23,844
A HIGH EFFICIENCY MUON BEAM*

by

T. KIRK

University of Illinois, Urbana-Champaign, Illinois 61801

MASTER

INTRODUCTION

The investigation of nucleon structure has been a central problem in physics since the observation of Rutherford that the positive charge in an atom was concentrated in a pointlike region (the atomic nucleus). Beyond demonstrating that a second distinct level of structure, the nucleon, exists, and that the nucleon exhibits a scaling behavior for weak and electromagnetic scattering, the systematic investigation of nucleon structure has not progressed much further in six decades. One dramatic exception to this observation is the very great detail in which the special case of elastic scattering has been treated. It now seems an appropriate time to begin a similar program for investigating the more general circumstance of inelastic scattering.

Actually, such a program has been in force for several years at electron accelerators in the United States and Europe, but the energy limitations of these accelerators has largely limited the results to the study of nucleon resonances and to some extent, electroproduction of the vector mesons. The data which have appeared are already very interesting, albeit sketchy, and they give the promise of making a significant forward step in our understanding of nucleon structure.

Even more recently that "other" electron, the muon, has come to be competitive as a probe of nucleon structure and with the onset of muon physics at NAL it is expected to take the lead in these investigations. It will be the purpose of this paper to discuss an improved muon beam facility for NAL whose goal is to provide a potent muon beam available for use whenever the accelerator is running. Its demand for targeted protons could be 10% or less of the accelerated proton beam. I call

*Work supported in part by U. S. Atomic Energy Commission.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

such a facility a "high efficiency" muon beam to emphasize these features. Obviously, it will also be a "high intensity" muon beam for periods when a large fraction of the extracted proton beam is allocated for muon physics. Both modes of running have important advantages, but the high-efficiency, moderate-intensity mode might well be more important for the program of nucleon structure.

CONSTRAINTS

The final outcome of any new system is determined by the constraints placed upon it initially as well as the practical considerations which arise during planning and construction. The latter are very difficult to anticipate completely in the initial planning stage and will not be considered at length here. Instead, we will set out a list of constraints which should be satisfied by the actual beam. The constraints may be arguable and to some extent a matter of taste, but they will be stated explicitly, nevertheless.

- 1) High Duty Factor: The muon beam should be capable of delivering a slow spill at the highest machine energies for which flat-top operation is possible. Even more important, the beam should be available whenever the machine is extracting a slow spill proton beam. Slow spill is necessary for any experiment which uses the incident beam particle in coincidence (the great majority of muon experiments completed or contemplated so far impose this requirement). This general principle has been recognized and implemented for beams elsewhere in the laboratory through the use of splitters at several points along the external proton beam transports.
- 2) Efficient Targeting and Beam Transport: To create a moderate intensity muon beam without wasting protons, requires a large acceptance for pions centered about a 0° production angle, coupled with a wide-band pion/muon beam transport. The wide band requirement arises from two considerations which are somewhat independent. Firstly, since the pion decays with uniform probability into muons with momenta between 0.57 and 1.00 of the parent pion's momentum, a large spectrum of pion energies contributes to a given muon momentum interval. Therefore, even a small momentum band of accepted muon energies is strongly enhanced by providing a wide band acceptance of higher momentum pion parents. Secondly, the development of momentum tagging methods has expanded the momentum band of acceptable beam particles to whatever width is compatible with transport of the muon beam to the experimental target. Thus,

an effort to maintain wide-band momentum acceptance for the muons, even after the pion absorber, is rewarded by a second large enhancement factor in the muon beam intensity. These two factors are highly desirable and are essentially independent.

3) Favorable Beam to Halo Ratio: In muon experiments attempted to date, the existence of penetrating muons outside the beam itself has imposed a strong constraint on the triggering flexibility. For this reason, it is very important to maximize the beam to halo ratio for the muon beam. As the beam energies climb into the range of hundreds of GeV, the problem becomes acute and must be borne in mind in any plans for beam transports. A combination of absorbers, energy loss and magnetic separation seems necessary since pure absorption requires impractically long transports.

4) Availability to the Muon Scattering Facility: The Chicago-Harvard-Illinois-Oxford Collaboration has constructed an elaborate muon spectrometer facility for NAL and expects to carry out the initial round of experiments with this facility. It therefore seems obvious that the muon beam should be brought to the spectrometer facility. To some people, however, it is not immediately obvious that the facility must needs remain in its present location. Movement of the facility would be a very large undertaking so it seems sensible to try hard to bring a beam to the facility rather than relocate the facility in some new beam line. A new beam line must needs be contemplated in any case.

