A HIGH INTENSITY MUON BEAM AT NAL

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I. Introduction

Historically, the electron scattering experiments have provided us with a great deal of knowledge on the structure of protons and neutrons. As the energy required is increasing, the muon beams at the high energy proton accelerators become the natural substitutes for the expensive electron accelerators. For example, NAL has a 200 GeV muon beam now operating. When the machine operates at 1 TeV in the future, this muon beam should have the capability of operating at an energy equal or greater than 1/2 TeV.

The present muon beam intensity at NAL is weak. It is useful for the study of the photon-fragmentation region, where the values of q^2 are relatively low and the values of ω are large, in muon-nucleon scatterings. But it is inadequate for the study of the parton-fragmentation region, where the q^2 values are high and the ω values are small; new physics phenomena are expected to occur there. A new high energy and high intensity muon beam at NAL can be justified with good physics argument, and such a beam can be constructed with expediency and economy. Also, it can take care of the immediate as well as the future needs.

In this note, effort is made to present a plan on the design of a 0.6 TeV, high intensity muon beam. This plan has been the product of many investigations, conducted by many members of the Summer Study group as well as those who did not attend. In the appendix, descriptions are given on the past and the present muon beam at NAL; and also, its conflict with the neutrino beam experiments. It is hopeful that this document could help those who are interested in this problem.

II The New Muon Beam

The new muon beam is designed with the following aims in mind:

1. The beam has no interference with the neutrino experiments;
2. The beam goes to the present Muon Laboratory where two major Muon Facilities are located;
3. The beam has the capability of 0.6 TeV or above; and

4. The μ/p ratio is of the order of 10^{-5} or better to satisfy the requirement in doing high q^2 muon-nucleon scattering experiments.

These goals can be achieved by the use of a separate proton beam and a FODO channel of periodic quadrupole lattice structure. Such a system at NAL has been considered at various occasions by Toohig, Teng, and Skuja*. The present plan, as agreed upon by most members of the Summer Study group who are working in this area, is described as follows:

A. The Proton Beam Line

The separate proton beam needed by the new muon beam is shown in Figure 1. It was designed by Teng. This beam requires the following elements:

2 Electrostatic splitters	(10' each)
4 Lambertson magnets	(10' each)
42 EPB Dipoles	(10' each)

to bend the proton beam 26' (or more) away from the present neutrino beam. Also, it requires a few quadrupoles to focus the proton onto the production target; and a few more dipoles to change the beam elevation. The distance between the final proton beam line and the neutrino beam line is negotiable. It purely depends on the convenience of construction (e.g. interference with the underground utilities); or the need (or not) of bending stations for the muon momentum analysis. It is important to notice that this proton beam line has the capability of handling 1 TeV.

B. The Muon Beam Line

The muon beam line is shown schematically in Figure 2. The magnet arrangement is listed in Table 1. After the production target, a quadrupole triplet matches the beam into a long FODO channel. Then a quadrupole triplet focuses the beam at a hadron absorber which removes all the hadrons. A cross-over focus at this point is necessary to minimize the effect of multiple scattering. The cross-over angle produced here is

* See T. E. Toohig, UCID 10180, 200 BeV Accelerator Studies, April,1966 (Vol. 1, page 409); L. C. Teng, NAL 1969 Summer Study (Vol. 1, page 297); A. Skuja, Design Study of High Intensity Muon Beams at NAL, June, 1973 (unpublished internal report of Oxford and Experiment 98 at NAL)

cancelled by a doublet. The last quadrupole doublet focuses the beam onto the experimental target. The dipole before the target is used to disperse the muon momentum for tagging purposes.

The FODO channel consists of thirteen 3Q120's, spaced 164' apart. With this arrangement, this channel has a momentum acceptance of approximately 20% as shown in Figure 3. As a pion decays, the momentum of the product muon lies within a band of ~40%. Therefore, approximately half of the muons produced along the decay path of pions will be accepted by the system; and the halo is not expected to be excessive even though no dipoles are used in this design for momentum analysis. This will be calculated. The halos can be eliminated by properly positioned spoiler magnets.

At 100 GeV, the characteristic pion production angle is about 1 mr, and the maximum muon angle is about 0.3 mr. The μ/p ratio for 100 GeV muons produced by 200 GeV protons impinging onto a 1 interaction length target is estimated by Skuja to be $\sim 10^{-5}$. For higher energies, this system should work better because both the production angle and the decay angle become smaller. The system is limited to 0.6 TeV only by the capacity of the 3Q120's. Also, the total number of quadrupoles is not a very critical factor.

This muon beam should have a small beam spot size (less than 2" dia.) at the experimental target. It is invaluable in doing spin-dependence studies with a polarized proton target.

