OPTIMIZATION OF THE CAPTURE SECTION OF A STAGED NEUTRINO FACTORY*

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Abstract

A proposed staged Neutrino Factory, producing lower muon intensity of 10^{20} muons per year and 10-14 GeV muon beam energy, initially requires target station for 1 MW proton beam power with a proton beam energy of 3 GeV, which could be upgraded to the full power of 4 MW at 8-GeV beam energy. The optimization of the initial Target Station and the following Decay Channel and Buncher/Phase Rotator are discussed.

INTRODUCTION

In the baseline Neutrino Factory / Muon Collider design [1], sketched in Fig. 1, the muon beam is produced from pion decay by bombarding a liquid-mercury-jet target with a 4-MW pulsed proton beam, which delivers an intense muon beam of 10^{14} muons/sec from the incident beam of 10^{15} proton/s. In the proposed staged Neutrino Factory [2] with a 1-MW proton beam of 3-GeV energy, the Target Station uses a solid graphite target and produces a muon intensity of 10^{20} per year The target is embedded in a 15 (or 20) T solenoid magnet for the pion collection, shown in Fig. 2, which is followed by a lower field Decay Channel. The baseline design of the Target Station/Decay Channel will be retained during later stages of the Neutrino Factory to save the cost at the time of upgrade to the full 4-MW scenario.

The target and proton beam sizes and their tilt angles in the initial 3-GeV configuration are given in Table 1, which configuration produces 0.42 muons/protons at the end of the Target System.

Table 1: Proton Beam and Graphite Target Parameters for the Staged Neutrino Factory

Carbon rod target	Proton beam
Length 0.72 [m]	$\sigma_t = 2$ [nsec]
Diameter 0.692 [cm]	$\sigma_{x,y} = 0.0865$ [cm]
Angle to solenoid axis 42 mrad	42 mrad

The adiabatic variation in solenoid field strength along the beam near the target performs an emittance exchange affects the performance of the downstream Buncher, Phase

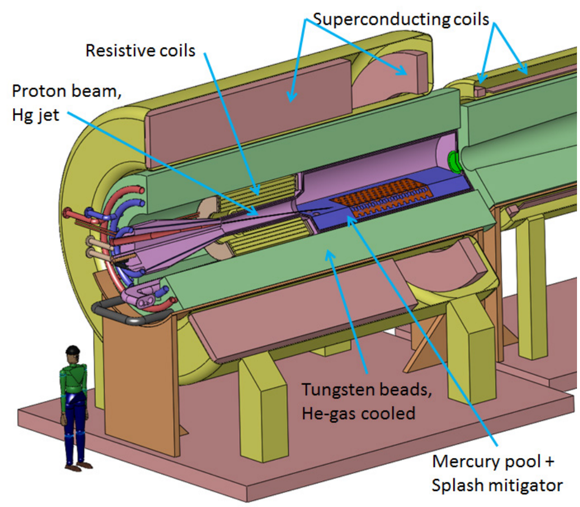

Figure 2: Neutrino Factory/Muon Collider target system.

Rotator, and Cooling Channel [3]. An optimization was performed using the MARS15 (2012) [4] and ICOOL [5] codes in which the rate of change of the field along the pion beam near the target was varied to maximize the number of muons that falls within the acceptance of the downstream accelerator chain (muons within 201.25 MHz RF bunches with momentum in the range 100300 MeV/c, transverse amplitude squared less than 0.03 m and longitudinal amplitude squared less than 0.15 m [3]).

The Target System utilizes a magnetic-field profile that peaks at $B_i = 15$ T at the target and tapers down to $B_f = 2.5$ T over a distance of L_{taper}. In this study we optimized the length of this tapering solenoid L_{taper}. The effect of solenoid-field profile on the captured-particle count and their phase-space distribution was studied by simulating the particles captured at the target and transported through the rest of the Front End. Various axial-field profiles were considered, based on an inverse-cubic form [6], from which the off-axis fields were calculated using Maxwellian series expansions. A sample of the axial-field profiles studied is shown in Fig. 3.

PION PRODUCTION AND CAPTURE AT THE TARGET

The MARS15 code [4] was used to simulate the particle production off the graphite target, using an incident 3-GeV proton beam with delta-function time distribution.

