Muon Ionization Cooling Experiment (MICE): Results & Prospects

C. T. Rogers on behalf of the MICE collaboration
ISIS
Rutherford Appleton Laboratory

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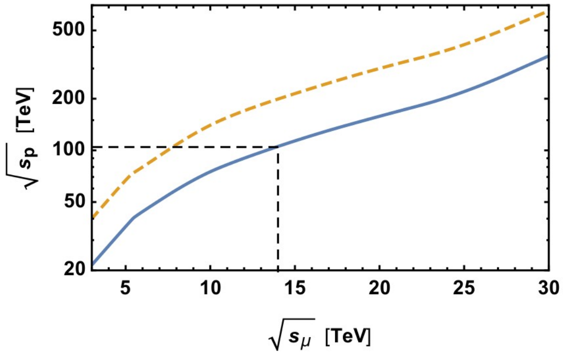
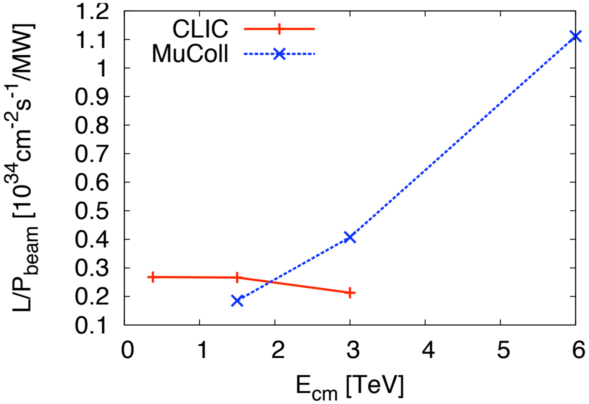
Accelerated Muons

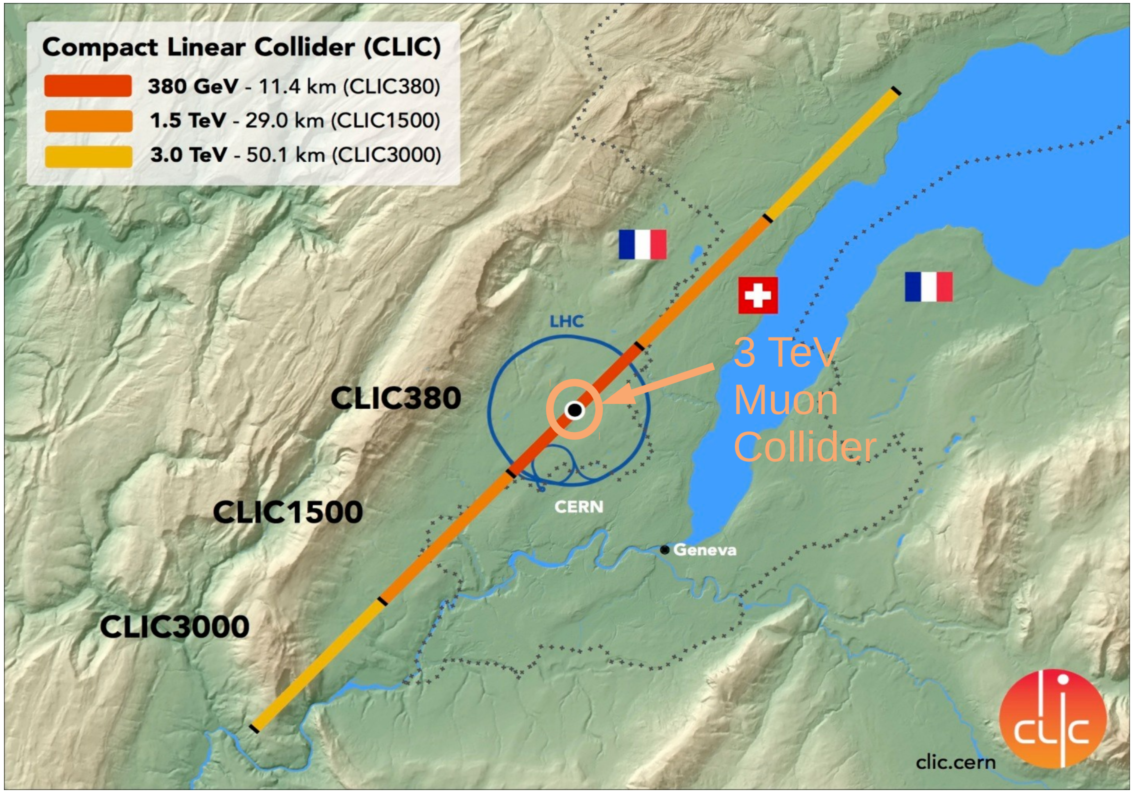
- High energy muons have applications for fundamental physics
  - Muon collision
  - Neutrino production
- Muon collider
  - Muon is a fundamental particle
  - Synchrotron radiation highly suppressed
  - Ideal collider!
- Neutrino source
  - Can characterise muon beam very well
  - Muon decay is well-known
  - Well-characterised neutrino beam

Muon Collider

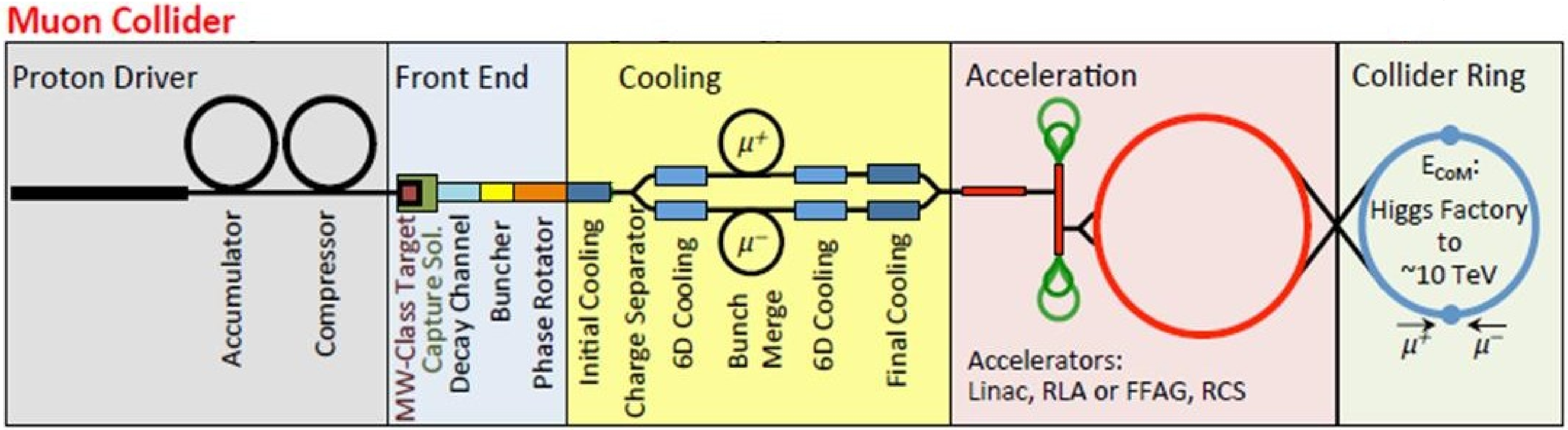
- Growing interest in muon collider as a future facility in Europe
  - Only lepton collider with potential to go beyond 3 TeV
  - At ~14 TeV, physics reach comparable to 100 TeV protons
  - Compact footprint
  - Efficient electrical power consumption even at high energy
  - Potential for phased construction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







