Muon Ionization Cooling Demonstration by Normalized Transverse Emittance Reduction 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]; further cooling performance analyses are presented here (flip) and in poster 56 (solenoid).

IONIZATION COOLING

- Rate of change of normalized transverse emittance due to ionization cooling reads:

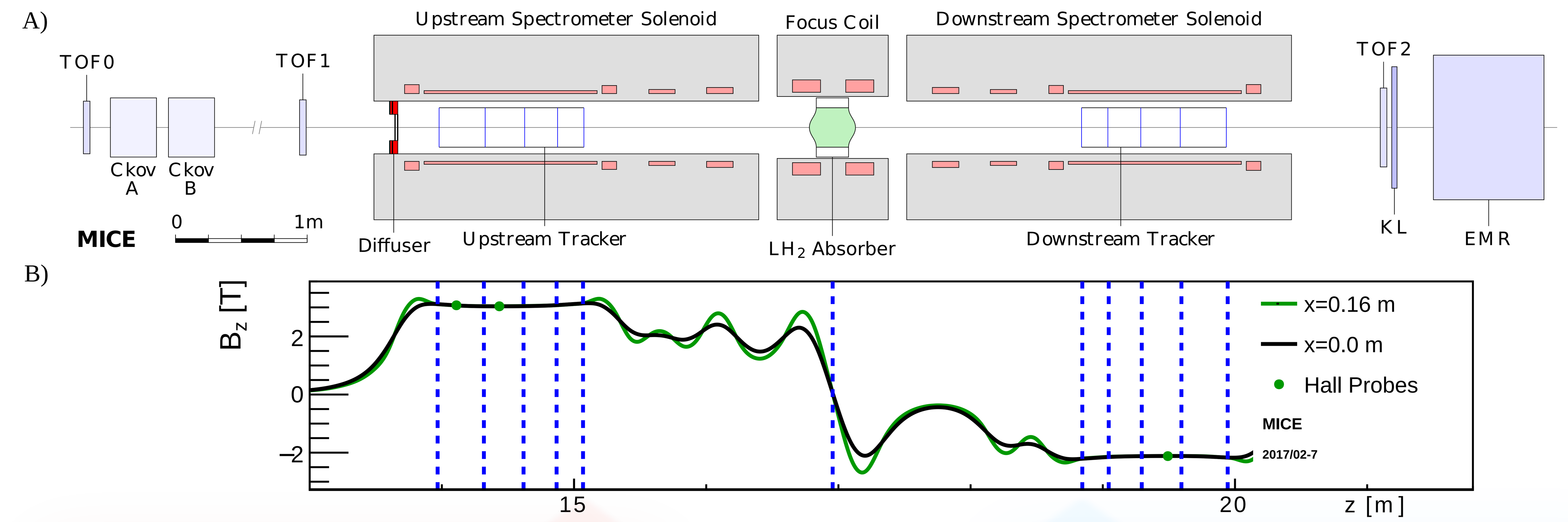
$$\frac{d\varepsilon_\perp}{dz} \simeq -\frac{1}{\beta^2}\frac{\varepsilon_\perp}{E_\mu}\left|\frac{dE_\mu}{dz}\right| + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2}\frac{1}{X_0}. \quad (1)$$

- (blue) Cooling realized via energy loss, (red) heating due to Coulomb scattering. Heating reduced by using low Z materials and minimizing $\beta_\perp = (\langle x^2\rangle + \langle y^2\rangle)/\varepsilon_\perp$.

COOLING APPARATUS

- The cooling channel (Fig. 1 A) - 12 solenoid magnets that could be individully 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')
  - 22 l liquid hydrogen vessel ('LH_2', empty & full)
  - 65 mm lithium hydride disk ('LiH')
  - a polyethylene wedge (not used in this study)

Figure 1: (A) Schematic layout of MICE cooling channel. Magnet coils shown in red, absorber in green and various detetectors are individually marked. (B) Modelled on-axis magnetic field along cooling channel (black 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.