C. <u>Halo Elimination and Muon Dumping</u>

Most of the unwanted muon halos can be eliminated at the beginning and the end of the FODO channel by spoiler magnets which bend the particles downward into the earth. After the Muon Laboratory, the muon beam should also be dumped into the earth because the present muon berm is only good up to 280 GeV.

We believe the plan presented above is a sound, and workable one. Tedious calculations on questions such as halos, number of muons as a function of energy, etc., can be done in the near future. The final detailed arrangement can be worked out by NAL. Our main concern here is the general plan, not the exact details.

TABLE 1

List of Magnet Arrangement

Element	Length (ft.)	Field Gradient (at 100 GeV/c, KG/in)
Drift space	30	
Quad (2)	10 each	-1.000
Drift space	30	
Quad (2)	10 each	1.090
Drift space	30	
Quad (2)	10 each	-0.705
Drift space	164	
FODO (13 quads, spaced 164' apart)		±0.755
Drift space	164	
Quad (2)	10 each	1.000
Drift space	10	
Quad (2)	10 each	-1.658
Drift space	10	
Quad (2)	10	1.358
Drift space	300	
Quad (2)	10 each	0.872
Drift space	20	
Quad (2)	10 each	0.796
Drift space	100	
Dipole (3)	20 each	3.000
Drift space	100	
Target		

Appendix

In this appendix, the initial and the present muon beam at NAL, and also its conflict with the neutrino experiments are summarized.

1. The Initial Muon Beam

The layout of the initial NAL muon is shown in Figure 4. Its optics are demonstrated schematically in Figure 5. This beam was designed by T. Yamanouchi, and it was meant to be a by-product of the neutrino beam.

The μ/p ratio of this beam was experimentally determined to be 5×10^{-9}. The trouble lies in the fact that the first focusing element (two 10' long 3Q120's) was located $\sim$1900' away from the production target. Most of the muons were lost at apertures defined by magnets located at Enclosure 100, which was the end of the decay pipe, because of the large beam divergence.

2. The Present Mark II Muon Beam

The possible improvement of the NAL muon beam has bee worked on by many people; particularly R. Stefanski and L. C. Teng of NAL, L. Hand of Experiment 26, and L. Verhey of Experiment 98.

The Mark II muon beam optics are shown schematically in Figure 6. A 5" quadrupole doublet is added at the 1400' position (Enclosure 100), and the dipole apertures are enlarged from 2" x 4" to 4" x 4". With these improvements in geometric factors, the μ/p ratio is expected to be $\sim 2 \times 10^{-7}$. Before the end of this Summer Study, there were already 10^5 muons per pulse seen in the Muon Laboratory.

Without waiting for the long-range beam to come, the Mark II beam can be improved further right away by:

a. Replacing the dichromatic neutrino trainload with a triplet quadrupole trainload;

b. Adding one quadrupole doublet at $\sim$300' before the end of the decay-pipe; and

c. Adding more power to the area, or using super-conducting dipoles to increase the beamline capability to 300 GeV.

These short-term improvements, together with the increase in accelerator beam intensity in the foreseable future, could push the muon beam intensity up to the level of 10^6 per pulse.

3. Conflicts Between Muon and Neutrino Experiments

At the present time there are two muon and three neutrino experiments at NAL, all sharing the same target and decay pipe. There are the following serious conflicts:

a. For the long-term planning, the neutrino experiments wish to elongate the decay-pipe by approximately another 1,000'. This will not only pre-empt the existence of the present muon beam, but may pre-empt the use of the present Muon Laboratory.

b. The narrow-band neutrino requirement cuts down the muon intensity and energy seriously.

c. The 100 μsec beam spill generated by the neutrino horn makes the muon experiments impossible.

d. The frequent changing of target trainload seriously cuts down the experimental data-taking time. The net result is the inefficient use of the precious high-energy protons.