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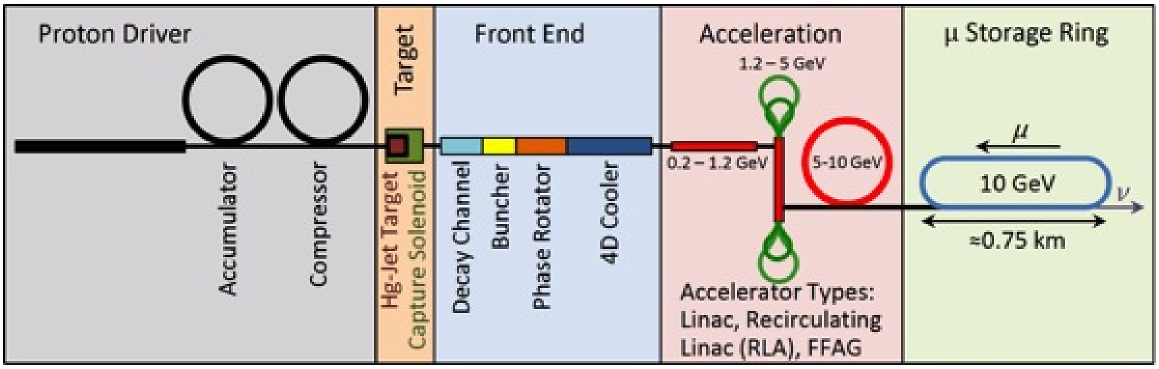

Figure 1: Neutrino Factory/Muon Collider Target System.

The kinematic parameters of the secondary pions, Kaons and muons at end of the graphite target were used as input for an ICOOL [5, 7] simulation through the tapered solenoid field and on to the end of the Cooling Channel. The transverse-momentum distribution of secondary pions at the downstream end of the graphite target is shown in Fig. 4. The beam-pipe geometry was simplified to have a constant 30-cm radius.

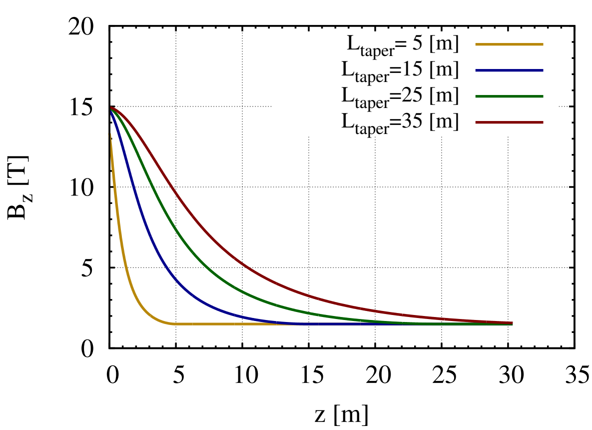

Figure 3: On-axis magnetic field profiles for the Target System.

THE FRONT END

The major systems of the Front End [3] of a Neutrino Factory are: Target System, Decay Channel, Buncher, Phase Rotator, and the Cooling Channel, as shown in Fig. 1. In this study, a constant solenoid field of 2.5 T was used to confined the muon beam throughout the Decay Channel, Buncher, and Phase Rotator, which ends some 150 m from the target, after which the beam was matched into the Ionization Cooling Channel [8] with ± 2.8-T axial field in the alternating solenoid magnets.

The pions collected off the target are transport by the capture solenoid to the decay channel of 50-m length where most of the pions decay into muons. The muon beam is then bunched using a sequence of RF cavities with frequencies varying from 320 to 230 MHz over ≈ 33 m, while the bunching-cavity RF voltage increases linearly along the channel from 3.42 to 9.01 MV/m. In the 42-m-long Phase Rotator, lower-energy muons are accelerated and higher-energy ones are decelerated, until at the end of the Rotator and the original 15-m-long bunch of muons of both signs has been formed into a 48-m-long train with 33 bunches of μ^+ interleaved with 33 bunches of μ^-.

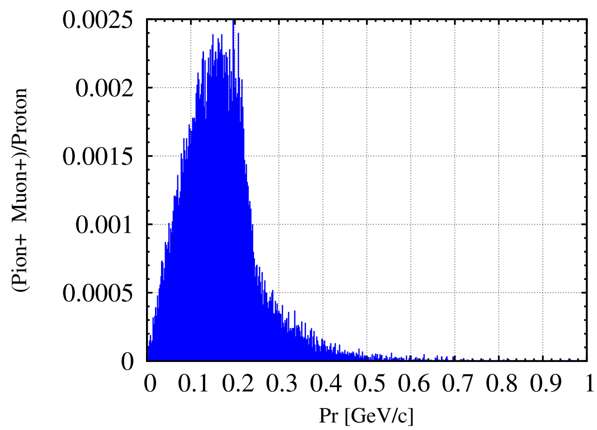

Figure 4: Pion transverse momentum at the end of the graphite target.

The transverse phase volume of the muon beam at the end of the Phase Rotator significantly larger than the acceptance of the later muon accelerator, but this volume is reduced by the Ionization Cooling section. The number of muons with the accelerator acceptances increases nearly linearly in the Cooler from $z = 150$ to 300 m as shown in Fig. 5.

