The Physics Program of MICE Step IV

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Abstract

The Muon Ionization Cooling Experiment (MICE) is progressing towards a demonstration of the cooling technology required for the Neutrino Factory and the Muon Collider. MICE Step IV will allow the cooling properties of liquid hydrogen and lithium hydride to be studied in detail and provide the first opportunity to observe the reduction of normalized transverse emittance. An absorber sited within a superconducting focus-coil magnet will cause the muon beam to lose energy. The muon-beam phase space upstream and downstream of the absorber/focus-coil module will be measured using two solenoidal spectrometers. After a brief summary of the status of the experiment, the physics program of Step IV is described. The timetable for the demonstration of a realistic cooling cell in which the beam is re-accelerated will also be discussed.

Ionization Cooling

- Conventional beam cooling methods take too long ($\tau_\mu \approx 2.2\ \mu s$)
- The rate of change emittance is described by:

$$\frac{d\epsilon_n}{dz} \approx \frac{-\epsilon_n}{\beta^2 E}\left\langle\frac{dE}{dz}\right\rangle + \frac{\beta_t (14\,MeV)^2}{2\beta^3 E m_\mu X_0}$$

β_t = Optical Beta function
X_0 = Radiation Length
$E\beta$ = Momentum

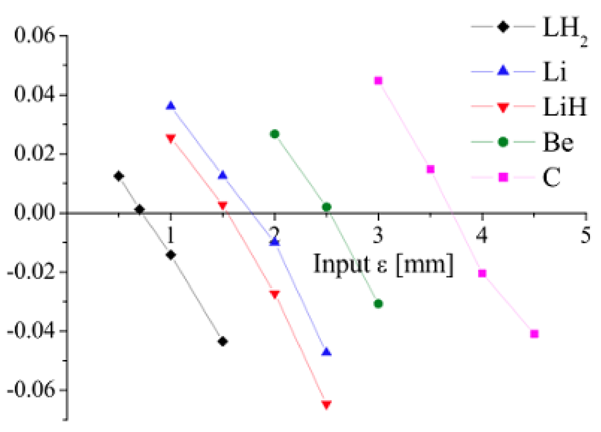
- The change in emittance is then the difference between the two terms:
  - *Cooling* from ionization and
  - *Heating* from multiple scattering.
- The Equilibrium emittance is:

$$\epsilon_0 \approx \frac{\beta_t (14\,MeV)^2}{2\beta m_\mu X_0}\left\langle\frac{dE}{dz}\right\rangle^{-1}$$

- Therefore to maximize the $X_0 \left\langle\frac{dE}{dz}\right\rangle$ term, the collaboration will study low Z materials.
- To facilitate this, Step IV has been designed to allow the study of various absorber materials.

Absorbers in the MICE Step IV program

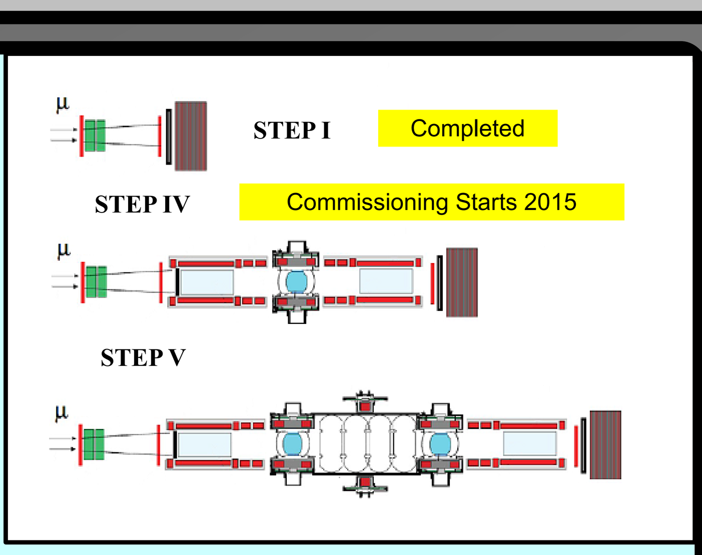
Material	X_0	dE/dX	ρ	Δz
	gcm^{-2}	$MeVg^{-1}cm^2$	gcm^{-3}	cm
LH_2	63.04	4.103	0.07	35
LiH	79.62	1.897	0.82	6.3

