Muon ionization cooling
MICE and the MICE Muon Beam
MICE - Step IV
Demonstration of Ionization Cooling
Summary
Muon ionization cooling

Proton Driver
Accumulator
Compressor
HG-target
Capture Solenoid
Front End
Decay Channel
Buncher
Phase Rotator
4D Cooler

Acceleration
0.2–1.2 GeV
1.2–5 GeV

μ Storage Ring
5 GeV
≈0.35 km

Accelerator Types:
Linac, Recirculating Linac (RLA) or FFAG

$\frac{dE}{dx}$
Muon ionization cooling

- Ionization cooling enables the operation of neutrino factories for precision oscillation physics and new-physics searches and multi-TeV muon colliders.
- Experimental verification of muon ionization cooling technique is important in understanding the engineering and operation of these facilities.
MICE : Muon Ionization Cooling Experiment

- MICE goal is to verify emittance reduction from ionization cooling

- Study properties of single muons from ISIS beam at STFC Rutherford-Appleton Laboratory, UK in the cooling channel

- Construct a beam from ensembles of single muons
MICE Muon Beam

- ISIS 800 MeV/c proton beam colliding with a titanium target dipped into the beam
- $p_\mu \in [140, 300]$ MeV/c
- $\varepsilon_n \in [2\pi, 10\pi]$ mm rad
- $\pi$ contamination < 1.4%
- electron tag efficiency > 98.6%
MICE Muon Beam

- ISIS 800 MeV/c proton beam colliding with a titanium target dipped into the beam
- $p_\mu \in [140, 300] \text{ MeV/c}$
- $\varepsilon_n \in [2\pi, 10\pi] \text{ mm rad}$
- $\pi$ contamination < 1.4 %
- electron tag efficiency > 98.6%

Pion Contamination in the MICE Muon Beam, JINST 11 P03001, 2016

EMR Performance in the MICE Muon Beam, JINST 10 P12012, 2015

Characterisation of the muon beams for MICE, EJP C73, 10, 2013
MICE – Step IV

\[
\frac{d\epsilon_n}{dz} \approx -\epsilon_n \left( \frac{dE}{dX} \right) \beta_t \left( 13.6 \text{ MeV} \right)^2 \frac{2 \beta^3 E m_\mu X_0}{2 \beta^3 E m_\mu X_0}
\]

Heating
(Multiple scattering)

Cooling
Particle ID detectors are on-line and operating stably
Solenoids, containing trackers, have been installed
Focus coil is operating well
Channel is being commissioned and characterised. All magnets operated together last week.

Incoming beam studies: 200 MeV/c with upstream solenoid on
Multiple scattering studies: straight track with He and LiH absorbers
# Measurement Program

<table>
<thead>
<tr>
<th>Study of properties that determine cooling performance</th>
<th>Step IV</th>
<th>Demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material properties of LH₂ and LiH</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Observation of $\epsilon^n_\perp$ reduction</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Demonstration of sustainable ionization cooling</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation of $\epsilon_\perp$ reduction</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>with re-acceleration</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Observation of $\epsilon_\perp$ reduction</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>with $\epsilon^L_\parallel$ “management”</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Observation of $\epsilon_\perp$ reduction</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>with $\epsilon^L_\parallel \oplus \mathcal{L}$ “management”</td>
<td>Yes$^\dagger$</td>
<td></td>
</tr>
</tbody>
</table>

$^\dagger$ Requires systematic study of “flip” optics.
Multiple Scattering Studies

MS theories do not agree with measurements of muon scattering on low Z materials (MuScat; NIM B, 251 (2006) 41-55)

<table>
<thead>
<tr>
<th>Material</th>
<th>Momentum (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td>172, 200, 240</td>
</tr>
<tr>
<td>He</td>
<td>240</td>
</tr>
<tr>
<td>LiH</td>
<td>172, 200, 240</td>
</tr>
</tbody>
</table>

Straight track data with empty absorber
I. Convolve with MS models and compare with material data
II. Unfold effect of absorber scattering

With spectrometers
- Energy loss measurements
- Precise input momentum
Input Beam Studies