Muon Collider

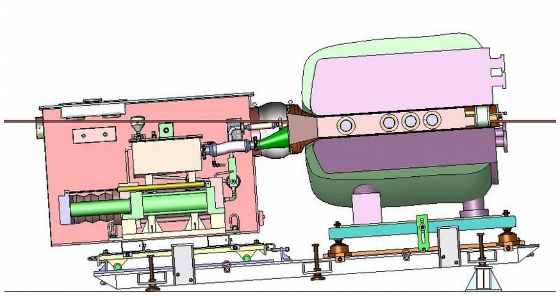


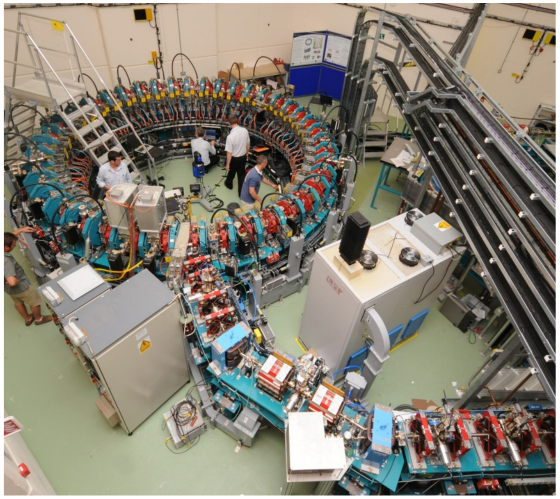
MAP collaboration

- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV scale
- Collisions
- Critical Issues:
  - Short muon lifetime
  - High initial beam emittance/Low beam brightness

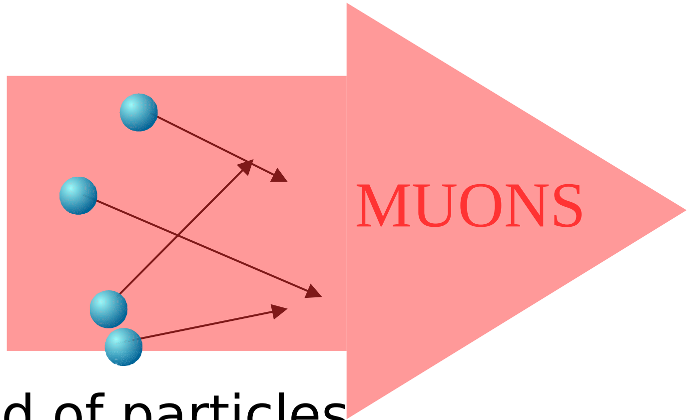
Muon Accelerator R&D

- MERIT
    - Demonstrated principles of pion production in solenoid field
- EMMA
    - Demonstrated fast acceleration in FFAs
- MUCOOL
    - Radio-frequency accelerating cavity R&D
    - Demonstrated operation of cavities at high voltage in magnetic field
        - Breakdown suppression using high pressure gas
        - Breakdown suppression using Be surface
- Muon Ionisation Cooling Experiment (MICE)
    - Need to increase beam brightness
        - Otherwise particles don’t collide
    - Technique known as ionisation cooling

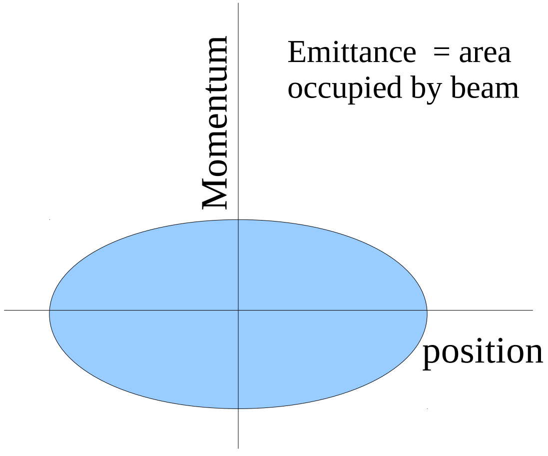


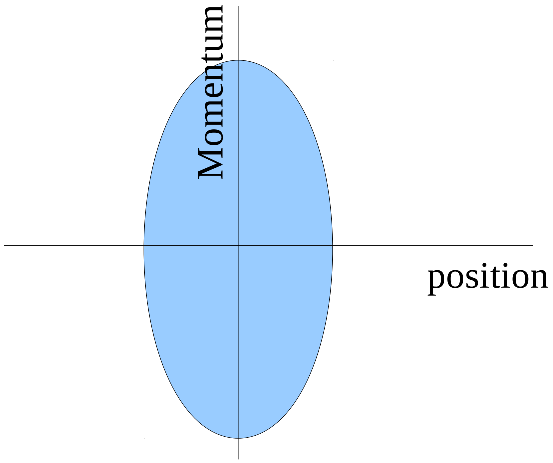


Beam Emittance

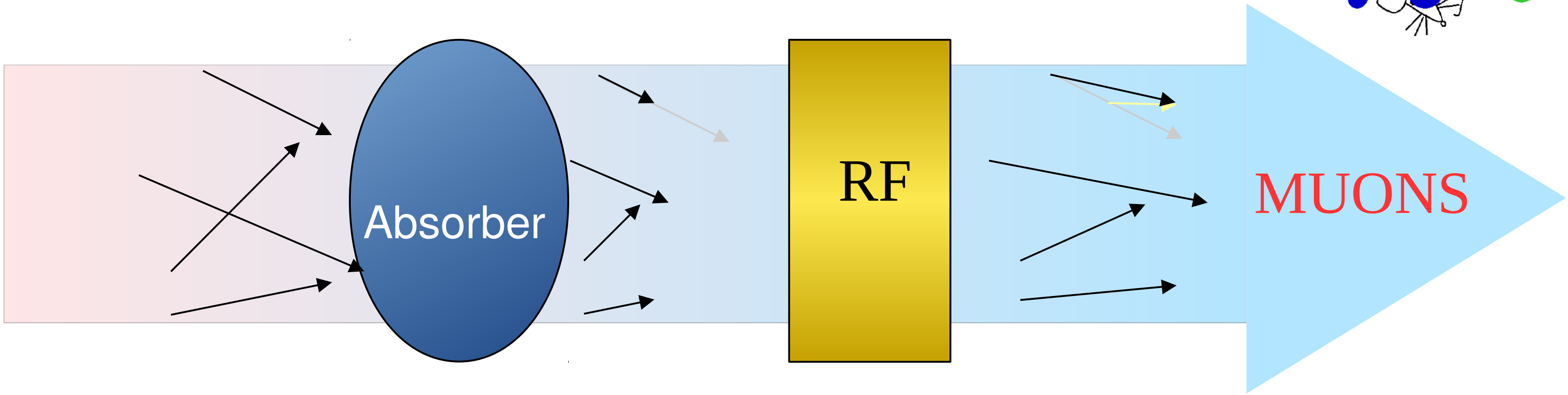


- Consider a cloud of particles
  - Particles move in many different directions
  - Particles have a spread in position
- Use a magnetic lens to focus the beam
  - Decrease the spread in position
  - Increase the spread in momentum
- Use a magnetic lens to defocus the beam
  - Increase the spread in position
  - Decrease the spread in momentum
- Emittance is area occupied by beam
- The emittance is **conserved**
  - Analogous to temperature





