Transverse Emittance Change in MICE 'Solenoid Mode' with Muon Ionization Cooling

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On behalf of the MICE Collaboration

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 (LiH)
  - 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

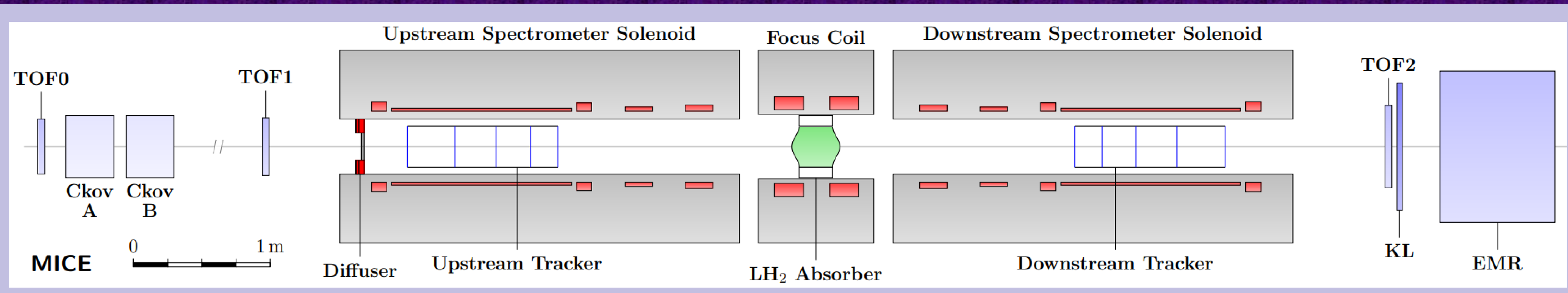
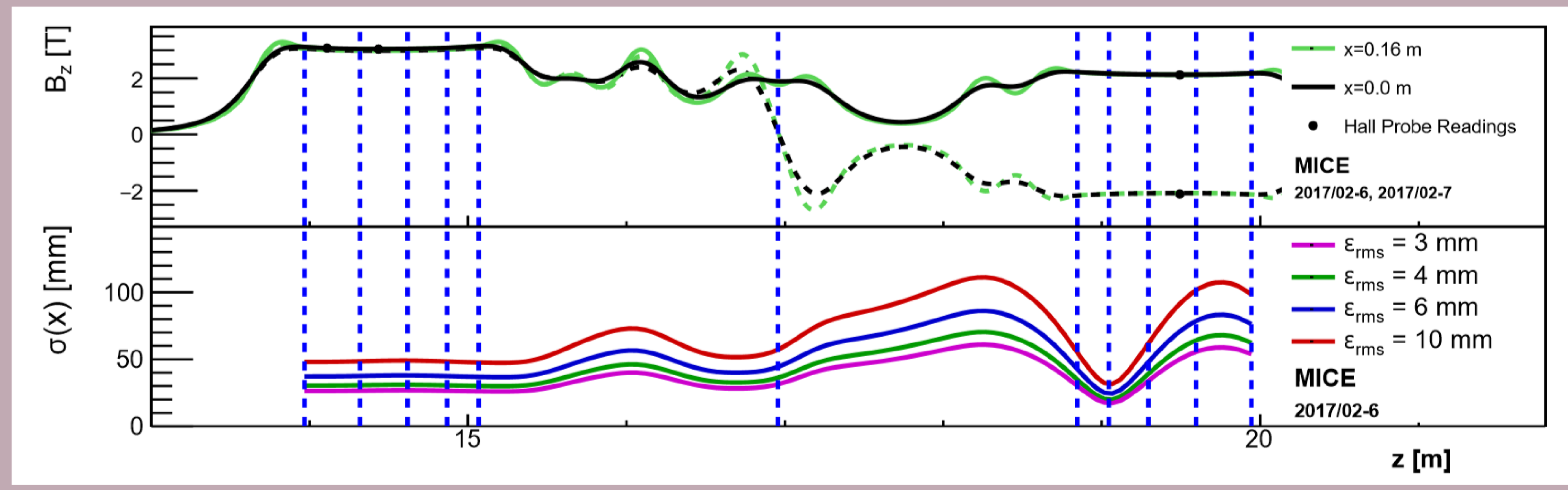


Fig. 1 – MICE layout: (red) magnet coils, (blue) tracker stations, time-of-flight (TOF) detectors, Cherenkov (Ckov) detectors, lead-scintillator sandwich (KL) detector, Electron-Muon Ranger (EMR)

Fig. 2 – (top) z-component of solenoid field (B_z) vs z for (solid) 'solenoid' mode and (dashed) 'flip' mode; (bottom) beam envelope in x for four emittance values. Blue dashed lines indicate tracker station locations and absorber centre. Hall probes positioned at 0.16 m radial displacement.



