# Progress On The Neutrino Factory Target System Design

Hisham Kamal Sayed*, H.G. Kirk* and K.T. McDonald†

*Brookhaven National Laboratory, Upton, NY 11973
†Princeton University, Joseph Henry Laboratories, Princeton University, NJ 08544

**Abstract.** The baseline target system for a Neutrino Factory or Muon Collider is a free liquid-metal (mercury) jet inside a 20-T capture solenoid magnet. A peak solenoid field of 15 T at the mercury target location is being considered as an alternative to simply the target system. The tapering field profile, from $B_i = 15-20$-T down to $B_f = 1.5-2$-T over distance $z_f - z_i$, is optimized to maximize the muon yield at 50 m downstream of the mercury target within a defined energy window. The axial magnetic field is specified analytically using a inverse-cubic form, and the off-axis field is computed from a series expansion based on axial derivation of the axial field. The simulation is performed using the MARS15 code, and results of the dependence of the muon yield on the field profile are discussed.

**Keywords:** Muon Target, Muon Collider, Neutrino Factory
**PACS:** 41.85.-p, 41.75.-i, 29.25.-t, 29.27.Eg

## INTRODUCTION

A Neutrino Factory offers an appealing opportunity to study neutrino oscillations with unprecedented high sensitivity [1, 2], and would be a first step towards a Muon Collider. The intense high-energy neutrinos of the Neutrino Factory are generated from a muon beam derived from the decay of pions produced in a target for a 4-MW proton beam of energy $\approx 8$ GeV.

The baseline design of the Neutrino Factory (see Fig. 1) generates $5 \times 10^{20}$ neutrinos per year in the beam directed to a distant neutrino detector [1, 2]. Low-energy pions produced in the target are captured in a 20-T solenoid magnet, which leads adiabatically into a 1-5-T solenoid channel where they decay to muons. Thereafter, the low-energy muons pass through bunching and phase rotation stages, followed by ionization cooling. Finally, muons are accelerated to 25 GeV in multiple accelerating stages and stored in a decay ring.

The current baseline design of the muon-production target system is shown in Fig 2. The target material in consideration is a liquid mercury jet which intercepts the multi-GeV proton beam within the confines of a 20-T solenoid field. The disrupted region of the mercury jet, due to the interaction with the proton beam, is replaced before the arrival of the following proton pulse, at repetition rates up to 50 Hz.

Alternative target capture-solenoid field profile have been investigated and a comparison to the current baseline is presented.

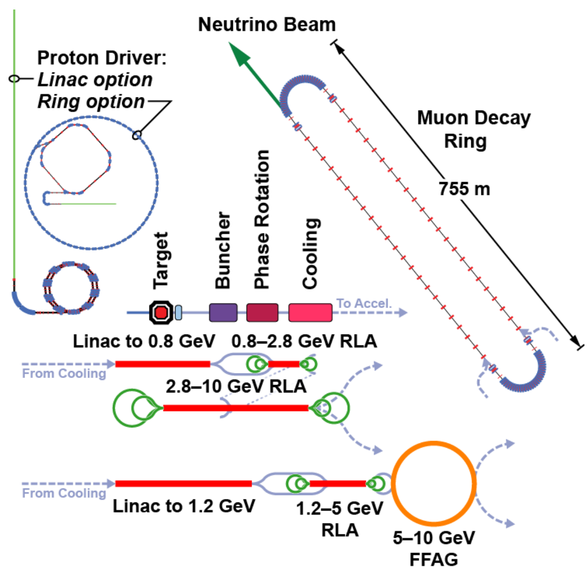


**FIGURE 1.** Neutrino Factory layout (From [2].

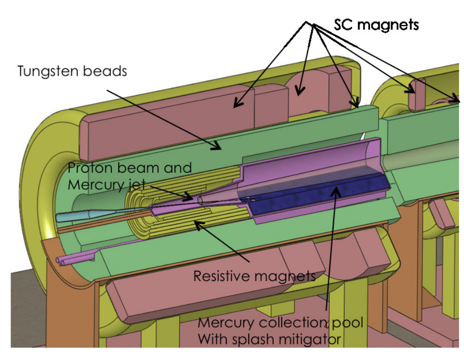


**FIGURE 2.** Neutrino Factory/ Muon Collider Target Layout.

**TABLE 1.** Baseline target parameters [5].

| Hg Jet | Proton Beam (Gaussian Distribution) |
|---|---|
| $\theta_{\mathrm{jet}} = 0.137$ rad | $\theta_{\mathrm{beam}} = 0.117$ rad |
| $R_{\mathrm{jet}} = 0.404$ cm | $\sigma_{x,y} = 0.1212$ cm |

