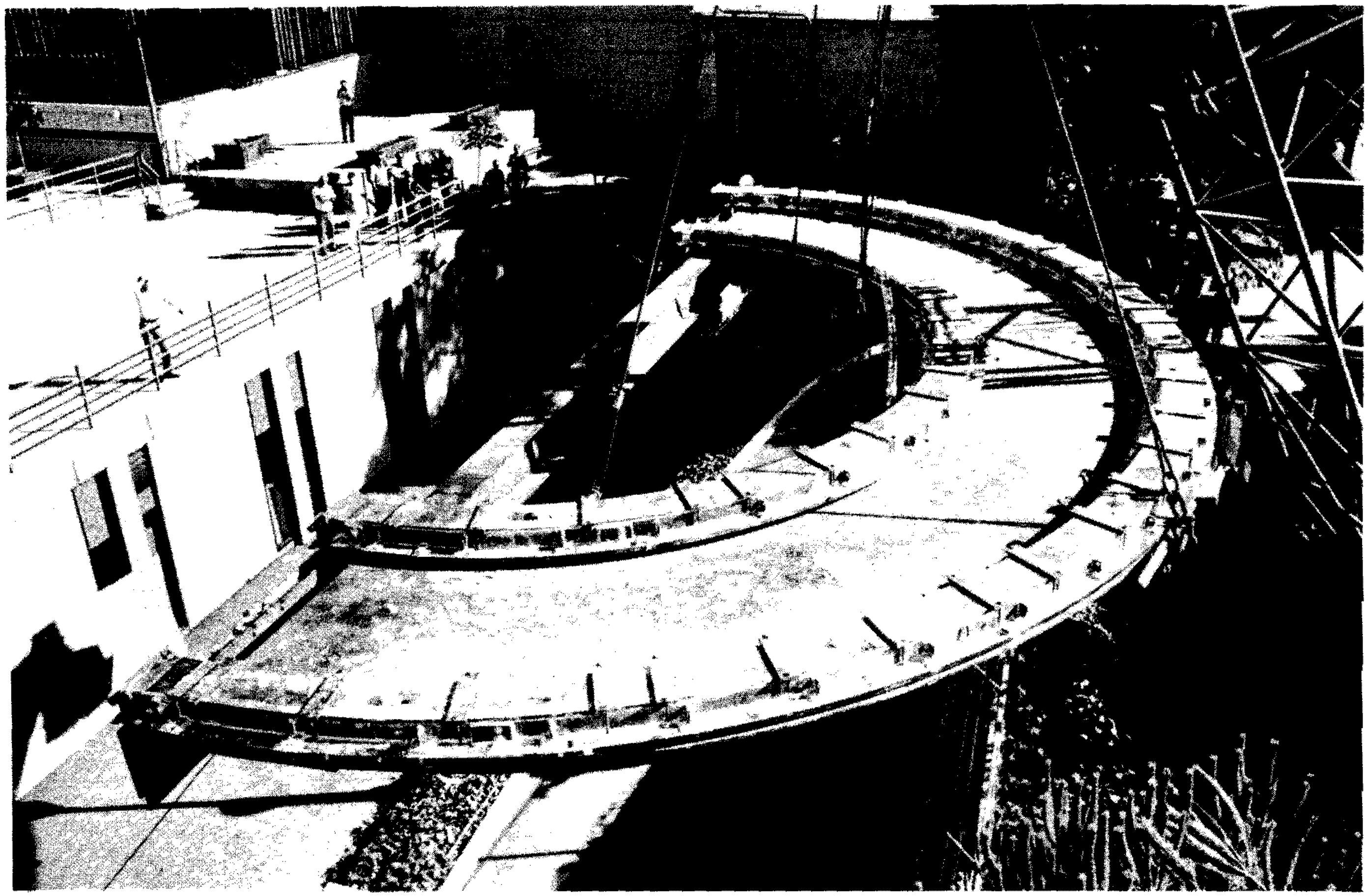


(a) Model of the H.E.P.L. 168" Focusing Spectrometer and Superstructure.



(b) Fabrication Coils of the 168" Focusing Spectrometer with Coil Forms, at H.E.P.L. End Station. (Delivered in Fall 1974.)

Figure 1



WORLD'S LARGEST MAGNET COIL, the first of two built by ELMA ENGINEERING, is a component of the 168-inch spectrometer now under construction at Stanford University's High Energy Physics Laboratory. Slightly over ½ of a mile -- 2,685 feet to be exact or 8 tons of extruded 1-inch by .8 inch copper conductor with .46-inch diameter cooling passage was required for the 44-turn coil. Operation will require 3.5 megawatts of power and 437 gallons of water per minute. A special technique and formulation for vacuum epoxy encapsulation of the coils was developed by Elma to withstand high radiation environments and to provide long, maintenance-free operation.

