Normalized Transverse Emittance Reduction via Ionization Cooling in MICE 'Flip Mode'

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on behalf of the MICE Collaboration

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Imperial College London

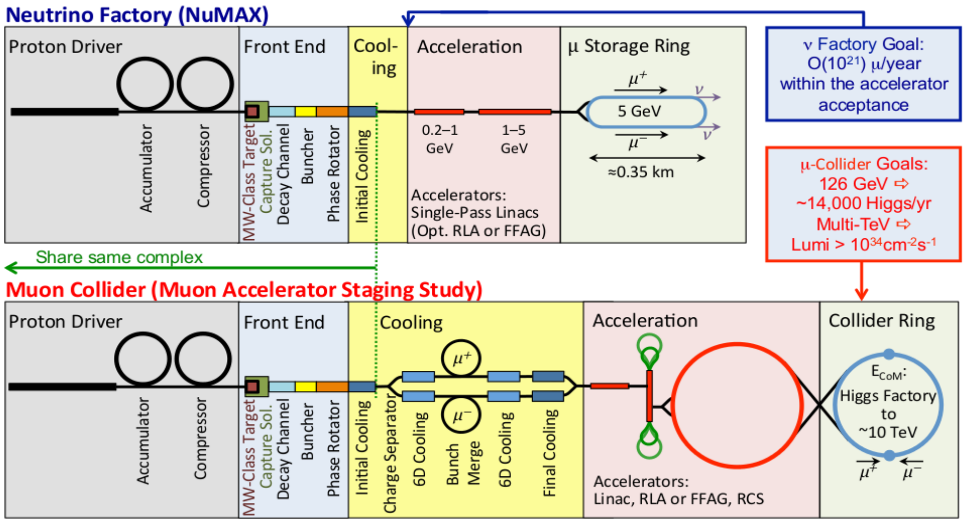
Science & Technology Facilities Council ISIS

JAI John Adams Institute for Accelerator Science

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

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?

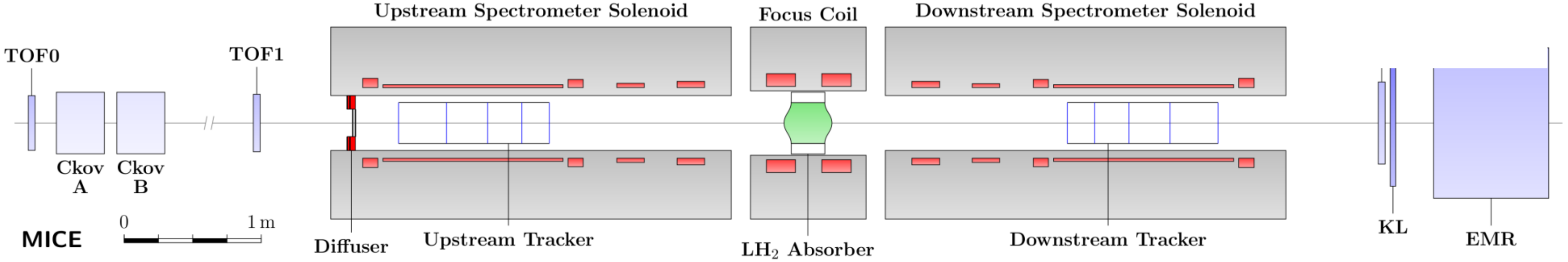
- Energy loss in the absorbers reduces both p_L and p_T
- Scattering heats the beam
- RF cavities restore p_L only
- The net effect is the reduction of beam emittance – cooling
  - strong focusing, low-Z absorber material and high RF gradient are required

Cooling Equation:

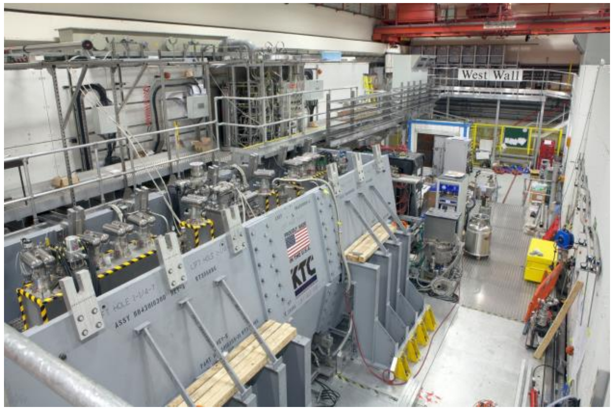
$$\frac{d\epsilon_n}{ds} \sim \underbrace{-\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu}}_{\text{Cooling}} + \underbrace{\frac{1}{\beta^3}\frac{\beta_\perp(0.014\text{GeV})^2}{2E_\mu m_\mu L_R}}_{\text{Heating}}$$

$d\epsilon_n/ds$ 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 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
- MICE operated at RAL between 2008 and 2017 and it groups over 100 collaborators, 10 countries, 30 institutions



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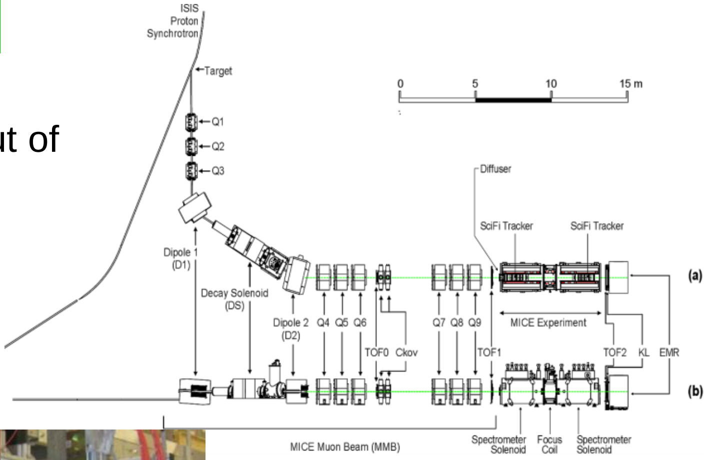
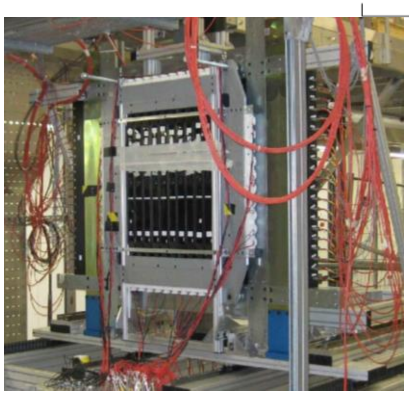
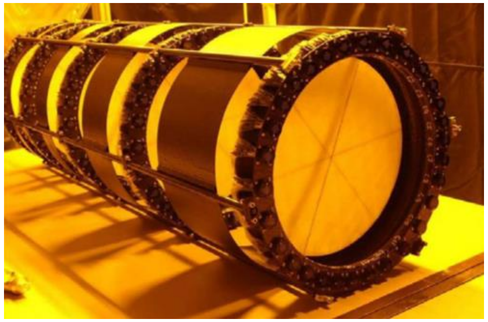
MICE experiment

