IMPACT OF THE INITIAL PROTON BUNCH LENGTH ON THE PERFORMANCE OF THE MUON FRONT END*

H.K. Sayed,[†] H.G. Kirk, J.S. Berg, Brookhaven National Laboratory, Upton, NY 11973, USA
K.T. McDonald, Joseph Henry Laboratories, Princeton University, NJ 08544, USA

Abstract

The dependence of the performance of the Front End of a Muon Collider/Neutrino Factory on the proton-beam bunch lengths of 0-20 ns is explored for beam kinetic energies of 3 and 8 GeV.

INTRODUCTION

Some of the requirements on the proton driver for a staged Neutrino Factory based on muons beams [1] are listed in Table 1. Efficient capture of muons in the Buncher of the Front End [2] of the Neutrino Factory favors very short proton bunch lengths. However, meeting the requirement of an intense proton bunch of length only 2 ns is challenging at 3-GeV beam energy because of space-charge effects [3]. We present here a study of the impact of a longer proton bunch on the performance of the Front End.

In the course of related studies [4], an advantage in capture efficiency was found in using a short "taper" to the profile of the capture-solenoid magnetic field, down from the 20 T peak at the target to 1.5-3.0 T at the beginning of the Decay Channel some 4-6 m downstream. Shorter tapers were found to deliver muon beams with smaller time spread at the Buncher for a given proton bunch length at the pion-production target, corresponding to increased capture efficiency of the Buncher. In this study we examined the performance of such short tapers, as well as long adiabatic ones, for proton bunches of 2-20 ns length.

The beam-dynamics simulations were performed using the ICOOL code [5], with input spectra of secondary particles produced at the proton-beam target as modeled by MARS15(2012) [6]. Figure 1 shows examples of pion beams at the end of the target, of length from 2-10 ns, before being tracked through the tapered capture-solenoid, Decay Channel, Buncher, Phase Rotator and Ionization Cooling sections.

Table 1: Proton-driver requirements for the final and initial stages of a Neutrino Factory.

Parameter	Final Stage	Initial Stage
Proton energy [GeV]	8	3
Beam power [MW]	4	1
Rep. frequency [Hz]	50	70
Bunch length [ns]	2 ±1	2 ±1

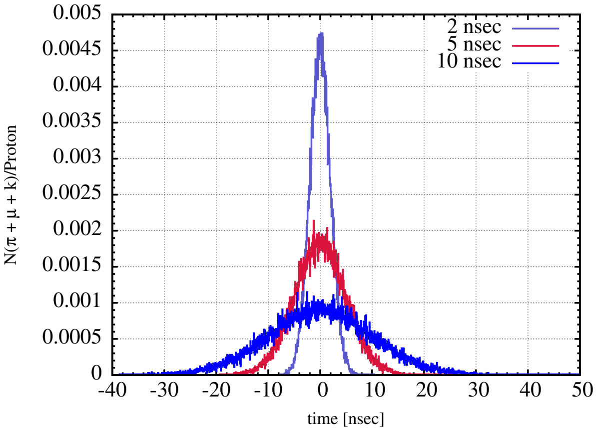


Figure 1: Pion beams with bunch lengths of 2-10 ns off the pion production target.

CAPTURE EFFICIENCY VERSUS TARGET SOLENOID TAPER LENGTH

Pions (which later decay to muons) are generated at the target with a wide spread in transverse momentum, largely uncorrelated with their longitudinal momentum As they move through the high target solenoid field they develop a correlation between the longitudinal velocity and the initial transverse momentum. The higher the field integral $\int Bdl$ of the target solenoid leads to a larger time spread (*i.e.*, more muons sent out of the longitudinal acceptance of the buncher and rotator). Figure 2 shows the longitudinal phase space of muon beam at the end of the Decay Channel for a short taper of 4‘m and a much longer adiabatic one of 40 m. The shorter solenoid taper delivers muon beam with smaller time spread at a fixed longitudinal momentum p_z to the Buncher. Consequently the short taper has an advantage over the more adiabatic long taper as it manages to pack more muons within the longitudinal acceptance of the buncher and phase rotation channels. Figure 3 shows the muon beam time spread at the end of decay channel (50 m from target) for various taper solenoid profiles.

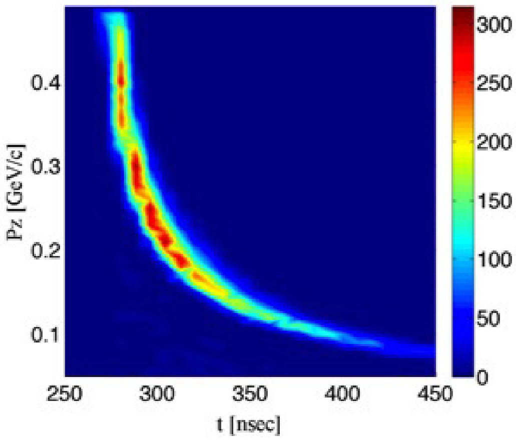
Pions (later muons) produced off the target were tracked through the Front End starting from the end of the target, through the tapered solenoid, Decay Channel, Buncher,

