Muon Ionization Cooling Experiment (MICE)

Progress in the Construction of the MICE Cooling Channel
First Measurement of Emittance with Particle Physics Detectors

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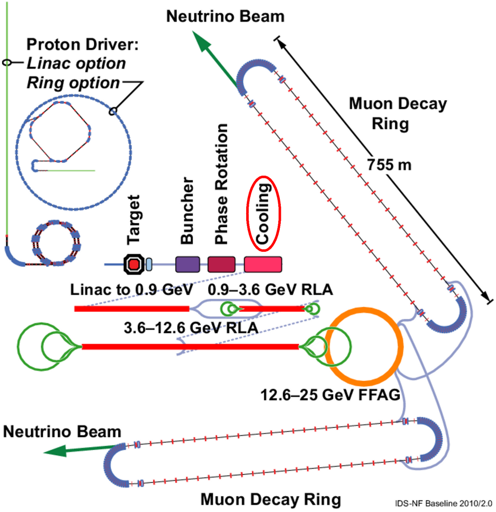
General Motivation



- A Neutrino Factory based on muon storage ring is the ultimate tool for studies of neutrino physics. It is also a step towards a muon collider.
- Ionization cooling has never been demonstrated in practice but has been shown by simulation and design studies to be an important factor both for the performance and for the cost of a Neutrino Factory.

Ionization Cooling: Principle

The principle of ionization cooling relies on the cooling rate formula, expressing the emittance variation in a medium with thickness X ($g \cdot cm^2$) due to ionization(cooling) and multiple scattering(heating):

$$\frac{d\epsilon_n}{dX} = -\frac{\epsilon_n}{\beta^2 E_\mu}\left\langle \frac{dE_\mu}{dX} \right\rangle + \frac{\beta_t (0.014 GeV)^2}{2\beta^3 E_\mu m_\mu X_0}$$

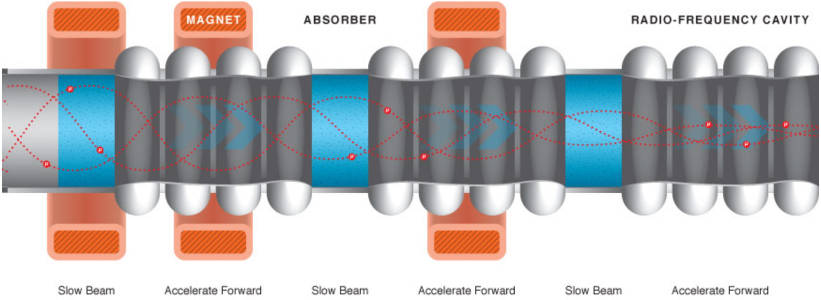
where ϵ_n is the normalized 4D emittance of the beam, β_t is the betatron function, and β is the velocity of the particle. The ideal cooling channel should produce the lowest possible emittance:

$$\epsilon_{eq} = \frac{\beta_t (0.014 GeV)^2}{2\beta m_\mu X_0} \left\langle \frac{dE_\mu}{dX} \right\rangle^{-1}$$

Hence, the goal is to minimize the β_t and maximize $X_0 \langle \frac{dE_\mu}{dX} \rangle$. Therefore liquid hydrogen has been chosen for the first realization of a cooling channel.

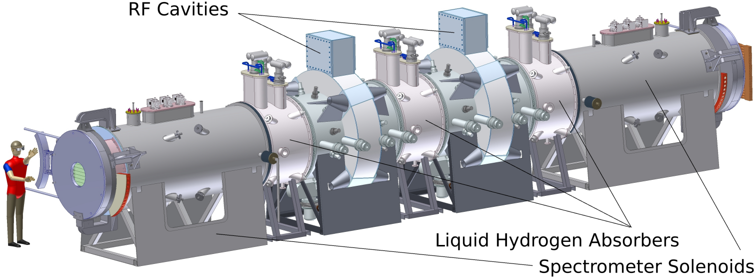
Ionizatoin Cooling: Concept

Due to the short muon lifetime (2.2 μs), ionization cooling must be used. The cooling of the transverse phase-space coordinates of a muon beam can be accomplished by passing it through a light energy-absorbing material and an accelerating structure, both embedded within a focusing magnetic lattice. Longitudinal and transverse momentum are lost in the absorber while the RF-cavities restore only the longitudinal component.



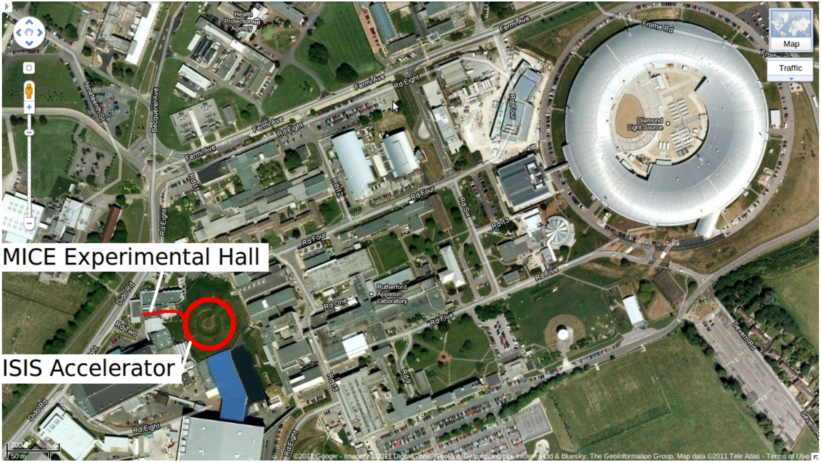
MICE

The Muon Ionization Cooling Experiment (MICE) aims to construct a cooling cell with all the equipment necessary to measure the emittance of a muon beam before and after this cell based on single particle measurements and achieve 10% cooling of 200 MeV/c muons. The cooling cell will be sandwiched between two identical trackers inside 4T superconducting solenoids, complemented by upstream and downstream particle detectors.



MICE: Location

The MICE is located at the Rutherford Appleton Laboratory, UK. The ISIS facility provides intense proton beam.



