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MICE Operation and Demonstration of Muon Ionization Cooling

Ao Liu, on behalf of the MICE collaboration

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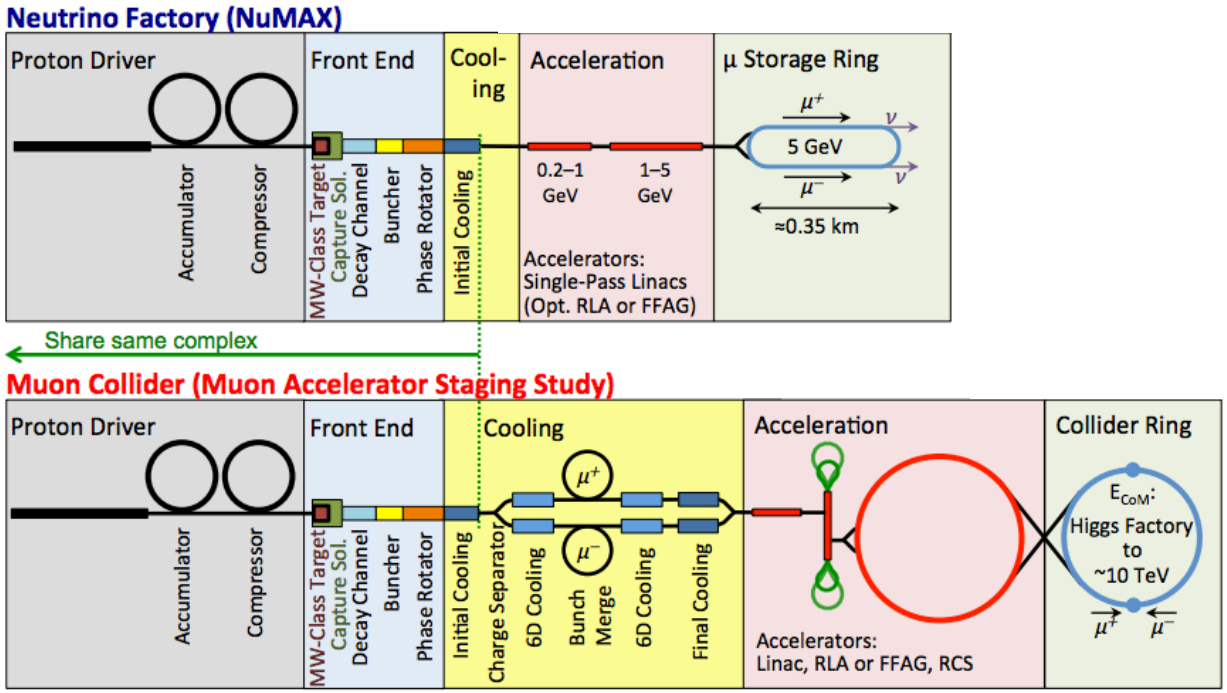
NAPAC2016

The Muon Ionization Cooling Experiment (MICE) Program

- Demonstration of muon ionization cooling feasibility
  - Only technique to cool a muon beam within its lifetime;
  - Cooled muon beam is required to achieve desired luminosity in a muon collider and to do precision neutrino physics in a neutrino factory



The MICE Program

- Demonstration of muon ionization cooling feasibility
  - Only technique to cool a muon beam within its lifetime;
  - Cooled muon beam is required to achieve desired luminosity in a muon collider and to do precision neutrino physics in a neutrino factory
- Experiment conducted with muons from ISIS beam at STFC Rutherford-Appleton Laboratory (RAL), UK
- **Validate the cooling equation**
  - Transverse emittance change when beam passes through an absorber

$$\frac{d\epsilon_n}{ds} \approx -\frac{1}{\beta^2}\frac{\epsilon_n}{E_\mu}\left\langle\frac{dE}{ds}\right\rangle + \frac{1}{\beta^3}\frac{\beta_\perp(0.014\text{GeV})^2}{2E_\mu m_\mu X_0}$$

Step IV

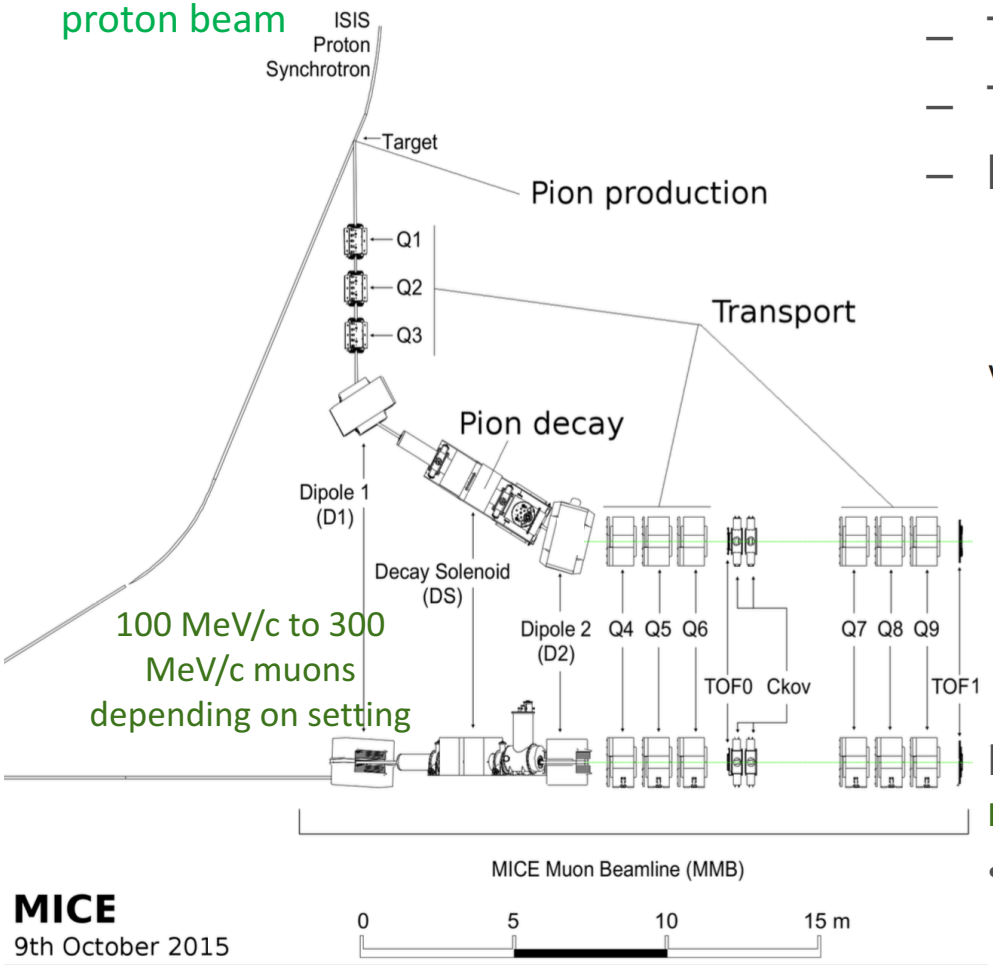
- **Study the energy loss and scattering of muons in the absorbers (material physics)**