OPTIMIZING THE TAPER LENGTH

The figure of merit for the optimization was taken to be the number of positive muons per incident proton within the subsequent muon-accelerator momentum acceptance [9], $100 < p_z < 300$ MeV/c, and acceptances in longitudinal and transverse phase space, $A_z < 150$ mm and $A_r < 30$ mm. The solenoid-taper length has a distinct in-

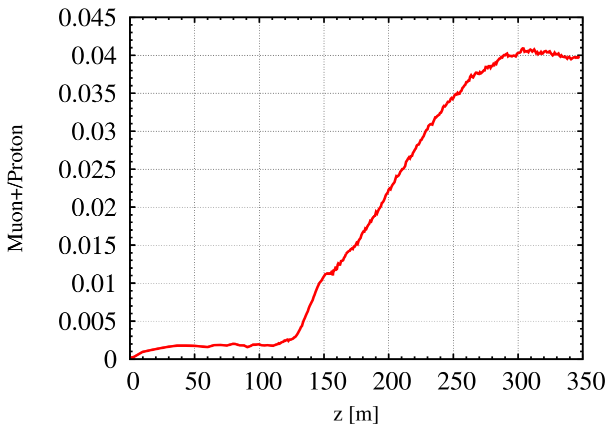

Figure 5: Number of muons within the accelerator-chain acceptance at various distances along the Front End.

fluence on the number of the transported muons to the end of cooling channel. Varying the length of the Taper resulted in higher muons yields, for $L_{\text{taper}} \approx$ 3-4 m, as shown in blue in Fig. 6.

As we varied the taper length the longitudinal phase space changed accordingly, requiring RF-phase optimization, which increased the yield by $\approx$ 16-40 See the black curve in Fig. 6.

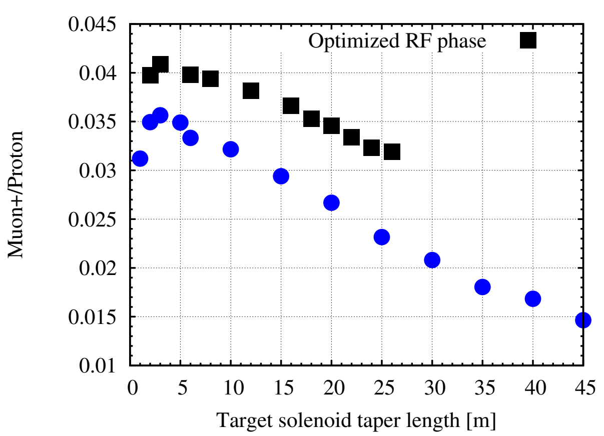

Figure 6: Muon yield from the Front End, within the acceptance of the accelerator chain *vs.* the solenoid taper length. The RF optimization (black curve) increased the Front End performance by $\approx$ 16-40%.

CONCLUSION

An optimization study of the capture section of the Front End of a staged Neutrino Factory was presented. The study was performed on a graphite target bombarded by a 3-GeV proton beam. The figure of merit of the optimization was the number of muons within the acceptance of the accelerator chains that follows the Front End. The target-solenoid field profile used in this study had an initial on-axis field $B_i = 15.0$ T, and final on-axis field $B_f = 2.5$ T, with the taper length L_{taper} being optimized for maximum yield of muons from the Front End (*i.e.*, at the beginning of the Muon Accelerator). Then, an optimization of the RF phase of the Buncher/Phase Rotator RF cavities was carried out. The best performance of the Front End was found to be $0.042\mu^+/p$. The optimum taper length was found to be 3-4 m, which is shorter than the optimum taper length when using an 8- GeV proton beam by 1-2 m.

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REFERENCES

[1] M.M. Alsharo'a *et al.*, Recent Progress In Neutrino Factory And Muon Collider Research Within The Muon Collaboration, Phys. Rev. ST Accel. Beams **6**, 081001 (2003).

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

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

[4] 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/

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

[6] K.T. McDonald, Analytic Forms for an Adiabatic Tapered Solenoid Gaussian Approximation to the Field Near $z = 0$, http://www.hep.princeton.edu/~mcdonald/mumu/target/taper.pdf

[7] R.C. Fernow, Physics analysis performed by ECALC9 (Sep. 30, 2003), http://nfmcc-docdb.fnal.gov/cgi-bin/ShowDocument?docid=280

[8] J. Gallardo *et al.*, An Ionization Cooling Channel for Muon Beams Based on Alternating Solenoids, Proc. PAC99, THP35.

[9] J.S. Berg *et al.*, Muon front end for the neutrino factory, Phys. Rev. ST Accel. Beams **9**, 011001 (2006).

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