Ionisation Cooling



- 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

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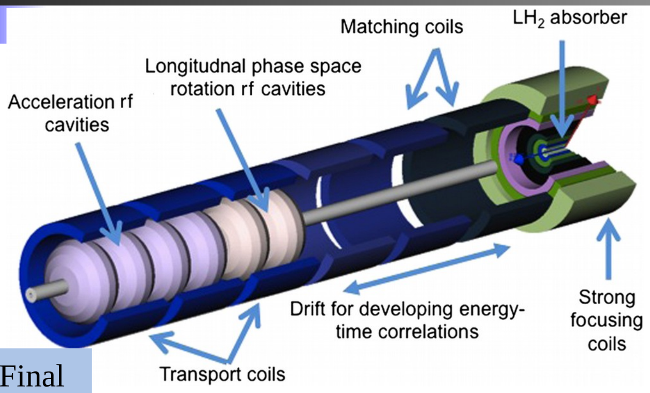
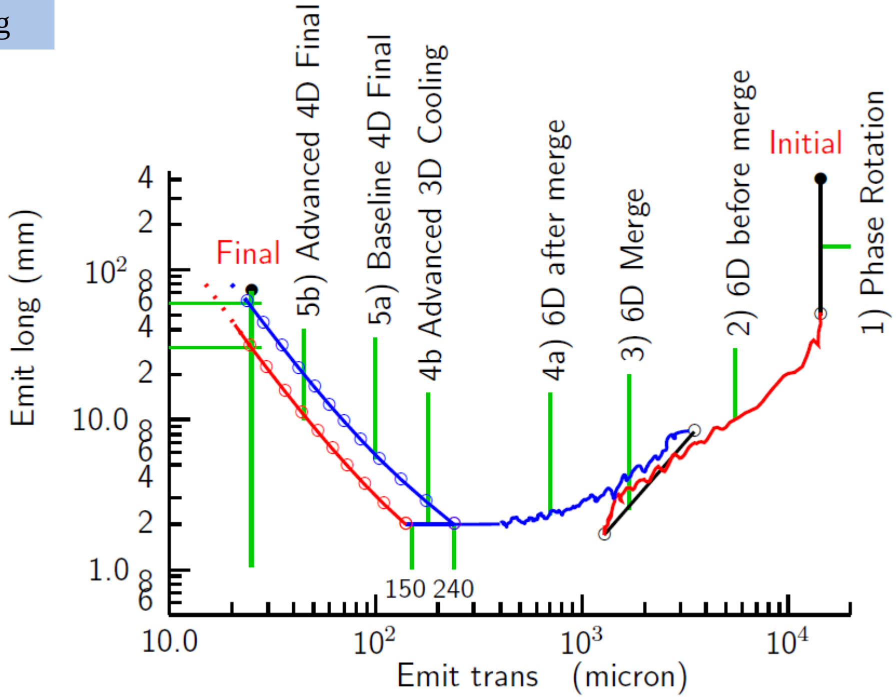
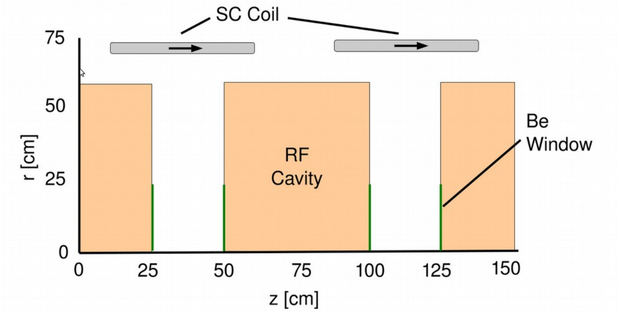
Muon Cooling



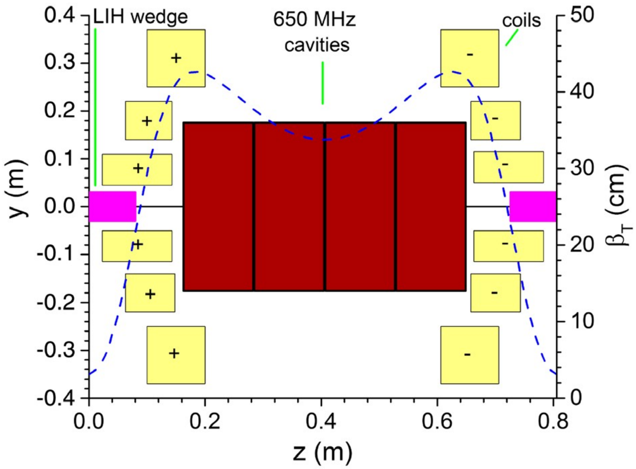
4D Final cooling



Phase rotation



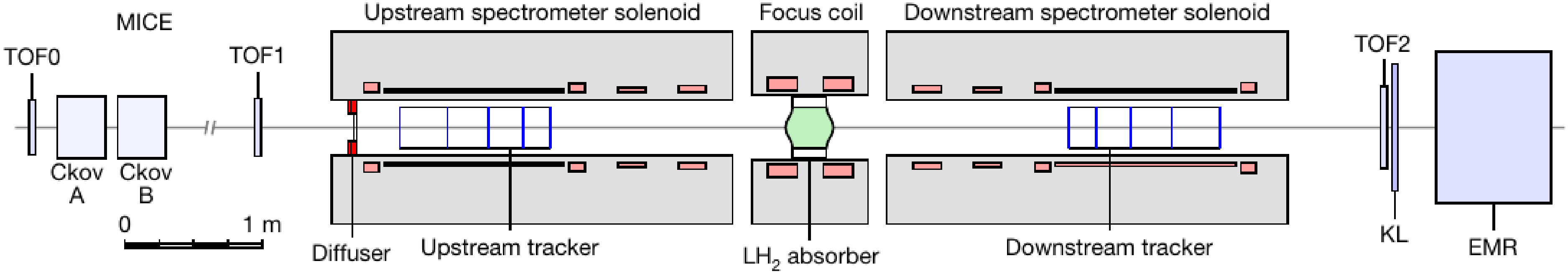
6D cooling



Cooling for Muon Accelerators

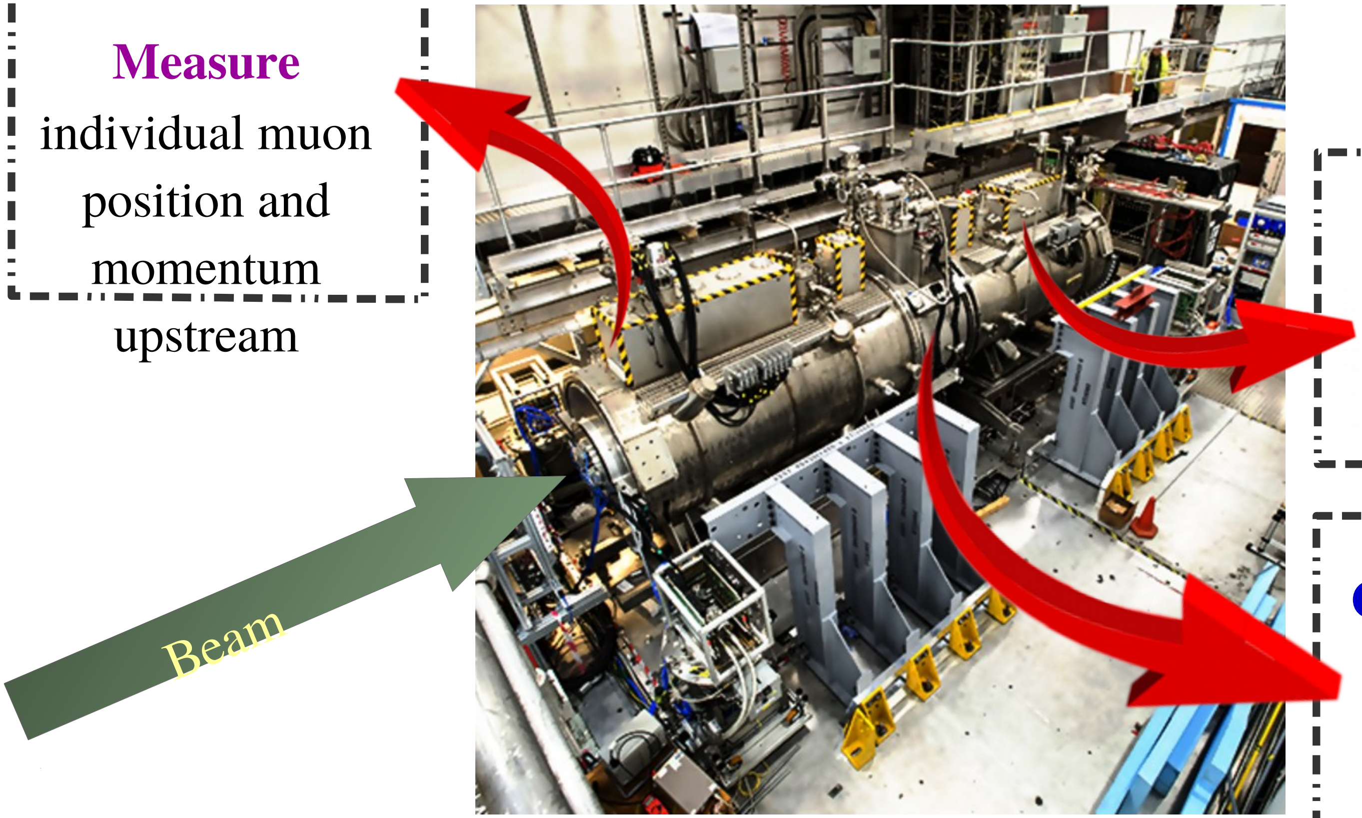
- How can we get muon beams so that we can accelerate them?
  - Ionisation Cooling!
- Ionisation cooling lattices share common principles
  - Compact lattice
  - Low-Z absorbers – lH_2 and LiH
  - Superconducting solenoids
- How can we demonstrate that such a lattice can work?
- **The international Muon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

