Recent Results from the Study of Emittance Evolution in MICE

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on behalf of

The MICE Collaboration

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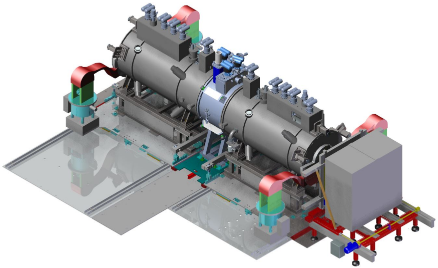

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Emittance and Amplitude

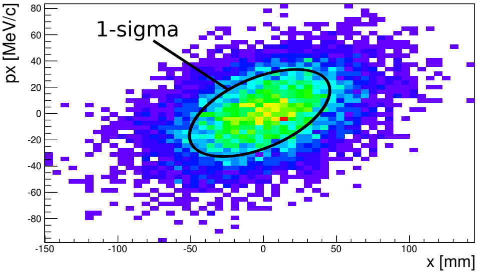
Defining Emittance

The volume of phase-space occupied by an ensemble of particles.

In MICE we focus on the *4-dimensional, transverse, normalised, RMS emittance*, $\epsilon_\perp$, which corresponds to the central 1-sigma of a Gaussian distribution in x, p_x, y, p_y space.

Calculated from the covariance matrix of the ensemble $\mathbf{\Sigma}$, and the muon mass, m.

$$\epsilon_\perp = \frac{|\mathbf{\Sigma}|^{\frac{1}{4}}}{mc}.$$



A typical phase-space projection in x-p_x.

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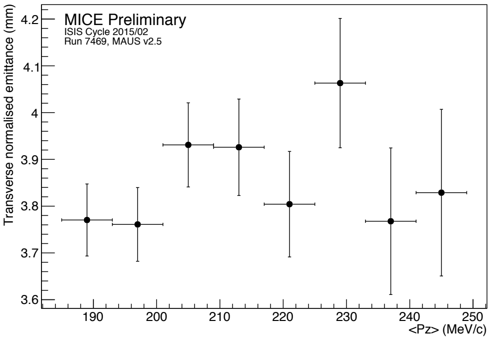
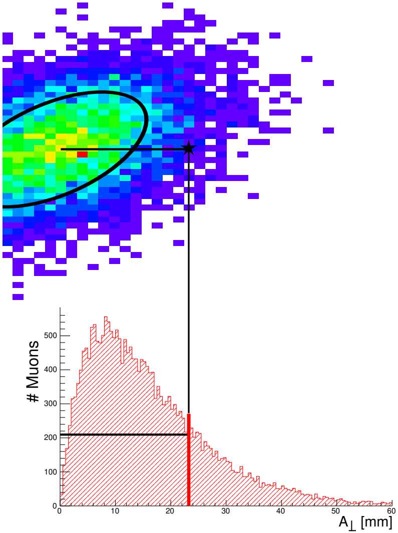
First measurement of emittance of the MICE Beam

- Time-of-flight counters used for primary event selection,
- Upstream spectrometer used for emittance reconstruction,
- Single-track events with a muonic time of flight and a good reconstruction,
- Analyse beam in 8 MeV/c momentum bins, twice the momentum uncertainty,
- Statistical and systematic errors evaluated from all correlations in covariance matrix.



Defining Amplitude



Analysing emittance evolution on a muon-by-muon basis.

The Single Particle Amplitude defined as the scalar distance in phase-space of a particle (with vector $\boldsymbol{v}$) from the centre of the ensemble (with covariance matrix $\boldsymbol{\Sigma}$).

$$A_{\perp} = \epsilon_{\perp} \boldsymbol{v}^{\intercal} \boldsymbol{\Sigma}^{-1} \boldsymbol{v}$$

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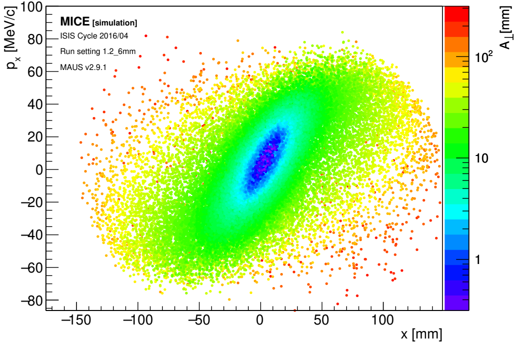
Amplitude and Emittance



x-p_x Phase space, coloured by the individual particle amplitudes.

