UK Overview and MICE Update

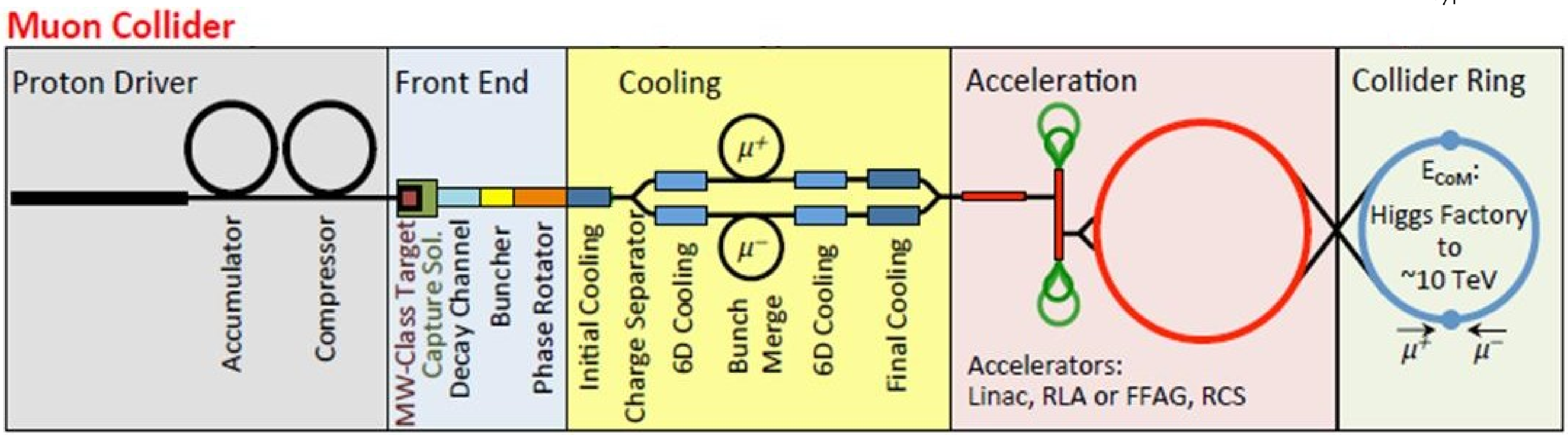
C. T. Rogers
Rutherford Appleton Laboratory

Science & Technology Facilities Council
ISIS

UK Overview and MICE Update

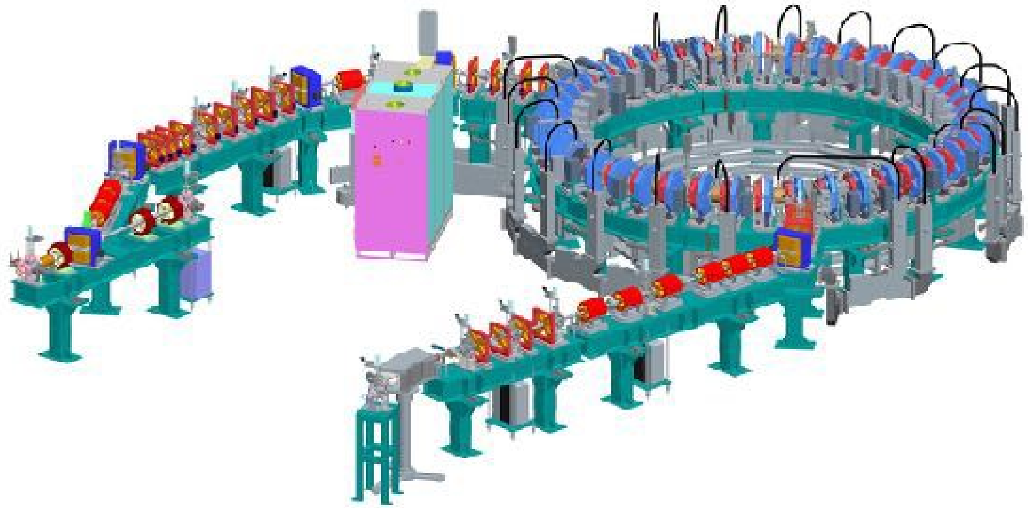
- UK has strong history of muon accelerator R&D
  - Neutrino factory design studies
  - EMMA prototype FFA for muon acceleration constructed at Daresbury lab
  - Muon Ionisation Cooling Experiment (MICE) hosted at RAL
- Continuing work
  - Analysis of MICE data
  - NuStorm design
  - Vertical FFA design/prototyping

