ALTERNATIVE CAPTURE SOLENOID STUDY
FOR THE MUON COLLIDER TARGET

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OVERVIEW

- Target layout
- Current baseline parameters
- Solenoid Taper field calculations
- MARS simulation setup
- Tracking through FE with ICOOL
- Muon count
- Transverse position & Momentum distribution
- Conclusion
- Production of $10^{14}$ μ/s from $10^{15}$ p/s ($\approx 4$ MW proton beam)
- Low-energy $\pi$'s collected from side of long, thin cylindrical target
- Solenoid coils can be some distance from proton beam.
  - $\geq 10$-year life against radiation damage at 4 MW.
- Proton beam readily tilted with respect to magnetic axis.
  - $\Rightarrow$ Beam dump (mercury pool) out of the way of secondary $\pi$'s and $\mu$'s.
- Shielding of the superconducting magnets from radiation is a major issue.
  - Magnet stored energy $\sim 3$ GJ

5-T copper magnet insert; 10-T Nb3Sn coil + 5-T NbTi outsert. Desirable to eliminate the copper magnet (or replace by a 20-T HTS insert).
Particle-capture requirement ($P_t \leq 0.225 \text{ GeV/c}$)
- $B \times r = 20 \text{ T} \times 7.5 \text{ cm} = 150 \text{ T-cm}$
- $B \times r = 15 \text{ T} \times 10 \text{ cm} = 150 \text{ T-cm}$

Fixed-flux requirement (Aperture requirement)
- $B \times r^2 = 20 \times 7.5^2 = 1125 \text{ T-cm}^2$
- $B \times r^2 = 15 \times 10^2 = 1500 \text{ T-cm}^2$

MARS simulations with 15-T peak field & new aperture settings (taper radius $r = 30 \text{ cm}$ at all $z$)

Particle loss due to scrapping with beam pipe!
(X. Ding et al.)

- **Hg Target**
  - $\theta_{\text{Target}} = 0.137$ rad
  - $R_{\text{Target}} = 0.404$ cm

- **Proton Beam**
  - $E = 8$ GeV
  - $\theta_{\text{Beam}} = 0.117$ rad
  - $\sigma_x = \sigma_y = 0.1212$ cm (Gaussian Distribution)

- **Solenoid Field**
  - IDS120h $\rightarrow$ 20 T peak field at target position ($Z=0$)
  - Aperture at Target $R=7.5$ cm - End aperture $R = 30$ cm
  - Fixed Field $B_z = 20 \rightarrow 1.5$ T $L_{\text{taper}} = 15$ m

- **Production:** Muons within energy $KE$ cut 40-180 MeV at $z=50$ m
  - $3.27 \times 10^4$ ($N_{\text{ini}} = 10^5$)
**ANALYTIC FORM FOR TAPERED SOLENOID**

**Inverse-Cubic Taper**

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

Field at R=0

\[
a_1 = -\frac{B_1}{pB_1} \\
a_2 = \frac{3(B_1 / B_2)^{1/p} - 1}{(z_2 - z_1)^2} - \frac{2a_1}{z_2 - z_1} \\
a_3 = -\frac{2(B_1 / B_2)^{1/p} - 1}{(z_2 - z_1)^3} + \frac{a_1}{(z_2 - z_1)^2}
\]

**Off-axis field approximation**

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

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

\[
a_0^{(n)} = \frac{d^n a_0}{dz^n} = \frac{d^n B_z(0, z)}{dz^n}
\]
**MARS Simulation Setup**

- Beam Pipe with constant R=30 cm (eliminate particle loss due to scrapping)
- Beam Pipe material changed to “Balckhole” -> speed calculations
- Added subroutine to m1510.f (FIELD- K. McDonald) to calculate the field using inverse cubic equations
- \( N_{\text{proton}} = 5 \times 10^5 \)
- Store particles information at \( z=0 \)
- Select \((\mu^+ - k^+ - \pi^+)\)
Tapered field using inverse-cubic field ($P = 1$)

Mesons count at $z=50$ m with K.E. 40-180 MeV

Present baseline: $B_i = 20$ T, $B_f = 1.5$ T, $z_{\text{end}} = 15$ m.

