Transverse Emittance Change and Canonical Angular Momentum Growth in MICE

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The MICE Apparatus
MICE was designed to observe and study muon ionization cooling in a tertiary muon beam (Fig. 1)
- Track reconstruction gives position and momentum of muons upstream (US) and downstream (DS) of absorber
- Muon beam constructed as ensemble of individually measured particles
- Data collected over range of input-beam emittance for various absorber configurations:
  - 22-L liquid hydrogen vessel (LH$_2$) in empty and full states
  - 65 mm lithium hydride disk (LH$_2$)
  - Empty drift space (no absorber)

Event Selection
- Single track US and no more than one track DS
- Time-of-flight (TOF) consistent with 140 +/- 5 MeV/c muon
- Tracks contained within fiducial volume
- Good chi-squared per degree of freedom for track reconstruction

Canonical Angular Momentum Growth

![Diagram of MICE layout](Fig. 1 – MICE layout: (red) magnet coils, (blue) tracker stations, time-of-flight (TOF) detectors, Cherenkov (Clov) detectors, lead-scintillator sandwich (KL) detector, Electron-Muon Ranger (EMR))

**Observation of Cooling**
- 4D normalised transverse emittance of a beam, \( \epsilon_{4D} \), calculated from determinant of covariance matrix, \( \Sigma \), in \( x, p_x, y, p_y \)
  \[ \epsilon_{4D} = \sqrt{\det(\Sigma)} \]
- Single-particle amplitude at \( p = (x, p_x, y, p_y) \) defined as
  \[ A_\perp = \epsilon_{4D} (p - \bar{p})^T \Sigma^{-1} (p - \bar{p}) \]
  with \( \bar{p} \) the centre of the distribution
- Estimates emittance of a beam characterised by ellipse passing through point \( p \)
- Cumulative amplitude distributions, integrated from zero, display particle migration in phase-space and density change in the beam’s core
- Increase (decrease) of small (large) amplitudes DS relative to US implies cooling: DS/US Ratio > 1. Opposite effect shows heating (Fig. 4)
  - 4 mm \( \approx \) equilibrium emittance – neither heating nor cooling observed
  - 3 mm beam: heating observed
  - 6 mm and 10 mm beams: cooling observed

**Solenoid Mode** vs **‘Flip Mode’**
MICE cooling operation in both ‘Solenoid’ and ‘Flip’ modes (Fig. 2)
- Solenoid mode: on-axis magnetic field points in same direction throughout channel
- Flip mode: field reverses direction across absorber

Due to energy loss within absorber, angular momentum induced by radial field in solenoid fringe US is not cancelled DS \( \rightarrow \) 2 choices:
- Alternate field direction at every absorber in channel – costly, but prevents build-up of canonical angular momentum & improves cooling performance [1,2], or
- Flip field only occasionally, solenoid mode elsewhere

MICE has demonstrated ionization cooling in flip mode [3], talk 53, poster 54; cooling performance in solenoid mode presented here

References
1. M. Bogomilov et al., Lattice design and expected performance of the Muon Ionization Cooling Experiment
4. M. Bogomilov et al., Demonstration of cooling by the Muon Ionization Cooling Experiment, Nature 578 (2020) 53