First Demonstration of Ionization Cooling by Muon Ionisation Cooling Experiment (MICE)

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On behalf of the MICE Collaboration

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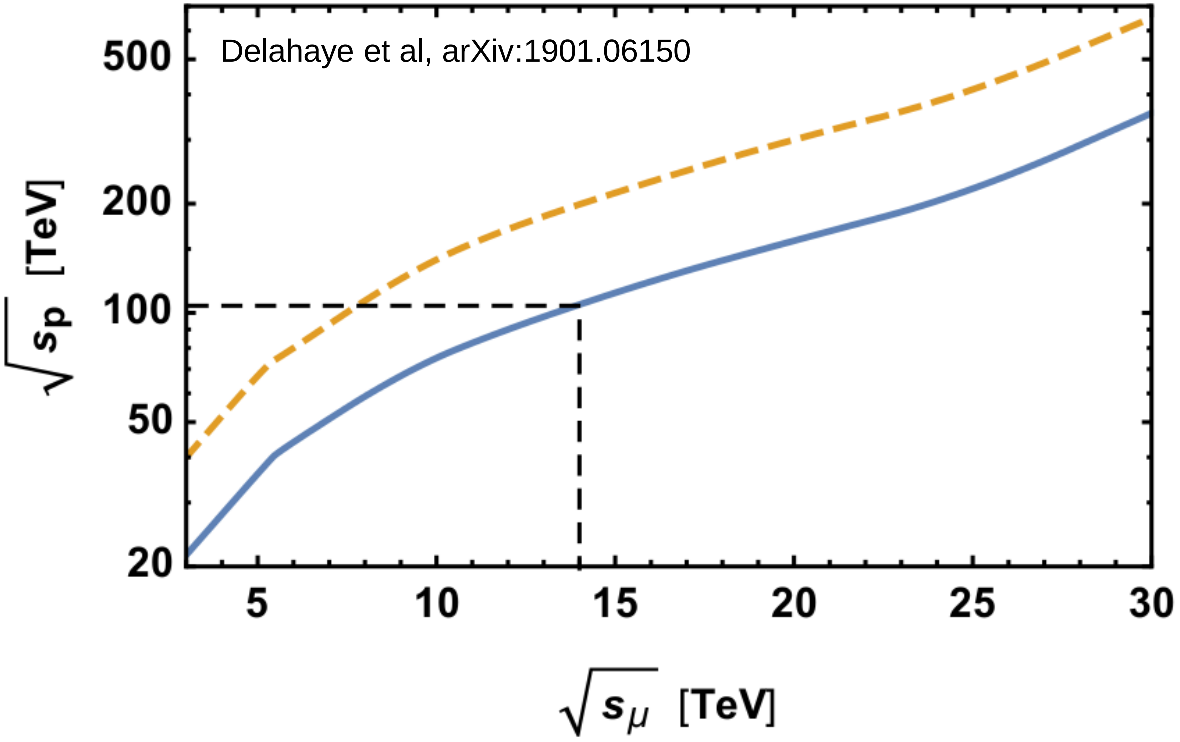
Muon beams for particle physics

- Muon as elementary lepton ~200 times heavier than electrons is an excellent particle for a collider
  - Avoiding a large QCD background known in hadron colliders
  - Offering a full CM energy for creating new states (in contrary to hadron colliders)
  - Rate of emission of synchrotron radiation is highly suppressed -> allows compact collider facility
  - This also suppresses beamstrahlung -> allows preserving the high quality beam
  - Large m_μ provides large coupling to the Higgs mechanism. Resonant Higgs production in the s-channel is possible.
- Muon beams are also important
  - Anomalous magnetic moment (g-2) – a possible sign of BSM physics
  - Searches for Lepton Flavour Violation -> complementary test of SM at a very high mass scale
  - High quality neutrino source -> nuSTORM and the Neutrino Factory

Muons Collider Physics Reach



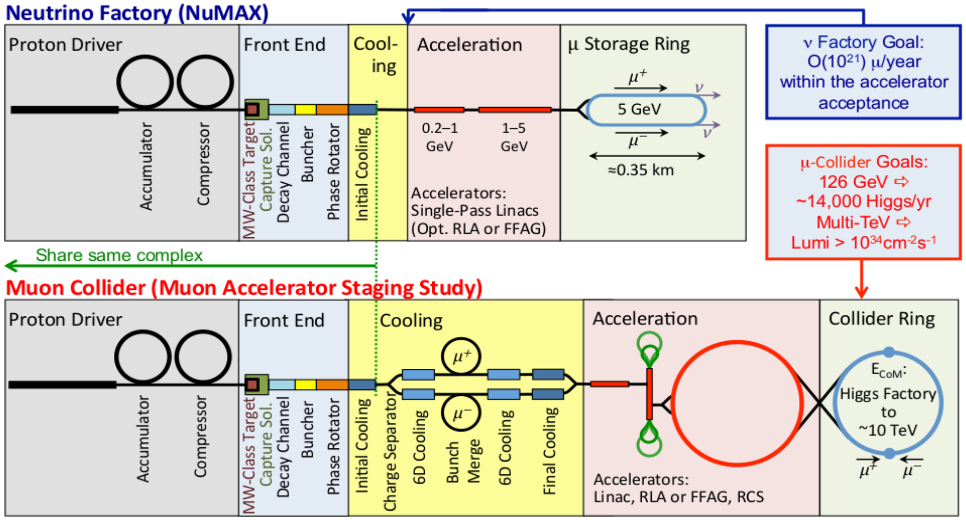
Energy at which cross-section is equal

Assuming equal Feynman amplitude

Assuming factor 10 enhancement in pp

- Muon Collider with CM energy similar to the current LHC is equivalent to 100 TeV Proton Collider (FCC-HH)

Muon Collider and Neutrino Factory



- In both facilities:
  - High power protons
  - Target → pions
  - Capture → muons
  - Cooling
  - Rapid acceleration
  - Storage ring

Challenges:

- Muon beams are unstable (muon lifetime at rest ~2.2 μs)
- Muons are produced as tertiary beam (p$\longrightarrow\pi\longrightarrow\mu$)

⇩

- Use ionization cooling, which is the only technique fast enough!
- Use high power proton driver
- Develop rapid accelerators

What is Muon Ionization Cooling?

