A HIGH INTENSITY, HIGH ENERGY MUON BEAM AT THE BROOKHAVEN AGS *

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Summary

Recently there has been interest in the use of the muon as a probe of QED at small distances. In particular a high energy, high intensity beam of muons opens up several interesting avenues of study. In this paper we present some preliminary results for the design of a muon beam of energy 2.5 Bev, and discuss some of the problems associated with such a design.

Introduction

The present work was undertaken in preparation for an experiment at the Brookhaven AGS to study the elastic scattering of muon from protons at very high momentum transfers[1]. The experiment required a beam with the following properties:

Flux = 5×10^6 muons/pulse
Momentum = 2.5 ±.25 Bev/c
Angular divergence < 1°
Beam diameter ≤ 8"
Contamination by strongly interacting particles $< 1 \times 10^6$

A sketch of a system[2] intended to fulfill these requirements is shown in Fig. 1. It is assumed that the AGS proton beam is extracted with long spill time and is formed into a well-collimated beam having cross-sectional dimensions of a few mm. The beam strikes a long and thin cylindrical target of Be (~ 50 gm/cm^2 in length). The first three quadrupoles (Q1 to Q3) collect pions with momenta between 6 and 10 Bev/c; the next ten quadrupoles (Q4 to Q13) act as a transport system to carry the pions and those decay muons having momenta near 5.5 Bev/c. The following quadrupoles Q14 and Q15 "shape" the beam for the magnetic analysis system (B1 and B2). The magnetic analysis system isolates particles having momenta in the band 5.5 ± .25 Bev/c; it is followed by a "filter" to remove the strongly interacting components from the beam. The muons lose about 3 Bev in the filter, so that the emergent beam has the proper mean momentum (2.5 Bev/c) and momentum spread.

The Entrance System

The entrance system is essentially a quadrupole doublet made up of three magnets, the first two of which are vertically focusing and the third is defocusing. The angular acceptance is about 15 x 90 mrad at 8 Bev/c decreasing to about 10 x 50 mrad. at 6 and 10 Bev/c. The settings of the quadrupoles used are summarized in Table I.

Table I

Quadrupole settings - entrance system

Quad 1	2270 gs./in.
Gap	10"
Quad 2	1790 gs./in.
Gap	20"
Quad 3	-2300 gs./in. (design limit)
Gap	50"

The Transport System

The transport system has two purposes. First it must be able to hold as many as possible of the pions present at the entrance. Second, and most important, it must be able to hold the 5.5 Bev/c muons produced by decay of the pions in flight. We have written a Monte Carlo program in order to evaluate the capture and transmission efficiency of the system up to the end of the transport system. The program simulates the production of pions in the target, the propagation of pions through the entrance and transport systems, and the decay of the pion at a random point within the system.

The program generates pions at the entrance with momentum and angular distributions derived from an analytic fit to the experimentally measured cross sections[3]. These pions are then traced through the system using standard matrix methods. For each pion generated, the distance to the point at which it decays is chosen at random from an exponential distribution appropriate to the pion momentum. For economy of computation the probability of decay integrated over the length of the system is taken to be 1, and a correction for this is introduced later. All pions striking a magnet are assumed lost at that point. The muon resulting from the decay is then traced to see if it reaches the end of the system. If it does, a card is punched containing the (vector) momentum and position of the muon at the end of the system. These cards are used as input to other programs. We have included an option to restrict the energy of the decay muons to a particular energy band.

The program also calculates the effective cross-section for muon production defined as follows:

$$\sigma_{eff} = \epsilon \iint \frac{d^2\sigma}{d\Omega\, dp} \left(1 - e^{-L_{syst}/\lambda(p)}\right) W(p) \times d\Omega\, dp$$

L_{syst} = total length of system

$\lambda(p)$ = mean flight distance of pion of momentum p

ϵ = efficiency for muon capture

(i.e., ϵ = No. of muons generated/No. of pions generated)

$$W(p) \begin{cases} = \text{correction if muon energy is restricted} \\ = \dfrac{(\text{Max. } \mu \text{ energy} - \text{Min. } \mu \text{ energy})}{(.43\ p)} \\ = 1 \text{ if no restrictions} \end{cases}$$

With this program we have investigated several different configurations of quadrupoles in the transport system. In all of the systems tested the quadrupoles were equally spaced, in accord with the findings of preliminary tests which indicated that such an arrangement was best. All of the quadrupoles also had the same strength, since it was found that in most systems no significant improvement was obtained by "tuning" the individual quadrupoles.