Figure 2

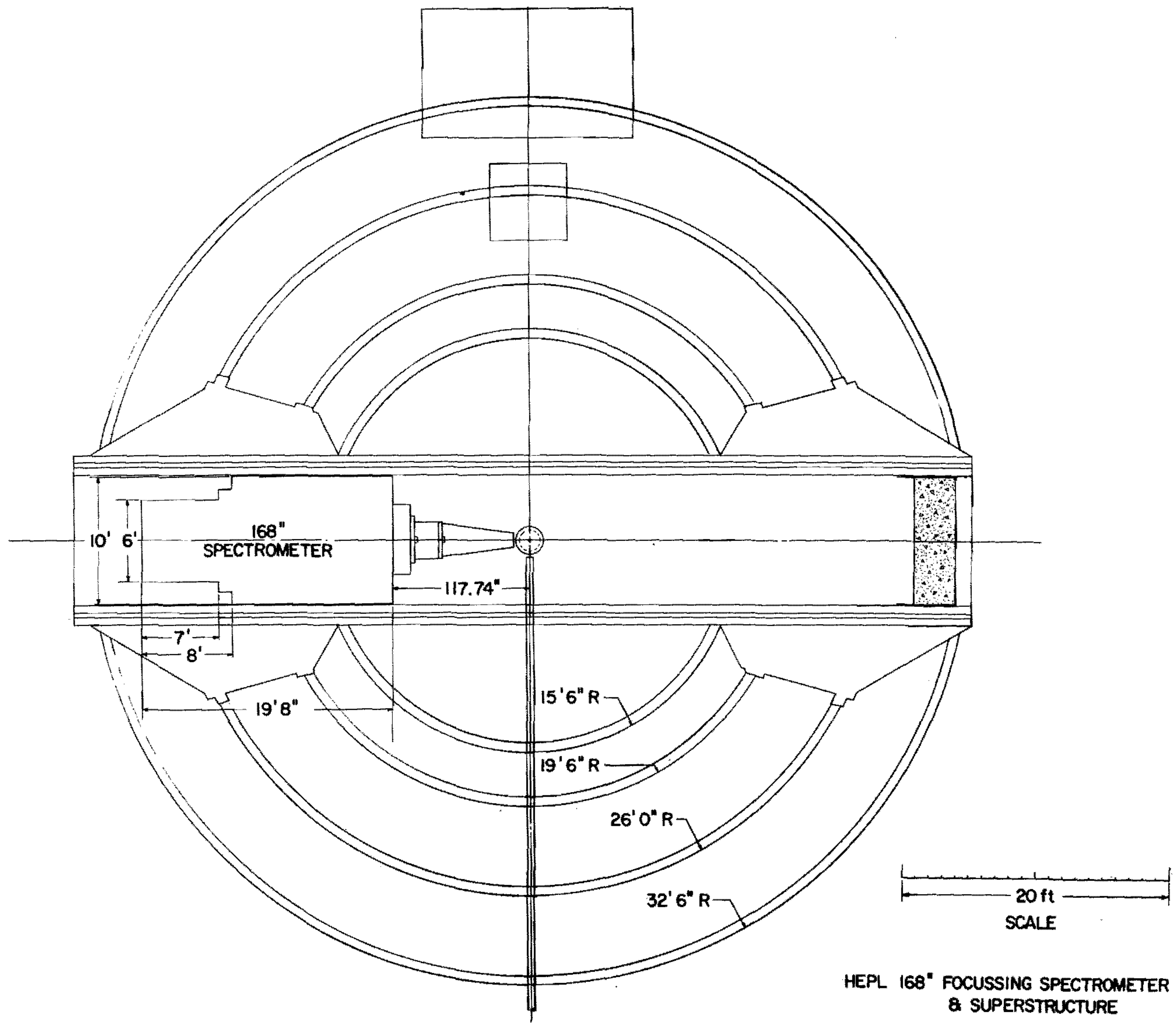