- Can see the effects of filamentation,
- Core of the beam has a different orientation to the tails,
- Ionisation cooling primarily affects the core of the beam,
- Filamented tails are unlikely to be transmitted in a real cooling channel.

Amplitude distributions can be used to analyse the migration of particles in the core of the beam.

The Cooling Equation

This was the equation driving the development of the MICE Experiment.

$$\frac{d\varepsilon_\perp}{dx} = -\frac{\varepsilon_\perp}{\beta^2 E}\left\langle\frac{dE}{dx}\right\rangle + \frac{\beta_\perp(13.6\mathrm{MeV/c})^2}{2\beta^3 E m_\mu X_0}$$

Rate of change of emittance	=	- Cooling Term (Mean Energy Loss)	+	Heating Term (Multiple Coulomb Scattering)

We needed material with large radiation lengths (X_0) and high mean energy loss ($\langle dE/dx\rangle$), variable emittance ($\epsilon_\perp$) and variable beta function ($\beta_\perp$).

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The MICE Experiment

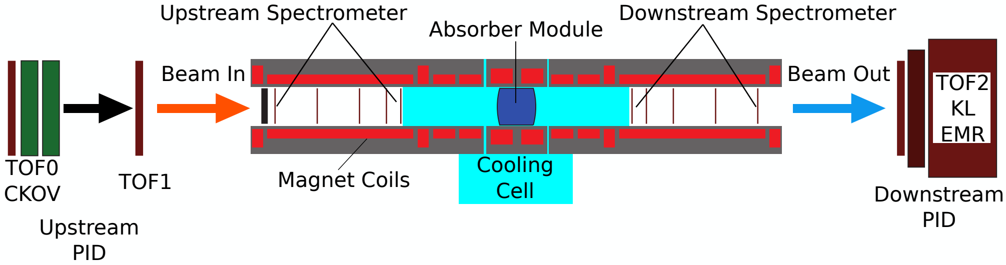
The Analyses

The MICE Experiment is finalising the results from our key measurements:

1. Precision measurements of muon phase space, with comparisons to simulation,
2. Studies of multiple coulomb scattering and energy loss through LH2 and LiH,
3. The first measurement of phase space evolution through LH2 and LiH absorbers,
4. Studies of non-parametric phase space evolution,

This is an exciting time us - what you see today is only a snapshot!

The Experiment



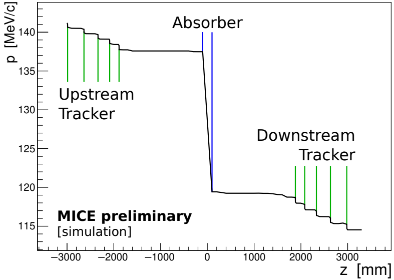
PID detectors and spectrometer select and measure the beam.

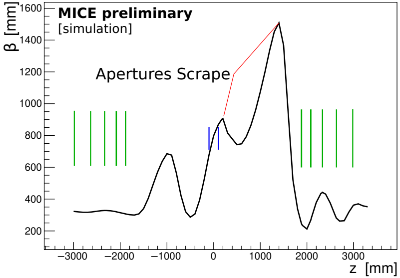
Absorber isometrically removes energy.

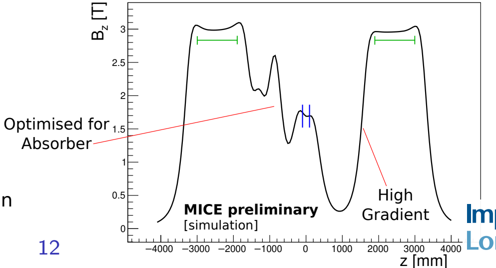
Multiple Coulomb scattering causes emittance growth.