MICE Collaboration: Facts

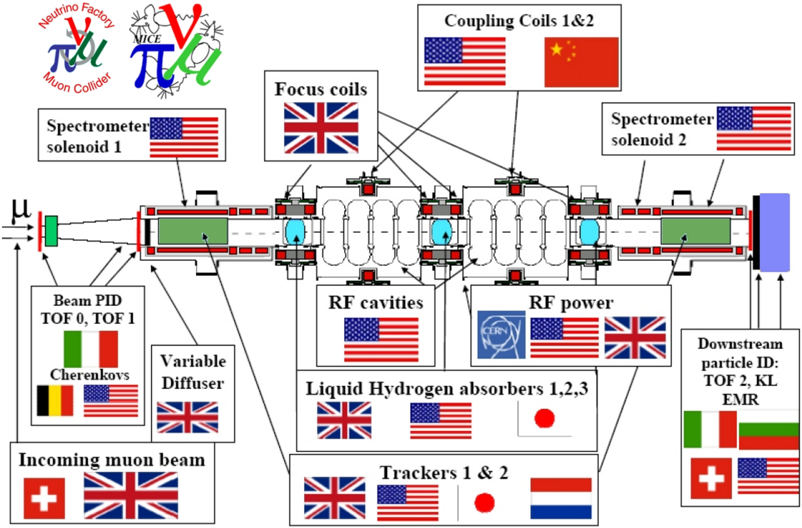
Statistics

- more than 140 scientists
- 37 institutes and universities
- 9 countries:
  - Bulgaria, Italy, Japan, China, Netherlands, Russian Federation, Switzerland, UK, USA

History

- Nov. 2001 - Letter of Intent (LOI) submitted to PSI and RAL
- Mar. 2002 - LOI reviewed at RAL
- Oct. 2003 - Scientific approval letter by RAL CEO
- Mar. 2005 - MICE Phase I approved officially

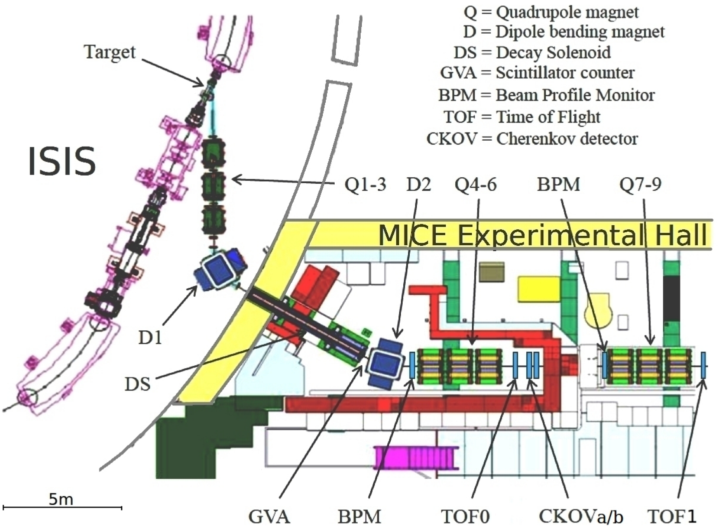
MICE Collaboration: International Involvement



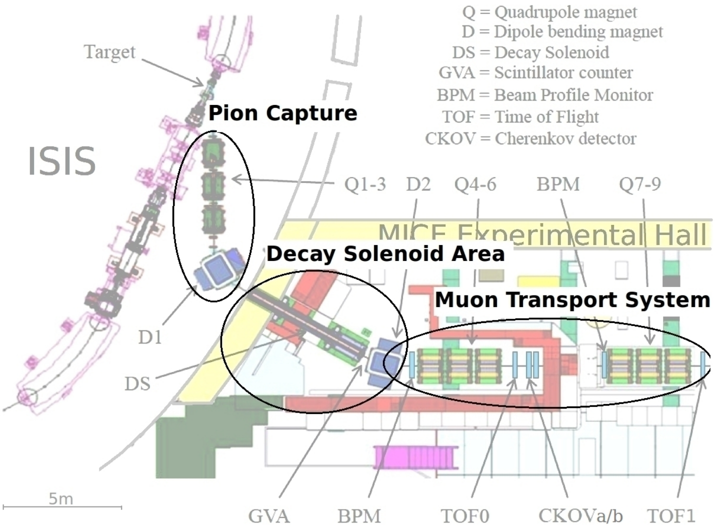
MICE Beam Line: Concept

- The ISIS synchrotron accelerates a high intensity proton up to 800MeV, 300μA at 50 Hz which hits the target providing pions for a pion-muon decay channel, and thereby muons for MICE.
- The muon beamline makes use of existing dipole and quadrupole magnets, together with a superconducting solenoid contributed by PSI in Switzerland. First dipole bending magnet allows to select pion momentum and the second one provides muon momentum selection yielding a high purity muon beam.
- MICE requires muon momenta 140-240 MeV/c, with a $\pm$10% momentum acceptance. Both muon signs can be obtained by switching magnet polarities.

MICE Beam Line: Description

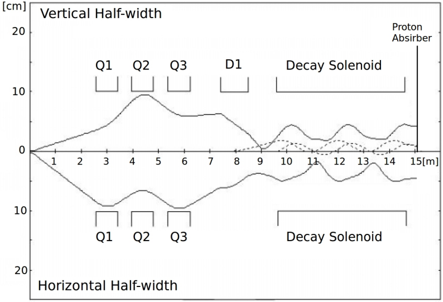


MICE Beam Line: Description



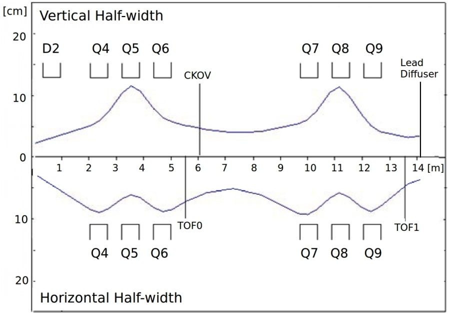
MICE Beam Line: Beam Profile Simulation

Pion capture and decay



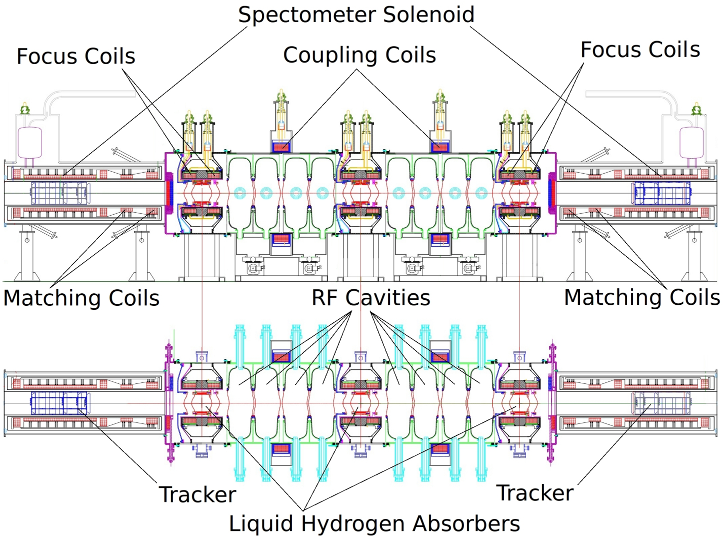
This section is designed to capture as large a pion acceptance as possible from the target, and to select the pions into the decay section. The decay solenoid then serves to accumulate as large a flux of muons as possible.