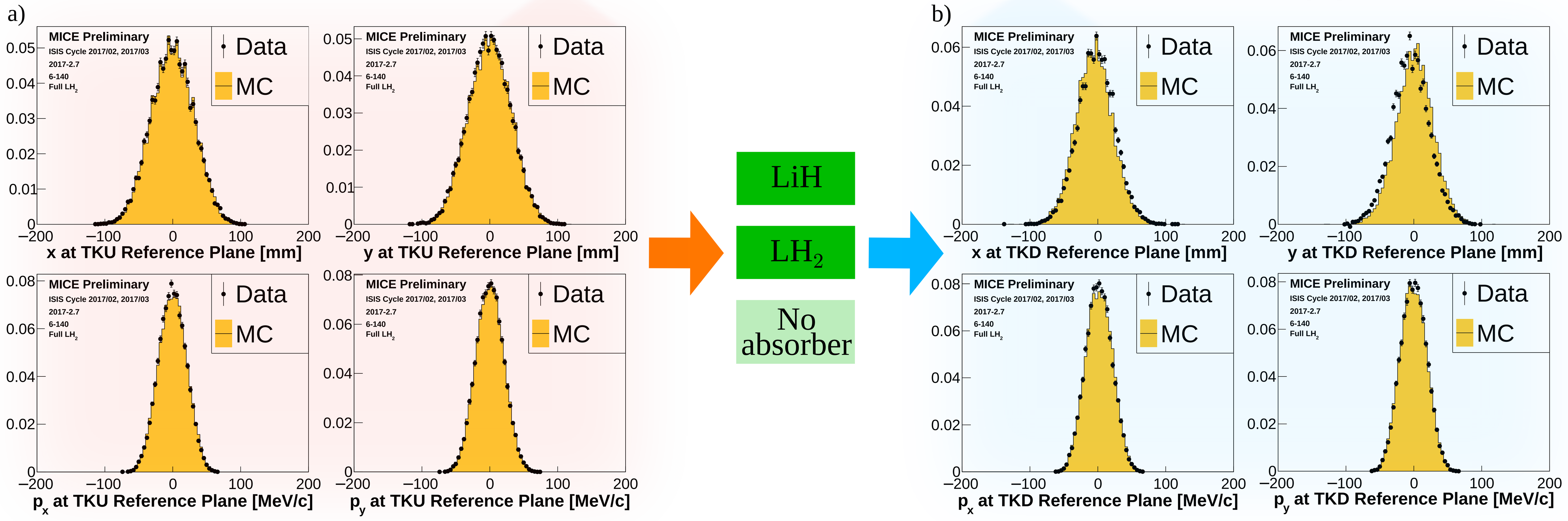


Figure 2: (top) Position and (bottom) momentum distributions of (a) upstream and (b) downstream tracks in (left) x and (right) y for 140 MeV/c beam crossing LH_2 absorber. (Measurement performed at tracker planes closest to absorber.) Good agreement observed between data and simulation; slight discrepancy in position downstream believed to be caused by slight magnet misalignment in simulation model (currently under investigation).

RECONSTRUCTION

- The 4-dimensional normalized transverse emittance, a measure of beam phase space volume, is calculated as:

$$\varepsilon_\perp = \frac{1}{m_\mu}\sqrt[4]{|\Sigma|}\ , \quad (2)$$

where the covariance matrix Σ is defined as:

$$\Sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xp_x} & \sigma_{xy} & \sigma_{xp_y} \\ \sigma_{p_x x} & \sigma_{p_x p_x} & \sigma_{p_x y} & \sigma_{p_x p_y} \\ \sigma_{yx} & \sigma_{yp_x} & \sigma_{yy} & \sigma_{yp_y} \\ \sigma_{p_y x} & \sigma_{p_y p_x} & \sigma_{p_y y} & \sigma_{p_y p_y} \end{pmatrix}. \quad (3)$$

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

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 $\beta_\perp$.