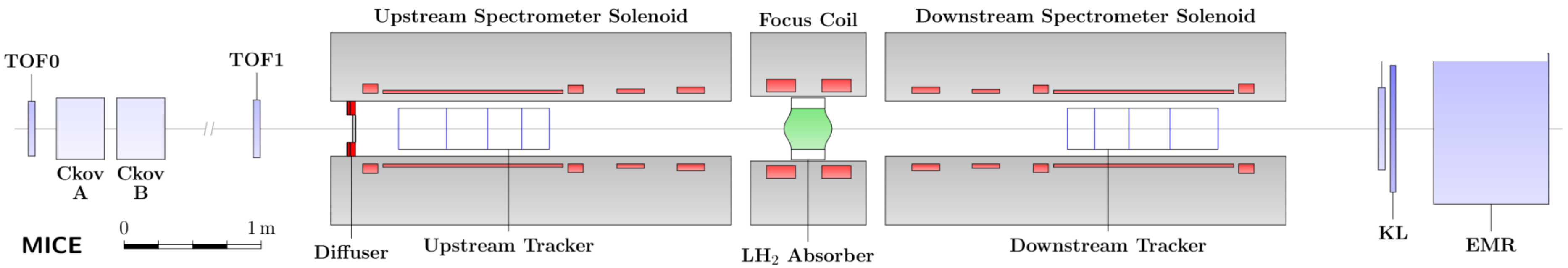
- Energy loss in the absorbers reduces both p_L and p_T
- Scattering heats the beam
- RF cavities restore p_L only
- The net effect is the reduction of beam emittance – cooling
  - strong focusing, low-Z absorber material and high RF gradient are required

Cooling Equation:

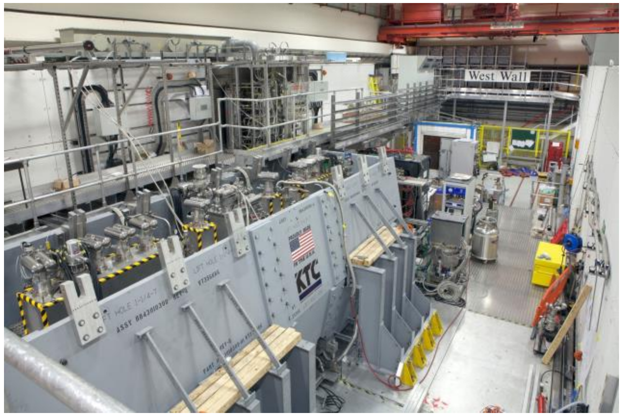
$$\frac{d\epsilon_n}{ds} \sim \underbrace{-\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu}}_{\text{Cooling}} + \underbrace{\frac{1}{\beta^3}\frac{\beta_\perp(0.014\text{GeV})^2}{2E_\mu m_\mu L_R}}_{\text{Heating}}$$

$d\epsilon_n/ds$ is the rate of change of normalised-emittance within the absorber; β, E_μ and m_μ the muon velocity, energy, and mass, respectively; $\beta_\perp$ is the lattice betatron function at the absorber; L_R is the radiation length of the absorber material.

Muon Ionization Cooling Experiment



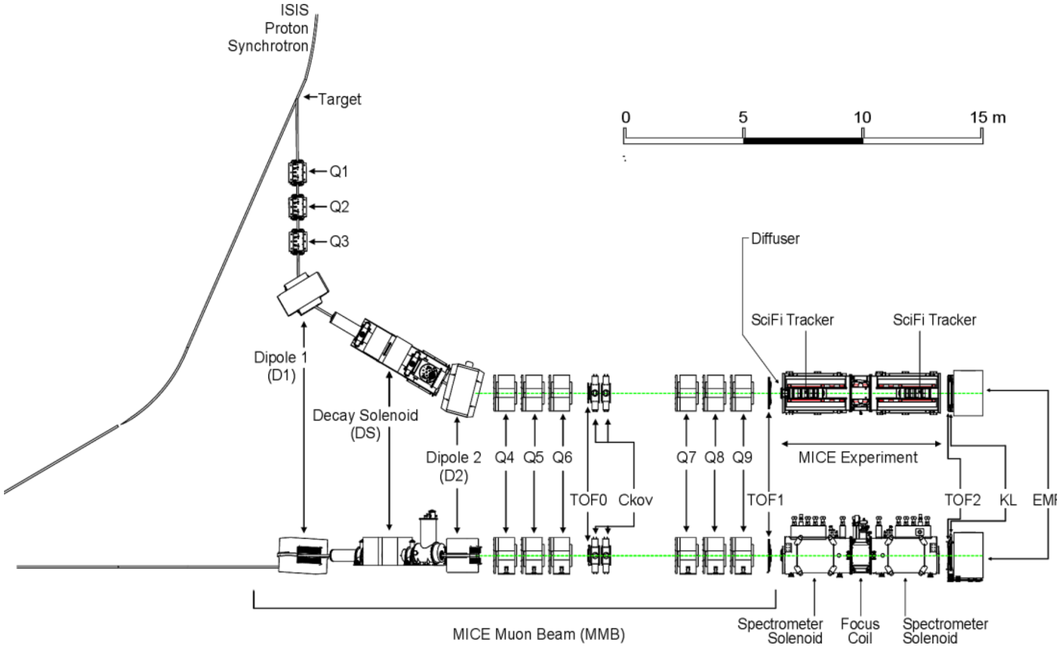
- Demonstrate high acceptance, tight focussing solenoid lattice
- Demonstrate integration of liquid hydrogen and lithium hydride absorbers
- Validate details of material physics models
- Demonstrate ionization cooling principle and amplitude non-conservation
- MICE operated at RAL between 2008 and 2017 and it groups over 100 collaborators, 10 countries, 30 institutions



Imperial College London

Science & Technology Facilities Council ISIS

MICE Muon Beam line

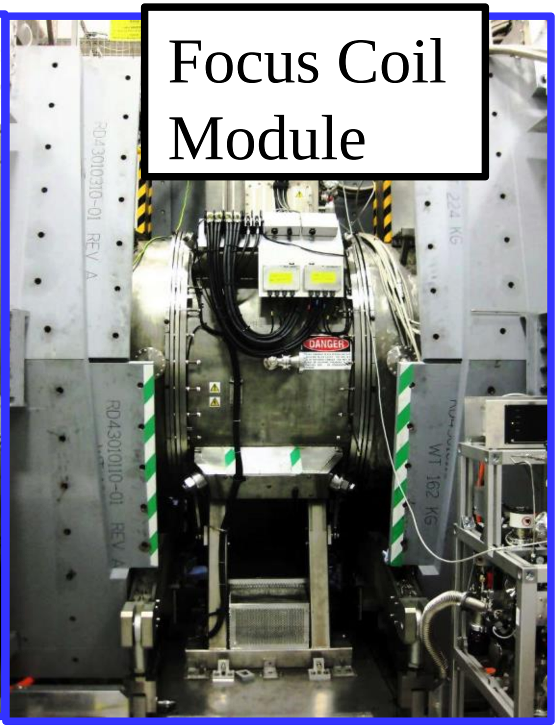


- Muon momenta between 120 and 260 MeV/c
- Muon emittance between 2 mm and 10 mm
- Pion impurity suppressed at up to 99 % level