Muon transport

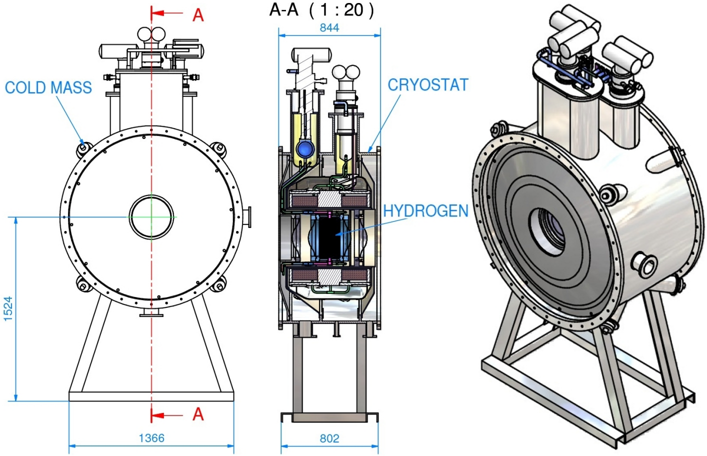


This section consists of a large aperture dipole, to select muons of the desired momentum, and two sets of large aperture quadrupole triplets to transport the muon beam towards the experiment. High-Z (lead) diffuser generates a tunable input emittance.

The Layout of the MICE Cooling Cell

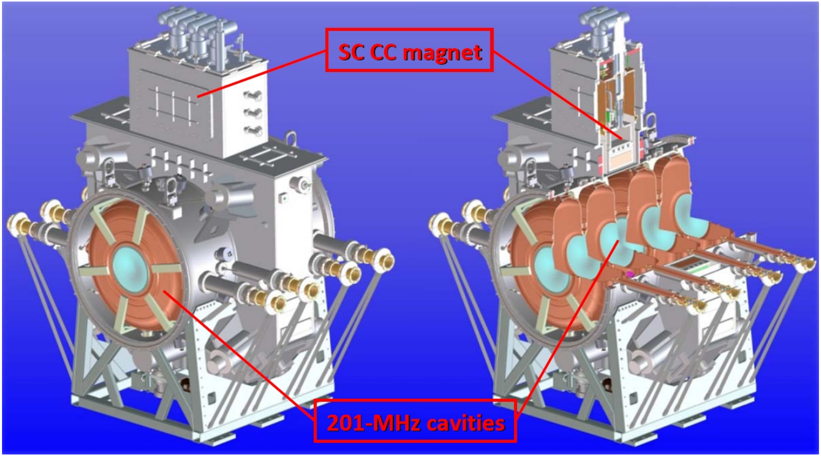


Liquid Hydrogen Absorber Module



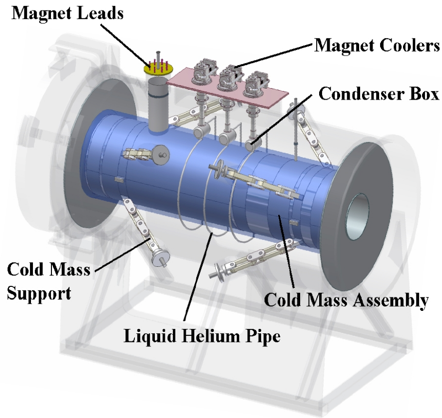
Each muon loses about 12 MeV in the absorber, i.e. 1 W for a beam of $5 \cdot 10^{11}$ muons per second. The set of two focus coils provides small β_t inside the absorber.

RF and Coupling Coil (RFCC) Module

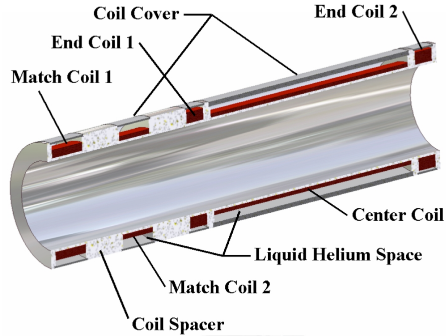


RFCC module has four 201 MHz normal-conducting RF cavities and one superconducting coupling coil (solenoid) magnet. Each RF cavity has a pair of curved Be windows and it operates in a few Tesla magnetic field at 8 MV/m.

Spectrometer Solenoids

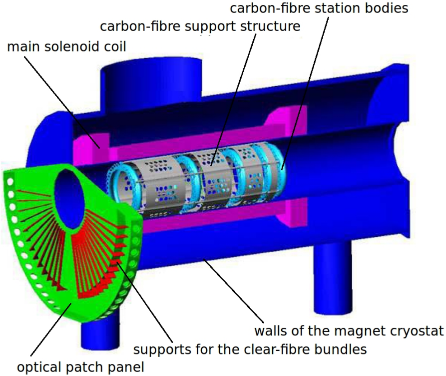


The two spectrometers modules are fully symmetrical. Each is made of a cylindrical tracker immersed into a solenoid field of 4 T.

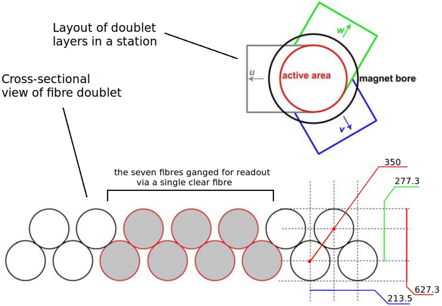


The main solenoid coil is flanked by two correcting coils ensuring field uniformity. Two additional coils on the absorber side provide matching optics with the cooling cell. The three coils are connected in series and are powered by a single 300 amp power supply.

Scintillating Fibers Tracker

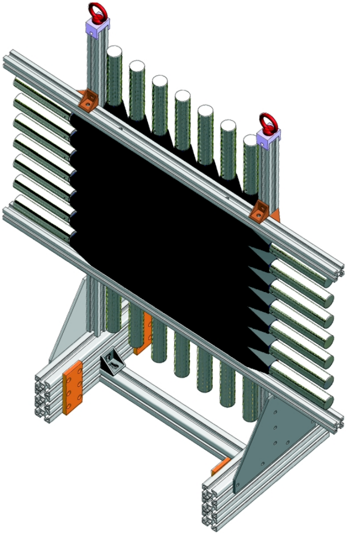


The tracker is made of 5 stations of 350μm scintillating fibers perpendicular to the beam axis. The station is made of three planes of fibers rotated by 120°. This allows to reconstruct the full helix track and obtain the momentum.



The optical connectors on the station mates seven scintillating fibers to 1.05 mm clear-fiber light guide which transports the light from the stations to an optical patch panel mounted on the end flange of the magnet cryostat. The scintillation light is detected by Visible Light Photon Counters - low band-gap silicon avalanche detectors operated at ~9K.