PID detectors and spectrometer measure the outgoing beam.

The Experiment







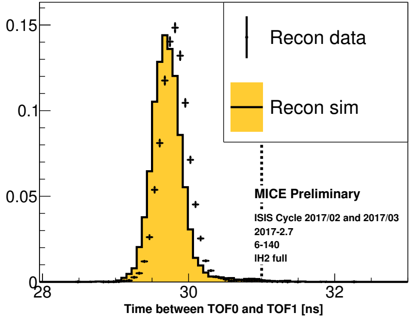
The magnetic lattice has been carefully designed within the hardware constraints of the magnets.

Care must be taken to control filamentation and scraping.

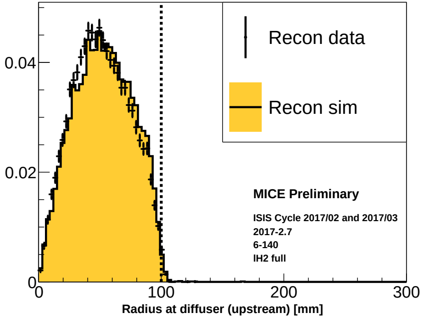
Beam Selection and Cuts

Beam Selection

Selecting the beam entering the cooling channel



Time of Flight between TOF0 and TOF1.



Radius of tracks extrapolated to the diffuser.

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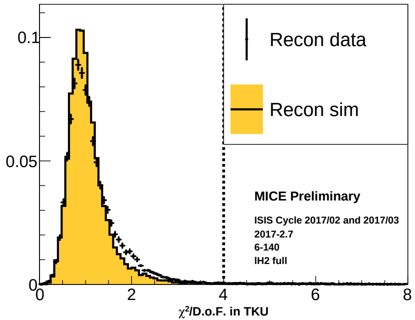
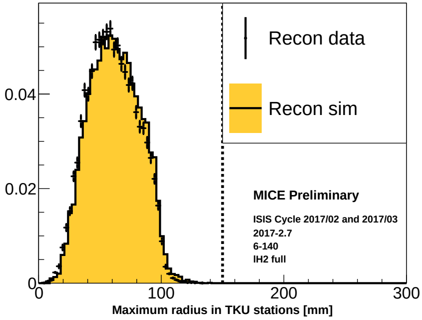
Upstream Cuts

Selecting the beam which is well reconstructed and contained within the fiducial volume.



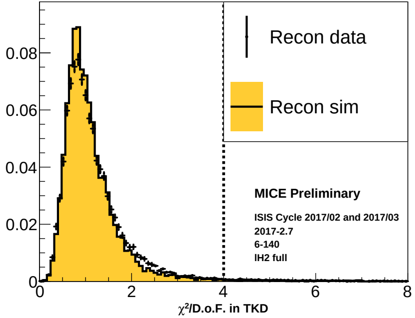
Upstream χ^2 per degree of freedom from reconstruction.



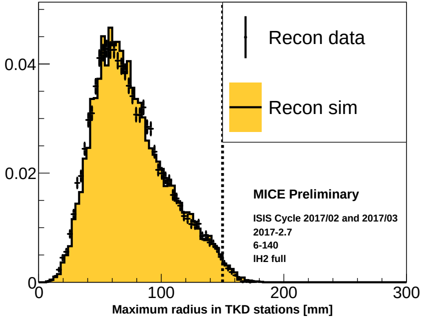
Upstream maximum track radius.

Downstream Cuts

Selecting the beam which is well reconstructed and contained within the fiducial volume.



Downstream χ^2 per degree of freedom from reconstruction.



Downstream maximum track radius.

