Frictional Cooling

NUFACT02

Studies at Columbia University & Nevis Labs
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Cooling Motivation

• μs not occur naturally so produce them from p on target – π beam – decay to μ
  • π & μ beam occupy diffuse phase space
    \[ \varepsilon_{6D} = \sigma (x) \sigma (P_x) \sigma (y) \sigma (P_y) \sigma (z) \sigma (P_z) \]

• Unlike e & p beams only have limited time \( \tau_\mu = 2.2 \mu s \) to cool and form beams
• Neutrino Factory/Muon Collider Collaboration are pursuing a scheme whereby they cool μs by directing particles through a low Z absorber material in a strong focusing magnetic channel and restoring the longitudinal momentum
  • IONIZATION COOLING COOL ENERGIES \( O(200\text{MeV}) \)
• Cooling factors of \( 10^6 \) are considered to be required for a Muon Collider and so far factors of 10-100 have been theoretically achieved through IONIZATION COOLING CHANNELS
Frictional Cooling

- Bring muons to a kinetic energy (T) range where dE/dx increases with T
- Constant E-field applied to muons resulting in equilibrium energy
Problems/Comments:

- large $dE/dx$ @ low kinetic energy
  - low average density
- Apply $\vec{E} \perp \vec{B}$ to get below the $dE/dx$ peak
- $\mu^+$ has the problem of Muonium formation
  - $\sigma(\text{Mu})$ dominates over e-stripping $\sigma$ in all gases except He
- $\mu^-$ has the problem of Atomic capture
  - $\sigma$ calculated up to 80 eV not measured below $\sim 1\text{KeV}$
- Cool $\mu$’s extracted from gas cell $T=1\mu$s so a scheme for reacceleration must be developed
Frictional Cooling: particle trajectory

- $\ln(1 - \tau) \sqrt{d \mu = 10 \text{cm} \times \sqrt{T(\text{eV})}}$
- keep $d$ small at low $T$
- reaccelerate quickly

** Using continuous energy loss**

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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

Start with low initial muon momenta
Cooling scheme

Phase rotation is $E(t)$ field to bring as many $\mu$’s to 0 Kinetic energy as possible
- Put Phase rotation into the ring
Target System

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

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$\pi$’s in red
$\mu$’s in green

View into beam
Target & Drift
Optimize yield

- Maximize 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
Frictional Cooling Channel

Cool $\mu$ beamlets reaccelerated and recombined.

Incoming $\mu$ beam

Solenoid

Gas Cell

$E(t)$

$E$

$B$
Cell Magnetic Field

- Realistic Solenoid fields in cooling ring
Simulations Improvements

- Incorporate scattering cross sections into the cooling program
  - Born Approx. for $T > 2\text{KeV}$
  - Classical Scattering $T < 2\text{KeV}$
- Include $\mu^-$ capture cross section using calculations of Cohen (Phys. Rev. A. Vol 62 022512-1)
Scattering Cross Sections

- Scan impact parameter $\theta(b)$ to get $d\sigma/d\theta$ from which one can get $\lambda_{\text{mean free}}$
- Simulate all scatters $\theta > 0.05$ rad
Barkas Effect

• Difference in $\mu^+$ & $\mu^-$ energy loss rates at dE/dx peak
• Due to extra processes charge exchange
• Only used for the electronic part of dE/dx
Frictional Cooling: Particle Trajectory

μ- use Hydrogen
  • Smaller Z help in $\sigma_{\text{capture}}$
  • Lower r fewer scatters
  • BUT at higher equilibrium energy

- 50cm long solenoid
- 10cm long cooling cells
- $\rho_{\text{gas}}$ for $\mu^+$ 0.7atm & $\mu^-$ 0.3atm
- $E_x=5\text{MV/m}$
- $B_z=5\text{T}$ realistic field configuration
Motion in Transverse Plane

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

- Assuming \( E_x = \text{constant} \)
Emittance Calculation

After drift cartesian coordinates
More natural

\[ \varepsilon_{\text{long}} = \sigma(z)\sigma(P_z) \]
\[ \varepsilon_{\text{trans}} = \sigma(x)\sigma(P_x)\sigma(y)\sigma(P_y) \]
\[ \varepsilon_{6D} = \varepsilon_{\text{long}}\varepsilon_{\text{trans}} \]

After cooling cylindrical coordinates are more natural

\[ \varepsilon'_{\text{long}} = \sigma(\beta_c t)\sigma(P_{\rho}) \]
\[ \varepsilon'_{\text{trans}} = \rho_0\sigma(\phi)\sigma(P_{\phi})\sigma(z)\sigma(P_z) \]
\[ \varepsilon'_{6D} = \varepsilon'_{\text{long}}\varepsilon'_{\text{trans}} \]