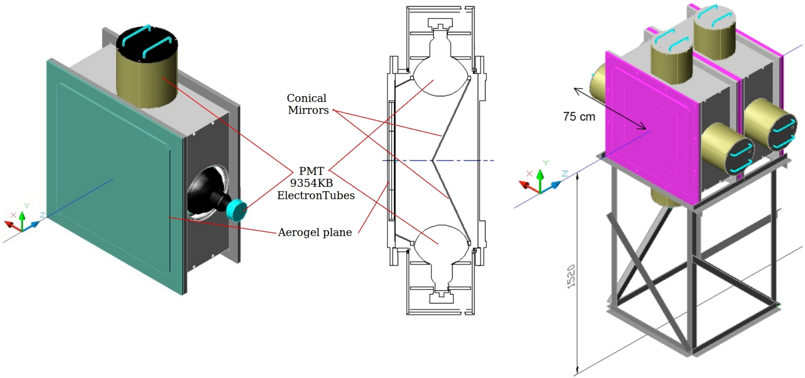
Time of Flight Stations: TOF0, TOF1, TOF2



The TOF stations are used for the particle trigger and timing. The timing of each muon allows synchronization to within 50-60 ps with the RF cavity phase. TOF0 and TOF1 are installed in the beamline and TOF2 - after the second spectrometer.

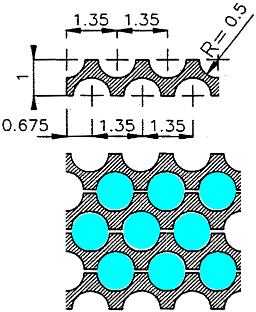
- made of two crossed planes of plastic scintillator 2.54 cm thick and 4-6 cm wide
- covers $\sim$50 cm^2 active area
- dual PMT readout
- shielded against stray magnetic field
- 50-60 ps intrinsic timing resolution
- a trigger signal is given by the first dual coincidence of the PMTs connected to the same TOF0 bar unit

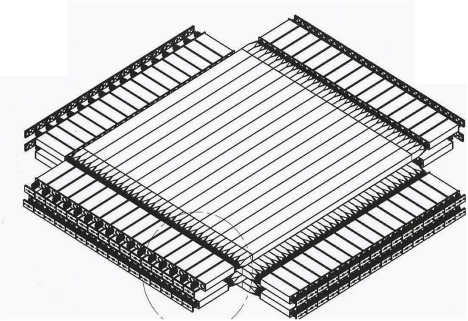
Cherenkov Counters: CKOVa, CKOVb



First two CKOVs are installed in the beamline. The Cherenkov light produced in a 2.3 cm thick layer of hydrophobic aerogel is collected by four intersecting conical mirrors reflecting it on four 8” PMTs. Refractive indices of 1.07 and 1.12 are used respectively for the two aerogel planes, ensuring a good muon/pion/electron separation at high momentum: electrons trigger both counters, muons - only one and pions - none.

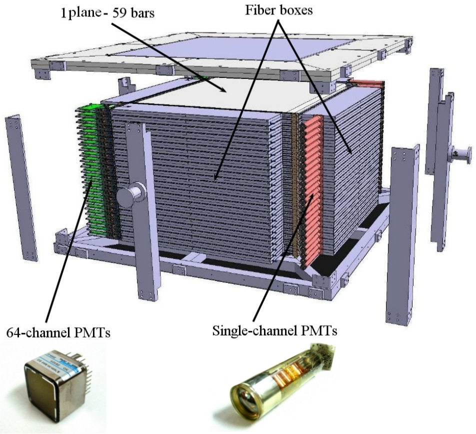
Calorimeter: KL





The calorimeters are dedicated to the separation between the muons and the electrons produced by muon decaying in the cooling channel. A design study has demonstrated that a better particle identification is obtained with a detector made of two parts. The first part (KL) is a 4 cm thick conventional sampling calorimeter made of grooved lead foils interleaved with scintillating fibers. It forces the electrons to shower while most of the muons are going through. The second part is EMR (see next page).

Calorimeter: Electron-Muon Ranger (EMR)

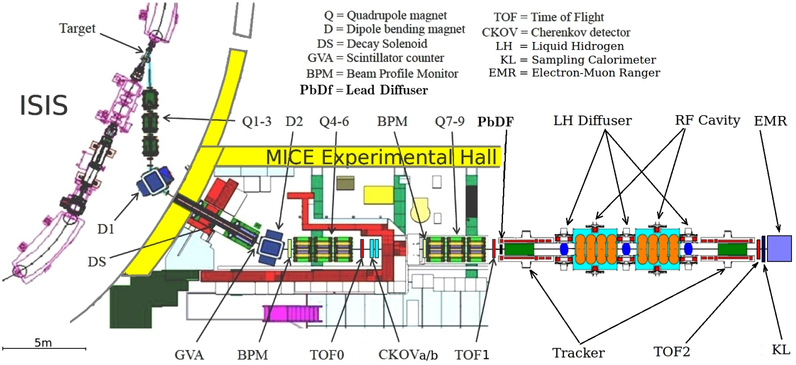


Fully active scintillator calorimeter is located at the very end of the cooling channel. It will stop all muons and electrons and give very distinct signatures for both allowing to measure a muon range. It has the following characteristics:

- 1 m^3 of active volume
- 48 planes composed of 59 triangular scintillator bars with glued 1.2 mm wavelength shifting fibers
- light is collected by single-anode PMT on one side of a plane and by 64-channel PMTs - on the other: 3120 channels in total

- the granularity of the detector allows it to reconstruct individual tracks and measure energy deposition in every bar

Beam Line + Cooling Channel + PID



- MICE is designed to produce a 10% cooling effect on the muon beam
- Use particle detectors to measure the cooling effect to $\sim$1%
- Measurements done using muon beams with momentum 140-240 MeV/c and different selected emittances

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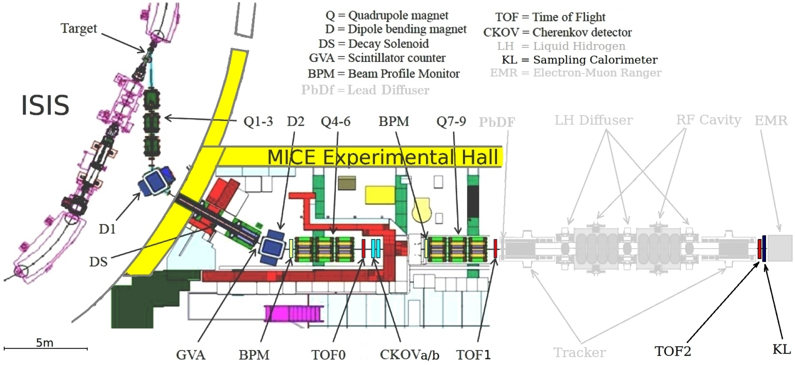
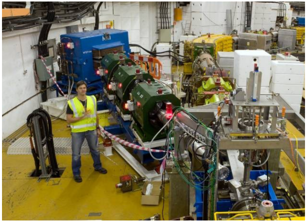
Beam Line Overview

The following (not shaded) components of the experiment have been already installed in the experimental hall. Shaded components have been mostly produced and under tests at the moment.