The constraints outlined above do not take any explicit account of practical details which will intrude themselves into the decision process; it is intended that they stand apart as fairly inviolable principles. It will be the subject of the remainder of this paper to discuss practical ways of achieving these goals.

A PROPOSED MUON BEAM

In light of the constraints discussed, we will attempt to outline a practical muon beam which will be possible of implementation in a two to three year period and which involves a minimum conflict with the present neutrino area and its ongoing program. Other proposals for beams will likely come from this summer study and they will be referred to at appropriate times. The beam consists, briefly, of a split in the main proton line to the neutrino area; a proton transport to a target hall approximately alongside the present Neuhall; a pion/muon decay channel of wide momentum acceptance; an absorber/beam dump to remove hadrons; and a muon beam transport and

halo rejection network to select the appropriate band of muons and bring them to the experiments.

The beam design outlined below is based upon discussions with many people who have been involved with muon beams at NAL as well as upon results obtained from a new Monte-Carlo beam program which calculates the beam transport along with the energy loss, multiple scattering, and yoke field bending for halo muons. This last capability has important ramifications for the intense, wide band beams now being contemplated in which the halo rejection problem becomes critical. The principle stages of the beam with comments about their relative advantages and disadvantages are taken in order below.

PROTON BEAM SPLIT AND TRANSPORT

Early in the summer study, the question of how to obtain a separate proton source and target for the muon beam was discussed and Mr. Lee Teng of NAL volunteered to look into the problem. His recommendation was to split the proton beam to the left shortly after the meson lab split and bend the protons away from the neutrino line and into a new target hall, henceforth called Muhall. The proton beam could then be targeted and the pions collected free of any constraints from the requirements of the neutrino research program. The proton beam splitting done thus far at NAL has been highly successful, and fractions of beam as low as 10^{-3} have been split off and targeted successfully. Actually, if the neutrino and bubble chamber programs come to rely exclusively upon short spill beams, it may be adequate to install pulsed switches to route the beam into one of the two channels and forego a true splitting station. This technical detail does not influence the basic question of where and how to acquire a variable fraction of the extracted proton beam for transport to a Muhall target.

The protons split off can be transported to a target in Muhall which has considerable flexibility with respect to its elevation, its distance away from NeuHall, and its initial beam direction. Besides the obvious advantage that this flexibility confers upon the beam designer, there is the very important point that the construction phase can proceed simultaneously with running in the present configuration. Only the period when the penetration is made into the present beam line will interfere with neutrino lab operations. Mr. John Peoples of NAL has

estimated that such a penetration could be accomplished within a three month period. All other construction would be outside the existing beam and could go forward while the neutrino lab is running.

TARGETING AND PION/MUON CHANNEL

The question of beam elevation at the target as well as the initial direction for pion transport is worthy of further study. At first glance, it appears to be attractive to transport pions below ground level parallel to the present neutrino line and at a distance of perhaps 30 feet from it. This would minimize the amount of new mounding necessary to shield the beam for radiation purposes as well as minimizing the interference of the new beam with present service facilities for the neutrino line (the muon pipe would tunnel under the existing service buildings as it is only a foot or so in diameter). Termination of the hadrons might be done underground and a magnetic halo rejection network and muon beam transport used to bring the muon beam up to the present beam elevation. The results for a simple transport of this type are shown later in Table I where the beam/halo ratios and μ/p ratios relative to the present conditions are summarized.

A second possibility might be to target underground, but slant the pion transport upward so that the final muon beam would require only one bend for momentum selection and halo rejection. This solution has advantages from an intensity point of view but suffers from lack of flexibility in treating halo. In this regard, the beam/halo ratios shown in Table I may be misleading since they do not include attempts to "spoil" the halo with special magnets. Although all proposed transports will be able to profit from some type of spoiler, the more distance and bend available, the more flexibility one has in spoiling the halo.

Thirdly, it may be best to target at ground level, directly in line with the present beam line in the muon lab. Such a beam would require a major sideways extension of the present neutrino beam, but would permit a dispersion free bending solution for momentum selection at the end of the transport. This initially less attractive solution may gain in acceptance if achromaticity conditions in the other approaches prove difficult of solution. Clearly, each of the three general possibilities will have to be studied in more detail than is possible in a summer study.