Muon Cooling Principles

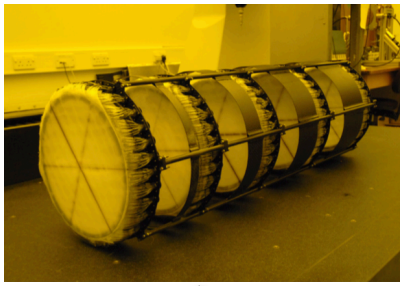
- Energy loss in all directions (+ scattering)
  - → Transverse normalized emittance reduction
  - – Reduce heating from scattering by *minimizing transverse β function (smaller beam)* at the absorber, and *maximizing the radiation length* X_0 of the absorber
  - – **This is MICE Step IV**
- Energy recovery in the longitudinal direction
  - – Geometric emittance reduction
  - – **This is in MICE Demonstration of the ionization cooling (Step DEMO)**
    - Requires addition of RF

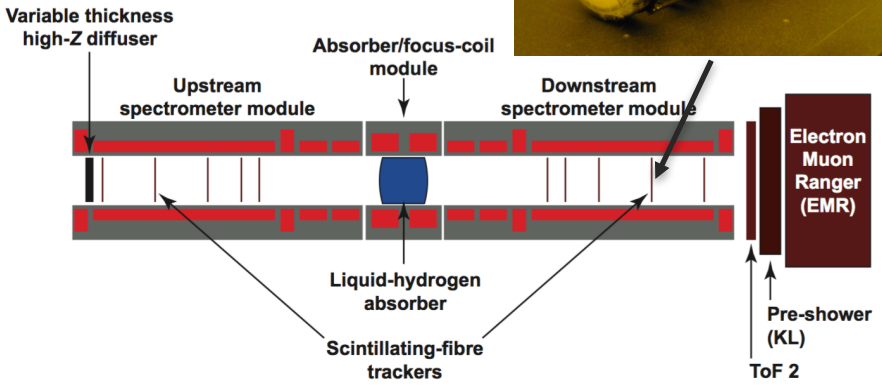
MICE Beamline

800 MeV ISIS proton beam



- Detectors for PID identification:
  - Three Time-Of-Flight (TOF) detectors;
  - Two Cherenkov detectors;
  - KL + EMR calorimeters



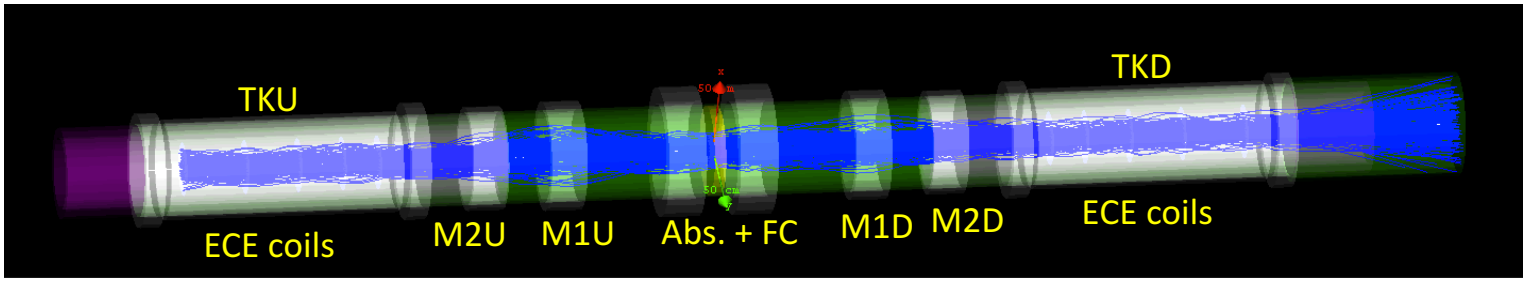


Detectors for position and momentum reconstruction:

- Two scintillating fiber (SciFi) trackers (TKU and TKD)
  - Position resolution ~ 470 μm
  - p_T and p_L resolution ~ 1.3 MeV/c and 4 MeV/c

MICE Emittance measurement

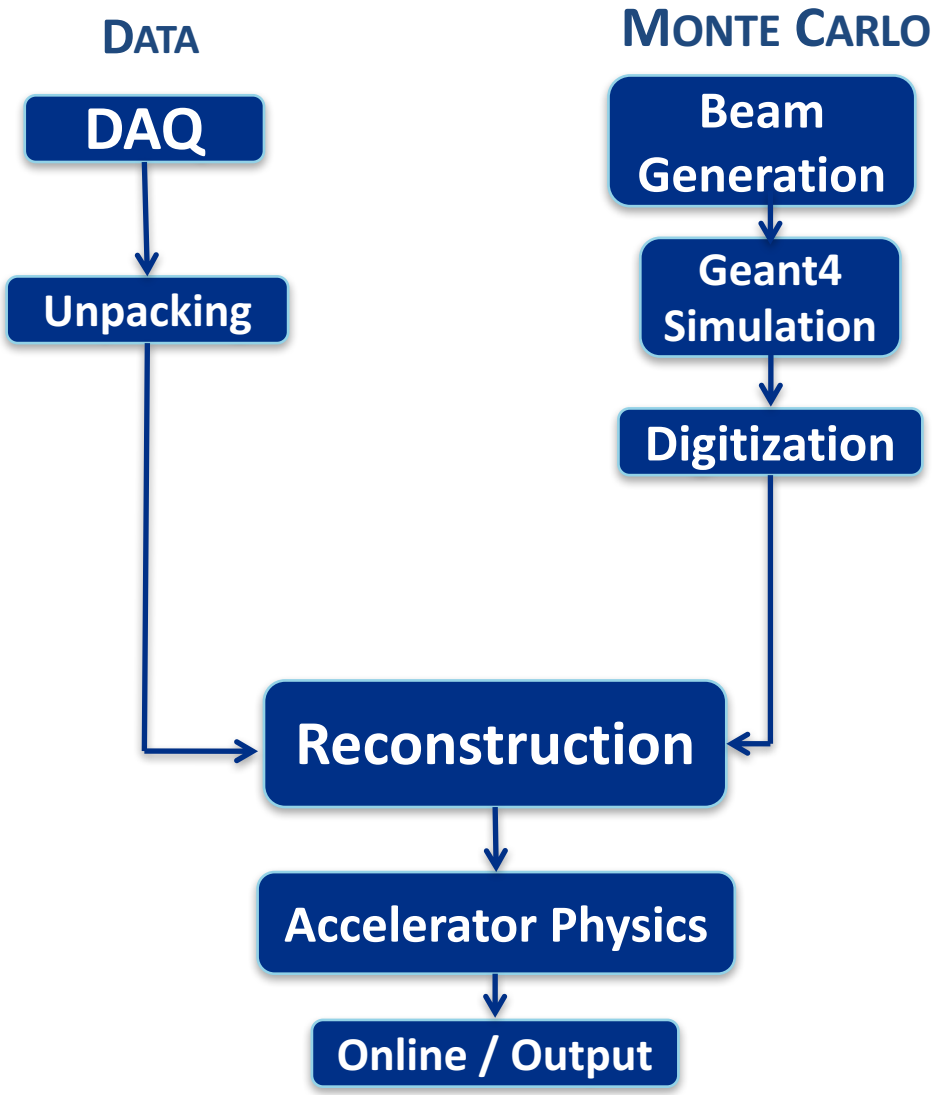
- Single particle → beam ensemble
  - Single particle trajectories measured by trackers;
  - Single particle phase space coordinates reconstructed;
  - Beam ensemble formed by collecting these particles, and then the beam emittance is calculated.