---

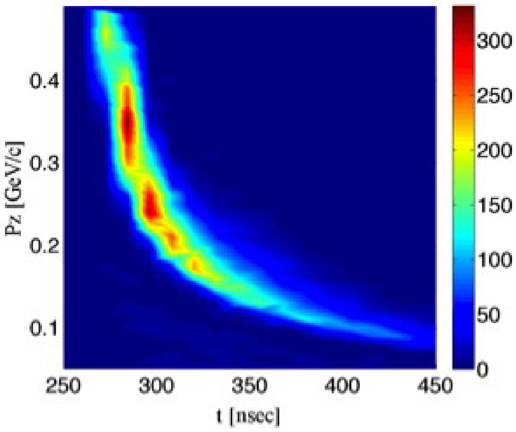
* Work supported by the US DOE Contract No. DE-AC02-98CH10886.

[†] hsayed@bnl.gov

Phase Rotator and Ionization Cooling channels. Fig. 4 shows the number of captured muons versus the solenoid taper length for various target solenoid configurations. The peak field of the target solenoid increases the transverse capture of the pions, as shown in Fig. 4. As the field tapers down to the constant field within the Buncher and Phase Rotator, the faster the taper the smaller the time spread and the better the performance. Increasing the taper-end field strength increases the acceptance of the Front End, as can be seen in Fig. 4).



(a) Short solenoid taper of 4 m.



(b) Long solenoid taper of 40 m.

Figure 2: Longitudinal phase space of pions and muons at the end of the Decay Channel, 50 m from the target.

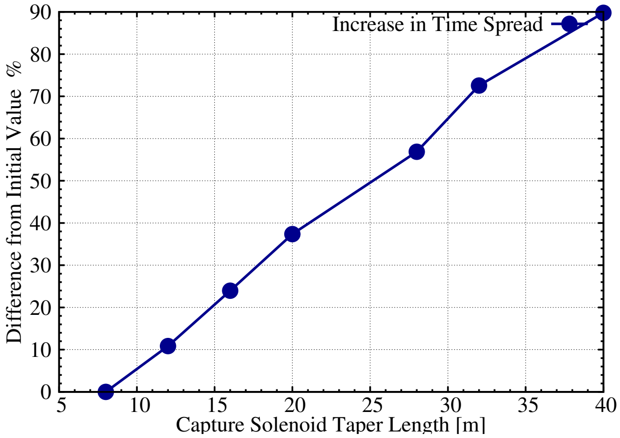


Figure 3: Relative increase in the time spread of the muon beam at the end of the Decay Channel as a function of the taper length. The distance from target to end of Decay Channel is constant.

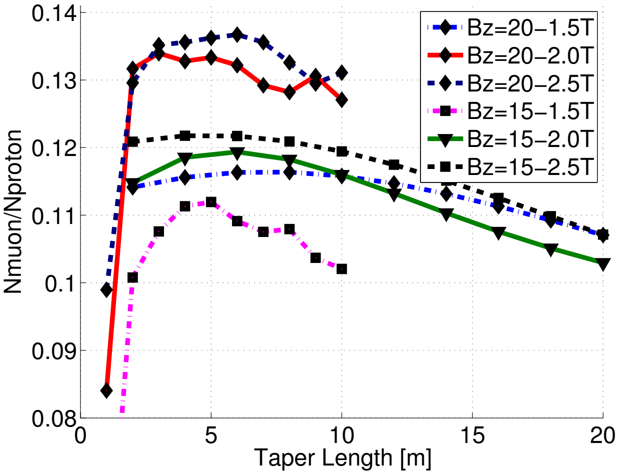


Figure 4: Muon yield after the transverse Ionization Cooling Channel, within the acceptance of the following accelerator chain, *vs.* the target solenoid taper length. Optimum yield is at taper length of 4-6 m.

As the initial pion bunch length gets longer the advantage of the short taper in preserving the time spread will not be the dominant effect on the performance of the Buncher and Rotator. To find the bunch-length limit over which the short solenoid taper holds its advantage, we tracked pions (muons) with bunch lengths varying from 1 to 30 ns through the Front End, Figure 5 shows the number of positive muons at the end of the Front End tracked through solenoid tapers of lengths 6, 20 and 40 m in case of an 8-GeV proton beam incident on a Hg-jet target, with solenoid-field profile tapering from 20 down to 2.5 T. The short taper looses its advantage gradually as bunch lengths increase from 1 to 20 ns. Bunches with length of 20 ns and longer will not benefit from the short-taper effect.

A similar study was carried for an initial Neutrino Factory with a 3-GeV proton beam on a graphite target and peak solenoid field of 15 T, with results shown in Fig. 6. The tracking study was done for a target solenoid taper length of 4 m and end field of 2.5 T. For this case the loss is $\approx 5\%$ per 1 ns increase in bunch length.