- The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment, JINST 7, P05009 (2012)
- Characterisation of the muon beams for the Muon Ionisation Cooling Experiment, EPJ C 73, 10 (2013)
- Pion contamination in the MICE muon beam, JINST 11 (2016)

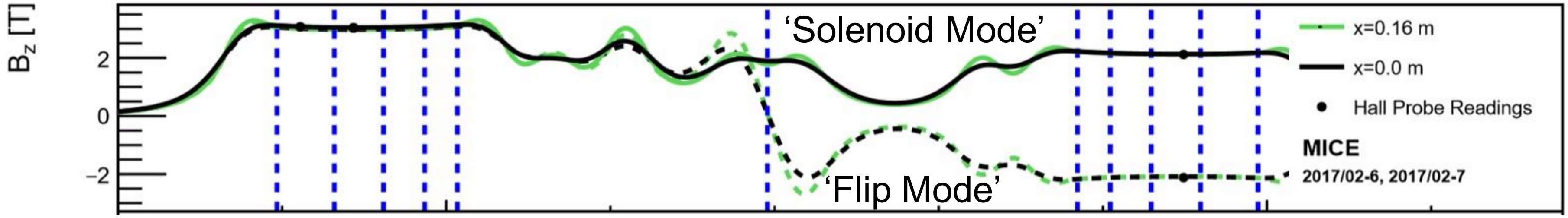
Magnets

Spectrometer Solenoid



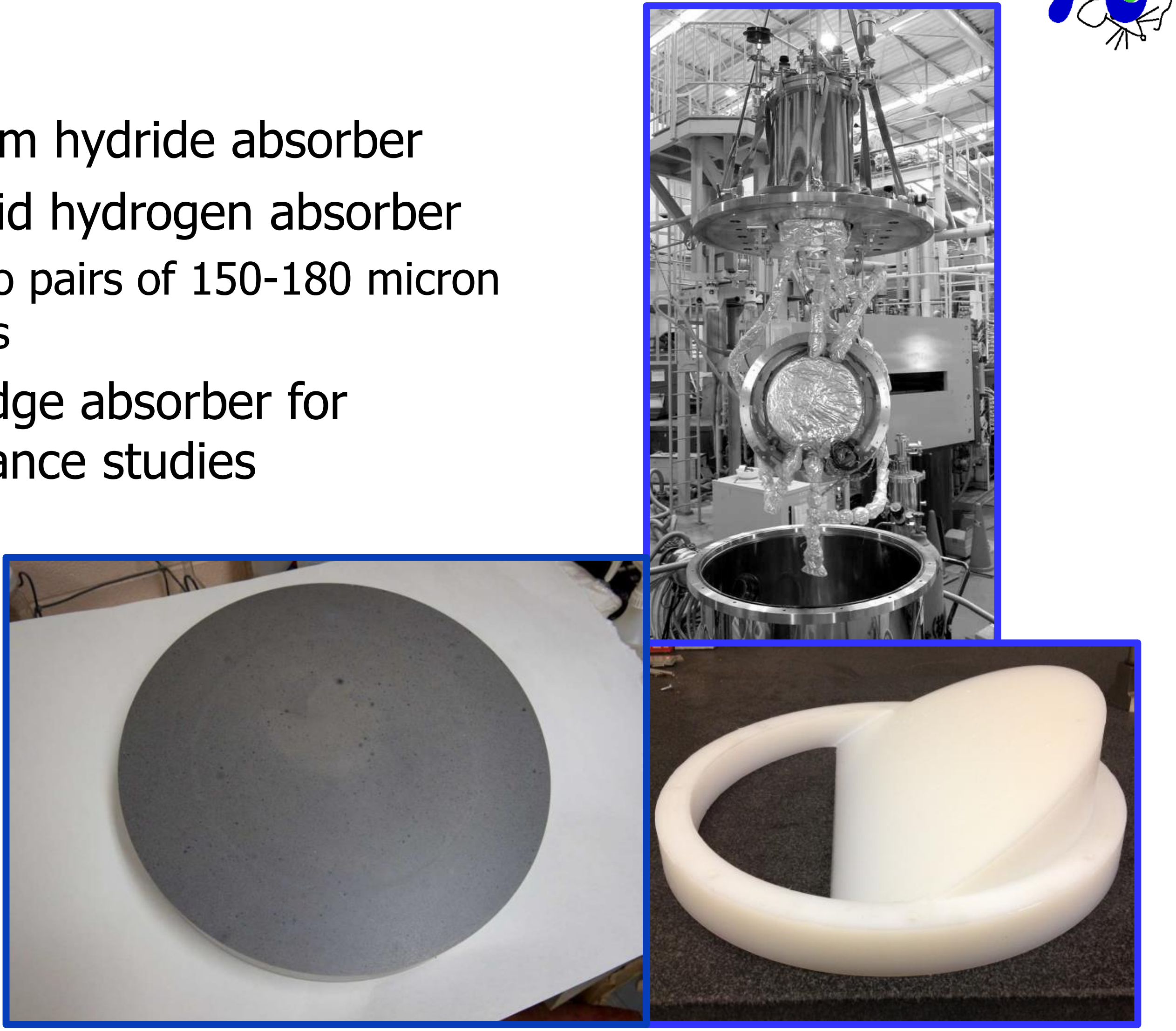
Focus Coil Module

- Spectrometer solenoids upstream and downstream
  - 400 mm diameter bore, 5 coil assembly
  - Provide uniform 2-4 T solenoid field for detector systems
  - Match coils enable choice of beam focus
- Focus coil module provides tight focus on absorber
  - Dual coil assembly - possible to flip polarity to avoid build up of canonical angular momentum