## THE TARGET SYSTEM

The main requirement of the target system is to deliver an intense, low-energy muon beam of $10^{14}$ muons/s from the incident proton beam ($\approx$ 4 MW proton beam power; $10^{15}$ $p$/c at 8 GeV). The incident proton beam interacts with the mercury target jet producing pions. Low-energy pions are then collected and transported to decay channel using a tapered solenoid field. The 20-T solenoid field is generated by a set of coils (5-T copper magnet insert, 10-T $Nb_3Sn$ coil and 5-T NbTi outsert). Subsequent superconduction coils taper the field down to 1.5 T over a distance of 15  m.

The proton beam is tilted with respect to the solenoid magnetic axis (and with respect to the mercury jet), and directed to the mercury collection pool which additionally serves as the proton beam dump. Superconducting coils (particularly their organic insulation) can tolerate radiation doses up to 10 MGy (0.1 mW/g over an operational life of 10 years of $10^7$ s each [3]). He-gas-cooled tungsten beads are used to shield the superconducting coils from radiation damage. The 4-MW beam power requires the outer radius of the shield and subsequently the inner radius of the superconducting coils near the target to be $\approx$ 120 cm [3, 4]. It is of interest to eliminate the resistive coils (which would reduce the peak field to 15 T) and use the freed space for shielding.

The beam-target parameters used in this study are given in Table 1 [5]. The baseline configuration of the target produces 0.4 $N_\mu/N_p$ at the end of the decay channel ($z = 50$ m).

### Target Capture Tapered solenoid

The current baseline (20-T peak field) solenoid field along the solenoid axis is shown in Fig. 3 along with one of the proposed alternative options. Alternative solenoid field profiles effect on particle production and capture was studied. The axial field was modeled by an inverse-cubic taper eq. (1) [6].

$$B_z(0,z) = \frac{B_i}{[1 + a_1(z-z_i) + a_2(z-z_i)^2 + a_3(z-z_i)^3]^p}, \quad (1)$$

$$a_1 = -\frac{B_i'}{pB_i}, \quad (2)$$

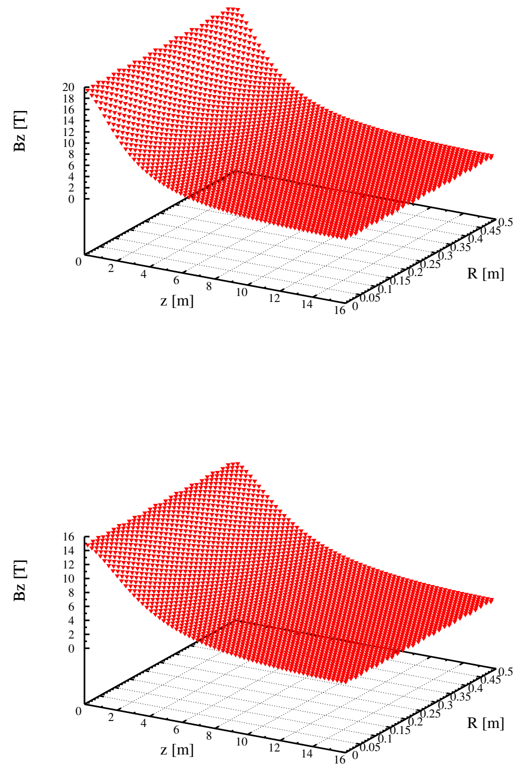


**FIGURE 3.** 20-T and 15-T target solenoid field maps.

$$a_2 = 3\frac{(B_i/B_f)^{1/p} - 1}{(z_f - z_i)^2} - \frac{2a_1}{z_f - z_i}, \quad (3)$$

$$a_3 = -2\frac{(B_i/B_f)^{1/p} - 1}{(z_f - z_i)^3} - \frac{a_1}{(z_f - z_i)^2}, \quad (4)$$