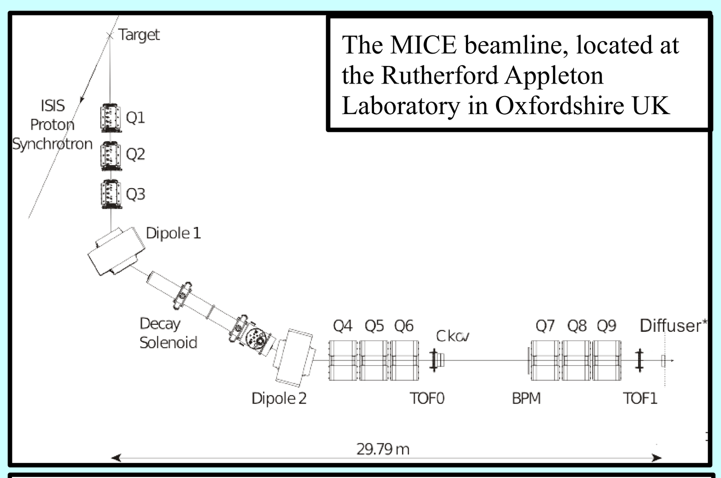


(Left) Mice Step IV will use LH_2 and LiH as absorbing materials. (Right) Expected change in emittance for various absorbing materials as determined by simulation.

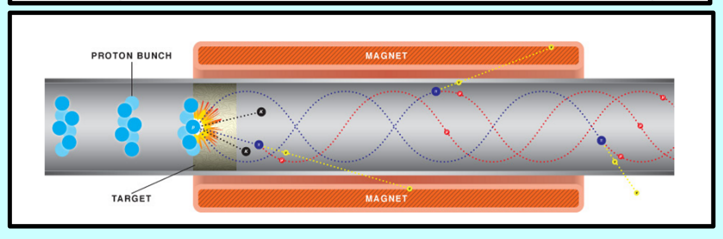
Overview

- Constructed in steps:
  - Step IV:
    - Study of the cooling properties of LH2 and LiH
  - Step V:
    - Measurement and detailed study of ionization cooling





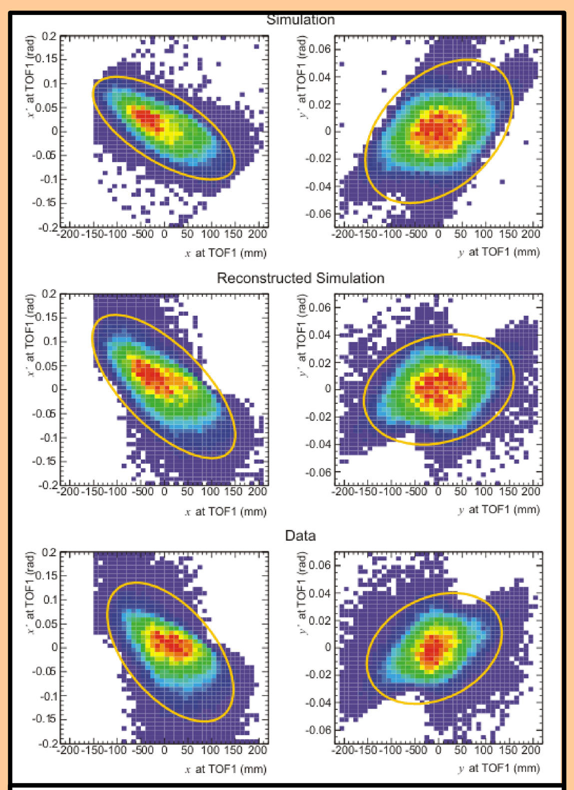
The MICE beamline, located at the Rutherford Appleton Laboratory in Oxfordshire UK



