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

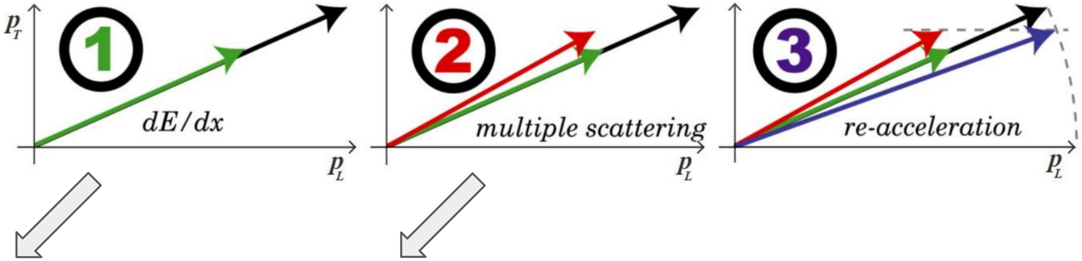
Paul Bogdan Jurj
Imperial College London
On behalf of the MICE collaboration

24/05/2021 IPAC Poster Session

Ionization cooling

- High brightness muon beams essential for development of facilities such as Neutrino Factory and Muon Collider
- Muons typically produced via pion decay ➞ diffuse beam; difficult to characterize and manipulate
- IONIZATION COOLING: proposed technique to reduce muon beam phase-space volume (emittance)

- Beam momentum spread reduced via energy loss in an absorber material



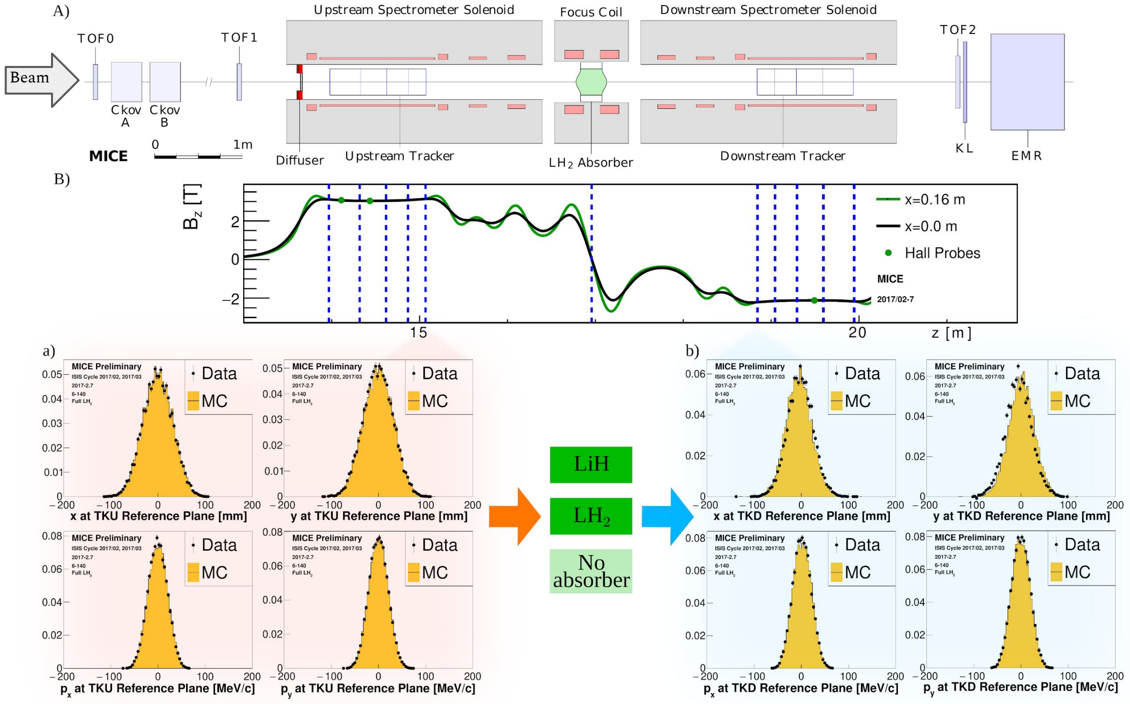
- Emittance evolution described by the cooling equation:

$$\frac{d\varepsilon_\perp}{dz} \simeq -\frac{1}{\beta^2}\frac{\varepsilon_\perp}{E_\mu}\left|\frac{dE_\mu}{dz}\right| + \frac{\beta_\perp(13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2}\frac{1}{X_0}. \quad (1)$$