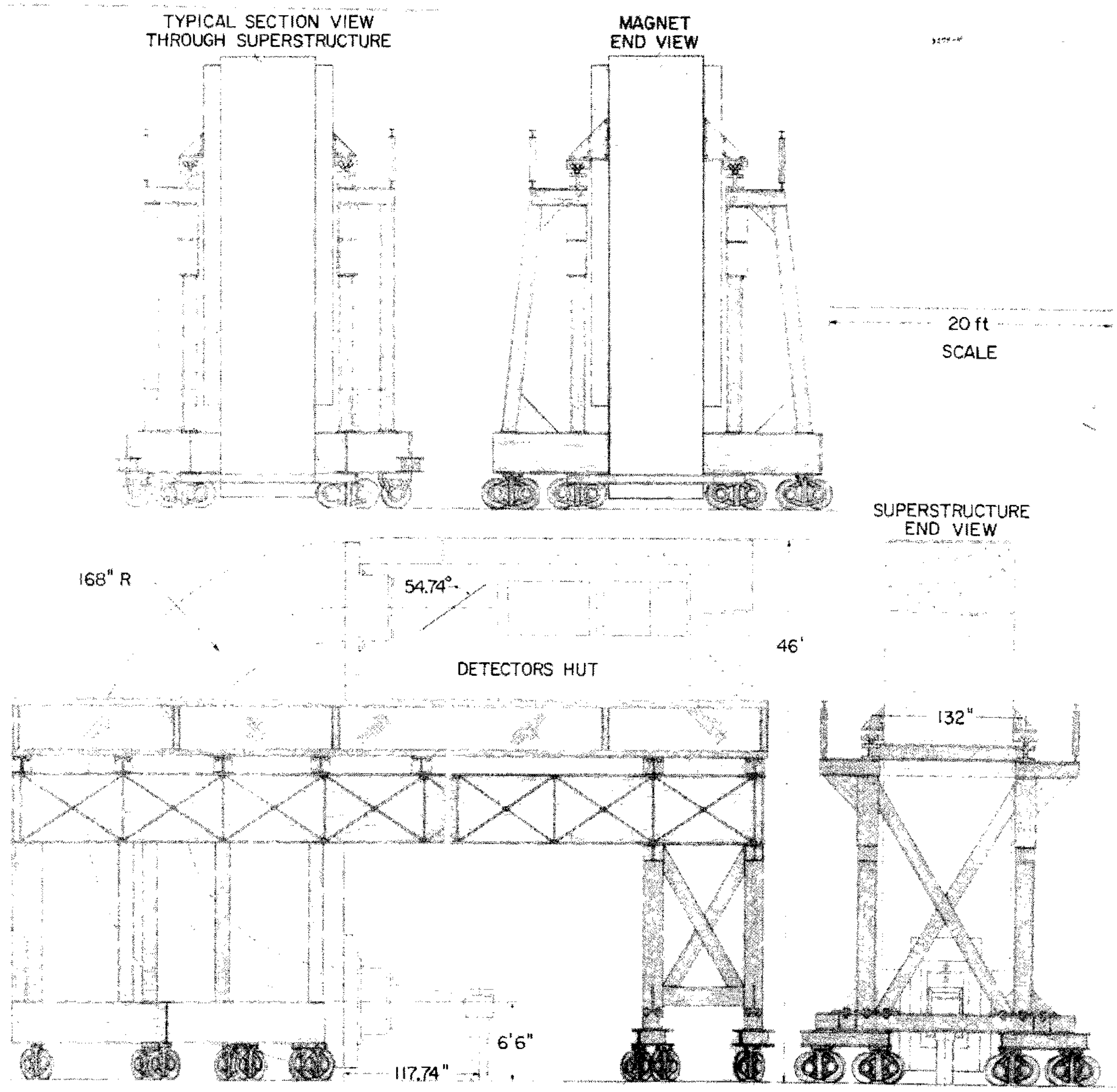
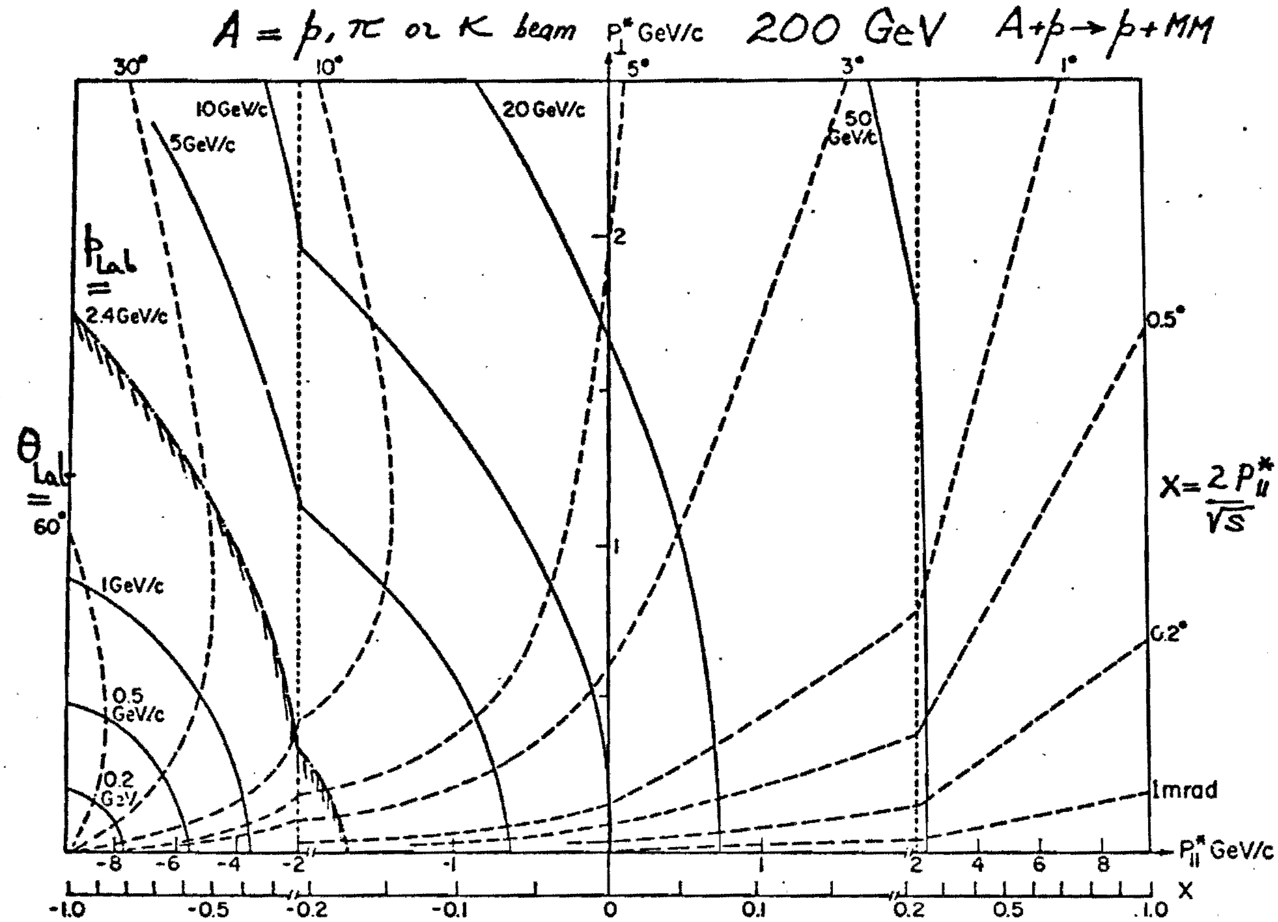

