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SIMULTANEOUS EXPERIMENTS WITH THE M ACCELERATOR

By
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The purpose of this note is to investigate the feasibility of multiple experimental arrangements operating simultaneously in conjunction with the Stanford two-mile electron accelerator (Project M). The intensity expected from M (30 μamps at 20 Bev) will, in many instances, certainly be adequate for this purpose. For example, an experiment for which the total cross section is ~ 1 μb can operate with counting rates of about 1/sec using between 0.1 and 1.0% of the available intensity. Several experiments can operate simultaneously only if there is no significant interference between them. The attempt here is to guess at: (a) what are the likely types of experiments?; (b) what beam conditions will be desirable for each type?; (c) how shall the experimental areas be located to minimize the interference between the various experiments?

The presently predictable uses of M seem to fall primarily into four categories:

(1) Production of particle beams. The work of Drell[1] and Ballam[2] indicates that M will be a rich source of various particle beams--very

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[1] S. D. Drell, "Production of Particle Beams at Very High Energy," M Report No. 200-7A, Project M, Stanford University, Stanford, California, August 1960.

[2] J. Ballam, "Secondary Particle Yields from High Energy Electron Accelerators," M Report No. 200-8, Project M, Stanford University, Stanford, California, August 1960.

likely the richest source in existence. There seems little doubt that a major aspect of the experimental program will be the production and use of such beams.

(2) Electrodynamics experiments. Large-angle pair production, μ-pairs, etc.

(3) Electron scattering.

(4) Electro- and photo-production of strongly interacting particles, e.g.,

$$\begin{aligned}\gamma + p &\rightarrow \pi^+ + n\\ &\rightarrow K^+ + \Lambda^0\\ &\rightarrow K^+ + \Sigma^0\\ &\rightarrow K^+ + \Lambda^0 + \pi^0\\ &\rightarrow \bar{p} + p + p\\ &\rightarrow K^- + K^+ + p\end{aligned}$$

and similarly with electrons. This list can be extended practically indefinitely. For instance, the above list doesn't even mention the production of antihyperons.

What are likely to be the desirable properties of the beam in each of these cases? For the production of beams of particles the situation seems clear. The beam should be of as high intensity and energy as possible. Precise definition of the energy will probably not be important, i.e., a change of a few percent in electron energy will not change the flux in the particle beams appreciably except at the highest energies. For the experiments in electrodynamics or electron scattering (particularly those interesting cases in which there is a large momentum transfer) the cross sections may be so small that even the intensity planned for M may become marginal.[3] The energy desired will probably vary from several Bev to the full energy, with good definition.

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[3] J. M. Cassels, "Electron-Proton Scattering in the Gev Range," M Report No. 200-5, Project M, Stanford University, Stanford, California, August, 1960.

In the fourth category, the photoproduction of strongly interacting particles, the beam requirements seem to me to be very different from the requirements for the production of particle beams. Firstly, I believe the energy region of major, or at least considerable, interest may well be below the peak energies available; for instance, from 2-15 Bev. It will be desirable to have the energy very well defined with the ability to make fine adjustments--changes of perhaps one or two percent. The intensity required, perhaps even desirable, will be considerably less (~ 1%) than the full intensity available. I shall argue the reasons for these conclusions below. Accepting provisionally these conclusions, it appears that the beam characteristics demanded by the various experiments will differ enormously. How can this variety of demands be met simultaneously?

The design of M seems particularly appropriate for satisfying the condition of supplying a variety of energies. It is clear that some fraction of the 360 pulses/sec can be supplied at the peak energy and the rest at any other energy or energies desired. One method of doing this[4] that has been suggested is to have various injection stations along the accelerating tube. Another obvious possibility is to provide experimental areas at various places along the accelerator--say at the nominal 5, 10, and 15 Bev positions. The latter possibility seems to me definitely superior for the following reasons: (a) It leaves the end-station free for additional experimental set ups. In effect, it simply provides more experimental area. (b) It provides experimental area appropriate to the energy for which the area is being used. The end stations must be prepared to handle beams of the maximum energy. The space allowed for experiments at 45 Bev will be very luxurious, expensive, and inconvenient when used for experiments at 5-10 Bev. (c) The intermediate stations will be more flexible and offer no significant interference to operation in the end station. These stations can be made safe for personnel to work in regardless of the beams going to other areas. The same condition can be satisfied in the end station but with much greater expense and difficulty. This last point seems

