Muon Cooling and the Muon Collider
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- Motivation
- Difficulties
- Focus on Cooling (frictional cooling)
Why a Muon Collider?

No synchrotron radiation problem (cf electron)

\[ P \propto (E/m)^4 \]

Can build a high energy circular accelerator.

Collide point particles rather than complex objects
Some Difficulties

• Muons decay, so are not readily available – need multi MW source. Large starting cost.
• Muons decay, so time available for cooling, bunching, acceleration is very limited. Need to develop new techniques, technologies.
• Large experimental backgrounds from muon decays (for a collider). Not the usual clean electron collider environment.
• High energy colliders with high muon flux will face critical limitation from neutrino induced radiation.
Dimensions of Some Colliders discussed
Physics at a Muon Collider

Muon Collider Complex:
- Proton Driver 2-16GeV; 1-4MW leading to $10^{22}p$/year
- $\pi$ production target & Strong Field Capture
- COOLING resultant $\mu$ beam
- $\mu$ acceleration
- Storage & collisions

- Stopped $\mu$ physics
- $\nu$ physics From target, stored $\mu$
- Higgs Factory $\sigma_{\mu\mu\rightarrow H} = 40000 \sigma_{ee\rightarrow H}$
- Higher Energy Frontier
# 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>$\mu$ power (MW)</td>
<td>2</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>$\sigma_z$ (cm)</td>
<td>2.6</td>
<td>0.3</td>
</tr>
<tr>
<td>$\sigma_z$ spot (µm)</td>
<td>2.6</td>
<td>3.2</td>
</tr>
<tr>
<td>$\sigma_\theta$ 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>
π’s in red
µ’s in green

Drift region for π decay ≈ 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 MeV/c

Normalized 6D emittance is product divided by (m_µc)^3
ε^{drift}_{6D,N} ≈ 1.7 10^{-4} (πm)^3

Emittance needed for Muon Collider
ε^{collider}_{6D,N} ≈ 1.7 10^{-10}(πm)^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
Cooling Ideas

Ionization cooling (Skrinsky, Neuffer, Palmer, …): muons are maintained at ca. 200 MeV. Transverse cooling of order x20 seems feasible (see ν-factory feasibility studies 1-2). Longitudinal cooling not solved.
Longitudinal Cooling via Emittance Exchange

Transform longitudinal phase space into transverse (know how to cool transverse)

Wedge shaped absorber

Bent solenoid produces dispersion
There are significant developments in achieving 6D phase space via ionization cooling (R. Palmer, MUTAC03), but still far from $10^6$ cooling factor.
Muon Ionization Cooling Experiment

at the Rutherford Appleton Laboratory
KEK – focus on FFAG acceleration

- 0.5-MeV Proton FFAG POP at KEK
- 150-MeV Proton FFAG Under construction at KEK

Series of FFAG acceleration
Frictional Cooling

Studies at Columbia University/MPI
Allen Caldwell, Raphael Galea
+
Stefan Schlenstedt (DESY/Zeuthen)
Halina Abramowicz (Tel Aviv University)

Summer Students:
Emily Alden
Christos Georgiou
Daniel Greenwald
Laura Newburgh
Yujin Ning
Inna Shpiro
Will Serber
Frictional Cooling

Nuclear scattering, excitation, charge exchange, ionization

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

![Graph showing stopping power and energy loss](image)
Problems/comments:

- **large** $dE/dx$ @ low kinetic energy
  $\Rightarrow$ **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
  $d = 10 \text{ cm} \sqrt{T}$ T 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

\[ \text{H}^4 + \text{He} \rightarrow \text{H} + \text{He}^4 \]

Stripping

\[ \text{H} + \text{He} \rightarrow \text{H}^4 + \text{He} + \text{e} \]

For \( \mu \), energy lower by \( M_\mu/M_P \)

Frictional Cooling: particle trajectory

B=5 T, E=5 MV/m, $\rho_{He}=1 \times 10^{-4}$ g/cm$^3$

** Using continuous energy loss**
Frictional Cooling: stop the $\mu$

- High energy $\mu$'s travel a long distance to stop
- High energy $\mu$'s take a long time to stop

Plots for

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

$$R(m) = 1.2 \times 10^{-4} P(\text{MeV/c})^{3.35}$$

Optimize for low initial muon momentum,
+ phase rotation
Schematic Layout for $\mu$ Collider Scheme Studied

Phase rotation sections

Cooling cells

Not to scale!!
Detailed Simulation

Full MARS target simulation, optimized for low energy muon yield: 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
Transverse (symmetric) scheme

π’s in red
μ’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
Cooling cell simulation

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
• Use screened Coulomb Potential (Everhart et. al. Phys. Rev. 99 (1955) 1287)
• Simulate all scatters $\theta > 0.05$ rad
• Simulation accurately reproduces ICRU tables
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**

- Motion controlled by $B$ field

**Longitudinal motion**

Lorentz angle drift, with nuclear scattering

**Final stages of muon trajectory in gas cell**
Oscillations about equilibrium define emittance.

Dangerous because of $\mu^-$ capture possibility

$$F = q(E + v \times B) - \frac{dT}{dx}$$
Initial reacceleration region

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

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

Yield: approx 0.002 µ per 2GeV proton after cooling cell.
Need to improve yield by factor 3 or more.

Emittance: rms

\[
x = 0.015 \text{ m} \\
y = 0.036 \text{ m} \\
z = 30 \text{ m (actually } \beta c t) \\
P_x = 0.18 \text{ MeV} \\
P_y = 0.18 \text{ MeV} \\
P_z = 4.0 \text{ MeV} \\
\]

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

• Extraction of $\mu$s through window 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

\[ \leq 4 \text{ MeV } p \]

VandeGraaf accelerator for biomedical research
H$_2^+$ beam

MCP
D=18.8mm

Thin Windows
D=4mm

Gas Feedthroughs

Si Detector
Thickness ~9μm

Support Structures

~30 cm

6.5 cm Reacc.

10 cm in Gas

~20 cm
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
Calibration Data:
3 distances, no cell, no grid

Time resolution of system = 17 ns

Protons have 100-200 KeV after Si window. Good agreement with SRIM.
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

$$\mu^- + \text{He} \rightarrow \text{He}_\mu + e+\gamma's$$

muon initially captured in large n orbit, then cascades down to n=1. Transition n=2→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!