Frictional Cooling for a Muon Collider
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- Motivation
- Simulation Studies
- Experimental Studies/Plans
## HIGH ENERGY MUON COLLIDER PARAMETERS


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM energy (TeV)</td>
<td>0.4</td>
<td>3.0</td>
</tr>
<tr>
<td>$p$ energy (GeV)</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$p$'s/bunch</td>
<td>$2.5 \times 10^{13}$</td>
<td>$2.5 \times 10^{13}$</td>
</tr>
<tr>
<td>Bunches/fill</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Rep. rate (Hz)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$p$ power (MW)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\mu$ / bunch</td>
<td>$2 \times 10^{12}$</td>
<td>$2 \times 10^{12}$</td>
</tr>
<tr>
<td>$\mu$ power (MW)</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>Wall power (MW)</td>
<td>120</td>
<td>204</td>
</tr>
<tr>
<td>Collider circum. (m)</td>
<td>1000</td>
<td>6000</td>
</tr>
<tr>
<td>Ave bending field (T)</td>
<td>4.7</td>
<td>5.2</td>
</tr>
<tr>
<td>rms $\delta p/p$ (%)</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td>$6D \varepsilon_{6,N}$ ($\pi m$)$^3$</td>
<td>$1.7 \times 10^{-10}$</td>
<td>$1.7 \times 10^{-10}$</td>
</tr>
<tr>
<td>rms $\varepsilon_n$ ($\pi$ mm mrad)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$\beta^*$ (cm)</td>
<td>2.6</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_2$ (cm)</td>
<td>2.6</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_s$ spot ($\mu$m)</td>
<td>2.6</td>
<td>3.2</td>
</tr>
<tr>
<td>$\sigma_0$ IP (mrad)</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Tune shift</td>
<td>0.044</td>
<td>0.044</td>
</tr>
<tr>
<td>$n_{\text{turns}}$ (effective)</td>
<td>700</td>
<td>785</td>
</tr>
<tr>
<td>Luminosity (cm$^{-2}$ s$^{-1}$)</td>
<td>$10^{33}$</td>
<td>$7 \times 10^{34}$</td>
</tr>
</tbody>
</table>
\( \pi \)'s in red
\( \mu \)'s in green

Drift region for \( \pi \) decay \( \approx 30 \) m

Solenoidal Magnets: few T … 20 T

P beam (few MW)
Target

**Simplified emittance estimate:**
At end of drift, rms \( x,y,z \) approx 0.05,0.05,10 m
\[
P_x,P_y,P_z \approx 50,50,100 \text{ MeV/c}
\]

Normalized 6D emittance is product divided by \( (m_\mu c)^3 \)
\[
\varepsilon_{6D,N}^{\text{drift}} \approx 1.7 \times 10^{-4} (\pi m)^3
\]

Emittance needed for Muon Collider
\[
\varepsilon_{6D,N}^{\text{collider}} \approx 1.7 \times 10^{-10} (\pi m)^3
\]

This reduction of 6 orders of magnitude must be done with reasonable efficiency!
Muon Cooling

Muon Cooling is the signature challenge of a Muon Collider

Cooler beams would allow fewer muons for a given luminosity, thereby
• Reducing the experimental background
• Reducing the radiation from muon decays
• Reducing the radiation from neutrino interactions
• Allowing for smaller apertures in machine elements, and so driving the cost down
Frictional Cooling

Nuclear scattering, excitation, charge exchange, ionization

- Bring muons to a kinetic energy (T) where \( \frac{dE}{dx} \) increases with T
- Constant E-field applied to muons resulting in equilibrium energy
- Big issue – how to maintain efficiency
- Similar idea first studied by Kottmann et al., PSI

Ionization stops, muon too slow

Effective \( \frac{dE}{dx} \) from E field

1/\( \beta^2 \) from ionization

Nominal Scheme

Stopping Power (MeV cm²/g)

\( T \) (MeV)
Problems/comments:

- large dE/dx @ low kinetic energy
  \[ \Rightarrow \text{low average density (gas)} \]
- Apply \( E \perp B \) to get below the dE/dx peak
  \[ F = q(E + vxB) - dT/dx \]
- \( \mu^- \) has the problem of Atomic capture
  \( \sigma \) small above electron binding energy, but not known. Keep T as high as possible
- Slow muons don’t go far before decaying
  \[ d = 10 \text{ cm } \sqrt{T} \quad T \text{ in eV} \]
  so extract sideways \( (E \perp B) \)
- \( \mu^+ \) has the problem of Muonium formation
  \( \sigma(M\mu) \) dominates over e-stripping in all gases except He
Neutralization

\[ \text{H}^+ + \text{He} \rightarrow \text{H} + \text{He}^+ \]


Stripping

\[ \text{H} + \text{He} \rightarrow \text{H}^+ + \text{He} + \text{e} \]

For \( \mu \), energy lower by \( \frac{M_\mu}{M_P} \)
Frictional Cooling: particle trajectory

Using continuous energy loss
Frictional Cooling: stop the μ

- High energy μ’s travel a long distance to stop
- High energy μ’s take a long time to stop

Plots for
1. $10^{-4}$ g/cm$^3$ He

Optimize for low initial muon momentum,
+ phase rotation
Schematic Layout for μ Collider Scheme Studied

Phase rotation sections

Cooling cells

Not to scale !!
Detailed Simulation

Full MARS target simulation, optimized for low energy muon yield: \textbf{2 GeV protons} on Cu with proton beam transverse to solenoids (capture low energy pion cloud).
Target System

- cool $\mu^+$ & $\mu^-$ at the same time
- calculated new symmetric magnet with gap for target
Target & Drift
Optimize yield

- Optimize drift length for $\mu$ yield
- Some $\pi$’s lost in Magnet aperture
$\pi$'s in red
$\mu$'s in green

GEANT simulation

View into beam
**Phase Rotation**

- First attempt simple form
- Vary $t_1$, $t_2$ & $E_{\text{max}}$ for maximum low energy yield
He gas is used for $\mu^+$, $H_2$ for $\mu^-$.