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[4] R. F. Mozley, private communication.

to me a very important one. (d) Any extensive remodeling of the end stations (for instance, installation of large shielding equipment for neutrino experiments) might well stop all experimentation in the end station for a period. The midway stations would be unaffected. (e) Large parts of the accelerator could be serviced without interfering with the midway station operation. The initial stages of the accelerator operation may well involve a period of a year or more in which modifications will be made and tested. This kind of development could be done simultaneously with an experimental program in the intermediate stations. (f) If desired, one could have two 10 Bev accelerators by providing an injector along the accelerating tube.

The above arguments for the desirability of the intermediate stations depend largely on the belief that experiments on certain electrodynamic processes, electron scattering, and on the photoproduction of strongly interacting particles will devote much of their attention to the energy region 2-15 Bev. I would like to point out some reasons for believing this. For electron-proton scattering, it is obvious that the complete energy range will be investigated. The intermediate stations allow this experiment to be done at several energies at once. For the photoproduction of strongly interacting particles, it is clear that this energy range offers a very rich vein for experimentation, particularly in the photoproduction of strange particles. (I would like for the present to consider only reactions in which the final state consists of 2- particles, i.e., $\gamma + p \rightarrow \pi^+ + n$; $\gamma + p \rightarrow K^+ + \Lambda^0$. Reactions in which three or more particles appear in the final state offer a particular problem for M because of the short duty cycle, and I shall defer discussion of this kind of process.) There is no a priori reason, as far as I can see, that the experimental information on these two-body reactions will have more theoretical interest at 45 Bev than at 5 Bev. In fact, the reverse seems likely because of the many channels opened up at the higher energies due to many-bodied reactions. The experimental difficulties increase rapidly at the higher energies.

To fix ideas on this last point, we consider specifically the reaction $\gamma + p \rightarrow K^+ + \Lambda^0$. At 5 Bev, one can do this experiment by purely conventional techniques. One can measure the energy and angle of the K^+, which determines the kinematics. The K^+ can be magnetically analyzed and detected in Cerenkov counters of conventional design. (I will make more detailed and quantitative statements about this experiment in a subsequent memo.) One precaution that must be taken is to make sure that the K's do not arise from the reaction $\gamma + p \rightarrow K^+ + \Lambda^0 + \pi^0$. This can, in general, be done by controlling the peak energy of the γ-ray beam carefully. There will be an energy interval of approximately 150 Mev for which the three-body final state is kinematically forbidden. At 5 Bev, the peak energy must therefore be $< 3\%$ greater than the energy at which the experiment is being done. The thin-target bremsstrahlung spectrum is up on the plateau at 3% below the peak energy. Thus, controlling the energy to the required accuracy and monitoring the relevant number of quanta are both essentially trivial problems.

At 20 Bev, the same experiment is beset by difficulties: (a) There are no conventional techniques for identifying K-mesons of this momentum. (b) To eliminate the inelastic processes requires working within 1% of the peak energy. Since the spectrum is varying rapidly at this energy, monitoring the number of quanta requires detailed information about the upper end of the spectrum. The energy must be kept constant to certainly better than 0.1%, and the resolution of the spectrometer must be considerably better than 1%.

In making such broad statements, I realize that I am neglecting several possible techniques which will relax considerably some of these restrictions, e.g., detecting the Λ^0 as a handle on the reaction. Also, one may anticipate the development of new techniques. However, I think it is safe to say that the experimental difficulties increase greatly at the higher energies with no obvious gain in theoretical value. I am not arguing that the experiments should <u>not</u> be done at higher energy, only that they <u>should</u> be done at the lower energies. It might be argued that the 2-6 Bev region will be well investigated by C.E.A. and Hamburg before M is operating. The richness of reactions (see the list) and the history of this kind of experiment over the last decade (the reaction $\gamma + p \rightarrow \pi^0 + p$ is still only qualitatively known in the region 200-500 Mev after a decade of investigation) show the unreliability of this argument. In addition, of course, the 6-15 Bev region will certainly not have been looked at. At the risk of laboring the point, let me repeat the main contention of this discussion. The energy region below 15 Bev is apt to be one of major interest for some important classes of experiments. It seems to me that low energy beams can be provided more simply, conveniently, and flexibly, and perhaps, less expensively, in intermediate experimental stations than in the logistically complex end station.

