LOW-BUDGET MUON SOURCE*

V. I. Balbekov† and N. V. Mokhov, FNAL, Batavia, IL 60510, USA

Abstract

Generation of muon beams with protons on a current-carrying target followed by a lithium lens and a quadrupole decay channel is considered. A 8 GeV proton beam from the Fermilab Booster is used to provide a muon beam for the MUCOOL experiment for ionization cooling demonstration. The proposed scheme can also be used to create muon beams with a fraction of a 1 GeV proton beam of the Spallation Neutron Source. Monte Carlo simulations of the entire system are performed. For both cases optimization of the target and matching lithium lens is done. It is shown that such a set followed by an inexpensive decay channel based on quadrupole magnets with and without RF cavities provides a rather intense bunched muon beam.

1 INTRODUCTION

To achieve adequate parameters of a neutrino factory based on a muon storage ring [1, 2] it is necessary to produce and collect large numbers of muons. A baseline scheme [3] is based on 16 or 24 GeV proton beam impinging on a tilted carbon or mercury jet target in a high-field solenoid (20 T, about 1-m long, aperture radius R_a=7.5 cm), followed by a matching section and a solenoidal decay channel (1.25 T, 50-100 m in length, R_a=30 cm) which collects muons resulting from pion decay. In this paper we are exploring a drastically cheaper scheme that still can produce a muon beam usable for an entry level neutrino factory, other applications with intense muon beams and for the MUCOOL experiment [4] to study ionization cooling. The scheme starts with the existing 8-GeV Fermilab Booster proton beam on a current-carrying target followed by a low-gradient lithium lens [5]. Pion beam, primarily focused in the lens, decays into muons in the decay channel based on (also existing) quadrupole magnets from the BNL D2 channel. Pion production and capture in the target station as well as formation of a bunched muon beam in the decay channel were simulated with the MARS code [6]. The later was also performed with an independent specialized Monte Carlo code. A good agreement was found, therefore most of the tracking results below were obtained with this fast code.

2 TARGET STATION

Layout of the target station is shown in Fig.1, and its parameters are listed in Table 1. The station includes a current-carried target for pion production and collection,

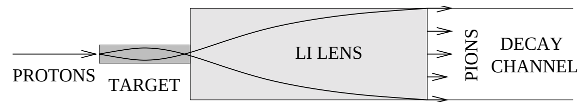

Figure 1: Layout of the target station.

Table 1: Parameters of the target station

Parameter	Symbol	**Target**	**Li lens**
Material		Cu	Li
Length (cm)	L	15.0	40.0
Radius (cm)	R	1.60	8.50
Current (kA)	J	560	560
Maximal field (T)	B	7.00	1.33
Field gradient(T/cm)	G	4.38	0.155
Beta-function (cm)	β	4.78	25.4

and a Li-lens for matching to the decay channel. Phase rotation of pions or muons is not presumed in this scheme, therefore the system is tuned to provide the best condition for pions with momentum $p_0 \simeq 300$ MeV/c where pion yield is close to maximum [3]. At 8 GeV, a 15-cm long copper target provides maximal yield (see Fig. 2). The magnetic field gradient inside the target is taken to get betatron phase advance 180°, attaining by this the best filling of transverse phase space by pions with momentum p_0. The target radius is taken to get an acceptance of about 0.54 cm, which is slightly less than expected acceptance of the decay channel (see below). It follows also from Table 1 that phase advance is about 90° at the Li lens. At such conditions, the lens provides the optimal matching of

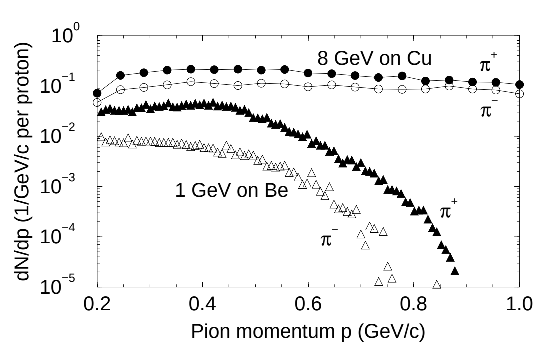

Figure 2: MARS calculated pion spectra (per interacting proton) at the downstream end of a Li-lens for 8-GeV protons on a 15-cm copper target, and 1-GeV protons on a 15-cm beryllium target.