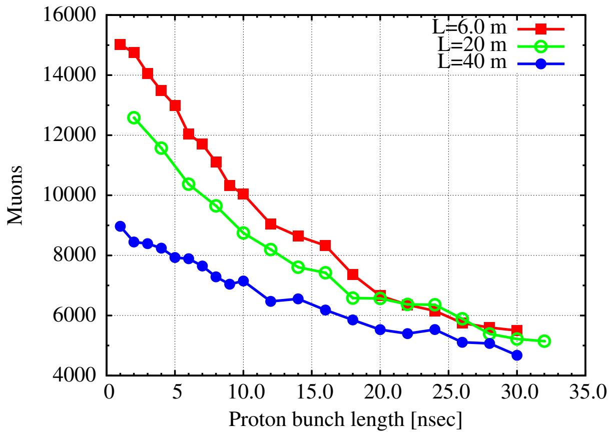


Figure 5: Number of positive muons within the accelerator chain acceptance *vs.* the initial proton bunch length for 8 GeV proton beam on a Hg-jet target. The tracking study was done for different target solenoid taper length of 6, 20, 40 m (red, green, blue). The short taper loses its advantage gradually as the bunches get longer.

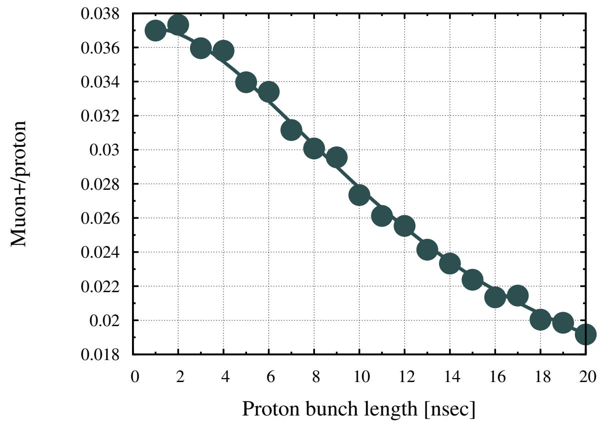


Figure 6: Number of positive muons within the accelerator-chain acceptance *vs.* the initial proton bunch length for 3-GeV proton beam on a graphite target. The tracking study was done for a target solenoid peak field of 15 T, taper length of 4 m, and end field of 2.5 T. For this case the loss is $\approx 5\%$ per 1 ns increase in bunch length.

PERFORMANCE OF THE DESIGN BUNCH LENGTH 2-8 NS

The performance of the Front End at various design bunch lengths of 2, 5, 8 ns *vs.* the target-solenoid taper length is shown in Fig. 7. For bunch lengths of interest for a Muon Collider and Neutrino Factory (2-8 ns), the short taper holds its advantage. The difference in performance of the front end between a 2 and 8 ns decreases gradually with the taper length.

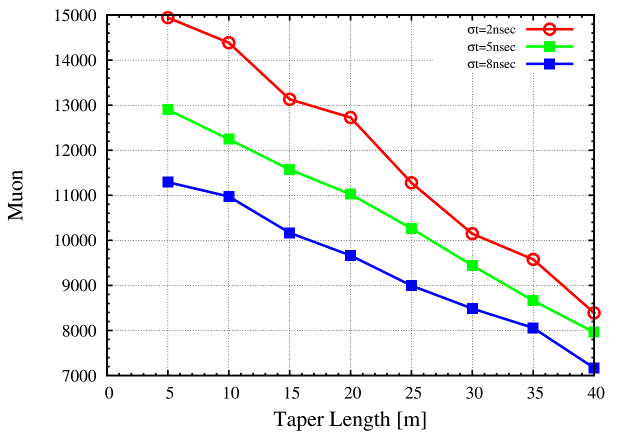


Figure 7: Number of positive muons within the accelerator-chain acceptance *vs.* the target solenoid taper length at three different bunch lengths of 2, 5, 8 ns.

ACKNOWLEDGMENT

The authors would like to thank X. Ding for useful discussions.

REFERENCES

[1] M.A. Palmer *et al.*, Muon Accelerators for the Next Generation of High Energy Physics Experiments, Proc. IPAC13, TUPFI057 (2013).

[2] C.T. Rogers *et al.*, Muon front end for the neutrino factory, Phys. Rev. ST Accel. Beams **16**, 040104 (2013).

[3] R. Palmer, Proton Bunching Options, Applications of High Intensity Proton Accelerators, BNL-90917-2010-CP, (2009).

[4] H.K. Sayed *et al.*, Optimization of the Capture Section of a Staged Neutrino Factory, THPHO11, NA-PAC'13.

[5] R.C. Fernow,Ionization Cooling Code, https://pubweb.bnl.gov/˜fernow/icool/

[6] N.V. Mokhov, The MARS Code System User's Guide, Fermilab-FN-628 (1995); N.V. Mokhov and S.I. Striganov, MARS15 Overview, AIP Conf. Proc. **896**, 50 (2007), http://www-ap.fnal.gov/MARS/