The answer - MICE



Experimental configuration

Measure individual muon position and momentum upstream



Measure muon position and momentum downstream

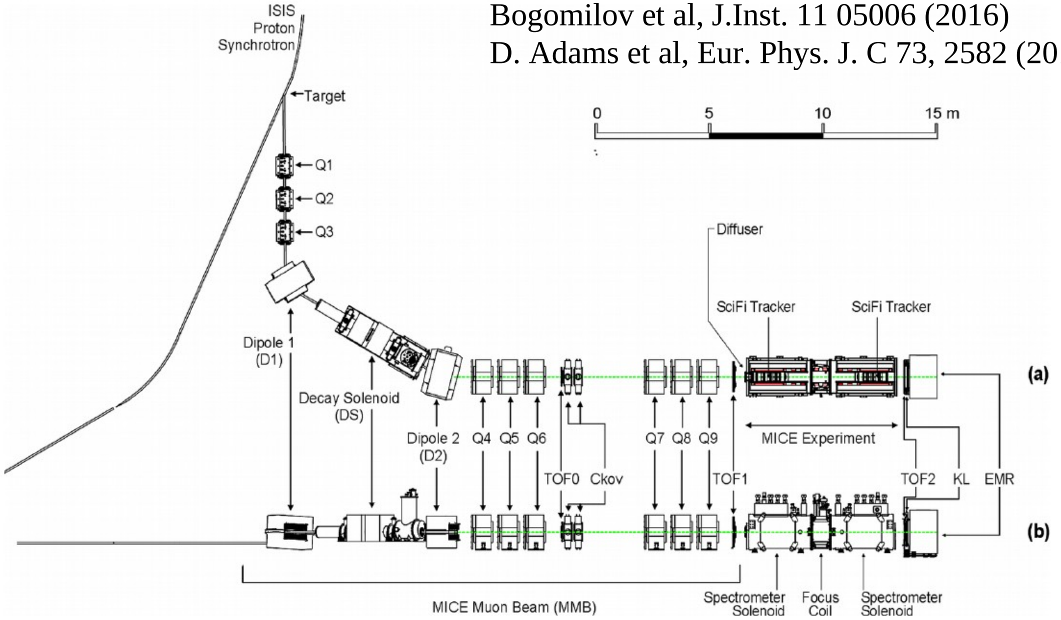
Cool the muon beam using LiH, LH_2, or polyethylene wedge absorbers

Collaboration

- Over 100 collaborators, 10 countries, 30 institutions
- Operated at Rutherford Appleton Laboratory between 2008 and 2017
- Dedicated transport line bringing pions/muons from ISIS synchrotron

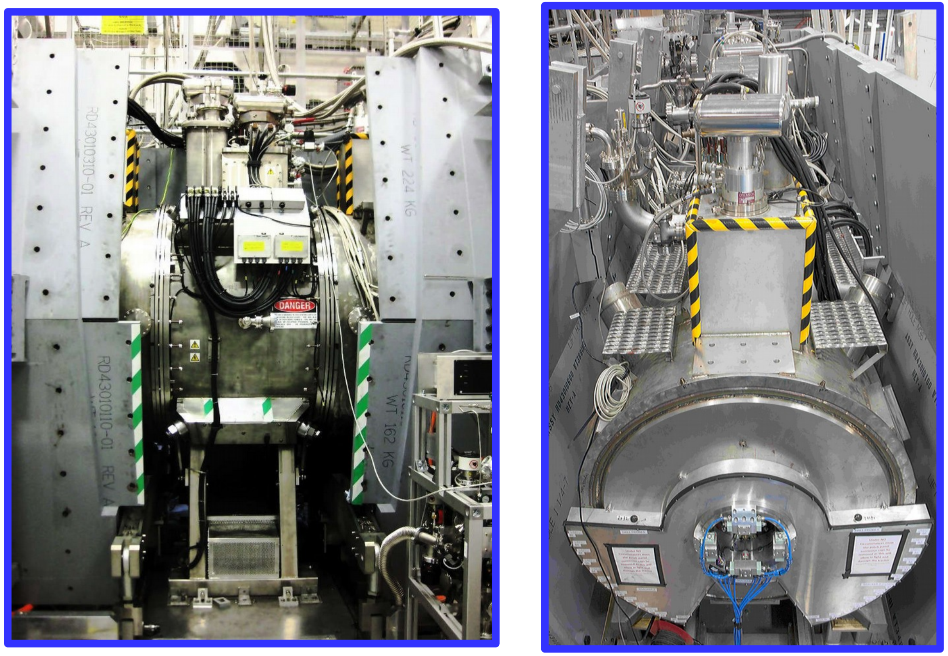
MICE Muon Beam Line

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

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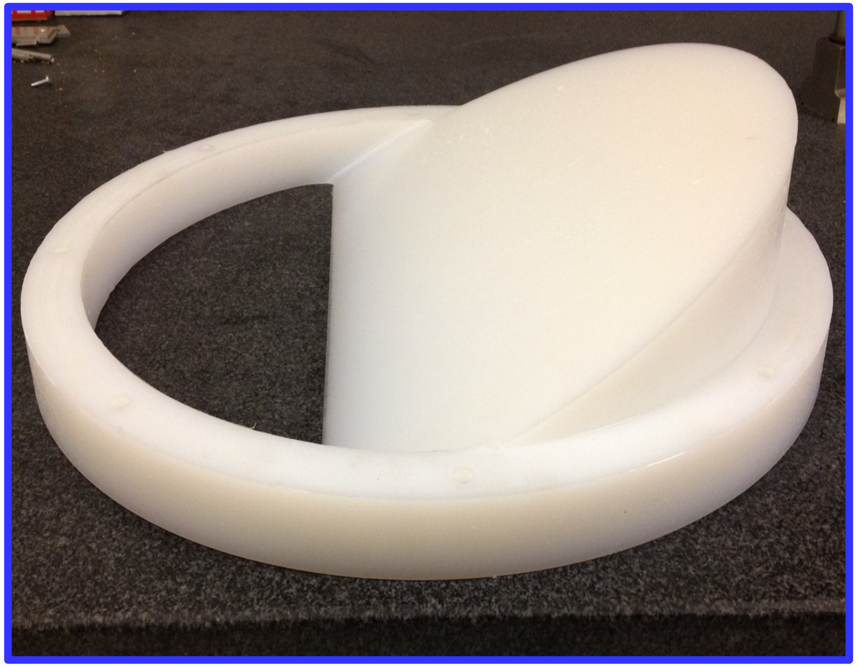
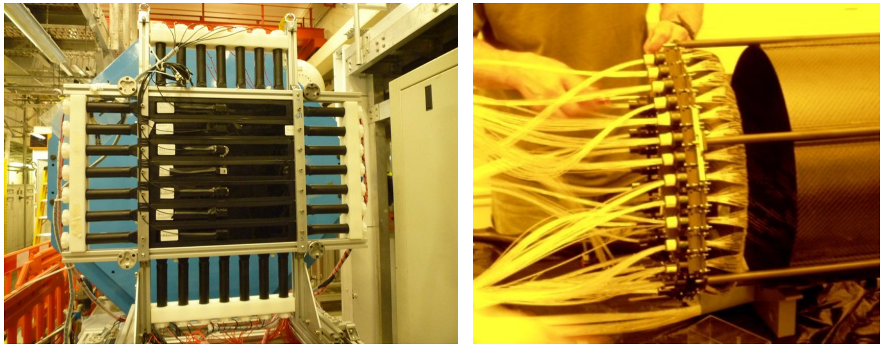
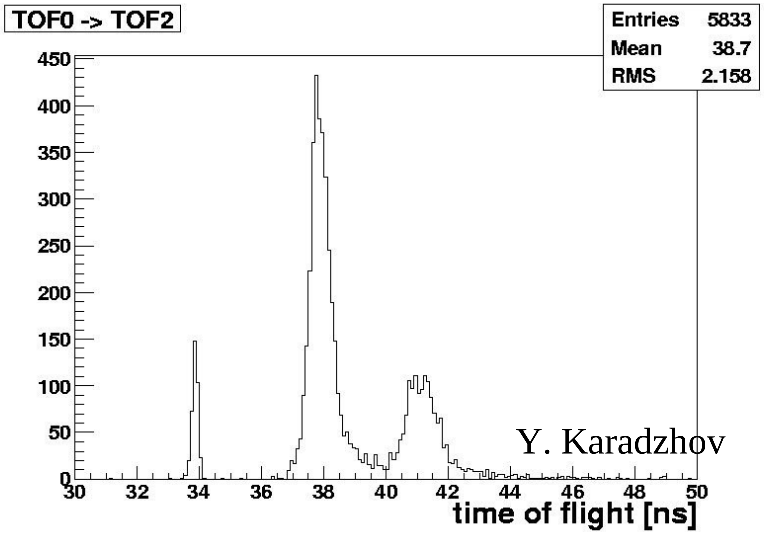
Absorber



