Analysis of MICE Data

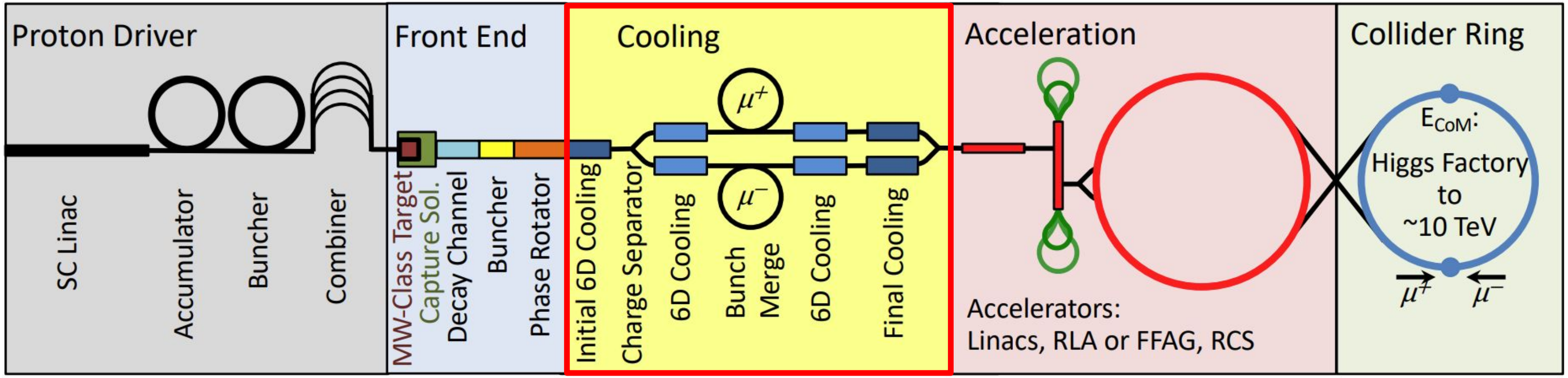
Paul Bogdan Jurj

Imperial College London

Sep 24, 2020

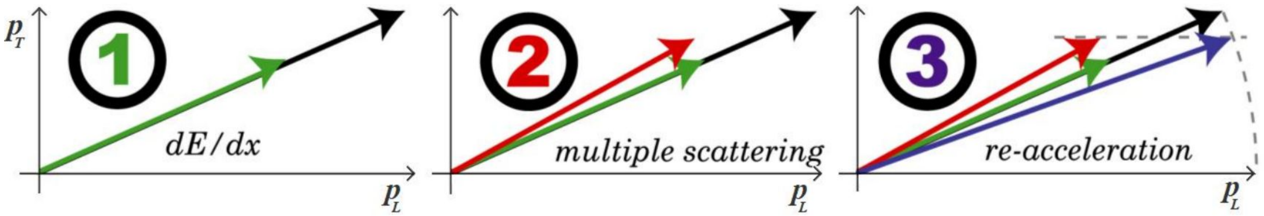
Muon Cooling Working Group Meeting

Muon Cooling



- In the proton driver scheme, muons produced at tertiary particles
- Large transverse and longitudinal emittances $\longrightarrow$ cooling required!
- Ionization cooling, the only technique fast enough

Ionization Cooling



- Energy loss in the absorbers reduces both p_L and p_T
- Multiple scattering heats the beam
- p_L restored using RF cavities; net effect is reduction of p_T, emittance (cooling)

Cooling equation:

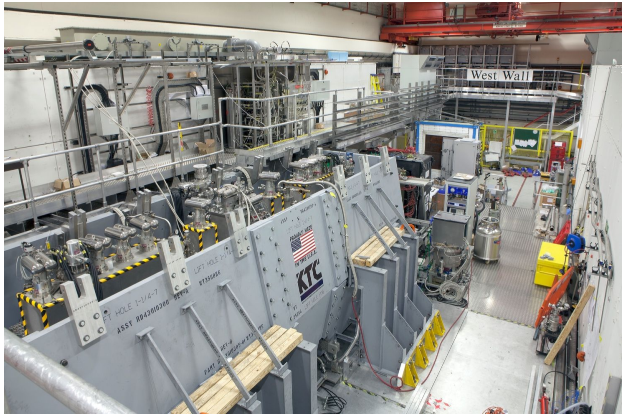
$$\frac{d\varepsilon_\perp}{dz} \simeq -\frac{1}{\beta^2}\frac{\varepsilon_\perp}{E_\mu}\left|\frac{dE_\mu}{dz}\right| + \frac{\beta_\perp (13.6\,\mathrm{MeV})^2}{2\beta^3 E_\mu m_\mu c^2}\frac{1}{X_0}$$

