Results from Step I of MICE and the Physics Plan for Step IV

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on behalf of the MICE Collaboration

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FACULTÉ DES SCIENCES

Motivation

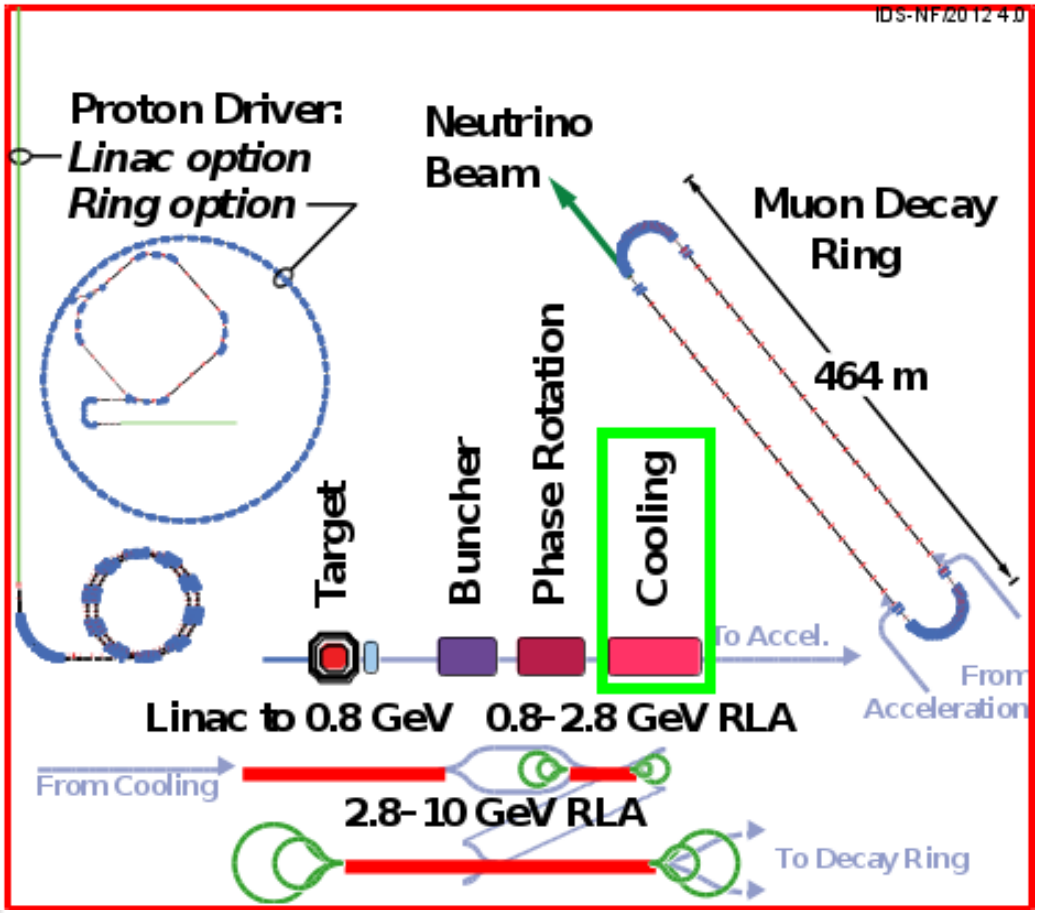
Neutrino Factory

Neutrinos produced from the decay of muons circulating in a storage ring.

- 10^{21} useful muon decays per year
- 10 *GeV* stored-muon energy
- neutrino flux known to $< \pm 1\%$
- 2000 *km* source-detector baseline

Cooling increases the muon flux by a factor of two to ten.

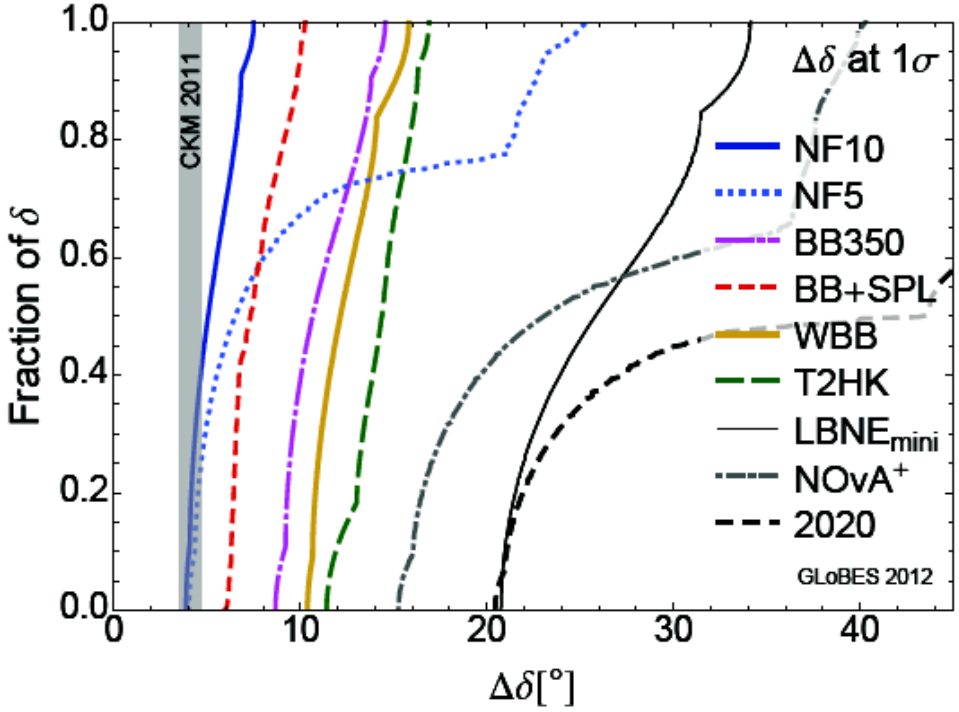
IDS-NF

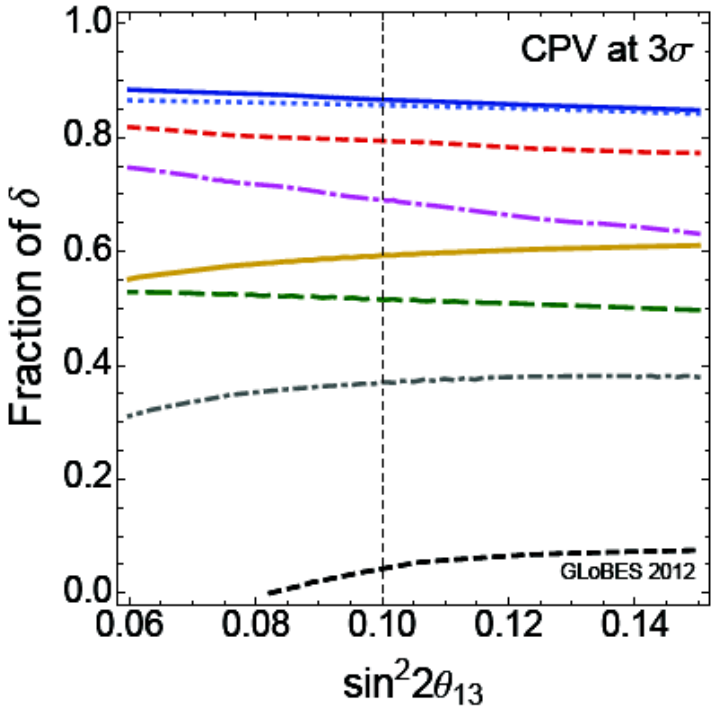


$$\mu^- \rightarrow e^- \ \overline{\nu}_e \ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \ \nu_e \ \overline{\nu}_\mu$$