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† balbekov@fnal.gov

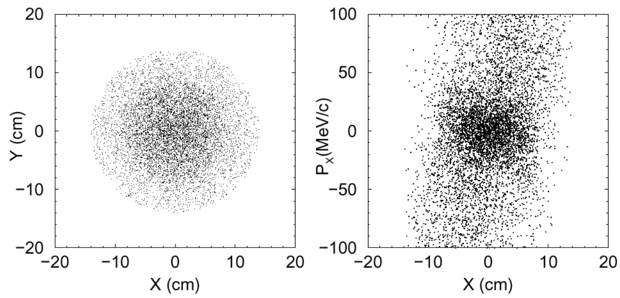

Figure 3: Transverse phase space of pions.

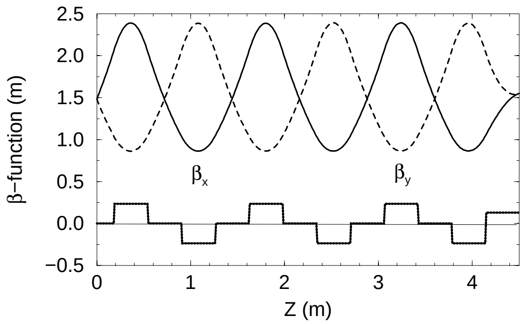

Figure 4: Layout and β-functions of the decay channel.

the target with a channel with a β-function of $\beta_{chan} = \beta^2_{lens}/\beta_{targ} \simeq$135 cm.

The MARS calculations were performed for the 8-GeV Booster beam with $\sigma_{x,y} = 6$ mm and r.m.s. bunch length σ_z=30 cm. Pion spectra at the exit from the lithium lens are shown in Fig. 2. The results are also shown for the system with the proton energy reduced to 1 GeV (SNS beam) and copper replaced with beryllium of the same longitudinal and transverse dimensions. We found that for low-energy proton beams a usage of low-Z materials maximizes the positive pion yield. For a 8 GeV proton beam, total number of π^+ per proton after the lens is 0.119 with 0.002 μ^+ created already (π^- yield is somewhat less). However, only 0.028 $\pi^+ + \mu^+$ per proton fall in the total energy interval of 280 to 420 MeV acceptable for subsequent utilization [1]. Transverse phase space of these particles is shown in Fig. 3. A central core and halo are seen very distinctly in these plots. Higher energy pions, as well as particles produced in the lens, appear in the halo, most probably. The number of $\pi^+ + \mu^+$ in the central core is about 0.020 per proton, within the r<8.5 cm radius with the above energy cut. It means that with a careful design of the decay channel one can get quite intense muon beam at its end.

For the considered parameters of a Booster beam at 5×10^{12} ppp at 15 Hz, the peak energy deposition, temperature and power dissipation in the copper target are quite manageable with an appropriate cooling system. Radiation levels in the target station are quite high but can be localized within several meters from the target and controlled with a corresponding shielding.

3 DECAY CHANNEL

A channel without RF and a bunching channel with RF are considered below. Both of them utilize the BNL D2 pion beam line quadrupoles. These quadrupoles have a maximum gradient of 0.1 T/cm, an effective length of 36 cm and aperture radius of 13.7 cm.

3.1 Beam Line without RF

This decay channel consists of FODO cells, each with two 0.059 T/cm quads and two 36-cm straight sections. The number of cells is 34 in this design, and additionally one lens of the same length but lower gradient (0.033 T/cm) is put at the channel downstream end. It provides $\alpha_x = \alpha_y$ and $\beta_x = \beta_y$ that is convenient for matching with the following solenoidal cooling channel. Total length of the channel is 50.6 m. Fig. 4 shows three cells and the matching lens at its downstream end. The channel acceptance of 0.78 cm (=7800 mm×mrad) is almost 1.5 times larger than the target station acceptance. The margin is required because the beam emittance increases due to pion decays.

Evolution of the beam parameters in the decay channel is shown in Fig. 5. The upper curve represents sum of pions and muons. A fast decrease at the first 1-2 m is explained by loss of pions with p_t >30 MeV/c which are outside the channel acceptance. Slower loss after that testifies that the channel acceptance is not sufficient to save all muons, because some of them get large additional transverse momentum at the decay of their parent pions. The number of muons at the end of the channel is 7.8×10^{-3} total, and 2.4×10^{-3} with the $255 < E_{tot} < 355$ MeV interval. A normalized transverse r.m.s. emittances are 0.53 cm and 0.47 cm, correspondingly. The absolute maximum of the yield is obtained for a 80-m channel, but it is only slightly higher, 2.5×10^{-3}, within the above energy interval. Muon

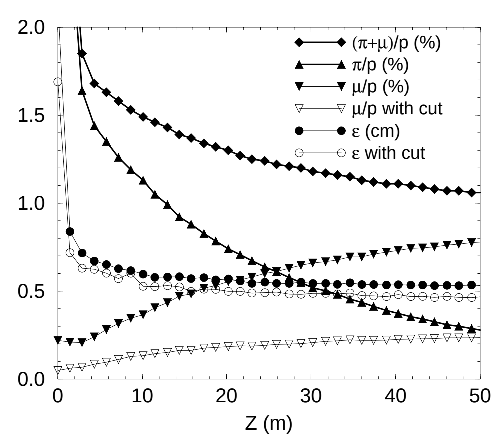

Figure 5: Evolution of the beam parameters in the decay channel.

