NOTE ON NEUTRINO BEAM DESIGN

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ABSTRACT

Several different designs for neutrino beams are considered in an attempt to minimize shielding and maximize intensity over as wide an energy range as possible. Both one- and two-target systems and magnetic muon sweeping systems are considered.

I. INTRODUCTION

The neutrino beam, or beams, for bubble and spark chambers should cover an amazingly wide neutrino energy region, from about 1 GeV up to perhaps 250 GeV. Very important work is to be attempted over the whole range, and some part of it may well turn out to be the most exciting work of the accelerator. In what follows the increase to 400 GeV will be taken as a pressing design consideration.

In almost all energy regions a factor of as little as two in intensity may prove quite important. Indeed, the case for building the 25-ft BC has been based primarily on only a couple of such factors.

The most favorable proton bombarding energy for making very low energy neutrinos has not yet been determined. To do so will require estimates of the effects of cascading pions and nucleons in targets of various shapes at various energies, with appropriate focusing systems. The choice of E_p for low-energy neutrinos interacts interestingly with the shielding problem if, as proposed here, a somewhat lower proton energy, perhaps about 150 GeV, is about as useful as 400 GeV in producing low-energy neutrinos when rep rate is taken into account.

For very high energy neutrinos, the full 400 GeV is assumed for E_p. The resultant E_ν = 250 GeV figure is a wild guess at what will just be useful for a $M_W \lesssim 16$ GeV W-search with very massive (several hundred tons) spark chambers and for total cross-section work with both bubble and spark chambers.

There are two well-known facts which make it comparatively easy to produce in the same tunnel, with good intensity, neutrinos covering this wide range of energies.

1. π's go some 15 times farther before decaying than those K's which typically give the same neutrino energies; thus, low-energy π's and high-energy K's can profitably use the same decay space.

2. The rather small lateral dimensions of the detectors to be used make it rather unprofitable to have very long decay distances for maximizing the decays of the highest energy K's, which are those giving the highest energy ν's. This is particularly true for spark chambers, in which the total mass can easily be used in a long configuration with a cross section ≤ 1 meter in radius.

Nevertheless, if two rather than only one beam could be installed a factor of perhaps 10 might be gained on the very low end and perhaps 1.5 on the high end of the spectrum. If there is a fixed amount of time available for neutrino work, and half is spent in high-energy and half in low-energy work, this potential gain would be less by a factor of 2 for those pairs of experiments which could be run simultaneously in a compromise beam. However, high-energy experiments will generally profit greatly by having the low-energy end of the neutrino spectrum depleted by a large factor, thus reducing noise, so that the runs may well in any case be separate, and thus the gain of effective intensity given by these factors be real.

Instead of two different tunnels for two beams we can use a tunnel with two target locations and also possibly two different shielding arrangements. We shall consider several two-target, two-shield setups here, in the hope that having specific possibilities for later quantitative comparison with a single-target setup (Y. Kang and F. Nezrick, SS-146) will allow a fair measure of what intensity and beam quality can be gained and what the cost would be in money and convenience of accelerator operation. Scaled to the cost of the 25-ft BC and the gain of intensity expected from it, an added cost of \$5 M for a factor of 2 in neutrino intensity available for most experiments is reasonable. No effort is made in the setups schematized here to describe how hadron beams for the BC or μ beams might be fitted in.

II. USE OF SPECIAL COMPONENTS

We want to reduce the shield thickness as much as possible, particularly for very low energy neutrinos, which diverge from pion decays typically about 100 m in front of the shield, so that a shield thickness ≥ 100 m puts the detector in a $1/r^2$ region. Then either 1) the shield is passive, yet thick enough to stop the μ's from 400 GeV but thin compared with 300 m (the thickness for iron); in this case it almost certainly must be uranium, or 2) the shield contains magnetized iron and can sweep out the μ's from 400-GeV protons in about 100 meters, or 3) E_p is lowered enough for low-energy neutrino work that a wall 100 m thick stops enough μ's. This requires a two-target system.

1. With respect to uranium alone, my guess--not a serious calculation--is that the thickness necessary to reduce the μ flux sufficiently for the BC in a single target setup using $E_p = 400$ GeV is about 100 m (at density 18.7), and 55 m at $E_p = 200$ GeV. That is, despite the large average losses by radiative processes, the fluctuations prevent the μ flux from being brought down to a level acceptable for the 25-ft BC if the shield is shortened by more than ~10% from its ionization thickness. With practical packing factors these distances would be ≥ 110 and ≥ 60 m respectively.