In Fig. 2 we have plotted the effective cross section, σ_{eff}, as a function of the gradient in the quadrupoles for two different spacings of the quadrupoles. We expected that the larger spacing would be more effective, since it provides a longer decay path for the pions. However, the shorter spaced system is found to be appreciably more efficient; it is so much more effective at collecting muons that the loss of decay path is more than compensated.

Fig. 3 shows the momentum spectrum of the muons computed for the most promising system studied to date. (Here no restriction has been put on the acceptable muon momentum). Note that the distribution is peaked at about 5.5 Bev/c. Figs. 4-6 show the profile of the beam at the exit of the transport system, as well as the horizontal and vertical phase space plots of the beam at this point. (In these plots, X and Y are the vertical and horizontal coordinates and XP and YP the corresponding slopes). The latter show that, at this point, the beam is diverging vertically and converging horizontally. In order to reduce the size of the beam vertically so that it may pass through the bending magnets B1 and B2 without severe loss, we have added a pair of quadrupoles Q14 and Q15. These also bring the beam to horizontal focus at the momentum defining slit in the magnetic analysis system.

Magnetic Analysis System

The magnetic analysis system consists of two large bending magnets (18" x 6" aperture, 72" long, maximum field ~ 2000 gs.) with equal and opposite fields to give zero momentum dispersion. The momentum is defined by a slit immediately in front of the second bending magnet; this slit is, in fact, a thick wall, since many cm. of lead are required to absorb muons of wrong momentum. The length between the magnets is determined by the bend angle (10°) and the horizontal size of the beam at the slit (≈ 2.5"). For a momentum definition of ± 5% the length is 225".

Although we have not yet completed the design of this part of the system, we expect that we will be able to achieve the desired momentum definition and also obtain a transmission efficiency of 50% or more for the desirable muons.

The Pion Filter

After the momentum analysis the ratio of pions to muons is of the order of 10:1. Since the pion and muon cross sections for elastic scattering from hydrogen are about in the ratio of 10^4:1 at momentum transfers of 1 to 2 Bev/c we must reduce the pion contamination in the beam to a level of a few parts in 10^7. The most direct manner of accomplishing this is to pass the beam through an absorber which provides the necessary nuclear attenuation of pions. The results of a previous experiment of this type[4] indicated that 15 mean free paths would be sufficient to reduce the pion contamination to the desired level. The absorber reduces the muon energy (by ≈ 3 Bev), but also spreads the beam considerably because of multiple scattering. The absorber should be of low-Z material in order to minimize these losses. We have chosen carbon as a compromise between availability and ease of handling, and added five quadrupoles (Q16 to Q20) whose function is to provide a net focusing effect.

In order to evaluate the effects of the combination of absorber and quadrupoles, a beam tracing program was written with a set of Monte Carlo routines added to include the effects of multiple scattering[5]. With this program, we intend eventually to trace the paths of muons which have already passed through the magnetic analysis portion of the system, and to compute the fraction which reach the center of a target some 15' downstream from the end of the filter. At this stage, however, we have only evaluated the transmission efficiency of the filter for particles which originate from a virtual source 200" before the absorber (this roughly simulates the angular spread which is to be expected in the final system). For this case, the transmission, defined as that fraction of muons which remain inside of an 8" diameter cylinder while in the absorber, is shown in Fig. 7. The results indicate that the quadrupole focusing produces an enhancement of almost a factor of 3.

Conclusions

Our study of the system is evidently incomplete at this time. The entrance system and transport system now seem fairly straightforward and we expect that the present design will be retained. The magnetic analysis system presents problems which have not yet been completely resolved. The geometry of the pion filter and associated focusing quadrupole array will probably not be drastically altered, although some adjustments in the gradients and spacings of the quadrupoles may be needed to bring the transmitted beam to a final focus at the experimental target.