200 MeV/c muon beam
Upstream spectrometer operational

See poster “Emittance Measurement in the MICE Ionization Cooling Experiment” by V. Blackmore
Demonstration of Ionization Cooling

200 MeV/c muon beam

See poster “MICE Demonstration of Ionization Cooling” by T. Mohayai
Summary

- All components required for Step IV are now online
- Commissioning of the full channel is under way
- Data taking to date has:
  - Validated functioning of muon beam and detectors
  - Validated particle reconstruction and analysis codes
  - Delivered a preliminary multiple scattering study
  - Characterised the input muon beam characteristics
- Run plan for Step IV to August 2017 is well-defined
- Plans for the demonstration of ionisation cooling phase are being defined now
- MICE physics program is under way.
Backups
Tracker resolution

\[ \sigma(p_z) \sim 3.7 \text{ MeV} / \text{c} \]

“Characterisation of the muon beams for the Muon Ionization Cooling Experiment”, EJP C, Vol 73, Number 10
MS – Particle Selection

- TOF (PID) selection is vital for beam momentum and position selection
- Requires an US track. If a DS track is not extant, statistics and set to overflow values
- Require projection of US track to appear within central 150 mm radius of DS station 1
Angle Distributions

- Particles follow straight paths through spectrometers.
- Scatter off of materials along its path.
  - Need to identify scattering from absorber material only.
- Use TOFs to measure momentum.
  - Consider scattering as a function of momentum.
- Define scattering angles for trajectories
  - $\Delta \theta_x = \tan\left(\frac{dy}{dz}\right)_{US} - \tan\left(\frac{dy}{dz}\right)_{DS}$
  - $\Delta \theta_y = \tan\left(\frac{dx}{dz}\right)_{US} - \tan\left(\frac{dx}{dz}\right)_{DS}$
  - $\theta_{scatt} = \cos\left(\frac{p_u \cdot p_d}{|p_u| |p_d|}\right)$
Deconvolution

- Measurement of the scattering in the absorber
- Unfold underlying scattering from absorber model from measured scattering
- Uses iterative Bayes deconvolution (other unfolding methods being investigated)
ELMS

Wentzel-Moliere form including effect of scattering from atomic electrons and of nuclear screening by atomic electrons

\[
\frac{d\langle \theta^2 \rangle}{dx} = 4\pi N \frac{Z^2}{A} r_e^2 \left( \frac{m_e c}{\beta p} \right)^2 \left\{ \ln \left[ \left( \frac{\theta_2}{\theta_1} \right)^2 + 1 \right] - 1 + \frac{1}{Z} \left[ \ln \left( \left( \frac{\theta_{2e}}{\theta_{1e}} \right)^2 + 1 \right) - 1 \right] \right\}
\]

\[\theta_{1e} = \theta_1 \quad \theta_{2e} \sim \frac{m_e}{m_\mu}\]

ELMS : uses photoabsorption coefficients to describe atomic structure

Only for \( \text{LH}_2 \)


Cobb-Carlisle : uses a Monte Carlo method to extend Wentzel-Moliere to other materials.
Building a covariance matrix

Each particle that passes the selection criterion
Generates a \((x, p_x, y, p_y)\) tuple
Over ensemble of muons, calculate

\[
\Sigma_{4D} = \begin{pmatrix}
\sigma_{xx} & \sigma_{xp_x} & \sigma_{xy} & \sigma_{xp_y} \\
\sigma_{xp_x} & \sigma_{p_xp_x} & \sigma_{yp_x} & \sigma_{p_xp_y} \\
\sigma_{xy} & \sigma_{yp_x} & \sigma_{yy} & \sigma_{yp_y} \\
\sigma_{xp_y} & \sigma_{p_xp_y} & \sigma_{yp_y} & \sigma_{p_yp_y}
\end{pmatrix}
\]

\[
\sigma_{ab} = \langle ab \rangle - \langle a \rangle \langle b \rangle
\]

\[
\epsilon_N = \frac{1}{m_\mu} \left( \det |\Sigma_{4D}| \right)^{1/4}
\]
Beam dispersion

MICE Preliminary
ISIS Cycle 2015/02
Run 7469, MAUS v2.5

Radius of beam centre (mm)

<Pz> (MeV/c)