- Cooling performance increased by using low Z, high radiation length materials and tightly focusing the beam at the absorber (low $\beta_\perp$)

MICE Cooling Apparatus

- Muon beam tightly focused using 12 superconducting solenoids
- Field polarity flipped at absorber: prevents canonical angular momentum increase
- Phase space measured before (B_z = + 3 T) and after (B_z = - 2 T) absorber
- Absorbers: liquid hydrogen (LH_2) and lithium hydride (LiH)
- First cooling results presented by Chris Rogers in Talk ID 2627 (Program Code FRXB05)



First demonstration of cooling published in Nature **578** (2020) 53, doi: 10.1038/s41586-020-1958-9

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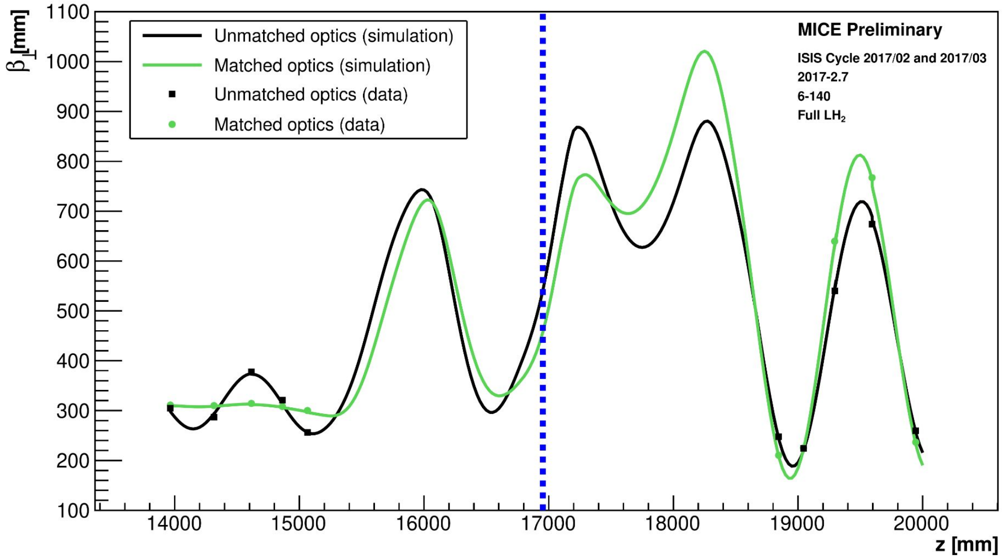
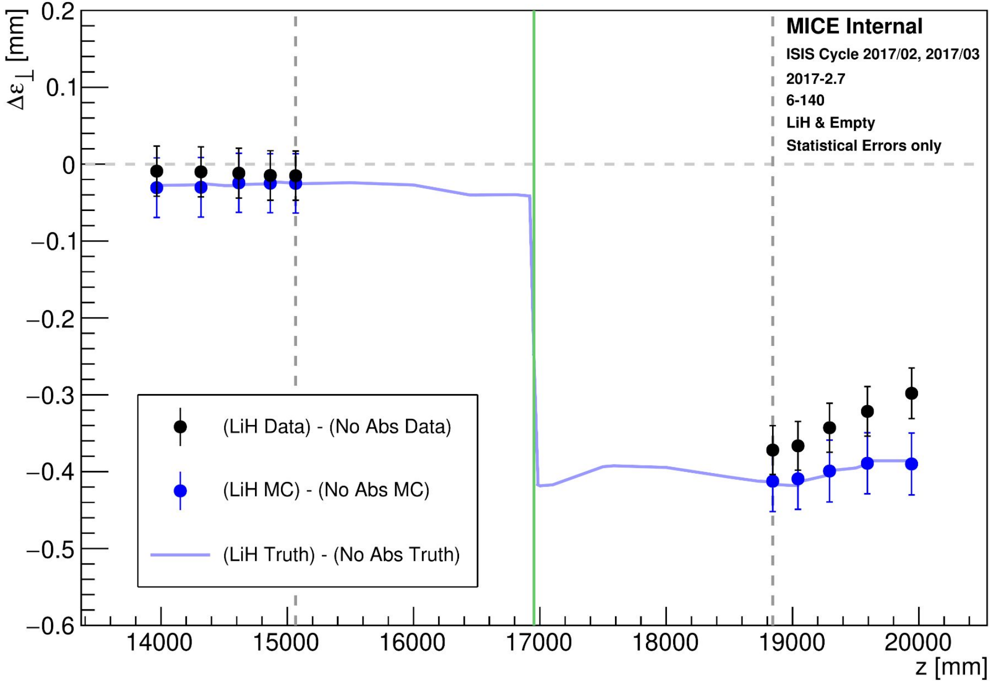
Beam Sampling