- Tight focusing, low Z & high radiation length absorber materials required

Paul Bogdan Jurj

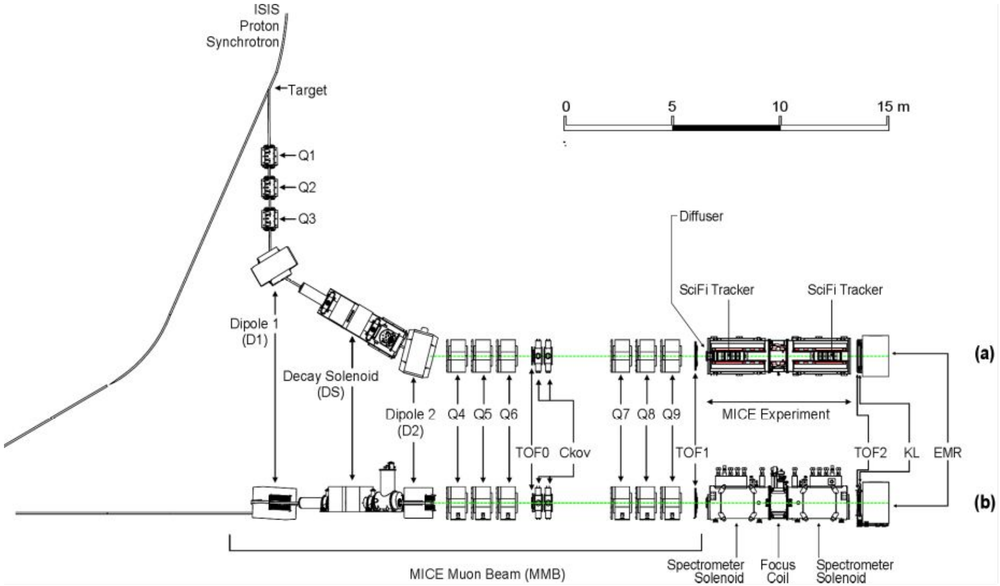
Muon Ionization Cooling Experiment

- MICE operated at Rutherford Appleton Laboratory in UK between 2008 and 2017
- Collaboration of over 100 members from 30 institutes in 10 countries
- It aimed to:
    - Demonstrate high acceptance, tight focusing solenoid lattice
    - Demonstrate integration of liquid hydrogen and lithium hydride absorbers
    - Validate details of material physics models
    - Demonstrate ionization cooling principle and amplitude non-conservation



Imperial College London

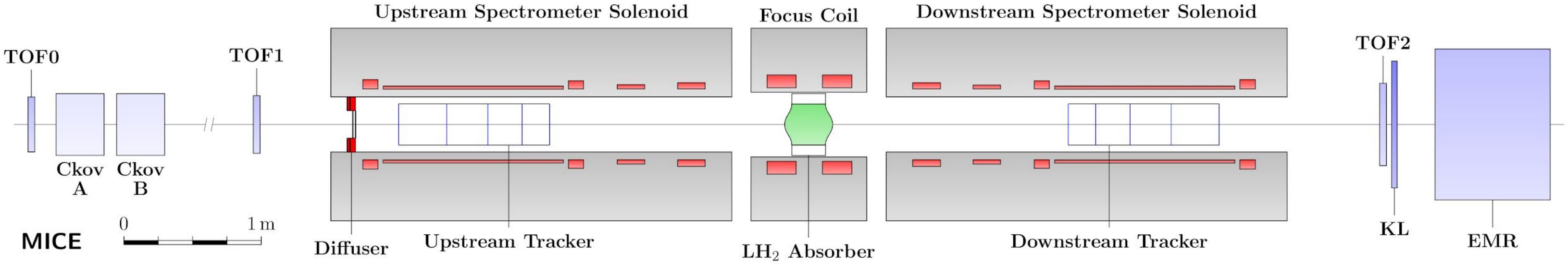
MICE Muon Beamline



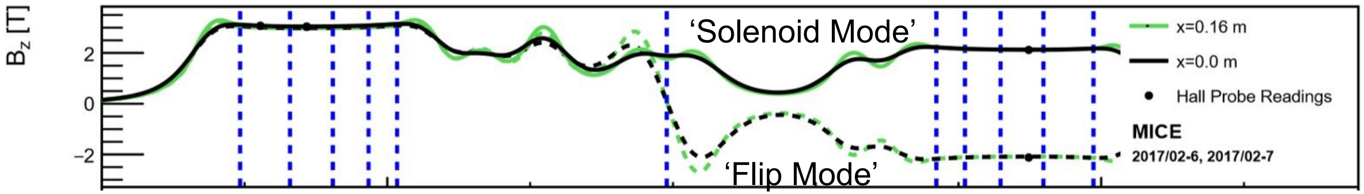
- Muon momenta: 120 - 260 MeV/c
- Muon emittance: 2 - 10 mm
- Pion impurity suppressed at up to 99 % level