Motivation

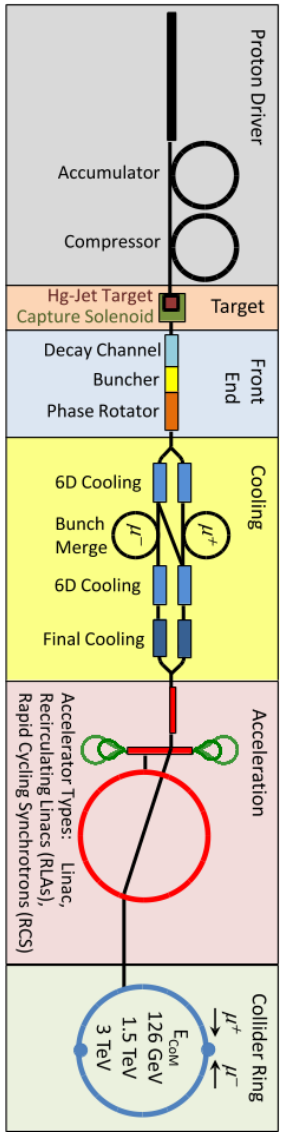
arXiv:1209.5973





Neutrino factories achieve the best absolute precision in the measurement of the CP violating phase δ_{cp} (comparable to that in the quark sector) and are very robust with respect to systematic errors.

Motivation



Muon Collider

- Strong coupling to the Higgs ($muon\ mass \approx 200 \times electron\ mass$)
- Superb Energy Resolution (95% luminosity in $dE/E \approx 0.1\%$)

- Muon Collider will permit more precise studies of phenomena discovered at LHC
- Shed light on new physics

Cooling is essential to deliver requisite flux.

Ionization Cooling

Muon ionization cooling technique provides the only practical solution to prepare high brilliance beams necessary for a neutrino factory or muon colliders because it is fast enough to cool the beam within the muon lifetime.

1. Energy loss by ionization (dE/dx)
2. Heating from multiple scattering
3. Longitudinal momentum restored by RF cavities

Ionization Cooling

Cooling formula:

Two components:

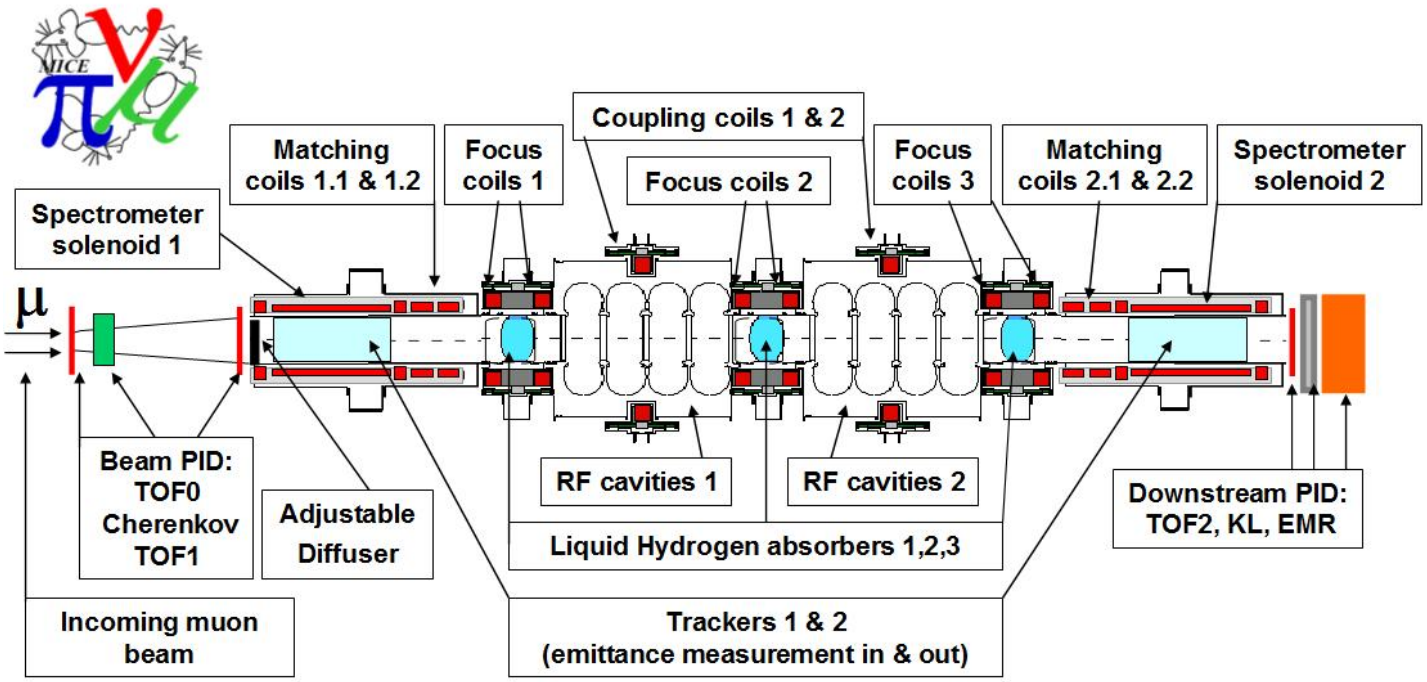
- cooling from ionization energy loss
- heating from multiple scattering

$$\frac{d\varepsilon_N}{dz} = \underbrace{-\frac{\varepsilon_N}{\beta^2 E_\mu}\frac{dE_\mu}{dz}}_{\text{cooling}} + \underbrace{\frac{\beta_\perp (13.6MeV)^2}{2\beta^3 E_\mu m_\mu X_0}}_{\text{heating}}$$

Equilibrium emittance (*cooling* = *heating*)

To maximize cooling we need material with low-Z and beam channel with low $\beta_\perp$.

Muon Ionization Cooling Experiment (MICE)



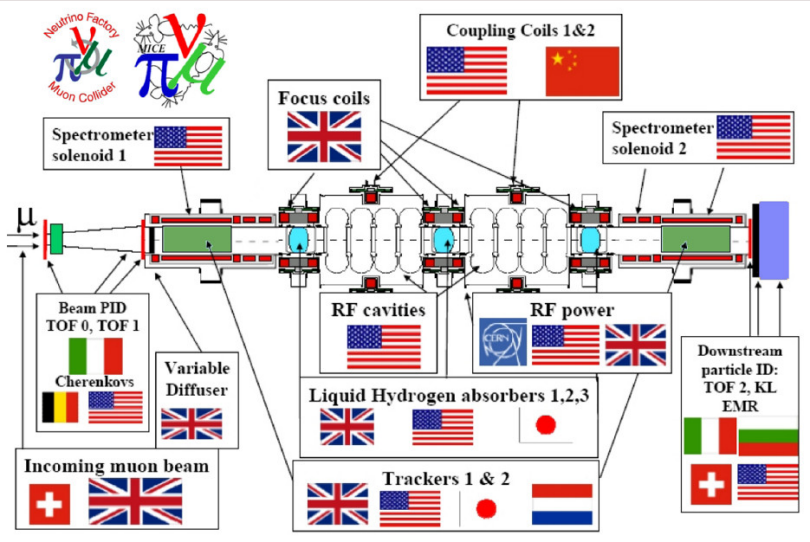
Goals

- Build a section of a cooling channel that can demonstrate the principle of ionization cooling
- Achieve emittance cooling of at least 10% with a precision of 1%
- Verify the cooling performance for various configurations and beam conditions

