Muon Ionization Cooling Experiment (MICE): Results & Prospects

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Muon Beams

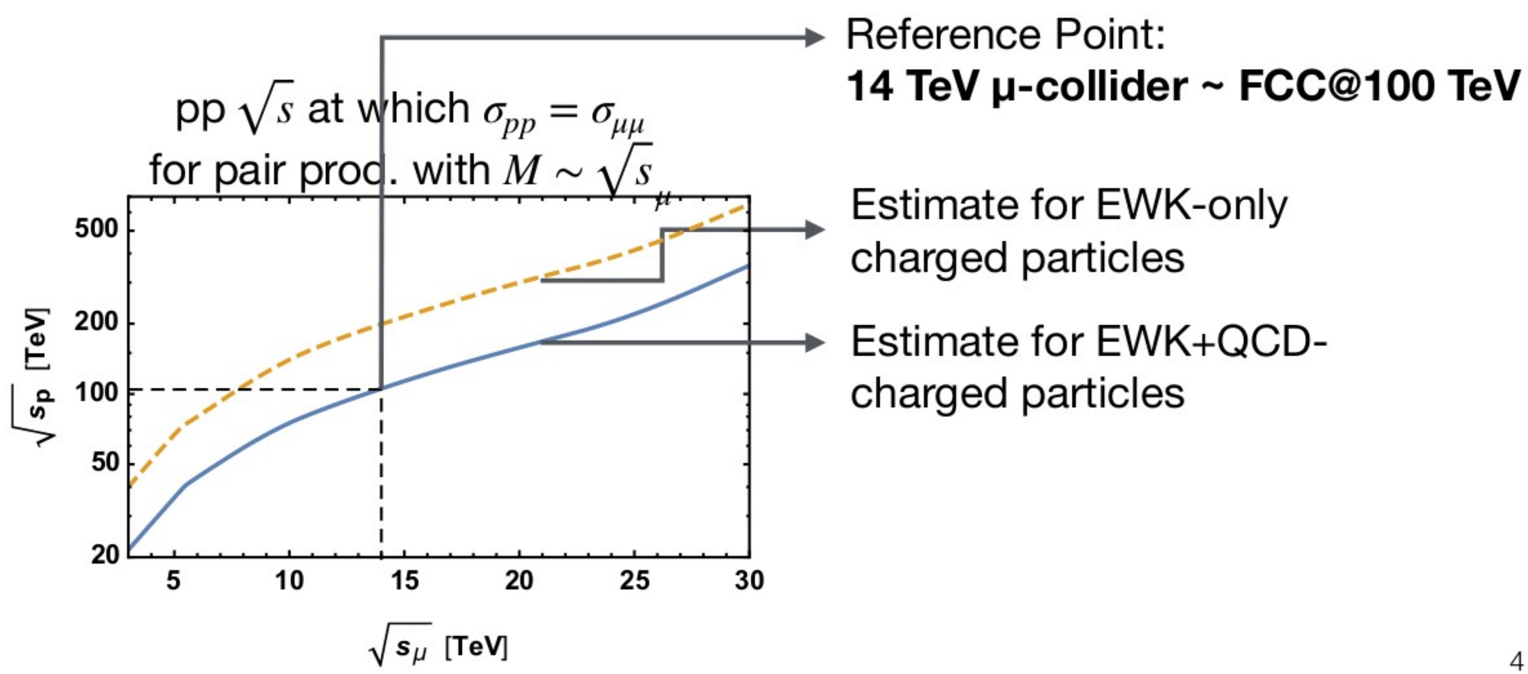
- High energy muons have applications for fundamental physics
  - Muon collision
  - Neutrino production

- Muon collider
  - Muon is a fundamental particle - all the energy is stored in colliding partons
  - Due to muon beeing ~200 times heavier than electron
    - Synchrotron radiation highly suppressed
    - Muon has large coupling to Higgs mechanism
  - HEP can be probed with much smaller collider energy

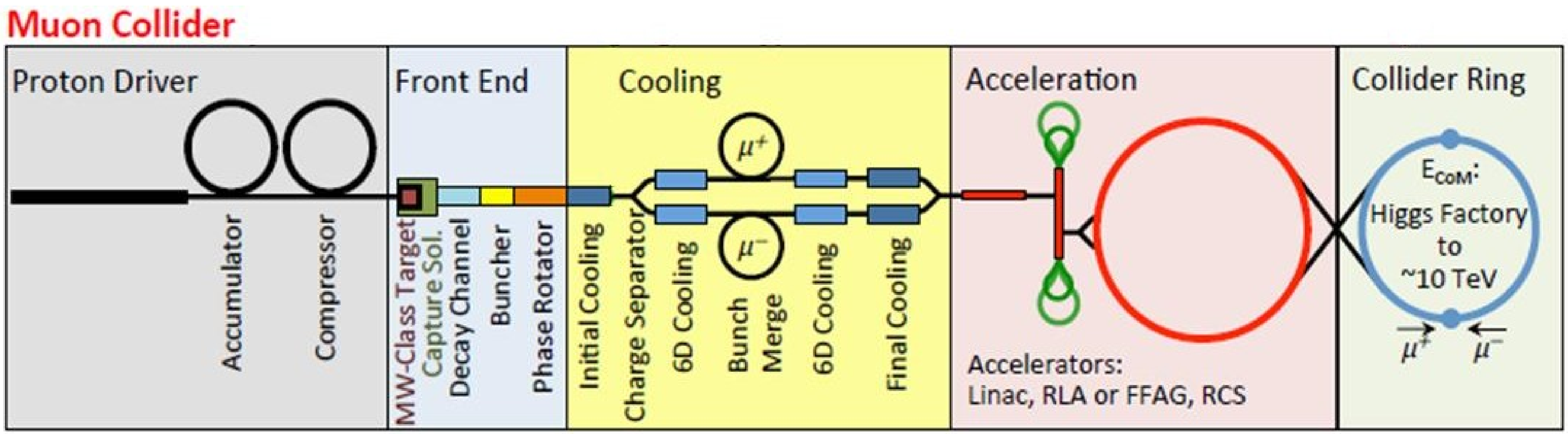
- Neutrino source
  - Can characterise muon beam very well
  - Muon decay is well-known
  - Well-characterised neutrino beam

Muon Collider

- Growing interest in muon collider as a future facility in **Europe**
  - Only lepton collider with potential to go beyond 3 TeV
  - At ~14 TeV, physics reach comparable to 100 TeV protons
  - Compact footprint
  - Efficient electrical power consumption even at high energy
  - Potential for phased construction with physics at each stage



Muon Collider FNAL

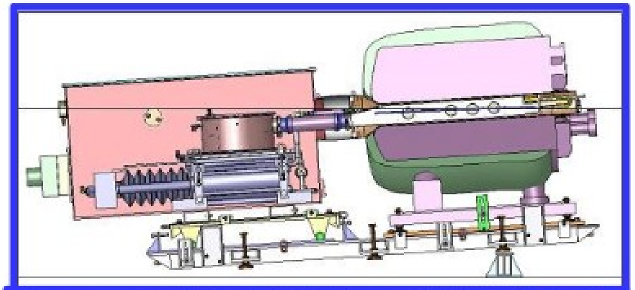


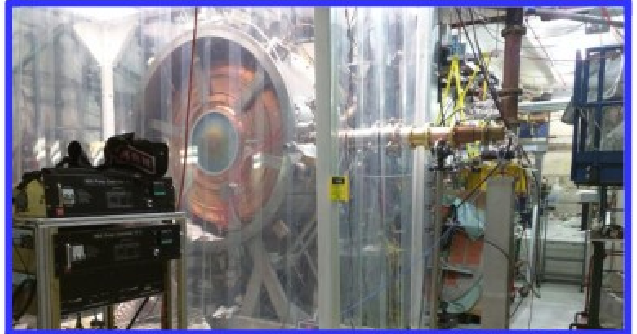
MAP collaboration

- MW-class proton driver → target
- Pions produced; decay to muons (tertiary beam production)
- Muon capture and cooling
- Acceleration to TeV scale
- Collisions
- Critical Issues:
  - Short muon lifetime,
    use ionization cooling, which is the only technique fast enough
  - High initial beam emittance/Low beam brightness