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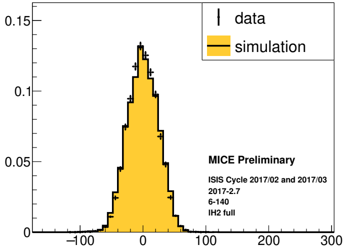
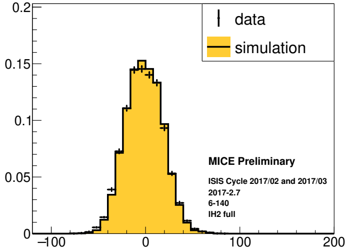
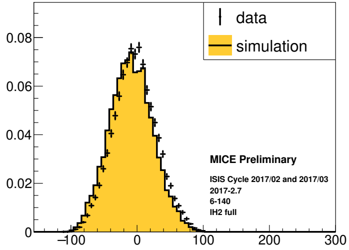
Comparison with Simulation



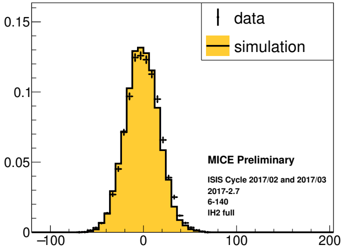
Upstream
x



Upstream
p_y



Downstream
x



Downstream
p_y

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Reconstruction and Analysis

Analysis Process

1. Combine raw data from all runs with the same configuration,
2. Perform detector-level reconstruction: track fitting, spacepoint identification, etc.
3. Use global tracking routines to extrapolate tracks between detectors, ensure only one muon was present within the apparatus,
4. Apply cuts to select events with muonic properties,
5. Perform emittance and amplitude reconstruction.

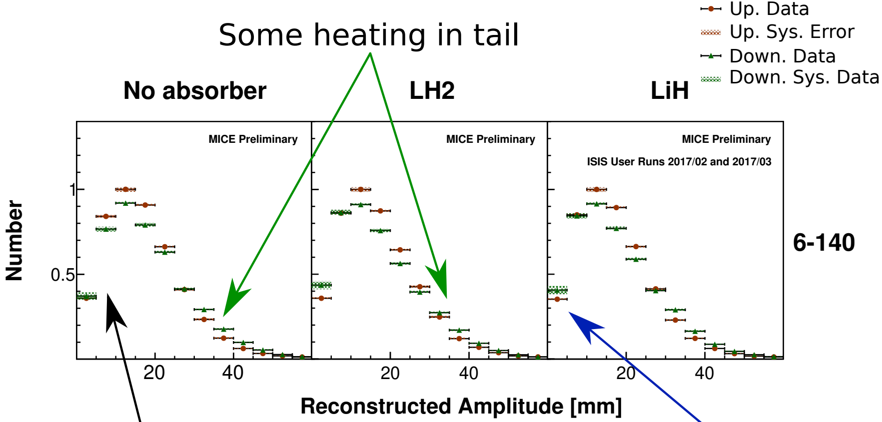
The Data

I will show data from a single magnetic configuration (out of ≈16 recorded).

- Recorded during ISIS User Runs 2017/02 & 2017/03,
- Nominal beam emittances of 6 mm and 10 mm,
- Mean total momentum of 140 MeV/c,
- Absorber Settings:
  1. "No Absorber" Empty volume with single set of vacuum windows,
  2. Liquid Hydrogen Absorber ("LH2") 21 litre Al flask,
  3. Lithium Hydride Absorber ("LiH") Disk ~ 65mm thick.

From simulation we expect both 6 mm and 10 mm beams to demonstrate emittance reduction.