168"
SPECTROMETER
10'
6'
117.74"
7'
8'
19'8"
15'6" R
19'6" R
26'0" R
32'6" R
20 ft
SCALE
HEPL 168" FOCUSSING SPECTROMETER
& SUPERSTRUCTURE

Figure 3



DETAILS OF THE HEPL 168" FOCUSSING SPECTROMETER & SUPERSTRUCTURE

Figure 4


A = p, π or K beam
200 GeV A+p→p+MM
P⊥* GeV/c
30°
10°
5°
3°
1°
10 GeV/c
5 GeV/c
20 GeV/c
50 GeV/c
P Lab =
2.4 GeV/c
θ Lab =
60°
1 GeV/c
0.5 GeV/c
0.2 GeV/c
0.5°
0.2°
1mrad
X = 2P∥*/√s
P∥* GeV/c
X

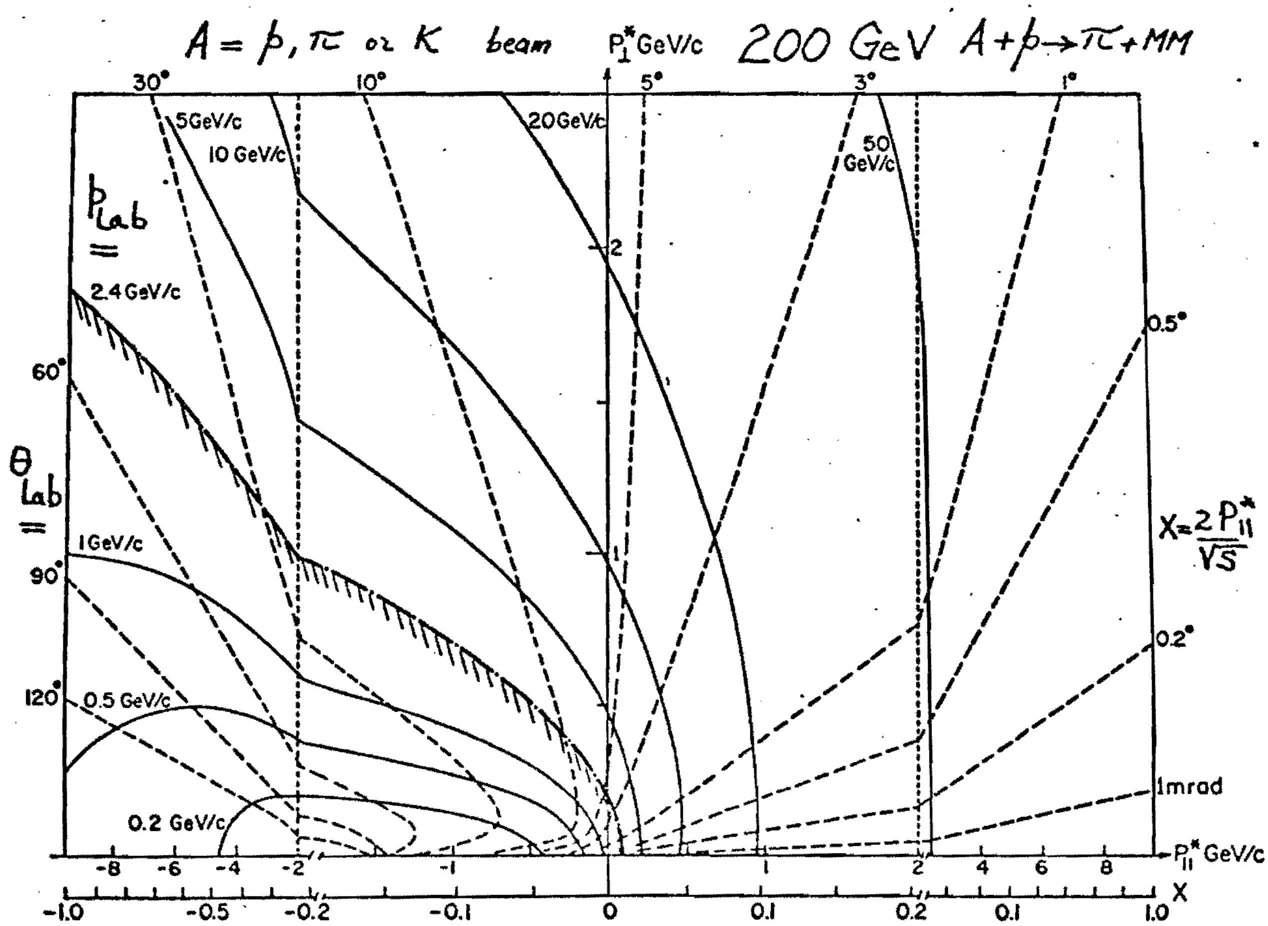

A = p, π or K beam
200 GeV A+p→π+MM
P⊥* GeV/c
30°
10°
5°
3°
1°
5 GeV/c
10 GeV/c
20 GeV/c
50 GeV/c
P Lab =
2.4 GeV/c
60°
θ Lab =
1 GeV/c
90°
120°
0.5 GeV/c
0.2 GeV/c
0.5°
0.2°
1mrad
X = 2P∥*/√s
P∥* GeV/c
X

