OPTIMIZING MUON CAPTURE AND TRANSPORT FOR A NEUTRINO FACTORY/MUON COLLIDER FRONT END*

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Abstract

In the current baseline scheme of the Neutrino Factory/Muon Collider a muon beam from pion decay is produced by bombarding a liquid-mercury-jet target with a 4-MW pulsed proton beam. The target is embedded in a high-field solenoid magnet that is followed by a lower field Decay Channel. The adiabatic variation in solenoid field strength along the beam near the target performs an emittance exchange that affects the performance of the downstream Buncher, Phase Rotator, and Cooling Channel. An optimization was performed using MARS1510 and ICOOL codes in which the initial and final solenoid fields strengths, as well as the rate of change of the field along the beam, were varied to maximize the number of muons delivered to the Cooling Channel that fall within the acceptance cuts of the subsequent muon-acceleration systems.

INTRODUCTION

The Neutrino Factory and Muon Collider have similar designs for their muon-production and -capture channels [1]. In both cases the muon beam is produced by bombarding a pion-production target with a 4-MW proton beam that is pulsed at 50 Hz. Subsequent to the decay channel muons go through bunching, phase rotation, cooling, acceleration and finally storage in a ring.

The baseline design of the Target System is shown in Fig. 1 [2]. The liquid-mercury-jet target intercepts the ≈ 8 proton beam inside a 20-T solenoid field. The portion of the mercury jet disrupted by the proton beam is replaced before the arrival of the following proton pulse. The proton beam and mercury jet are tilted with respect to the solenoid magnetic axis, such that noninteracting projects impinge on the mercury-jet collection pool which acts as the a proton beam dump. The target and proton beam sizes and their tilt angles according to the baseline configuration are given in Table 1. The baseline configuration produces 0.4 muons/protons at the end of the Target System.

Previous studies [3] showed that a slow, adiabatic reduction of the solenoid field between the target and decay region maximizes the rate of muons at the end of the latter. However, the transmission of muons through the Buncher has a strong dependence on the time-energy correlations of the muons, which are affected by the magnetic-field profile in the Target System. In this work, the capture-solenoid-field profile was modified to maximize the number of muons at the end of the Neutrino Factory Cooling Channel that fall within the acceptance cuts of the subsequent muon-acceleration system.

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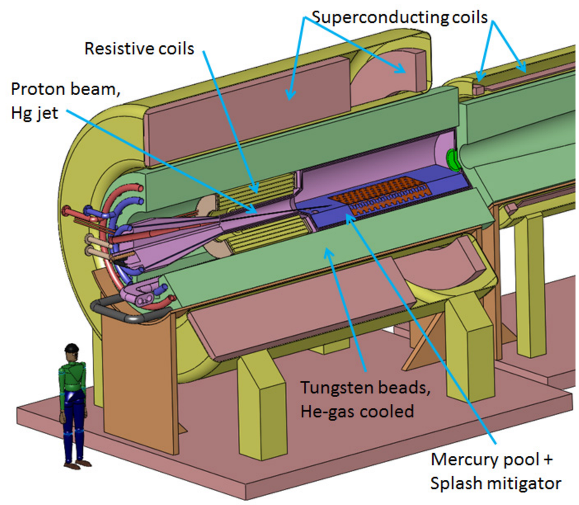

Figure 1: Neutrino Factory/Muon Collider Target System.

Table 1: The Hg target jet and the incident proton beam parameters.

Target Hg Jet	Proton Beam
$\theta_{\mathrm{target}} = 0.137$ rad	$\theta_{\mathrm{beam}} = 0.117$ rad
$R_{\mathrm{target}} = 0.404$ cm	$\sigma_{x,y} = 0.1212$ cm

THE FRONT END

The Front End [4] of a Neutrino Factory consists of three major systems: target + Decay Channel, Buncher + Phase Rotator, and the Cooling Channel. After the particles leave the tapered target solenoid they are transported in the Decay Channel, Buncher, and Phase Rotator in a constant solenoid field, nominally 1.5 T. At the end of the Decay Channel ≈ 70 m from the target, most pions have decayed into muons and the beam is about 15 m long. The beam is then bunched in a sequence of RF cavities with frequencies from 320 to 230 MHz over ≈ 33 m that capture muons with kinetic energy ranging from 50-400 MeV. In the 42-m-long phase-rotation section, lower energy muons are accelerated and high energy ones are decelerated, until at the end of the rotator the central momentum is 232 MeV/c, 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^-. The muon beam is then matched into the alternating, 2.8-T solenoid field in the Cooling Channel.