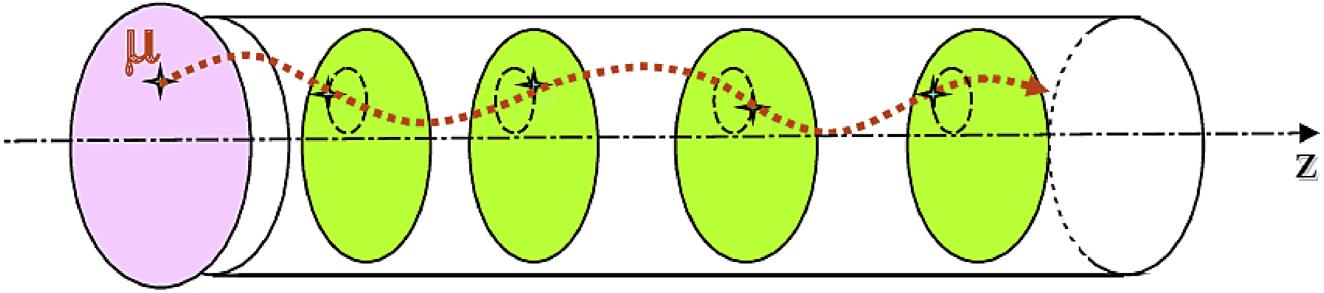


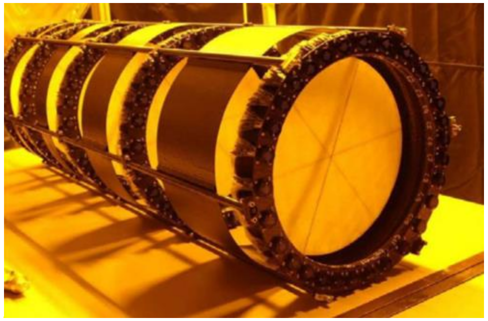
Absorbers

- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- 45^{o} polythene wedge absorber for longitudinal emittance studies



Scintillating Fibre trackers

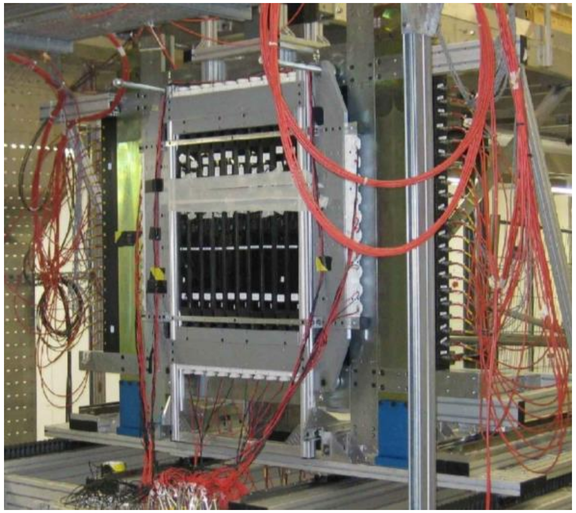


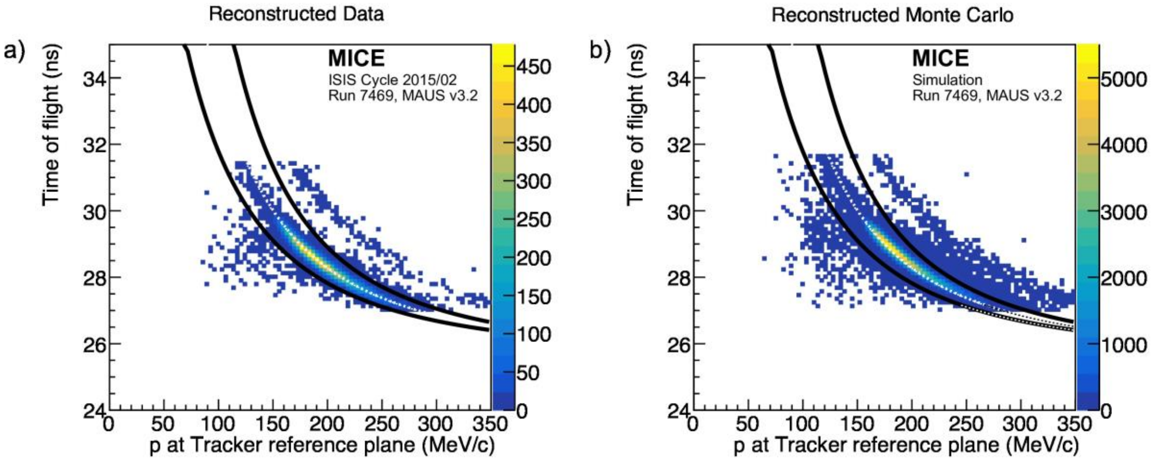


- Tracks form a helix in spectrometer solenoids
- Position of particles measured by 5 stations of scintillating fibres
- Reconstruct helix in two phases
  - Pattern recognition to reject noise
  - Kalman filter to get optimal trajectory
- Yields momentum and position of particles at reference plane
- **A scintillating fibre tracker for MICE**, NIM A 659, 2011
- **The reconstruction software for the MICE scintillating fibre trackers**, JINST11, 2016

Time-of-Flight, Chkov and Calorimetry

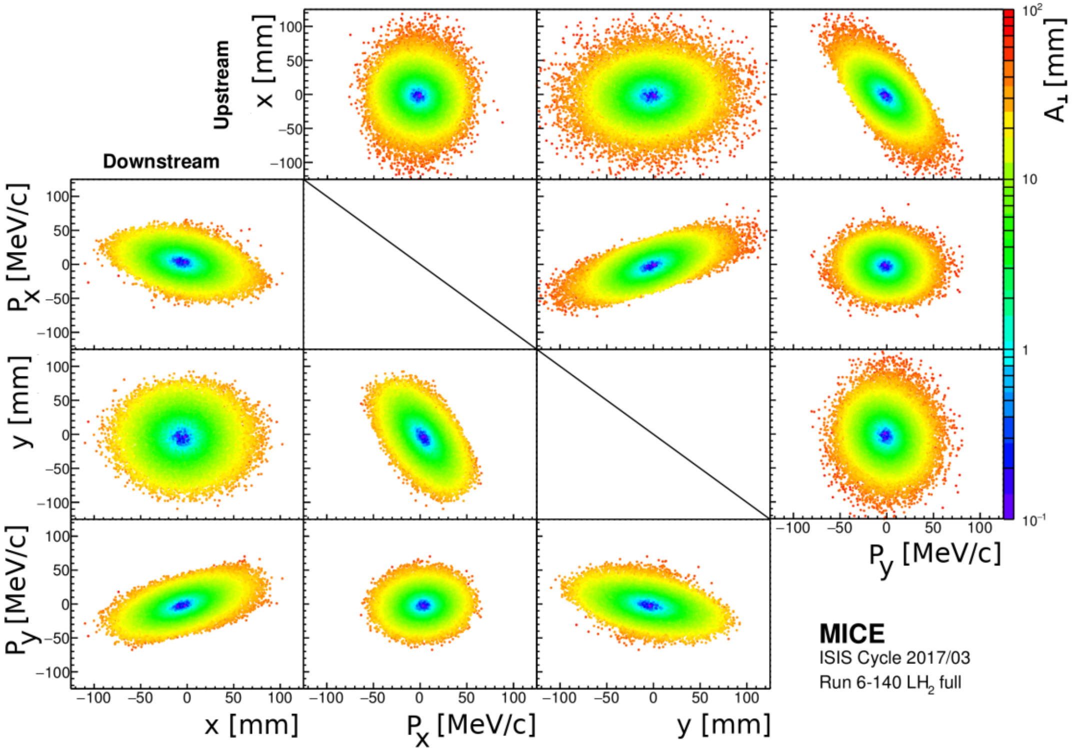
- High precision Time-of-Flight detectors
  - Comparison of time-of-Flight with momentum allows rejection of impurities
- Threshold Cherenkov detectors provide rejection of impurities near the relativistic limit
- KLOE Light and Electron Muon Ranger provide calorimetry and rejection of decay electrons in downstream region
- **Electron-Muon Ranger (EMR) Performance in the MICE Muon Beam**, JINST 10 P12012 (2015)
- **The design and commissioning of the MICE upstream time-of-flight system**, **NIM** A 615 (2010) 14-26