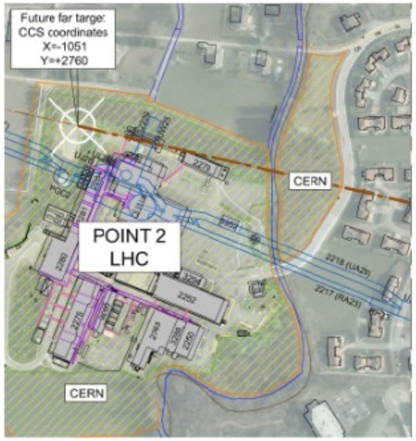
R&D Programme

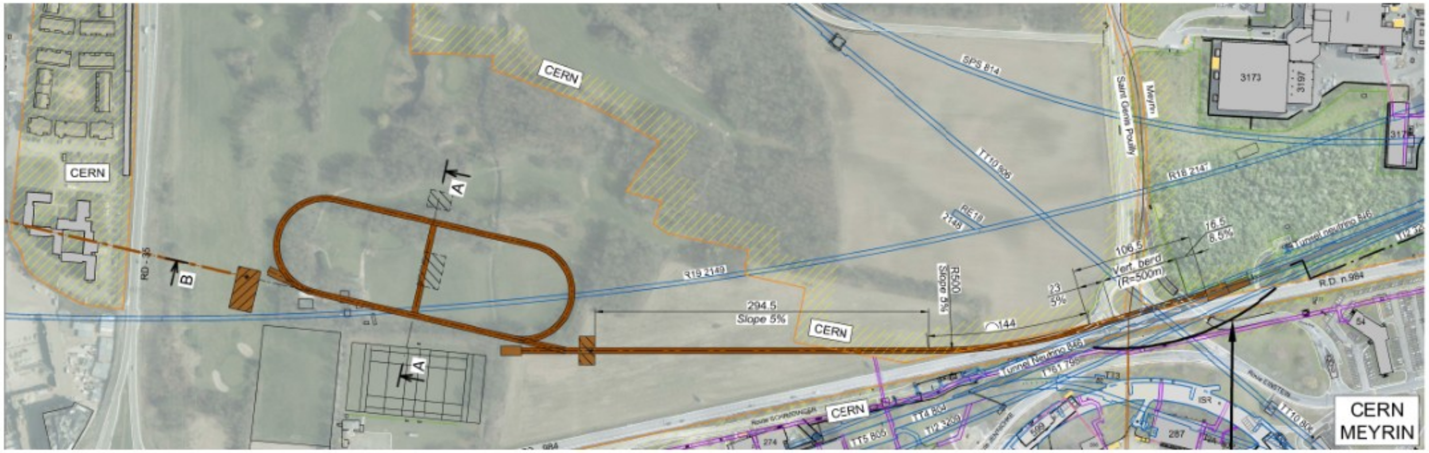
- MERIT
  - Demonstrated principle of liquid Mercury jet target
- MuCool Test Area
  - Demonstrated operation of RF cavities in strong B-fields
- EMMA
  - Showed rapid acceleration in non-scaling FFA (Fixed Field Alternating Gradient) accelerators
- MICE
  - Demonstrated ionisation cooling principle
  - Increase inherent beam brightness → number of particles in beam core





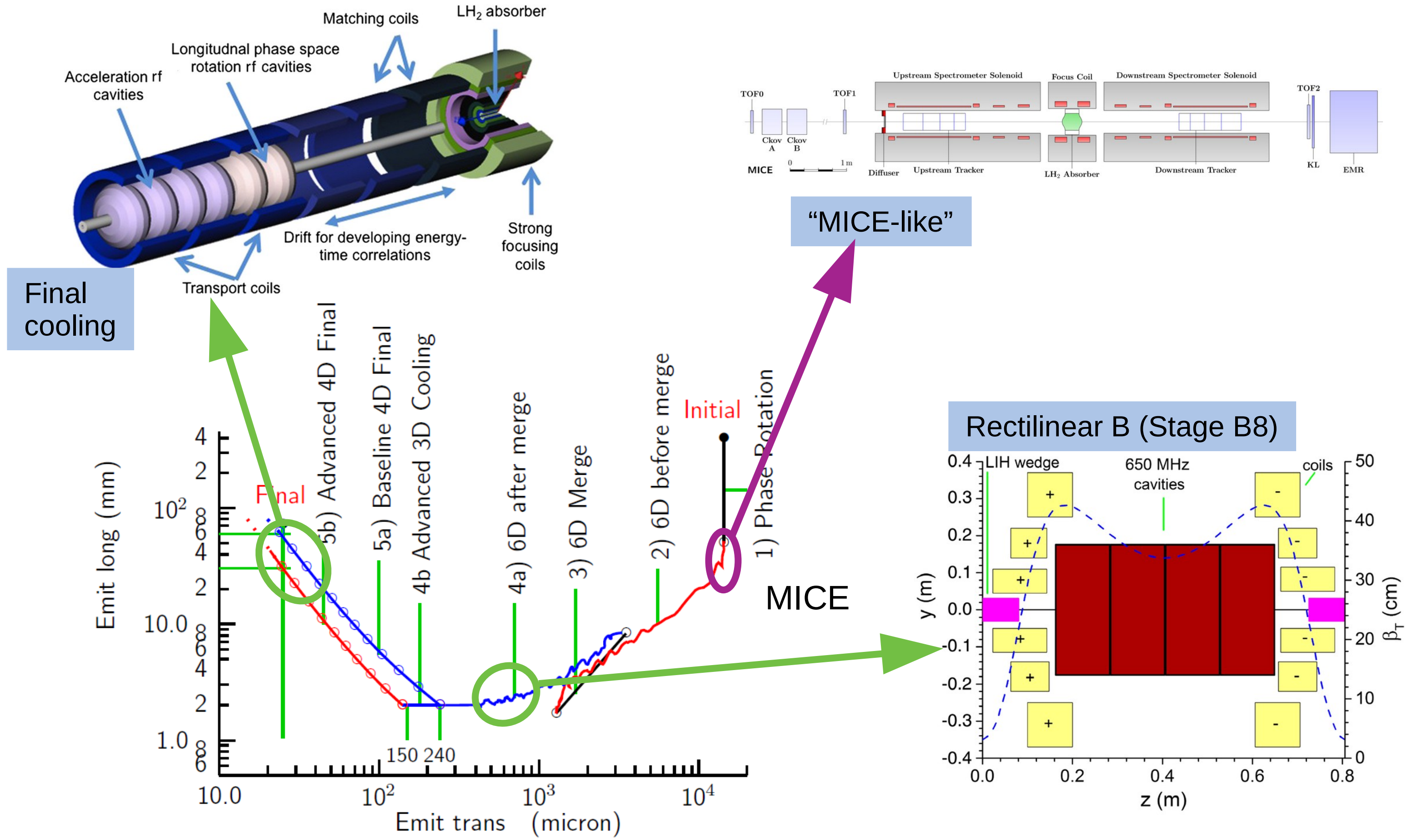
nuSTORM as a Neutrino Source





- Neutrions from StORed Muons - “nuSTORM”
- High-brightness muon source needed for a future experiment
- NuSTORM would make an ideal candidate
  - Demonstrate capture and storage of high energy, high current muon beam
- Important physics goals
  - Beyond Standard Model physics including sterile neutrinos
  - Neutrino scattering cross section measurements

Future experiment



- Significant interest in a follow-up experiment
- To build a muon collider, need lots of cooling
  - Transverse emittance
  - Longitudinal emittance
- MICE has explored only the initial part of a muon cooling channel