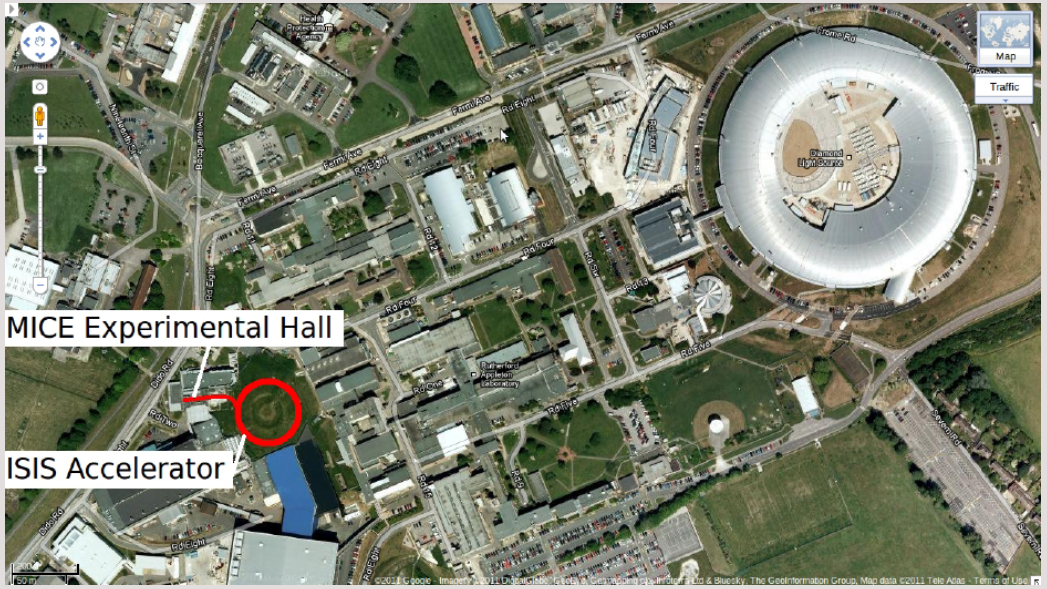
Muon Ionization Cooling Experiment (MICE)

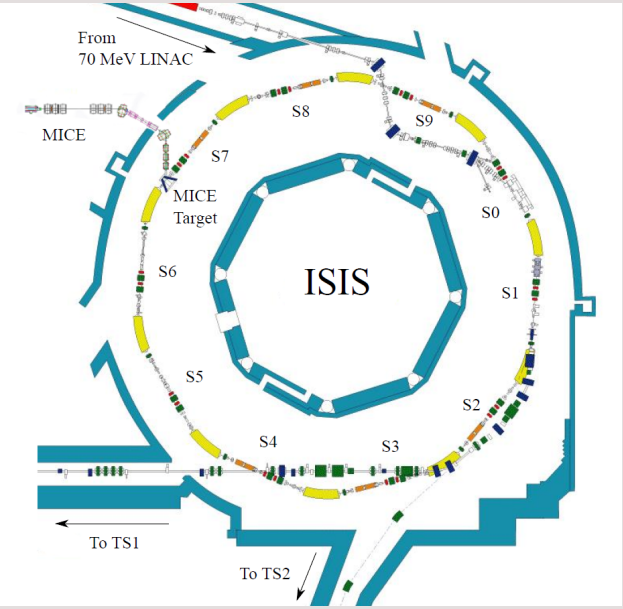
MICE collaboration:

Belgium, Bulgaria, China, Holland, Italy, Japan, Switzerland, UK, USA:
$\sim$ 150 collaborators



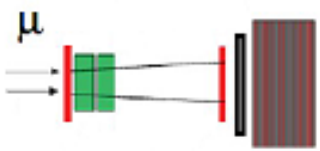
Based at Rutherford Appleton Laboratory (UK)



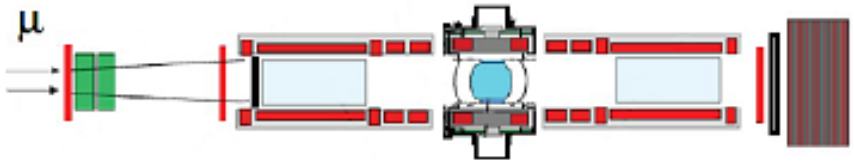


Implementation in Steps

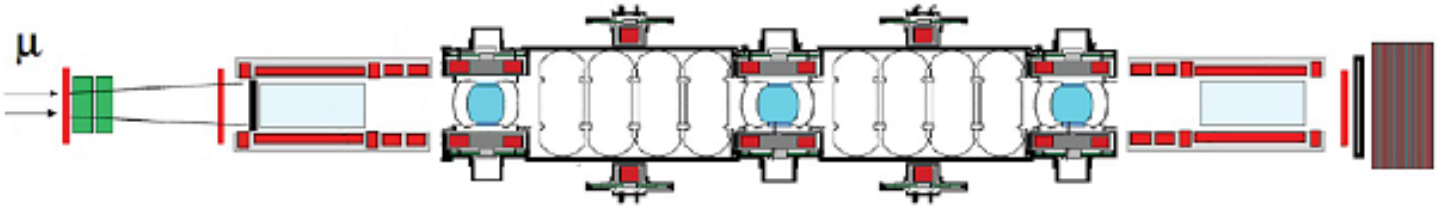
The experiment will be assembled, tested and operated in steps. Each step will validate different parts of the setup. Some steps have been removed from the original schedule.



Step I (completed)