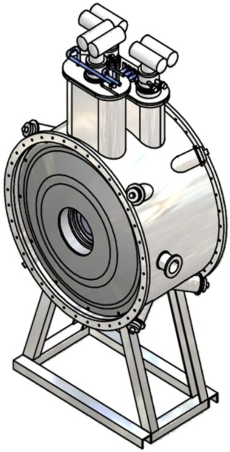


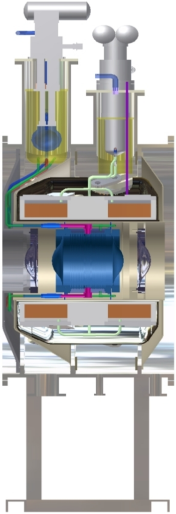
Beam Line Installations

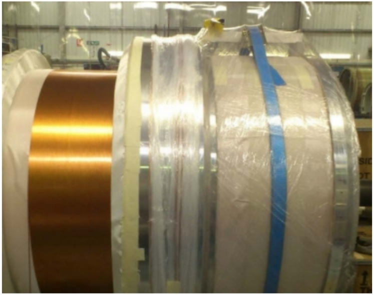


- Target, Q1, Q2, Q3, D1 are installed inside ISIS synchrotron enclosure
- Decay Solenoid, Q4, Q5, Q6, TOF0, CKOVa/b are inside decay solenoid area
- Q7, Q8, Q9 are in MICE Hall

Absorber Focusing Coils

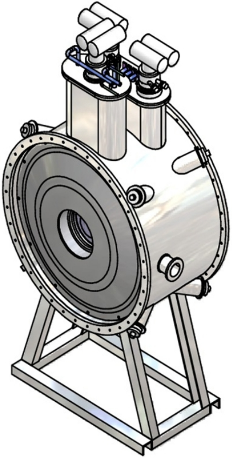


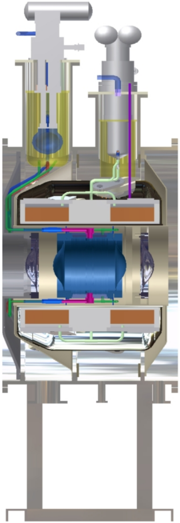


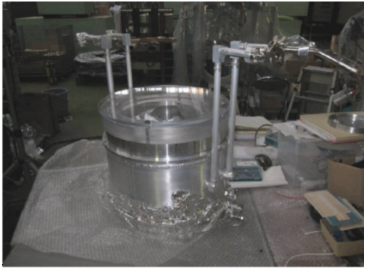


- Winding of absorber focusing coils is complete
- Cryocooler test is in progress
- Installation in MICE hall at RAL in October / December 2011

Liquid Hydrogen Absorber

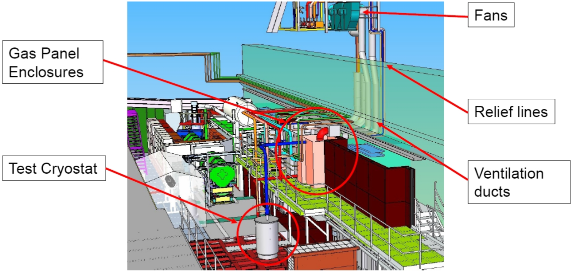






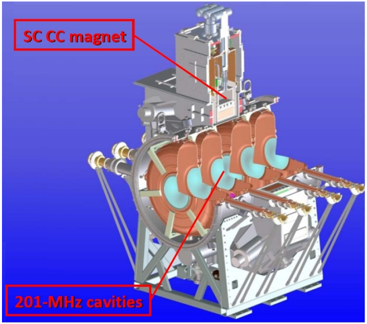
- Liquid Hidrogen absorbers have been built at KEK, Japan in 2010
- First absorber has been tested and delivered to RAL
- Second absorber is ready for cooling down after final set-up

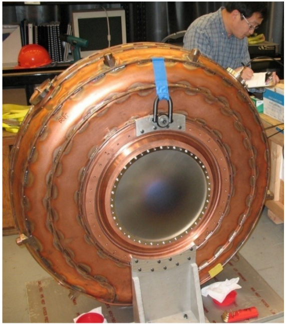
Liquid Hydrogen Delivery System

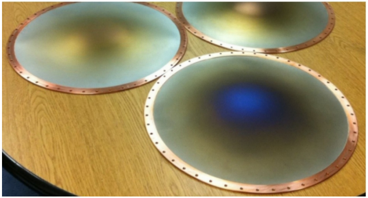


- Installation of the Hydrogen Delivery System infrastructure is well advanced and progressing well
- Gas Panel, Cryostat and Transfer Line delivered to the MICE Hall and installed in December 2010
- Aim to complete R&D with hydrogen by the end of 2011

RFCC Module

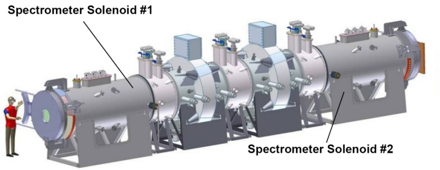


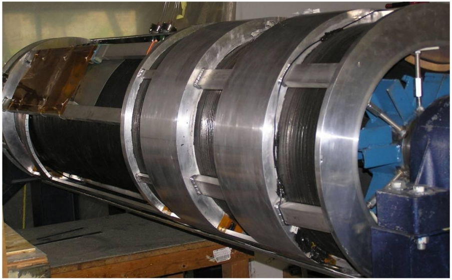


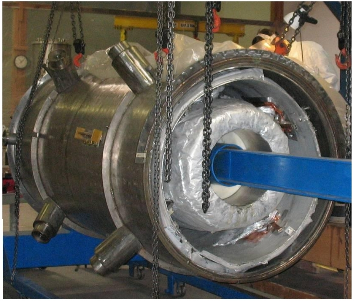


- All ten cavities (two spares) and nine beryllium windows manufactured and received at BNL in 2010
- First coupling coil winding complete at Qi Huan Company
- Cryostat design complete

Spectrometer Solenoids

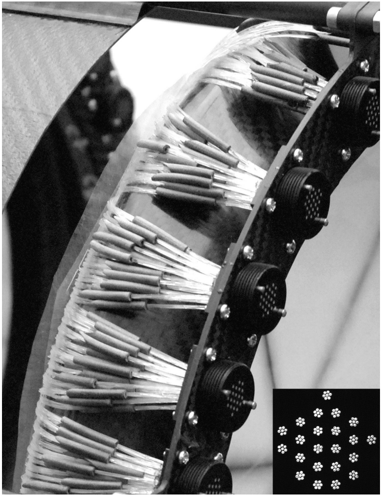






- Magnets produced in US but need to be modified
- 1st to be completed and ready for test by end of 2011, 2nd, roughly 3 months later
- Will be delivered to RAL in 2012