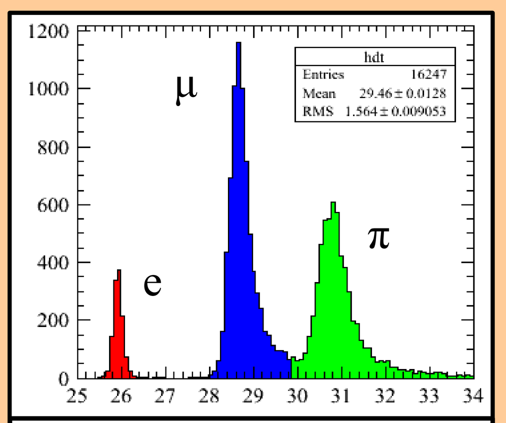
- Single particle measurements
- Ti target "dipped" into ISIS proton beam
- Momentum range: 140 MeV/c to 240 MeV/c
- Emittance range: 2 π mm rads to 10 π mm rads

MICE Step I

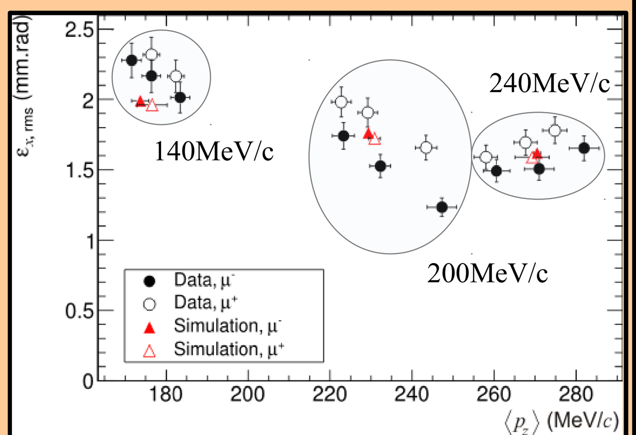
- Step I goal to characterize the MICE beam and the commissioning of the PID detectors
  - Collected 1.3×10^7 triggers since start in 2010
  - Emittance measured using time-of-flight hodoscopes
- Demonstrated that MICE beam can deliver the range of momentum and emittance needed to carry out the MICE experimental program



Data vs Simulation in TOF1, ellipses define trace space to be used in emittance calculation



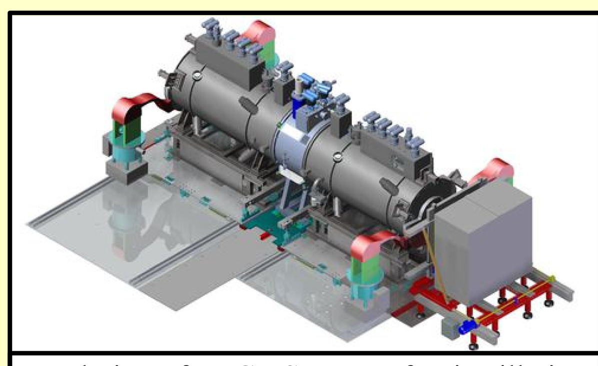
Characterization of the MICE beam from time of flight data



