Optimization of Beam Line Settings for MICE Step IV

John Nugent

University of Glasgow

j.nugent.1@research.gla.ac.uk

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Muon Ionisation Cooling

The International Muon Ionisation Cooling Experiment (MICE) aims to give the first demonstration of ionisation cooling. MICE is a stepping stone to a neutrino factory or muon collider.

Cooling Formula

The rate of change of normalised emittance due to ionisation cooling is:

\[ \frac{d\varepsilon_N}{dX} \approx - \frac{\varepsilon_N}{\beta^2 E_\mu} \left( \frac{dE}{dX} \right) + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}; \quad (1) \]

The emittance of the beam at equilibrium is:

\[ \varepsilon_{eq} \approx \frac{\beta_\perp (0.014 (\text{GeV}))^2}{2\beta m_\mu X_0} \left( \frac{dE}{dX} \right)^{-1}. \quad (2) \]
11 conventional magnets in beam line

Current settings must be optimised to deliver matched beam to the MICE cooling channel
Diffuser

- Diffuser will be used to vary the input emittance (by intercepting the beam with Cu and W)
- It consists of four in-line irises contained in cassettes stacked in a drum inserted through Tracker patch-panel
- It will see the magnetic field of the SS and so will create the net canonical angular momentum at the input to the MICE Channel.
- Commissioning of the Diffuser will be a core activity within the beam line commissioning task.
The MICE channel at Step IV will use three superconducting-magnet modules: two spectrometer solenoids (SS) in which the trackers are installed and one focus-coil (FC) modules in which the absorber is installed.

Optical properties of the Step IV channel must be verified experimentally.
MICE Cooling Channel

- It is planned to operate the central coil and end coils with current values close to the nominal ones.
- However, the currents in matching coils and in the FC will vary considerably between different momentum and optical settings.
- In addition to various momentum and optical settings, MICE can be operated in ‘flip’ and ‘solenoid’ modes.
- These modes differ in the magnetic field direction in the upstream and downstream halves of the experiment.
- By comparing the transmitted phase space distributions between the two modes it will be possible to examine the behaviour of the beam envelope and canonical angular momentum.
MICE Cooling Channel

- Each beam delivered is designed to be matched into the upstream tracking volume, satisfying $\alpha_\perp = 0$, $\beta_\perp = 333$ mm at $p_z = 200$ MeV/c.

- Matching into and out of the cooling cell will be examined by altering the tuning of the lattice and measuring the beams optical parameters.
Object of Commissioning Beam

**Beam Line**
- It is necessary to ensure that the optimum beam can be provided by the MICE Muon Beam (MMB)
- Verify the optical properties of the MICE Muon Beam which delivers beam from the pion-production target on ISIS to the MICE experiment;

**Lattice**
- Verify that satisfactory matching conditions can be achieved between the MMB and the MICE experiment for each of the numerous operating conditions.
- Verify the matching conditions into the MICE channel including the effect of the diffuser that will allow the manipulation of the value of the input emittance
- Verify the properties of optics in the Step IV channel.
A ‘physics block’ assumes data taking at each of three momenta and three different input emittance settings. This requires that nine matching conditions be tested.

<table>
<thead>
<tr>
<th>$\epsilon_N$ ((\alpha \text{ mm. rad)})</th>
<th>$p_z$ (MeV/c)</th>
<th>$p_z$ (MeV/c)</th>
<th>$p_z$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>140</td>
<td>200</td>
<td>240</td>
</tr>
<tr>
<td>3</td>
<td>$d = 0.0$</td>
<td>$d = 0.0$</td>
<td>$d = 0.0$</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{diff}} = 151$ MeV/c</td>
<td>$P_{\text{diff}} = 207$ MeV/c</td>
<td>$P_{\text{diff}} = 245$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>$\alpha = 0.2$</td>
<td>$\alpha = 0.1$</td>
<td>$\alpha = 0.1$</td>
</tr>
<tr>
<td></td>
<td>$\beta = 56$ cm</td>
<td>$\beta = 36$ cm</td>
<td>$\beta = 42$ cm</td>
</tr>
<tr>
<td>6</td>
<td>$d = 0.9X_0$</td>
<td>$d = 1.3X_0$</td>
<td>$d = 1.3X_0$</td>
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<tr>
<td></td>
<td>$P_{\text{diff}} = 156$ MeV/c</td>
<td>$P_{\text{diff}} = 215$ MeV/c</td>
<td>$P_{\text{diff}} = 256$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>$\alpha = 0.3$</td>
<td>$\alpha = 0.2$</td>
<td>$\alpha = 0.2$</td>
</tr>
<tr>
<td></td>
<td>$\beta = 113$ cm</td>
<td>$\beta = 78$ cm</td>
<td>$\beta = 80$ cm</td>
</tr>
<tr>
<td>10</td>
<td>$d = 1.8X_0$</td>
<td>$d = 2.8X_0$</td>
<td>$d = 2.8X_0$</td>
</tr>
<tr>
<td></td>
<td>$P_{\text{diff}} = 164$ MeV/c</td>
<td>$P_{\text{diff}} = 229$ MeV/c</td>
<td>$P_{\text{diff}} = 267$ MeV/c</td>
</tr>
<tr>
<td></td>
<td>$\alpha = 0.6$</td>
<td>$\alpha = 0.4$</td>
<td>$\alpha = 0.3$</td>
</tr>
<tr>
<td></td>
<td>$\beta = 198$ cm</td>
<td>$\beta = 131$ cm</td>
<td>$\beta = 129$ cm</td>
</tr>
</tbody>
</table>