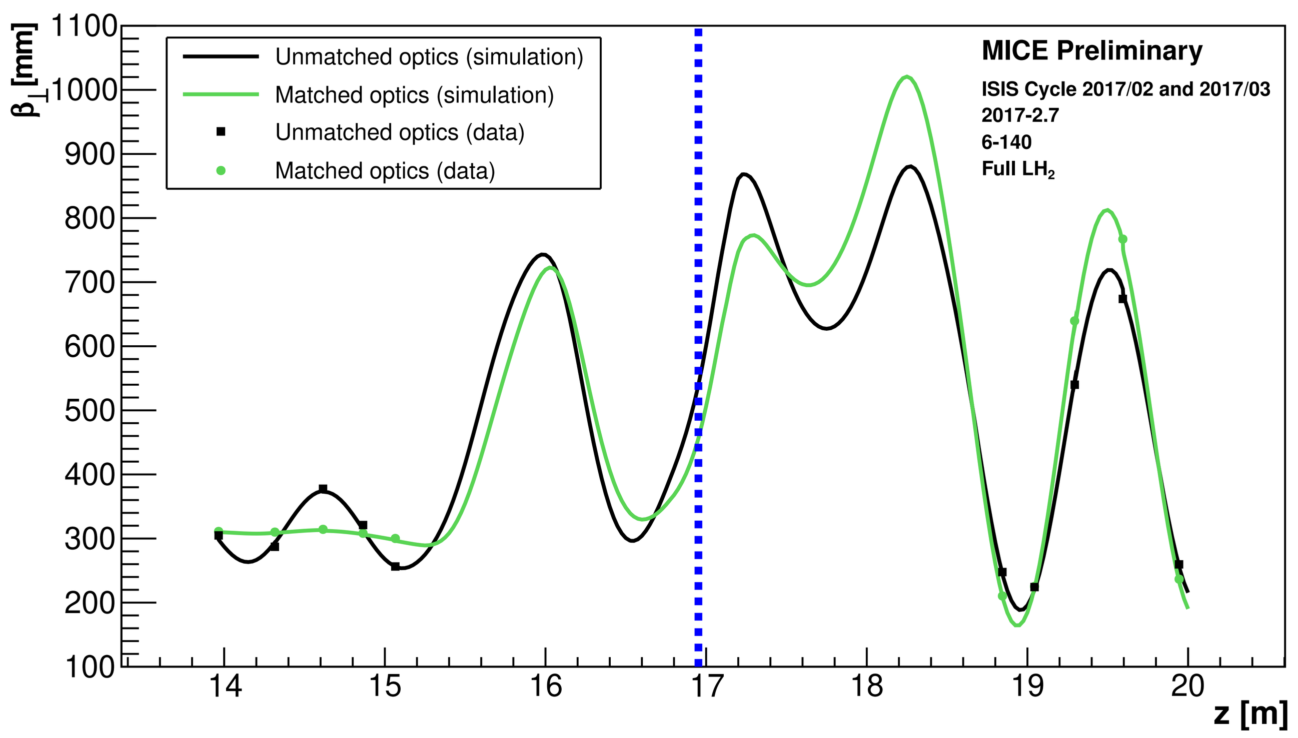


Figure 3: Comparison between (black) unmatched betatron function of parent beam and (green) improved optics of a beam sampled from parent, using a rejection sampling algorithm tuned to match beam optics in upstream tracker. Good agreement between (dots) data and (line) simulation observed at tracker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

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EMITTANCE REDUCTION

- $\Delta\varepsilon_\perp = \varepsilon_{\perp downstream} - \varepsilon_{\perp upstream}$
- $\Delta\varepsilon_\perp < 0$ → COOLING (Fig. 4)
- 'No absorber': no significant emittance change observed.
- 'Empty LH_2': slight heating due to muon scattering in vessel windows.
- 'Full LH_2' and 'LiH' cases demonstrate emittance reduction, a clear signal of ionization cooling.
- Cooling effect increases with initial emittance, as expected from ionization cooling equation (1).