- First direct and precise measurement of the emittance of a muon beam
  - Definition: $\epsilon_{4D} = \sqrt[4]{\Sigma_{4D}}/m_\mu$
  - Σ_{4D} is the transverse x, P_x, y, P_y covariance matrix

MAUS – MICE Analysis User Software

- Monte Carlo simulation of the experiment
  - GDML-based geometry updated with latest hall surveys, support for field-models and field-maps
  - GEANT4 for simulation and tracking
- Reconstruction & Particle ID
- Online reconstruction & monitoring during data-taking: multithreaded
- Configurations Database for calibrations, geometries, cabling maps, etc
- Data-processing
  - During data-taking reconstruction is performed “live” as data come in

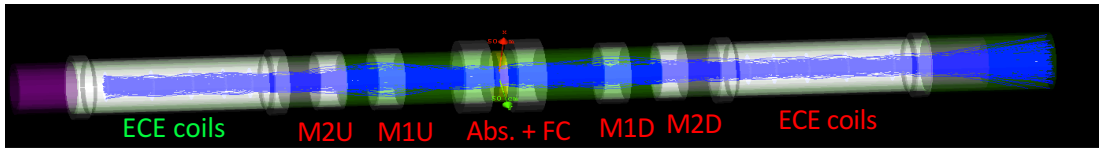


MICE Current Status

- Detectors:
  - Ckov in place and functional;
  - Both trackers are in place, functional and validated;
  - KL, TOF and EMR in place, functional and calibrated;
- Magnets:
  - Pion beamline functional;
  - Cooling channel magnets commissioned and match the current optics run requirements;
- Software:
  - Online, offline reconstruction functional;
  - Geometry files being updated on a run-by-run basis;
- A lot of data has been taken, many analyses under way.

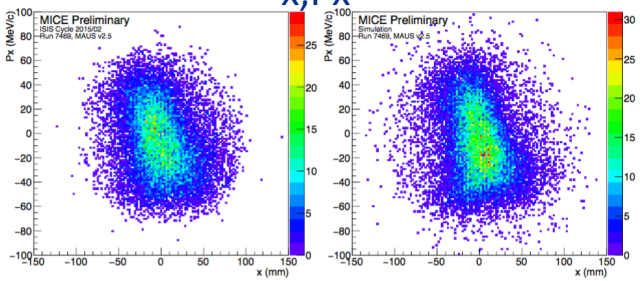
MICE Tracker Reconstruction Validated

- Validated by run 7469, October 2015
  - 200 MeV/c positive muon run;
  - ECE upstream ramped to full current;
    - Other coils turned off

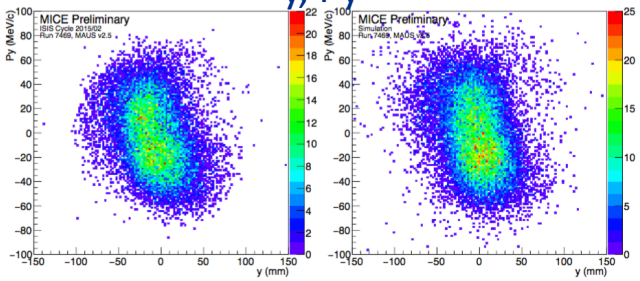


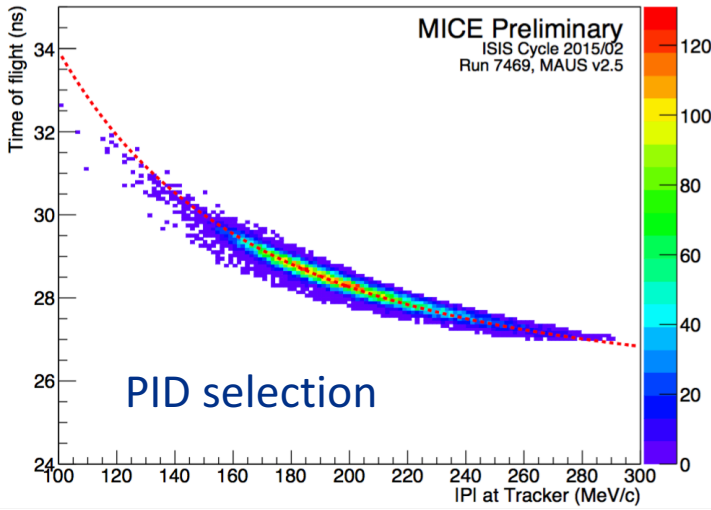
  - PID selection based on time-of-flight;
  - Comparison with simulation showed good agreement: (left: data; right: MC)

