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Author

Keefe, Denis.

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Ernest O. Lawrence Radiation Laboratory

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I. Introduction

The basic starting point in trying to define and specify the nature of the experimental areas and facilities is to consider, first, the output of the accelerator--viz., types and fluxes of various elementary particles--and second, the ways in which these particles might conceivably be used. The abundance and distribution of particles produced in high-energy interactions have a vital influence on the shielding configuration (especially, close to targets), on how efficient targeting arrangements can be achieved for high-energy particle beams, and on the nature of experimental activity, since this is largely controlled by the qualities of the available beams. Although it is impossible to be prescient about the experiments of most interest in physics a decade from now, one can nevertheless proceed quite far in exploring the general properties of beams and certain boundary conditions associated with them, at least in terms of the known elementary particles. A second aspect of the experimental use, which was a necessary ingredient of the 200-GeV Accelerator Design Study, is the consideration of the level of use, viz., the number of experimental arrangements which could be set up and how many could operate simultaneously within broad limits. This helps define whether the number of experimental areas in the design is too meager or too lavish.

II. Particle Production at High Energies

The measurements of fluxes of secondary particles as a function of angle and momentum produced by high-energy protons still leaves a lot to be desired. The data obtained by Dekkers et al.[1] are the most useful set because they included measurements at 0 deg production angle. Their results indicate that at CPS energies there are two components, one of low energy and one of high energy in the c. m. system, in the production of pions and kaons. Using this model and making certain assumptions about how to extrapolate it to 200 GeV, Trilling[2] has arrived at estimates of particle production for pions and kaons. Data from the same experiment were also used to estimate proton (neutron) and antiproton fluxes. These forecasts are shown in Figs. 1, 2, and 3. In the meson flux extrapolations, the effect of the separation of the two energy components (in the laboratory system) at high energies can be seen. For comparison, the form predicted by the Cocconi-Koester-Perkins formula[3] is also shown. An interesting feature of the more recent extrapolation is that the expressions for the double differential cross sections all contain terms of the type exp($-$const. θ^2) and only the terms describing the high-energy component of the pions contains the familiar term exp(-const. θ) predicted in Ref. 3. The value of the mean transverse momentum associated with this high-energy term alone is about 0.5 GeV/c, rather higher than hitherto assumed.

III. Targeting

It is fair to assume that a 200-GeV accelerator should be optimized to provide beams in the energy regions beyond the efficient reach of the CPS or AGS, say above 15 to 20 GeV/c. (Beams of lower energy are, of course, obtainable as easily as at present accelerators.) Targeting problems arise, then, because high-energy secondary particles are produced in abundance only at very small angles to the forward direction. If we define a "typical" angle of production $\alpha = 0.25/p$ (where p is in GeV/c), then about one-third of the flux is contained within a cone of half-angle α and more than half within a cone 2α. A secondary beam which can capture one-third the available flux when looking at 0-deg production angle will capture only 1% of the flux if forced to look at the target at an angle about 3α to 4α.

For a secondary momentum of 100 GeV/c, α is 2.5 mrad. In using a target in a field-free straight section, either in the internal or external beam, it is difficult to set up equipment at production angles less than 10 mrad, and if several experimenters are using the same target, most must accept much larger angles. Thus yields from targets in a straight section are certain to be inefficient.[4] This inefficiency is a consequence of the fact that the angle of production is small and is therefore a poor effect to exploit to achieve spatial displacement between the primary proton beam and the desired secondary beam. Magnetic fields supply a much more powerful means of creating physical displacement. In a field of B (tesla) of length L (meters), the angle of bend is

$$\phi = \frac{BL}{B\rho} = \frac{3BL}{10p} = \alpha, \text{ if } BL = 0.8.$$

Thus a field of 1.6 T just 0.5 meter long is sufficient to give angular deflections comparable to the production angle. A field a few meters long is therefore sufficient to cause angular deflection of secondary particles much greater than attainable by using production-angle effects. In particular, for a secondary beam, the entire forward cone can be diverted away from the proton beam, and capture into the secondary channel can be achieved at a production angle of 0 deg. Thus targeting in a magnetic field can be highly efficient. There are three obvious ways in which to achieve this: first, to use a target in the gradient-magnet part of the accelerator; second, to use a group of bending magnets in a Collins straight section;[3] and, third, to use target magnets in the external beam.[4] The last allows the most flexible arrangement and minimizes the coupling of the secondary beams with the accelerator.

For this reason, considerable effort has been expended on a critical examination of the relative advantages of internal and external beam operation and how far the desirable features associated with internal beam operation at AG synchrotrons can be achieved externally. In brief, the conclusion is that the major part of the physics program can be operated with assurance, and often with advantages, externally, but that at the moment one cannot eliminate from the design some sort of internal area, however rudimentary. When this study was begun the external proton beam (EPB) at the Cosmotron was being used and preliminary work with the Bevatron external beam being begun. The later experiments and discoveries about the efficiency of resonant extraction from AG machines greatly bolstered the arguments described below.

First, a major emphasis on the use of external beams provides critical advantages in the preservation of the accelerator (namely, ease of maintenance, lifetime of components, and minimum interferences with operation) and in the overall running efficiency of the accelerator and physics program. These advantages are:

(i) Because internal-target areas are directly coupled to the main ring, the accelerator must be turned off to allow setup or repair of the front end of an experiment. The unstacking of the enormous mass of shielding and the handling and surveying of equipment in a radioactive environment involve shutdown times of several weeks. Conversely, if troubles develop in the early transport sections of an experiment, repairs will have to be delayed until a shutdown of substantial length can be negotiated. The more internal-target areas there are, the more interferences with continuous beam operation will follow. Since similar disadvantages are associated with a single EPB area, it is desirable to have a minimum of two extracted beams. Each of the two external beams--and, independently, certain of the target areas in each beam--can be easily turned off without halting operation of the internal beam and with only partial interruption to the experimental program.

(ii) Work in an internal-target area must be started immediately after turnoff because accelerator time is at a premium; this is the time of highest radioactivity. In an external area, a cool-down period of several days is not difficult to arrange.

(iii) If the extraction efficiency is approximately 90% for slow beams and approximately 100% for fast beams, the induced activity and the radiation damage in the accelerator are smaller by a factor of approximately 20 than for internal targets, for both local and distributed losses. Development of the extraction system to permit simultaneous extraction in two separate straight sections is possible with a doubling of the total beam loss.

(iv) Movement and restacking of large amounts of shielding close to a target can result in misalignments of neighboring magnets. This may be annoying but tolerable in an external beam, which the protons traverse only once, but intolerable in the main ring. An allied effect, also resulting in closed-orbit deviations, arises from the proximity of pieces of experimenters' equipment to the target, such as separators or magnets with stray fields. Again the EPB is much less sensitive to this effect.