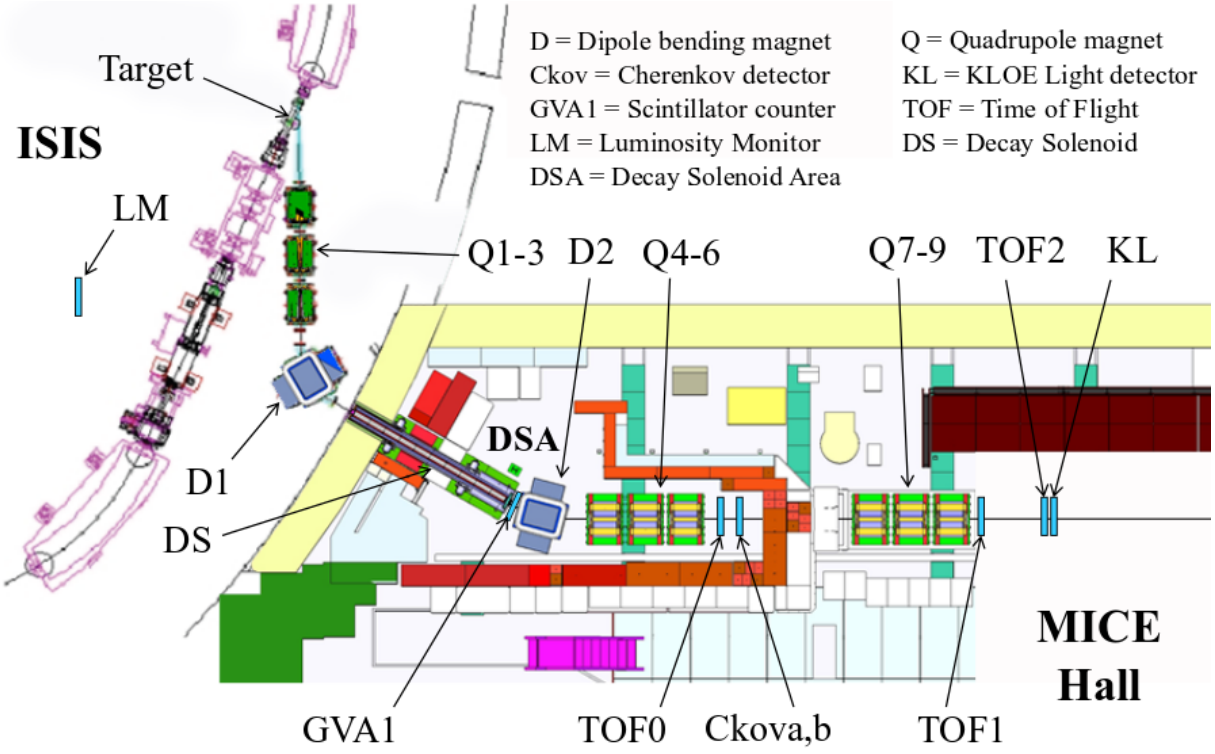


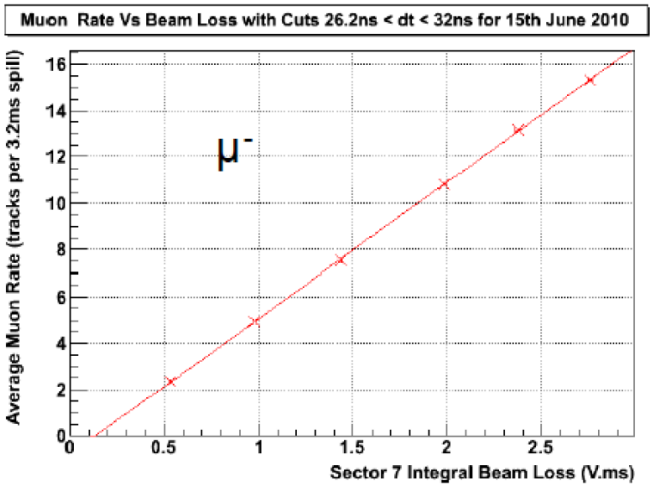
Step IV (2015-2016)

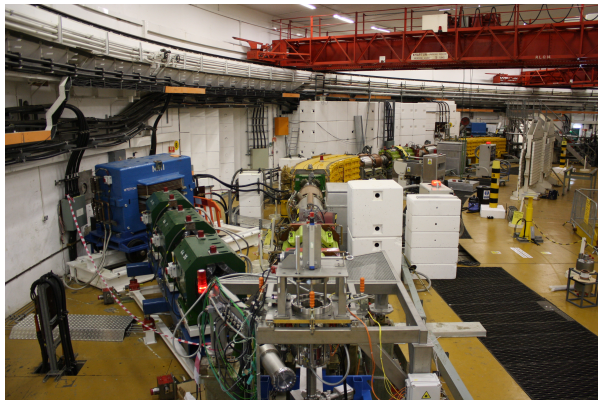


Step VI (2019)

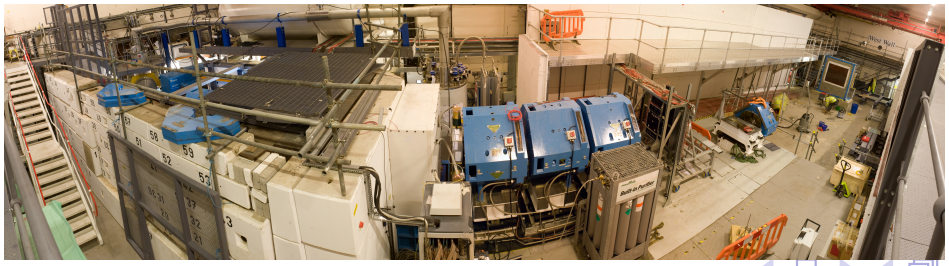
MICE beam line



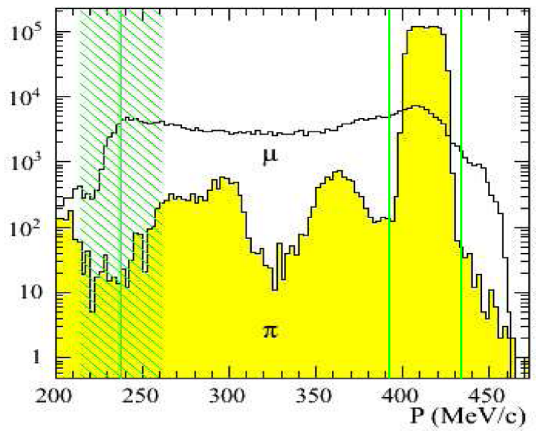


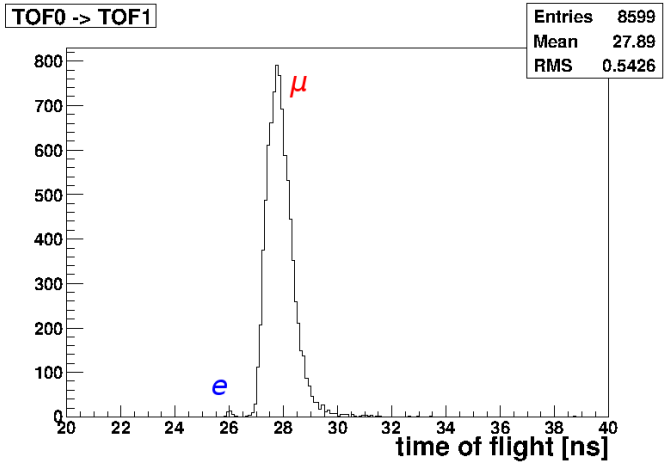


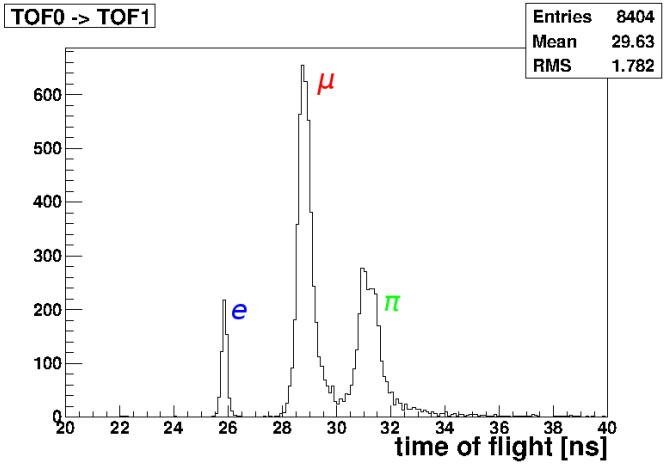
MICE beam and instrumentation fully constructed and operational.