What about

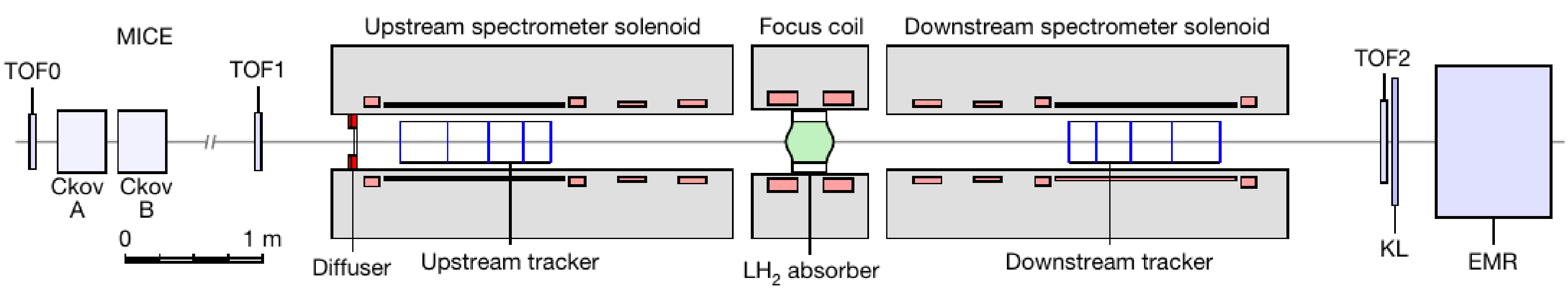
- 6D cooling (reduce energy spread)
- Cooling at low emittance
- Reacceleration and multi-cell cooling

Demonstrator

- Muon cooling demonstrator
  - Demonstrate 6D cooling
  - Low emittance
  - Many cells
- Potential to share the pion source
  - E.g. with neutrino experiment like nuSTORM

Cooling for Muon Accelerators

- How can we get muon beams so that we can accelerate them?
  - Ionisation Cooling!
- Ionisation cooling lattices share common principles
  - Compact lattice
  - Low-Z absorbers – lH_2 and LiH
  - Superconducting solenoids
- How can we demonstrate that such a lattice can work?
- **The international Muon Ionisation Cooling Experiment**



Ionisation cooling

- Emittance (phase space area of a beam) is **conserved**
- Beam **loses energy** in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- **Degraded** by Multiple Coulomb scattering from nucleus
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
- Equilibrium emittance where the effects balance

- Cooling Equation: $$\frac{d\epsilon_\perp}{ds} \sim -\frac{1}{\beta^2}\left|\frac{dE_\mu}{dz}\right|\frac{\epsilon_\perp}{E_\mu} + \frac{\beta_\perp (13.6\ MeV)^2}{2\beta^3 E_\mu m_\mu c^2\ X_0}$$

$\frac{d\epsilon_\perp}{ds}$ is rate of change of transverse emittance within the absorber; β, E_μ and m_μ the muon velocity, energy, and mass, respectively; $\beta_\perp$ is the lattice betatron function at the absorber; X_0 is the radiation length of the absorber material.

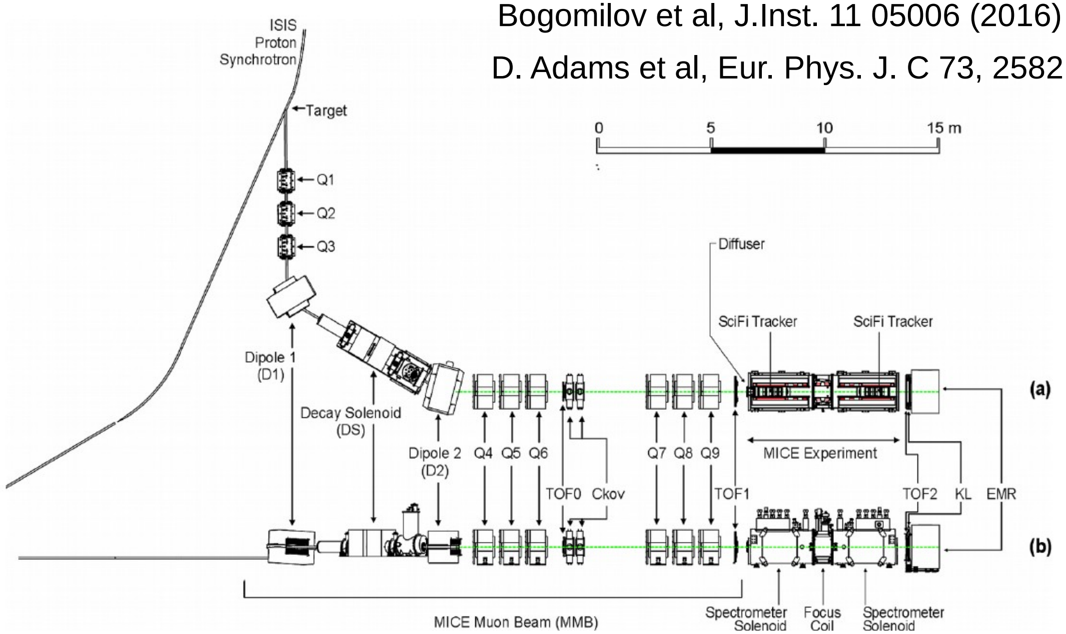
Muon Ionization Cooling Experiment

- Demonstrate high acceptance, tight focussing solenoid lattice
- Demonstrate integration of liquid hydrogen and lithium hydride absorbers
- validate details of material physics models
- Demonstrate ionisation cooling principle and amplitude non-conservation
- Using the unique particle-by-particle beam reconstruction
- MICE operated at RAL between 2008 and 2017 and it groups over 100 collaborators from 30 institutions in 10 countries.

MICE Muon Beam Line

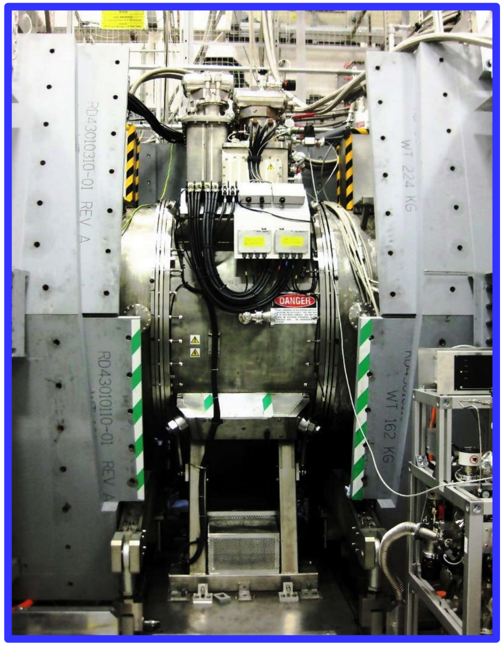
Bogomilov et al, J.Inst. 11 05006 (2016)

D. Adams et al, Eur. Phys. J. C 73, 2582 (2013)



- Muon momenta between 120 and 260 MeV/c
- Muon emittance between 2 mm and 10 mm
- Pion impurity suppressed at up to 99 % level

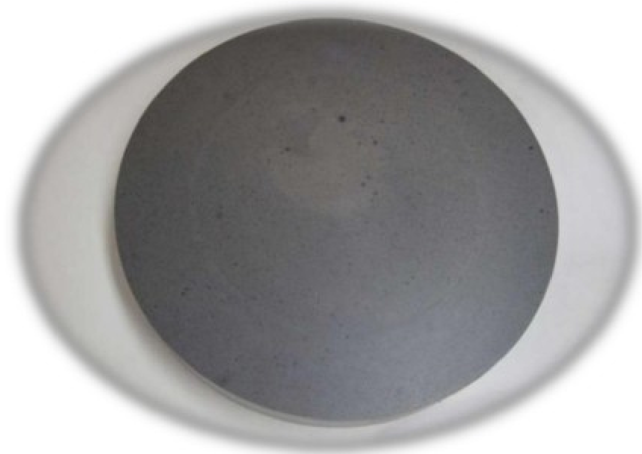
Superconducting Magnets



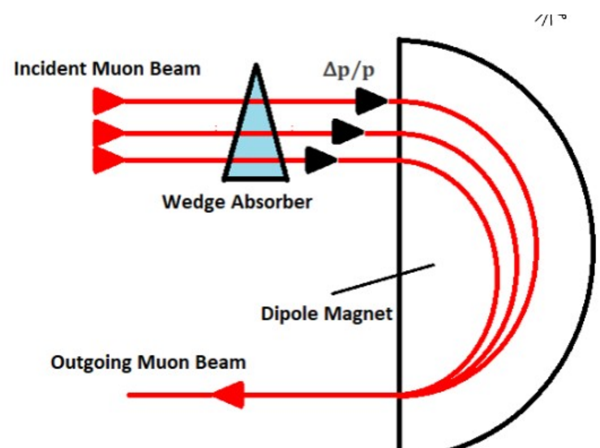
- Spectrometer solenoids upstream and downstream
  - 400 mm diameter bore, 5 coil assembly
  - Provide uniform 2-4 T solenoid field for detector systems
  - Match coils enable choice of beam focus
- Focus coil module provides final focus on absorber
  - Dual coil assembly - possible to flip polarity