(v) In the external-beam target areas, crane handling is freed of the restrictions of the magnet structure and enclosure, and also from the maximum pressure for reassembly of the shielding in the shortest possible time.

Second, there are also distinct gains in the ease of targeting.

(i) The cooling problem is reduced in proportion to the single-to-multiple traversal ratio. Further the freedom of access to the EPB vacuum chamber allows the use of more complicated target arrangements, e.g., a ribbon target cooled from the edges and through radiation to surfaces placed nearby, above and below it.

(ii) For plunge or flip targets the travel distance need be only a few millimeters, because allowances for a large beam at injection are not needed.

(iii) A system using small deflecting magnets and the long lever arms available in the EPB can be used to achieve rapid and controlled switching from target to target, thereby minimizing the need for mechanically moved targets. Such a system is in one-to-one correspondence with the methods applied to control of spills from many internal targets by using closed-orbit perturbations.

Third, from the experimenters' point of view, the main advantages of using external beams can be summarized as follows:

(i) Access to 0-deg production angle for both positive and negative beams, a necessity for high energies, is easily achieved by means of a targeting magnet in the external beam.

(ii) Very good target optics (transverse target size of the order of 0.005 in.) are possible, because the external beam has small emittance and can be focused. If the emittance of the external beam is πA, then it can be matched into a target of height $h = 2\sqrt{AL}$. With $A = 0.03$ mm-mrad and $L = 15$ cm, then $h = 0.13$ mm = 0.005 in.

(iii) A single-target efficiency very close to that obtainable with a multiple-traversal internal target can be obtained. In general, the accelerator productivity integrated over all experiments can be as good as the best achievable internally. The internal and external target efficiencies for a single target in the 200-GeV design are shown in Figs. 4 and 5 respectively. Note, however, that with multiple targets, at most 74% of the protons can be usefully employed internally but the extracted protons can essentially all be used.[6]

(iv) For low-energy (0 to 30 GeV) parasitic experiments with decoupled secondary momenta, operation off a "straight section" target in the external beam allows access to smaller angles of production than internally, because the smaller size of vacuum chamber constitutes a smaller transverse interference.

(v) The possibility of rebuilding the configuration of the target magnets to cater to special experimental setups is an important illustration of the flexibility of external-beam targeting. The EPB channel has constraints, but these still allow considerable latitude in the positioning of the individual magnets making up the target-magnet complex. These magnets can be interchanged or moved apart, or, for special reasons, a very-high-field short magnet can be substituted in their place.

(vi) Another form of rebuilding of the target station is possible when maximum flux is of utmost importance. The target can be moved upstream from the target magnet and a quadrupole placed between target and magnet. Thus focusing of the secondary beam can begin before dispersion. In some cases it may be necessary to have it only 2 to 3 m from the target, whereas downstream from the target magnet, the quadrupole is required to be $\gtrsim$ 10 m away.

(vii) Multiple secondary-beam setups are easily achieved because the target magnet fans out beams of different momenta and charge. There is a distinction between the number of secondary beams operating from a given target (for example, between three and five) and the number of experiments that can actually use the same beam spill on the same target at that station (for example, two or three). In general, several targets will be available at any target station, but perhaps only one operating at a given time for certain prime users--the other installed channels accepting particles of any momentum in order to time counters, test spark chambers, etc.

IV. The Role of the Internal-Target Area

Although the case for placing heavy reliance on external-target areas for serving the physics program is very strong,it is too soon to argue for complete abandonment of all internal-target facilities. Given, however, the existance of external beams serving several target areas, it is unreasonable to consider the inclusion of more than one internal area in the initial design. Not enough experience has yet been gained with external beams at AG machines to be certain that there are not some practical difficulties associated with running a large experimental program entirely externally. Features in favor of the retention of some internal-target facilities are:

(i) Physics experiments utilizing an experimental target in the circulating beam, rather than using an internal metal target to produce secondary particles for experimental use. One good example is the use of a thin polyethylene foil target or a gaseous hydrogen target, to study low-momentum-transfer p-p interactions. In this case, the thickness of the target is determined only by the need to allow low-energy protons to escape from the target without too much scattering or energy loss. As a second example, large energy loss may dictate the use of a thin production target in searching for the magnetic monopole. Such experiments may require a straight section free of accelerator equipment to allow the secondary analyzing and detection channel to be set up. These provisions constitute a rudimentary internal area, although the shielding need be far less extensive than in a conventional internal area.

(ii) Production of fewer electrons from thin rather than thick targets because of the decreased absorption of γ rays.

(iii) The tune-up period after turn-on. For several months, secondary-beam survey work and certain experiments could usefully be operating from an internal target, when the beam is naturally low and when the damage and activation due to internal targeting are least.

(iv) Decoupled "point" optics. When studied in detail, the advantages for high-energy beams have been found to be rather marginal compared with external beams.

(v) Indefinitely small target emittance. In principle, an extremely small target can be inserted in the internal beam and, provided a long enough flat-top is available, all particles in the circulating beam (apart from those lost to the walls) will eventually interact in the target. This is a fundamental point of superiority of internal over external targets, but it is not clear that the gain is not illusory in that it implies conditions that cannot be exploited. The design of internal targets of very small dimensions is hampered by the problems of finite target-holder size and of cooling.

(vi) Convenience for future modifications. The crane cover and modular shielding blocks at the internal-target area would provide convenient access to a straight-section area if, for example, some major and massive piece of equipment needed to be added to the accelerator facility at some future date.

In conclusion, it appears that some form of modest internal area with crane cover and shielding is necessary. It should be possible to define better the most appropriate extent of the internal area in the next few years, after experience has been gained from external-beam operation at the CPS and the AGS.

V. Interpretation of These Considerations in the Proposed Design

The configuration of the experimental areas chosen for initial installation at the 200-GeV accelerator is shown in Fig. 6. They are located at adjacent Collins straight sections and comprise an internal area (H), a "short" EPB area (I), and a "long" EPB area (J). The internal area is of conventional design, where the earth shielding around the ring is interrupted for 400 ft and replaced by modular heavy concrete blocks handled by overhead cranes. The internal target is assumed to be located in the Collins straight section and an upper limit of 10 to 15% of the beam spilled on it. The target could be moved upstream into the curved section of the ring, but then extra precautions must be taken against muons because their angular spread would be increased by dispersion in the magnetic field. This area is shown in more detail in Fig. 7.