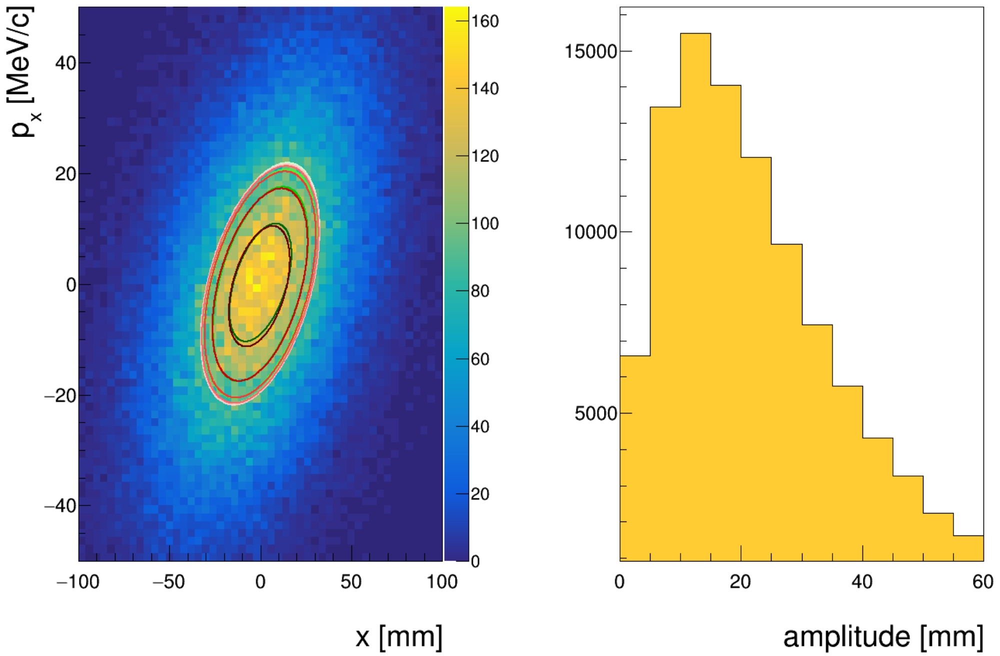
Measurement of Beam Properties

- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision
- E.g. coupling of x-y from solenoid fields



First particle-by-particle measurement of emittance in the Muon Ionization Cooling Experiment, *Eur. Phys. J. C* **79,** 257 (2019)

Amplitude



Phase space $u=(x, p_x, y, p_y)$

Normalise phase space to RMS beam ellipse

- Clean up tails

Amplitude is distance of muon from beam core

- Conserved quantity in normal accelerators

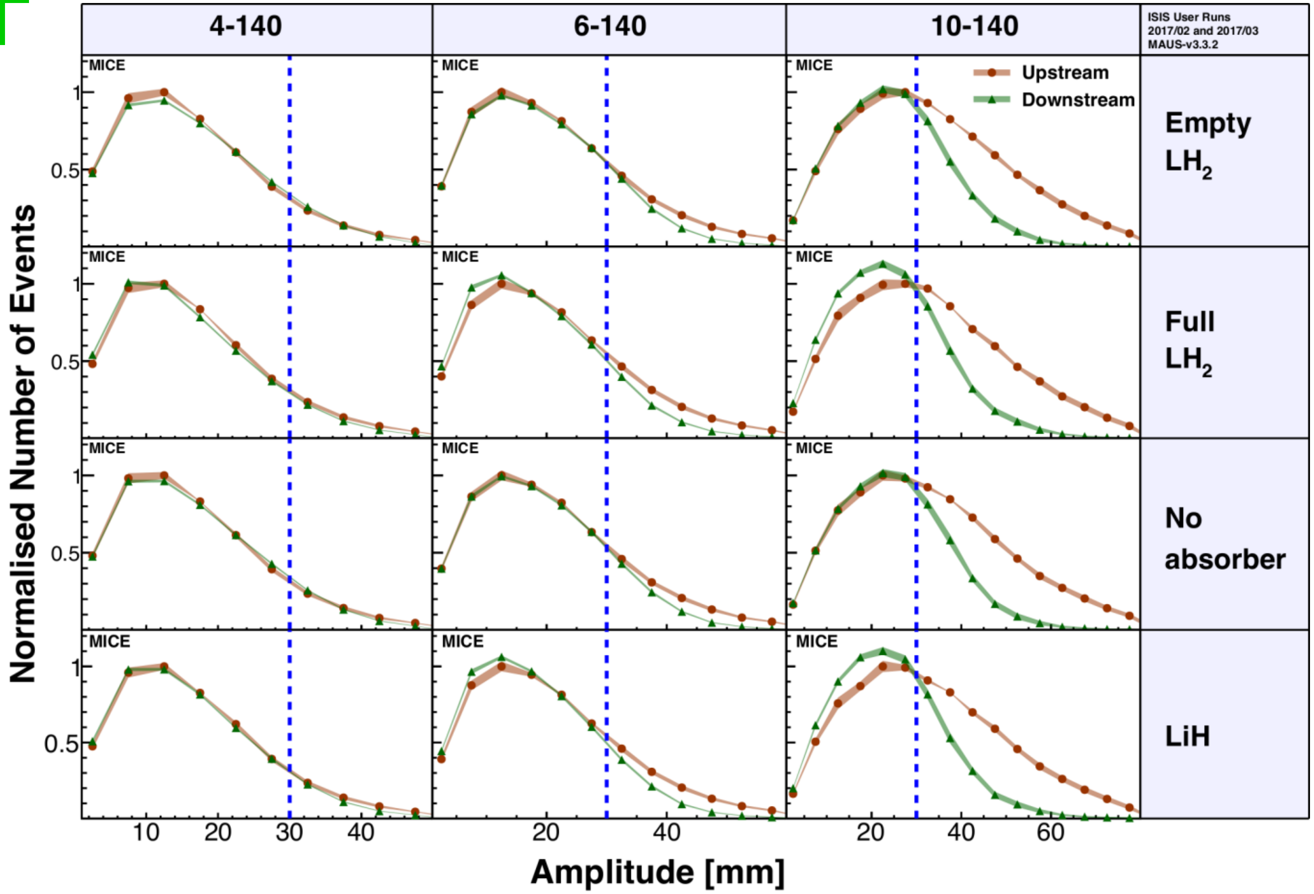
$$A_\perp = \varepsilon_\perp R^2(\mathbf{u}, \langle \mathbf{u} \rangle)$$