Layout of MICE





TOF

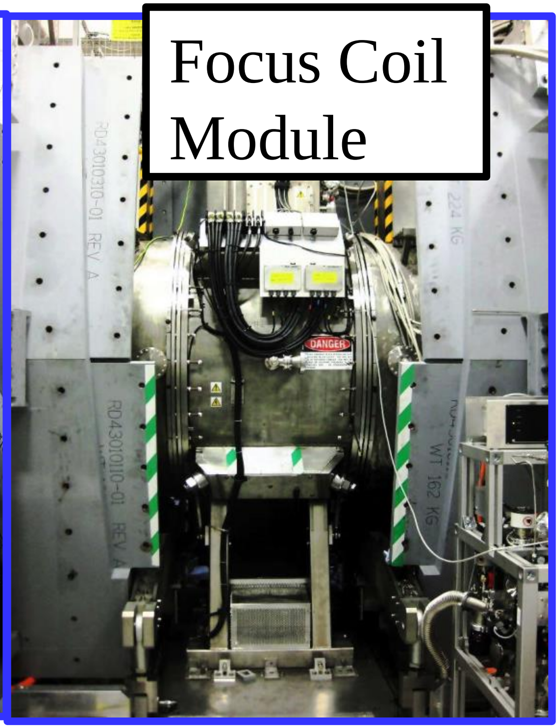


Scintillating fibre tracker

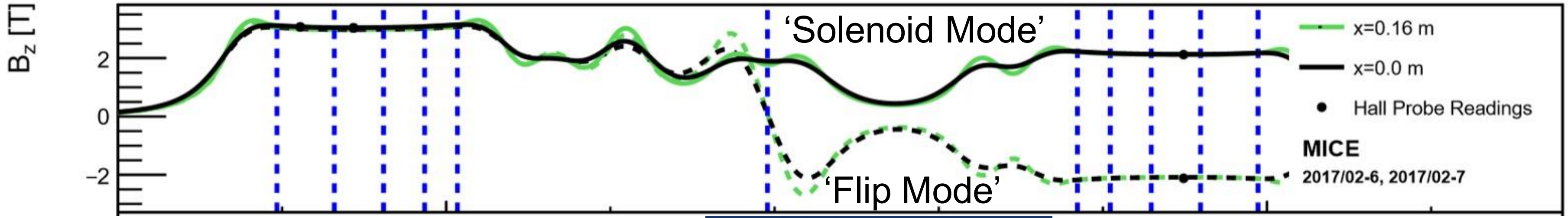
- Fed by pions produced at the internal target (Ti) in ISIS proton synchrotron at RAL
- Beamline consisting of dipoles, quads and SC decay solenoid transported the muon beam to the cooling apparatus with variable input conditions
- MICE detectors
  - Scintillating fibre trackers for particle by particle phase space reconstruction by matching the helical tracks in SC solenoids placed before and after the absorber
  - High precision Time-of-Flight (TOF) detectors for momentum measurement and PID
  - Threshold Cherenkov detectors for PID
  - KLOE Light and Electron Muon Ranger for calorimetry and rejection of decay electrons in downstream region
- Experimentation with three absorber types
  - Lithium hydride absorber, liquid hydrogen absorber and polythene wedge absorber

