Transverse Emittance Change in MICE ‘Solenoid Mode’ with Muon Ionization Cooling

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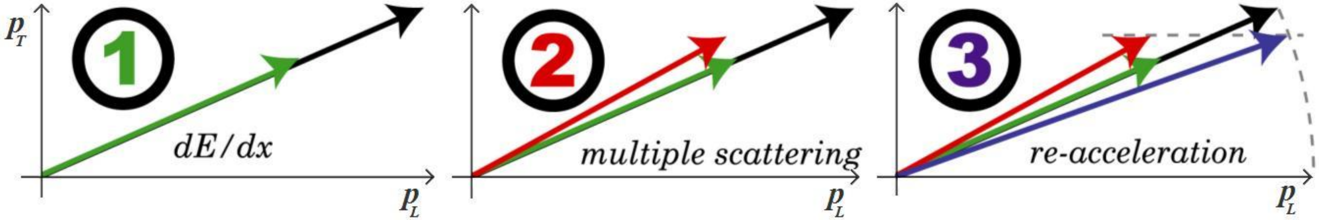
Muon Ionization Cooling at MICE

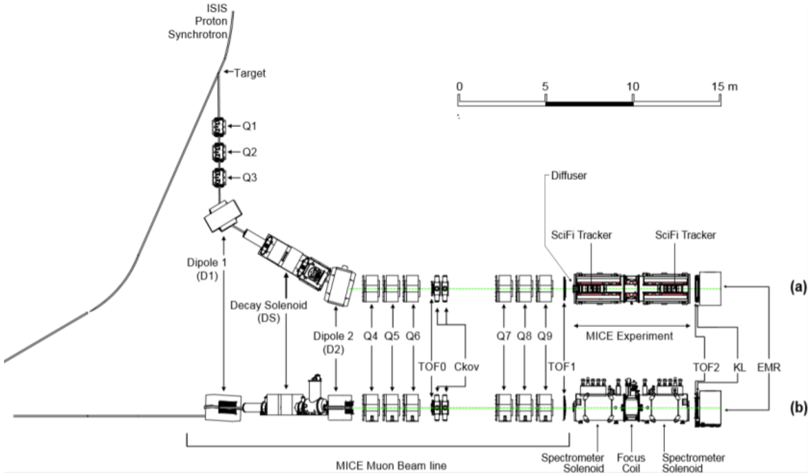


Emittance gives phase-space volume occupied by beam – volume conserved under Liouville's theorem

Emittance change (cooling/heating) in material follows:

$$\frac{d\epsilon_{4D}}{ds} \simeq -\frac{1}{\beta^2}\frac{\epsilon_{4D}}{E_\mu}\left|\frac{dE_\mu}{ds}\right| + \frac{\beta_{4D}(13.6\ \mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2}\frac{1}{X_0}.$$

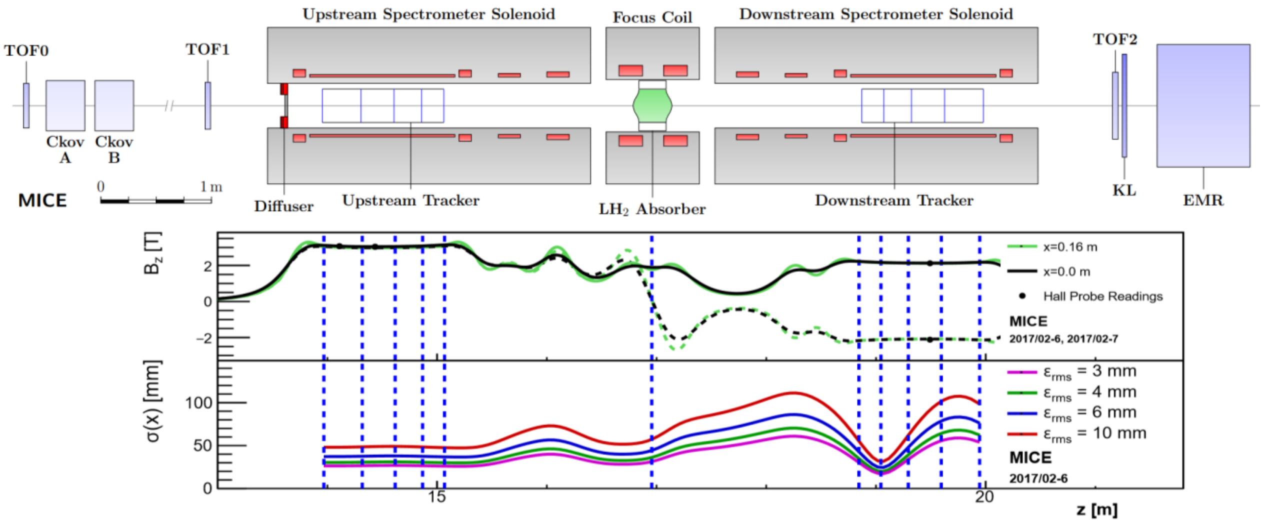
- Equilibrium emittance highly material dependant – desire low Z, high radiation length absorber
- Heating term $\propto \beta_{4D}$ → want strong focusing
- RF accelerating cavities restore momentum in longitudinal direction only