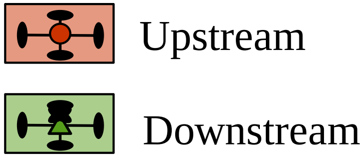
where *R* is the normalised distance in phase space:

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

- Ionization cooling reduces transverse momentum spread
  - Reduces amplitude
- Mean amplitude ~ "RMS emittance"

Change in Amplitude Across Absorber – 'Flip Mode'



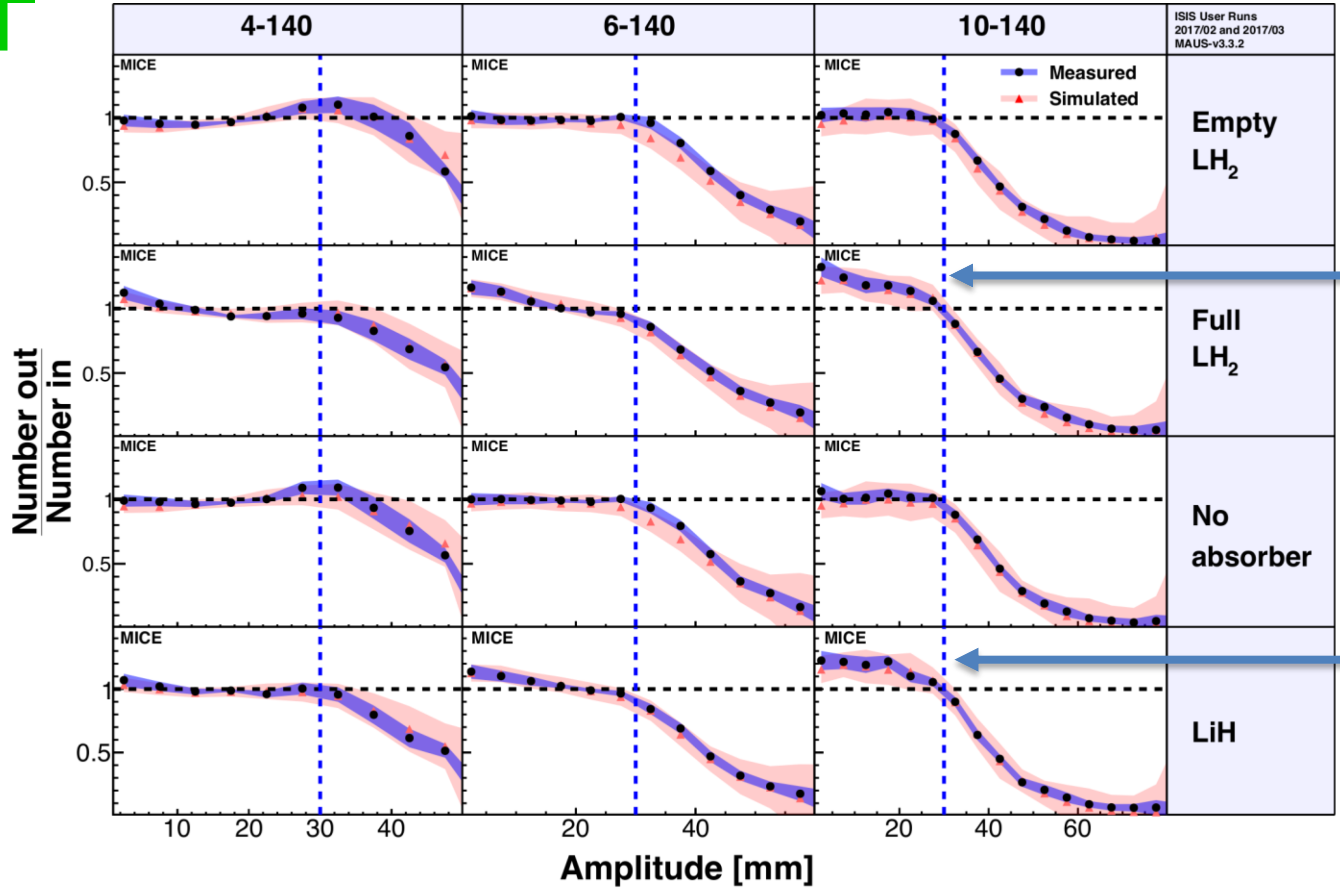


Results from 140 MeV/c beam

- No absorber → decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal

Nature volume 578, pages 53–59 (2020)

Ratio of core densities – ‘Flip Mode’