Magnets

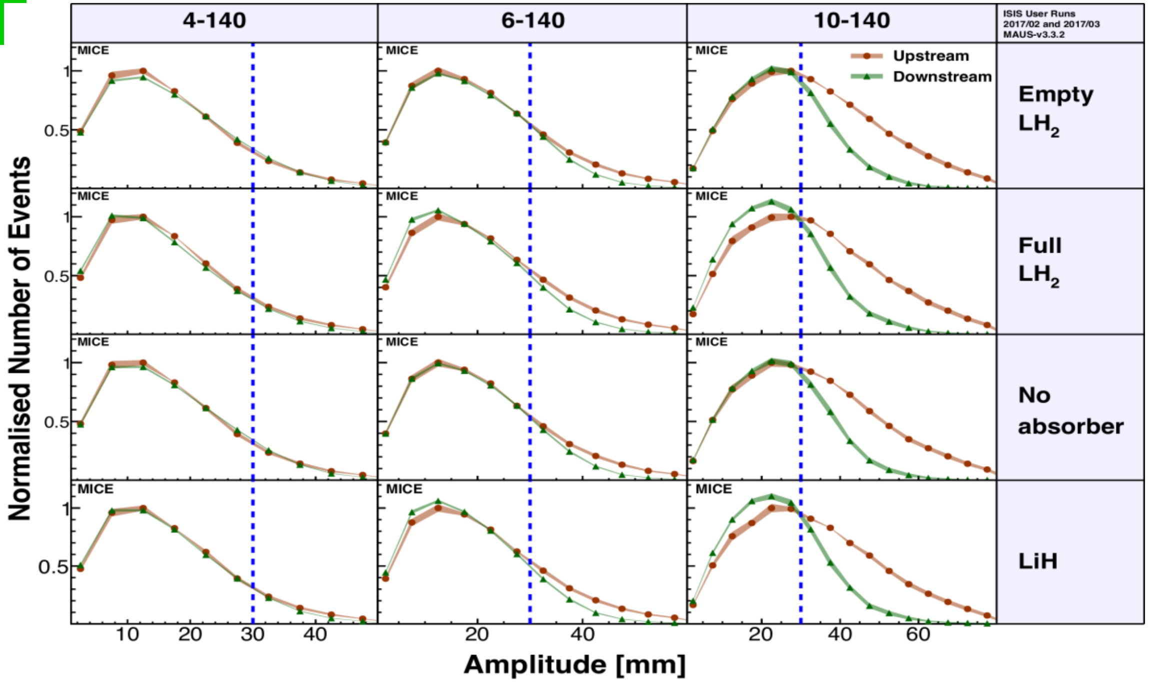

Spectrometer Solenoid

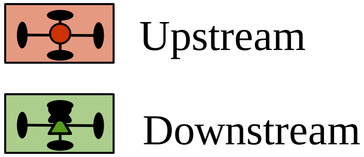

Focus Coil Module

- Spectrometer solenoids upstream and downstream
  - 400 mm diameter bore, 5 coil assembly
  - Provide uniform 2-4 T solenoid field for detector systems
  - Integral superconducting match coils enable choice of beam focus
- Focus coil module provides tight focus on absorber
  - Two parallel coils - possible to be energised in opposition to flip polarity avoiding build up of canonical angular momentum



Change in Amplitude Across Absorber – ‘Flip Mode’





Nature, volume 578, pages 53–59 (2020)

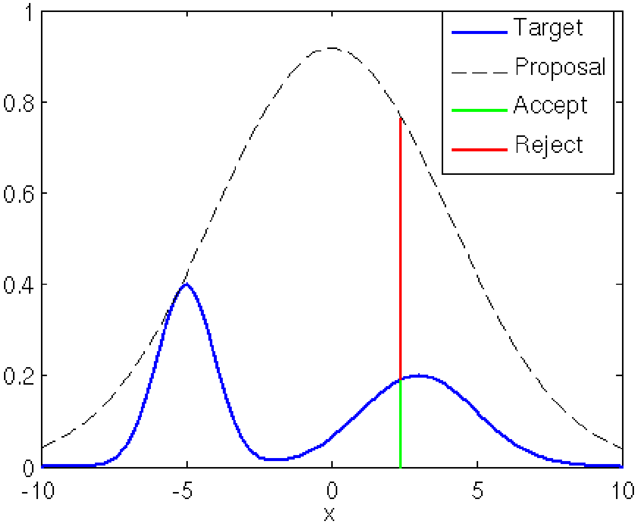
Results from 140 MeV/c beam

Details presented in C. Rogers’s talk at this conference. For similar analysis in the solenoid mode, see P. Kyberd’s talk

- No absorber → decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal
- This provided the world’s first qualitative demonstration of ionization cooling of muon beam
  - The quantitative demonstration is provided by the analysis presented here (publication in preparation)