MICE beam line



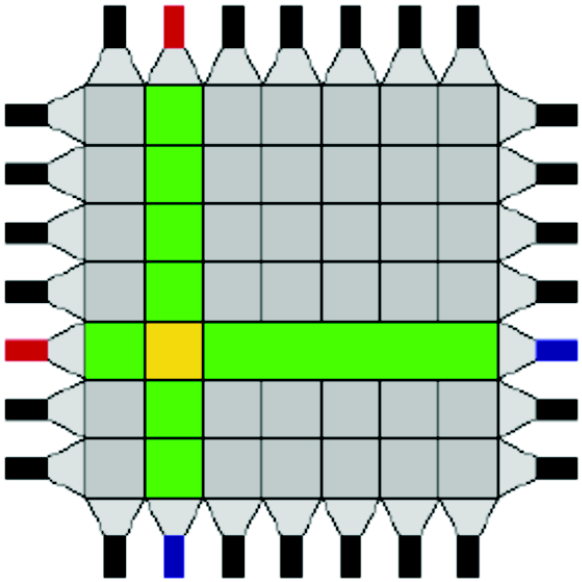


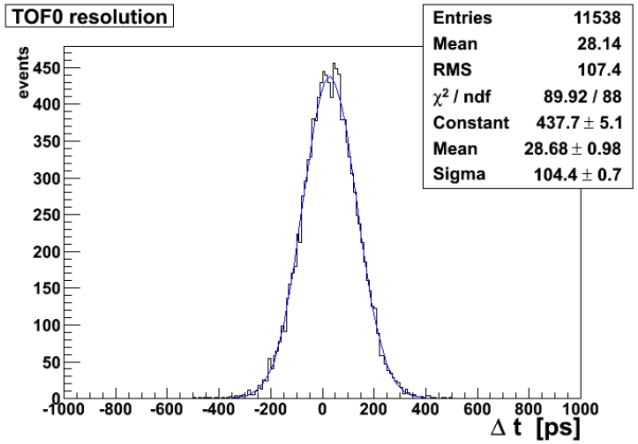


Making a muon beam

- $P1 \approx 2 \times P2$ - Select muons moving backward in centre-of-mass system. Optimal muon purity, large longitudinal momentum spread, will be used for the demonstration of ionization cooling.
- $P1 \approx P2$ - Select muons moving forward in centre-of-mass system. Very useful for calibration of the detectors. Electrons, muons and pions fall into three well defined time-of-flight peaks.

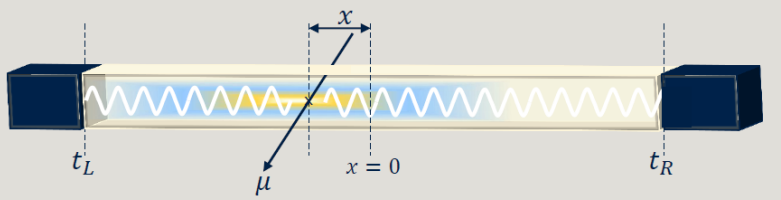
Time-of-flight system





- $X \setminus Y$ scintillator hodoscopes.
- Hamamatsu R4998 PMT
- CAEN V1724 FADC
- CAEN V1290 TDC

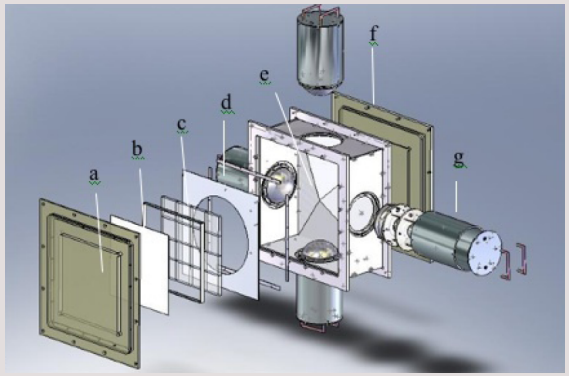
TOF



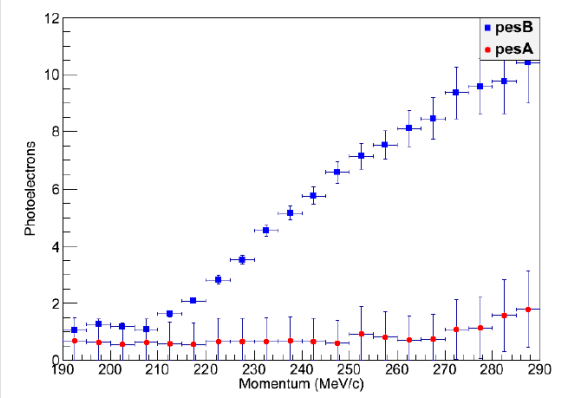
$$t \sim \frac{(t_L + t_R)}{2}; \qquad x \sim \frac{(t_L - t_R)}{2}$$

- Time resolution $\sigma_t \approx 50\ ps$
- Position resolution $\sigma_x \approx 1\ cm$

Two aerogel threshold Cherenkov counters ($Ckov_{a/b}$)

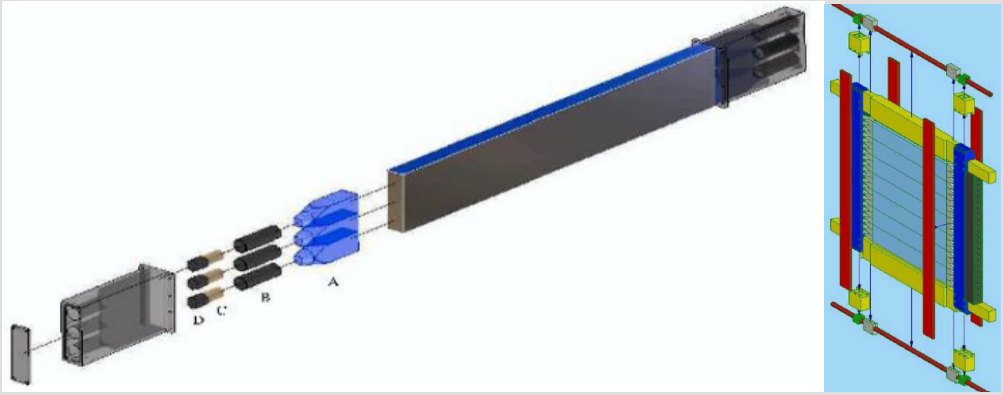


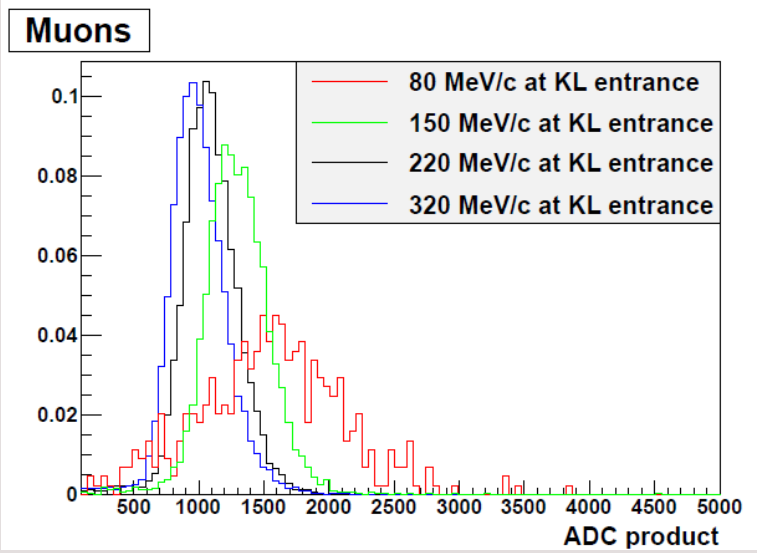
Photoelectron distributions in $Ckov_a$ and $Ckov_b$ (data, preliminary)



200 MeV/c μ_+ beam

KLOE-type sampling calorimeter (KL)