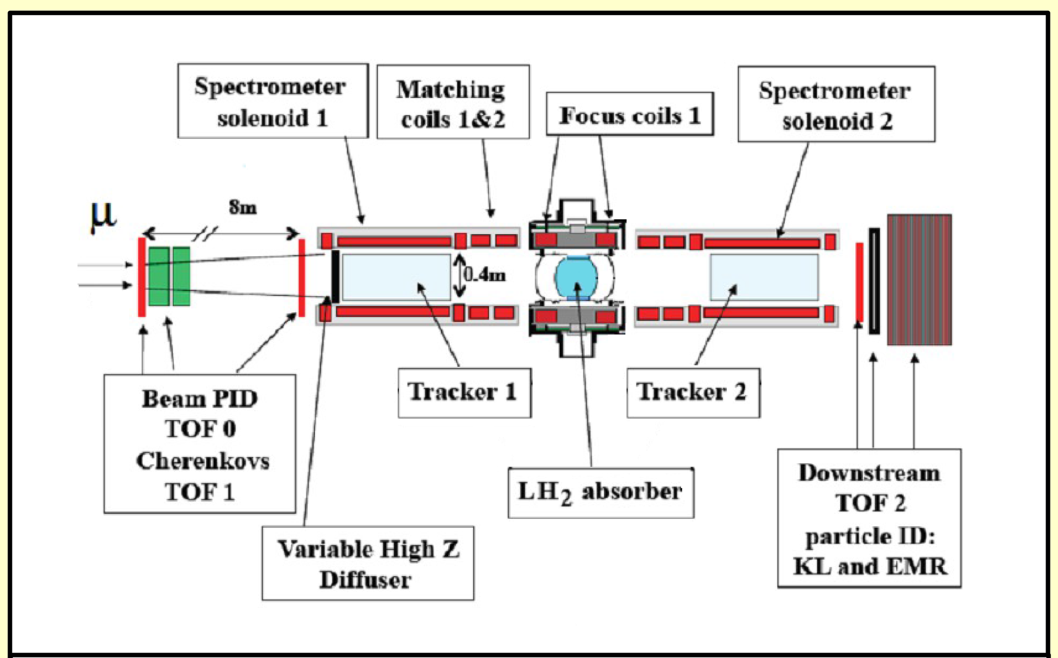
Reconstructed emittances using TOF0 and TOF1

MICE Step IV

- First measurement of emittance cooling
- Step IV consist of:
  - Diffuser; produces a range of emittances
  - Absorber and focusing coil module
  - Two scintillating fiber trackers, upstream and downstream of the absorber
  - Two spectrometer solenoids, providing the uniform 4T field for the trackers
  - A suite of detectors used for PID
    - Two TOFs and two Cherenkov detectors to identify muons in the upstream tracker
    - An additional TOF, a Kloe-Light calorimeter and an Electron Muon Ranger to reject electrons from decayed muons in the downstream tracker



Rendering of MICE Step IV after instillation is completed in 2015



Final design of MICE Step IV with components labeled

Acknowledgments and References

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- **More MICE at ICHEP?** See Prof Kenneth Long's *The status of the construction of MICE Step IV*, 3 Jul 2014 16:05, as part of the Accelerator Physics and Future Colliders session

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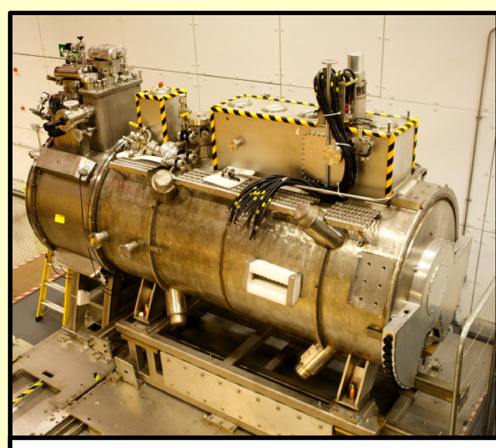
Step IV Measurements