In the "short" EPB area, the full beam can be spilled. Either a slow or fast external beam is brought outside the shield wall to a target placed at a target magnet. The target magnet is designed in four separate units for ease of handling (see Fig. 8). Targets can be placed at different longitudinal locations to provide a degree of freedom in selecting different momenta down a secondary channel. Transversely the shield is composed of an inner layer of steel and an outer layer of heavy concrete. Longitudinally the shielding requirement is dominated by the need to eliminate muons. A high-Z material is desirable because it results in enhanced collision losses, while a high-density material is desirable because the shield can be made compact and so allow experimental beams to emerge quickly into the outside world. Uranium has been proposed in the initial design; it is possible that it could be superseded by lead as a result of further studies, with some saving in cost and some loss in compactness.

The "long" EPB area includes an upstream target magnet which also forms a switchyard to divert the external beam into one of two downstream backstop target stations (Fig. 9). Targeting in a "straight section" can be accomplished in the straight EPB runs between target stations. A feature of the switchyard target-magnet complex is that it is composed of magnets with different fields to allow secondary momenta to be varied without altering the EPB angle or position at emergence.[4]

VI. Remarks on Physics Program

The possible nature of secondary beams and physics experiments has been studied in some detail to make sure the areas are adequate at least for those beams one might construct with present-day equipment. In electronically separated beams, Cerenkov counters remain supreme in providing clean separation at these energies, although other types of counter, e.g., those relying on the relativistic rise effect, could be useful in special circumstance. The technique of rf separation using frequencies of 10 or even 20 kMc/sec looks extremely attractive in the new energy range. Long spill times (≈ 100 millisec) seem achievable even without resorting to superconducting cavities.

About 4 years after turn-on it is believed that the experimental target facilities could support about 25 experimental beams set up, with more than half capable of simultaneous running. Figure 10 shows some typical layouts in the long-EPB area. Current estimates indicate individual beam lengths may be between 300 and 4000 feet. The total integrated length of beam at that time may be about 5 miles. This can be compared with an integrated length of approximately one-half mile at the AGS or CPS today.

References

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3. G. Cocconi, L. J. Koester, and D. H. Perkins, UCRL-10022, January 1962, p. 167.
4. D. Keefe, Design of Target Facilities at the 200 BeV Accelerator, Lawrence Radiation Laboratory Report UCID-10138, Dec. 1964.
5. L. T. Kerth, in the Berkeley High-Energy Physics Study, UCRL-10022, Jan. 1962, p. 47.
6. 200 BeV Accelerator Design Study, UCRL-16000, June 1965.

Figure Captions

Fig. 1. Secondary pion momentum spectrum dn/dp. The kaon spectrum is assumed to be one-tenth of this.

Fig. 2. Secondary proton momentum spectrum.

Fig. 3. Secondary antiproton momentum spectrum.

Fig. 4. Internal multiple-traversal target efficiency for different energies of the circulating beam. Note the drastic reduction in efficiency at reduced primary energy.

Fig. 5. External target efficiency (RYE) for different materials of different lengths (measured in terms of the nuclear absorption length, λ). The standard of reference is a perfectly efficient internal multiple-traversal target--RYE = 1.

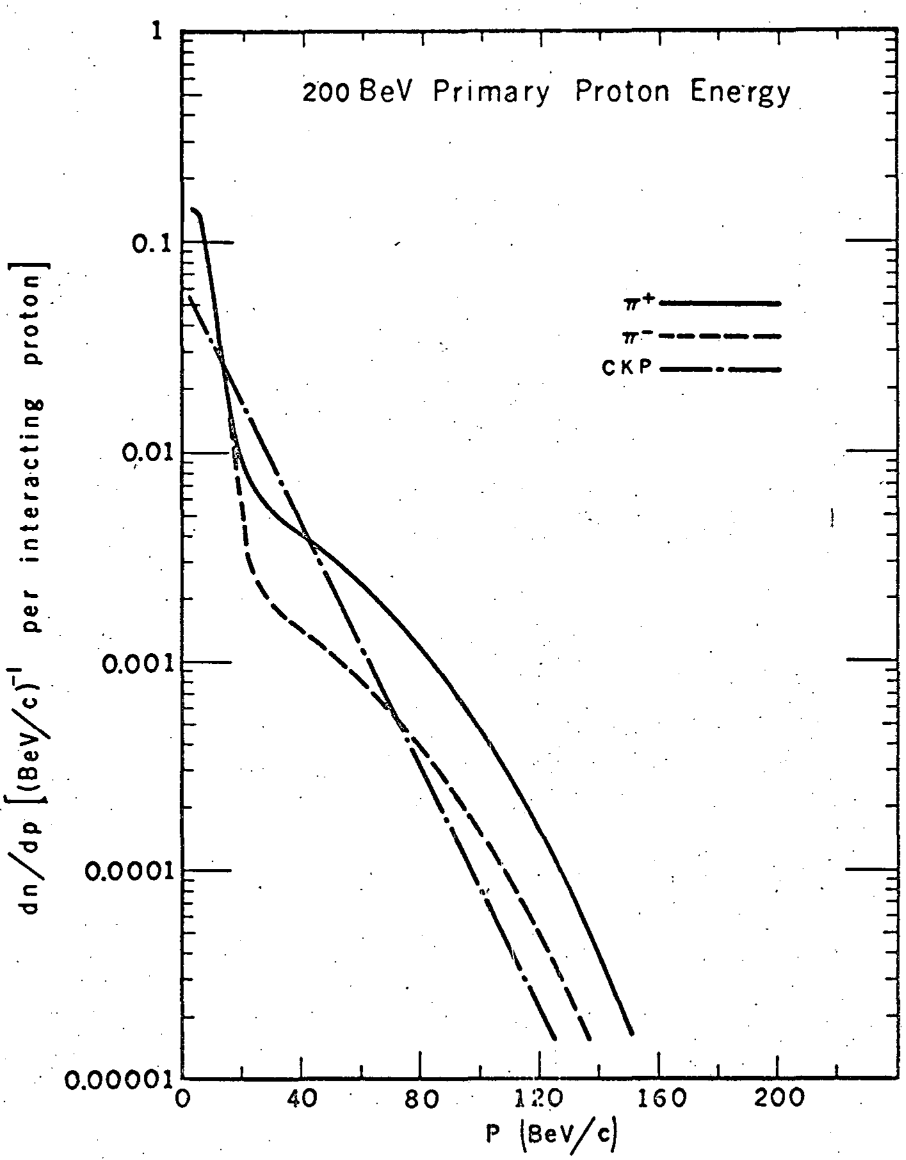
Fig. 6. Proposed configuration of the experimental areas at three adjacent straight sections (H, I, and J).