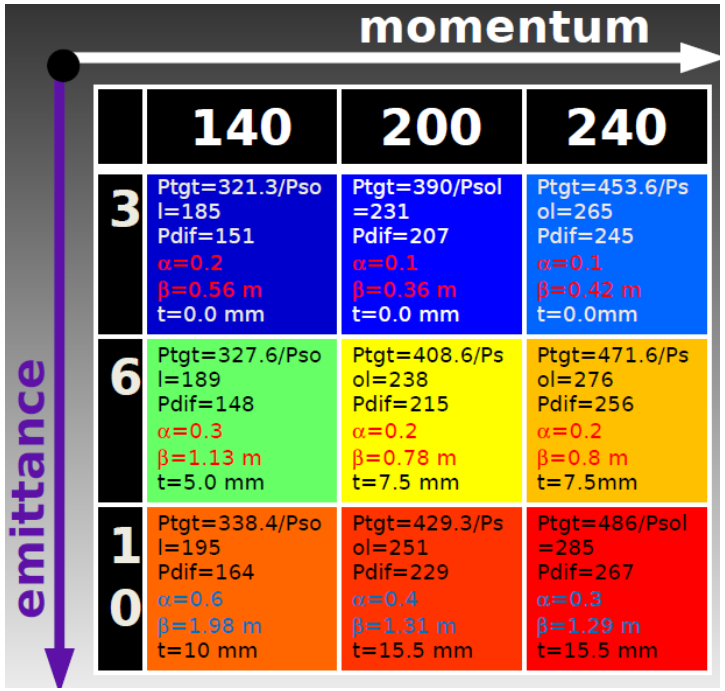




KL response to muons for various incident momenta (data)

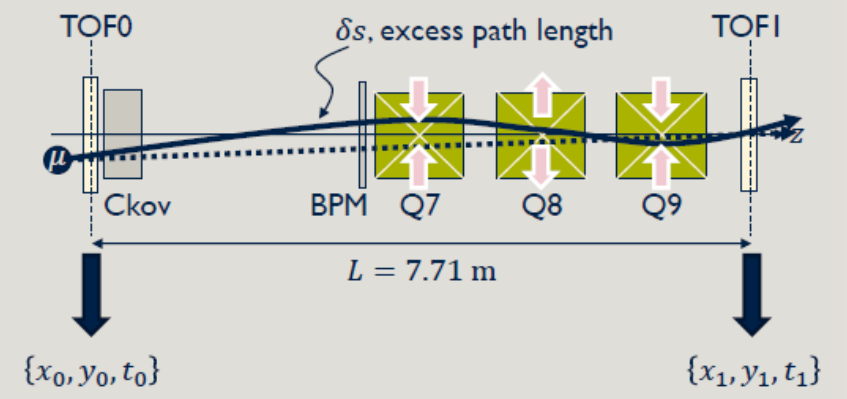
Step 1 data sets

- The MICE beam line has been designed to produce beams of three different emittances at each of three central momenta.
- 9 beam settings x 2 muon polarities = 18 beams (17 measured)

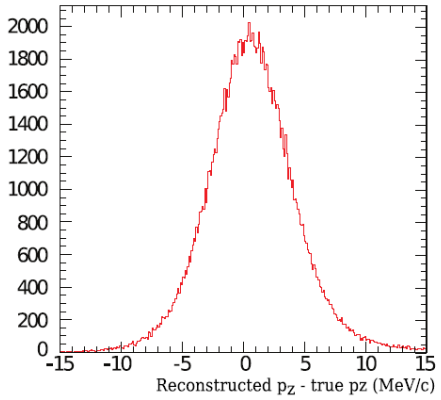


The values of the emittance (3/6/10 mm.rad) are after the diffuser.

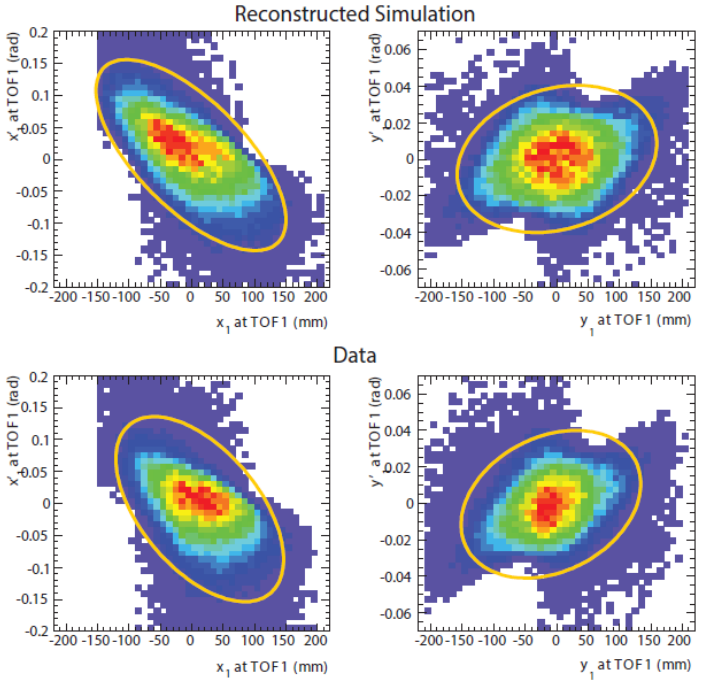
Emittance Measurement



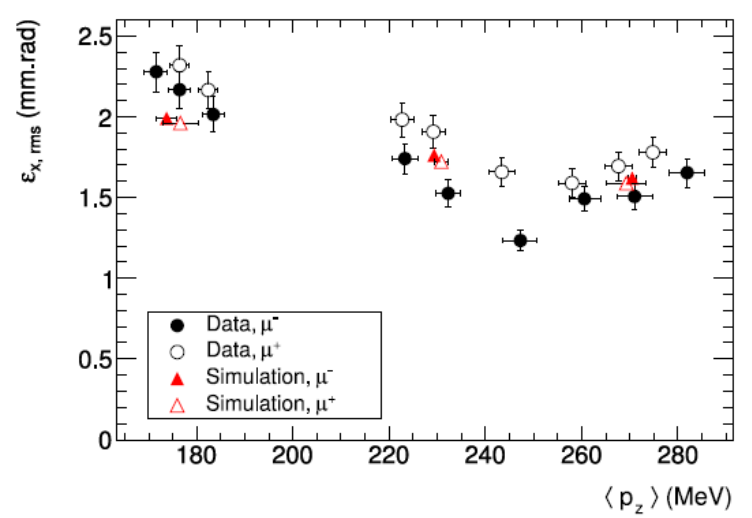
1. Calculate p_z from time of flight
2. Calculate the transfer matrix
3. Deduce (x', y') from (x, y)
4. Track the muon between TOF0 and TOF1 and obtain an improved estimate of the trajectory
5. Go back to 1



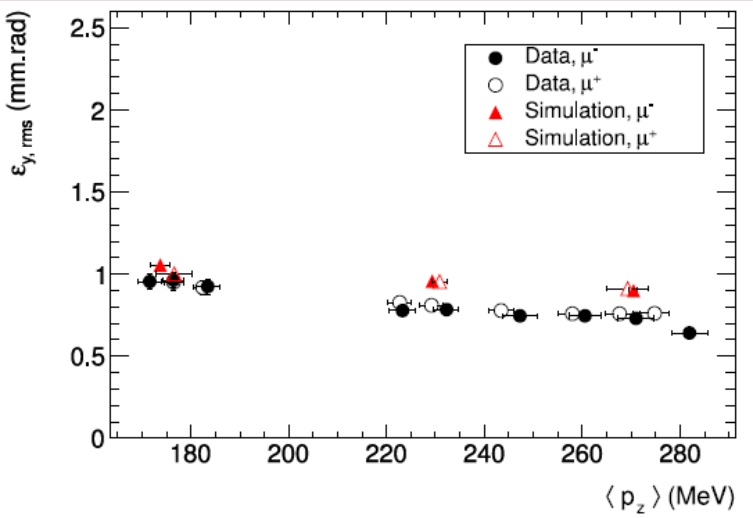
3.7 MeV/c resolution for 240MeV/c muons (1.5%)