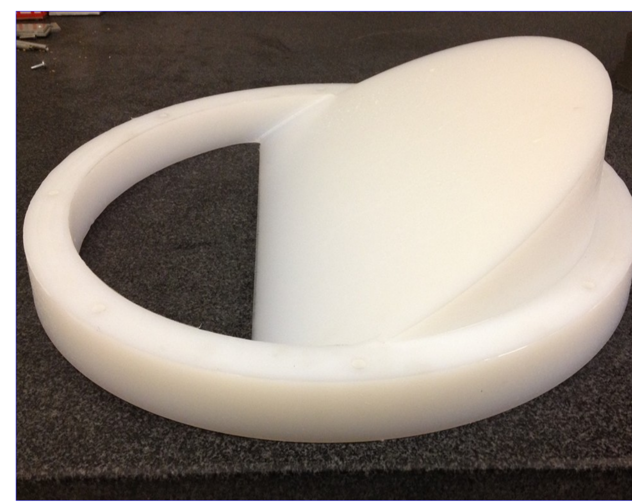
Absorbers

LiH

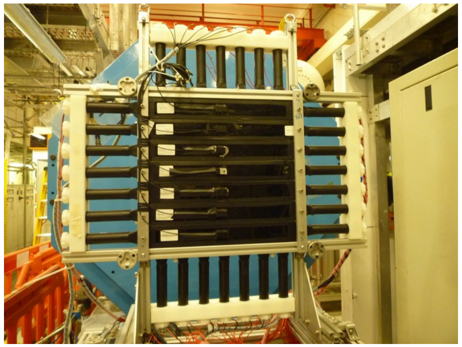


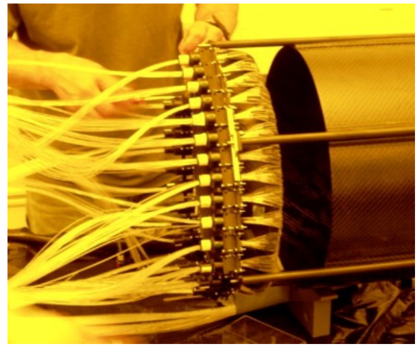
- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- 45^{o} polythene wedge absorber for longitudinal emittance studies

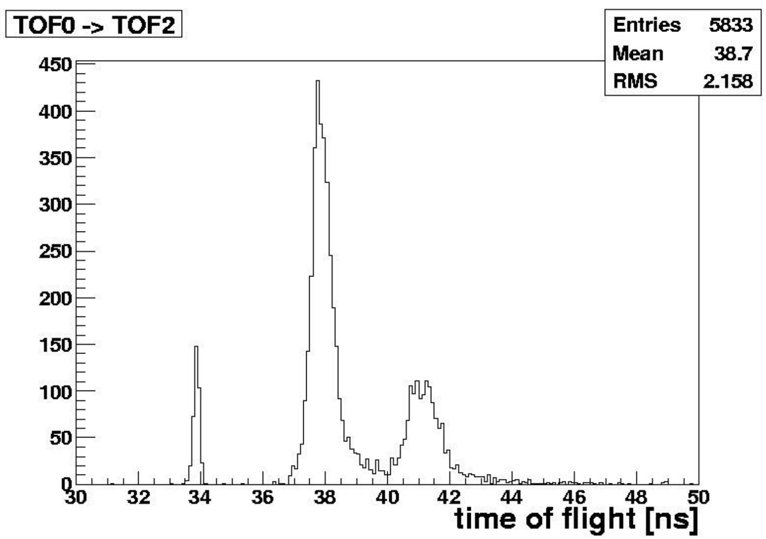




MICE Diagnostics

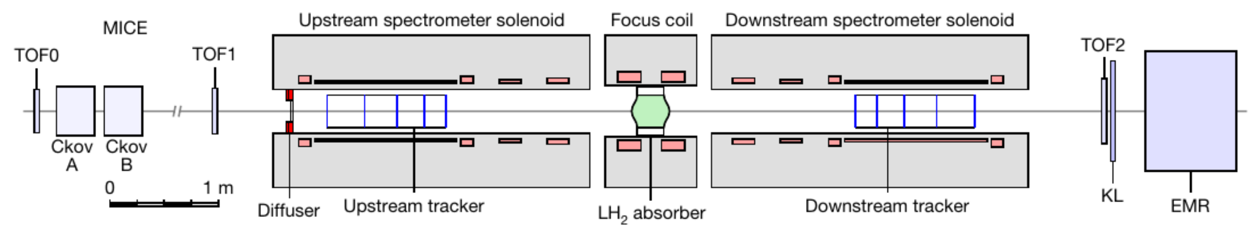




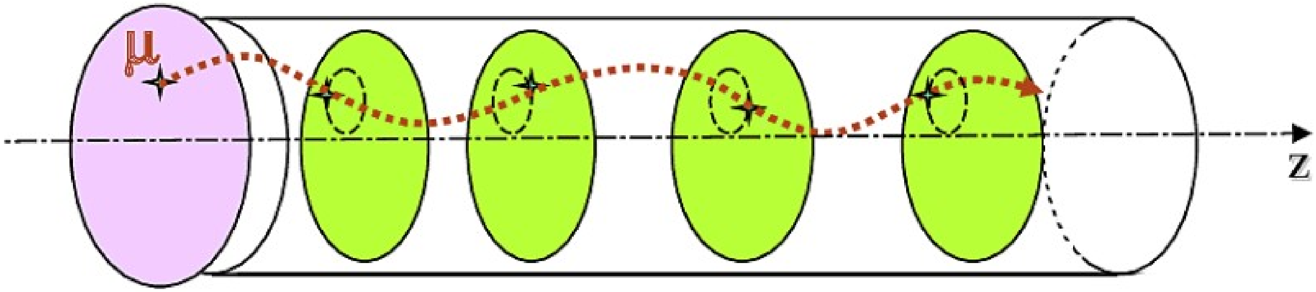


Y. Karadzhov

- Three scintillating TOF stations
  - Time resolution ~ 50 ps
  - Commissioned in 2009
- Two Scintillating Fibre Trackers
  - Position resolution ~ 0.7 mm
  - Simulated momentum resolution ~ 2 MeV/c
- Threshold Cerenkov counter
- KL pre-shower detector
- Electron-muon ranger