Fig. 7. The internal target area with some hypothetical-beam layouts.

Fig. 8. A backstop area in the EPB.

Fig. 9. The long EPB area, showing the switchyard.

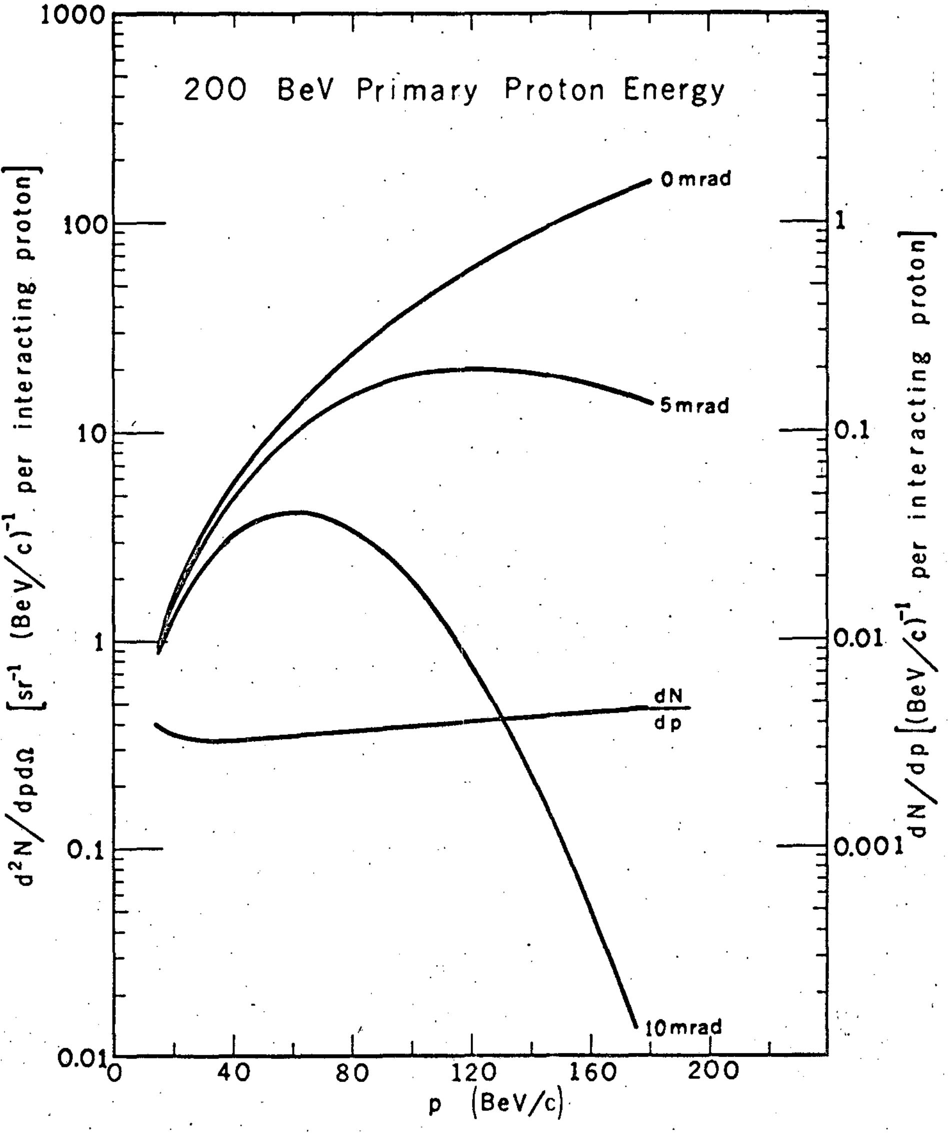
Fig. 10. Some typical beams originating from one of the backstops in the long EPB area (after A. L. Read).