At MICE

- Tertiary muon beam from pion decays, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, with muon momenta 120 – 260 MeV/c
- Muon emittance spans 2 – 10 mm
- Liquid hydrogen (LH_2), lithium-hydride (LiH) absorbers
- Scintillating fibre trackers + TOFs provide particle momentum and position reconstruction

'Solenoid' vs 'Flip' Mode



2 magnetic field modes – 'Solenoid' (solid) & 'Flip' (dashed)

Solenoid

- Constant-sign B_z throughout - straightforward to implement
- Successive passes result in canonical angular momentum growth – negatively impacts cooling performance

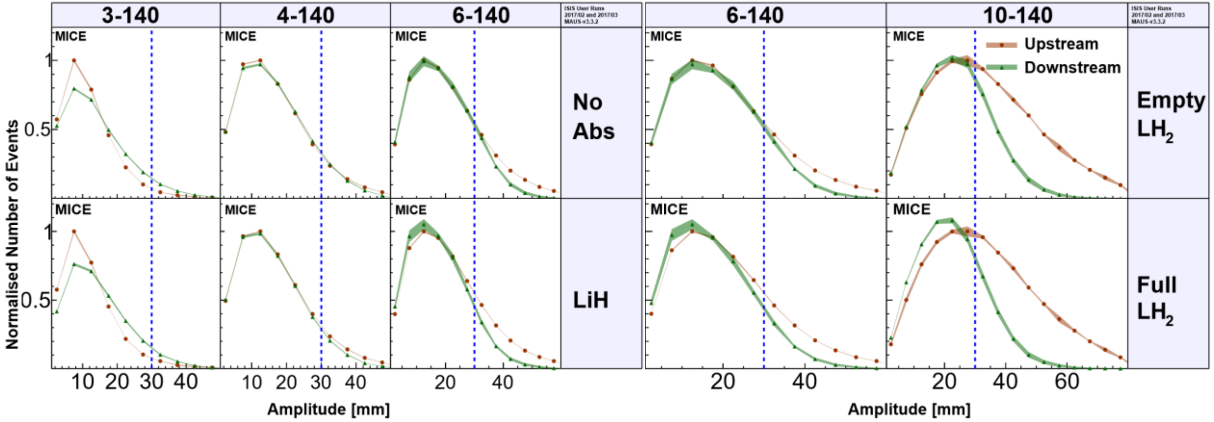
Flip

- Alternates field polarity across absorber, cancels canonical angular momentum build-up
- Field reversal throughout facility costly – can use 'flip' occasionally, 'solenoid' elsewhere

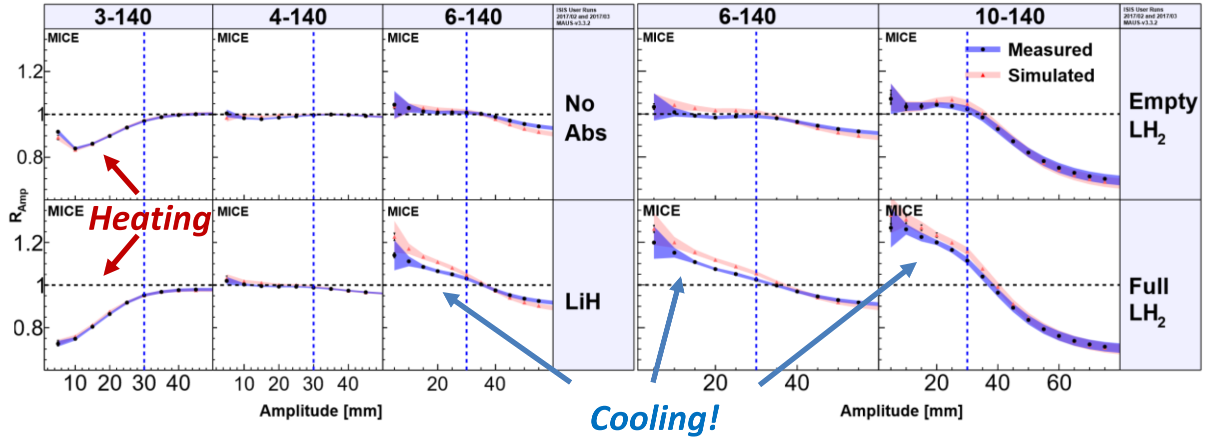
MICE has demonstrated ionization cooling in 'flip' mode - Nature 578 (**2020**) 53, doi: 10.1038/s41586-020-1958-9
This analysis presents solenoid mode cooling performance

Amplitude Analysis

Solenoid Mode Amplitude Distributions



Cumulative Amplitude Ratios



Transverse amplitude is distance of muon from beam core in phase-space

Related to transverse emittance by

$$A_{4D} = \epsilon_{4D}(p-\bar{p})^T\Sigma^{-1}(p-\bar{p}),$$

Transverse emittance

Normalised distance in phase-space

Cumulative distributions, integrated from zero, display particle migration in phase-space

Increase (decrease) of small (large) amplitudes downstream relative to upstream implies **cooling**: DS/US ratio > 1

Opposite effect shows **heating**