x,Px



y, Py





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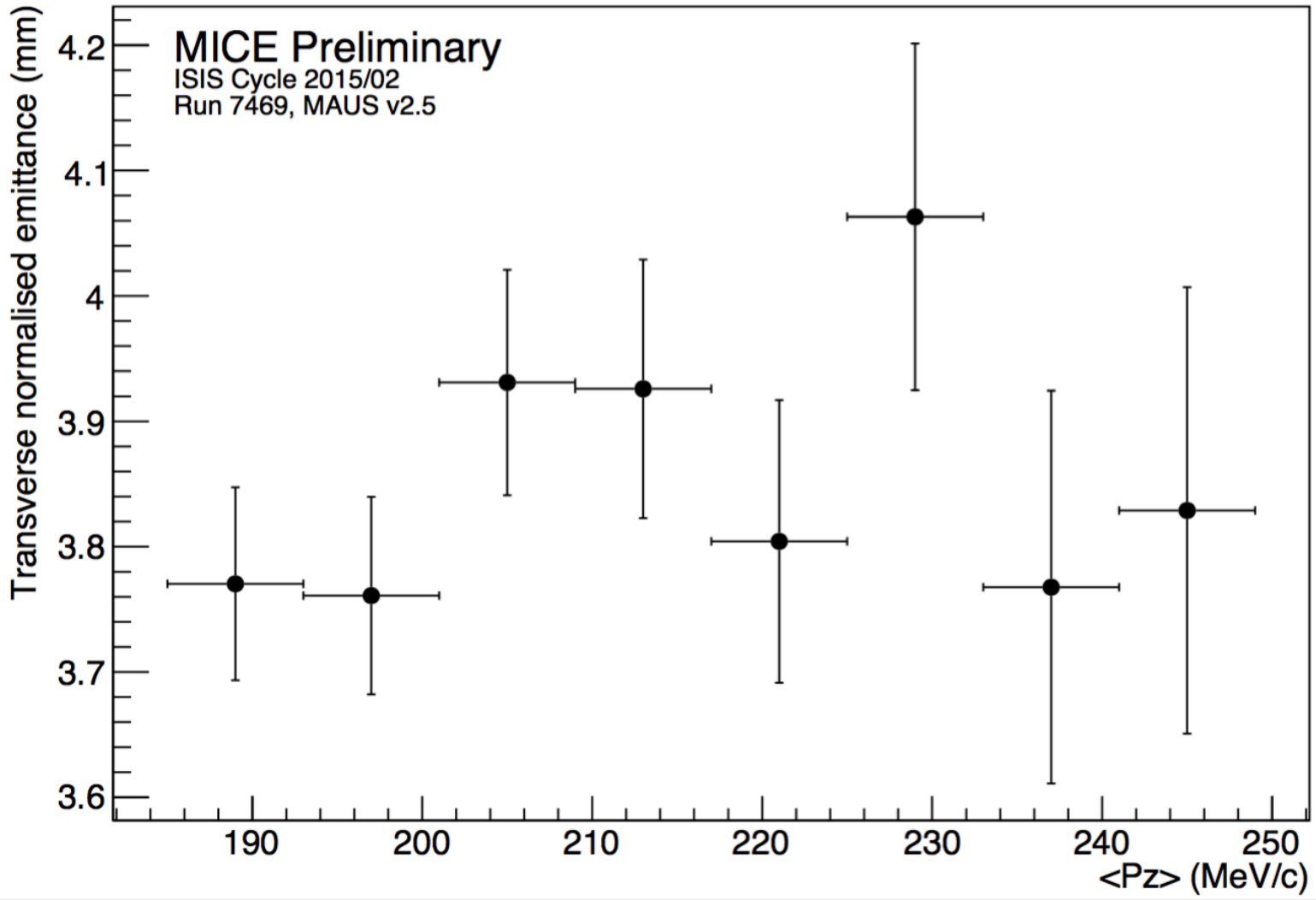
MICE First Direct Muon Emittance Measurement



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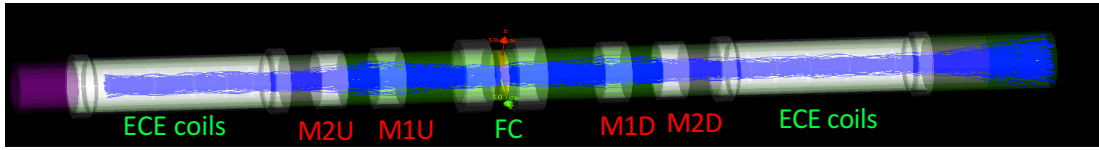
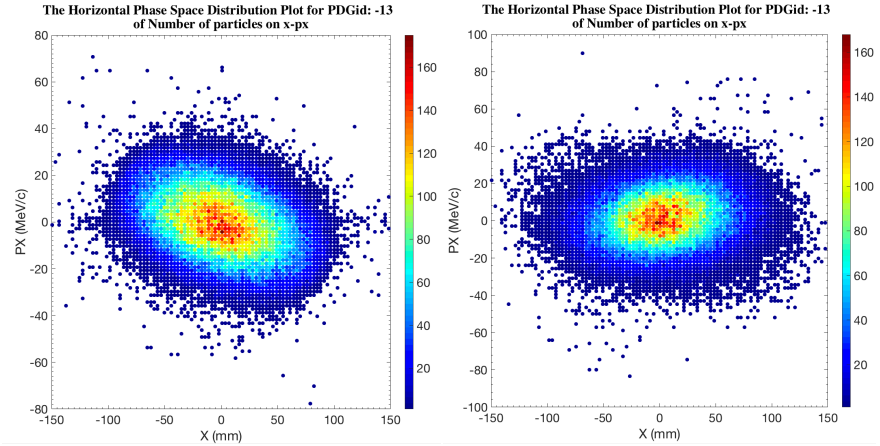
MICE Operation Status – July run

- In July MICE took data with “empty absorber” with both ECE coils giving 2 T and FC at 50 A, but no matching coils, to validate optics
- 2*ECE and FC work beautifully together!





left: TKU station 5; right: TKD station 5

Run 8155 reconstructed using MAUS

Preliminary

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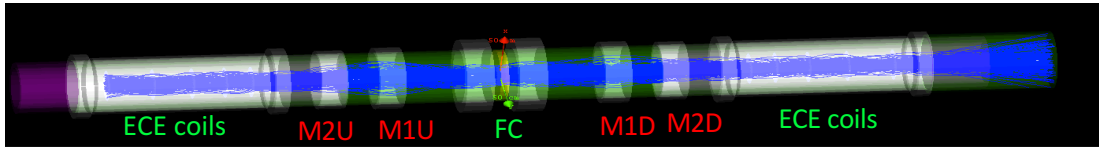

