Frictional Cooling

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A. Caldwell

MPI f. Physik, Munich
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
μ beam production

Drift region for π decay ≈ 30 m

Proton beam

Solenoidal Magnets: few T \ldots 20 T

Target

\begin{align*}
\text{beam description using 6D emittance} \\
\text{(6D phase space of the beam)}
\end{align*}

\[ \varepsilon_{6D,N} = \frac{\sigma_x \sigma_y \sigma_z \sigma_{p_x} \sigma_{p_y} \sigma_{p_z}}{(\pi mc)^3} \]

\begin{align*}
\text{after drift estimate} \\
\text{rms: } x, y, z & \quad 0.05, 0.05, 10 \text{ m} \\
p_x, p_y, p_z & \quad 50, 50, 100 \text{ MeV} \\
\varepsilon_{6D,N} & \approx 1.7 \times 10^{-4} (\pi \text{m})^3
\end{align*}

\begin{align*}
\text{required} \\
\varepsilon_{6D,N} & \approx 1.7 \times 10^{-10} (\pi \text{m})^3
\end{align*}
Typical muon collider scheme

Proton accelerator – 2-16 GeV, few MW ($10^{22}$ 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

$\mu$ accelerators

Muon collider
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 $d = 10 \text{ cm} \times \sqrt{T}$ with $T$ 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

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

Stripping

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

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

Frictional Cooling: particle trajectory

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

- cooling cell
- phase rotation
- capture & drift
- target
- reacceleration
- collider ring
- Not to scale !!

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

- He gas used for $\mu^+$
- H gas for $\mu^-$
- transverse $E$ field 5 MV/m

- continuous electronic energy loss
- individual nuclear scatters simulated
  → they result in large angles

Simulations performed to this point
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
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

$\propto \text{rms.}$

Oscillations around equilibrium define the emittance
Resulting emittance and yield

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

\[
\begin{array}{c|c}
\text{rms: } & x, y, z \quad 0.015, 0.036, 30 \text{ m} \\
p_x, p_y, p_z & 0.18, 0.18, 4.0 \text{ MeV}
\end{array}
\]

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

→ better than required \(1.7 \times 10^{-10} \ (\pi m)^3\)

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

→ need improvement by factor of 5 or more

Results for \(\mu^+\), still working on \(\mu^-\)
Motivated by the promising results from the first simulations, the FCD experiment at the MPP aims to verify the principle behind frictional cooling.

Accelerating-grid and gas-cell construction:

Detector mounted in gas-cell flange:
Proton Source Mechanism

Protons created by stripping $e^-$ from H atoms in Mylar

Silicon Drift Detector (from MPI-HLL)
The grid has been operated up to 90 kV (0.9 MV/m), and run stably at 60 kV (0.6 MV/m) with the gas-cell filled with Helium at pressures up to 1.25 Atm.
We observe protons with energies between 5 keV and 30 keV. At these energies they deposite all their energy in the first several hundred nanometers of the detector. The detector’s dead layers greatly effect how much energy is measured.

The expected proton energies are used to discover the dead-layer characteristics of the SDD.
Future plans

run the experiment – demonstrate the frictional cooling

Develop scheme for producing slow muon beam using surface muon source (paper in preparation)