The decision as to the number and location of such stations requires careful consideration. For orientation purposes, I will assume three such stations at 5, 10, and 15 Bev energies. What should be the size of these stations? What facilities should they contain? I believe the size will be determined primarily by the size of the magnetic analyzing systems. One need only look at the experimental programs at Stanford, Cornell, Cal Tech, and Frascati to realize that practically no experimental set up is without an analyzing magnet for at least one of the reaction products. The momentum range desirable for an analyzing system is obvious. Reaction products emerging in the forward direction in the laboratory, in the multi-Bev region, tend to carry the full momentum of the initial beam. Thus, the systems should be capable of going to the momentum of the particles in the beam, i.e., 5, 10, and 15 Bev. Particles emerging at large angles to the beam direction tend to have very low momenta.

More precisely, consider a reaction $\gamma + p \rightarrow A + B$. Let particle A emerge at 90° in the laboratory. Then

$$E_A = \frac{2kM + M^2 + M_A^2 - M_B^2}{2(k + M)}$$

where E_A is the total energy of particle A, k is the energy of the incident γ-ray or electron, M_A is the mass of particle A, M_B is the mass of particle B, and M is the proton mass.

In limit of large k (i.e., $k \gg M$, M_A or M_B),

$$E_A \rightarrow \frac{2kM}{2(k + M)} = \frac{2M}{2\left(1 + \frac{M}{k}\right)} \cong M$$

Thus the total energy approaches 1 Bev and the maximum momentum approaches 1 Bev/c. For a variety of obvious reasons, it would be unwise to use a magnet designed for 5 or 10 Bev/c at 1 Bev/c. Therefore, it seems that each station should be equipped with two analyzing systems: one capable of reaching the momentum of the beam particles, and one capable of going to approximately 1 Bev/c. No pretense is made here to design all-purpose magnetic analyzing systems. We are investigating the most general properties of such systems primarily to orient ourselves as to the nature of the experimental areas. From the arguments made above, it is clear that the magnetic analyzers should be capable of high momentum resolution. We assume (somewhat, but not completely, arbitrarily) a $\Delta p/p \cong 1\%$. What solid angle? Of course, the answer is as large as possible. A somewhat more quantitative guess can be made from the following consideration. We imagine an experiment

$$\gamma + p \rightarrow A + B$$

for which $\sigma_T \cong 10^{-30}$ cm^2, where σ_T is the total cross section (a reasonable cross section for strange-particle production by γ-rays). The hydrogen target length is 6 inches, and the γ-ray intensity $Q = 5 \times 10^{11}$ equivalent quanta/sec. This corresponds to taking every sixth pulse of the accelerator through a converter thickness of 0.01 radiation lengths.

The γ-ray energy interval used in the experiment is $dk/k = 0.01$. This condition implies, generally, a spectrometer resolution of 1%. We define

$d\Omega_L$ = solid angle of spectrometer

N = number of counts/sec

$$N = Q \frac{dk}{k} N_T \left(\frac{d\sigma}{d\Omega}\right) d\Omega_L \left(\frac{d\Omega_{cm}}{d\Omega_L}\right) \quad .$$