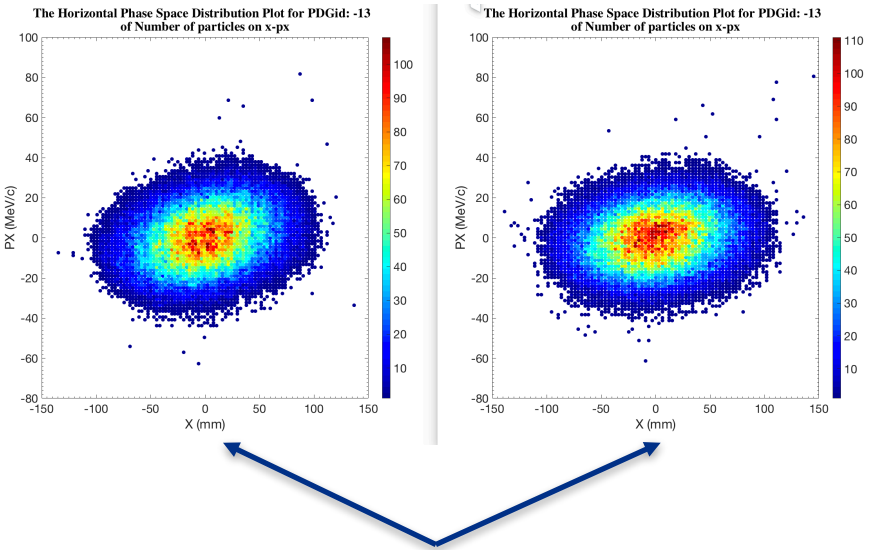

left: TKU station 1 measured; right: TKU station 1 MC

Preliminary

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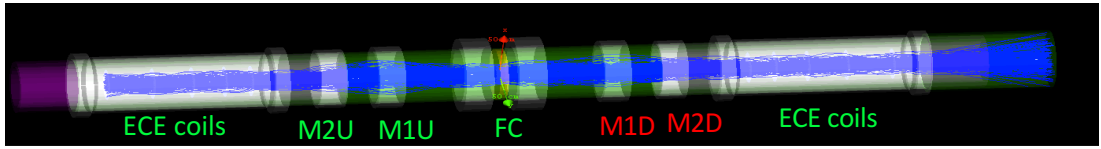
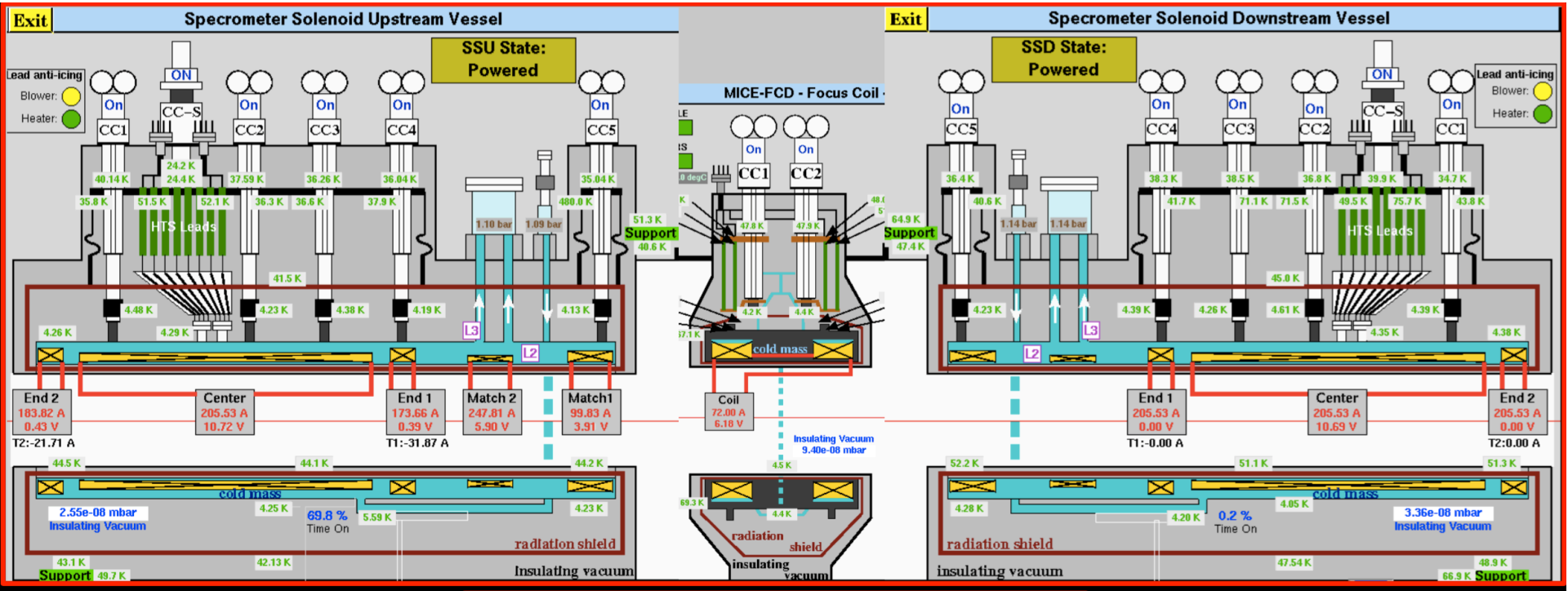
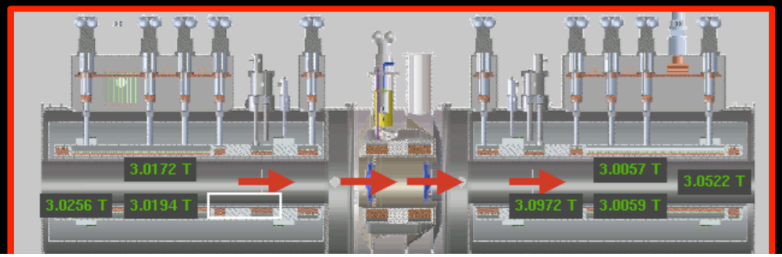
MICE Ongoing Run

Current run cycle (Sep. to Oct.): Powered on upstream matching coils for further optics validation + material physics



