Canonical Angular Momentum Growth in MICE ‘Solenoid Mode’ with Muon Ionization Cooling

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On behalf of the MICE collaboration
The principle of ionization cooling

- Competition between:
  - \( \frac{dE}{dx} \) [cooling]
  - MCS [heating]

Requires compact magnetic lattice

- Optimum:
  - Low \( Z \), large \( X_0 \)
  - Tight focus / large acceptance
  - \( H_2 \) gives best performance
• Ionization cooling essential:
  – Gives $x2-3$ in $\mu$/proton
Angular momentum

Entering solenoid, muons get a “$pt$ kick” proportional to radial position:

Angular momentum

Leaving solenoid, muons get a smaller kick ...

1. Flip/solenoid mode lattice performance may differ
2. Need to study performance of solenoid mode
Cooling Channel Lattice

- Spectrometer solenoids upstream and downstream provide uniform 2-4 T field for SciFi trackers / detector systems
- Focus coil module provides tight focussing on absorber
- Can flip field polarity across absorber, prevents canonical angular momentum buildup
Amplitude

- Transverse amplitude is distance of muon at point \( p = (x, p_x, y, p_y) \) from beam core in phase-space
  - Normalise phase space to RMS beam ellipse
- Related to transverse emittance by
  \[
  A_{\perp} = \epsilon_{\perp} (p - \bar{p})^T \Sigma^{-1} (p - \bar{p}),
  \]
  with \( \Sigma = 4D \) covariance matrix

- Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread, reducing amplitude
- Mean amplitude \( \langle A_{\perp} \rangle \sim \text{RMS emittance} \)

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Amplitude Change Across Absorber

- No absorber → similar number of core muons
- With absorber → increase in number of core muons
  - Cooling signal
- Decrease in core muons for 3mm beam

140 MeV/c data

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Ratio of core densities

- Ratio of downstream over upstream CDFs
- Core density increase for LH$_2$ & LiH absorbers $\rightarrow$ cooling
- More cooling at higher emittances
- Heating for 3mm beam

140 MeV/c data

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Canonical Angular Momentum Growth

- $L_{\text{canon}} \approx xP_y - yP_x + \frac{qr^2B_z}{2}$ (to first order)
- No absorber case shows little change
- Bias in canonical angular momentum distribution with LiH and LH$_2$

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Conclusions

- Ionization cooling measured in solenoid mode
  - Simulation gives good description of data
- MICE cooling demonstration encompasses:
  - A variety of solenoid- and flip-mode optical set-ups
  - A range of beam momentum and emittance
  - Two absorber types (liquid hydrogen, lithium hydride)
- Solid demonstration of ionization cooling principle
- Foundations for development of 6D-cooling demo