Taking $(d\Omega_{cm}/d\Omega_L) = 1$ (in general larger than unity for forward going particles), we calculate $d\Omega_L$ for $N = 1$ count/second:

$$1 = (5 \times 10^{11})\ (10^{-2})\ (6 \times 10^{23})\ (10^{-31})\ d\Omega_L$$

$$d\Omega_L = 3 \times 10^{-3} \text{ sr.}$$

The desirable features of the analyzing systems are thus specified. We would now like to design the 5, 10, and 15 Bev/c spectrometers with $\Delta p/p \cong 0.01$ and $d\Omega \cong 3 \times 10^{-3}$ sr. There are a number of possible types; at this stage it isn't clear which system is best. Various developments are being pursued which may greatly simplify multi-Bev analyzing systems, e.g., superconducting magnets which offer a promise of reducing the size, weight, and power by an order of magnitude. Even moderate advances in technique (such as the attempt at Hamburg to produce quadrupoles with 1.5 times the gradient of conventional quadrupoles) will reduce considerably the size and weight. Whatever systems we design, based on present technology, we can be quite confident will prove to be pessimistic. Of the various possible designs, we follow Penner,[5] primarily because Penner gives recipes for designing such a system for any momentum and aperture. There is considerable doubt that this system is the least expensive, and it certainly is not the most convenient to use; but it is probably true that the scale set by the Penner system will not differ greatly from that of any other system using conventionally designed quadrupoles and bending magnets. Thus, each system will have the components indicated in Fig. 1. I shall not show the detail of the calculations. The Penner data make the design trivial. The solid angles chosen for the three energies are such as to keep the cross sections of the quadrupole magnets constant--they are otherwise irrational. Table 1 lists the characteristics of the magnets for the three systems.

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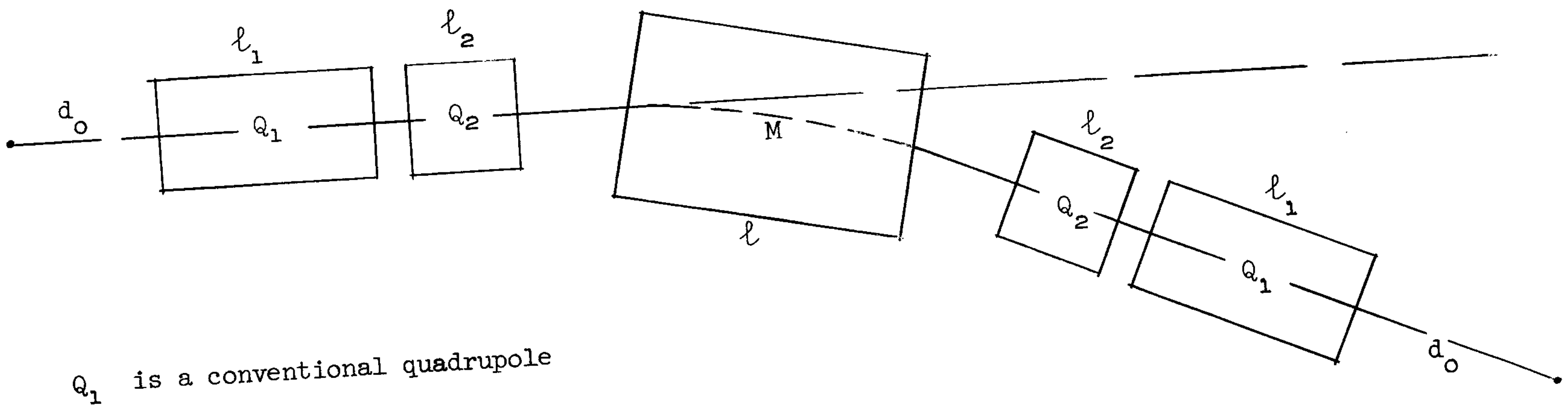
[5] S. Penner, "Quadrupole Focusing Systems for Particles of Large Momenta," M Report No. 200-12, Project M, Stanford University, Stanford, California, August, 1960.



Q_1	is a conventional quadrupole
Q_2	is a Panofsky type quadrupole
M	is a bending magnet with uniform field
d_o	is the target distance and image distance from the first and last quadrupoles, respectively

FIG. 1--Prototype of the analyzing system for the 5, 10, and 15 Bev spectrometers (following Penner).

TABLE 1

Estimates of the characteristics of the individual magnets in the 5, 10, and 15 Bev/c analyzing systems. (The cost, weight and power estimates are very crude.)