Secondary Pion Momentum Spectrum Integrated Over All Angles

Fig. 1

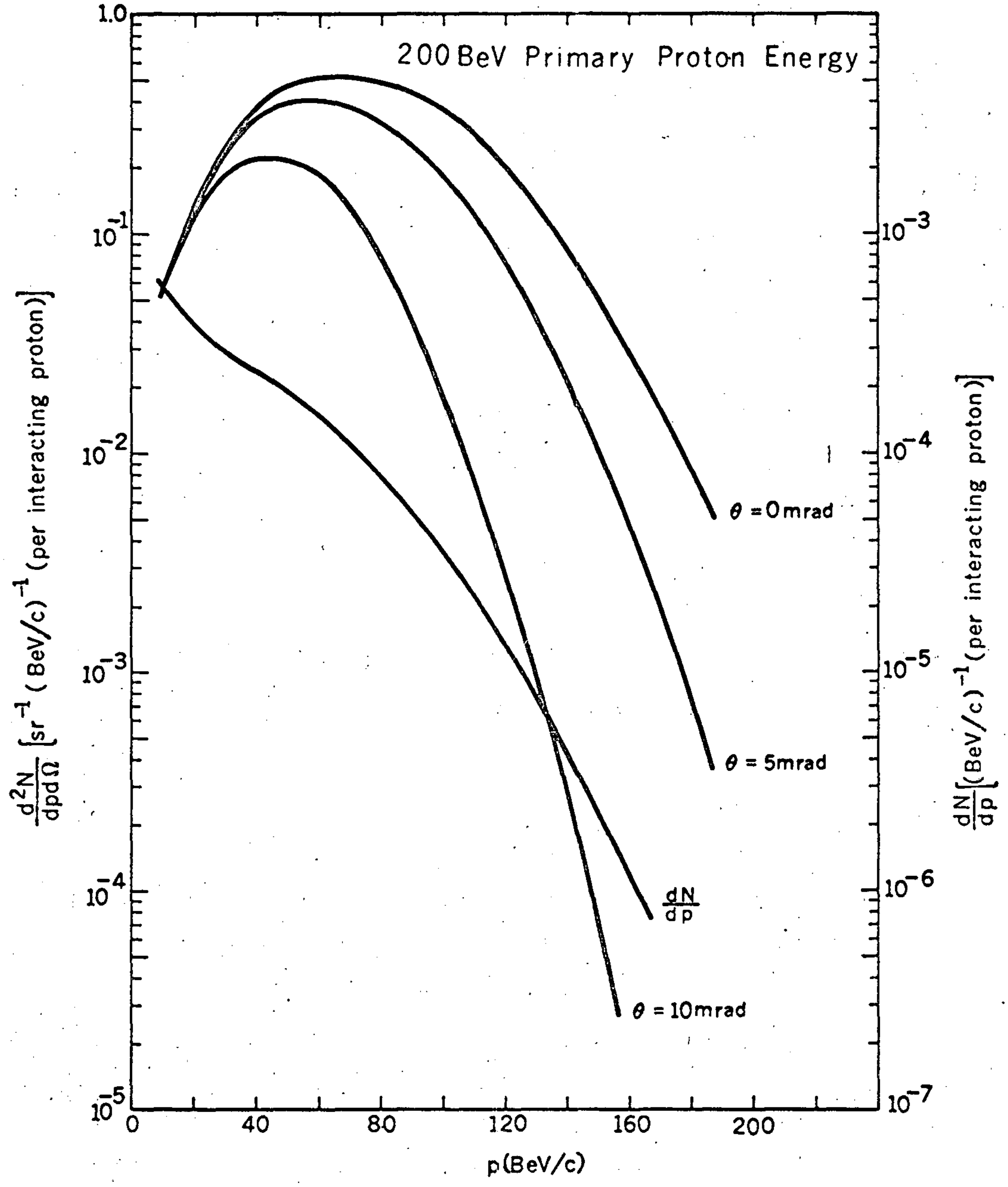
MUB-6402



Secondary Proton Momentum Spectrum

Fig. 2

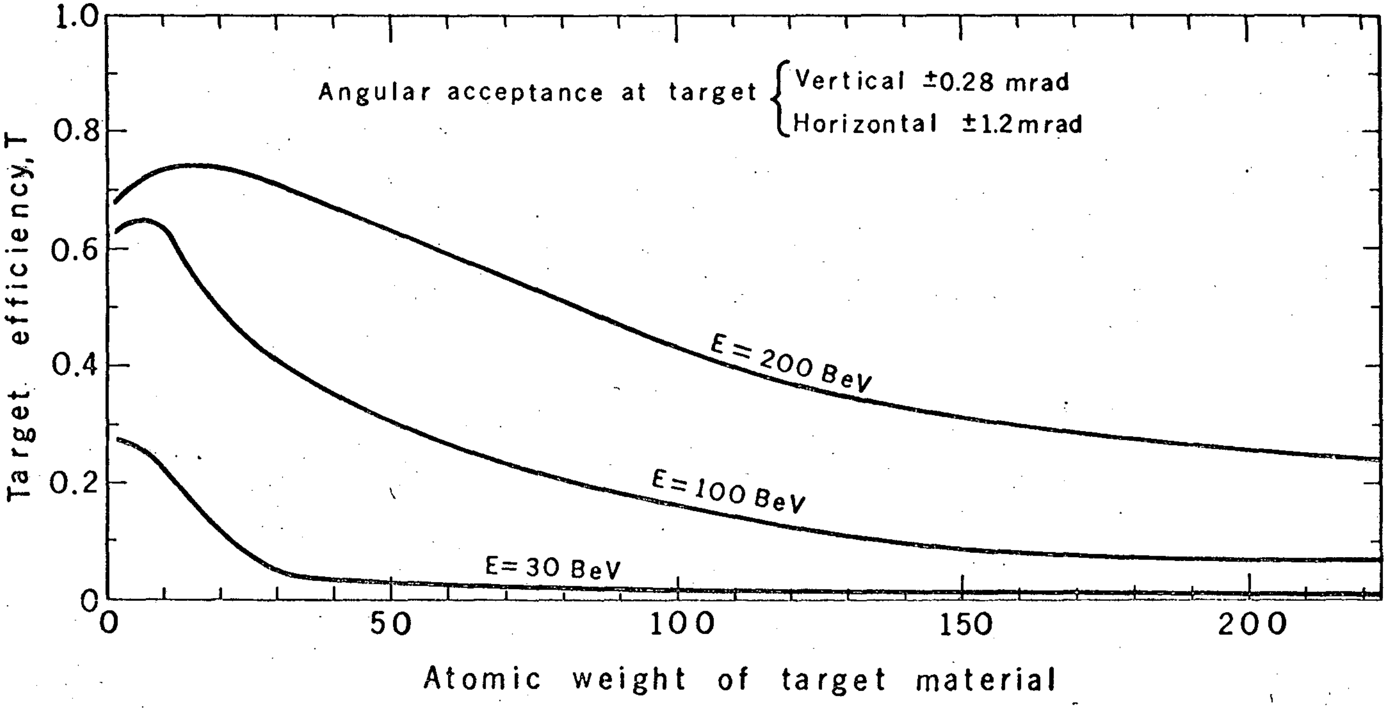
MUB-6403



Secondary Antiproton Momentum Spectrum