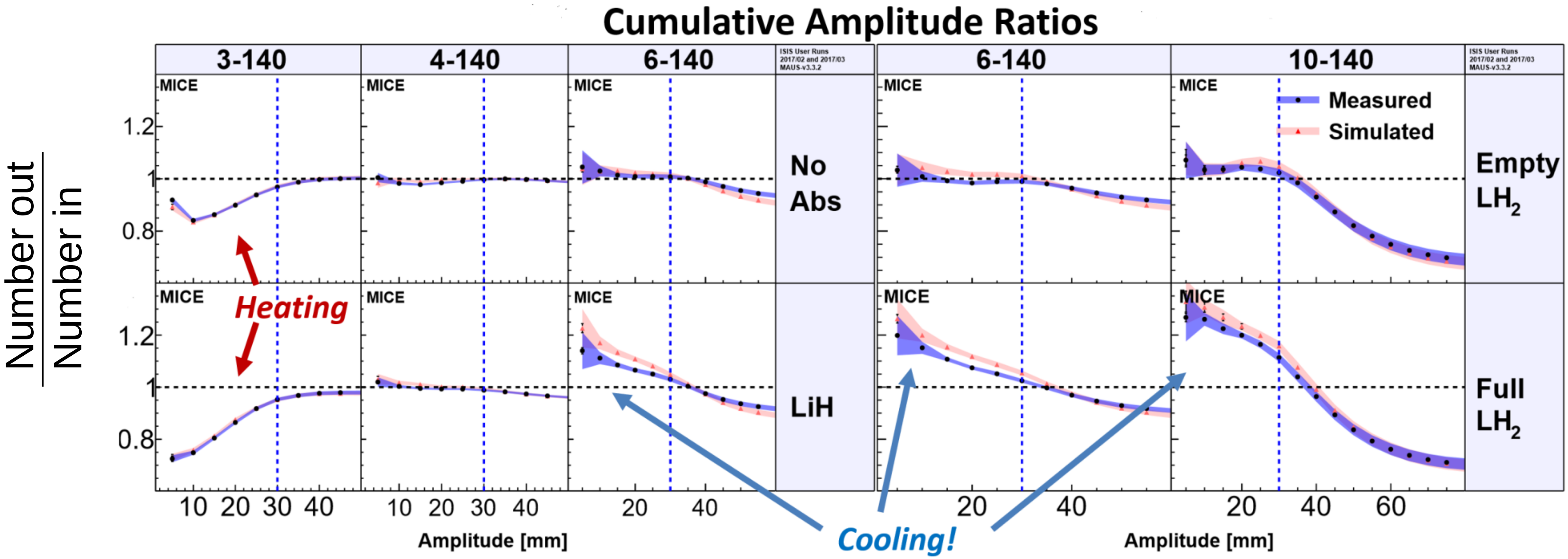
Cooling!

Cooling!

Results from 140 MeV/c beam

- Ratio of CDF
- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances

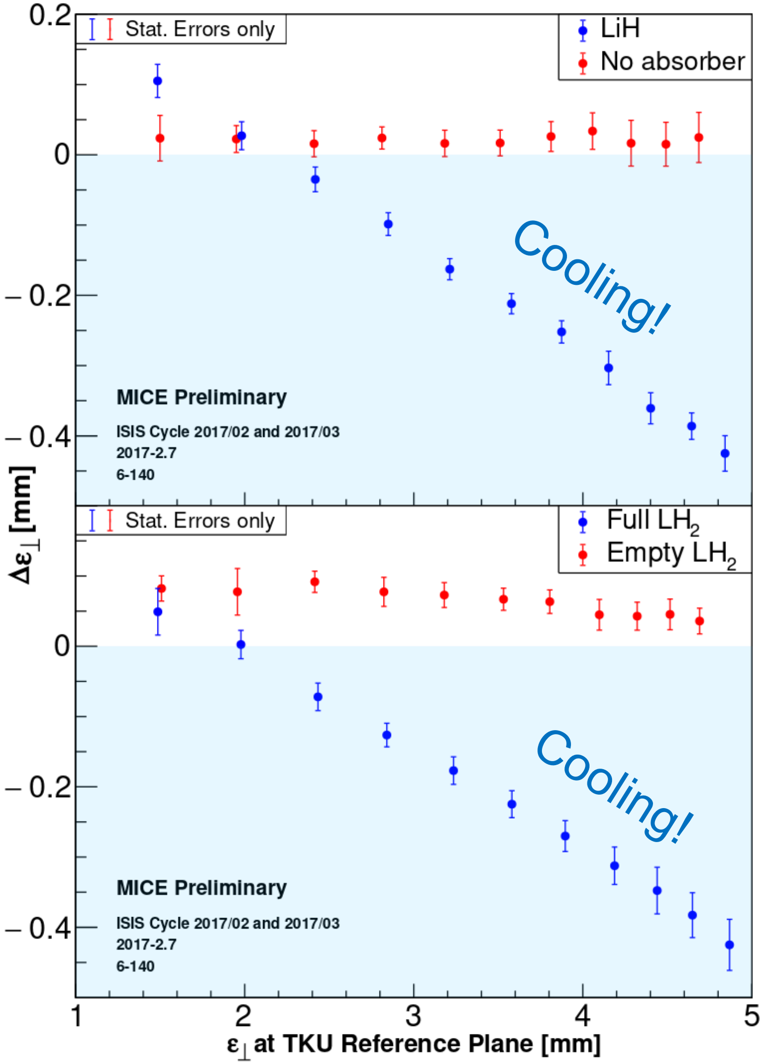
Results in ‘Solenoid Mode’



140 MeV/c beam

Transverse Emittance Change in MICE ‘Solenoid Mode’ with Muon Ionization Cooling – T. Lord, ICHEP2020, Poster/56

Normalized Emittance reduction in ‘Flip Mode’