CAPTURE-SOLENOID FIELD PROFILE

The baseline for the Target System utilizes a field profile that peaks at $B_i = 20$ T at the target and tapers down to $B_f = 1.5$ T over a distance of $L_{\rm taper} = 15$ m. Alternative axial-field profiles were considered, based on an inverse-cubic form [5], from which the off-axis fields were calculated using Maxwellian series expansions. Peaks fields of $B_i = 15$ and 20 T were studied, along with final fields of $B_f = 1.5$-3.5 T and taper lengths $L_{\rm taper} = 1$-40 m. A sample of the axial-field profiles studied is shown in Fig. 2.

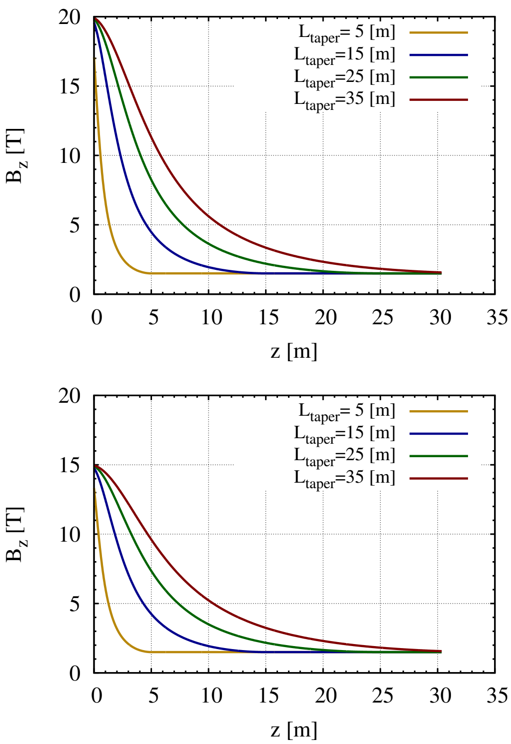

Figure 2: On-axis magnetic field profiles for the Target System. Top: $B_i = 20$ T; Bottom: $B_i = 15$ T.

SIMULATION SETUP

The MARS simulation code [6] was used to simulate the particle production off the Hg-jet target, using an incident 4-MW proton beam with delta-function time distribution. The kinematic parameters of the secondary pions, kaons, and muons at $z = 0$ (downstream end of the beam-jet interaction region) were recorded, and then used as input for an ICOOL [7, 8] simulation, through the Tapered Solenoid and onto the end of the Cooling Channel. The beam pipe geometry was simplified to have a constant 30-cm radius.

MUON PRODUCTION AND TRANSPORT

The figure of merit was taken to be the number of positive muons per incident proton within the subsequent Muon-Accelerator momentum acceptance, $100 < p_z <$ 300 MeV/c, and acceptances in longitudinal and transverse phase space, $A_z < 150$ mm and $A_r < 30$ mm.

A first result is that the normalized muon yield $N_{\rm muon}/N_{\rm proton}$ within the Muon-Accelerator acceptance decreased by 6% when the peak solenoid field was decreased from 20 to 15 T, keeping $L_{\rm taper}$ at the baseline value of 15 m.

Decreasing the length of the Taper resulted in higher muons yields, for $L_{\rm taper} > 4$ m, as shown in Fig. 3, provided the launch time of the proton beam relative to the phase of the RF cavities in the Buncher/Rotator was re-optimized.

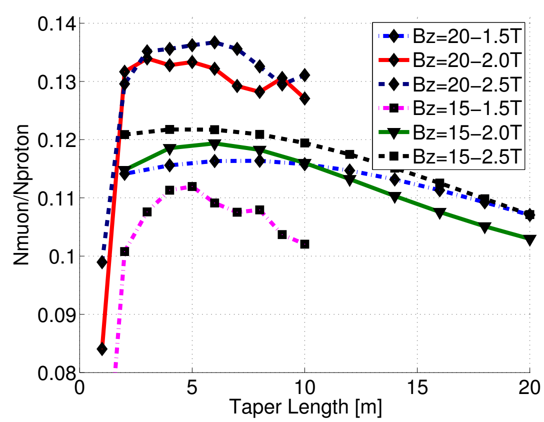

Figure 3: Normalized muon yield within the Muon-Accelerator acceptance cuts for various target solenoid configurations.

It was found that the baseline number of 140 cooling cells was not optimal for shorter $L_{\rm taper}$, while adding 10-20 more cooling cells was sufficient to maximize the muon yield. Going from the baseline 15-m-long target solenoid Taper to a short 5-m Taper increased the performance by 10%.