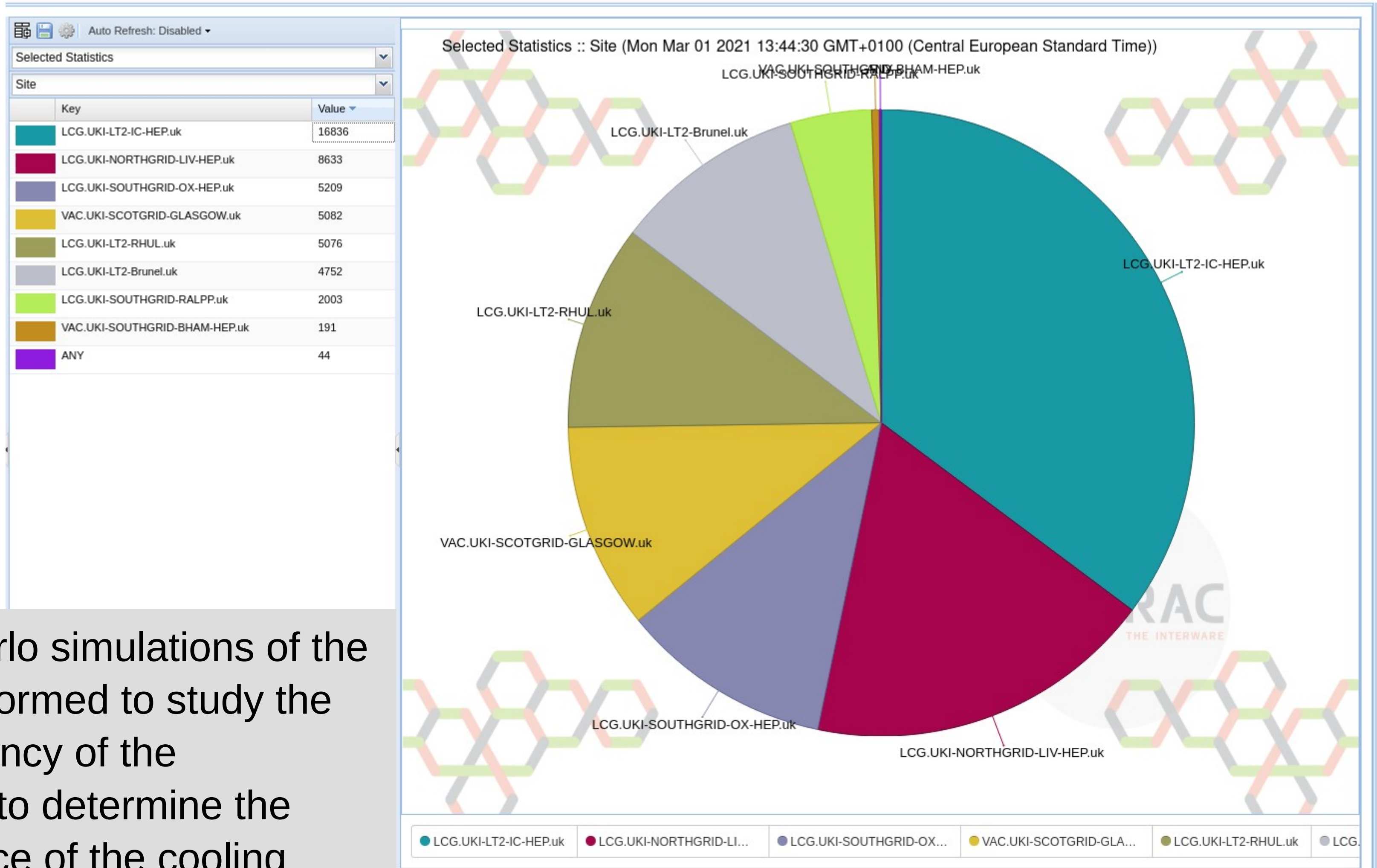


Scintillating Fibre Tracker



- Scintillating fibre trackers placed upstream and downstream of the cooling channel
  - Based on D0 SciFi technology
  - 5 scintillator stations in up to 4 T uniform field
    - Reconstruction of helical path yields particle momentum
  - Measured 470 micron position resolution
  - Simulated 1-2 MeV/c p_t resolution
  - Simulated 3-4 MeV/c p_z resolution
- Simulated emittance measurement precision at 1e-3 level

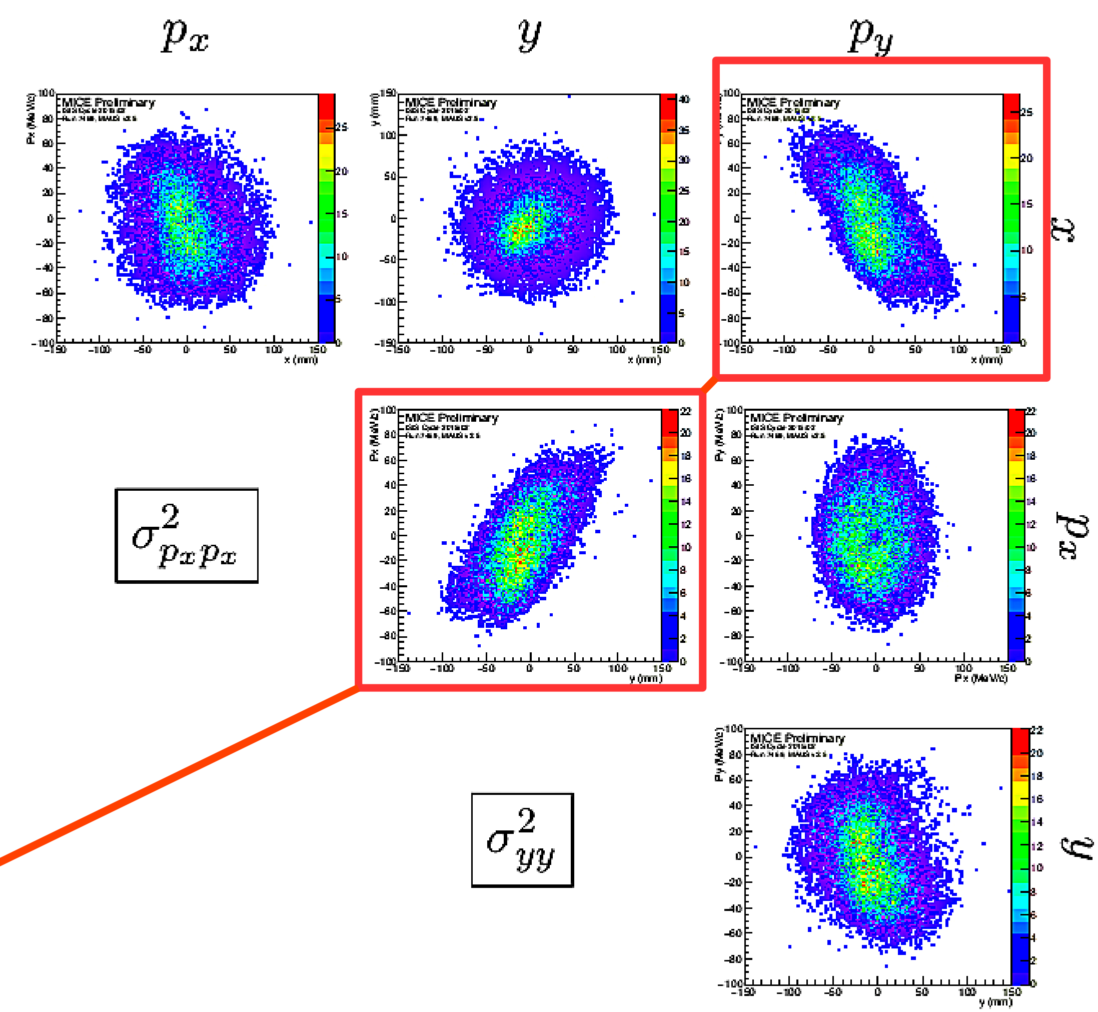
MAUS: The MICE Analysis User Software



A detailed Monte Carlo simulations of the experiment was performed to study the resolution and efficiency of the instrumentation and to determine the expected performance of the cooling apparatus.