P	Conventional Quad.					Panofsky Quad.					Bending Magnet				
	Length (in.)	Bore (in.)	Wgt. (tons)	Power (kw)	Cost ($)	Length (in.)	Apert. (in.)	Wgt. (tons)	Power (kw)	Cost ($)	Length (in.)	Apert. (in.)	Wgt. (tons)	Power (kw)	Cost ($)
5 Bev/c	96	8.5	9	125	25,000	48	7 × 14	7	350	25,000	120	7 × 14	25	400	50,000
10 Bev/c	133	8.5	12.5	175	35,000	66.5	7 × 14	10	500	35,000	120	7 × 14	25	400	50,000
15 Bev/c	163	8.5	15	220	40,000	81.5	7 × 14	13	600	40,000	150	7 × 14	30	500	65,000

The total estimates for the three systems are as follows:

P	$\frac{\Delta p}{p}$	dΩ (sr.)	Total Length (feet)	Total Weight (tons)	Power Used (kw)	Cost ($)
5 Bev/c	0.01	5×10^{-3}	28	57	1350	150,000
10 Bev/c	0.01	2.5×10^{-3}	47	70	1750	190,000
15 Bev/c	0.01	1.7×10^{-3}	58	86	2140	225,000

It should be noted that the cost, weight and power estimates are all very crude. However, the over-all length estimates are reasonably accurate.

Estimates of Space Requirements and Cost for a 10-Bev Experimental Station

To estimate the size and cost of a 10-Bev experimental area, we have to specify some objectives. How many beam lines? How many simultaneous experimental set ups? How cleanly shall the electron beam be ditched when photon beams are to be used? And so on. The variation in space and cost can be very large depending on what answers are given to these questions. I shall make the following assumptions.

(a) A single beam line but long enough to have at least two non-interfering experimental arrangements permanently set up and simultaneously operating.

(b) Each experiment shall have room for a 10-Bev/c analyzing magnet on one side of the beam and a 2-Bev/c magnet on the other side.

(c) A clean γ-ray beam.

(d) The electron beam buried well enough so that its contribution to the background radiation is small.

These requirements define a useful but not lavish area. A plan view of such an area is shown in Fig. 2. I shall discuss briefly some of the considerations which determined the size of the areas shown.

Electron Beam Ditching Area

This is a room 25 ft × 35 ft, 15 ft high, separated from the main experimental area by a 10-foot thick wall of loaded concrete. The

A = 20° ditching magnet
B = 10 ft beam stop
C = Fe shield
D = Pb coll. for γ-ray beam, 4 ft cube
E = broom magnet 1 in. gap, 5 ft long