- 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

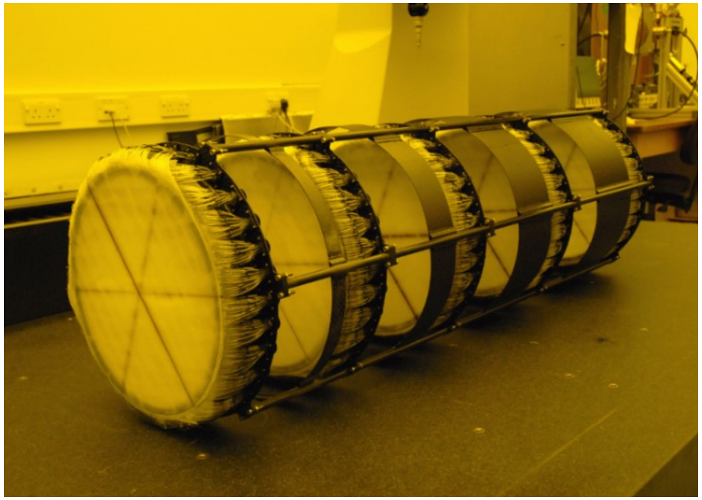


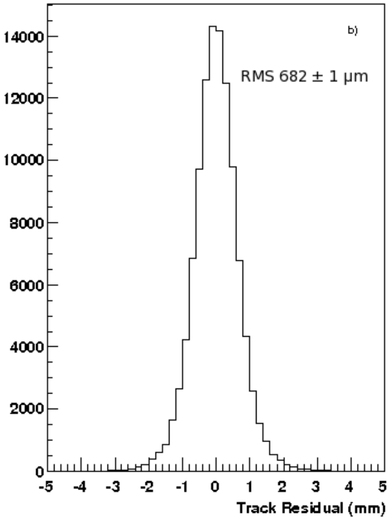


Y. Karadzhov

- Three scintillating TOF stations
  - Time resolution ~ 50-60 ps
  - Commissioned in 2009
- Two Scintillating Fibre Trackers
  - Position resolution ~ 0.5 mm
  - Simulated momentum resolution ~ 2 MeV/c
- Threshold Cerenkov counter
- KL pre-shower detector
- Electron-muon ranger

Scintillating Fibre Tracker





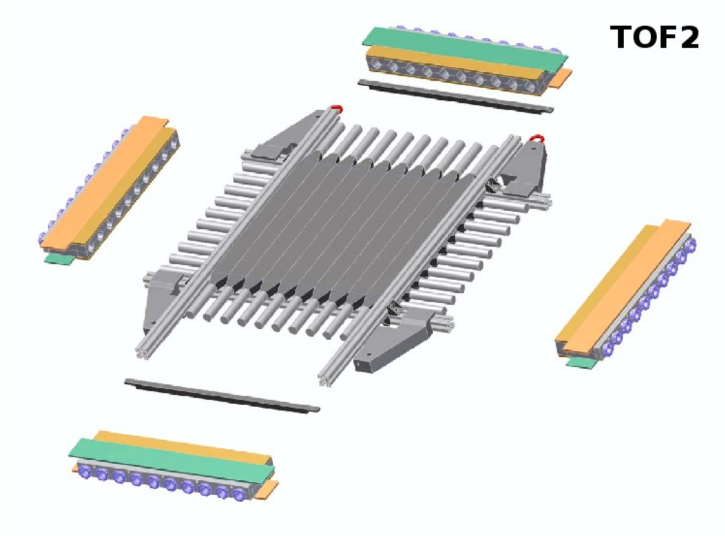
Ellis et al, NIM A 659, 136 (2011)

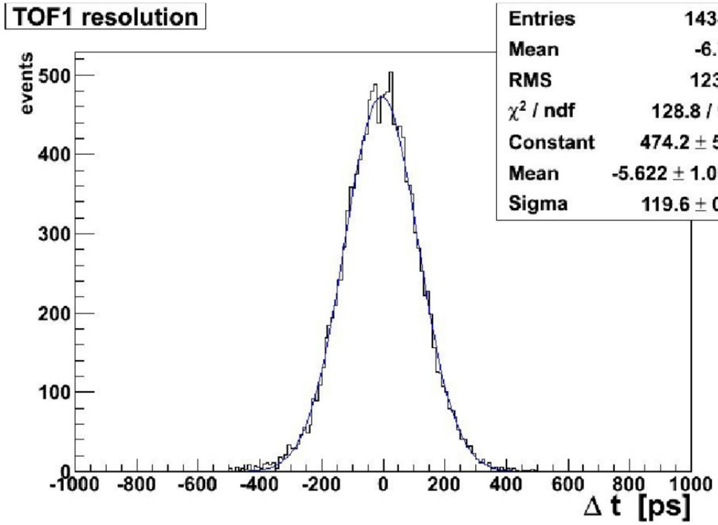
Dobbs et al, Jinst 11, 12001 (2016)

- 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

TOF

Bertoni et al, NIMA 625, 14 (2010)