The structure of the transport itself is certainly open to further study. If the only requirement was for muon intensity, the FODO channel provides a straight-forward solution. Such a solution was outlined by Toohig^{1/} in The Berkeley 200 GeV Design Study and similar approaches have been discussed by individuals in the U. S.^{2/} and Europe^{3/} since then. The appropriate spacing of elements is governed by the energy range of the beam desired and by the diameter of the focussing elements. The FODO lattice has the property of holding together with high efficiency all particles with momenta above some critical value P_0 . Below this momentum, the lattice quickly cuts off in acceptance and essentially becomes a rejection network. The high pass band behavior when combined with the sharp decrease in pion production as a function of X (the ratio of the pion momentum to that of the incident protons) causes the actual pion beam to have a momentum band of perhaps 25% FWHM centered somewhat above the P_0 cutoff. (This is certainly true above an X value of say 0.5).

Now, here comes the rub...The pions in the 25% pass band decay about half the time into muons which lie below P_0 and which are rejected soon after having been born. The transport thus becomes a "leaky pipe" of muons as long as pions continue to decay. The escaping muons become halo. The final beam muons must therefore be contained and the halo dispatched after termination of the hadrons in a nuclear absorber.

At this point, a second complication arises. The removal of hadrons causes the beam angular phase space to increase appreciably due to multiple scattering in the absorber. In an optimum material such as beryllium, the average value of transverse momentum imparted is about 120 MeV/c, (5 times the maximum value which the pion-muon decay process contributes). In order to minimize the increase in the area of the beam phase space ellipse during this step, one usually attempts to achieve a double focus in the absorber, thus maximizing the angular dimension of the constant area phase space ellipse and combining it more favorably with the absorber multiple scattering (which adds in quadrature). This causes a problem with matching out of the FODO channel, which is now expected to focus its wide band beam achromatically into an absorber. This is difficult as can be imagined, but possibly a combination of dipole, quadrupole and sextupole elements can achieve an acceptable solution.

The point to be made is that a trade off must be established between the halo benefits gained from an early hadron termination, the blowup of phase space in the absorber, and the subsequent problems with momentum dispersion.

One way out, of course, is the method presently used at NAL wherein a long unfocused decay space is used to create a population of relatively parallel particles with a fairly wide momentum band. At the end, a suitable magnetic dipole-quadrupole array selects a narrow momentum subset of this spectrum and transports it to the muon lab. The yield is much poorer for this type of beam relative to a FODO channel, but the beam/halo ratio is better. L. Hand^{4/} has reported to the summer study an improved version of this type of beam with impressive performance relative to the present beam and within range of a FODO type channel. The beam/halo ratio, in particular, looks very favorable. Most likely, some intermediate solution will be found which combines the best features of both.

An intriguing suggestion for transporting a very wide band muon beam after hadron termination has been made by H. Anderson who contemplates a superconducting coaxial pipe with a toroidal focussing field arising from currents flowing down the center conductor and back along the outer one. Focussing fields of 0.25 GeV/c per meter could easily be achieved. Such a pipe would be equivalent to a magnetic channel with an infinite number of elements and essentially all muons would be preserved. The idea is certainly worthy of serious study. At present, we will end this section on pion beam transport with the observation that whatever the details of the final transport, it stands to make a very large gain in efficiency over the present beam. The freedom provided by a dedicated target and transport make this possible.

MUON SELECTION AND HALO REJECTION

As noted in the preceding section, the principle problem to be dealt with here is the separation of the raw muon flux emerging from the absorber (together with its surrounding halo) into a beam which can be transported to an experiment and a halo which can be dumped. Pure absorption is a very poor choice for halo removal as can be seen by noting that a muon loses only about 0.5 GeV of energy per meter of NAL dirt. A combination of magnetic separation and absorption can work, but there is plenty of room for clever ideas as to

the exact method. For the beam itself, the desire for efficiency and intensity requires a large momentum acceptance (of order 10%-15% FWHM). Means of achieving this are known, but rather large magnets (possibly including sextupoles) will be necessary. We will briefly discuss both aspects of the muon transport.

There are several basic combinations of quadrupoles and dipoles with first order achromaticity for beams with well defined and small initial phase space populations (say from a target small with respect to the following quadrupole lens diameters). Sextupoles can be used to correct for second order chromatic effects in such beams. The muon beams which emerge from FODO channels, however, are of such large size in phase space that many of the simple prescriptions fall short of expectations. In these circumstances, ray-tracing methods, with or without Monte-Carlo treatment are more helpful, and a certain amount of empirical feedback is useful for optimizing a transport system. Powerful matrix method programs such as TRANSPORT exist which are extremely helpful for doing this part of the job. One variation of the FODO channel was designed and optimized by L. Mo and A. Skuja^{5/} using a modified version of TRANSPORT and the results were reported to this Summer Study. Other people 1, 2, 3, 6, 7/ have used Monte-Carlo methods in order to treat the pion decay and halo propagation properly. There is room for both approaches, and each has its own value. No amount of perspiration can take the place of a little inspiration in either case!

