Normalized Transverse Emittance Reduction via Ionization Cooling in MICE 'Flip Mode'

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INTRODUCTION

Low emittance muon beams are central to the development of facilities such as a Neutrino Factory or a Muon Collider. The International Muon Ionization Cooling Experiment (MICE) was designed to demonstrate and study the cooling of muon beams. First cooling results in MICE ‘flip mode’ were published in [1]; a further analysis of the cooling performance is presented here.

IONIZATION COOLING

- Rate of change of normalized transverse emittance due to ionization cooling reads:
  \[
  \frac{d \varepsilon_T}{dz} \approx - \frac{1}{\beta^2} \varepsilon_T \frac{dE_T}{dz} + \frac{1}{2 \beta^3} \left( \varepsilon_{\text{T}} + \varepsilon_{\text{LH}} \right) X_0
  \]  

- (blue) Cooling realized via energy loss, (red) heating due to Coulomb scattering. Heating reduced by using low Z materials and minimizing \(\beta_z = (\gamma^2 + \gamma^2) / \gamma\).

Figure 1: (A) Schematic layout of MICE cooling channel. Magnet coils shown in red, absorber in green and various detectors are individually marked. (B) Modelled on-axis magnetic field along cooling channel (blue line). Hall probe measurements included as verification; (green) field strength at position of the Hall probes (160 mm off-axis). Magnetic field flips polarity at absorber.

COOLING APPARATUS

- The cooling channel (Fig. 1 A) - 12 solenoids magnets that could be individually powered, symmetrically placed up- and downstream of an absorber chamber.
- Individual muon positions and momenta measured before and after passing through an absorber (Fig. 2) by scintillating fiber trackers immersed in 3 T and -2 T uniform fields (Fig. 1 B).
- MICE measured individual muons crossing:
  - an empty drift space (‘No absorber’)
  - 221 l liquid hydrogen vessel (‘LH\textsubscript{1}’, empty & full)
  - 65 mm lithium hydride disk (‘LH\textsubscript{T}’)
  - a polyethylene wedge (not used in this study)

RECONSTRUCTION

- The 4-dimensional normalized transverse emittance, a measure of beam phase space volume, is calculated as:
  \[
  \varepsilon_T = \frac{1}{\mu_p} \left( \frac{\beta_T}{\sqrt{\Sigma}} \right) .
  \]  

- Analysis only included events with:
  - an upstream time of flight consistent with a muon,
  - a measured total momentum in the upstream tracker in the 135-145 MeV/c range, consistent with the time of flight,
  - a single, well-reconstructed track in each tracking detector, fully contained within the fiducial volume.

BEAM SAMPLING

- Beams with matched optics at entrance of cooling channel selected using a rejection sampling algorithm.
- Good matching performance achieved in upstream tracker in both data and simulation (Fig. 3).

Cooling measurement improved by reducing amount of heating in absorber through decrease in \(\Delta \varepsilon\).

EMITTANCE REDUCTION

- \(\Delta \varepsilon = \varepsilon_{\text{downstream}} - \varepsilon_{\text{upstream}}\)
- \(\Delta \varepsilon < 0\) cooling (Fig. 4).
- ‘No absorber’: no significant emittance change observed.
- ‘Empty LH\textsubscript{1}’; slight heating due to muon scattering in vessel windows.
- ‘Full LH\textsubscript{1}’ and ‘LH\textsubscript{T}’ cases demonstrate emittance reduction, a clear signal of ionization cooling.

Cooling effect increases with initial emittance, as expected from ionization cooling equation (1).

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REFERENCES


Figure 2: (top) Position and (bottom) momentum distributions of (a) upstream and (b) downstream tracks in (left) x and (right) y for 140 MeV/c beam crossing the LH\textsubscript{1} absorber (measured at tracker plane closest to the absorber). Good agreement observed between data and simulation.

Figure 3: Comparison between (black) unmatched betatron function of parent beam and (green) improved optics of a beam sampled from parent, using a rejection sampling algorithm tuned to matched optics in upstream absorber. Good agreement between (dots) data and (line) simulation observed at tracker stations.

Figure 4: Emittance change between upstream and downstream tracker reference planes as function of beam emittance at the upstream tracker (TKU). Comparisons between (top) circles ‘LH\textsubscript{T}’ and (triangles) ‘No absorber’ and (bottom) circles ‘Full LH\textsubscript{1}’ and (triangles) ‘Empty LH\textsubscript{1}’ cases indicate cooling in presence of an ionizing material. Good agreement between (blue) data and (red) simulation is observed. The solid lines represent an approximate theoretical calculation.