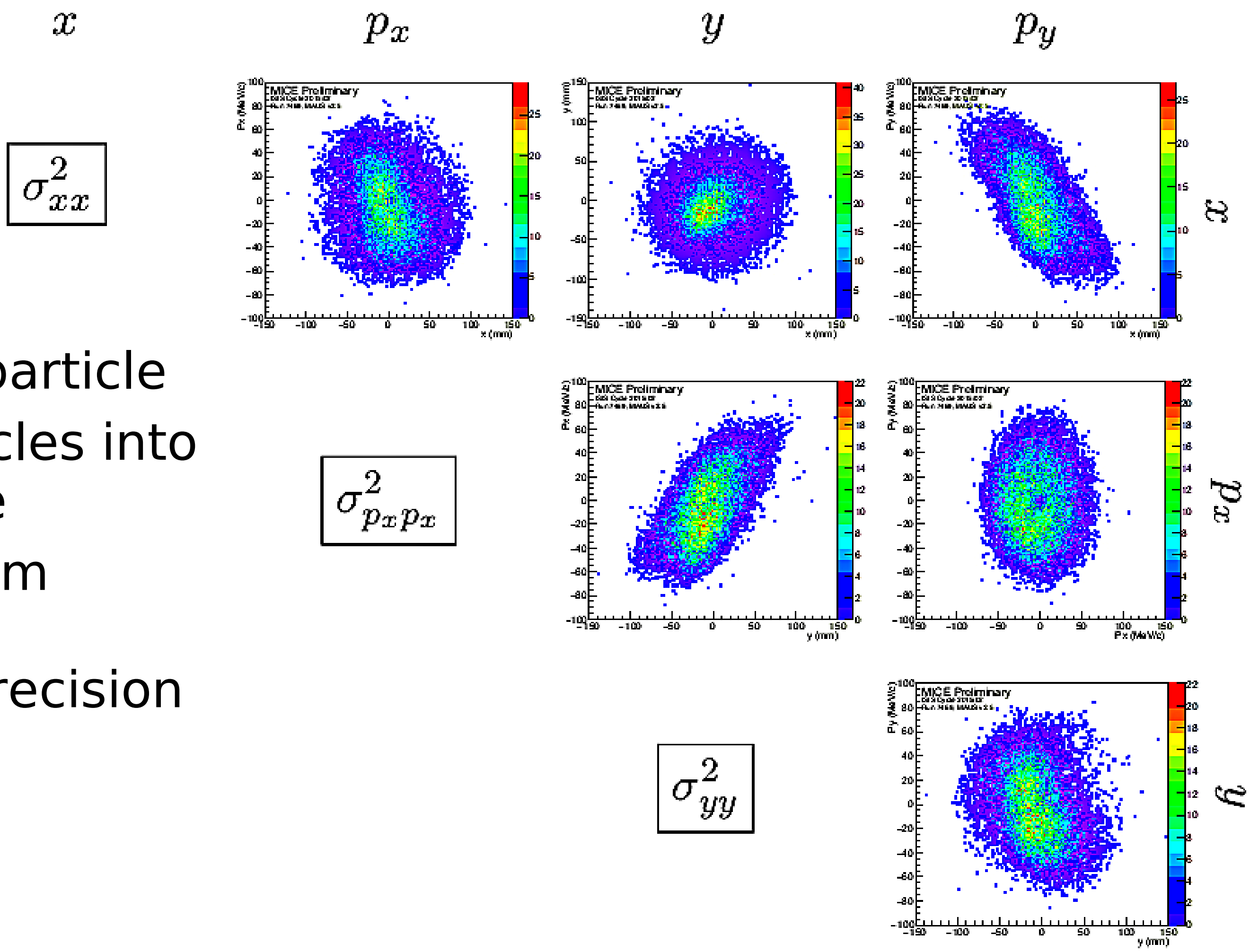


- 3 Time-of-Flight stations
- Two planes of scintillator bars
  - Measured 50 – 60 ps time resolution
- Combination of TOF (time→ velocity) and tracker (momentum) yields particle mass → PID

Data-Taking 2008-2017

- Data was taken between 2008 and 2017
- Measured
  - Scattering
  - Energy loss
  - Emittance change
- Using the unique particle-by-particle beam reconstruction

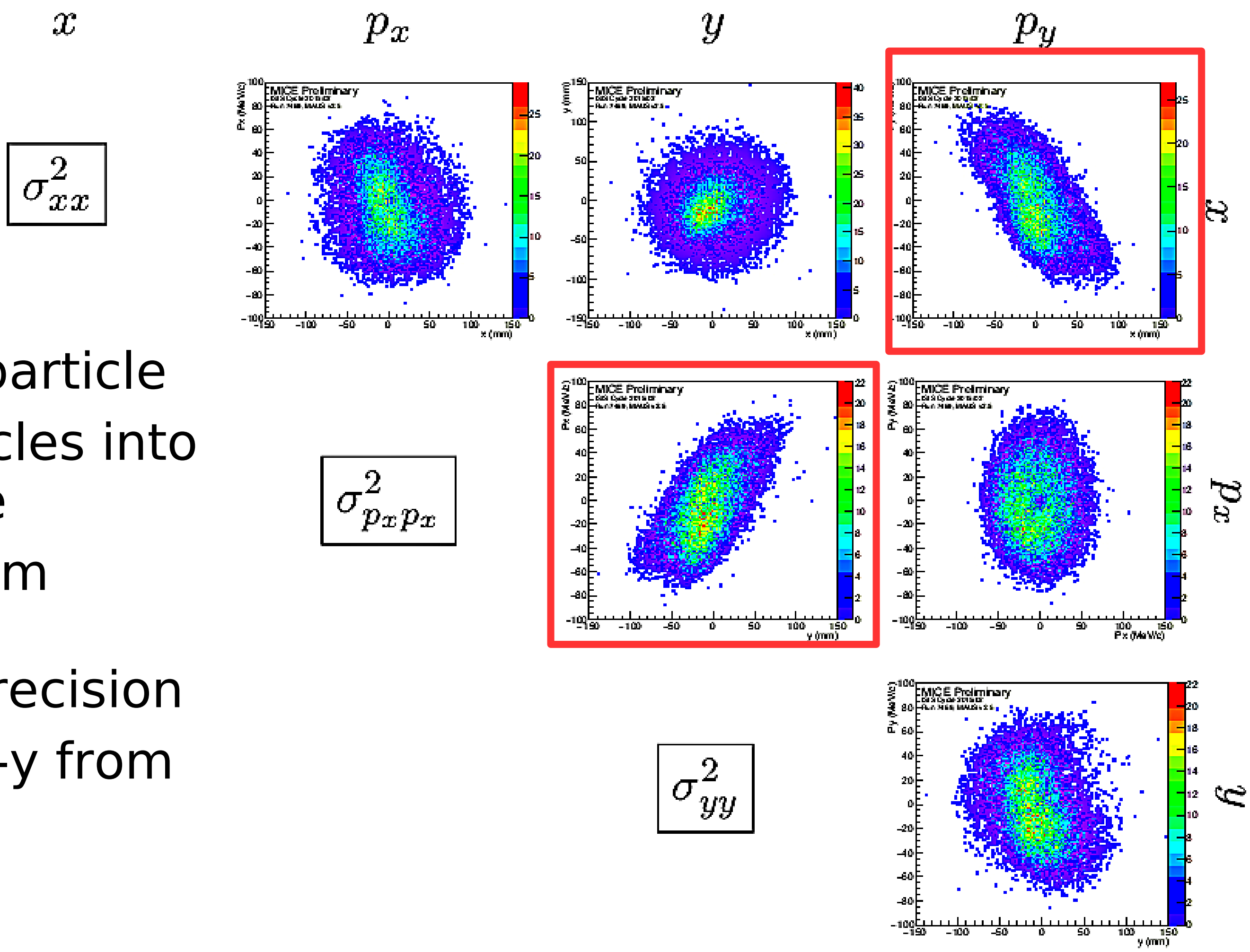
Phase space reconstruction



- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision

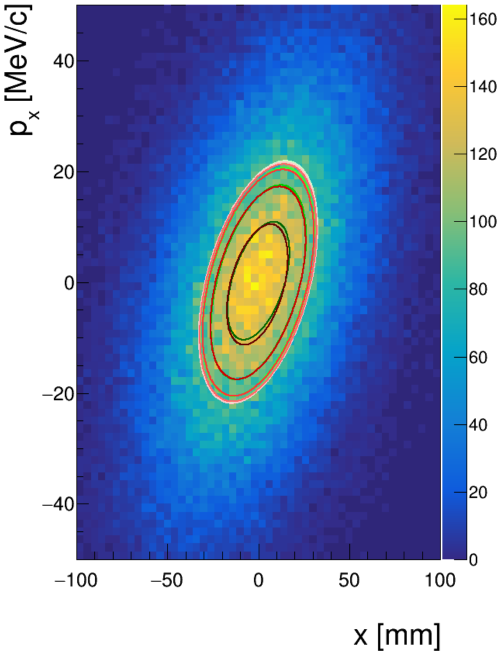
Blackmore et al, Eur. Phys. J. C 79, 257 (2019)