- Rejection sampling employed to select beams with matched optics in the upstream tracker
- Good matching performance achieved in both Data and Simulation
- The transverse betatron function at the absorber is reduced, beam experiences less heating due to multiple scattering



Emittance evolution in the MICE Cooling Channel

- Selected Data and Simulation (MC) beams with ~ 4.5 mm emittance at the upstream tracker reference plane
- Evolution of beam emittance in the presence of the ‘LiH’ absorber, normalized by the emittance in the ‘No absorber’ case is shown
- Ionization cooling signal observed in Data and MC, supported by Truth simulation
- Slight offset from 0 in upstream tracker due to limited sampling accuracy

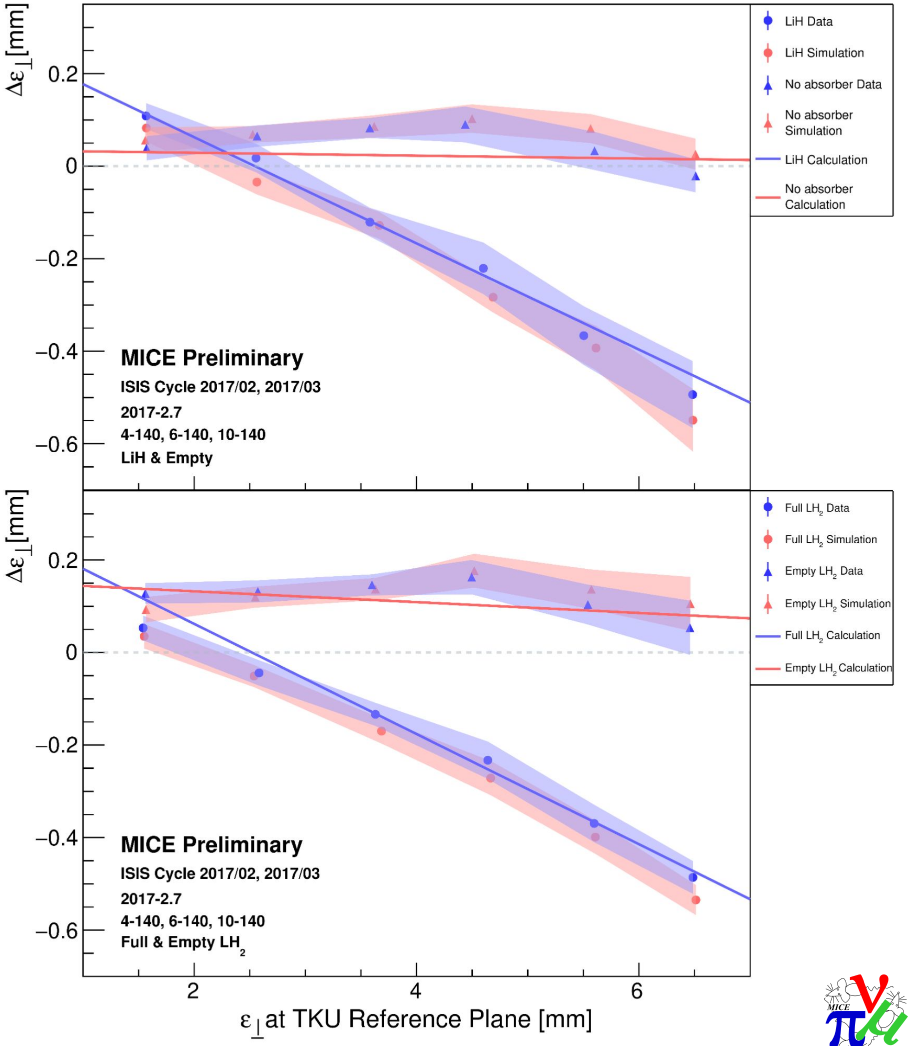


Emittance reduction

- Emittance change:

$$\Delta\varepsilon_\perp = \varepsilon_{\perp downstream} - \varepsilon_{\perp upstream}$$

