OPTIMIZED SOLENOID BASED CAPTURE MECHANISM FOR A MUON COLLIDER/NEUTRINO FACTORY TARGET SYSTEM

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INTRODUCTION & LAYOUT

Muon Capture in Target & Front END

- Capture Solenoid Field Study:
  - Optimizing quantity: Muon (Pions) count – transverse capture
    - Target Solenoid peak field
    - Final end field
  - Optimizing quality: Muon (Pions) longitudinal phase space (transverse-longitudinal coupling) – transverse-longitudinal capture
    - Taper field profile

- Optimizing the time of flight of incident beam (Buncher-Rotator RF phase)
- Transverse focusing field in decay-channel-buncher-rotator
- Match to ionization cooling channel for every end field case 1.5 T → 3.5 T
- Performance of front end as a function of proton bunch length
- Realistic Coil Design & performance optimization
Target System Solenoid:
Capture $\mu^\pm$ of energies $\sim 100$-$400$ MeV from a 4-MW proton beam ($E \sim 8$ GeV).
TARGET SYSTEM CURRENT BASELINE DESIGN

- Production of $10^{14} \mu/s$ from $10^{15} \text{p/s} \approx 4 \text{MW proton beam}$
- Proton beam readily tilted with respect to magnetic axis.
- Shielding of the superconducting magnets from radiation is a major issue.
- Hg Target
- Proton Beam
  - $E=8 \text{GeV}$
- Solenoid Field
  - $\text{IDS120h} \rightarrow 20 \text{T peak field at target position (Z=-37.5)}$
  - Aperture at Target $R=7.5 \text{ cm} \rightarrow \text{End aperture } R = 30 \text{ cm}$
  - Fixed Field $Z = 15 \text{ m} \rightarrow B_z=1.5 \text{T}$

- Production: Muons within energy KE cut 40-180 MeV end of decay channel
  - $N_{\mu+\pi+\kappa}/N_p = 0.3-0.4$
TAPERED TARGET SOLENOID OPTIMIZATION

Inverse-Cubic Taper

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

\[
a_1 = -\frac{B_z}{pB_1}, \quad a_2 = 3\left(\frac{B_z}{B_2}\right)^{1/p} - 1 - \frac{2a_1}{z_2 - z_1}, \quad a_3 = -2\left(\frac{B_z}{B_2}\right)^{1/p} - 1 + \frac{a_1}{(z_2 - z_1)^2}
\]

Off-axis field approximation

\[
B_r(r, z) = \sum_{n} (-1)^{n+1} a_0^{(2n+1)}(z) \left(\frac{r}{2}\right)^{2n+1}
\]

\[
a_0^{(n)} = \frac{d^n a_0}{dz^n} = \frac{d^n B_z(0, z)}{dz^n}
\]
MARS1510 Simulation:
Counting muons at 50 m with K.E. 80-140 MeV

MARS SIMULATIONS & TRANSMISSION

R_{ini}=7.5-10 cm
B_i=20-15 T

N[\muons]/N[p]

Bz=20 -> 1.5 T
15 -> 1.5 T
15 -> 1.66 T
15 -> 1.8 T

0.35

L_{taper} [cm]

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LONGITUDINAL PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

End of taper

Long adiabatic taper 40 m

End of Decay

Short taper 4 m

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T-Pz Correlations at end of decay channel

Long Solenoid taper:
- More particles
- More dispersed (misses the buncher acceptance windows)

Short Solenoid taper:
more condensed distributions that fits more particles within the buncher acceptance windows
PHASE SPACE DISTRIBUTIONS (SHORT VERSUS LONG TAPER)

T-Pz phase space at end of decay channel

Long Taper 40 m

- More particles
- More dispersed (misses the buncher acceptance windows)

Short Taper 4 m

- Higher density t-pz distribution
- Fits more particles within the acceptance of buncher/rotator
**PHASE SPACE - SHORT VERSUS LONG TAPER**