FIGURE 5

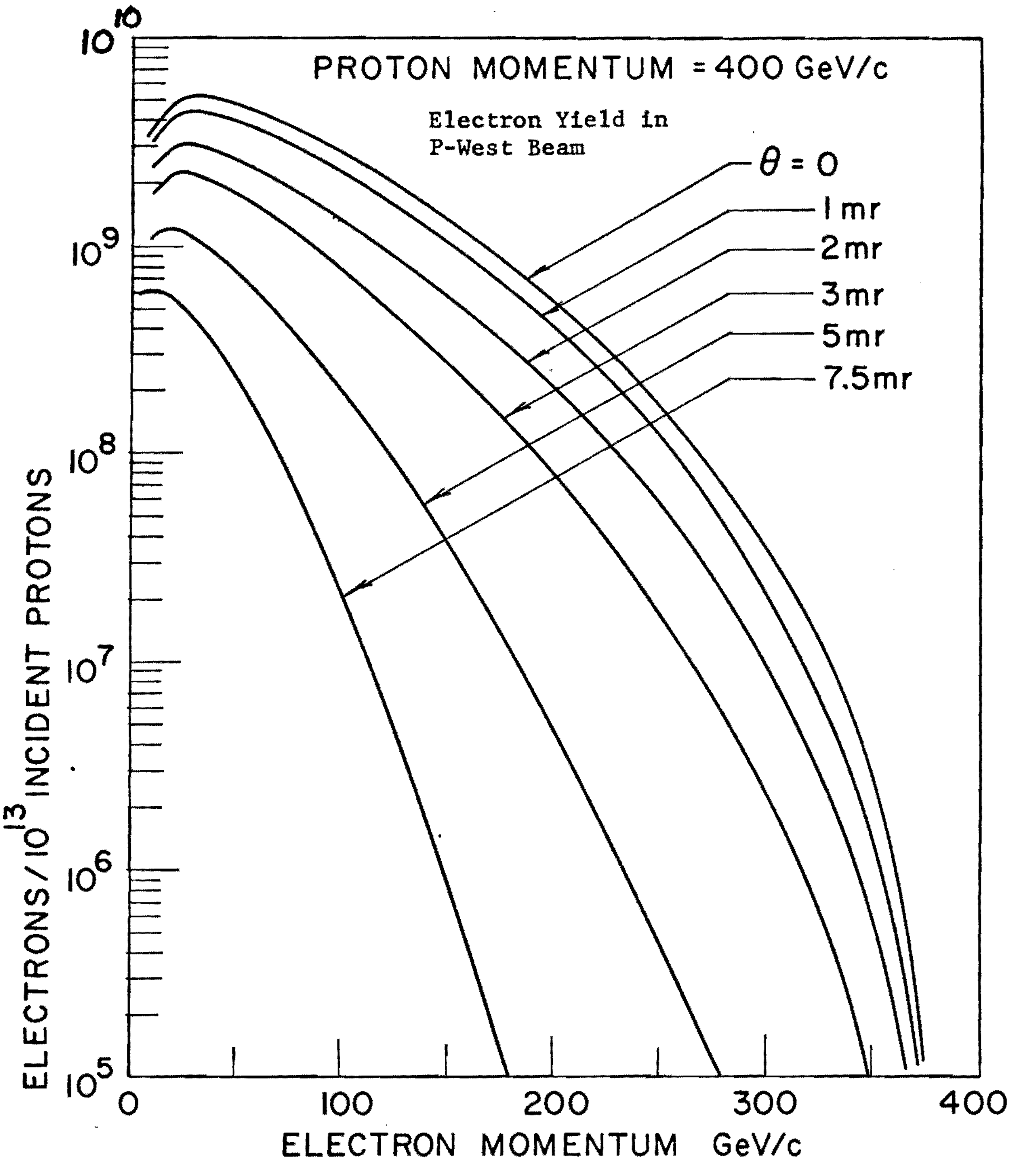

PROTON MOMENTUM = 400 GeV/c
Electron Yield in
P-West Beam
θ = 0