- $\Delta\varepsilon_\perp < 0$ ➡ **COOLING**
- Data: 140 MeV/c input momentum with $\varepsilon_{\perp,\,input}$ = 4, 6, 10 mm
- Rejection sampling: beams with optimized optics to reduce heating
- 'No absorber' - weak heating due to optical aberrations
- 'Empty LH_2' - weak additional heating due to hydrogen vessel windows
- 'Full LH_2' and 'LiH' demonstrate emittance reduction (ionization cooling)
- Approximate theory: analytical estimate of cooling effect
- Good agreement between Data / Simulation / Approximate theory



Canonical angular momentum change

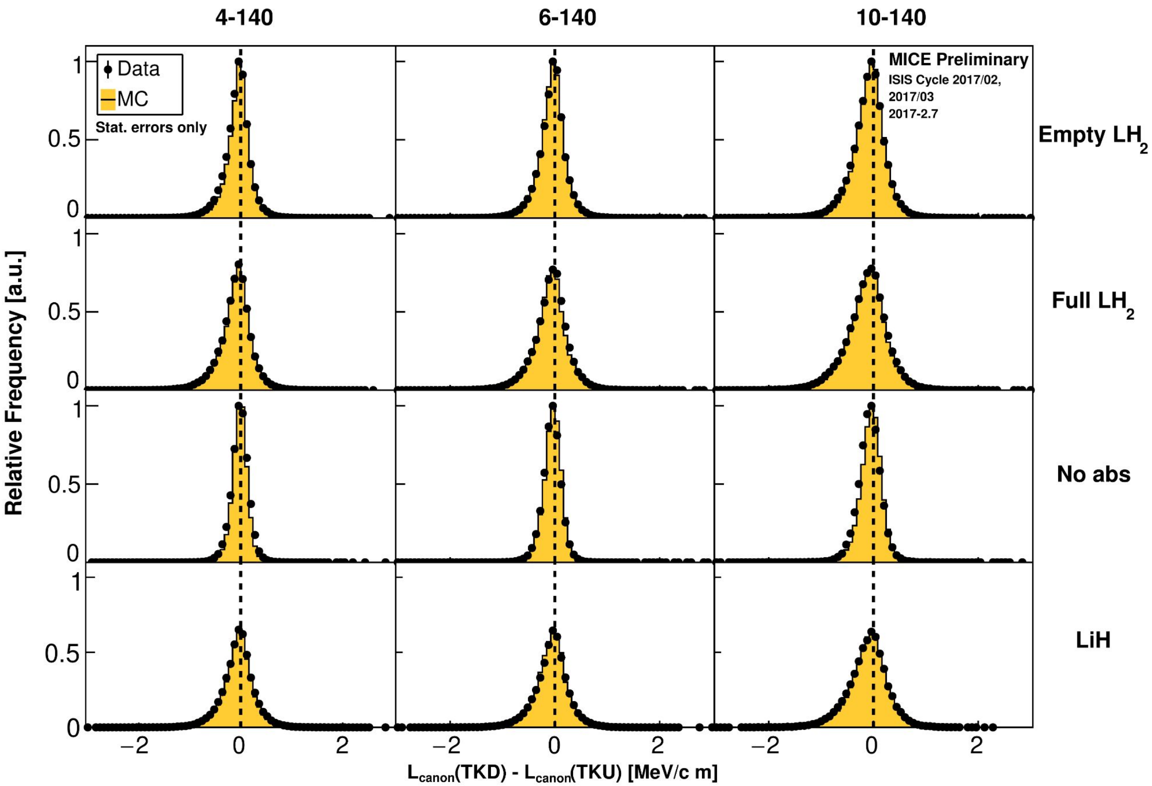
$$\Delta L_{canon} = L_{canon}^{downstream} - L_{canon}^{upstream}$$

$$L_{canon} = L_{kin} + L_{field}$$

$$L_{kin} = xp_y - yp_x$$

$$L_{field} = qrA \approx \frac{qr^2 B_z}{2}$$

- No net mean change observed between the ‘empty’ and ‘absorber’ cases, as expected for a flipped field configuration
- In contrast to the ‘Solenoid mode’, where a net increase is observed, as shown by Tom Lord in Poster ID 2634 (Program Code WEPAB277)



Thank you!