2. With respect to magnetized iron (see R. March, NAL SS-27, 1969, for general comments), a 35 m length of 18 kG field transverse to the beam axis will bend 350-GeV μ's initially parallel to beam axis, so that after another 85 m (65 m for the rest of the shield, and 20 m to the BC) they would be displaced a total of 5.3 m. The rms multiple scattering in the plane of bending is only about 2 mrad, as compared with the 52-mrad bend, but occasional large momentum-transfer inelastic nuclear scattering will give scattering angles comparable with the total bending angle. An expression for the inelastic cross section $d^2\sigma(E, E', \theta)/dE'd\Omega$ for μ's of energy E scattering down to E' through angle θ has been put together by L. Hand, and will be applied by Y. Kang to particular cases.

3. Now we discuss two-target systems. Note that for simplicity, the protective hadron-absorbing iron layers (~ 5 m thick) on the front faces of uranium and magnetized iron pieces will not be shown in the figures. Note also that SC's are shown behind the BC in all cases because these layouts are made to optimize the low-energy neutrino flux for the BC.

A sketch of a two-target setup using one sweeping magnet and a uranium wall is shown in Fig. 1. A setup with two sweeping magnets, and with iron instead of uranium, is shown in Fig. 2, with sketches of the two different kinds of magnets in Figs. 3 and 4. A setup with both magnets of the Fig. 4 type is sketched in Fig. 5.

For high energy, the idea is to use the distance between the upstream target T_1 to the sweeping magnet M_1 (or M_1') as the decay distance, with the distance from M_1 to the uranium shield, or to M_2, providing lateral drift space for the muons bent by M_1 (or M_1') and with some uranium or iron shielding beyond for whatever gets through the one or two steps of magnetic sweeping.

For low-energy use M_1 (or M_1') is turned off and a plug in it (or in front of M_1') is retracted to let the lower energy protons fall on a downstream target T_2, with the decays occuring only between T_2 and the uranium shield or M_2. The multiple scattering of the proton beam in the He gas in the now unused long high-energy decay path is corrected somewhat by quadrupole lenses at the entrance to M1. The target T2 must nevertheless have a fairly large diameter, perhaps 10 cm. It also flares out downstream, and is dense there, to absorb particles produced in the 0 - 30 mrad angular region, thus absorbing most of the particles which would otherwise decay into high-energy μ's.

The drift space for the low-energy neutrino beam is only 150 m long. In Fig. 1 100 GeV μ's are then ranged out in 30 m of uranium. In Figs. 2 and 5, there is then a 35 m sweeping magnet M2 (a toriod with a very small hole, only large enough for the windings) and 40 m of iron, so that ~100 GeV μ's are ranged out in a total of 75 m of iron. It could well be that detailed calculation will show that (at least with presently predicted spectra) this target arrangement, when used for the low-energy beam, should cut down the μ's to a tolerable level even with $E_p \geq 200$ GeV, but in any case we can use $E_p \geq 100$ GeV.

The problems with sweeping magnets are 1) rescattering, mentioned above, and 2) focusing of particles of one sign along the coils running parallel to the beam axis. In M1, an H-magnet with no gap (R. March, SS-8, 1969), the particles swept to one side are bent back if they cross through the coils into the return yoke of the magnet. The large amount of iron lining the tunnel tends to minimize the number of particles bent back toward the detector. Note that M1 is not square in cross section, but longer in the direction perpendicular to its central field, in order to keep the reflecting surface formed by the coils well out to the sides.

In M2 particles of one sign only are focused, while the others are always dispersed unless they are incident at a steep angle. For most work at high energy the focused (μ^-) to dispersed (μ^+) ratio will probably be ~1/100, depending on the details of the focusing, and capitalizing on the large K^+/K^- ratio. Because a toroidal magnet focuses particles of one sign along the axis, rather than off to the side where shielding can be used more effectively, it is probably less effective to use a toroid as the primary high-energy sweeping magnet (M1 in Fig. 2). Since the toroidal geometry is much cheaper, because it has no return yoke, it is worth sketching a toroidal replacement for M1, shown as M_1' in Fig. 3. Detailed calculation of trajectories are necessary to predict the μ rejection factor this arrangement would give.

III. COSTS OF SPECIAL COMPONENTS

1. Uranium: At a price (T. Toohig, NAL Trip Report, August 1, 1969) of \$600/ton, the uranium wall in Fig. 1 would cost about \$4.2 M, and even the uranium plug in Fig. 3 would cost \$1.4 M.

2. Magnets: We have assumed (perhaps too pessimistically) that M1 has to be very large, and have especially good usptream shielding, to minimize the number of μ's trapped along the coils. At \$250/ton (this rough estimate includes appropriately

machined surfaces to keep down the magnetic reluctance) M1 in Fig. 2 would cost \$4.5 M.

M2 ($\equiv M_1'$) probably has more carefully machined surfaces, and thus at \$350/ton would cost about \$1.5 M.