where $B_i$ and $B_f$ are the initial (peak) and final axial fields at $z = z_i$ and $z_f$ respectively, and $p$ is the power to which the cubic fit is exponentiated. The off-axis field was calculated from the series expansions, based on the axial field (1), given in eqs. (5)-(6),

$$B_z(r,z) = \sum_n (-1)^n \frac{a_0^{(2n)}(z)}{(n!)^2}\left(\frac{r}{2}\right)^{2n}, \quad (5)$$

$$B_r(r,z) = \sum_n (-1)^{n+1} \frac{a_0^{(2n+1)}(z)}{(n+1)(n!)^2}\left(\frac{r}{2}\right)^{2n+1}, \quad (6)$$

where $a_0^{(n)}$ is the $n$th derivative of $a_0$,

$$a_0^{(n)} = \frac{d^n a_0}{dz^n} = \frac{d^n B_z(0,z)}{dz^n}. \quad (7)$$

## MARS SIMULATION SETUP

The MARS15 simulation code [7] was used to simulate the particle production off the target. The beam-pipe geometry was simplified to have a constant 30-cm radius for $z = 0$-50 m to simulate particle loss due to scraping.

## MUON PRODUCTION OFF THE TARGET

The particle production was simulated using a variety of solenoid field profiles, using peak field of 20 T and 15 T while varying the taper length $(z_f - z_i)$ from 5 m up to 40 m. The final constant field. $B_f$, was varied in 3 steps (1.5, 1.66, and 1.8 T) as well. The number of muons (and remaining pions) with kinetic energy in the range 80-140 MeV, and in the aperture $r < 30$ cm), at $z = 50$ m from the target (entrance to the buncher/phase rotator) was used as the figure of merit in comparing the performance of the capture solenoid profile. Future studies will use the muon yield at the end of the buncher/phase rotator as the figure of merit).

Figure 4 shows the number of positive mesons (muons and pions) as function of the taper length for various values of the axial $B_i$. The simulations show that $N_{\text{meson/proton}}$ decreased by 8% when the peak solenoid field was decreased from $B_i = 20$ to 15 T, if the final field was kept constant at $B_f = 1.5$ T. As the final constant field was increased to 1.8 T for the 15-T peak field case, the ratio $N_{\text{meson/proton}}$ matched that of the $B_z = 20$-1.5-T case.

The solenoid taper length has a distinct influence on the number of the transported meson to the decay channel. The ratio $N_{\text{meson/proton}}$ increases linearly with the taper length, based on the figure of merit used here. As the taper length increases to 40 m, $N_{\text{meson/proton}}$ rises by 6%.

The distribution of the meson radii at $z = 0$, shown in Fig. 5(top), extends out to 10 cm for peak solenoid fields of 15-20 T. In the current baseline design the aperture at the target is set to 7.5 cm. In instances where the peak solenoid field is 15 T the distribution slightly shifts to larger radii as expected; in these cases it is recommended that the aperture at the target be increased to 10 cm. As the solenoid field tapers down to 1.5 T (or 1.8 T) the maximum radius of the muon distribution extends to 30 cm.

The transverse-momentum distributions, shown in Fig. 5(bottom), verify that the target solenoid captures mesons with maximum transverse momentum of 0.25 GeV/c at the target, and the exchange of transverse and longitudinal momentum in the tapered-field region down to 1.5 T (1.8 T) reduces the spread of transverse momenta.