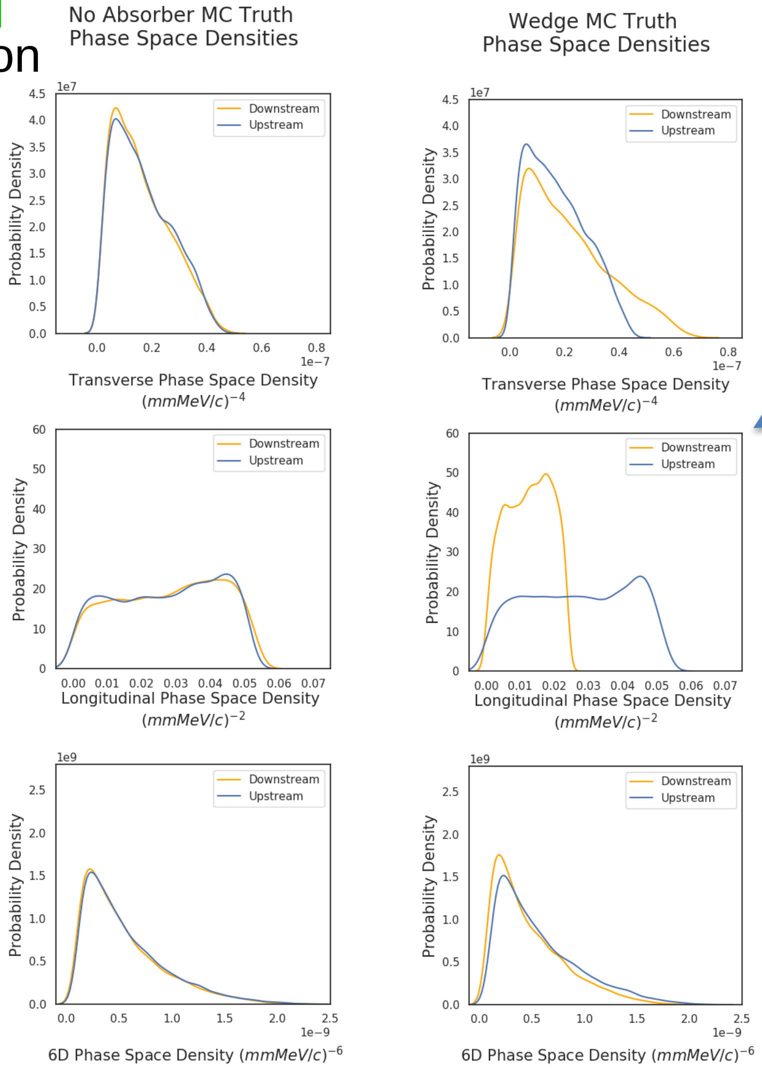


- Results from 140 MeV/c beam
- Matched distribution selected in the upstream Tracker using rejection sampling
- Clear cooling signal in change of normalized emittance

Muon Ionization Cooling Demonstration by Normalized Transverse Emittance Reduction in MICE ‘Flip Mode’, P. Jurj, ICHEP2020, Poster/54

Wedge Absorber in action

Simulation results


No Absorber MC Truth Phase Space Densities

Wedge MC Truth Phase Space Densities

- Reverse emittance exchange effect is simulated in MICE with wedge absorber causing
    - decrease in longitudinal phase space density with
    - increase in 4D transverse phase space density
- Data analysis – work in progress
- This will help to understand longitudinal cooling
    - Essential for the Muon Collider

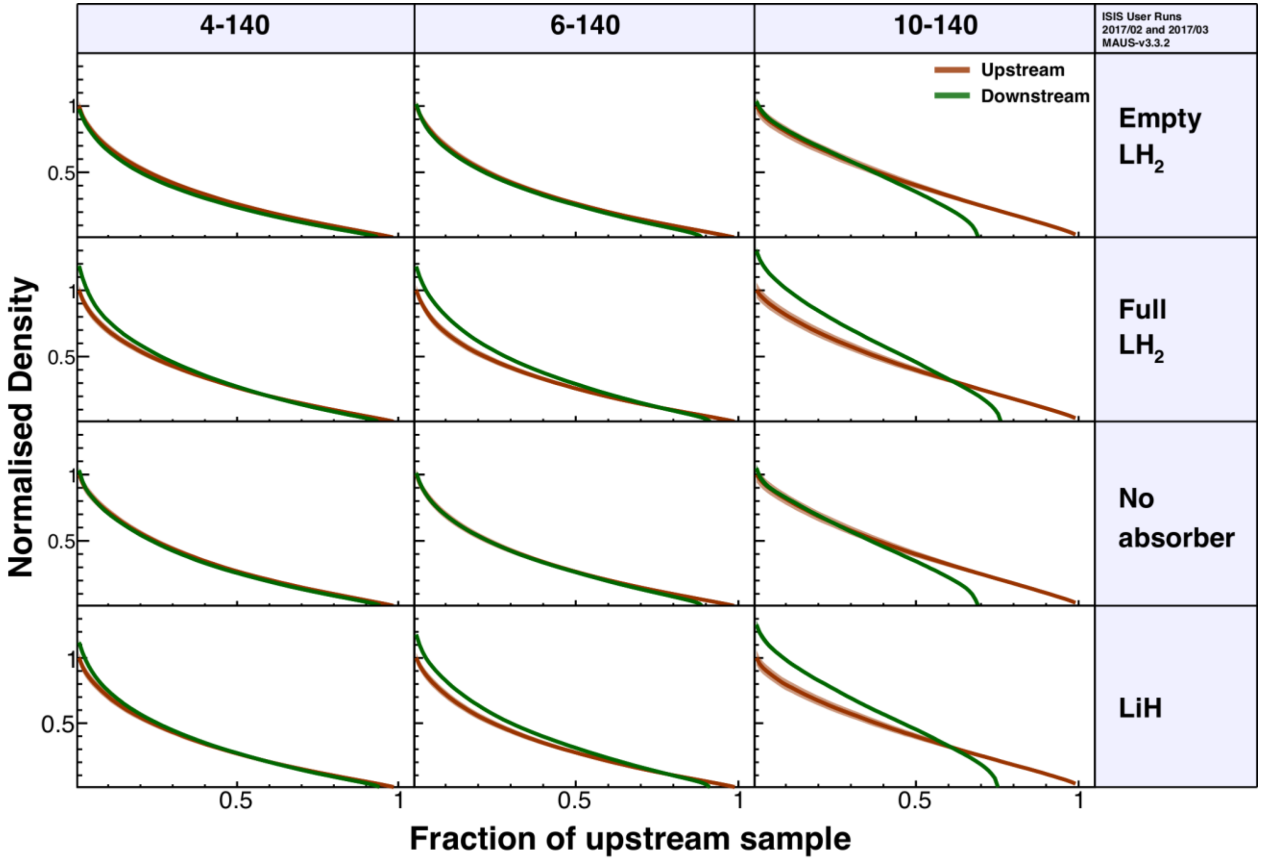
Emittance exchange in MICE, C. Brown, ICHEP2020, Poster/55

Summary

- Muon cooling is last “in-principle” challenge for neutrino factory or muon collider R&D
- MICE has measured the underlying physics processes that govern cooling
- MICE has made an unprecedented single particle measurement of particle trajectories in an accelerator lattice
- MICE has made first observation of ionization cooling
  - Nature volume 578, pages 53–59 (2020)
- Opens the door for high energy muon accelerators as a probe of fundamental physics

Backup

Normalised density – ‘Flip Mode’



Results from
140 MeV/c beam

- R_{amp} is ratio of CDF
- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances

R&D Programme

- MERIT
  - Demonstrated principle of liquid Mercury jet target
- MuCool Test Area
  - Demonstrated operation of RF cavities in strong B-fields
- EMMA
  - Showed rapid acceleration in non-scaling FFA
- MICE
  - Demonstrate ionization cooling principle
  - Increase inherent beam brightness → number of particles in the beam core