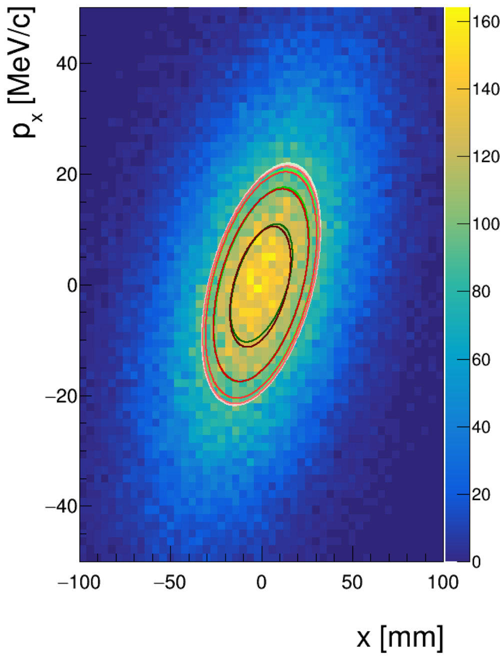
The simulation was found to give a good description of the data.

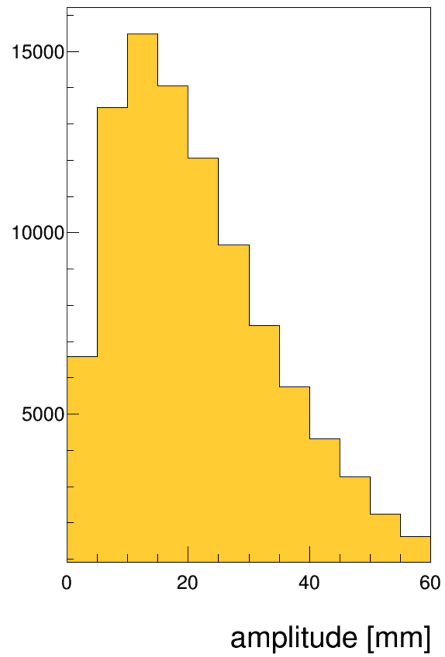
Phase space reconstruction



- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision
- E.g. coupling of x-y from solenoid fields

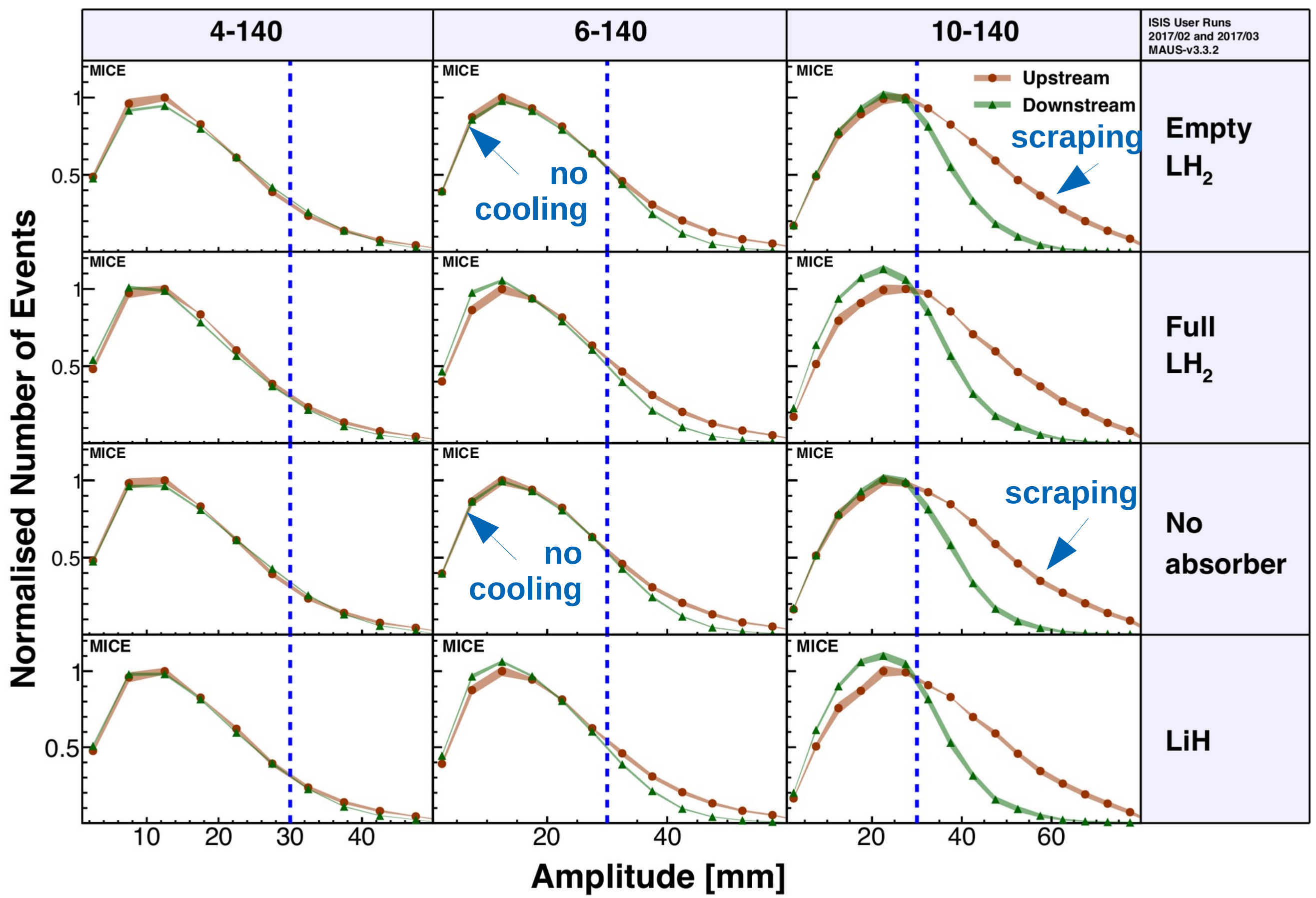
Amplitude reconstruction

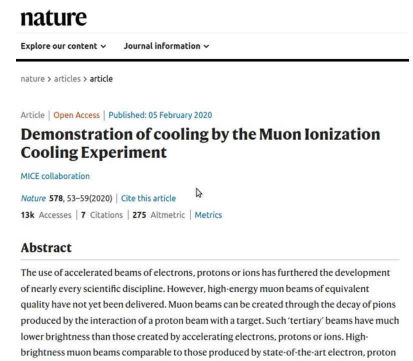




- Phase space (x, p_x, y, p_y)
- Normalise phase space to RMS beam ellipse
  - Clean up tails
- Amplitude is distance of muon from beam core
  - Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread
  - Reduces amplitude
- Mean amplitude ~ "RMS emittance"

Change in Amplitude Across Absorber





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Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