1 mr
2 mr
3 mr
5 mr
7.5 mr
ELECTRONS/10^13 INCIDENT PROTONS
10^10
10^9
10^8
10^7
10^6
10^5
0
100
200
300
400
ELECTRON MOMENTUM GeV/c

FIGURE 6

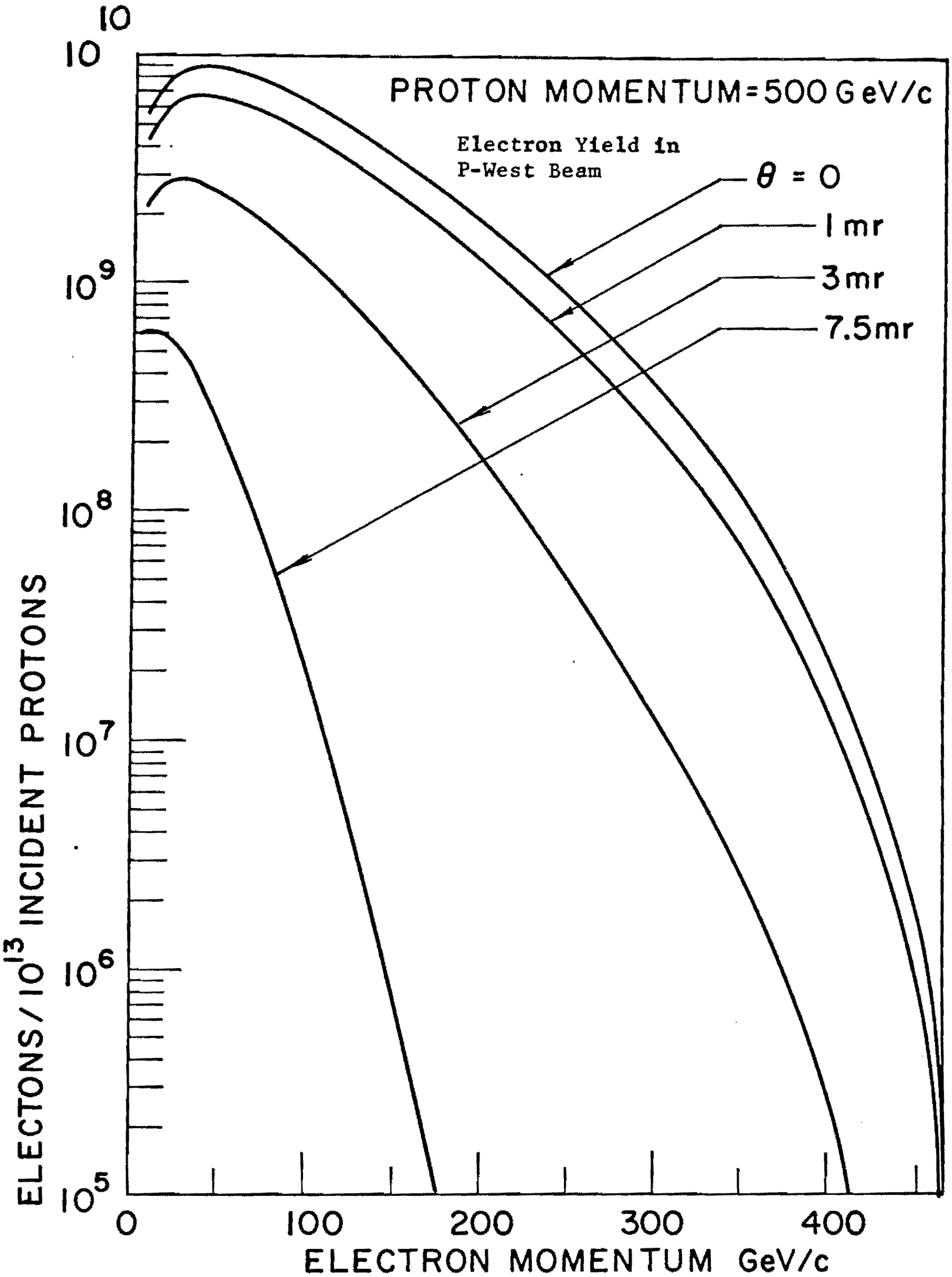
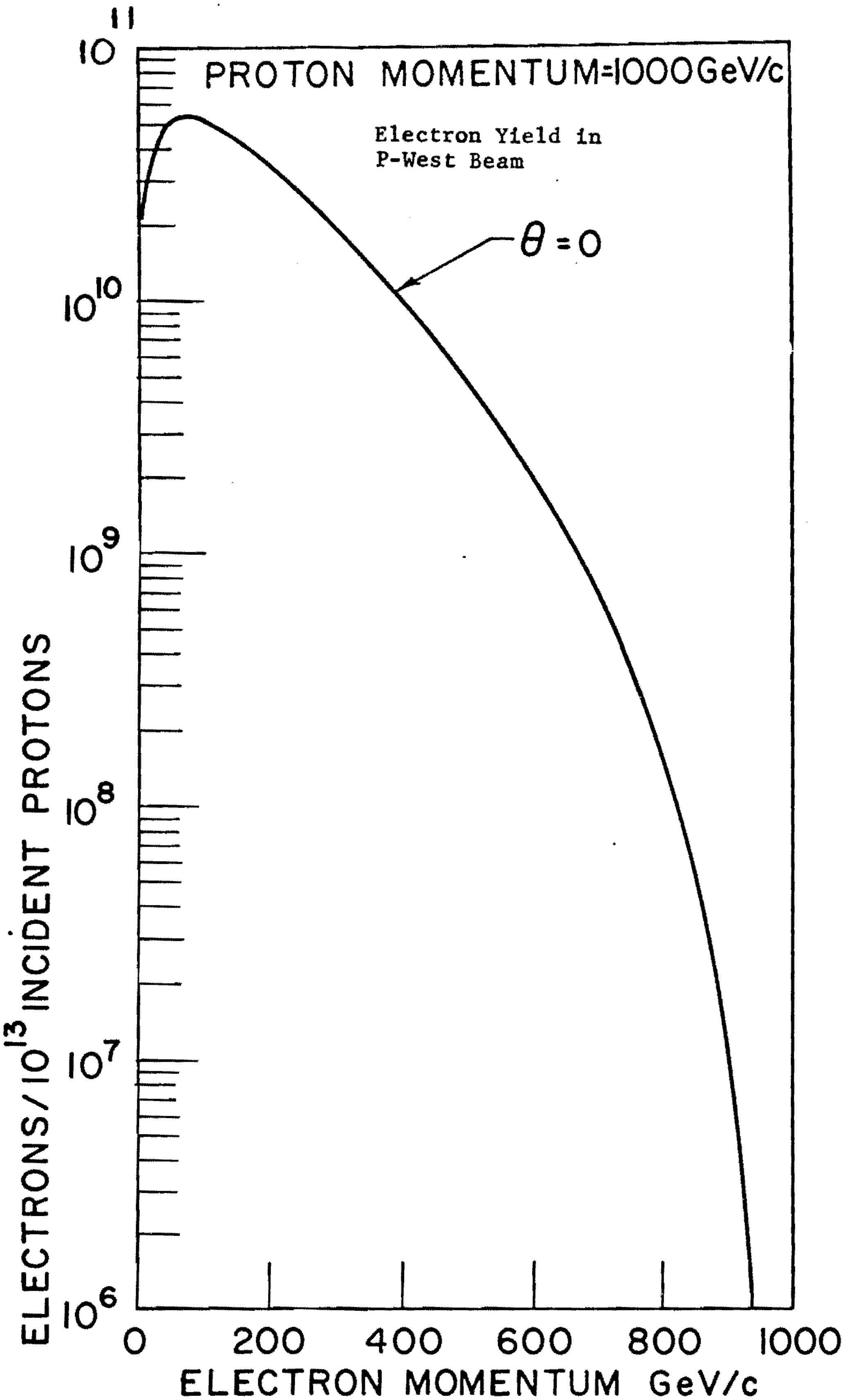