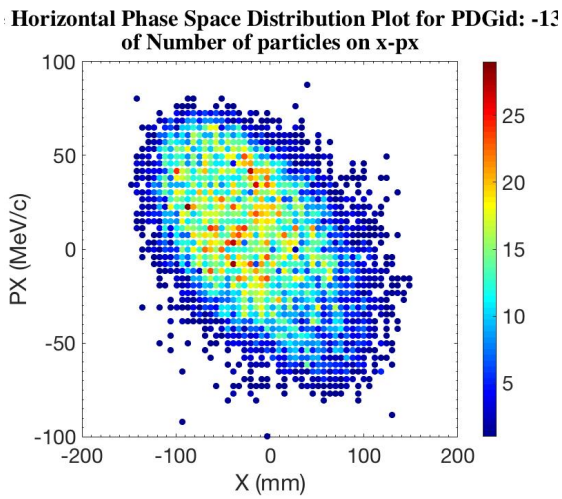


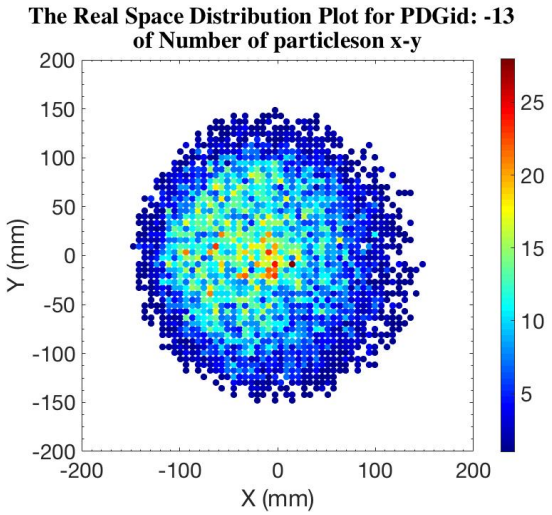
MICE control room monitors

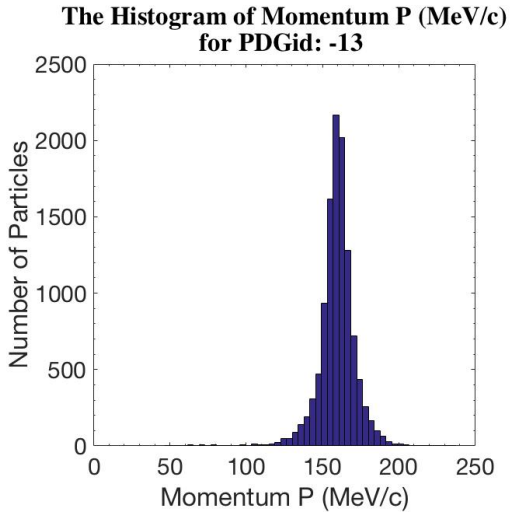


3T in Trackers, coils work beautifully together

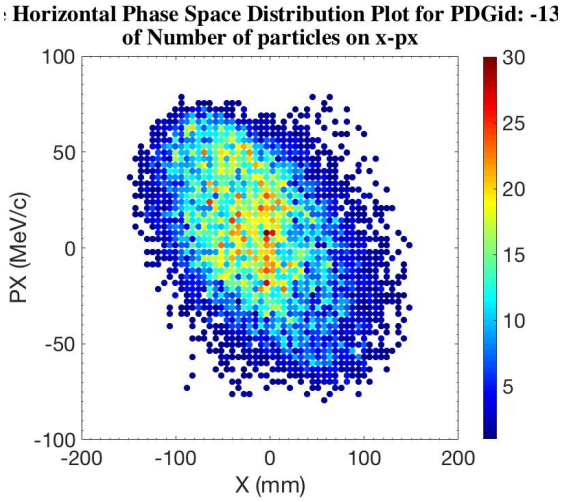
MICE Ongoing Run First-look Preliminary

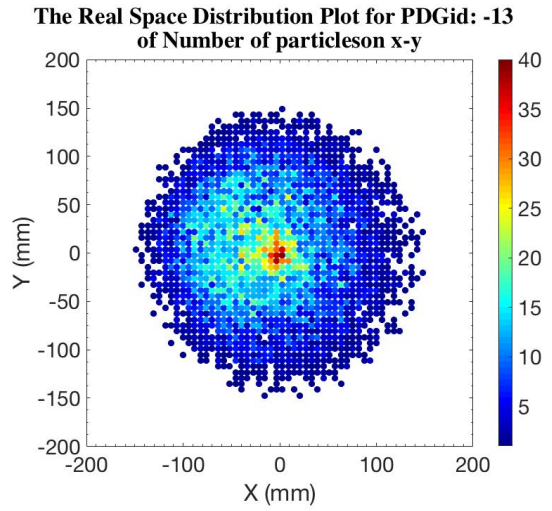


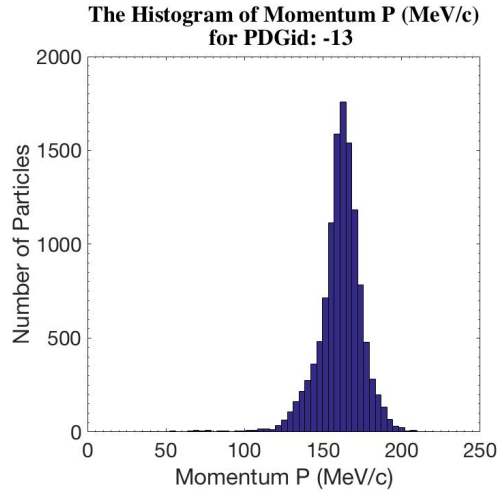




Upper: Run 08280, 170 MeV/c muon beam data; Lower: Run 08280 from MC simulation

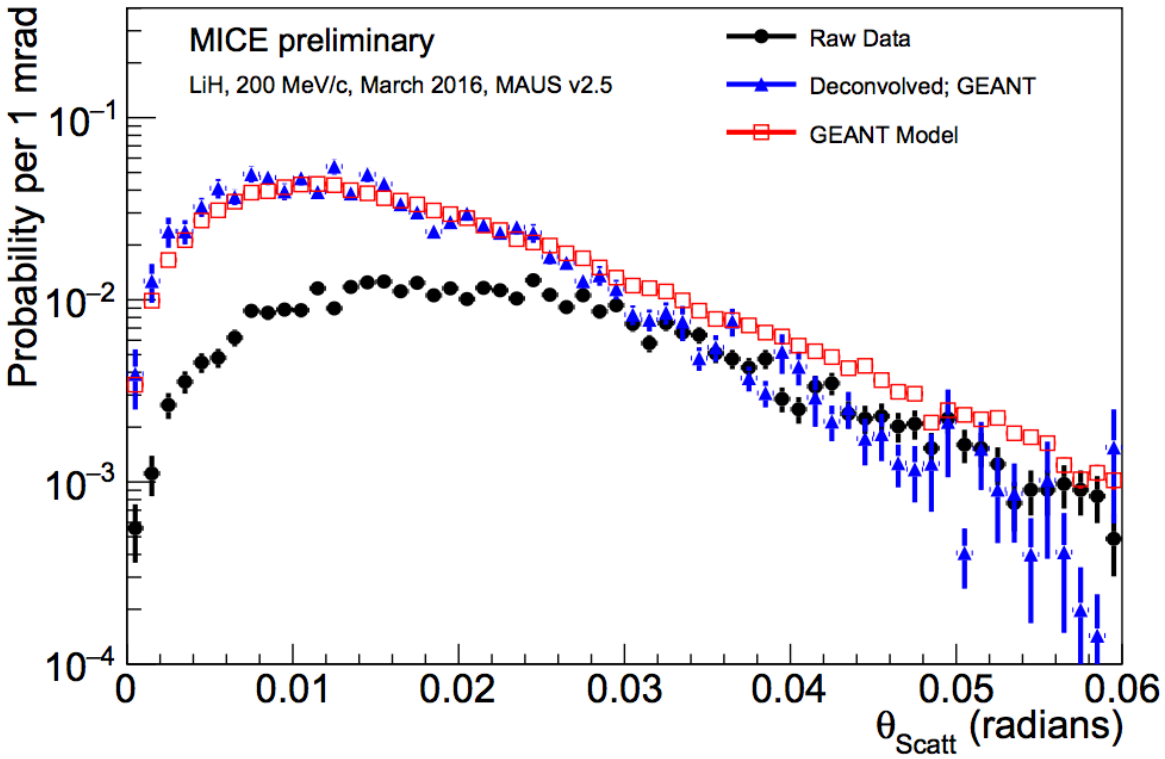






MICE Multiple Scattering Studies

- Geant4 simulations do not match data well for low Z materials;
- Data collected and analyzed at three central momenta: 172, 200 and 240 MeV/c with LiH absorber;
- Empty absorber data taken, and convolved with MS models to untangle the real absorber scattering effect



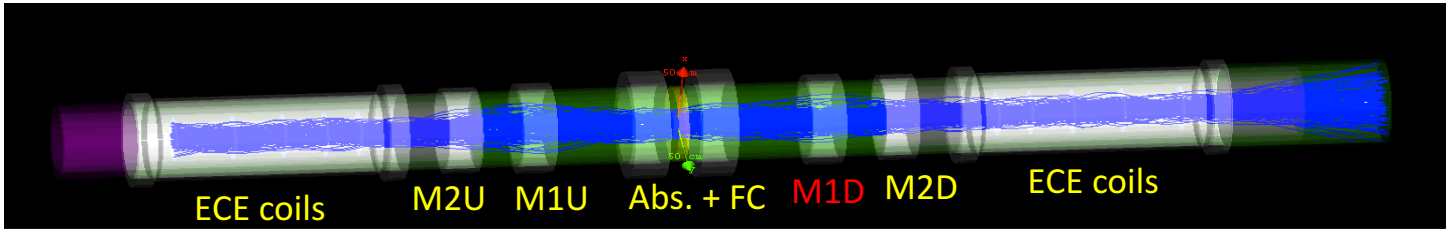