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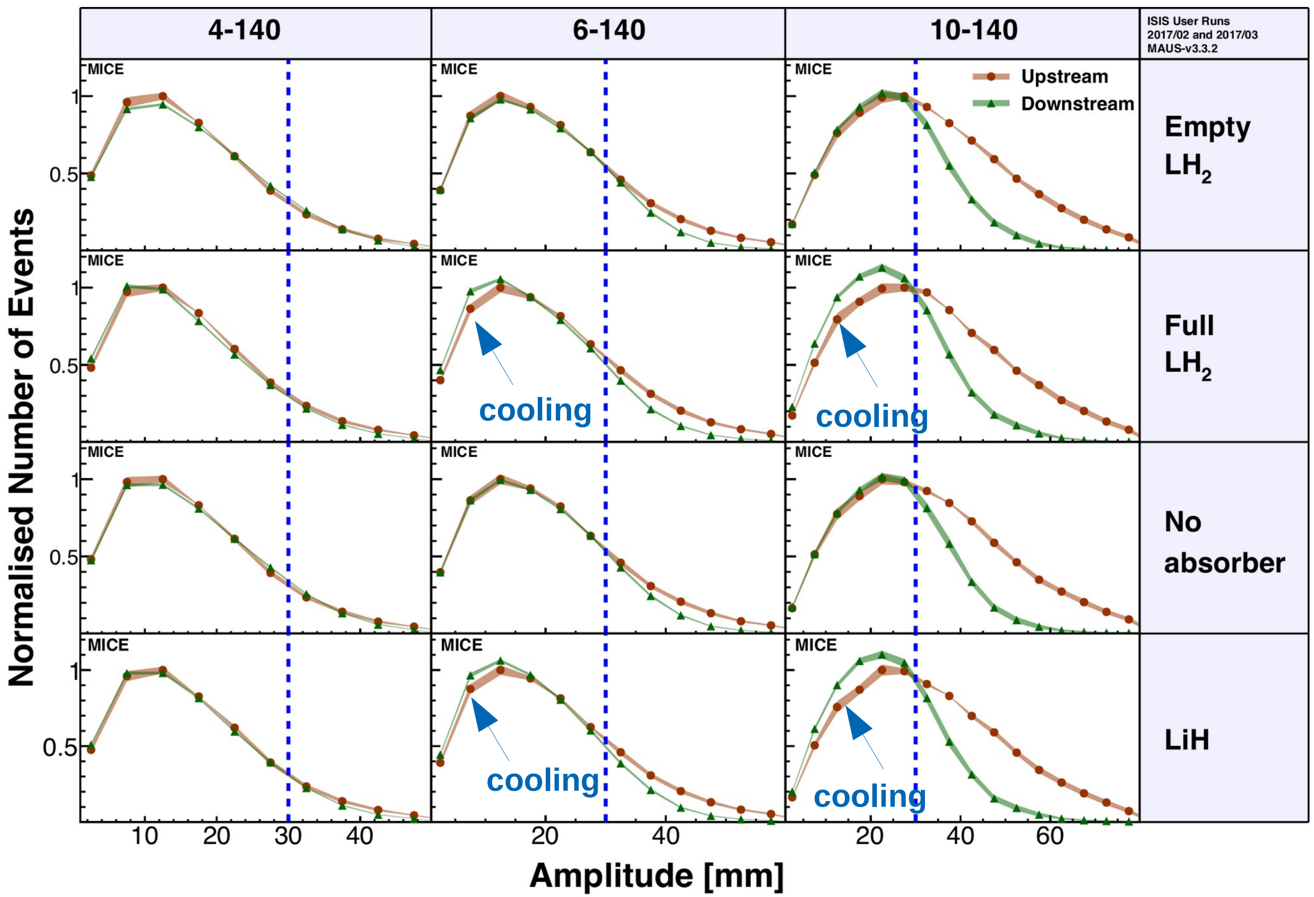
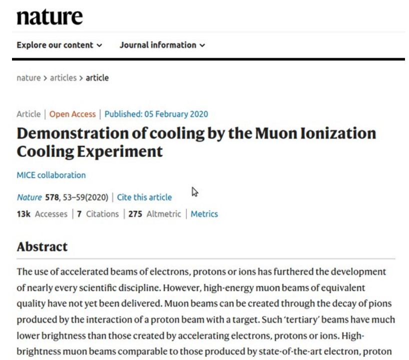
Abstract

The use of accelerated beams of electrons, protons or ions has furthered the development of nearly every scientific discipline. However, high-energy muon beams of equivalent quality have not yet been delivered. Muon beams can be created through the decay of pions produced by the interaction of a proton beam with a target. Such 'tertiary' beams have much lower brightness than those created by accelerating electrons, protons or ions. High-brightness muon beams comparable to those produced by state-of-the-art electron, proton

- No absorber → slight decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal

Change in Amplitude Across Absorber

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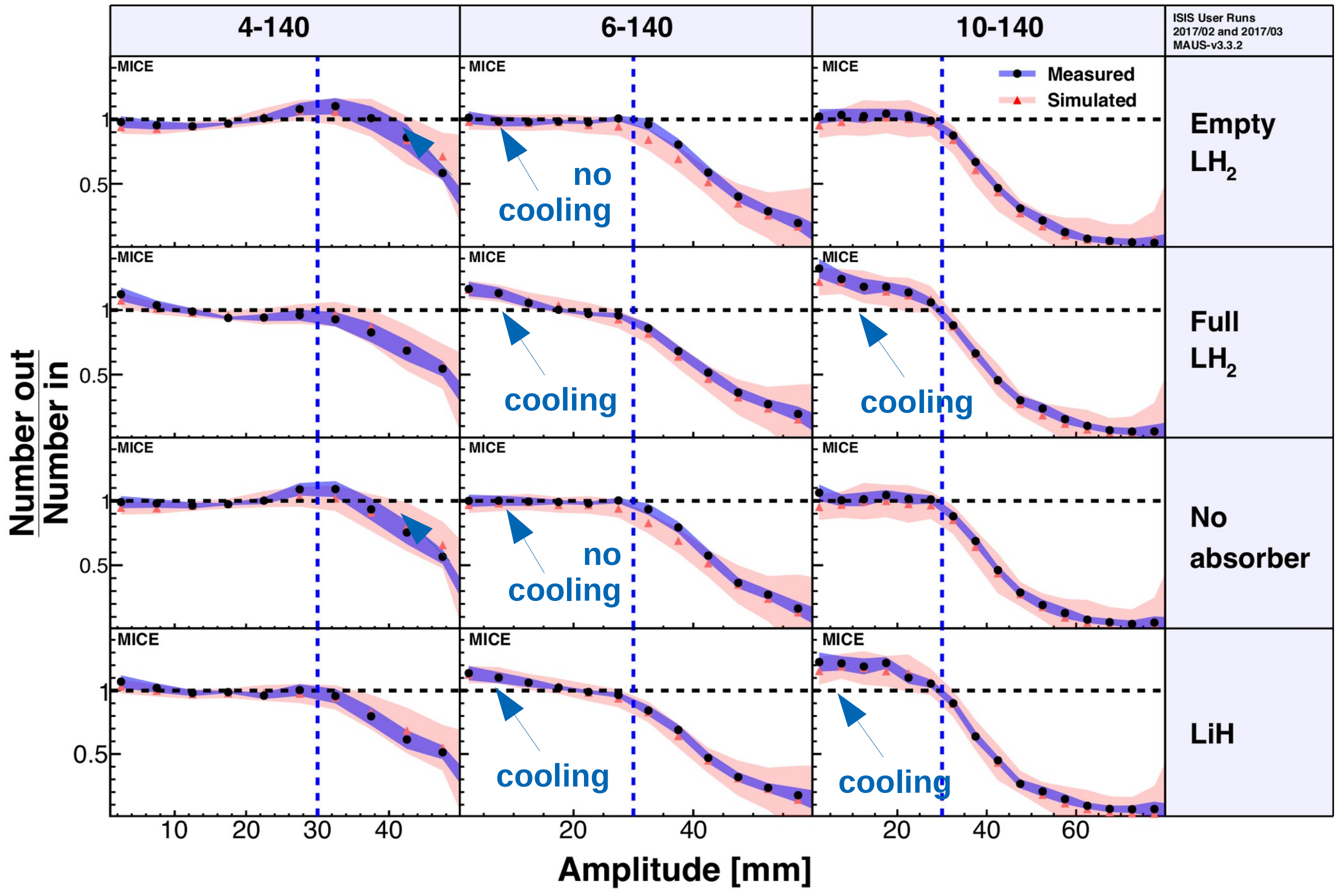
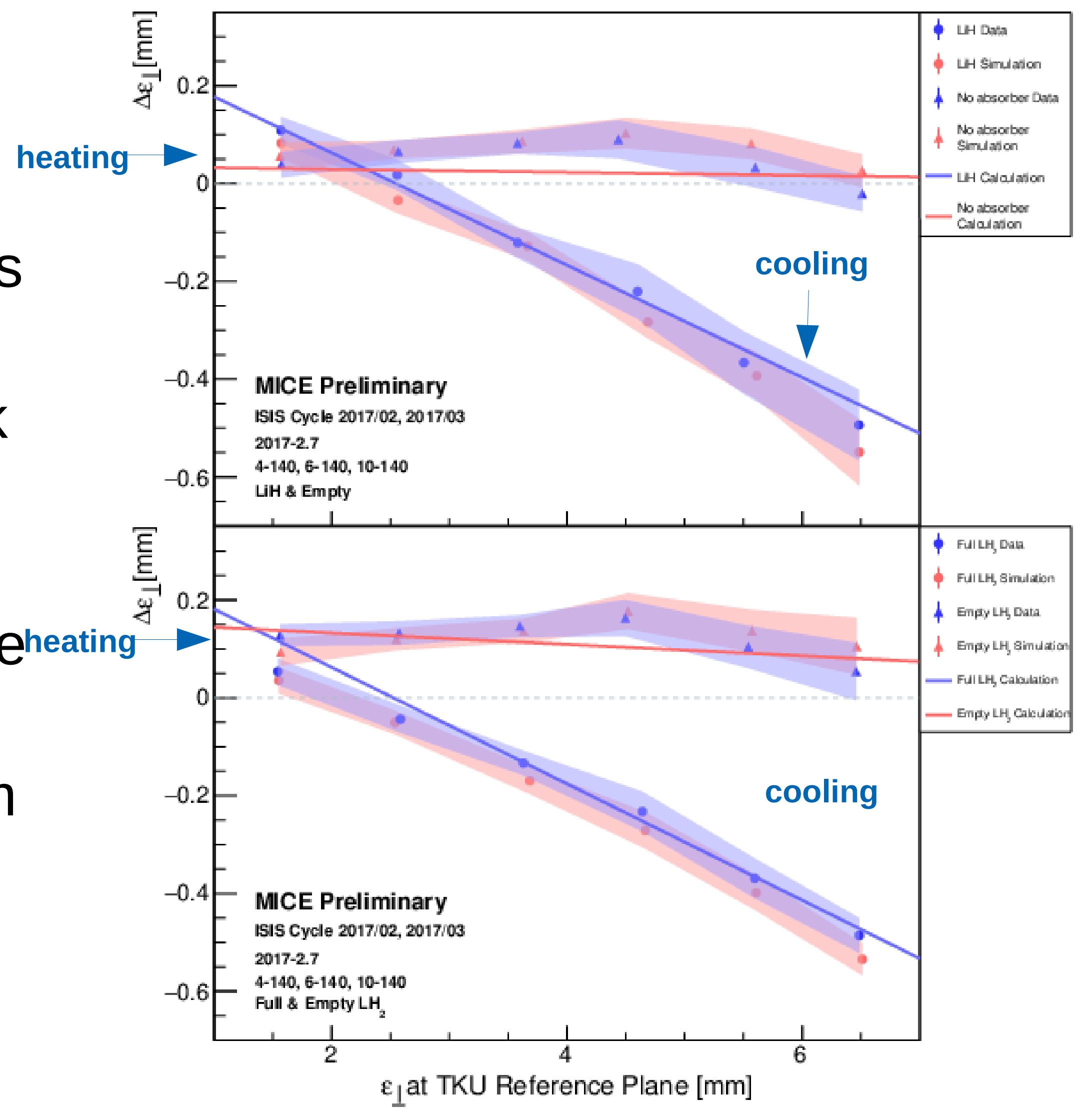
Ratio of core densities