Beam emittance - MC vs. Data for various beam configurations



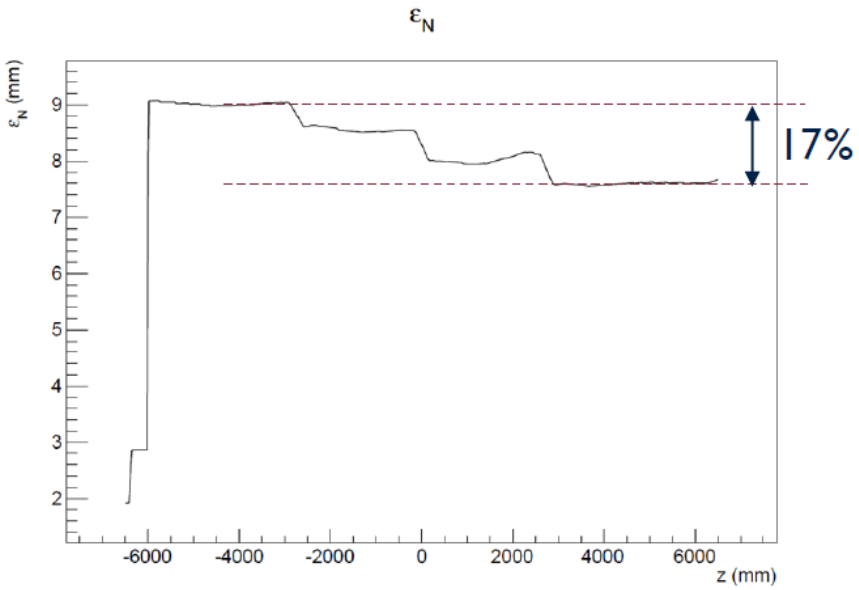
Horizontal emittance



Vertical emittance

Expected Performance of the Cooling Channel

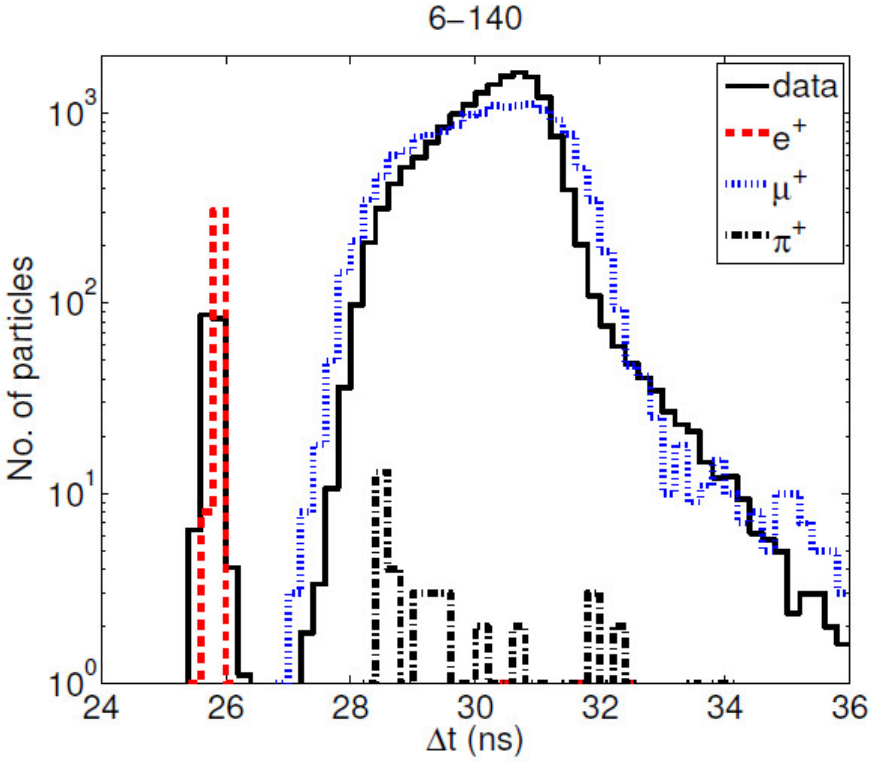
Measured beams are propagated forward through full simulated cooling channel