Paul Bogdan Jurj

Cooling lattice



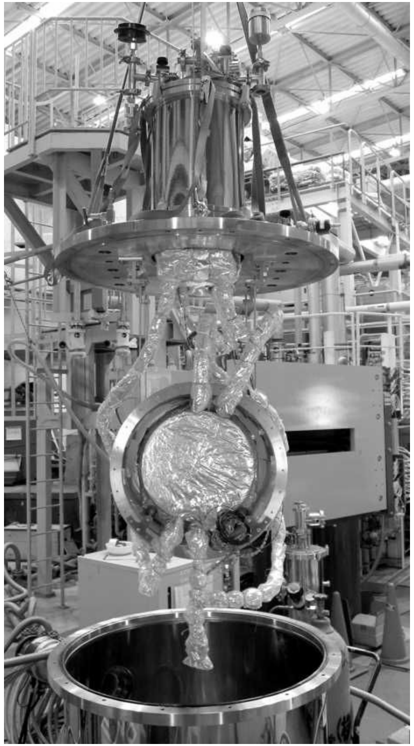
- Spectrometer solenoids provided uniform 2-4 T fields for the tracking systems; focus coil tightly focussed the beam at the absorber; option to operate with flipped polarity downstream to prevent canonical angular momentum build-up



Absorbers

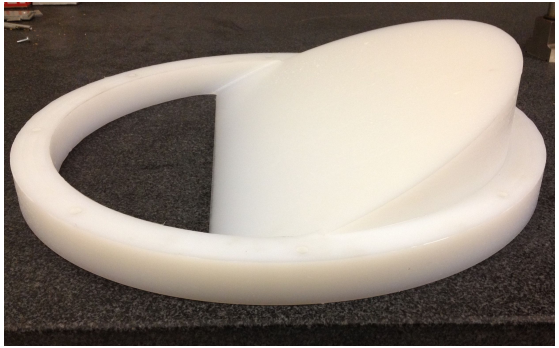
1. 65 mm thick lithium hydride absorber
2. 350 mm thick liquid hydrogen absorber
   - Contained in two pairs of 150-180 micron thick Al windows
3. 45° polythene wedge absorber for longitudinal emittance studies

2



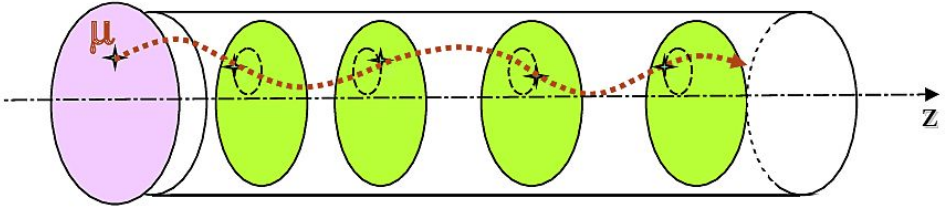
1

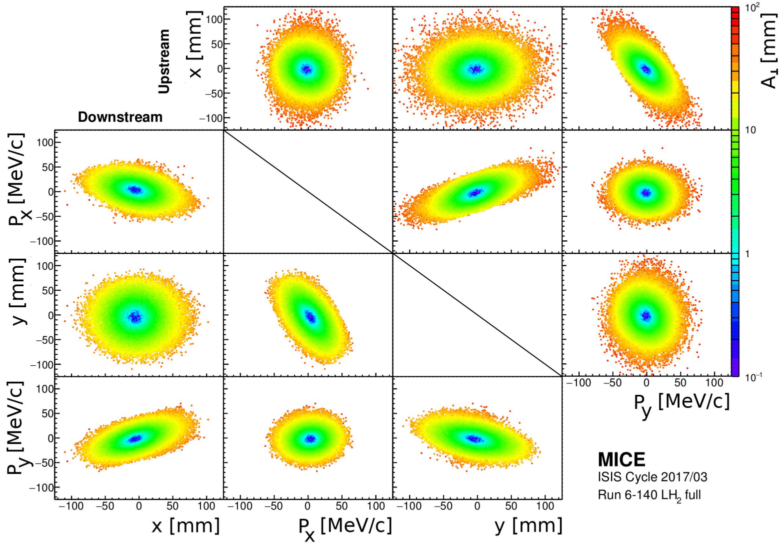
3



Scintillating Fibre Trackers

- Helical tracks in the spectrometer solenoids
- Particle positions measured by five stations of scintillating fibres
- Helix reconstruction provided 6D position - momentum measurement; **particle-by-particle**
- Particles accumulated into a beam ensemble





Cooling analysis - Amplitude

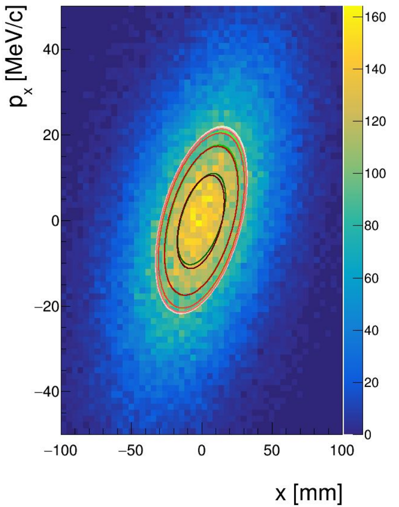
Amplitude is the distance between muon at u = (x, p_x, y, p_y) and the core of the beam:

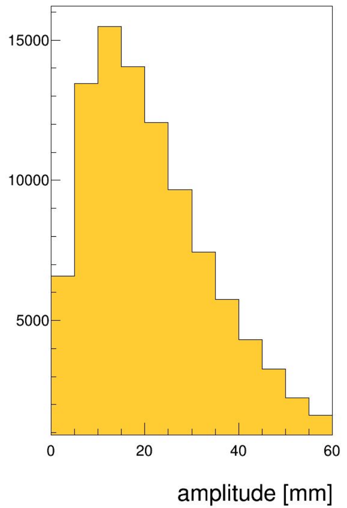
$$A_\perp = \varepsilon_\perp R^2(\mathbf{u}, \langle \mathbf{u} \rangle)$$

where R is the normalised distance in phase space:

$$R^2(\mathbf{u}, \mathbf{v}) = (\mathbf{u} - \mathbf{v})^T \mathbf{V}^{-1} (\mathbf{u} - \mathbf{v})$$

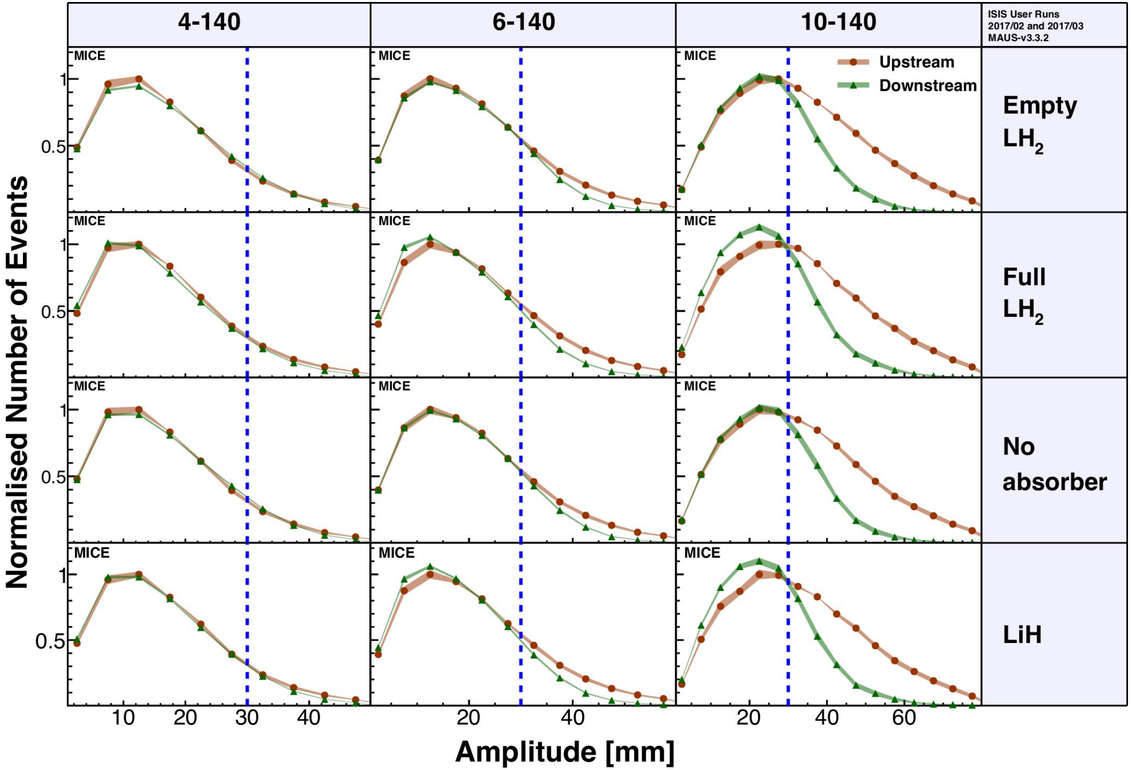
- Conserved quantity in normal accelerator lattices
- Ionization cooling reduces transverse momentum spread $\longrightarrow$ reduces amplitude
- $\langle A_\perp \rangle$ ~ RMS emittance