Fig. 3

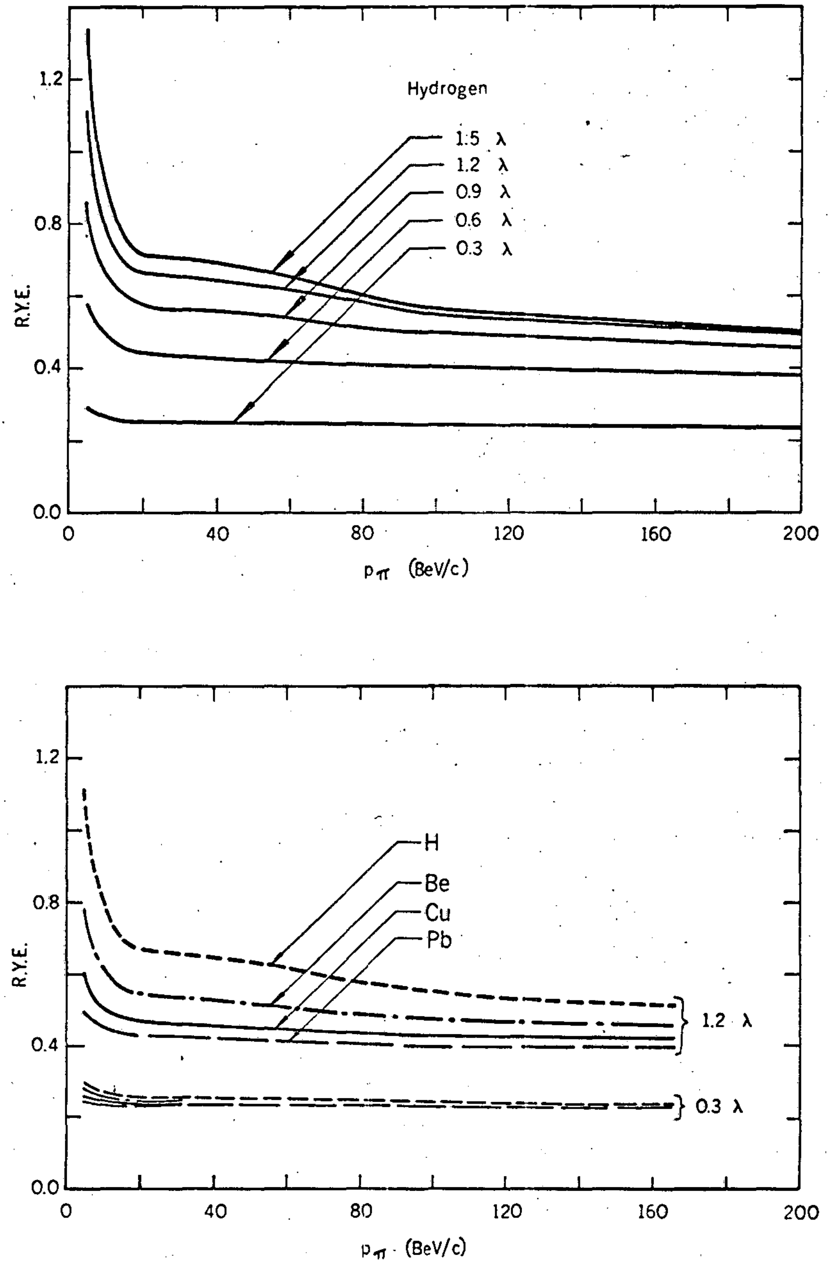
MUB-6404



Internal-Target Efficiency, T,
as a Function of Atomic Weight

Fig. 4

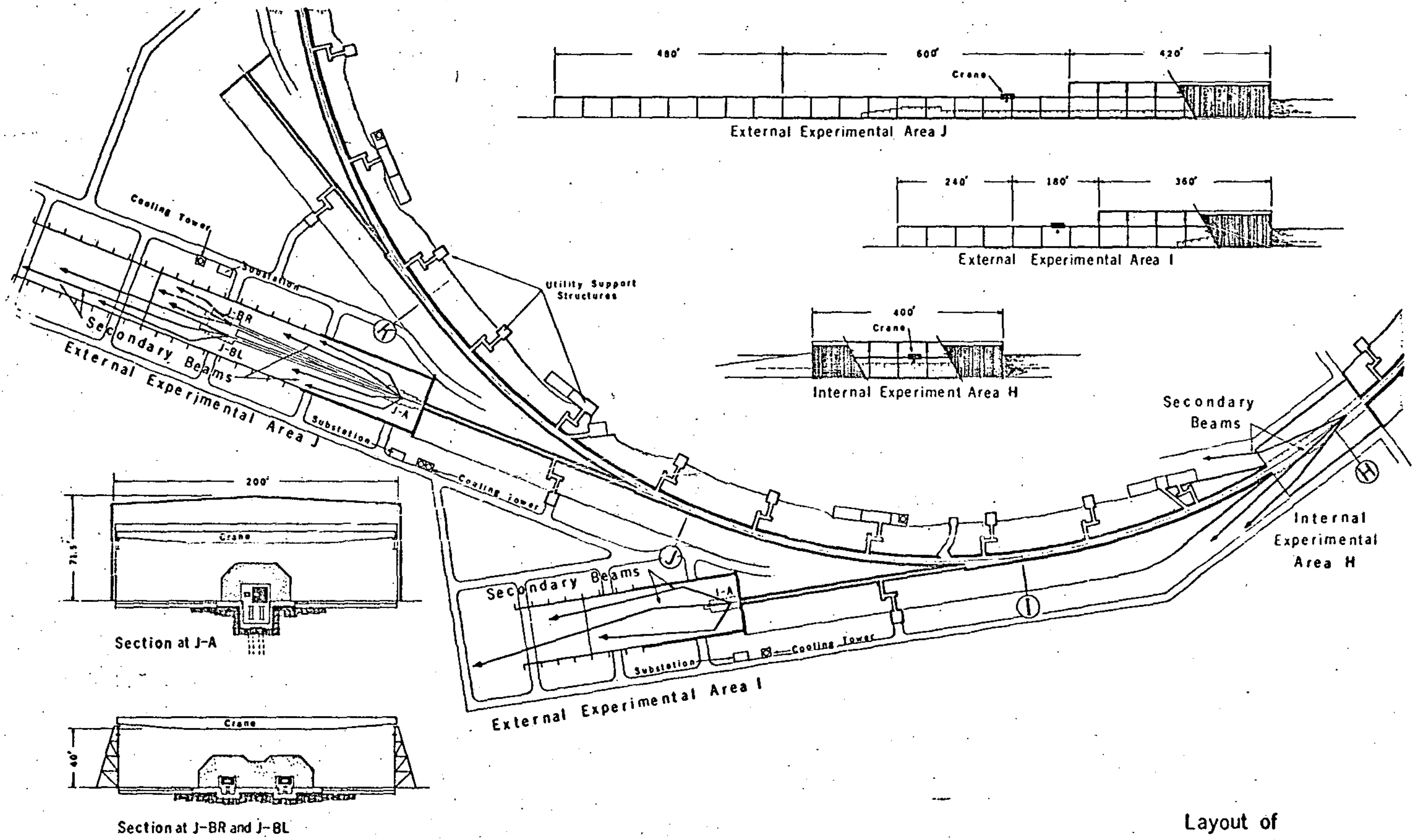
MUB-6409



R.Y.E. for Pions

Fig. 5