3. The iron wall of the drift space upstream of M1 in Figs. 1 and 2 would cost an extra \$1.5 M at \$60/ton, but it might be proved unnecessary. The iron wall of the drift space downstream of T_2 would cost about \$1 M in all cases shown. However, removal of the upstream iron from Figs. 1 and 2 may be contingent on increasing the lateral extent of the downstream iron.

The total costs will not be estimated here because of the large uncertainties both in design and in costs of the components of a given design. It is likely that for the designs discussed here the ordering of costliness, from cheapest to most expensive, is 1) best single-target design with 300 m iron wall; this is the Nezrick-Kang design--not only is the shield probably comparatively inexpensive, but some tunnel costs and second target and focusing components are saved; 2) a two-target system with two toroidal sweeping magnets and a thin iron wall as in Fig. 5, also probably comparatively inexpensive; 3) a two-target system with one H sweeping magnet with a thin uranium (or somewhat thicker iron) shield, as in Fig. 1; 4) a two-target system with one H and one toroidal sweeping magnet, as in Fig. 2. These are, or course, only some of the combinations possible.

IV. CONCLUSIONS

Some two-target systems are designed. The idea is to use a long drift space followed by very powerful magnetic sweeping with a long lens arm for high-energy neutrinos, and to cut down the proton energy and the drift space and use more modest sweeping for low energies. All this is so that a short decay distance and comparatively thin shield wall can be used for low energies in the same tunnel and with the same shield wall used for high energies. It will take detailed calculation to compute the residual muon fluxes, the useful neutrino fluxes, and the costs of these systems. My guess is that at least one of these or related systems will be worth the planning effort, cost, and operation effort when normalized to total investment in neutrino physics at NAL. The main payoff will be for low-energy BC work.

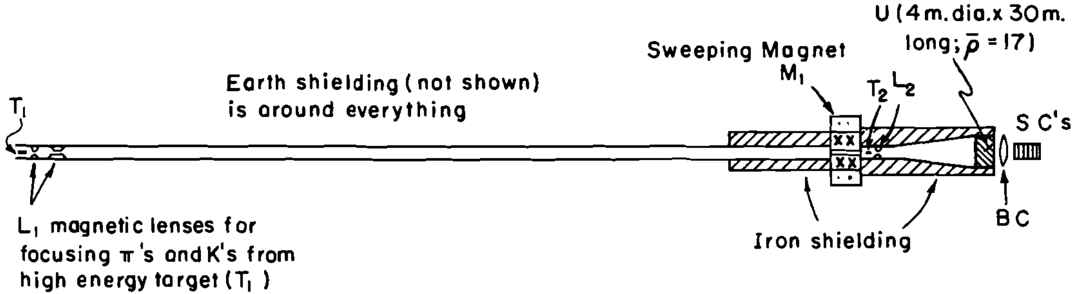


Fig. 1. Layout of neutrino area with two targets for high- and low-energy beams of neutrinos.

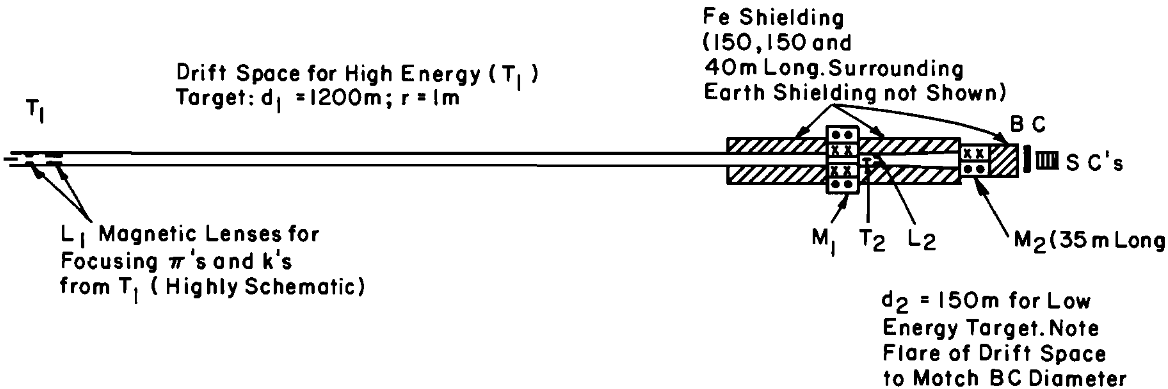


Fig. 2. Two-target neutrino area layout, using magnetic sweeping of muons.