Some understanding of why a shorter Taper is favored can be gotten from Fig. 4, which plots the distribution of muons in longitudinal phase space at the end of the Decay Channel for a long and a short Taper. While the longer Taper transports more muons to the beginning of the Buncher, it produces a more diffuse longitudinal-phase-space distribution,. The short Taper produces a denser phase-space distribution that permits more muons to be captured into the acceptance windows (green) of the Buncher and Phase-Rotator.

Use of a higher final field $B_f = 2.5$ T increased the yield

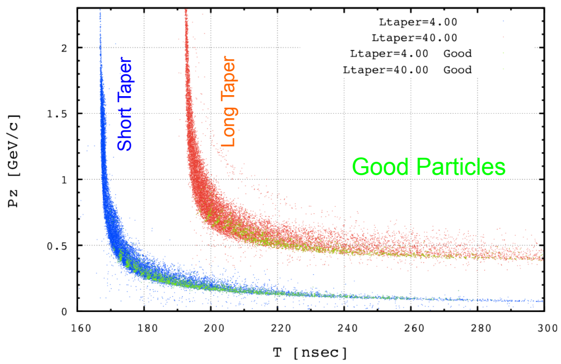

Figure 4: Time-longitudinal momentum phase space distribution at the end of Decay Channel for a short (4 m) Taper and long (40 m) Taper (shifted in momentum & time).

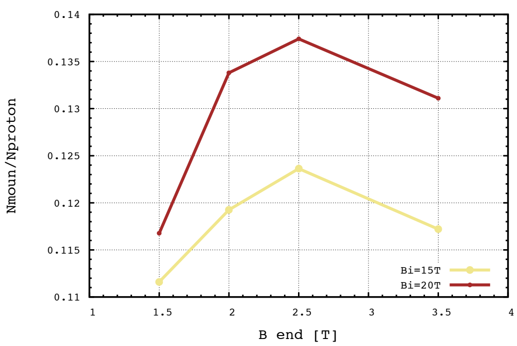

Figure 5: Normalized muon yield within the Muon-Accelerator acceptance cuts *vs.* B_f for B_i = 15 and 20 T and $L_{\mathrm{taper}} = 5$ m.

$N_{\mathrm{muon}}/N_{\mathrm{proton}}$ by $15 - 20\%$, as shown in Fig. 5, provided that higher field was also used throughout the Decay Channel, Buncher and Rotator. The drop in performance at $B_f = 3.5$ T is due to a mismatch between the Phase Rotator and Cooling Channel.

The preceding results were all obtained assuming zero length of the initial proton bunch. The effect of the proton bunch length on the muon yield is shown in Fig. 6; the yield $N_{\mathrm{muon}}/N_{\mathrm{proton}}$ decreased by 3% when using the baseline bunch length of 2-ns.

CONCLUSION

An extensive study of the effect of the target solenoid field profile on the performance of the Front End of a Neutrino Factory/Muon Collider was presented. The basic finding of the study was that to achieve a robust optimization of the Front-End performance, the Target-System optimizations can not be decoupled from that of the rest of the Front End.

Three parameters of the target-solenoid-field profile (initial on-axis field B_i, final on-axis field B_f, and taper length L_{taper}) were used to characterize the field in the target system, which was then optimized for maximum yield of

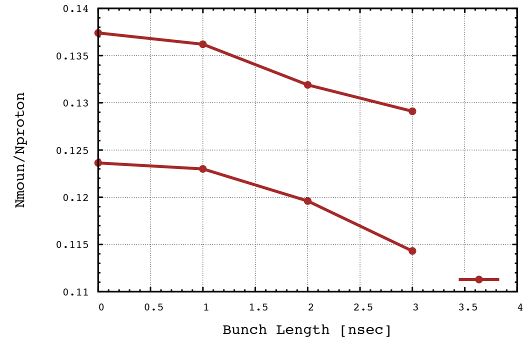

Figure 6: Normalized muon yield within the Muon-Accelerator acceptance cuts *vs.* initial proton bunch length for $B_i = 15$ and 20 T, $B_f = 2.5$ T and $L_{\mathrm{taper}} = 5$ m.

muons from the Front End (*i.e.*, at the beginning of the Muon Accelerator). A counterintuitive finding was that a short Taper Solenoid outperforms a long adiabatic Taper, as the shorter Taper deliveries a denser distribution of muons in longitudinal phase space, which permits more effective bunch formation in the Buncher and Phase Rotator, despite the fact that the longer Taper deliveries more muons to the Buncher.

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