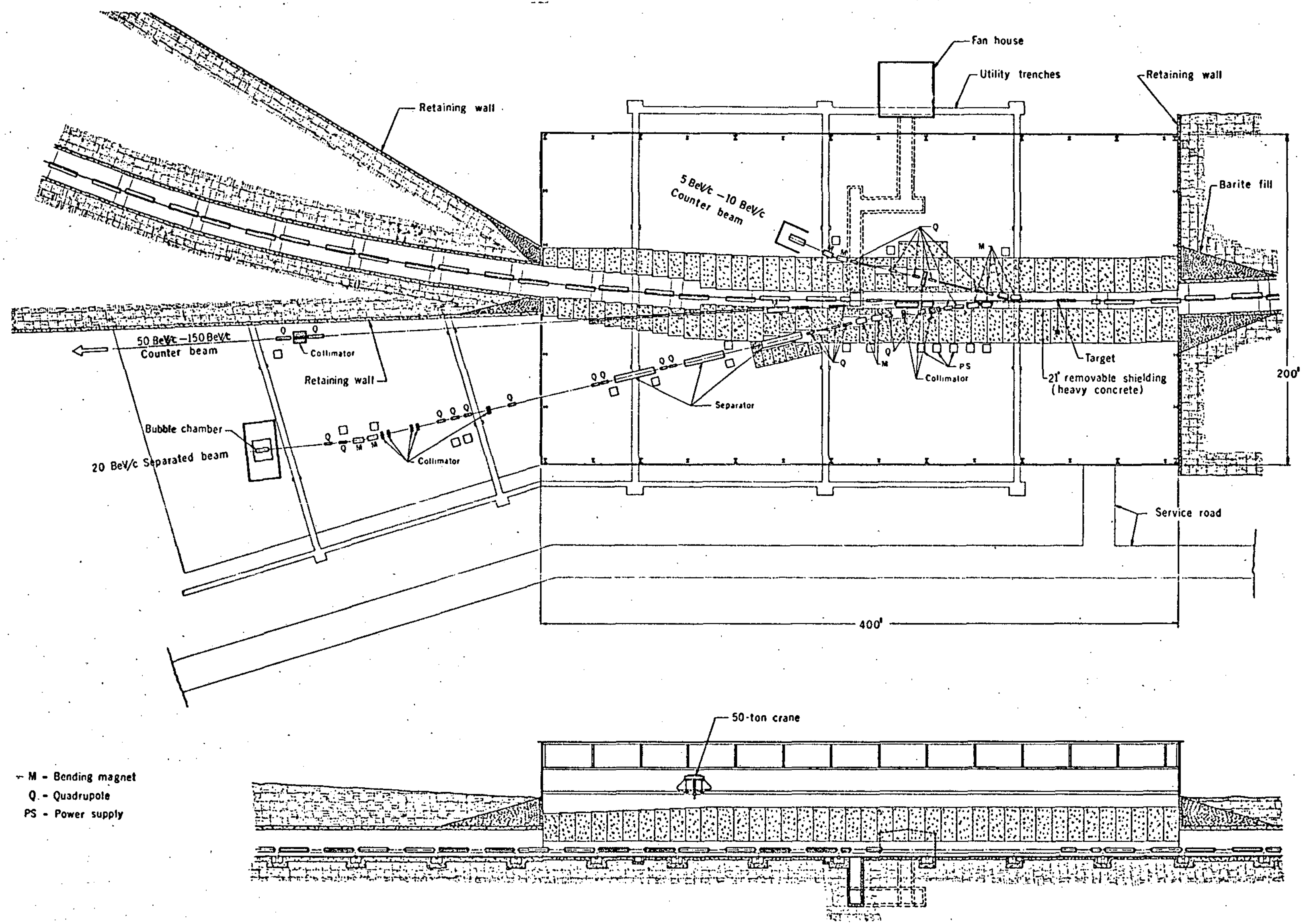
MUB-6468



Layout of Experimental Areas

Fig. 6

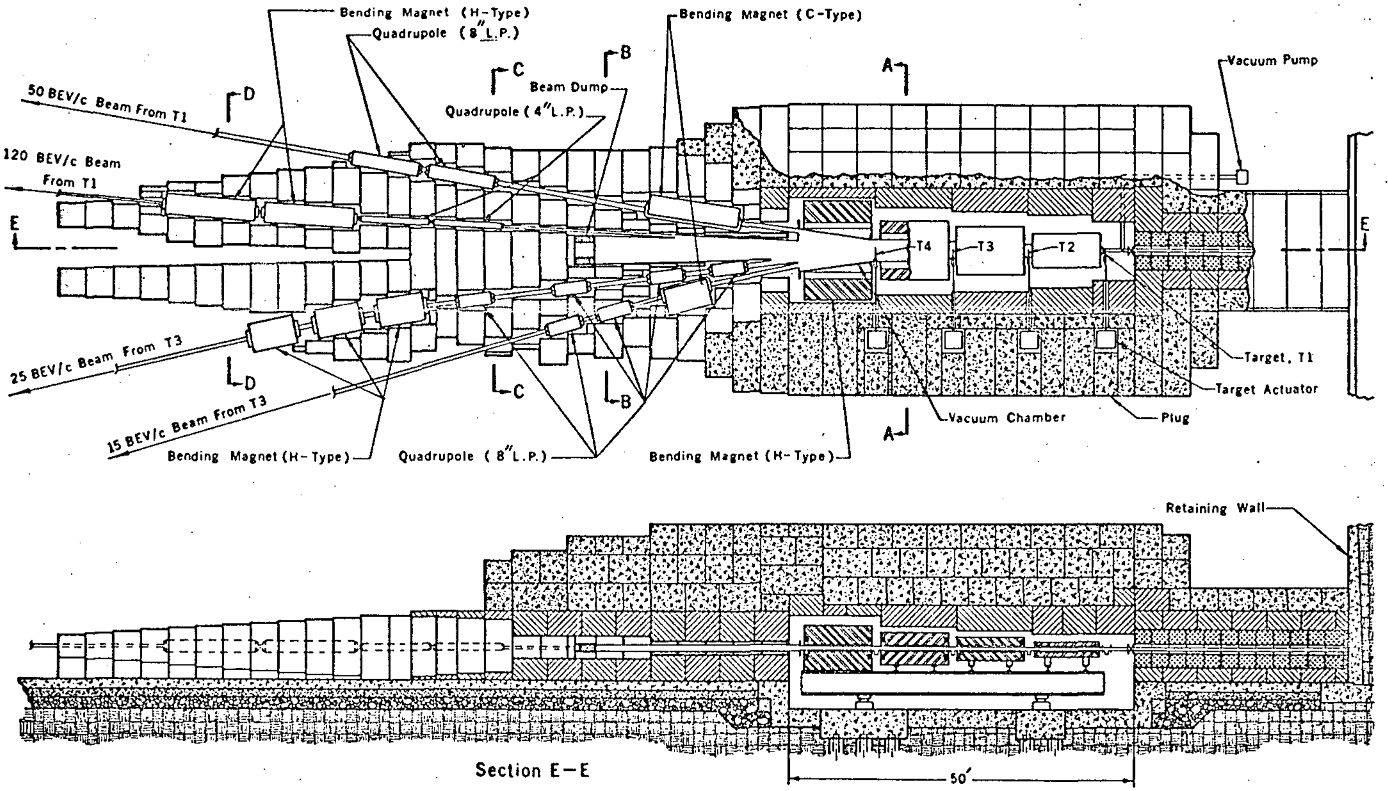
MUB-6416



Internal – Target Area H

Fig. 7

MUB 6421



EPB Target Station I—A

Fig. 8

