Optimizing Muon Capture and Transport for a Neutrino Factory Front End

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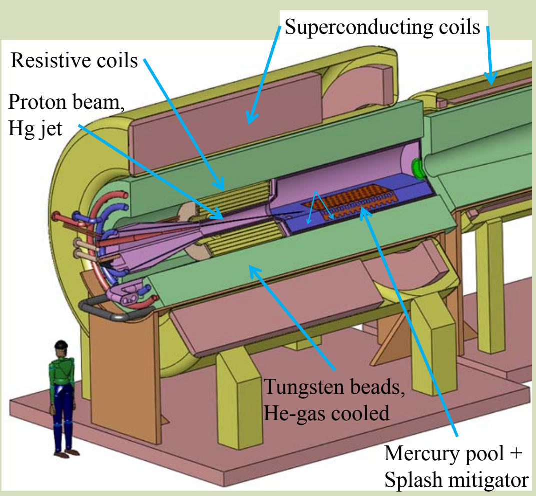
Abstract

In the 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.

Target system and mercury jet geometry

- **Mercury-Target Parameters**
  - Angle of target to solenoid axis θ_{target}= 0.137 rad
  - Target radius r_{target} = 0.404 cm
- **Proton Beam Parameters**
  - E = 8 GeV
  - θ_{beam} = 0.117 rad
  - $\sigma_x = \sigma_y$ = 0.1212 cm (Gaussian distribution)



Target Tapered-Solenoid Profile

Inverse-Cubic Taper, defined by initial & final axial fields (B_1 & B_2), their derivatives, and position of end of taper (z_{end}):

$$B_z(0, z_i < z < z_{end}) = \frac{B_1}{[1 + a_1(z-z_1) + a_2(z-z_1)^2 + a_3(z-z_1)^3]^p}$$

$$a_1 = -\frac{B_1'}{pB_1}, \qquad a_2 = 3\frac{(B_1/B_2)^{1/p} - 1}{(z_2-z_1)^2} - \frac{2a_1}{z_2-z_1},$$

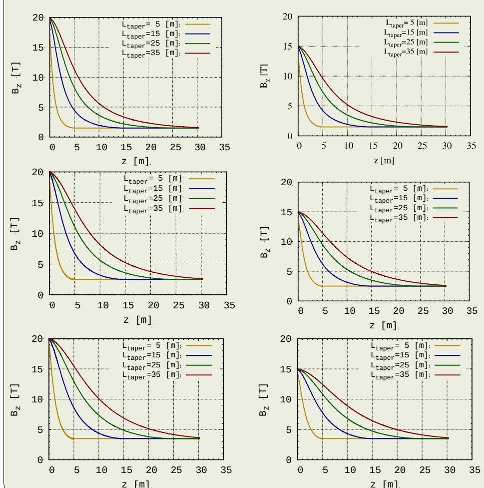
$$a_3 = -2\frac{(B_1/B_2)^{1/p} - 1}{(z_2-z_1)^3} + \frac{a_1}{(z_2-z_1)^2}$$

Off-axis field approximation:

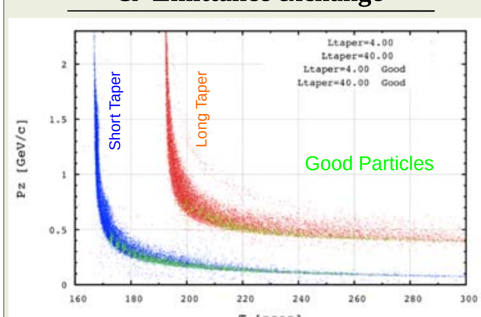
$$B_z(r,z) = \sum_n (-1)^n \frac{a_0^{(2n)}(z)}{(n!)^2}\left(\frac{r}{2}\right)^{2n},$$

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

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



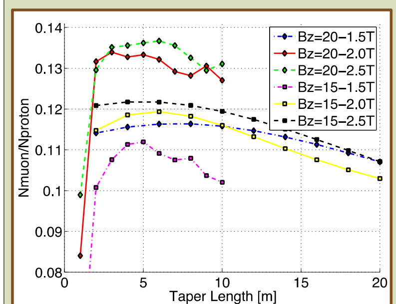
Longitudinal Phase Space & Emittance exchange



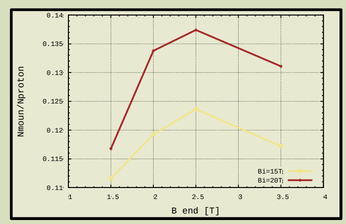
Time-longitudinal momentum phase space distribution at the end of Decay Channel for a short (4 m) Taper and long (40 m) Taper (shifted in momentum & time).

The shorter taper results in a denser distribution in longitudinal phase space, which is preferable for the Buncher/Phase Rotator.

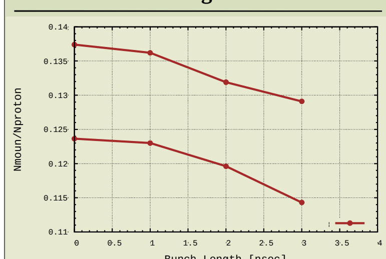
Muons within Acceptance Cuts at End of Transverse Cooling Channel



Dependency of Muon Capture and Transport on constant field of solenoid channel up to the cooling section



Dependence of Muon Capture and Transport on Initial proton Bunch Length



Conclusion

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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