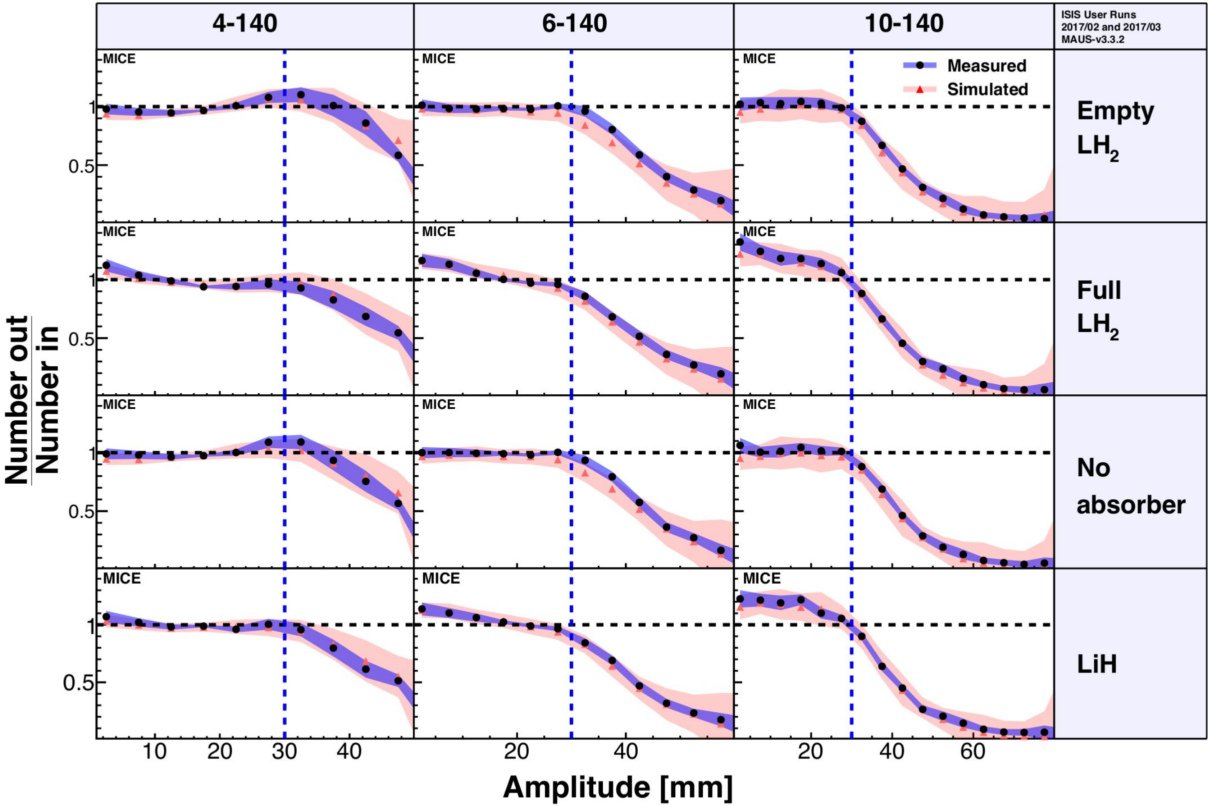
Amplitude change across the absorber - ‘Flip Mode’

- 140 MeV/c data
- No absorber - number of muons with low amplitude stays similar downstream
- With absorber - significant increase in number of core muons ⟶ cooling



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

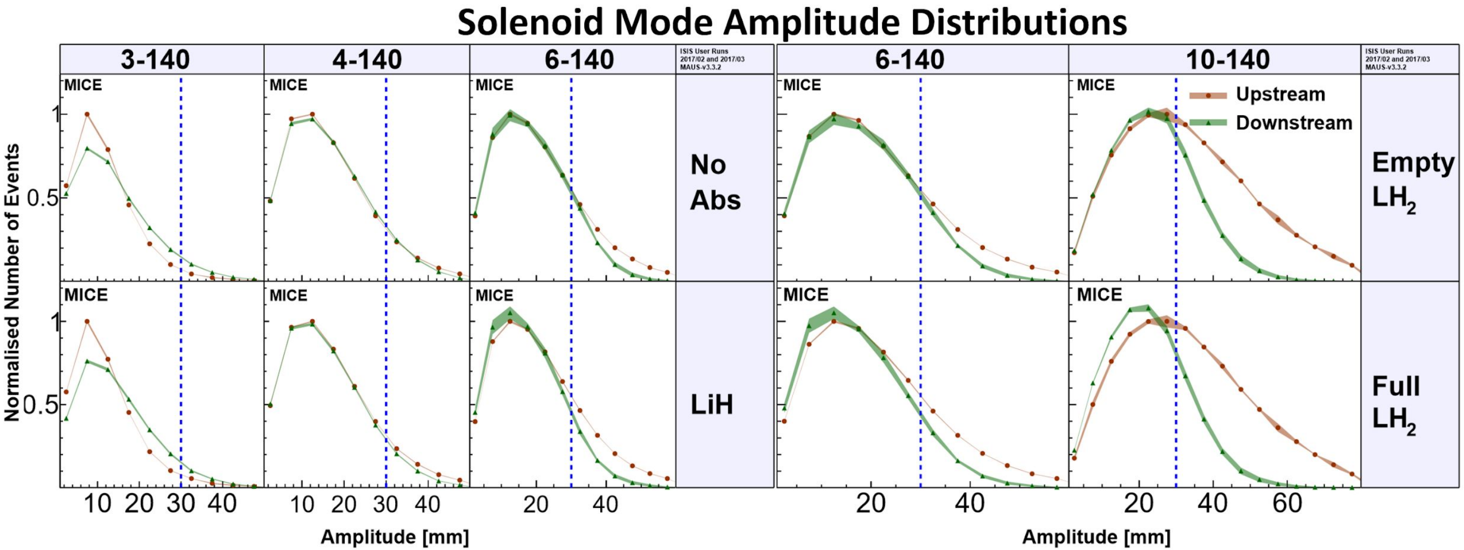
Ratio of core densities - ‘Flip Mode’