Beam Sampling

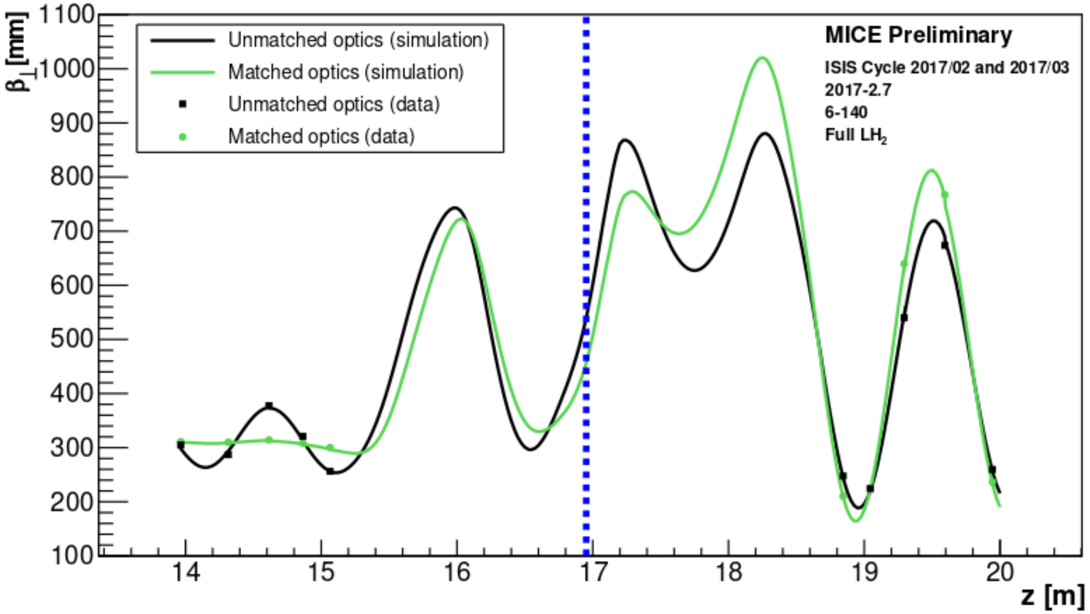
- To improve beam at the entrance to the cooling channel beam sampling is applied
  - This is possible as MICE allows for particle by particle reconstruction
  - Sampling routine is applied only to the data collected at the same cooling channel setting but different input beams are allowed
  - The aim is to improve the matching to the cooling channel reducing the emittance growth, improving the transmission and reducing the value of the betatron function at the absorber



- Beam sampling is based on the rejection algorithm
  - $P_{selection}(x)$ = Norm * Target(x) / Parent (x)
  - Draw u from u[0,1]. If u < $P_{selection}(x)$, then accept event. Otherwise reject it.
  - Normalisation ensures that $P_{selection}(x) <= 1$
  - Parent PDF is estimated using Kernel Density Estimation (KDE)

Beam Sampling (2)

- Beams matched to the upstream spectrometer solenoid are sampled at the upstream reference plane
- Six beams with different emittances are sampled:
  - 1.5, 2.5 mm from the 4 mm dataset
  - 3.5, 4.5 mm from the 6 mm dataset
  - 5.5, 6.5 mm from the 10 mm dataset



Emittance Calculation

The 4D normalised RMS transverse emittance is defined as

$$\epsilon_n = \frac{1}{m_\mu} \sqrt[4]{\det \Sigma}$$

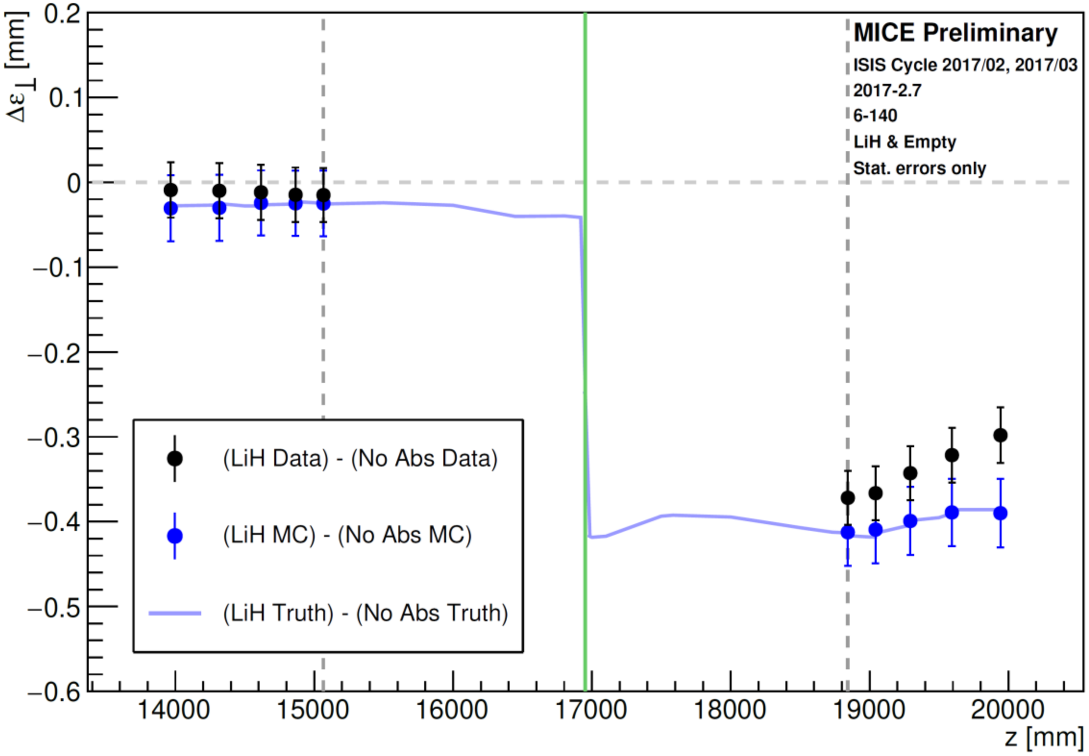
Where m_μ the muon mass and Σ the covariance matrix:

$$\Sigma = \begin{pmatrix} \sigma^2_{xx} & \sigma^2_{xp_x} & \sigma^2_{xy} & \sigma^2_{xp_y} \\ \sigma^2_{p_x x} & \sigma^2_{p_x p_x} & \sigma^2_{p_x y} & \sigma^2_{p_x p_y} \\ \sigma^2_{yx} & \sigma^2_{yp_x} & \sigma^2_{yy} & \sigma^2_{yp_y} \\ \sigma^2_{p_y x} & \sigma^2_{p_y p_x} & \sigma^2_{p_y y} & \sigma^2_{p_y p_y} \end{pmatrix}$$

And $\sigma^2_{ij} = \langle ij \rangle - \langle i \rangle \langle j \rangle$ the covariance of i and j.

Emittance evolution in the MICE Cooling Channel

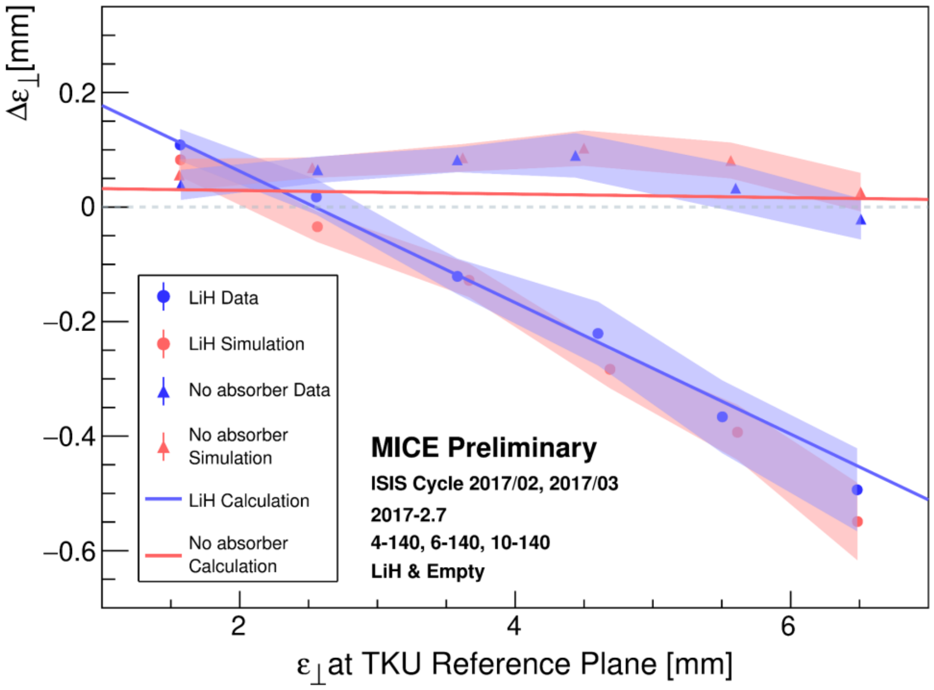
- Selected Data and Simulation (MC) beams with ~ 4.5 mm emittance at the upstream tracker reference plane has been used to plot the emittance evolution in the MICE Channel
- Evolution of beam emittance in the presence of the ‘LiH’ absorber relative to the emittance in the ‘No absorber’ case is shown
- Ionization cooling signal observed in Data and reconstructed MC, supported by MC Truth simulation
- Slight offset from 0 in upstream tracker due to limited sampling accuracy