After drift cartesian coordinates
More natural

Beamlet uniform z distribution:

\[ \rho_0 = 20\text{cm} \]
\[ \sigma(z) = 10\text{cm}/\sqrt{12} * N \]
\[ N = 100\text{cells} \]
Beamlet coordinates:

\[ \rho, \phi, z \]

\[ P_\rho = \frac{xP_x + yP_y}{\rho} \quad P_\phi = \frac{xP_y - yP_x}{\rho^2} \quad P_z \]

X 100 beamlets

Beamlet coordinates:

\[ \rho, \phi, z \]

\[ P_\rho = \frac{xP_x + yP_y}{\rho} \quad P_\phi = \frac{xP_y - yP_x}{\rho^2} \quad P_z \]
$\beta_{ct}$ vs $z$ for $\mu^+\text{He}$ on Cu

Mean($\beta_{ct}$) = 1.02 cm
RMS($\beta_{ct}$) = 8.1 cm
$\beta_{ct}$ vs $z$ for $\mu$-H on W
$P_{\text{long}} \text{ vs } P_{\text{trans}} \text{ for } \mu^+\text{He on CU}$
$P_{\text{long}}$ vs $P_{\text{trans}}$ for $\mu^{-}\text{H}$ on W
RΦ vs z for μ⁺He on CU

Mean(RΦ) = −3.3 cm
RMS(RΦ) = 4.7 cm
Rφ vs z for μ-H on W
Conclusions

<table>
<thead>
<tr>
<th>Cooling factors</th>
<th>Yield $(\mu/p)$</th>
<th>$\varepsilon_{\text{trans}}$</th>
<th>$\varepsilon_{\text{long}}$</th>
<th>$\varepsilon_{6D}$ $(1\times10^6)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\text{He on Cu}$</td>
<td>0.005</td>
<td>11239</td>
<td>2012</td>
<td>22</td>
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<tr>
<td>$\mu^-\text{He on Cu}$</td>
<td>0.002</td>
<td>403</td>
<td>156</td>
<td>0.06</td>
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<tr>
<td>$\mu^-\text{H on Cu}$</td>
<td>0.003</td>
<td>1970</td>
<td>406</td>
<td>0.8</td>
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<tr>
<td>$\mu^+\text{He on W}$</td>
<td>0.006</td>
<td>9533</td>
<td>1940</td>
<td>18</td>
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<tr>
<td>$\mu^-\text{He on W}$</td>
<td>0.003</td>
<td>401</td>
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<tr>
<td>$\mu^-\text{H on W}$</td>
<td>0.004</td>
<td>1718</td>
<td>347</td>
<td>0.6</td>
</tr>
</tbody>
</table>
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 gas tight and sustain pressures $O(0.1-1)$ atm
• Can we applied high electric fields in small gas cell without breakdown?
• Reacceleration & recombine beamlets for injection into storage ring
• The $\mu^-$ capture cross section depends very sensitively on kinetic energy & fall off sharply for kinetic energies greater than $e^-$ binding energy. NO DATA – simulations use calculation
  Critical path item intend to make measurement
Work at NEVIS labs

• Want to measure the energy loss, $\mu \cdot \sigma_{\text{capture}}$, test cooling principle
• Developing Microchannel Plate & MWPC detectors
A simpler approach

- Avoid difficulties of kickers & multiple windows
- Without optimization initial attempts have 60% survival & cooling factor $10^5$
- Still need to bunch the beam in time
Conclusions

• Frictional cooling shows promise with potential cooling factors of $O(10^5-10^6)$
  – Simulations contain realistic magnet field configurations and detailed particle tracking
  – Built up a lab at Nevis to test technical difficulties

• There is room for improvement
  – Phase rotation and extraction field concepts very simple
  – Need to evaluate a reacceleration scheme
Summary of Frictional Cooling

- Works below the Ionization Peak
- Possibility to capture both signs
- Cooling factors $O(10^6)$ or more?
- Still unanswered questions being worked on but work is encouraging.

Nevis Labs work on $\mu^+ \sigma_{\text{capture}}$

Schematic layout of this cooling system

- Target Magnet
- Drift
- Cooling ring (100 cells)
- Muon Re-Acceleration

produce and collect p/mu

$\text{p-time corr}$

$\text{max #muls}$

$\text{phase rotation and cooling and extraction}$