- \((\epsilon_N, p_z)\) matrix for the MICE programme. The Twiss parameters \((\alpha, \beta)\) are those required at the upstream face of the diffuser of thickness \(d\) for a matched beam.
Beam Line Pre-commissioning

- Dedicated run to commission Tracker without $B$ field
- Shakedown of the beam line hardware.
- Repeat Step I run settings
  - Check that nothing has changed
- Test the new MMB settings required for Step IV operations with the diffuser.
- Tomography-like phase-space reconstruction developed and tested in Step I operations will allow the matching condition at TOF0 to be measured and compared with Monte Carlo (MC) predictions for the new settings.
- It will be necessary to collect $\sim 10k$ good triggers per setting ($\sim 8$ shifts for all settings).
- Completed before magnet commissioning in the MICE cooling channel
Beam Line Commissioning

- Necessary to test the muon beam matching to the MICE Channel
- Requires DS, proton absorber, all beam line magnets, TOF0 and TOF1, the Diffuser and commissioned Upstream Tracker (requires B field in USS)
- 9 settings (beam matrix), each ~10k triggers, ~10h of useful beam
- Most likely will need to be repeated - 15 shifts (including the contingency)
- Needs to be done after Magnet Commissioning (at least USS)
Beam commissioning of Step IV Channel

- The trajectory through the channel will be measured. The mean positions and divergence are expected to be close to zero.
- The $\alpha$ and $\beta$ functions and the emittance will be measured at all 10 tracker planes. The transfer matrix through the channel can be calculated and the predicted evolution of the $\beta$ function measured.
- Comparison with the MC predictions and potentially allowing for retuning.

- Including additional time for calibration runs, for extra tuning and including contingency the estimated number of shifts is $\sim21$ for assessing all three momentum settings.
Beam Envelope

- Place VirtualDetector planes every 10 cm from centre of DS to TOF1
- Calculate the rms beam size at every plane and plot as a function of Z (where Z is oriented along the direction of the MICE beam line)

- G4BL beam envelope as a function of position along the MICE beam line (6, 140)\(\mu^+\) beam
Data collected in the commissioning will be compared with Monte Carlo predictions of the beam line behaviour. Tracking beam parameters along the beam line allows the beam line settings to be optimised.

- Muons scattering off of beam line components corresponds to growth in $\alpha$ & $\beta$
- Displacement of beam from beam line centre results in scraping.
  - This can be tracked and the discontinuities in the beam parameters matched to muons being killed in the iron of the beam line magnets - muons scattering out of the beam line
Data collected in the commissioning will be compared with Monte Carlo predictions of the beam line behaviour. Tracking beam parameters along the beam line allows the beam line settings to be optimised.

- **Energy loss** in the muon beam matches the position of the beam line material.
  - The focusing of the beam in both orientations can be cross-checked and the origin of beam mismatching located quickly with these visual tools.
Plan for Beam Optimisation

- Set of equations describing the beam evolution in the presence of matter and solenoidal fields (G. Penn):

\[
\begin{align*}
\epsilon_N' &= \beta_{\perp} \frac{P \mathcal{D}}{2mc} + \epsilon_N \frac{1}{v P_z} \frac{dE}{ds} \\
\beta_{\perp}' &= -2\alpha_{\perp} + \beta_{\perp} \frac{qE_z}{v_z P_z} + \frac{\beta_{\perp}^2}{\epsilon_N} \frac{P \mathcal{D}}{2mc} \\
\alpha_{\perp}' &= -\gamma_{\perp} + 2\kappa (\beta_{\perp} \kappa - \mathcal{L}) - \frac{\alpha_{\perp} \beta_{\perp}}{\epsilon_N} \frac{P \mathcal{D}}{2mc} \\
\mathcal{L}' &= -\beta_{\perp} \kappa \frac{1}{v P_z} \frac{dE}{ds} - \frac{\mathcal{L} \beta_{\perp}}{\epsilon_N} \frac{P \mathcal{D}}{2mc}
\end{align*}
\]

- Optics of the beam line magnets together with the matter effects of TOF0, TOFI and the Diffuser needs to be taken into account in the modelling (for the first order prediction).
- Beam must be matched closely to the uniform field of the Spectrometer Solenoid in the Tracker region (4T) with \( \alpha = 0 \).
- Settings need to be verified and optimised using MC simulations (MAUS).
The procedure for commissioning the MICE muon beam and cooling channel at Step IV has been outlined.

The timescale and number of shift required to complete this work has been calculated.

G4beamline simulations showing the evolution of beam parameters through the beam line have been run. These results will be used in the commissioning to calculate the optimal beam line settings.
References

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The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon
Ionization Cooling Experiment

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Magnet and Beam Commissioning at Step IV

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The Expected Performace of MICE Step IV
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(15/04/2011)