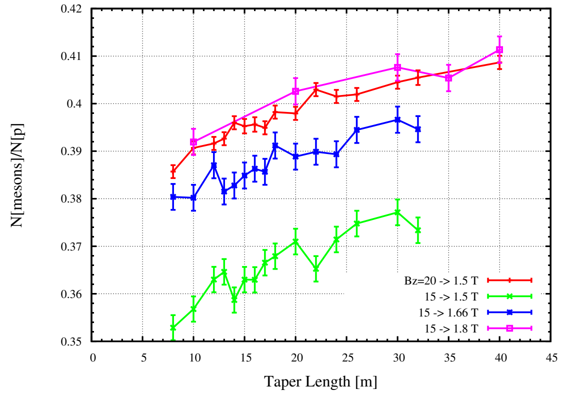


**FIGURE 4.** Number of positive mesons (muons and pions) counted at z=50 m as a function of the solenoid taper length.

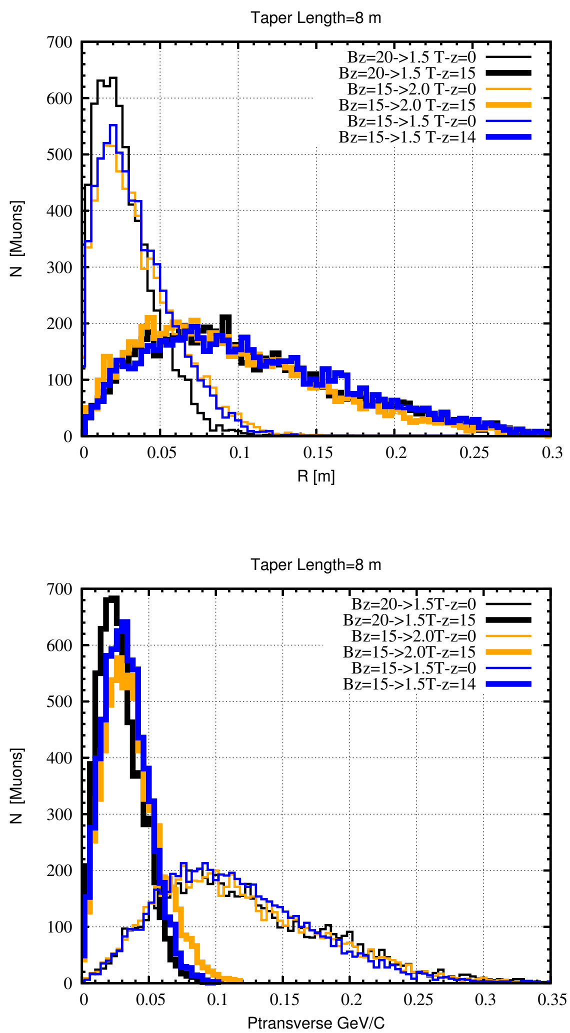


**FIGURE 5.** Distributions of meson radius (top), and of transverse momentum (bottom), at $z = 0$ and 15 m (in bold) for three solenoid field profiles with taper length of 8 m.

## CONCLUSION

An alternative capture-solenoid field has been studied for the mercury jet target for a Neutrino Factory or Muon Collider. The influence of the field strength and the taper length on the meson yield within KE of 80-140 MeV at $z = 50$ m downstream from the target was examined.

The solenoid field profile with 15-T peak at the mercury-target location was studied in comparison to the current baseline value of 20 T. Three parameters were considered for optimization; the taper length, $z_f - z_i$, and the tapered field strength in both ends, $B_i$ and $B_f$. The axial magnetic field profile was specified analytically using an inverse-cubic equation and the off-axis field was computed from a series expansion. Particle transport and decay simulations were performed using the MARS15 code. We found that using a field taper of 15 down to 1.8 T will result in the capture of the same number of mesons as the baseline case of 20 down to 1.5 T, according to the criteria used for particle yield as $z = 50$ m. In addition, we found that a 10-cm aperture at the target location would be sufficient for if the peak field were reduced to 15 T.

## ACKNOWLEDGMENTS

This work was supported in part by the US DOE Contract No. DE-AC02-98CHI10886.

## REFERENCES

1. A. Bandyopadhyay*et al.*, *Physics at a future Neutrino Factory and super-beam facility*, Rep. Prog. Phys. **72**, 106201 (2009).
2. S. Choubey *et al.*, *International Design Study for the Neutrino Factory: First Progress Report*, IDS-NF-017 (2010), http://www.cap.bnl.gov/mumu/IDS/IDS-ProgRep-201-4-16.pdf
3. N. Souchlas *et al.*, *Energy Flow and Deposition in a 4-MW Muon-Collider Target System*, Proc. IPAC12, p. 2588.
4. R.J. Weggel *et al.*, *Shielding of Superconducting Coils for a 4-MW Muon-Collider Target System*, Proc. IPAC12, p. 2591.
5. X. Ding *et al.*, *Optimization of a mercury jet target for a neutrino factory or a muon collider* Phys. Rev. STAB **14**, 111002 (2011).
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. N. Mokhov and N. Krivosheev, *The MARS Code System* (2010), http://www-ap.fnal.gov/MARS/