Emittance Reduction



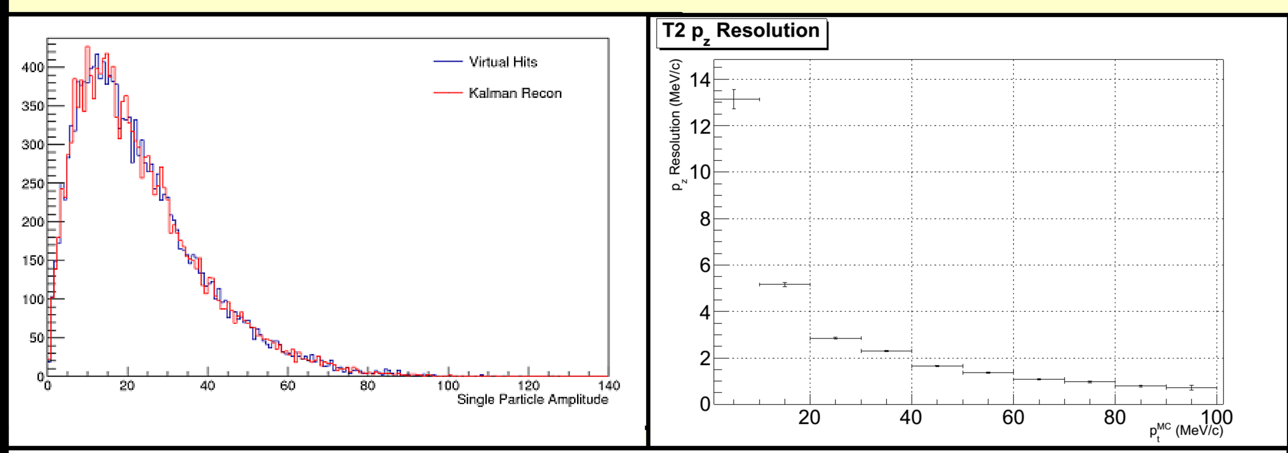
The upstream MICE Spectrometer Solenoid and the first Focusing Coil module in the MICE hall

- Scintillating fiber tracker placed in a 4T solenoidal field
  - Each tracker consists of five tracking planes which gives single particle positions with a 470 μm resolution
  - Allows for precision measurements of x, p_x, y, p_y, and E
- Kalman fitting will be used to take into account multiple scattering as particle moves though trackers
- Beam optics determined from ensemble of single particle measurements, emittance is give by:

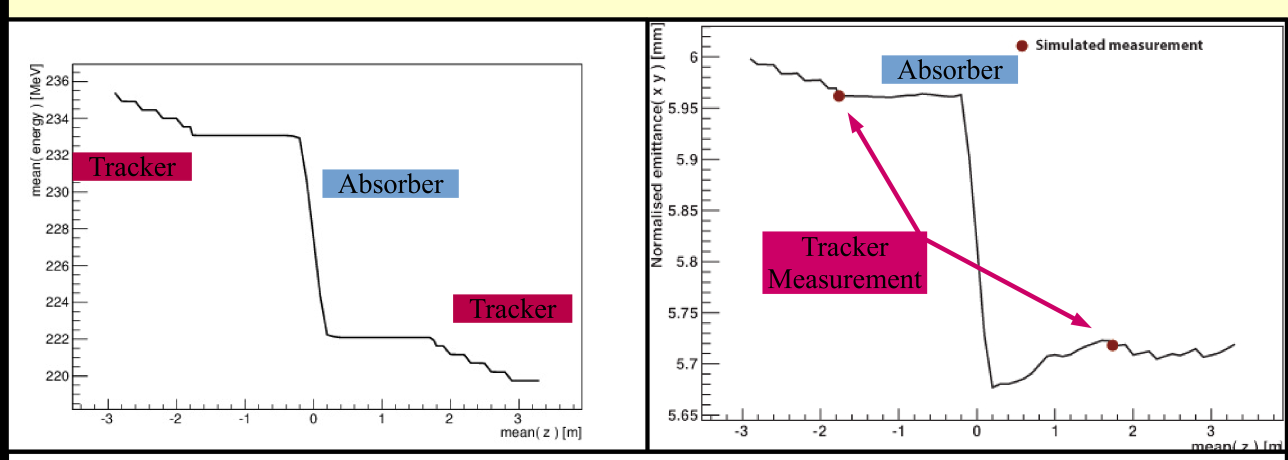
$$\epsilon_n^{4D} = \frac{1}{m_\mu}\sqrt[4]{\left|V^{4D}_{(x,p_x,y,p_y)}\right|} \qquad \epsilon_n^{2D} = \frac{1}{m_\mu}\sqrt{\left|V^{2D}_{(t,p_t)}\right|}$$