At this stage, we can only estimate the intensity of the muon beam which will be transmitted by the entire system. Using an effective cross section σ_{eff} = 15 μbarns for the entrance and transport portions of the system, and estimating the transmission efficiencies of the magnetic analysis system and of the absorbing filter to be 65% and 20%, respectively, we obtain a flux of negative muons of 2×10^6 for each pulse of 3×10^{11} protons. It may be possible to improve this figure by as much as a factor of two by improving the design of the filter. The flux of positive muons is about twice the negative muons that because of the larger cross section for production of π^+ by protons.

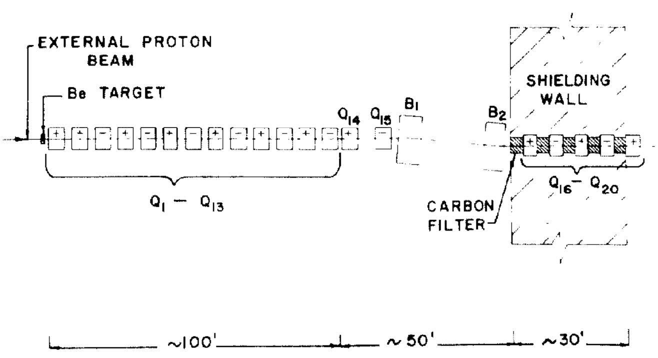

Fig. 1. Beam Layout.

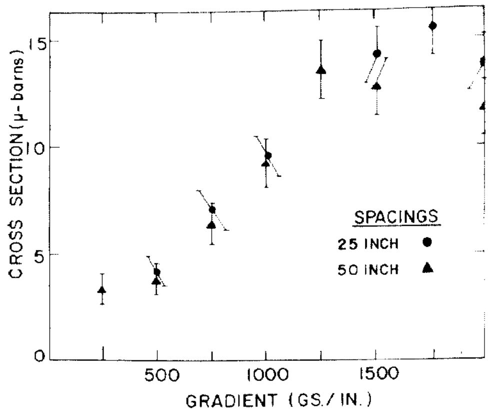

Fig. 2. Effective cross section vs Gradient for two different spacings.

Acknowledgements

Many of the computations reported here were performed on the 7094 computer at the CIMS, New York University. We thank the staff of the center for their cooperation.

References

1. G. Feinberg and L.M. Lederman, Ann. Rev. Nuc. Sci., 13 (1963)

2. All quadrupoles in the entrance and transport systems are 12" in diameter and 60" long and have a maximum gradient of 2300 gs./in.; those used in the filter are 8" in diameter, 48" long and have a maximum gradient of 3200 gs./in.

3. L.M. Lederman, private communication.

4. T. Yamanouchi, R. W. Ellsworth et al, Bull. Am. Phys. Soc. 10, 79 (1965)

5. This part of the program was adapted from a set of routines written by Dr. M. J. Tannenbaum

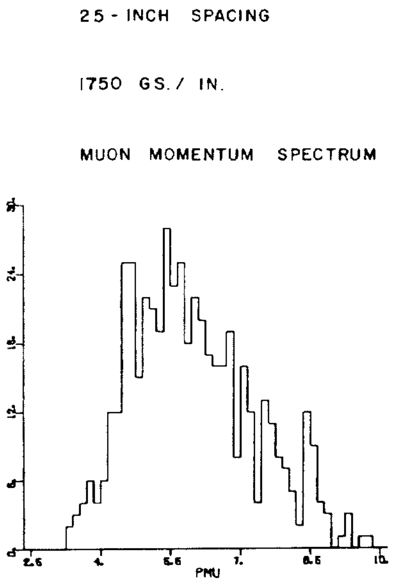

Fig. 3. Muon momentum spectrum.