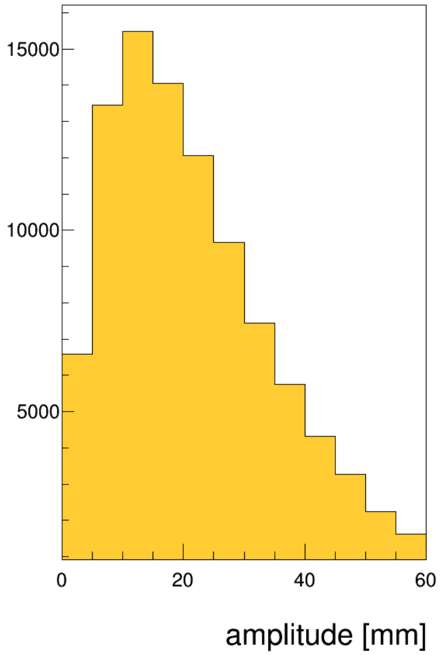
Phase space reconstruction



- 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

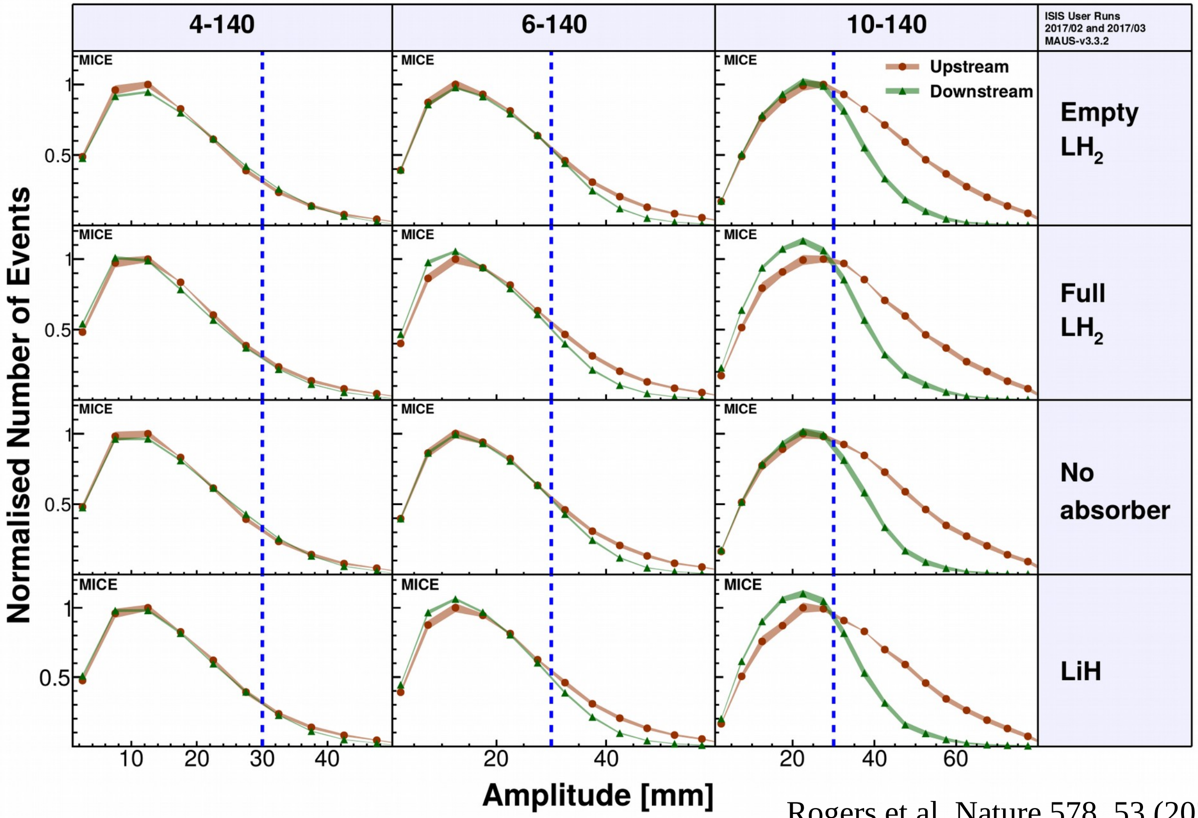
Amplitude reconstruction





- 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 distribution



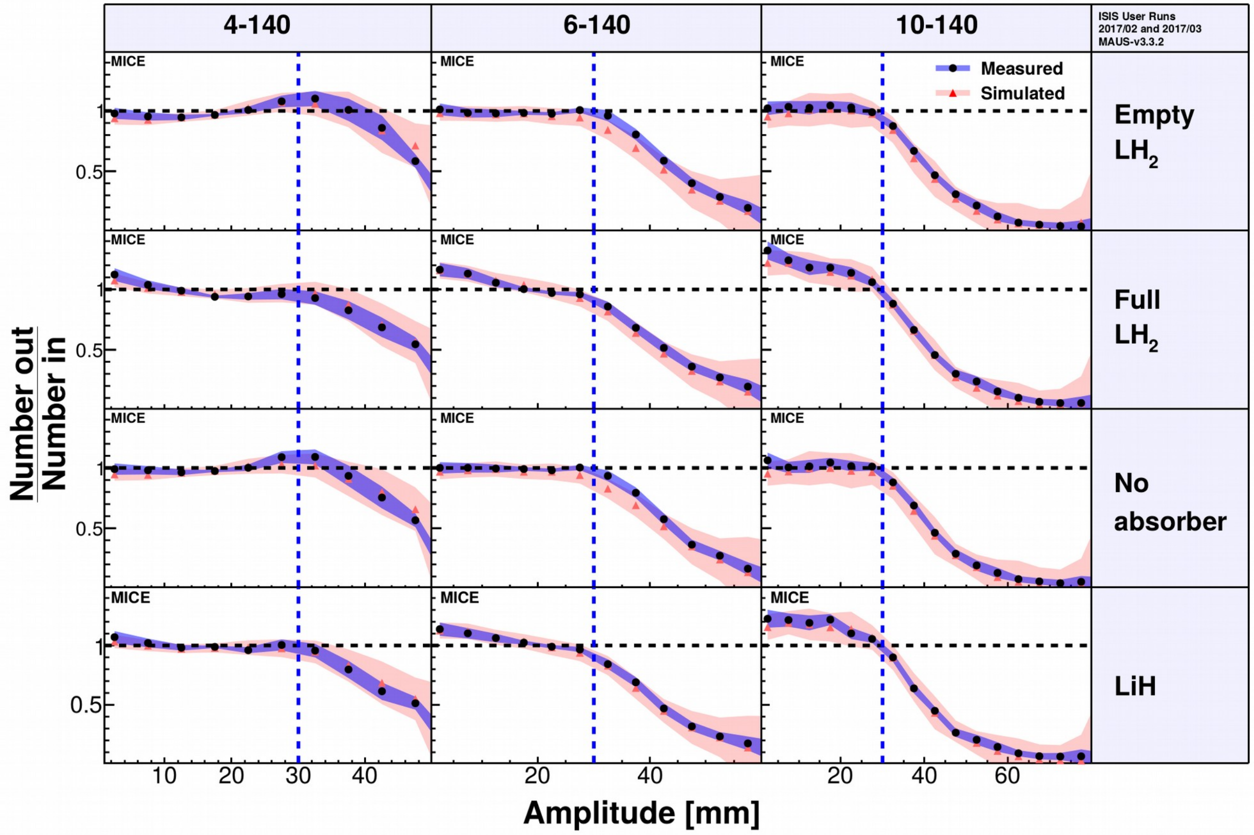
Rogers et al, Nature 578, 53 (2020)

🟥 Upstream

🟩 Downstream

- No absorber → no change in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal

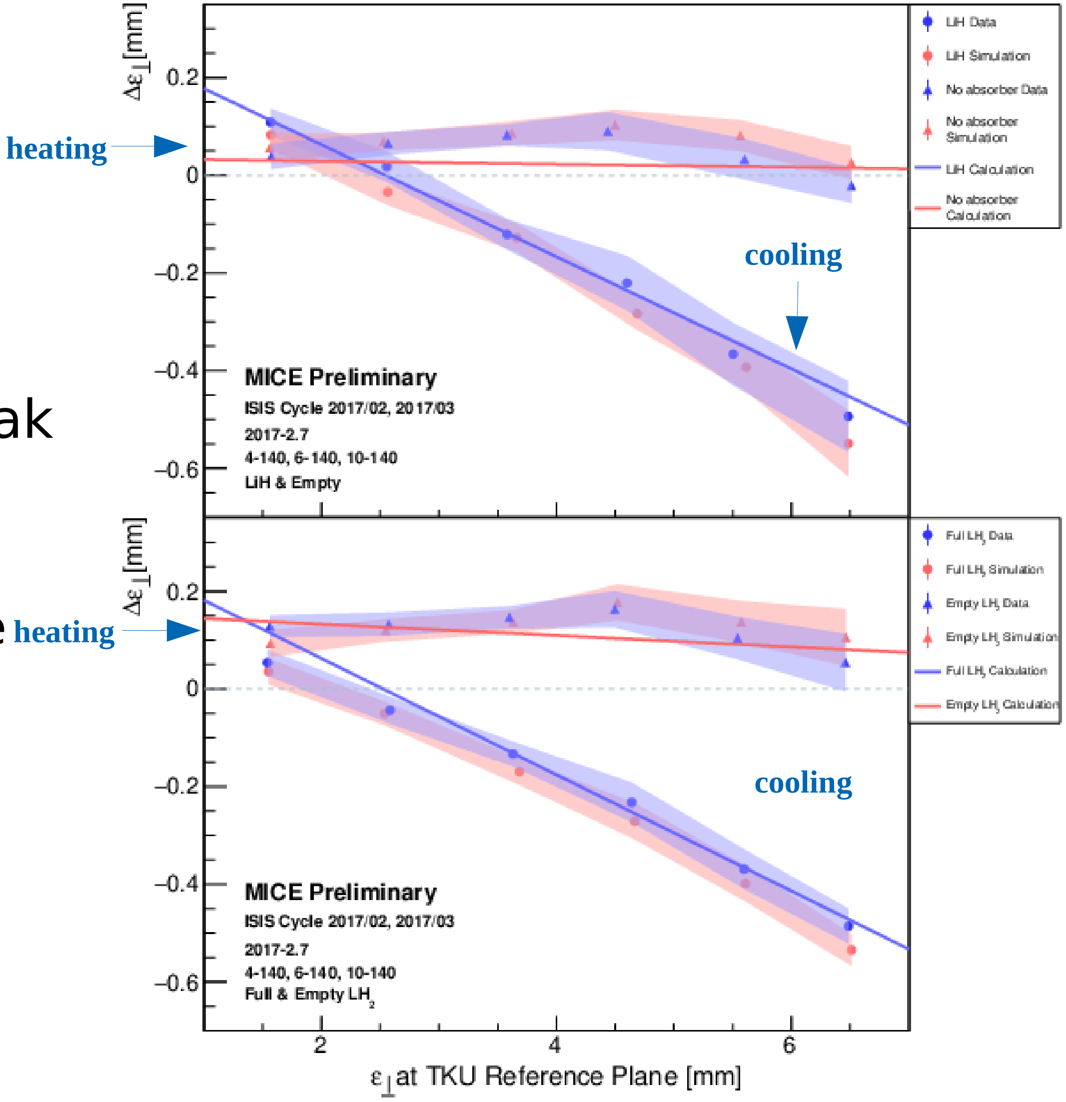
Ratio of amplitudes



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

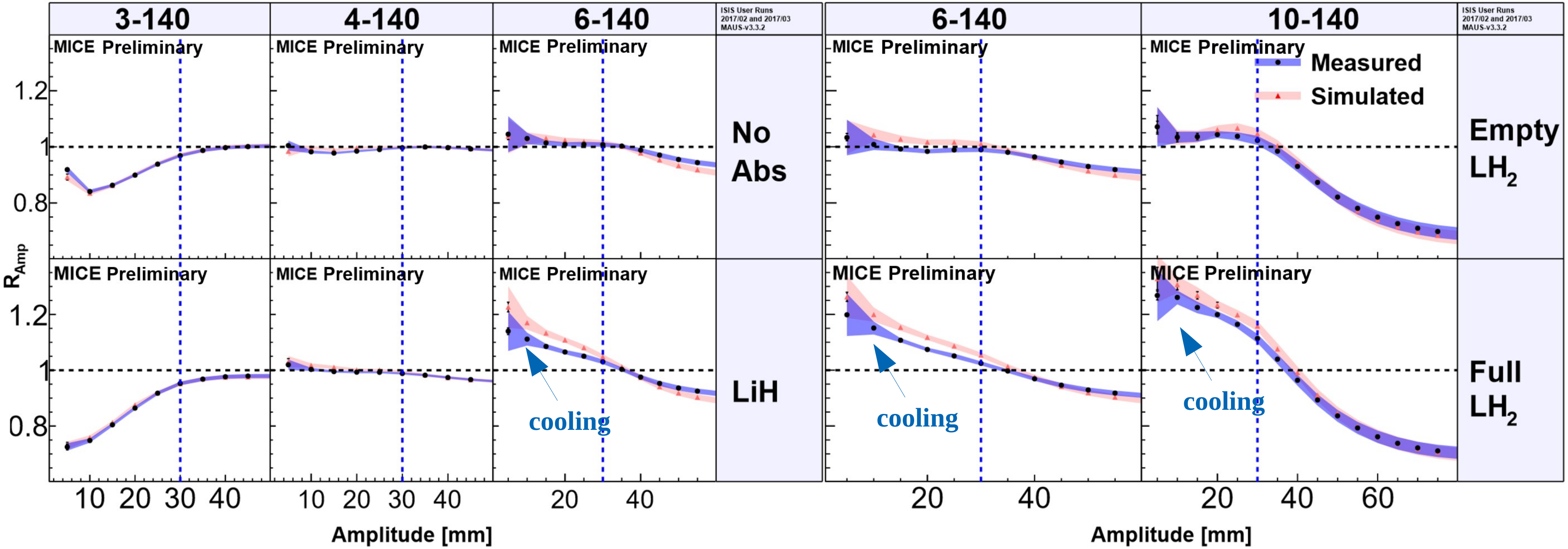
Transverse Emittance

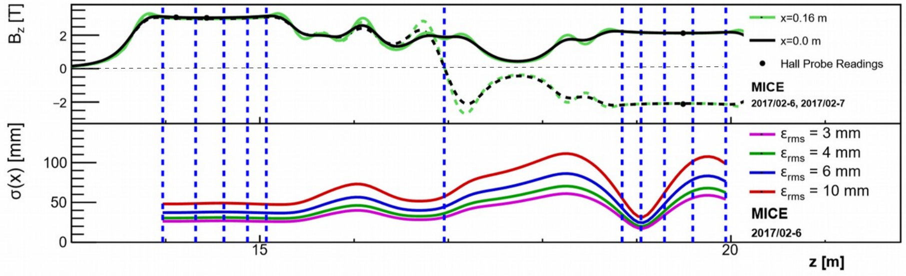
- Also measure change in RMS emittance
  - Mean of the amplitude distribution
- Look at different sub-samples of the muon ensemble
- In absence of absorber weak heating
- With absorber
  - Cooling for high emittance beams
  - Heating below equilibrium emittance
  - Consistent with theory
- Publication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



Solenoid Mode

Cumulative Amplitude Ratios

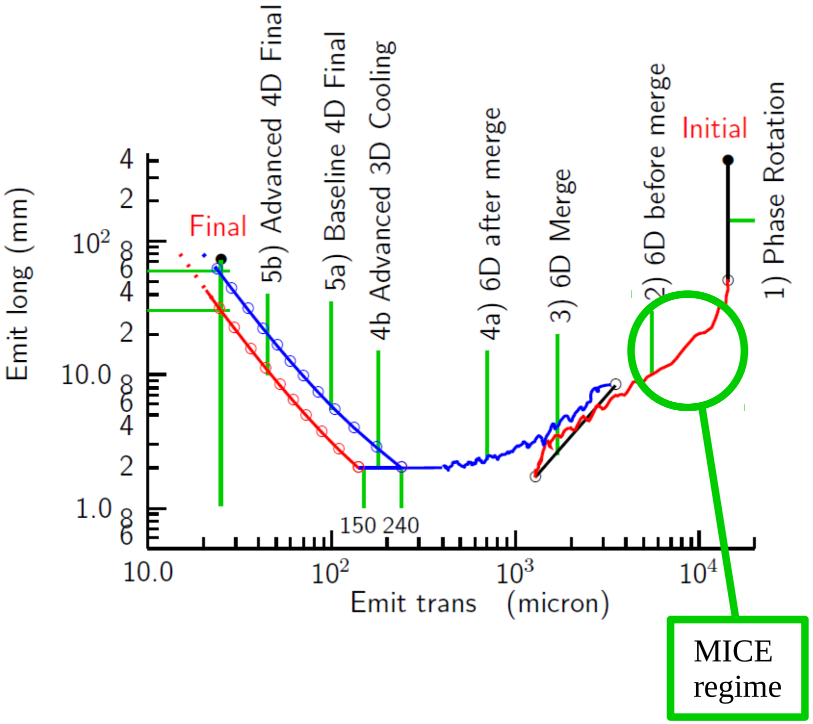




- Most cooling is done at 0 T
- Non-zero field
  - easier magnets
  - angular momentum non-conservation
- Studies in progress on cooling performance in solenoid mode

Where next?

- 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
  - Focus on transverse emittance
- 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

Conclusions

- Muons are fascinating particles with many applications
- Muon accelerators have the potential to:
    - Provide multi-TeV lepton-antilepton collisions
    - Provide well-characterised neutrino beam
    - Open up an entirely new regime of accelerators
- A significant hardware R&D effort has continued over the past two decades
    - MERIT
    - MuCool
    - EMMA
    - MICE
- MICE has demonstrated ionization cooling, a key enabling technology for muon accelerators
- Studies ongoing for a follow-up experiment