Comparison of Single Particle Amplitudes - 6 mm



No change at low amplitude

Small increase in core density

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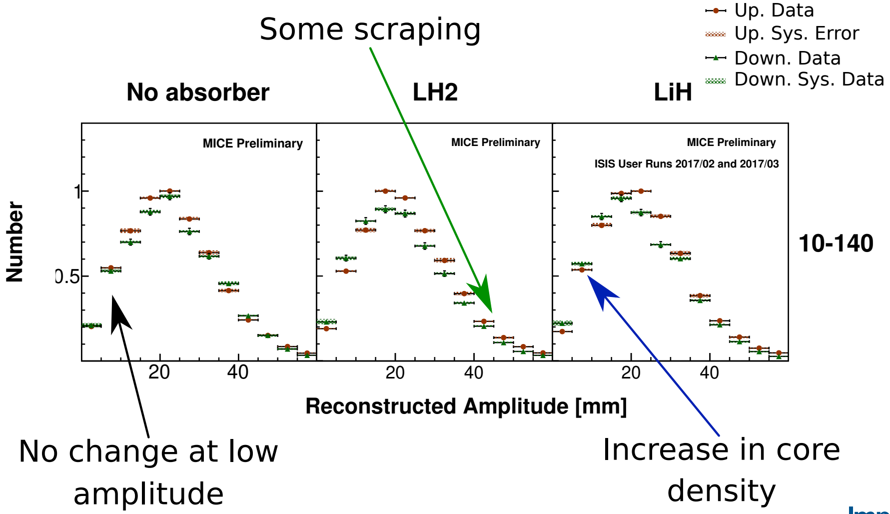
Comparison of Single Particle Amplitudes - 10 mm



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Cumulative Distributions

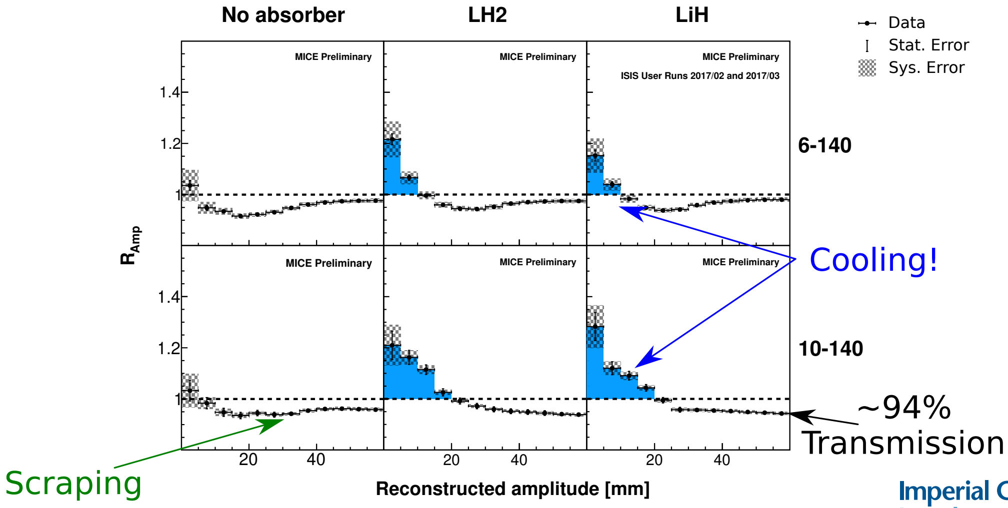
In amplitude-space we are actually looking for a subtle effect, so consider the ratio of the cumulative distributions. i.e. define:

$$R^{N}_{\mathrm{Amp}} = \frac{\sum_{n=1}^{\mathrm{N}} \mathrm{Amp}_n^{\mathrm{down}}}{\sum_{n=1}^{\mathrm{N}} \mathrm{Amp}_n^{\mathrm{up}}}$$

This highlights the effect of muons migrating from high amplitudes to lower amplitudes.

When $R_{Amp} > 1$ We have cooling!

Comparison of Cumulative Amplitude Distributions



Conclusions

1. We have successfully demonstrated that Low-Z materials cause particles to migrate from higher to lower amplitudes - *Ionisation Cooling Works!*
2. The last impediment of a neutrino factory has been removed,
3. We have a simulation that accurately represents the behaviour of the beam,
4. Demonstrated high purity, high efficiency, and high precision in all measurements,
5. A good understanding of the statistical and systematic sources of uncertainty.

And this is just the tip of the iceberg!
We're now engaging in a systematic study of ionisation cooling.