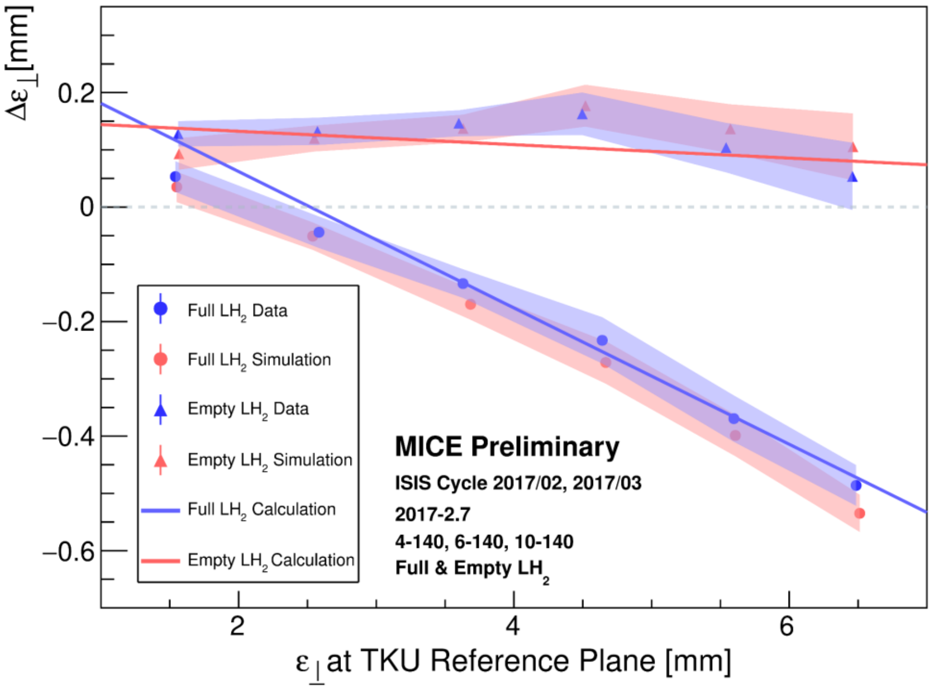
Normalized Emittance reduction in ‘Flip Mode’

- Results from 140 MeV/c beam
- Matched distribution selected in the upstream Tracker using rejection sampling
- Clear cooling signal in change of normalized emittance (downstream – upstream)
- ‘No absorber’ - weak heating due to optical aberrations
- ‘Empty LH2 ’ – weak additional heating due to hydrogen vessel windows
- ‘Full LH2 ’ and ‘LiH’ demonstrate emittance reduction (ionization cooling)
- Approximate theory: analytical estimate of cooling effect
- Good agreement between Data / Simulation / Approximate theory