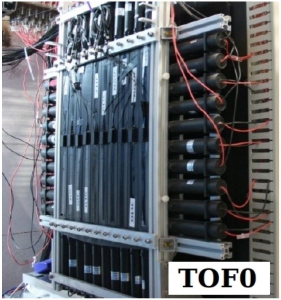
Scintillating Fibers Tracker

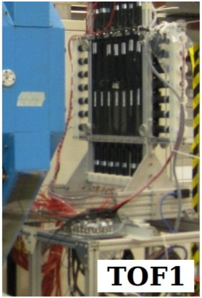


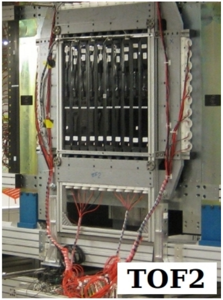
Both of the upstream and downstream tracker have been constructed and performance has been examined with cosmic-ray runs performed at RAL in 2008-2009:

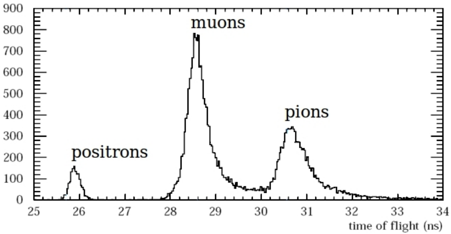
- light-yield - 11.23$\pm$0.01 photo electrons
- RMS of the residual distributions 682μm$\pm$1μm
- channel resolution - 470μm
- space-point efficiencies - 99.7% for each station

Time of Flight Stations: TOF0, TOF1, TOF2



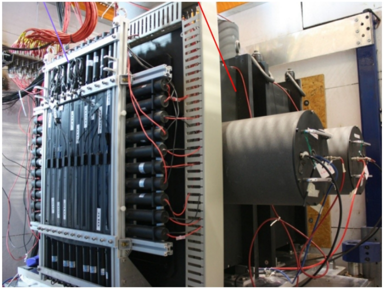


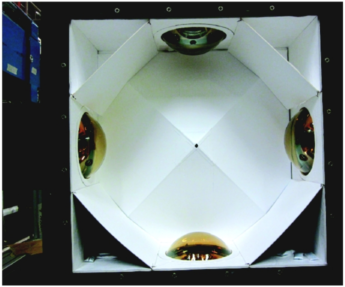


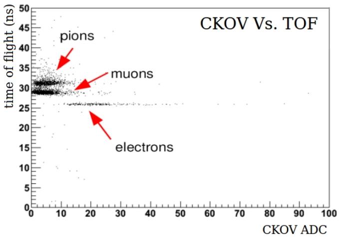


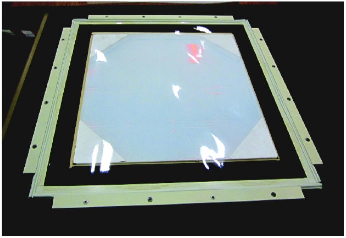
- Time resolution after calibration:
  - TOF0: 51ps
  - TOF1: 58ps
  - TOF2: 52ps
- This allows effective particle identification.

Cherenkov Counters: CKOVa, CKOVb

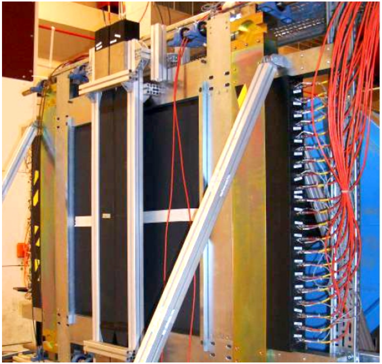


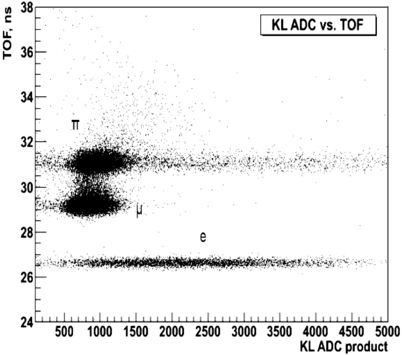






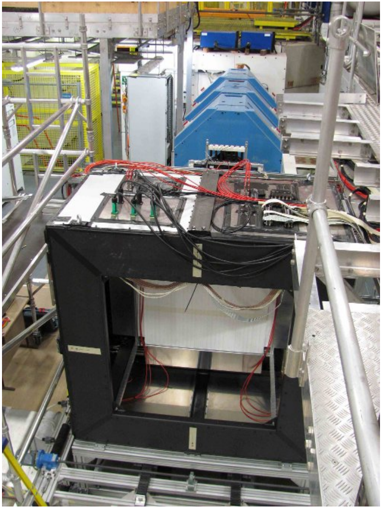
Calorimeter: KL

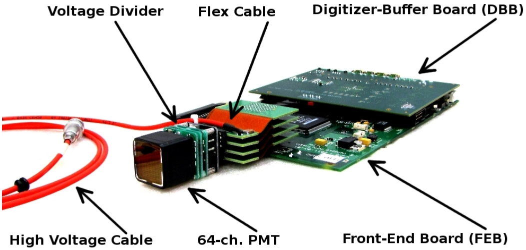




The KL electromagnetic calorimeter was installed in the MICE Hall in June 2008 and operates successfully since then. It allows to distinguish between electrons, muons and pions at different energies. Muons/electrons/pions with momentum above 135/160/70 MeV/c at KL entrance will pass through KL.