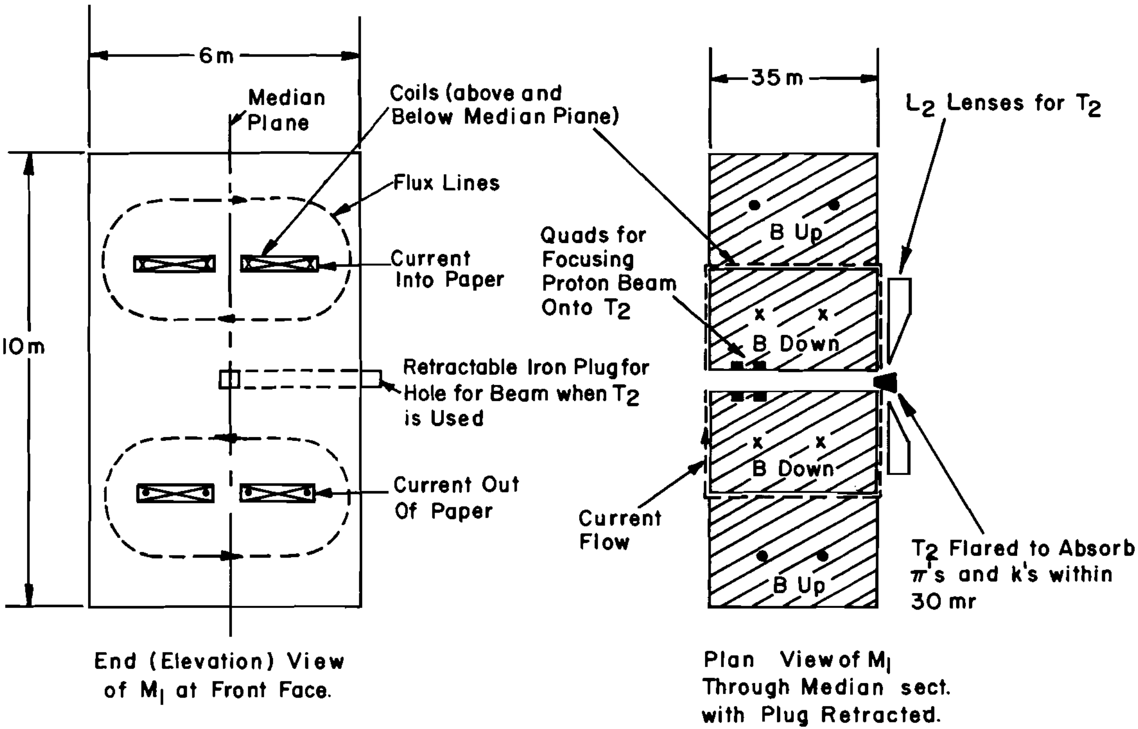
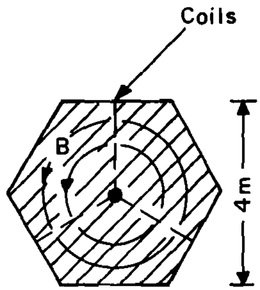


Fig. 3. Design of sweeping magnet for muons.



End View of M_2 at Face

Fig. 4. End view of muon sweeping magnet.

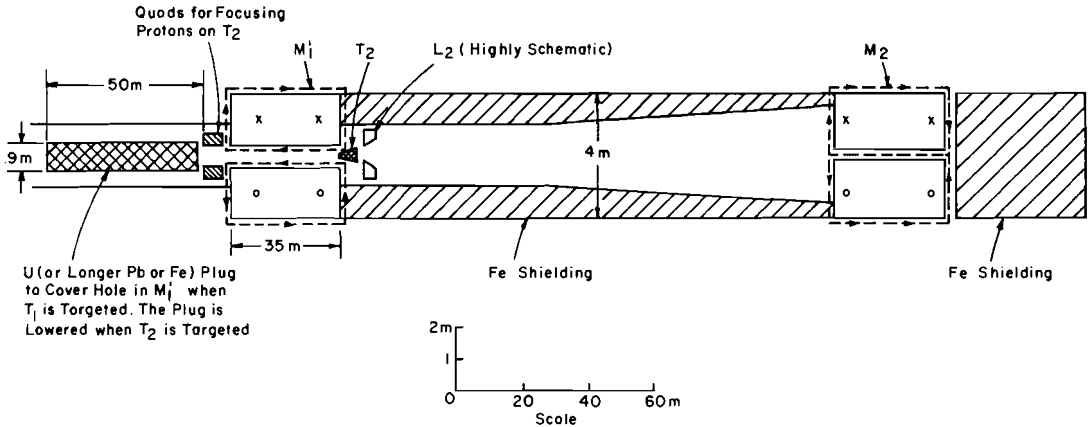


Fig. 5. Detail of second target area showing shielding and sweeping magnets.