The rejection of halo is the less well understood of the two principal aspects of muon beam design. The stochastic nature of the halo origin, plus the complication of energy loss, multiple scattering, and magnet yoke deflection make the problem all but intractable of calculation except by Monte-Carlo methods. The first program to attempt this was written by L. Verhey^{6/} and applied successfully to muon beams at NAL and BNL. Since then, several other programs have emerged to do the same type of calculations. The present conclusions and the results quoted in Table I were reached by the author's version of such a program.

The general principles which emerge from a study of halo are as follows: 1) Dipole bends are very useful separators as their back legs bend halo opposite to the beam. 2) Quadrupole yokes neither concentrate nor disperse halo efficiency. 3) Iron toroids with the beam passing through a central field free region can be very effective dispersers. 4) Absorption in dirt or iron always helps, but can't be relied upon unassisted by magnetic separation. 5) All beam, left to its own devices, likes to become halo.

The beams calculated by the author's program are displayed in Table I, and shown in schematic detail in Figs. 1, 2, 3, and 4. The absolute yield of example 4 is about a factor 10 higher than observed for the MARK II beam at NAL. At the time of this writing that beam had not been optimized and how much of the discrepancy is due to tuning and how much to the program model is unclear. Other models of the beam have tended to be optimistic in the past by factors of 2 to 4. Aside from the absolute normalization, comparative numbers for performance of the different beams is likely to be reliable if past results are any indication. In particular, the size of the MARK II beam, its momentum spectrum, and its beam/halo ratio all conform well to be observed properties of that beam. None of the beams calculated have been included spoilers, but the energy loss, multiple scattering and yoke field bending have all been accounted for. The results are rather interesting, for we see that the beam with the best beam/halo ratio (Hand) is also quite intense. The two bend FODO beam would become very attractive if its halo problems can be solved. Probably, some intermediate approach between the 2 bend FODO and the Hand beam can be evolved to give a relative gain of about 30 times MARK II and a beam/halo ratio (assisted by spoilers) of greater than 10. Time did not permit such a design to materialize for this report, but it is being worked on and will be available at a later date.

CONCLUSIONS

Aspects of muon beams pertinent to the establishment of an effective nucleon structure facility have been discussed and a preliminary design for such a beam at NAL advanced. The optical properties, duty factor and proton

beam source are already able to be sharply specified, but the pion and muon transports need more work to be optimal. It is already clear, however, that efficiency gains of at least 20 can be made and probably factors of 50 or even 100 are not impossible. Beam/halo ratios can probably be raised to perhaps 10:1 with proper spoilers. Most important of all, the effective beam time can be raised an order of magnitude over present prospects by establishing a separate source of protons for a muon beam by means of a split or pulsed switch in the present neutrino beam time. An upgrading of the muon beam at this time would be a very appropriate and effective way to invest a portion of the construction resources of the laboratory.

References

1. T. E. Toohig, UCID - 10180
2. A. Skuja and L. Mo, 1973 Aspen Summer Study Report
3. H. J. Behrend, et al, ECFA Working Group Report 1972, p. 199
4. L. Hand, 1973 Aspen Summer Study Report
5. A. Skuja, Muon Beam Design Study, Exp 98 Design Report (Unpublished).
6. L. Verhey, Private communication
7. M. Strovink, Private communication

FIGURE CAPTIONS

- Fig. 1. A FODO configuration which has only one bend to provide halo rejection and momentum selection.
- Fig. 2 A FODO configuration which has two symmetric bends for momentum selection and halo rejection.
- Fig. 3 Beam design of L. Hand as described in 1972 Aspen Summer Study.
- Fig. 4 Present Mark II Muon Beam at NAL.

TABLE I

Comparison of Various Muon Beams for NAL

Beam Name	E_p (GeV)	E_μ (GeV)	$\mu/p_{inc.}$ (yield)	B/H (beam to halo)
2 Bend FODO	300	100	170×10^{-6}	0.13
1 Bend FODO	300	100	380×10^{-6}	0.2
Hand Beam	300	100	70×10^{-6}	1.0
Mark II NAL	300	100	4.3×10^{-6}	0.5

Note: The absolute yield for Mark II is larger than the measured value by a Factor 10. This is not yet understood, but the scaling ratios tend to be more reliable. Also, no fine tuning has been done, so beam/halo ratios are likely pessimistic. No spoilers are included.

FIG 1

FIG 2

FIG 3

FIG 4