Measured scattering with 65 mm of LiH assuming preferred scattering model with stat. err. only:

- 15.6 +- 0.1 mrad at 172 MeV/c
- 12.8 +- 0.2 mrad at 200 MeV/c
- 10.8 +- 0.1 mrad at 240 MeV/c

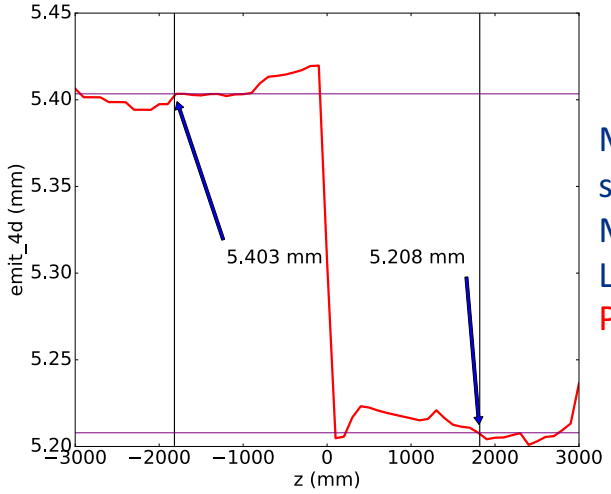
More information in MuScat; NIM B, 251 (2006) 41-55 and NuFact 2016 talk by R. Bayes

MICE Magnet Status

- The matching coil 1 downstream (M1D) is not operable



- Based on the MC and a Genetic Algorithm application, cooling channel optics redefined to achieve the best performance
  - Optimization objective convolves transmission and emittance reduction;
  - More than 90% transmission to TOF2, and ~ 5 percent emittance reduction between TKU and TKD
  - Optimizations results indicate robust Step IV optics designs for cooling measurements.
  - Alternative emittance measurement using Kernel Density Estimation being studied (see iPAC'16 paper and poster WEPOA36 by T. Mohayai)