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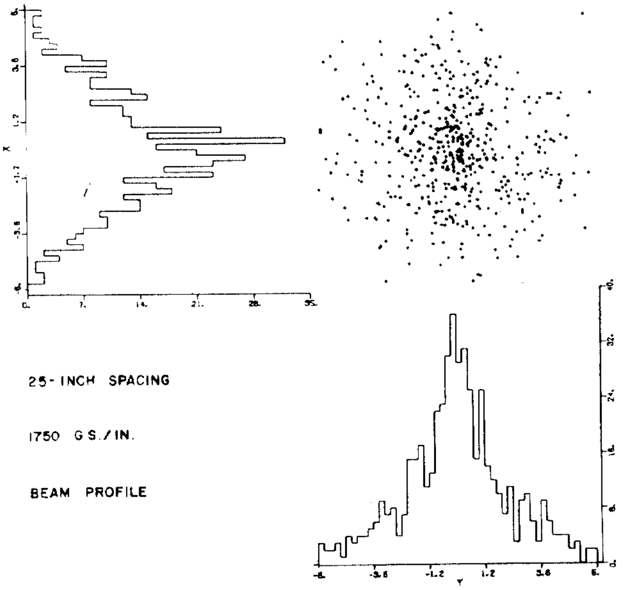

Fig. 4. Beam profile.

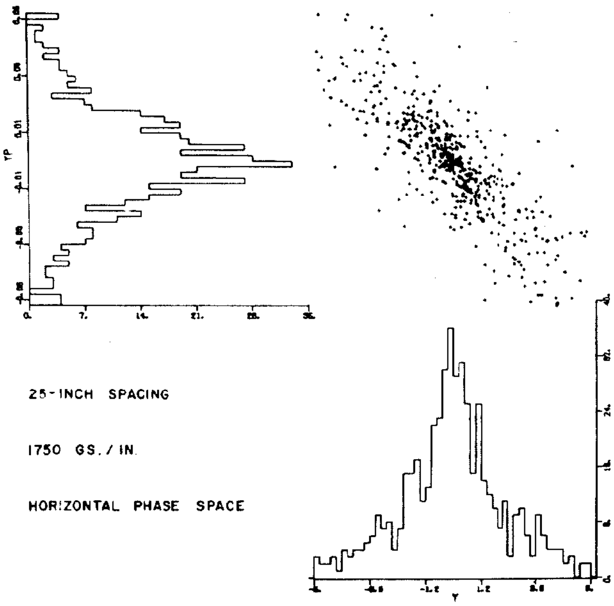

Fig. 5. Horizontal phase space.

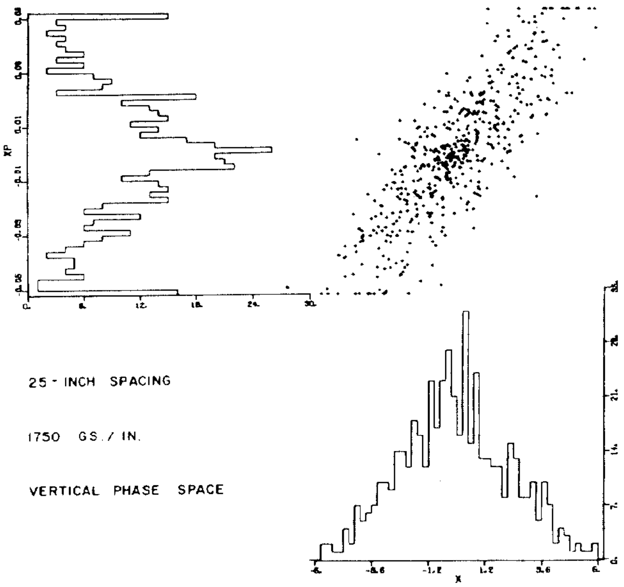

Fig. 6. Vertical phase space.

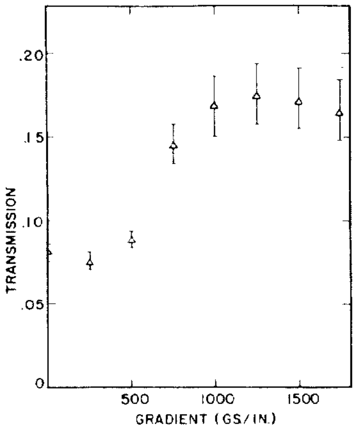

Fig. 7. Transmission vs Gradient.