'Solenoid Mode' vs 'Flip Mode'

MICE cooling channel operated in both 'Solenoid' and 'Flip' modes (Fig. 2)

- Solenoid mode: on-axis magnetic field points in same direction throughout channel
- Flip mode: field changes direction across absorber

Due to energy loss within absorber, angular momentum induced by radial field in solenoid fringe US is not cancelled DS → 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], analyses in posters 14, 16; cooling performance in solenoid mode presented here

Reconstructed position and momentum in data and MC agree (Fig. 3).

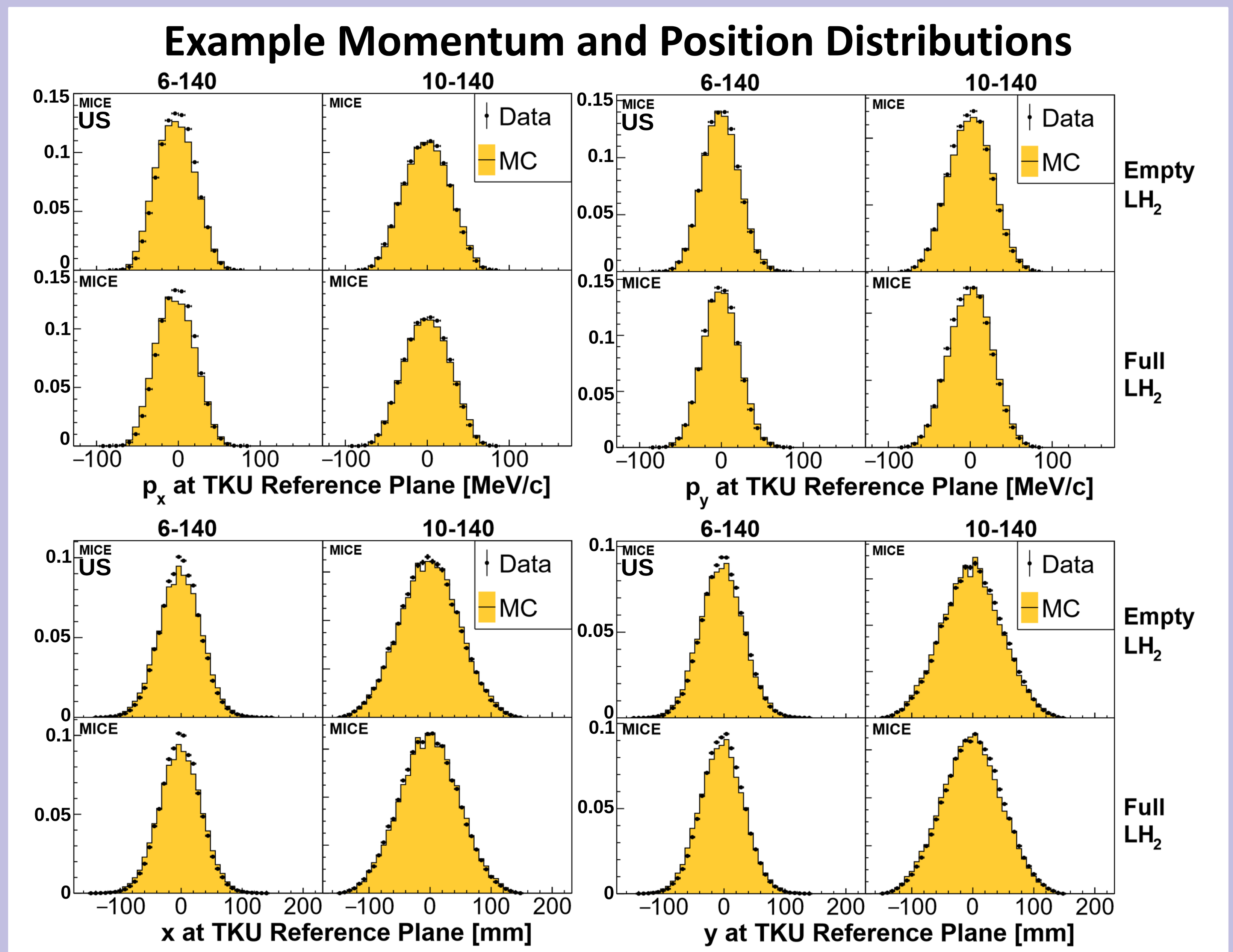


Fig. 3 – (top) Momentum and (bottom) position in (left) x and (right) y for LH_2-empty and -full at 6 and 10 mm emittances

Observation of Cooling

- 4D normalised transverse emittance of a beam, ϵ_{4D}, calculated from determinant of covariance matrix, Σ, in x, p_x, y, p_y as

$$\epsilon_{4D} = \frac{\sqrt[4]{|\Sigma|}}{m_\mu}.$$

- 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

Amplitude increase DS relative to US (DS/US Ratio >1) implies ***cooling***. Decrease shows ***heating*** (Fig. 4)

- 4 mm ≈ equilibrium emittance – neither heating nor cooling observed
- 3 mm beam: ***heating*** observed
- 6 mm and 10mm beams: ***cooling*** observed!