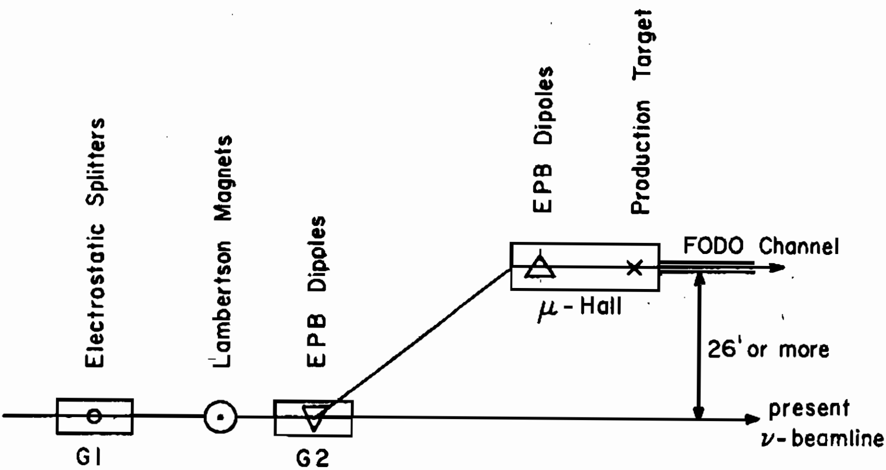
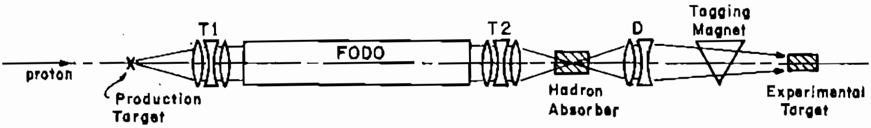


Figure 1 1 TeV Proton Beam for the New Muon Beam (Designed by L.C. Teng)



T1:	6 Quads
FODO:	13 Quads (spaced 164')
T2:	6 Quads
D:	4 Quads
Total:	29 Quads (all 3Q120's)

Figure 2 Schematic diagram of a 0.6 TeV FODO muon beam

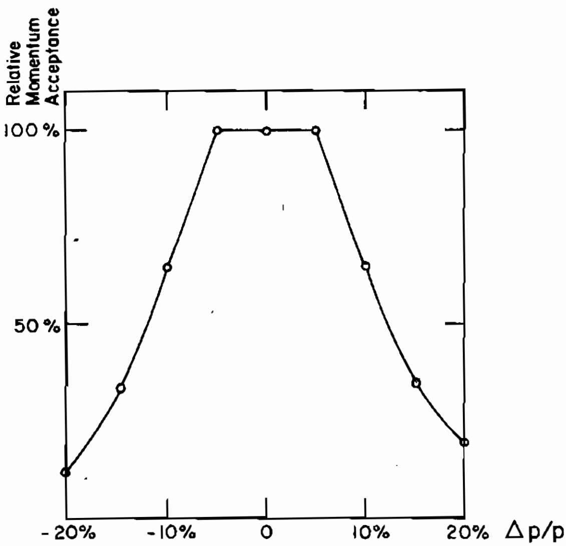


Figure 3 Relative momentum acceptance of the 0.6 TeV Muon Beam

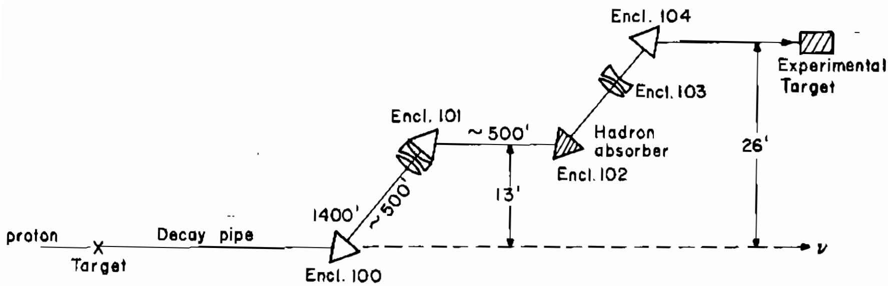


Figure 4 Schematic layout of NAL muon beam

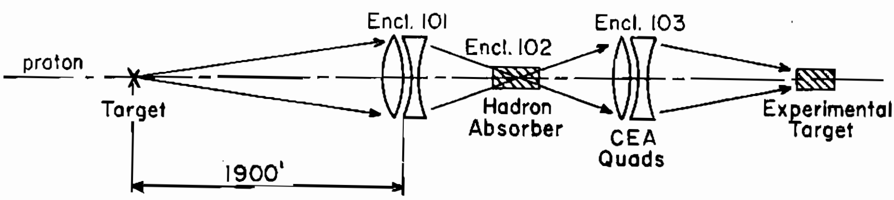


Figure 5 Beam Optics of Initial NAL Muon Beam

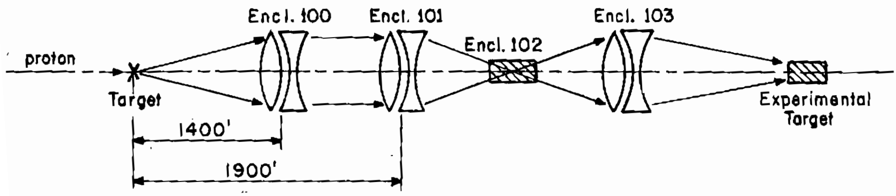


Figure 6 Beam Optics of MARK II Muon Beam at NAL