**Conclusion**

End of Decay Channel
Raising final const. $Bz \leftrightarrow$ Meson Yield
More adiabatic taper $\leftrightarrow$ Meson Yield
Taper solenoid field with different settings

- $B_z(r=0)$ 20 $\rightarrow$ 1.5 T  Taper Length 8 $\rightarrow$ 43 m
- $B_z(r=0)$ 15 $\rightarrow$ 1.5 T  Taper Length 8 $\rightarrow$ 43 m
- $B_z(r=0)$ 15 $\rightarrow$ 1.8 T  Taper Length 8 $\rightarrow$ 43 m
- $B_z(r=0)$ 15 $\rightarrow$ 2.0 T  Taper Length 8 $\rightarrow$ 43 m

![Diagram showing particle tracking through front end with magnetic field settings.]
2- ICOOL applied aperture for decay region $R_{\text{aperture}} = 0.4 \text{ m} \& 0.3 \text{ m} $ to end

3- Good particles are those who satisfy the following conditions/cuts
   1- Survived the phase rotator and cooling sections
   2- Fall within required acceleration acceptance cuts (ecalc)
      - $0.1 < P_z < 0.3 \text{ GeV}$
      - Transverse cut 0.03 m
      - Longitudinal cut 0.15 m
**Muon Count at End of "Frontend"**

Muons within required acceleration acceptance cuts after cooling section:
- $0.1 < P_z < 0.3$ GeV
- Transverse cut 0.03 m
- Longitudinal cut 0.15 m

**Solenoid Field along z-axis**

**Shorter taper better survive buncher**
- phase rotator & cooling

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**Graphs**

- Lines represent different taper lengths with solenoid fields.
- Labels indicate transition points and taper field strengths.

- **Legend**:
  - $B_z [T]$ vs $Z [m]$: Magnetic field strength vs distance.
  - $N_{proton} = 5 \times 10^5$: Proton count.

- **Curves**:
  - Baseline: 20->1.5T
  - 15->1.5T
  - 15->1.8T to end
  - 15->2.0T to end

**Same yield**

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**Additional Text**

- Muons (w transvers cut n1)
- Taper Length [m]
- 20->1.5T
- 15->1.5T
- 15->1.8T to end
- 15->2.0T to end

TRANSMISSION & TRANSVERSE EMITTANCE

![Graph showing transmission and transverse emittance](image)

- **Transverse emittance**
  - Z [m]: 20->1.5T, 15->1.5T, 15->1.8T to end, 15->2.0T to end, Baseline 20->1.5T

- **Muons (w transvers cut n1)**
  - Z [m]: 20->1.5T, 15->1.5T, 15->1.8T to end, 15->2.0T to end, Baseline 20->1.5T
**MUON COUNT AT END OF “FRONTEND”**

What will happen if we do not raise the constant solenoid field to 1.8/2.0 T?!

[Solenoid Field along z-axis](#)

[Shorter taper better survive buncher - phase rotator & cooling](#)

Discontinuity 1.8(2.0) → 1.5 T

**Bz [T]**

0 2 4 6 8 10 12 14 16 18 20

**Z [m]**

0 5 10 15 20 25 30

**Muons (w transvers cut n1)**

20->1.5T 15->1.5T 15->1.8T 15->2.0T 15->1.8T to end 15->2.0T to end

Baseline 20->1.5T

N_{proton} = 5 \times 10^5
Transmission through front end

Pz & Σ cut

Aperture 0.4 → 0.3 m

Trans, Pz, & Σ cut

~7%
DISTRIBUTIONS OF PARTICLES SURVIVED THE FRONT END AND ACCELERATION CUTS

Radii distribution Taper Length =15 m
Distributions of particles survived the front end and acceleration cuts.

Momentum distribution Taper Length = 15 m

![Graph showing momentum distributions for different magnetic fields and taper lengths.]
Distributions of particles survived the front end and acceleration cuts

Invariant of motion

Z=0 & 15 m

Z=0 & 15 m
CONCLUSION

- Mesons count within KE cut only at 50 m increases with longer taper.
- $B_z = 15 \rightarrow 1.5T$ with 8 m taper length production matches the current 20T peak field baseline.
- 15 T peak field case has ~ 7% less yield at end of cooling though it produces about the same number of muons at the target.
- No clear mismatch in the lattice that shows huge particle loss
- Particle radii extends from 0.1 at $z=0$ to 0.3 m at $z=15$ m
- Particles transverse momenta extends from 0.3 at $z=0$ to 0.1 m at $z=15$ m

<table>
<thead>
<tr>
<th>Taper Length</th>
<th>End of Decay Channel $z=50$ m No cuts</th>
<th>End of FE $z=265$ m Eclac acceleration acceptance cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td></td>
<td>Better</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td>Better</td>
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</tbody>
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Needs to be investigated & understood