- Ratio of downstream and upstream CDFs
- 140 MeV/c data
- Core density increase for LH_2 and LiH absorbers ⟶ cooling
- More cooling at higher emittances

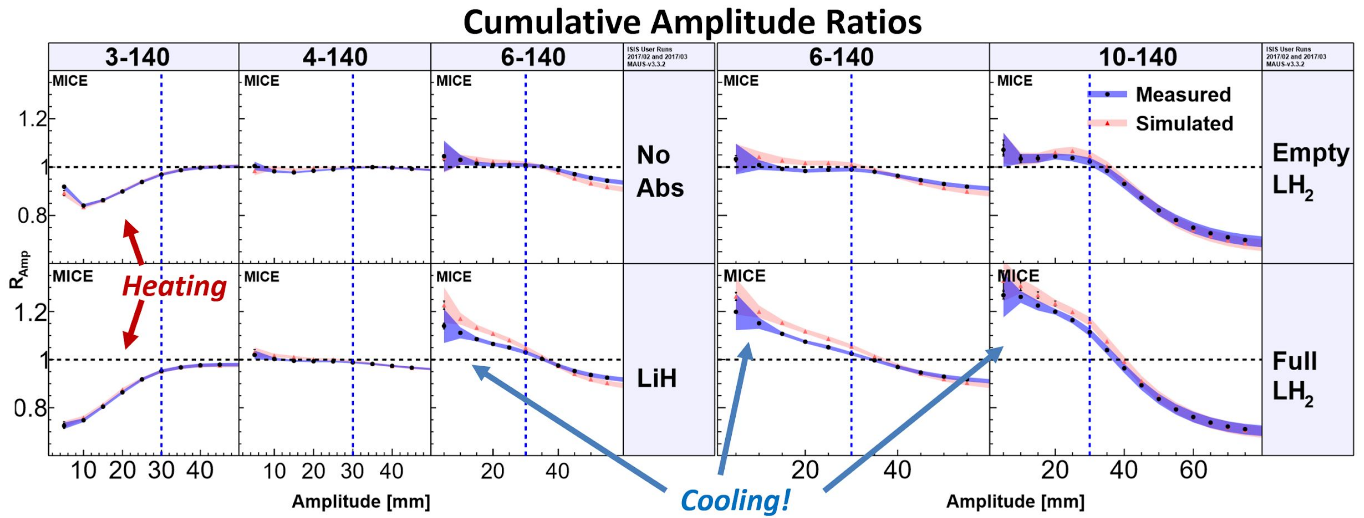
Paul Bogdan Jurj

Amplitude change across the absorber - ‘Solenoid Mode’



- 140 MeV/c data
- No absorber - number of muons with low amplitude stays similar downstream except for the 3 mm beam
- With absorber - significant increase in number of core muons ⟶ cooling

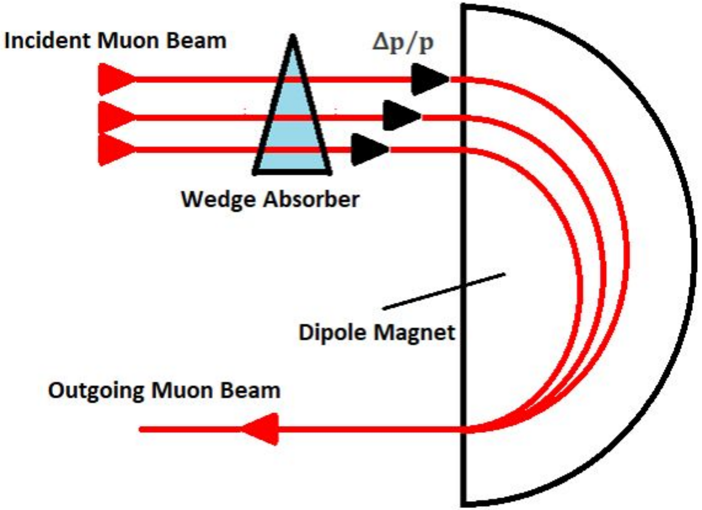
Ratio of core densities - 'Solenoid Mode'

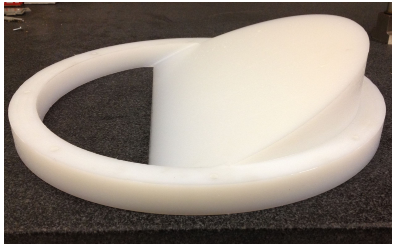


- 140 MeV/c data
- Core density increase for LH_2 and LiH absorbers ⟶ cooling
- More cooling at higher emittances
- 3 mm beams show heating