**T-Pz Correlations at end of decay channel of good particles**

**Green:** Initial distribution of good particles which were bunched and cooled in 4D cooling channel.
PERFORMANCE DEPENDENCE ON TIME OF FLIGHT (RF PHASE)

- TOA Protons at z = 75 cm
- TOA Protons at z = 200 cm

Graphs showing the dependence of performance on time of flight for different RF phases:
- TOA at various time points and distances
- Optimizing RF Phase

Graphs with axes showing:
- Time [nsec]
- TOA
- Muon
- Iteration

6/20/13

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FRONT END PERFORMANCE

Using baseline cooling section
(140 cooling cell)

Using longer cooling section
(200 Cooling cell)

High statistics tracking of Muons through the front end
Using longer cooling section (200 Cooling cell)

High statistics tracking of Muons through the front end
**Muon yield versus end field & Bunch Length**

**Muon yield versus end field**

- Bunch length = 0 nsec
- \( B_z(\text{Target}) = 20 \ T \)

20% for every 1 T increase in constant field

- \( B_z(\text{Target}) = 15 \ T \)
- \( B_z(\text{Target}) = 20 \ T \)

Baseline

Performance of FE as function of Constant solenoid filed in Decay Channel – Buncher – Rotator (matched to +/- 2.8 T ionization cooling channel)

**Muon yield versus Proton Bunch Length**

- \( B_z(\text{Target}) = 15 \ T \)
- \( B_z(\text{Target}) = 20 \ T \)

\(~ 3\%\) loss per 1 nsec increase in bunch length

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New Short Target Capture Realistic Magnet (Weggel)

Muon Target Capture Magnet
Short Taper length = 7 m - B = 20-1.5 T

Muon Target Capture Magnet
Short Taper length = 5 m - B = 20-2.5 T
NEW SHORT TARGET CAPTURE MAGNET (WEGGEL)

Muon Target Short Taper Magnet taper length = 7 m - B=20-1.5 & 2.5 T

Target SC Magnets Field Map calculated from realistic coils

Engineering (V. Grave)
IDS120_20-1.5T7m2+5 Cryo 1
The pions produced in the target decay to muons in a Decay Channel (50 m)

- Three superconducting coils (5-m-long) $B_z(r=0) \sim 1.5$ or $2.5$ T solenoid field.
- Suppress stop bands in the momentum transmission.

Axial-field profile of two Decay-Channel modules

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Length [m]</th>
<th>Inner R [m]</th>
<th>Outer R [m]</th>
<th>$J$ [A/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.19</td>
<td>0.6</td>
<td>0.68</td>
<td>47.18</td>
</tr>
<tr>
<td>2</td>
<td>3.8</td>
<td>0.6</td>
<td>0.63</td>
<td>40.00</td>
</tr>
<tr>
<td>3</td>
<td>0.19</td>
<td>0.6</td>
<td>0.68</td>
<td>47.18</td>
</tr>
</tbody>
</table>
Suppression of stop bands in the Decay Channel:
Tracking muons through decay channel 10 cells (50 m) optimize magnet design for best performance.

Transmission:
Constant 1.5 Solenoid Field %67
IDS120L20to1.5T7m %62
Modified IDS120L20to1.5T7m %66
CONCLUSION & SUMMARY

1- Target Solenoid parameters that affect the particle Capture & Transmission at target or after cooling

   Initial peak Field – Taper length – End Field

2- Impact:
   Short taper preserves the longitudinal phase-space → muons can be captured efficiently in the buncher-phase rotation sections and more muons at the end of cooling.
   The maximum yield requires taper length of 7-5 m for all cases (20-15T) (1.5-3.5T) for any bunch length.

3- Final constant end field increases the yield by 20% for every 1 T increase in the field beyond the 1.5 T baseline

4- Initial proton bunch length influence the muon/proton yield at the end of the cooling channel ~ 3% reduction per 1 nsec increase in bunch length.

5- Realistic Coil design.