PROTON MOMENTUM = 500 GeV/c
Electron Yield in
P-West Beam
θ = 0
1 mr
3 mr
7.5 mr
ELECTONS/10^13 INCIDENT PROTONS
10^10
10^9
10^8
10^7
10^6
10^5
0
100
200
300
400
ELECTRON MOMENTUM GeV/c

FIGURE 7



PROTON MOMENTUM=1000GeV/c
Electron Yield in
P-West Beam
θ=0
ELECTRONS/10^13 INCIDENT PROTONS
ELECTRON MOMENTUM GeV/c
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
0
200
400
600
800
1000

FIGURE 8

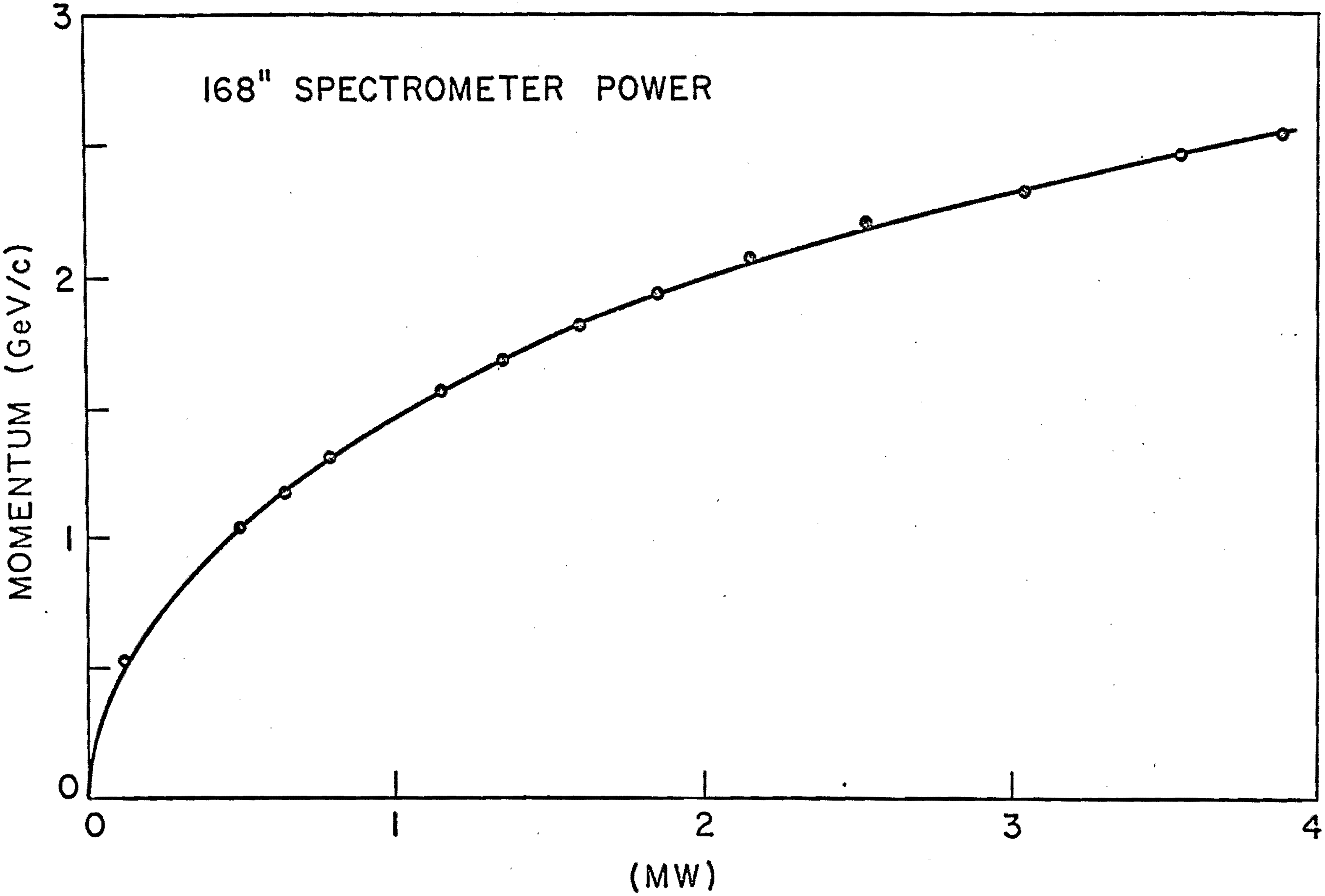


FIGURE 9

REFERENCES

1. R. R. Wilson, Scientific American, 230, 72 (1974).
2. Z.G.T. Guiragossián and R. Hofstadter, "Technical Description of the HEPL 168" Focussing Spectrometer," HEPL-Report No. 754, (1975).
3. G. Barbiellini *et al*, Phys. Letts., 39B, 663 (1972).
4. V. A. Tsarev, NAL-Pub-74/17-THY/EXP (1974).
5. A. Böhm *et al*, Phys. Letts., 49B, 491 (1974).
6. Z.G.T. Guiragossián, "50-800 GeV, 10^8-10^{10} Pure Electron and Broad-Band Photon Beams at FERMILAB," HEPL-Report No. 756 (1975); see also, Z.G.T. Guiragossián *et al*, Amendment of FERMILAB Proposal No. 193 (1975).
7. Yung-Su Tsai, "Radiative Corrections to Electron Scatterings," SLAC-PUB-848 (1971), and private communications (1975).
8. cf. the proposal of FERMILAB Experiment No. E-192 by Z.G.T. Guiragossián *et al*, (Stanford-University FERMILAB Rice-University Collaboration).
9. B. Knapp *et al*, Phys. Rev. Letts., 34, 1040 (1975).
10. Z.G.T. Guiragossián and A. L. Read, "The Potential Physics Program of the 168" HEPL Focussing Spectrometer at FERMILAB," HEPL-Report No. 755 and FERMILAB TM (1975).
11. Thin 1 mil Beryllium sheets are supplied by Beryllco and Brush Beryllium companies. The technology of fabricating Beryllium window flanges is developed at the Lawrence Livermore Laboratory.
12. D. L. Judd, Phys. Rev. 21, 213 (1950); S. Penner, Phys. Rev. 32, 150 (1961).
13. B. C. Cox, "P-West High Intensity Secondary Beam Area Design Report," FERMILAB TM (1975).