- Individual nuclear scatters are simulated – crucial in determining final phase space, survival probability.
- Incorporate scattering cross sections into the cooling program.
- Include $\mu^-$ capture cross section using calculations of Cohen (Phys. Rev. A. Vol 62 022512-1)
- Electronic energy loss treated as continuous.
Scattering Cross Sections

- Scan impact parameter and calculate $\theta(b)$, $d\sigma/d\theta$ from which one can get $\lambda$, mean free path
- Simulate all scatters $\theta>0.05$ rad
- Simulation accurately reproduces ICRU tables for protons
Barkas Effect

- Difference in $\mu^+$ & $\mu^-$ energy loss rates at dE/dx peak
- Due to charge exchange for $\mu^+$
- Only used for the electronic part of dE/dx
Trajectories in detailed simulation

Transverse motion

Longitudinal motion

Motion controlled by $B$ field

Lorentz angle drift, with nuclear scattering

Final stages of muon trajectory in gas cell
E dominates

Oscillations about equilibrium define emittance.

\[ F = q(E + v \times B) - \frac{dT}{dx} \]

vxB dominates

Dangerous because of \( \mu^- \) capture possibility
Initial reacceleration region

\[ E(\tau, t) \]

After gas cell, \( E(z, t) \)

\[ \sigma_T = 4 \text{ ns at } Z=444\text{m} \]
\[ P = 200 \text{ MeV/c} \]
\[ \text{Eff} = 40\% \]
Yields & Emittance

Look at muons coming out of 11m cooling cell region after initial reacceleration.

Yield: approx 0.002 $\mu$ per 2GeV proton after cooling cell.
Need to improve yield by factor 5 or more to match $\# \mu$/proton/GeV in specifications.

Emittance: rms

$x = 0.015\ m$

$y = 0.036\ m$

$z = 30\ m$ (actually $\beta ct$)

$P_x = 0.18\ MeV$

$P_y = 0.18\ MeV$

$P_z = 4.0\ MeV$

$\varepsilon_{6D.N} = 5.7 \times 10^{-11}\ (\pi m)^3$
Problems/Things to investigate…

• Extraction of $\mu$s through windows in gas cell
  • Must be very thin to pass low energy $\mu$s
  • Must be reasonably gas tight
• Can we apply high electric fields in gas cell without breakdown (large number of free electrons, ions)?
  Plasma generation $\rightarrow$ screening of field.
• Reacceleration & bunch compression for injection into storage ring
  • The $\mu^-$ capture cross section depends very sensitively on kinetic energy & falls off sharply for kinetic energies greater than $e^-$ binding energy. NO DATA – simulations use theoretical calculation
  • +…
First try to demonstrate frictional cooling with protons.

RARAF Facility – Nevis Lab/Columbia University

$\leq 4$ MeV p

VandeGraaf accelerator for biomedical research
$H_2^+$ beam

- MCP
  - D=18.8mm
- Thin Windows
  - D~4mm
- Support Structures
- 6.5 cm Reacc.
- 10 cm in Gas
- Gas Feedthroughs
- Si Detector
  - Thickness ~9μm

~30 cm

~20 cm
Accelerating grid

Gas cell

Vacuum chamber

Contains 20nm window

To MCP

Si detector

Proton beam
The proton energy spectrum from the Si calculated using SRIM (J. F. Ziegler, J. P. Biersack and U. Littmark, Pergamon Press, 1985). The transport through the gas performed with our detailed simulation. Need first to fix the window thickness and gas pressure.

Min Kin Energy fixed by reacc potential
Protons have 100-200 KeV after Si window. Good agreement with SRIM.

Calibration Data:
3 distances, no cell, no grid

Time resolution of system=17ns
Add cell, no gas, no E field. Extract effective window thickness by comparison with simulation. **Much thicker than expected!**

Add gas, still no field. Gas pressure extracted from comparison with simulation. Compatible with expectations.
Summary of calibration using the time spectrum
After background subtraction, see no hint of cooled protons. Also predicted by simulation. Problem – windows too thick, acceptance, particularly for slow protons, too small. Need to repeat the experiment with solenoid, no windows.
Future Plans

- Frictional cooling tests at MPI with 5T Solenoid, alpha source
- Study gas breakdown in high E,B fields
- R&D on thin windows
- Beam tests with muons to measure $\mu$ capture cross section
  \[ \mu^- + \text{He} \rightarrow \text{He}_\mu + e + \gamma \text{'s} \]

muon initially captured in large $n$ orbit, then cascades down to $n=1$. Transition $n=2 \rightarrow n=1$ releases few KeV x-ray.

Si drift detector
Developed my MPI
HLL
Lab situated at MPI-WHI in Munich
Conclusions

- Muon Collider complex would be a boon for physics
- We need to solve the muon cooling problem
- Different schemes should be investigated
- We are doing some simulation and experimental studies of frictional cooling. So far, so good, but a long way to go!