Calorimeter: Electron-Muon Ranger (EMR)





- EMR box with 3 X-Y modules (6 planes) was installed in the MICE hall on June 16th for preliminary tests
- electronics and DAQ have been successfully tested
- many modifications will be implemented this year
- construction will be finished next year

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Definition of Emittance

The normalized root mean square (RMS) emittance in 6 dimensions is defined as

$$\epsilon_{rms} = \frac{1}{m_\mu}\sqrt{|V|}$$

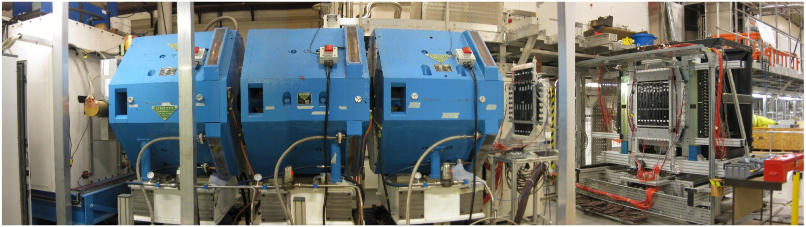
$|V|$ is the determinant of the 6×6 covariance matrix of the phase space vector

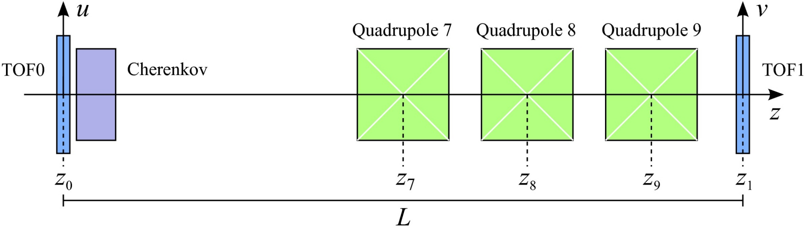
$$\vec{U} = (\vec{x}, \vec{p})$$

where $\vec{x} = (x, y, t)$ and $\vec{p} = (p_x, p_y, E)$.

- All these 6 variables will be measured in spectrometers before and after cooling cell on a particle-by-particle basis and then bunched to up to 10^6 particles for emittance calculation.
- The beam before colling channel can be measured by timing detectors. Data from TOF0 and T0F1 were used already to analyze the performance of the existing MICE muon beam line.

Measuring Emittance with Upstream TOF system



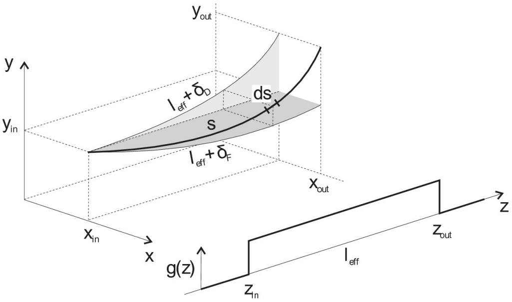


Estimation of the Momentum

The average momentum between the TOFs is given by

$$p(s,t) = \frac{m_0 s/t}{\sqrt{1 - s^2/(ct)^2}},$$

where the path length $s = L + \delta$ is reconstructed by tracking the particle's trace-space vectors $(x, dx/dz)$ and $(y, dt/dz)$ through the beam line, and integrating the path length through each section. The initial trace space vector at TOF0 can be transported to TOF1 by a transfer matrix $(x_1, x_1') = M(x_0, x_0')$ defined by quadrupole parameters. Since the TOFs provide a measurement of (x_0, x_1) and that det M = 1 for linear transformation, it is possible to find the angles $x' = dx/dz$ and $y' = dy/dz$ needed for path length calculation:



$$\begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}$$

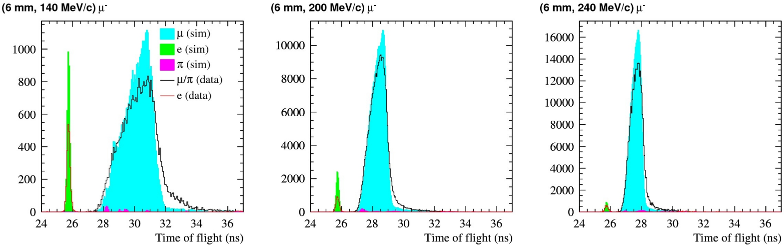
A set of beam line optics configurations have been generated and corresponding beam parameter measured by TOF system. All variables measured in data have been compared with simulation.

Comparison Between Data and Simulation

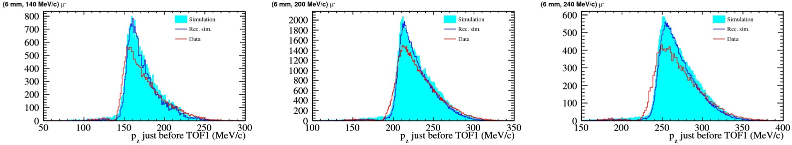
Time of Flight and Momentum

p_z = 140 MeV/c p_z = 200 MeV/c p_z = 240 MeV/c

Time of flight shows π cannot be distinguished from μ, but at < 5%

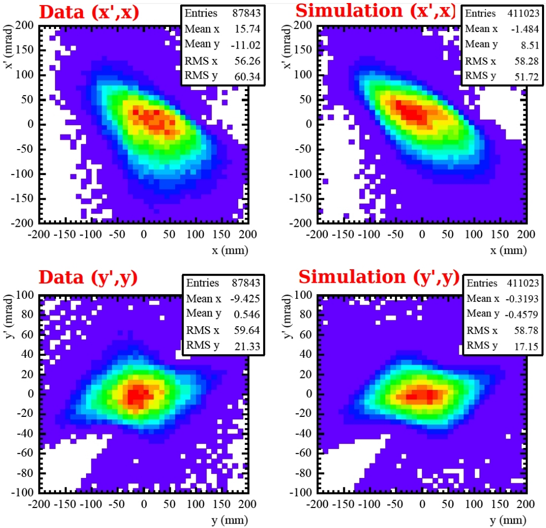


Momentum distributions also agree quite well with simulation



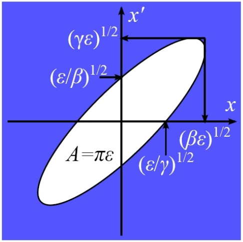
Comparison Between Data and Simulation

Transverse Trace Space



Now calculate:

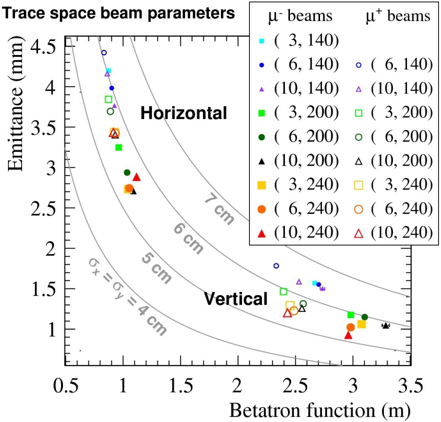
- $\epsilon_x = |\mathrm{Cov}(x, x')|$
- $\beta_x = \sigma_x^2 / \epsilon_x$



And in 4D:

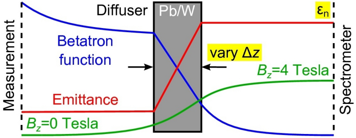
$$\epsilon_n \approx (p_z/m_\mu)\sqrt{\epsilon_x \epsilon_y}$$