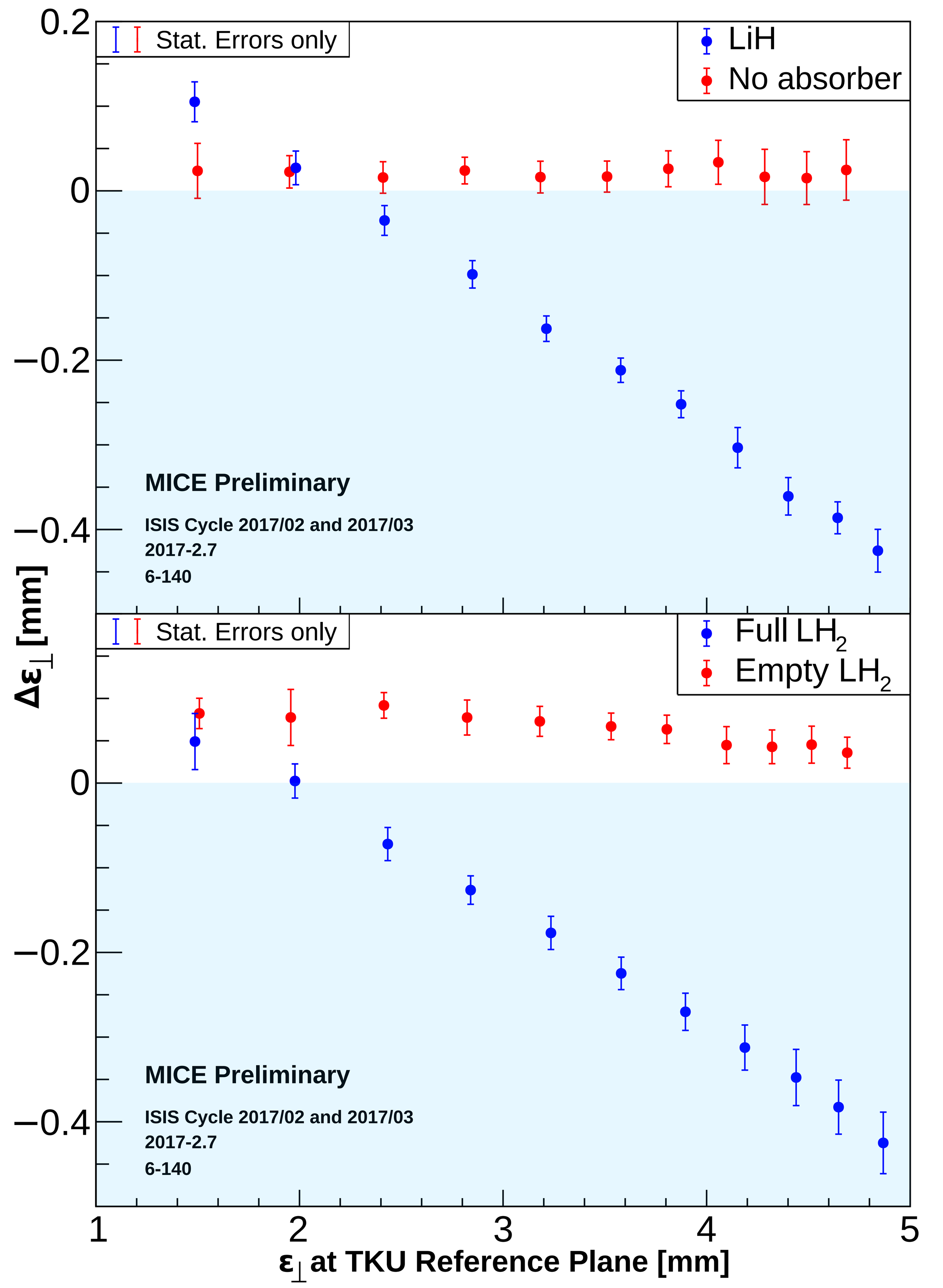

Figure 4: Absolute emittance change between upstream and downstream tracker reference planes as function of beam emittance at upstream tracker (TKU) for beams with nominal input momentum of 140 MeV/c. Comparisons between (top) 'LiH' and 'No absorber' data and (bottom) 'Full LH_2' and 'Empty LH_2' vessel data indicate cooling in presence of an ionizing material. Correction applied to account for detector resolution. Systematic errors - work in progress.

REFERENCES

[1] M. Bogomilov et al., Demonstration of cooling by the Muon Ionization Cooling Experiment, Nature 578 (2020) 53