Update of the frictional cooling studies at Nevis Labs/Columbia University

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for the Nevis group:
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and the Columbia summer students
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- Frictional cooling
- Simulation and optimization
  - Target and magnet
  - Phase rotation
  - Cooling
- The experimental set-up
Frictional cooling: The idea

Cool μ’s where $\frac{dE}{dx} \propto \beta$

and compensate the energy loss by an E-field: **cooling**

Below the ionization peak $dE/dx$ is dominated by:

- nuclear recoil
- excitation
- charge exchange (muonium) for $\mu^+$ and capture for $\mu^-$

Issues/ consequences/ comments:

- large $dE/dx$ ⇒ work with a gas
- with $\vec{E} \parallel \vec{B}$ we never get below the peak ⇒ apply $\vec{E} \perp \vec{B}$

Work with very low energy muons in Helium at low density.
Frictional cooling: particle trajectory

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

Calculated with continuous energy loss
Frictional cooling: stop the $\mu$

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

$\Rightarrow$ need low initial muon momenta
Frictional cooling scheme

Proton Beam → Target

Drift Region → B → Phase Rotation Region (Induction Linac)

30-50 m

Optimize: target, phase rotation and cooling channel (in a toroid)
Target system: study II

Longitudinal (StudyII) scheme

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Target (study II): MARS scan

Optimize $E_p$, target A, radius, length

![Graphs showing data analysis for MARS scan with different target materials and energies.](image-url)
- cool $\mu^+$ and $\mu^-$ in the same time
- exploit the non-leading behaviour of the low energy $\pi$
- calculated a new, symmetric magnet with a gap
Target (transverse): MARS scan

Further GEANT investigation of best configuration

Cu, $E_p = 2$ GeV, target 0.5 or 0.75 cm thick
MARS Cu 2–30m GeV 0.5 cm + GEANT

MARS Cu 2–30m GeV 0.75 cm + GEANT
Phase rotation: scheme

Phase rotation optimization

Length=30m, \( t_1 = 100 \text{ns}, t_2 = 225 \text{ns}, E\text{field}=5 \text{MV/m} \)

Before Phase Rotation

lost muons in Phase Rotation

After Phase Rotation

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Phase rotation: results

$p_z < 100$ MeV

$p_z < 50$ MeV
Include phase rotation inside cooling channel $|p_z| < 50$ MeV
Cooling: realistic simulation

- Electronic energy loss continuous (NIST table)
- Nuclear energy loss (multiple scattering) discrete
- Include Barkas effect and $\mu^-$ capture
- Incorporate scattering cross section into the cooling program: $T_\mu > 2$ keV Born approx, else classical $\theta(b)$ 
  $\rightarrow d\sigma/d\theta \rightarrow$ mean free path
Frictional cooling: particle trajectory

He w density $1.10^{-4}$ gm/cm$^3$
B = 5T uniform for now
E = 8 MV/m (increased from 5 to avoid $\mu^-$ capture)
cooling cell - 42x42x20 cm$^3$
the cells are placed between 1m solenoids, with radius 42 cm
No E field in solenoids

calculated with realistic energy loss

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Frictional cooling: survival probability

Survival Probability in Helium

Survivors

P_z (MeV/c)

P_T (MeV/c)

Probability

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**Frictional cooling: what did we achieve**

**First and preliminary result** (based on $\approx 80 \mu$'s with $p_{x,y,z} < 50$ MeV)

<table>
<thead>
<tr>
<th></th>
<th>$\mu^+$</th>
<th>$\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cooling</td>
<td>drift</td>
</tr>
<tr>
<td>$\mu$/proton</td>
<td>0.005</td>
<td>0.057†</td>
</tr>
<tr>
<td>rms($p_x$) (MeV)</td>
<td>0.07</td>
<td>9.4</td>
</tr>
<tr>
<td>rms($p_y$) (MeV)</td>
<td>0.08</td>
<td>10.3</td>
</tr>
<tr>
<td>rms($p_z$) (MeV)</td>
<td>0.07</td>
<td>53</td>
</tr>
<tr>
<td>rms(tran) (cm$^2$)</td>
<td>40 x 60</td>
<td>25</td>
</tr>
<tr>
<td>rms(long) (cm)</td>
<td>250</td>
<td>1200</td>
</tr>
<tr>
<td>phase space reduction*</td>
<td>$6 \times 10^5$</td>
<td></td>
</tr>
</tbody>
</table>

† for $T_z < 100$ MeV

* phase space factor for the $\mu$'s which are cooled

We continue to work on:

- finalizing MARS and GEANT studies
- the phase rotation optimization
- incorporate fringe fields into cooling
- matching B-fields between target (drift) region, phase rotation and cooling ring
- extraction of $\mu$ from the cooling ring, and first re-acceleration
Cooling: RING simulation

- 1m long solenoid
- 0.2m long cooling cell
- 60m ring
Frictional cooling: what did we achieve

First and preliminary RING result
(based on $\approx 10000 \mu$’s with $40 < T_{\text{arrival}} < 200$ ns)

<table>
<thead>
<tr>
<th>After</th>
<th>$\mu^+$ ($t_2 = 225$ns)</th>
<th>$\mu^-$ ($t_2 = 275$ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$/proton</td>
<td>cooling</td>
<td>drift</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rms($p_x$) (MeV)</td>
<td>0.07</td>
<td>16</td>
</tr>
<tr>
<td>rms($p_y$) (MeV)</td>
<td>0.07</td>
<td>16</td>
</tr>
<tr>
<td>rms($p_z$) (MeV)</td>
<td>0.09</td>
<td>37</td>
</tr>
<tr>
<td>rms(tran) (cm$^2$)</td>
<td>60x50</td>
<td>50</td>
</tr>
<tr>
<td>rms(long) (cm)</td>
<td>121</td>
<td>387</td>
</tr>
</tbody>
</table>

| phase space reduction* | $1.4 \times 10^6$ | $1.3 \times 10^5$ |

† for $T_{\mu} < 100$ MeV
* phase space factor for the $\mu$’s which are cooled

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finalizing MARS and GEANT studies
the phase rotation optimization
incorporate fringe fields into cooling
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Gas Breakdown

Can we apply high E-fields in gas without causing avalanche?

- High Magnetic field will help

- An Electron starting from rest in crossed E & B fields:  
  Max. Kinetic Energy $= 2m(e/B)^2$
  For $E = 5$ MV/m, $B = 5$ T $(KE)_{max} = 16$ eV

- A muon from rest in crossed E & B fields:  
  For $E = 5$ MV/m, $B = 5$ T $(KE)_{max} = 3.3$ keV

\[ E_{ion}(H_2) = 13.6 \text{ eV}, \quad E_{ion}(He) = 24.6 \text{ eV} \]
Experimental Work at Nevis

- We want to measure the energy loss, the capture, test cooling principle
MultiWire Proportional Chamber

- Single Wire prototype constructed, tested with P10
- **Ongoing**: Multiwire, use Xe gas.

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MicroChannelPlate

- MCP used to measure s & e
- Use , , sources in 4 MeV p beam at Nevis & 10-40 KeV beam at PSI

MCP: front  side  Accelerating grid