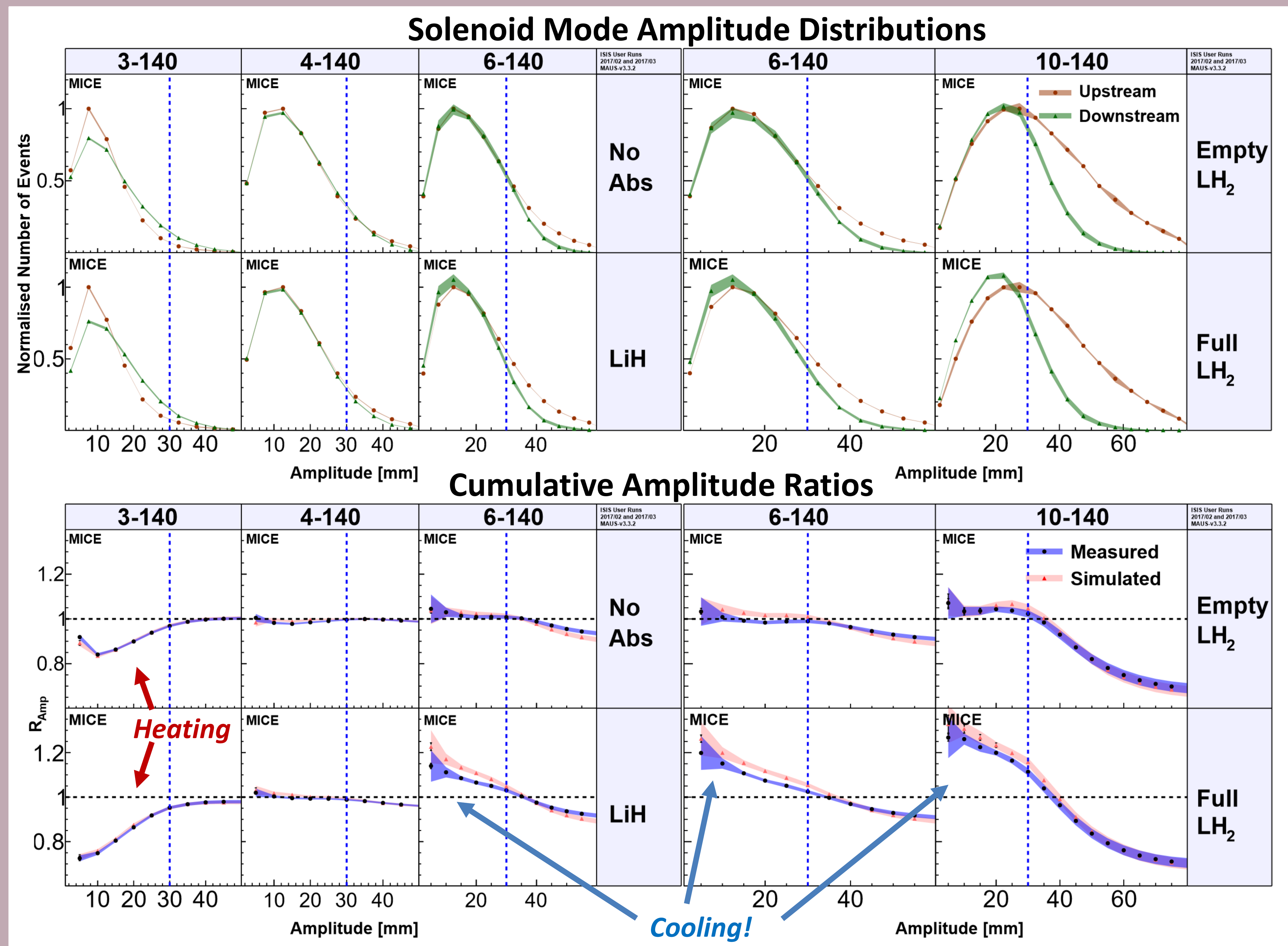


Fig. 4 – Normalised amplitude distributions for (top left) no absorber and LiH, (top right) LH_2 empty and LH_2 full, and (bottom) ratios of their corresponding cumulative distributions. Coloured bands show combined statistical and systematic errors

References

[1] M. Bogomilov et al., Lattice design and expected performance of the Muon Ionization Cooling Experiment demonstration of ionization cooling, Phys. Rev. Accel. Beams 20 (**2017**) 063501

[2] R. Fernow and R. Palmer, Solenoidal ionization cooling lattices, Phys. Rev. ST Accel. Beams 10 (**2007**) 06400

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