Measured Optical Beam Parameters



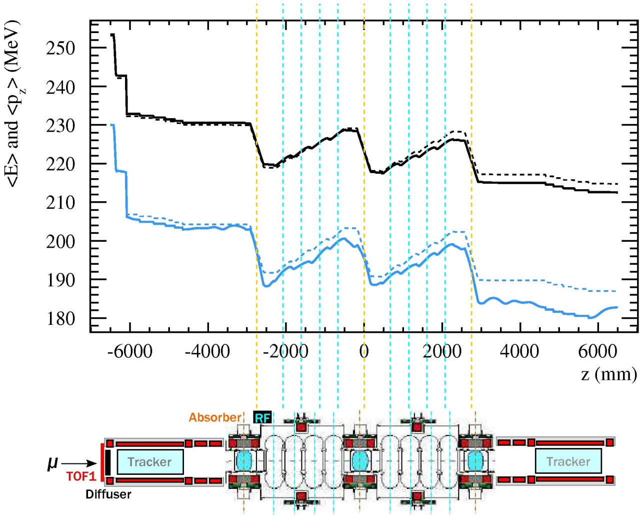
For each beam β_x, ϵ_x and β_y, ϵ_y and a contour of constant beam size $\sigma_i = \sqrt{\beta_i \epsilon_i}$ are plotted.

Beams designed to have every combination of ϵ_n = (3, 6, 10) mm upstream of the first liquid hydrogen absorber, and p_z = (140, 200, 240) MeV/c in the center of each absorber. Muon beams of both polarities were generated and key optics parameter measured at TOF1. The transverse normalized emittance is related to the measured values of ϵ_x and ϵ_y as $\epsilon_n \approx (p_z/m)\sqrt{\epsilon_x \epsilon_y}$. The emittance of the incoming beam, measured by TOF0, TOF1 is much smaller than that of the beam that will go through the cooling channel. In order to generate the desired large emittance the beam goes through a high Z diffuser of adjustable thickness situated inside the first solenoid.



Simulation of the Measured Beam in Cooling Channel

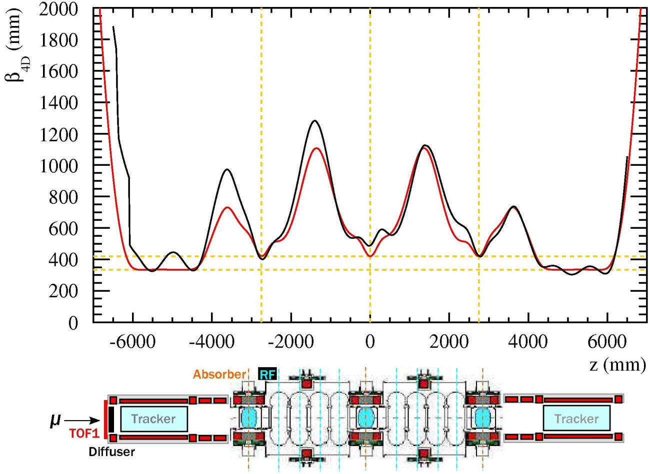
Energy and p_z



A beam, starting at TOF1, with the transverse distributions characteristic of the measured beam was simulated in full MICE cooling channel. The simulated beam was generated according to the measured covariance matrix of the four transverse phase space coordinates and therefore had the emittance and optical parameters of the real beam. *Dashed line is the reference particle traveling along the axis.*

Simulation of the Measured Beam in Cooling Channel

A Predicted Beam Envelope



The evolution of the transverse beta function along the MICE cooling channel of the real beam has been also simulated. The optics of the beam are seen to be similar to the ideal optics (red line) derived from a numerical solution to betatron equation:

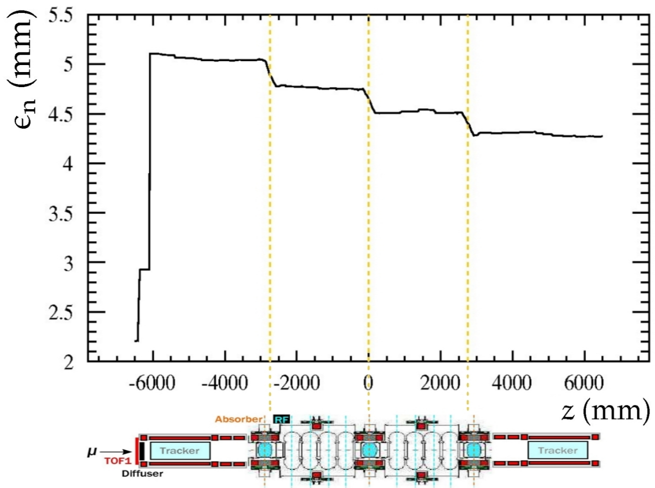
$$2\beta_\perp \beta_\perp'' - (\beta_\perp')^2 +$$

$$+4\beta_\perp^2 \kappa^2 - 4 = 0$$

where κ is the focusing strength.

Simulation of the Measured Beam in Cooling Channel

Emittance



The normalized emittance of the simulated real beam behaves as expected. The initial inflation is due to defuser. The emittance reduction in liquid hydrogen absorbers is clearly visible.

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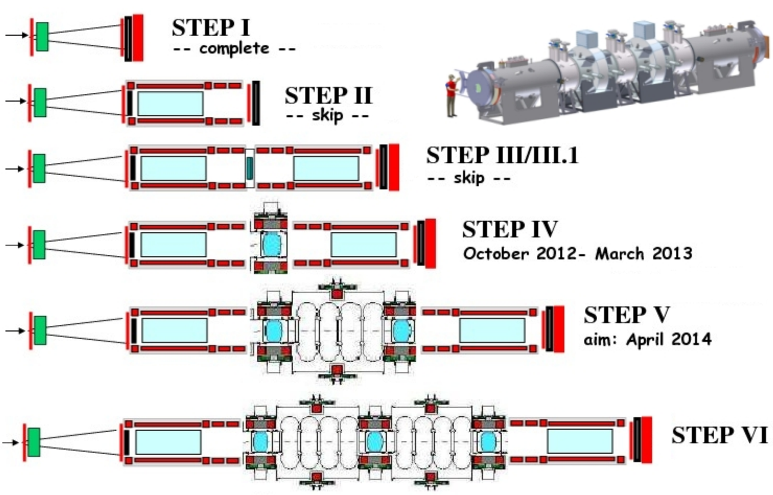
MICE Schedule



Summary

- Full beam line installed and commissioned at RAL
- Particle identification detectors installed in MICE hall and used for the first emittance measurements
- Most of the components of the cooling channel produced and under commissioning
- Beams containing > 95% $\mu^{\pm}$ generated for ϵ_n = (3,6,10) mm and p_z = (140,200,240) MeV/c
- Distributions of the trace space vectors of individual muons have been reconstructed for the various beams, and promising agreement is observed with Geant4 simulations
- The evolution through MICE of the optical parameters of a measured baseline beam has been simulated and the beams are relatively well matched
- MICE is on the way towards demonstrating ionization cooling

Thank you for your attention!