MICE MC simulation: 200 MeV/c beam, LiH absorber. Preliminary

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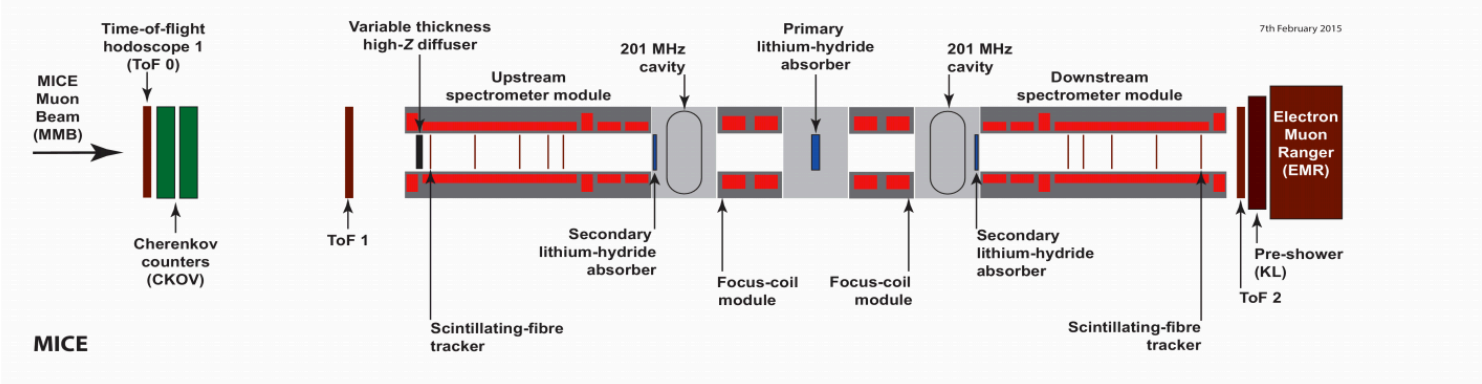
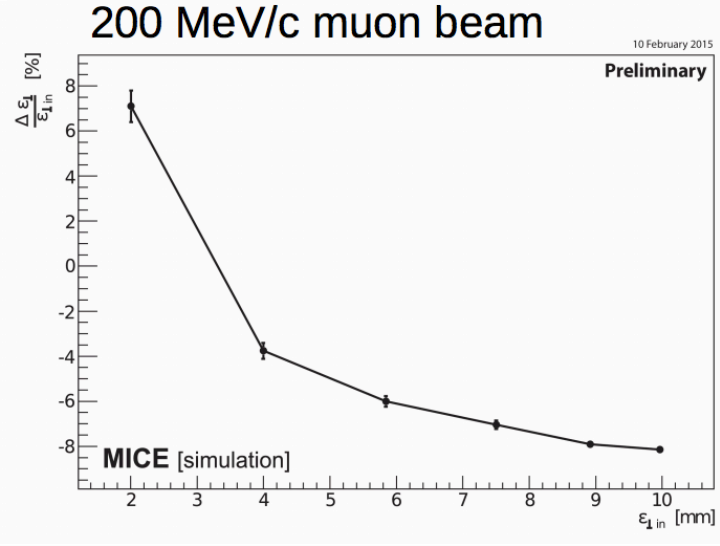
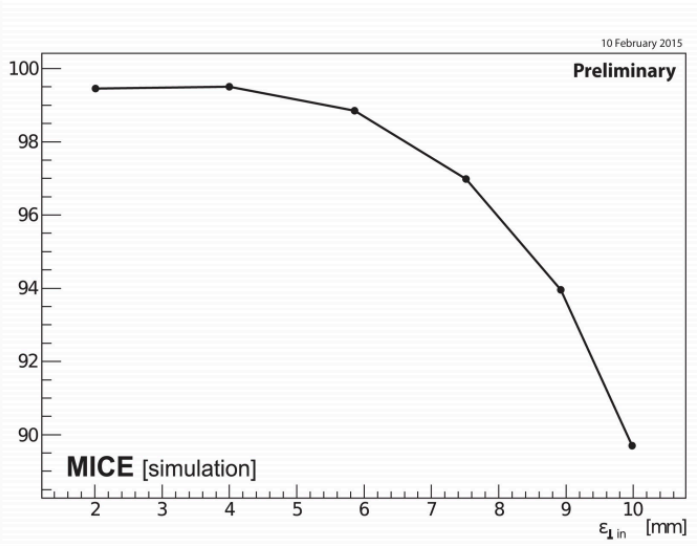
MICE Demonstration of Muon Ionization Cooling (Step DEMO)

- The full cooling scheme with longitudinal momentum recovery in cavities

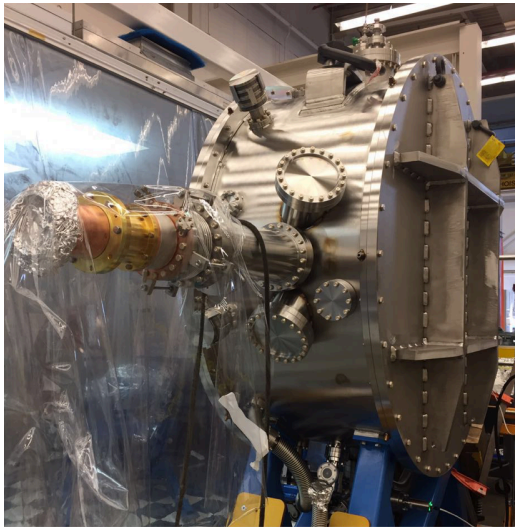


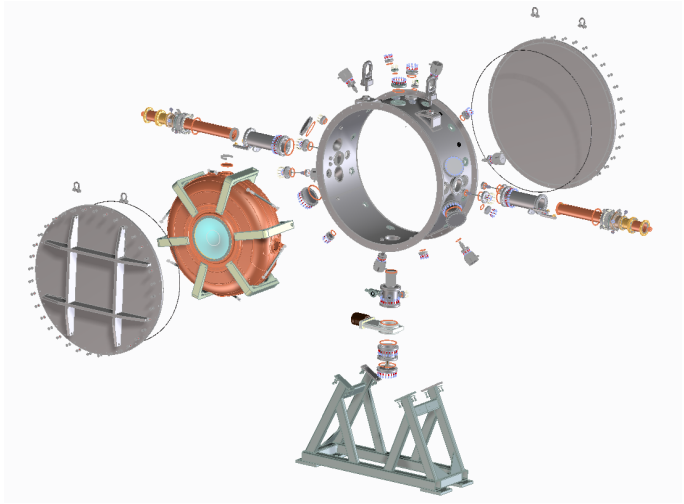




MICE Cooling Demo RF Cavity Preparation

- Testing of the prototype MICE RF Module at Fermilab is complete
  - Successful operation at MICE specifications was demonstrated
- First production unit assembled at LBNL using techniques used at Fermilab.
- Second unit final assembly to begin this week
- Both units in the UK by end of December





Conclusions

- MICE Step IV is running and taking data right now
- Detectors, magnets and optics designs are in hand and working
- Data taken for material physics and first emittance measurement, and now being taken for step-by-step optics studies
  - PID identification validated
  - MAUS software validated
  - Preliminary multiple scattering study delivered
  - Emittance measurement paper in preparation
- MICE has well-defined run plans for Step IV
- Necessary components for Step DEMO are in hand
- Recent MICE publications:
  - "The design and performance of an improved target for MICE" - **JINST 11 (2016)**
  - "Pion Contamination in the MICE Muon Beam" - **JINST 11 (2016)**
  - **Conference proceedings at Neutrino 2016, NuFact 2016, iPAC 2016, etc.**

Thank you!