Frictional Cooling

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Motivation: Muon Collider

→ compared to electrons:
  no synchrotron radiation problem
  \( P \propto (E/m)^4 \)

⇒ very high energy circular accelerator can be built

→ compared to protons:

• colliding **point particles** rather than complex objects
Why a Muon Collider?

Physics

→ High energy frontier: search for new physics beyond the Standard Model

→ Higgs Factory
  → $\sigma_{xx\rightarrow H} \propto m_x^2$

→ $\nu$ Deep Inelastic Scattering

→ $\nu$ Oscillation physics
  • from target – $\pi$ decay
  • from stored $\mu$ decay

→ Physics with slow $\mu$
What is the Problem?

Muons decay with lifetime 2.2 µs

→ need a multi MW source
  • large starting cost

→ large experimental backgrounds
  • lots of energetic e± from µ decay

→ limited time for cooling, bunching, and accelerating
  • need new techniques

→ limitations due to neutrino induced radiation
  • cannot be shielded
**μ beam production**

Drift region for π decay ≈ 30 m

Solenoidal Magnets: few T ... 20 T  
Target

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**beam description using 6D emittance**  
(6D phase space of the beam)

\[
e_{6D,N} = \frac{\sigma_x \sigma_y \sigma_z \sigma_{px} \sigma_{py} \sigma_{pz}}{\left(\pi mc\right)^3}
\]

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**after drift estimate**

rms: \(x, y, z\) 0.05, 0.05, 10 m  
\(p_x, p_y, p_z\) 50, 50, 100 MeV

\[e_{6D,N} \approx 1.7 \times 10^{-4} \ (\text{πm})^3\]

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**required**

\[e_{6D,N} \approx 1.7 \times 10^{-10} \ (\text{πm})^3\]
Typical muon collider scheme

Proton accelerator – 2-16 GeV, few MW \((10^{22} \text{ p/year})\)

\(\pi\) production target

\(\pi\) decay channel

\(\mu\) cooling channel

→ standard techniques too slow

→ new techniques are being developed
  • energy loses in interactions with matter
  • reaccelerating
  • magnetic focusing
Typical muon cooling scheme

Ionization cooling

• muons are maintained at ca. 200 MeV while passed successively through an energy loss medium followed by an acceleration stage

• with simulations cooling factors ~ 100 reached
  → not enough for collider
  → O.K. for $\nu$ factory
  → still problems to be solved

• demonstration experiments in preparation
  e.g. MICE
Frictional cooling

Idea

• bring muons to kinetic energy $T$ where $dE/dx$ increases with energy

• apply constant accelerating $E$ field to muons resulting in equilibrium energy

• big issue – how to maintain efficiency

• similar idea first studied by Kottmann et al. at PSI
Frictional cooling

Problems/Comments

• large $dT/dx$ at low $T$
  → low average density of stopping medium ⇒ gas

• apply $E \perp B$ to get below the $dE/dx$ peak
  \[ \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) - \frac{dT}{dx} \vec{v}_0 \]

• **slow** $\mu$’s don’t go far before decaying
  \[ d = 10 \text{ cm} \times \sqrt{T} \text{ with } T \text{ in eV} \]
  → sideward extraction ($E \perp B$)

• $\mu^+$ problem – **muonium formation** dominates over e-stripping except for He

• $\mu^-$ problem – **muon capture** at low energies; $\sigma$ not known
  ⇒ keep $T$ as high as possible
Neutralization

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

For $\mu$, energy lower by $M_\mu/M_P$

Stripping

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

Frictional Cooling: particle trajectory

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

**Using continuous energy loss**
Muon collider scheme based on frictional cooling

Full MARS simulation of the proton interactions in target (Cu) showed
- larger low energy $\pi$ yield in transverse directions
- nearly equal $\pi^+$ and $\pi^-$ yields with $T < 100$ MeV
- $\text{He}$ gas used for $\mu^+$
- $\text{H}$ gas for $\mu^-$
- transverse $E$ field 5 MV/m

- continuous electronic energy loss
- individual nuclear scatters simulated
  $\rightarrow$ they result in large angles
Target System

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

- Optimize drift length for $\mu$ yield
- Some $\pi$’s lost in Magnet aperture
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 $\mu^+$, $\text{H}_2$ 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

![Nuclear Energy Loss Graph](image-url)
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
Simulation of the cooling cell

Oscillations around equilibrium define the emittance

$\propto \text{rms.}$
Resulting emittance and yield

Muon beam coming out of 11 m long cooling cell and after initial reacceleration:

\[
\begin{align*}
\text{rms: } & \ x, y, z \quad 0.015, 0.036, 30 \text{ m} \\
\rho_x, \rho_y, \rho_z \quad & 0.18, 0.18, 4.0 \text{ MeV} \\
\end{align*}
\]

Results for \( \mu^+ \), still working on \( \mu^- \)

\[
\varepsilon_{6D,N} = 5.7 \times 10^{-11} \, (\pi \text{m})^3
\]

\[\rightarrow\] better than required \(1.7 \times 10^{-10} \, (\pi \text{m})^3\)

Yield \(\approx 0.002 \, \mu\) per 2 GeV proton after cooling cell

\[\rightarrow\] need \textbf{improvement by factor of 5} or more
Demonstration experiment with protons

RARAF

→ performed at Nevis Labs – 4 MeV Van de Graff Accel.

→ to demonstrate the principle of frictional cooling
  • has to work for all heavy charged particles ⇒ protons

T.o.F. experiment

H$_2^+$ beam
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.
Demonstration experiment with protons

MPI für Physik

Repeat the demonstration experiment with improvements:

• no windows
• 5 T superconducting solenoid for high acceptance
• Silicon Drift Detector (SDD) to measure energy directly

Cryostat housing 5 T solenoid in the lab at the MPI
Si Drift Detector
He gas
Source
Where do we get protons?

→ use strong $\alpha$ source + thin plastic (Hydrogen rich) foil
→ $\alpha$’s knock out H nuclei effectively at rest
What do we expect?

We are able to vary:
- pressure/density of the gas
- distance between the source and detector
- strength of the $E$ field

The ultimate question:
Can our MC simulation predict equilibrium energies?
Status

→ the superconducting magnet commissioned
→ the accelerating grid is ready
→ all support structures are constructed
→ detectors and electronics are available

We hope to solve all problems and start taking data soon
Future plans

→ run the experiment
  – demonstrate the frictional cooling
→ muon capture cross section measurement
→ studies of breakdown in high $E \perp B$ fields
→ R&D on thin windows

Build a muon collider.