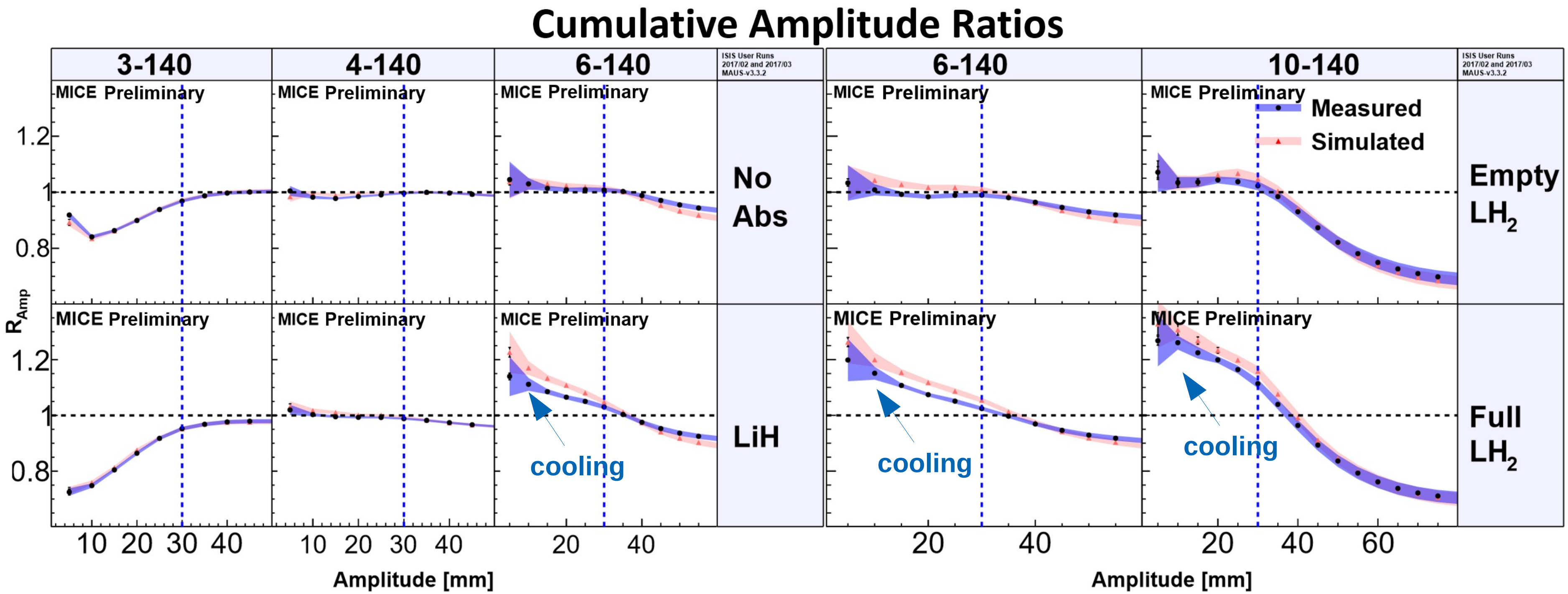
- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances
- Consistent with simulation

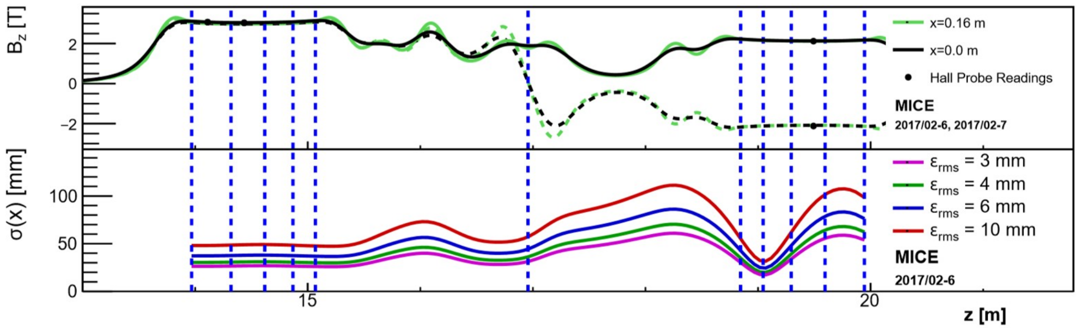
Transverse Emittance

- Also measure change in RMS emittance
  - Mean of the amplitude distribution
- Look at different sub-samples of the muon ensemble
- In absence of absorber weak heating
- With absorber
  - Cooling for high emittance beams
  - Heating below equilibrium emittance
  - Consistent with theory
- Publication in progress



Solenoid mode





- Most cooling is done at 0 T
- Non-zero field
  - Studies in progress on cooling performance in solenoid mode

Summary

- Muon collider high priority initiative in European Strategy
  - “Dream machine” for high-energy physics
- High-brightness muon source needed
  - Beam needs to be cooled using ionisation cooling
- MICE built to study muon cooling
  - Unprecedented single particle measurement of particle trajectories in an accelerator lattice
- MICE has made first observation of ionization cooling
- Growing excitement for a follow-up experiment
  - nuSTORM would make an excellent muon source
- More info:
  - http://mice.iit.edu
  - https://www.nustorm.org
  - https://muoncollider.web.cern.ch/