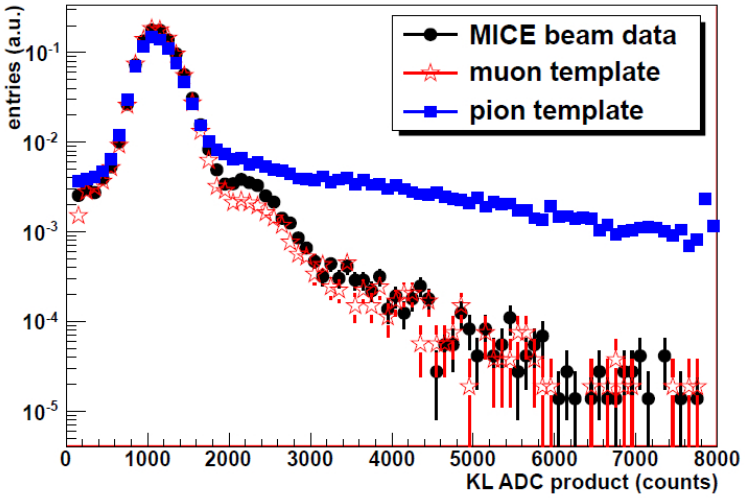
Pion contamination studies

Time-of-flight counters & KL sampling calorimeter

Simulation



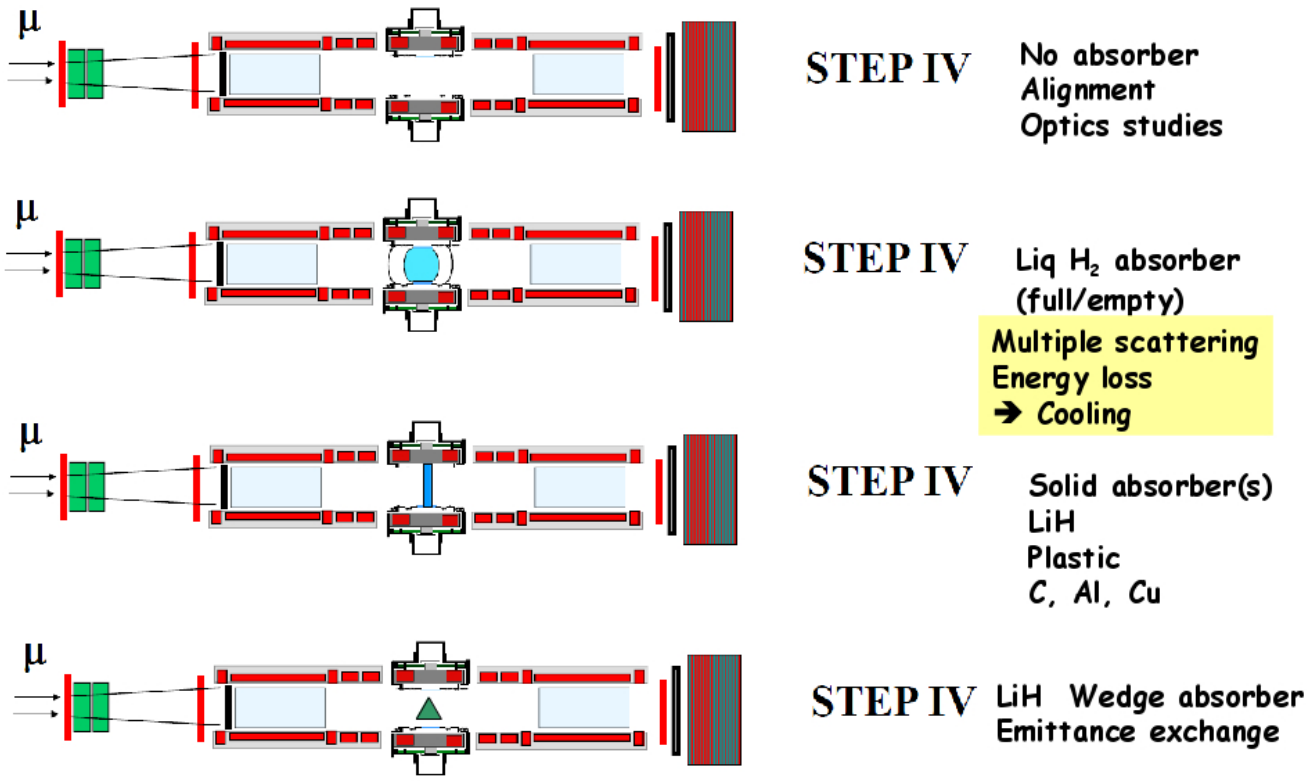
KL Data



Muon and pion templates from calibration runs, compared to MICE muon beam data

Data and Simulation are in agreement with contamination at or below the 1% level at the entrance of the cooling channel.

Physics programme for Step IV (2015 - 2016)

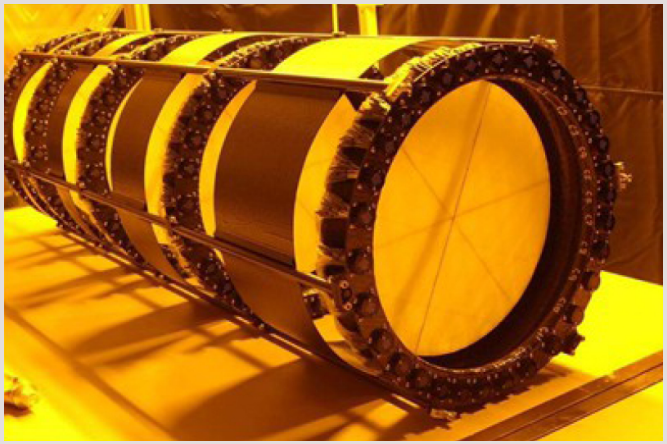


- Measure equilibrium emittance of given absorber and for given beta function
- Measurement of 6D emittance change
- Precision measurements of multiple scattering

Progress towards completion of MICE Step IV

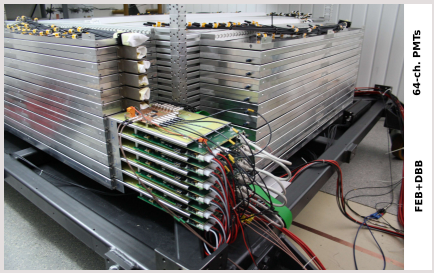
For more details see the poster "Progress towards completion of MICE"

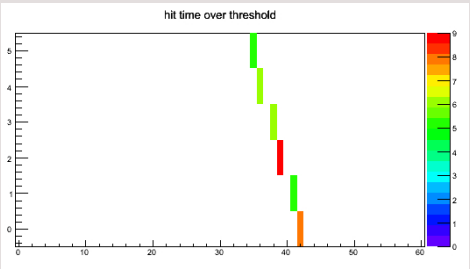
Trackers



- Both trackers have been extensively tested with cosmic rays
- A spare single station of the tracker has been tested at MICE beamline
- Single station test used also to demonstrate the integration of the tracker front-end electronics with the MICE DAQ system

Electron-Muon Ranger (EMR)

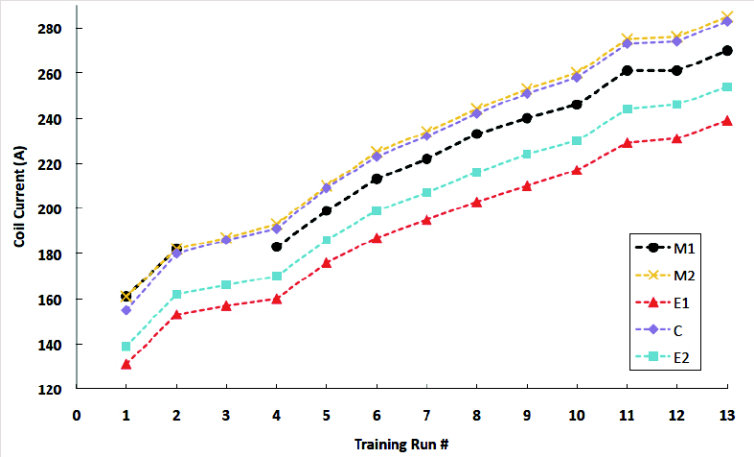


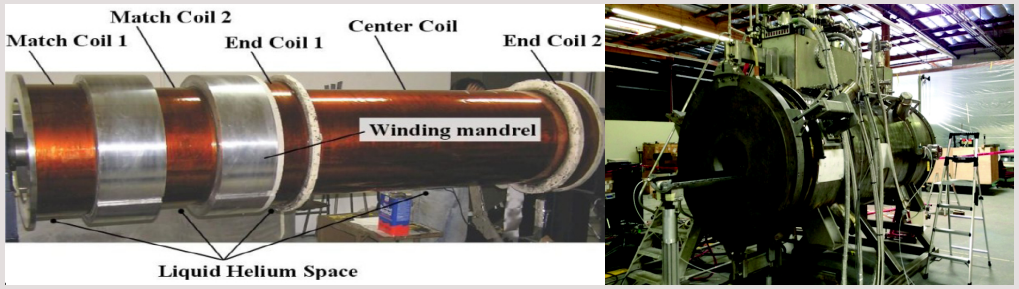


- Construction is almost completed
- First cosmic tracks seen
- Shipping to RAL, Sept 2013

Progress towards completion of MICE Step IV

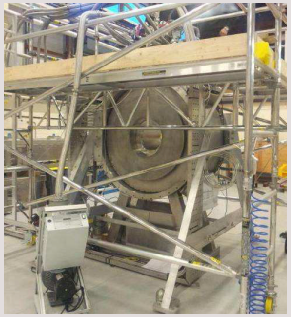
Spectrometer Solenoids





- Both Superconducting Solenoids assembled and tested
- Field mapping completed
- Shipping to RAL, Sept 2013

Absorber and Focus Coils



- Liquid H_2 system has been tested
- Liquid H_2 and LiH absorbers manufactured
- First AFC module being trained at RAL
- Second module to be delivered August 2013

Conclusions

- MICE is a key R&D towards Neutrino Factory and Muon Collider
- MICE beamline commissioned: over 13×10^6 triggers collected in Step I
- PID detectors (TOF0, TOF1, Ckov, TOF2, KL) installed and working well
- MICE Muon Beam meets requirements
- Trackers completed but need to be integrated with superconducting solenoids
- STEP IV in preparation and ready to take data in 2015