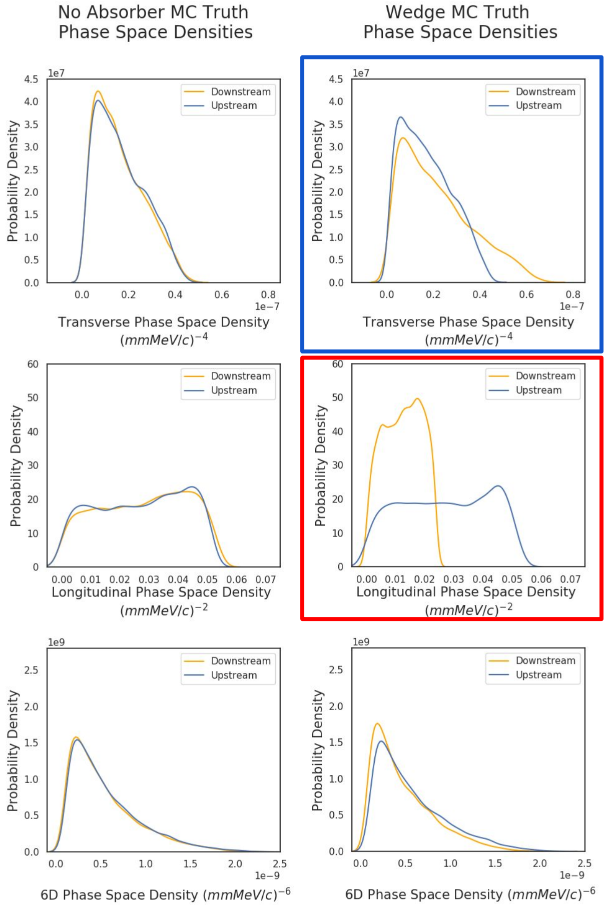
Reverse emittance exchange studies

- Process implies beam passing through a wedge absorber, followed by a pass through a dipole magnet
- An increase in the transverse phase space density is achieved at the cost of a decrease in the longitudinal phase space density
- In MICE, a polythene wedge absorber was placed between the two trackers, to study this effect





Wedge Absorber (simulation)



- Kernel Density Estimation (KDE) technique used to calculate the phase space density
- Simulations of the MICE experiment with and without the wedge in the path of a (6 mm, 140 MeV/c) beam show:
  - No absorber - transverse, longitudinal and 6D phase space density conservation
  - Wedge absorber
    - **Increase** in transverse phase space density
    - **Decrease** in longitudinal phase space density
- Data analysis - work in progress

Paul Bogdan Jurj

Cooling analysis - Emittance Change

- One can study the change of normalized transverse emittance across the absorber
- 4D normalized emittance defined as:

$$\varepsilon_{\perp} = \frac{1}{m_{\mu}} \sqrt[4]{|\Sigma|}$$

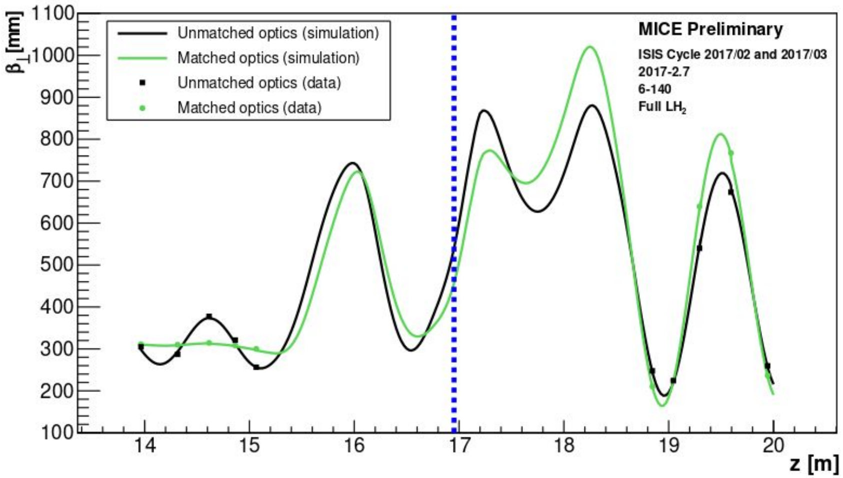
where Σ is the transverse phase space covariance matrix.

- Emittance change defined as:

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

Optics matching - beam sampling

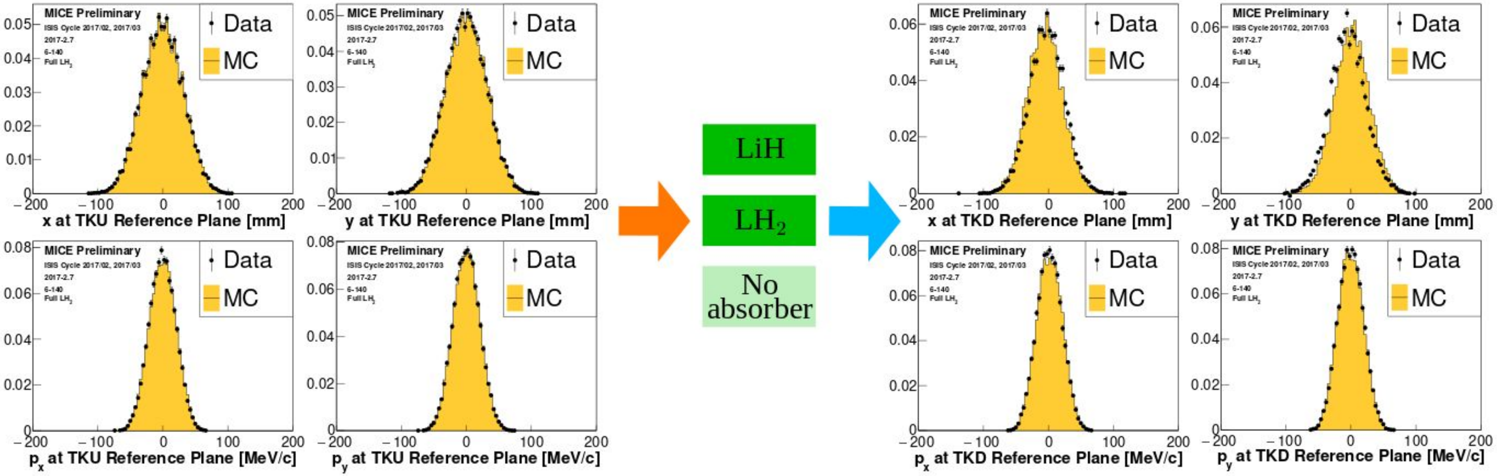
- Beam optics oscillations in the upstream tracker
- Higher $\beta_{\perp}$ at the absorber -> enhanced heating term
- A beam sampling routine based on rejection sampling was used to match the optics in the upstream tracker
- Beams with matched optics upstream observed a ~15-20 % decrease in $\beta_{\perp}$ at the absorber



Reconstruction and sample selection

The analysis includes events:

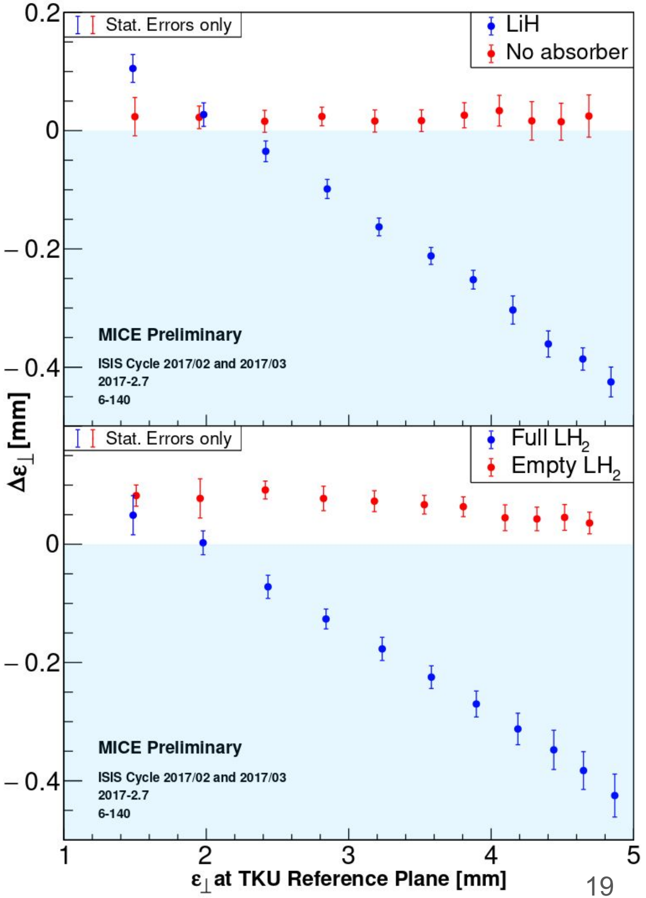
- that are identified as muons by the time-of-flight detectors and the upstream tracker
- with a reconstructed momentum in the upstream tracker falling in the 135 - 145 MeV/c range
- with a single, well-reconstructed track in each tracking detector, fully contained within the fiducial volume



Emittance reduction in 'Flip Mode'

Imperial College London

- Preliminary results from analysing data beams with 6 mm input emittance and 140 MeV/c momentum
- $\Delta\varepsilon_{\perp} < 0 \rightarrow$ **COOLING**
- 'No absorber' - no significant emittance change, small optical heating observed
- 'Empty LH_2' - slight heating due to muon scattering in the vessel windows
- 'Full LH_2' and 'LiH' demonstrate emittance reduction, clear signal of ionization cooling
- Systematic studies and simulations are in progress
- Analysis to include 3, 4, 10 mm data to cover a wider range of input emittances



Paul Bogdan Jurj

Imperial College London

Summary

- MICE has made an unprecedented single particle measurement of particle trajectories in an accelerator lattice
- MICE has made first observation of ionization cooling
- Quantitative studies of emittance change and canonical angular momentum evolution are currently in progress
- Reverse emittance exchange effect studies ongoing

Back-up

Optics matching - reduced heating