T_1 = Target # 1
T_2 = Target # 2

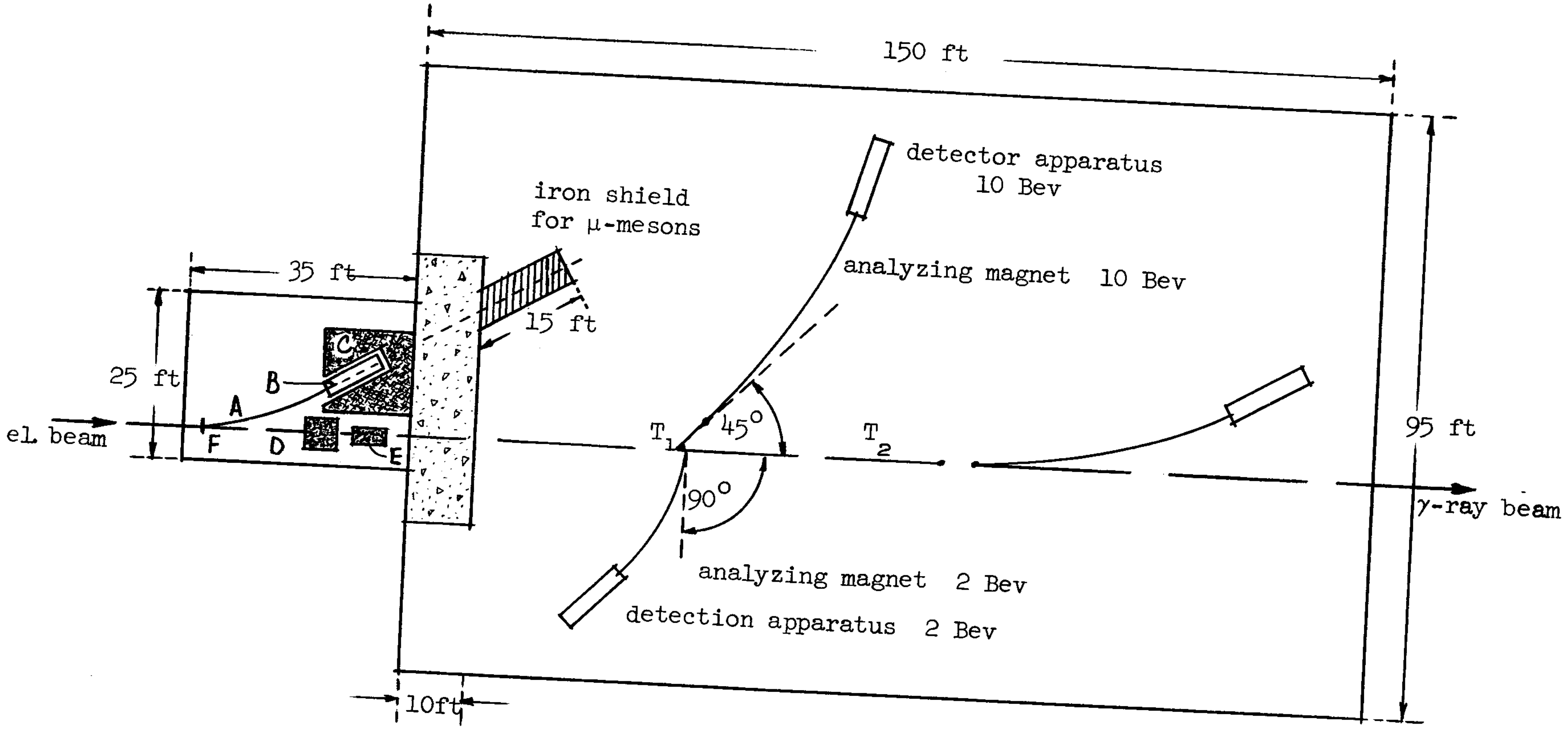


FIG. 2--Electron ditching area and beam room for 10-Bev photons.

other walls are 4-ft thick loaded concrete (density $\cong$ 300 lbs/ft^3).* The building is covered by 15 ft of earth for additional shielding. The electron beam is bent through 20° and buried in an aluminum beam stopper 10 feet long (30 radiation lengths). The beam stopper is enclosed in an iron shield 5 feet thick along the beam direction and several feet thick transverse to the beam. For a beam of 30 μamps at 10 Bev, such a beam stopper is marginal.[6] In the design shown, this question is not important since there is adequate space for a stopper consisting of thin foils with cooling water flowing between them. The in-line shielding, including the iron shield in the experimental area, is sufficient to bring 10 Bev μ-mesons to rest. The transverse shielding consists of 3 ft of iron, 4 ft of loaded concrete, and whatever earth thickness is necessary to bring the radiation to the desired level. Fifteen additional feet of earth would make a shield equivalent to the usual 35 feet of earth. This shielding should be adequate both for the radiation level and to keep the detector backgrounds in the experimental area small. However, there is adequate space provided to add as much additional shielding as may be necessary.

In the beam ditching room are also located a Pb collimator 4 ft × 4 ft × 4 ft and a 5 ft broom magnet. The hole in the 10-foot concrete wall conducting the beam into the experimental area should be slightly larger than the beam-defining hole in the Pb collimator. The 10-foot wall should probably have a one-foot hole with suitable inserts.

The dimensions of the experimental area are $L = 150$ ft, $W = 95$ ft, $h = 30$ ft (see Fig. 2). The dimensions were largely determined by assumptions (a) and (b). Two different types of spectrometers were calculated: one of the Penner type (see previous section), and the other a single bending magnet with 3 lenses as shown.

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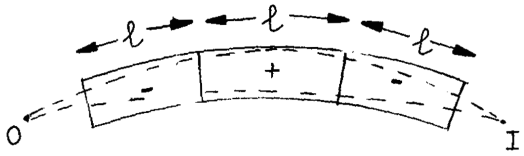
*This thickness is arbitrary. It was chosen so that the total shielding becomes equivalent to 35 feet of earth (see text).