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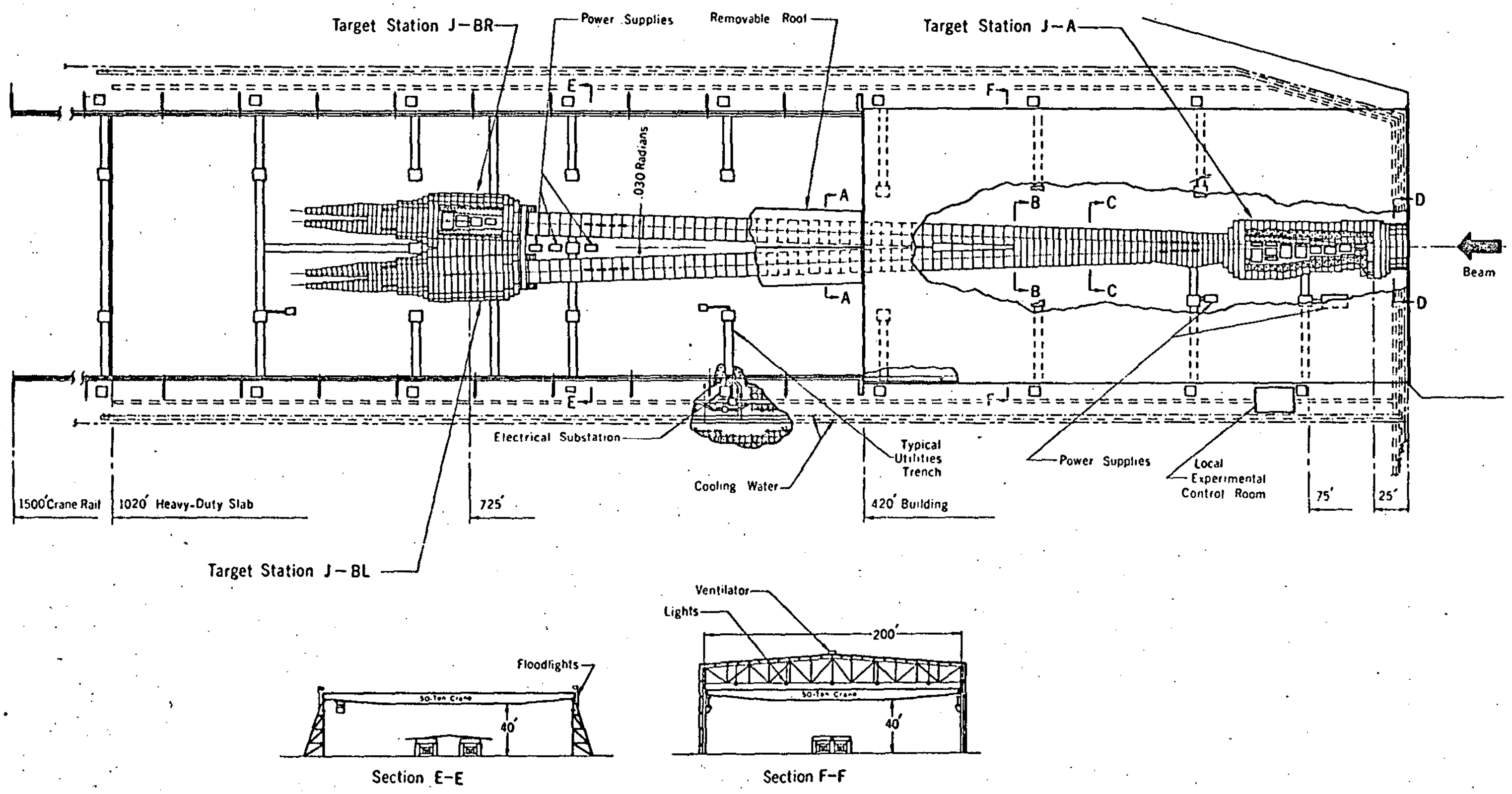

EPB Area J

Fig. 9

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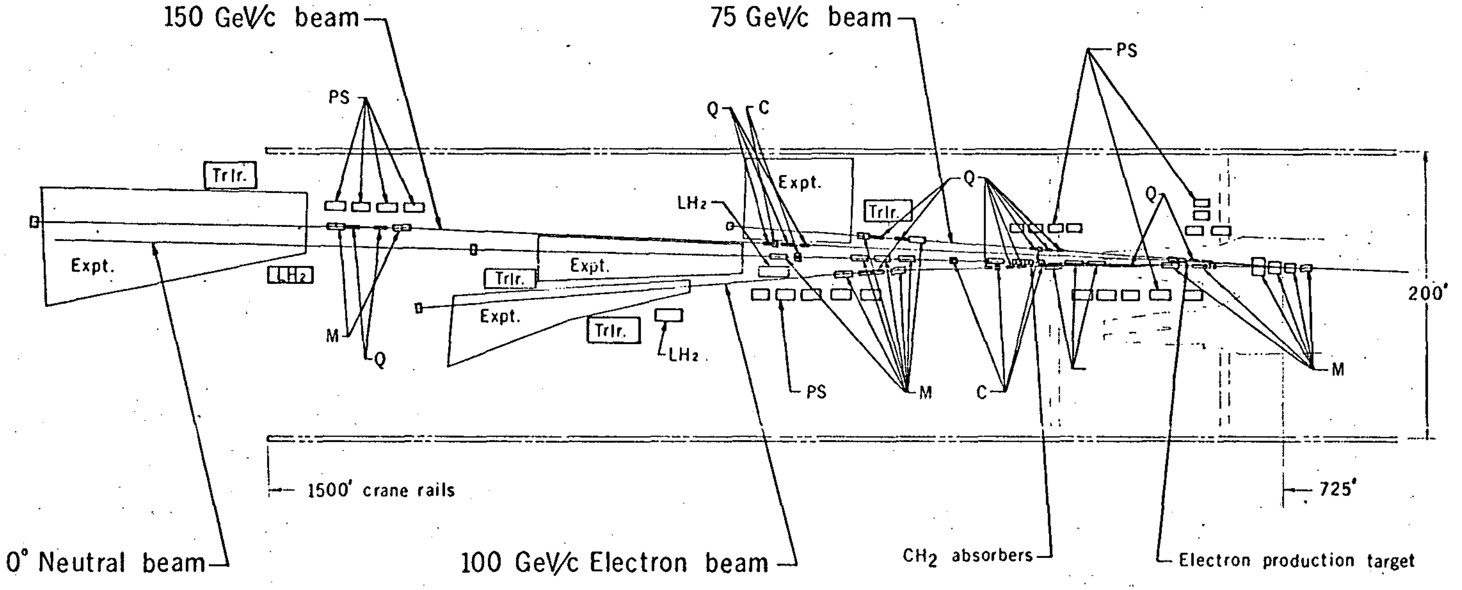

Fig. 10

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