Lithium Hydride



Liquid Hydrogen



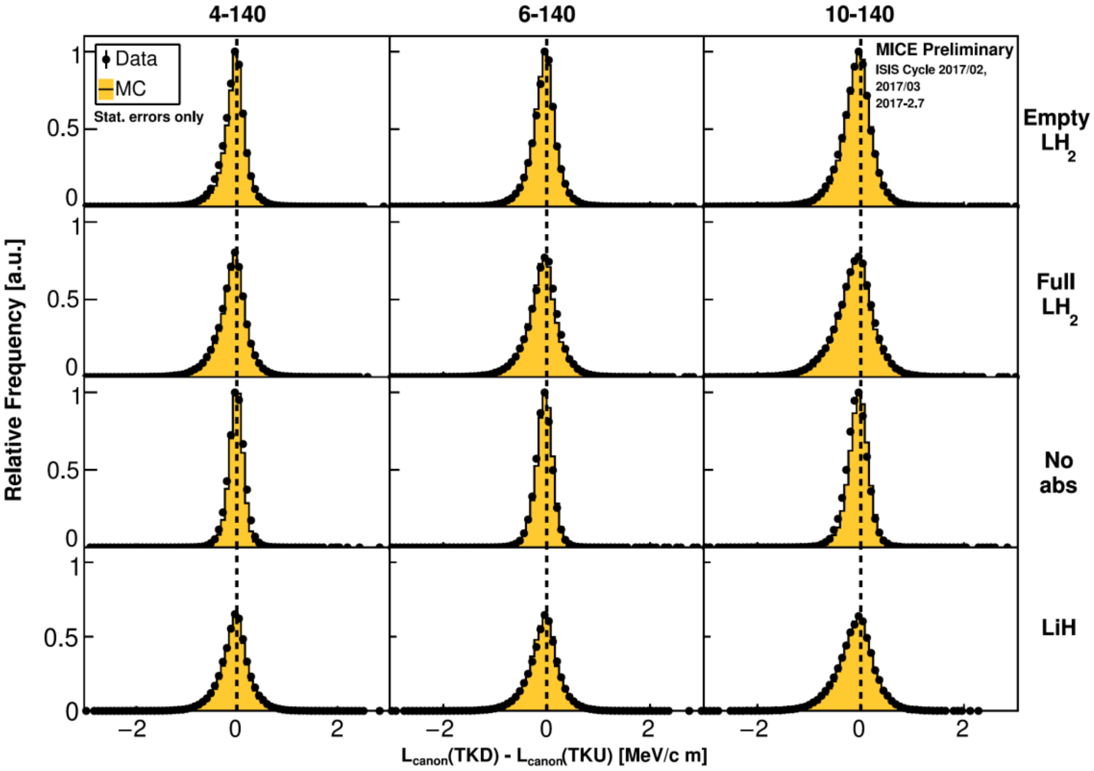
Canonical angular momentum change

$$L_{canon} = L_{kin} + L_{field}$$

$$L_{kin} = xp_y - yp_x$$

$$L_{field} = qrA \approx \frac{qr^2 B_z}{2}$$

- Build-up of the canonical angular momentum can be a problem in the long cooling channels proposed for a Muon Collider and the expected mitigation is provided by making field flips across absorbers
- MICE can verify this experimentally
- No net mean change observed between the ‘empty’ and ‘absorber’ cases, as expected for a flipped field configuration
- In contrast to the ‘Solenoid mode’, where a net increase is observed, see P. Kyberd’s talk



Summary

- MICE has measured the underlying physics processes that govern cooling
- The unprecedented single particle measurement of particle trajectories in accelerator lattice has been achieved
- MICE has made world's first observation of ionization cooling in 'Flip Mode'
  - Nature volume 578, pages 53–59 (2020)
  - 'Solenoid Mode' results are being prepared for publication
- The quantitative analysis of cooling effect by applying the beam sampling in 'Flip Mode' confirms the cooling effect and verifies the cooling theory
  - Publication in preparation
- Evolution of canonical angular momentum in 'Flip Mode' seems consistent with zero, as predicted by theory
- MICE opens the door for high energy muon accelerators as a probe of fundamental physics

Backup

Selected MICE publications

- The design and commissioning of the MICE upstream time-of-flight system, NIM A 615 (2010) 14-26
- A scintillating fibre tracker for MICE, NIM A 659, 2011
- 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)
- Electron-Muon Ranger (EMR) Performance in the MICE Muon Beam, JINST 10 P12012 (2015)
- Pion contamination in the MICE muon beam, JINST 11 (2016)
- The reconstruction software for the MICE scintillating fibre trackers, JINST11, (2016)
- First particle-by-particle measurement of emittance in the Muon Ionization Cooling Experiment, *Eur. Phys. J. C* 79, 257 (2019)
- Demonstration of cooling by the Muon Ionization Cooling Experiment, Nature 578, 53 (2020)
- Performance of the MICE diagnostic system, JINST 16 P08046 (2021)