V = Covariance matrix

- Upstream measurements compared against downstream to determine total cooling



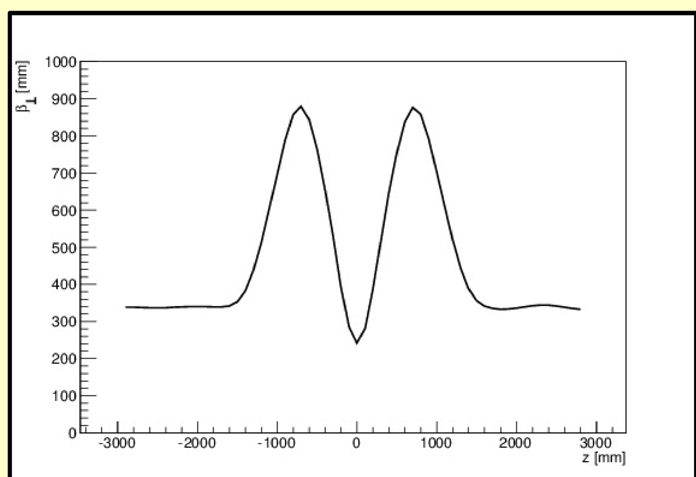
MC "virtual" hits against MC recon in single particle amplitude (left) and expected longitudinal resolution in the MICE downstream tracker (right) indicate tracker reconstruction software is prepared for STEP IV



Simulated mean energy loss (left) and emittance reduction (right) of MICE beam in the STEP IV cooling channel with LH2 absorber

Beam Matching

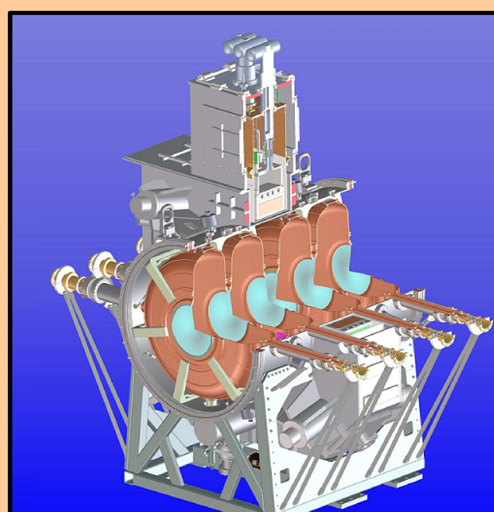
- A tightly focused beam allows for a maximized equilibrium emittance.
- Focus coil optics at the absorber are selected based upon incoming beam momentum
- Matching is preformed in Spectrometer matching coils
  - Designed to be matched to α_t=0, β_t=333 mm at p_z=200 MeV/c at the upstream tracking volume



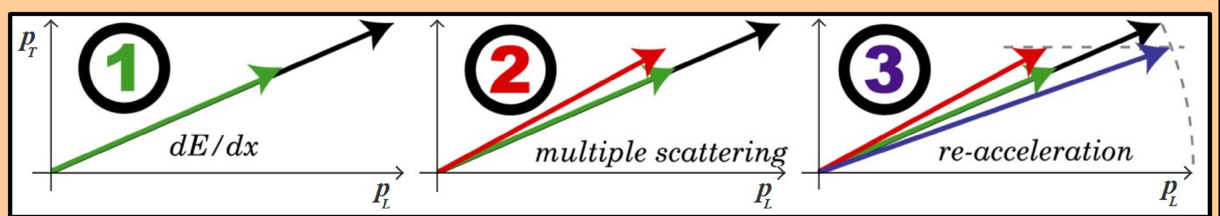
Expected β values in a matched beam as it moves through the MICE cooling channel with LH_2 absorber

MICE Step V

- Constitutes a half lattice cell based on the Neutrino Factory Study II cooling channel
- Changes to the cooling channel:
  - RF coupling coil module
    - Four copper cavities
    - 8 MV/m gradient
    - 201.25 MHz
  - Additional absorber and focusing coil module.



Design of the completed RFCC module



Cooling in Step V: 1. Ionization cooling 2. Multiple scattering 3. Re-acceleration from RF cavities