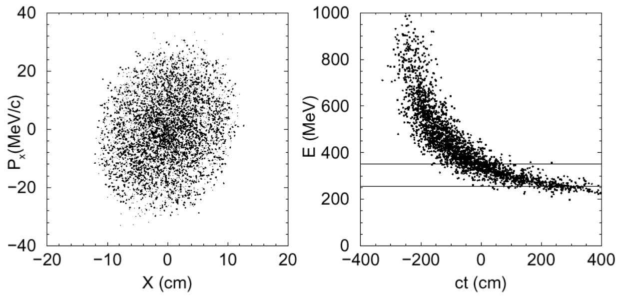

Figure 6: Transverse and longitudinal phase space of muons at the end of the decay channel.

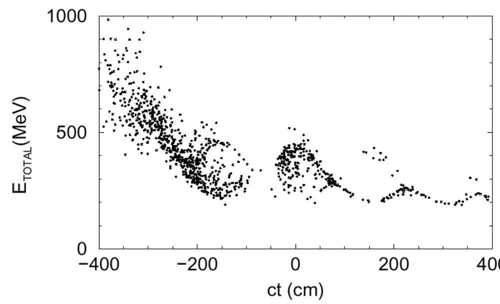

Figure 8: Longitudinal phase space of muons after the bunching.

phase space at the end of the decay channel is shown in Fig. 6.

3.2 Beam Line with RF-buncher

A part of the decay channel destined also for beam bunching is presented schematically in Fig. 7. The 118-cm long straight sections are included to provide the room for RF cavities. A central 4-m long cell has a periodical β-function and can be multiplied as many times as needed. Actually the channel contains 12 such cells. Two special doublets at the ends are included to provide the same β-functions both for X and Y directions. Total length of the channel is 50.2 m that is almost the same as in the previous design. The quadrupole gradient is 0.0404 T/cm, except for the first and the last lenses where it is 0.0143 T/cm. The maximum β-function in this channel is 1.4 times higher compared to the previous one. Therefore, it has smaller acceptance and provides (without RF) 2.6 times less muons than the previous scheme.

Twenty four 14.4-MV RF stations (201.25 MHz frequency, 96 cm long) are placed in the 118-cm straight sections. A longitudinal phase space after the bunching is shown in Fig. 8. The number of muons in a central bunch is about 0.5×10^{-3} per incident proton. The bunches are formed not very nicely because there is no factors to kill uncaptured muons. Beam bunching in the cooling channel itself seems to be more preferable. The efficiency of using a very expensive accelerating system would be higher in this case.

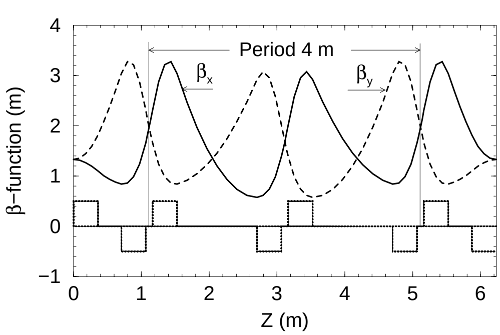

Figure 7: Layout and β-functions of the decay channel with bunchers.

4 MUON BEAM AT SNS

The scheme proposed above can be used to generate intense π/μ beams at the Spallation Neutron Source (SNS). Assume that 10% of its 1-GeV beam is directed onto a pion production target. As we found for such a beam, the maximum π^+ yield at $\sim$0.4 GeV/c one gets from a 30 cm beryllium target. At the end of the channel described above, we get 1.5×10^{-3} μ^+ per incident proton at the kinetic energy of 200$\pm$70 MeV. For the 2 MW, 2 mA SNS beam of 2.08×10^{14} ppp, with 10% on the pion production target, one has 4×10^{10} μ^+ per pulse or 2.4×10^{12} μ^+/s, i.e. about 10^4 more than the best existing beams. This beam is ready to be used directly (or after a modest cooling) in a muon storage ring as a source of intense ν-beams. It can be used for a test facility for a muon collider. There are also numerous research options with such muon beams, including material science and applications.

5 REFERENCES

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