[6] S. Penner, "Note on Power Dissipation from Collimators and Targets for High Energy High Power Electron Beams," M Report No. 200-6, Project M, Stanford University, Stanford, California, July 1960.



The space requirements for the two different spectrometers are essentially the same since the over-all lengths are approximately the same. Some of the characteristics of the two different systems are summarized below.

P = 10 Bev/c	$d\Omega$ (sr.)	$\frac{\Delta p}{p}$	Total Length (ft)	Total Weight (tons)	Power Required (Mw)
Penner Type*	2.5×10^{-3}	0.01	47	70	1.75
Single Bending Magnet	10^{-3}	0.01	50	130	0.280

*It is clear that in most respects the Penner type is superior. However, the single bending magnet spectrometer has several advantages.
(a) The power required only about 1/6 that of the Penner type.
(b) Measurements at 0° offer no problem; the first quadrupole of the Penner type interferes with the beam for angles less than about 30°.
(c) It is simpler to use: no tracking problem.

The minimum space available for the detection apparatus behind the 10-Bev/c spectrometer is 20 ft. The estimate of space required was based on assuming that the particles are detected in two gas Cerenkov counters. Six feet seems adequate for each counter.[7]

Cost Estimates

Some rough cost estimates[*] can be made for this 10-Bev facility:

Building	$ 500,000
Concrete	90,000
50 ton crane	200,000
4 Mw distributed power	700,000
Cooling water	40,000
Ventilation	60,000
Total	$1,590,000

Note that about 45% of the total cost is for power. The 4 Mw is based on all four magnets being of the Penner type. If one uses the single bending magnet, the power required is about 3/4 Mw and the cost is reduced by about $600,000, bringing the total to $1,000,000. These costs, of course, should be compared with a comparable facility in the end station.

Shielding Requirements

It is assumed in the cost estimate that the building provides no shielding. The beam is considered to travel in an evacuated region except at the thin target areas and to be buried in an adequate earth mound. The target areas are enclosed in a shield sufficiently thick to reduce the radiation to the desired levels. We estimate the shielding required. Panofsky has calculated the neutron yields from thin targets.[**] Using his input data, we calculate that a 30 μamp beam of 10-Bev electrons produces 5×10^9 high-energy neutrons/second in a 20 cm liquid-hydrogen target.[***] At 500 feet (project boundary), the unattenuated flux

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[7] A. Silverman, "Photon Experiments with M," M Report No. 286 Project M, Stanford University, Stanford, California, September 1961.

[*] I am indebted to L. Schwarcz for these estimates.

[**] W. K. H. Panofsky, "M-Remarks on 'Thin Targets'", M Report No. 171, Project M, Stanford University, Stanford, California, June 1959.

[***] A γ-ray beam produced by this electron beam transversing 0.1 radiation length gives substantially the same neutron yield.

is 2n/cm^2-sec. We wish to reduce this by a factor of 10^2. This requires an iron shield about 4 feet thick. Since the high-energy neutrons tend to be concentrated in the forward direction the shield should probably be somewhat thicker in the forward hemisphere and thinner in the backward one.

The requirement of shielding the target is a fairly oppressive one from the experimenter's point of view, and it would be desirable to do away with it. To shield the building adequately requires concrete walls 8 to 10 feet thick. A less inexpensive method would be to make the structural strength sufficient to support the necessary earth load of 12 to 15 feet.

These conclusions as to the shielding requirements are based on guesses which tend to be conservative. For instance, the cross section for neutron production used by Panofsky was 2×10^{-28} cm^2. It seems unlikely that the cross section will be that large. Furthermore, one may find that the .02n/cm^2-sec may be somewhat more stringent than necessary. It might be sensible to consider a compromise solution where the shielding of the building is sufficient to reduce the flux by a factor of ten (6 to 8 feet of earth). This may turn out to be adequate and is probably not very costly. If the factor of ten leaves the radiation levels too high, one will still have simplified the problem of shielding the targets. It sould seem worthwhile to have detailed cost estimates of these various alternatives.