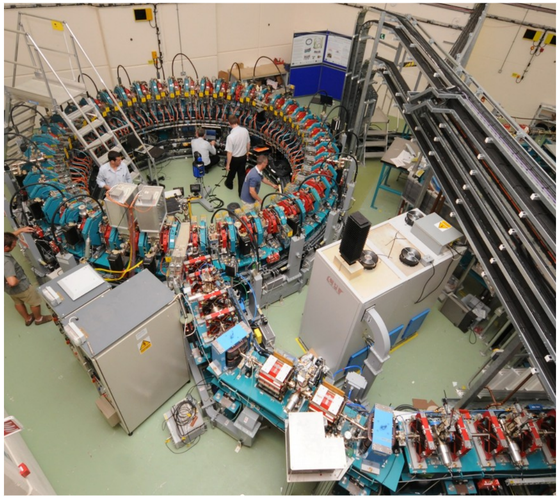
Muon Collider (US MAP)



- UK has invested significant effort in
  - Proton driver R&D
  - Front end and initial cooling
  - Acceleration (esp FFA-based)
- Addressing the challenges of muon accelerator
  - Short lifetime
  - Large initial emittance

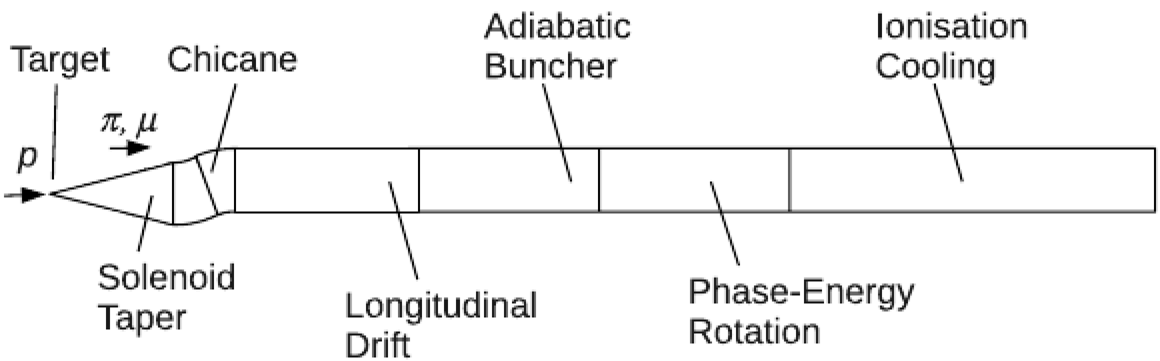
EMMA FFA Prototype

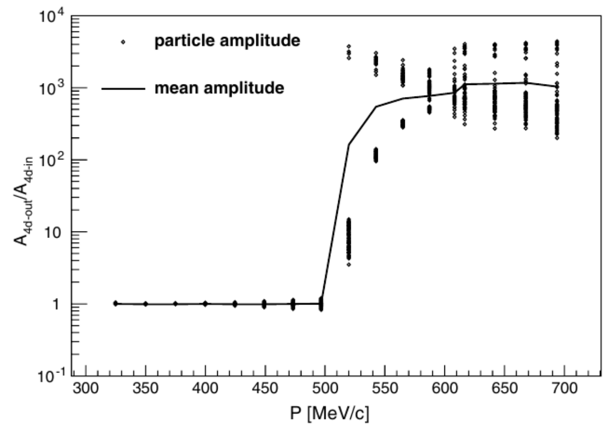




- Electron model of a non-scaling FFA
- Non-scaling FFA → resonance crossing
- Fast fixed-frequency "gutter" acceleration

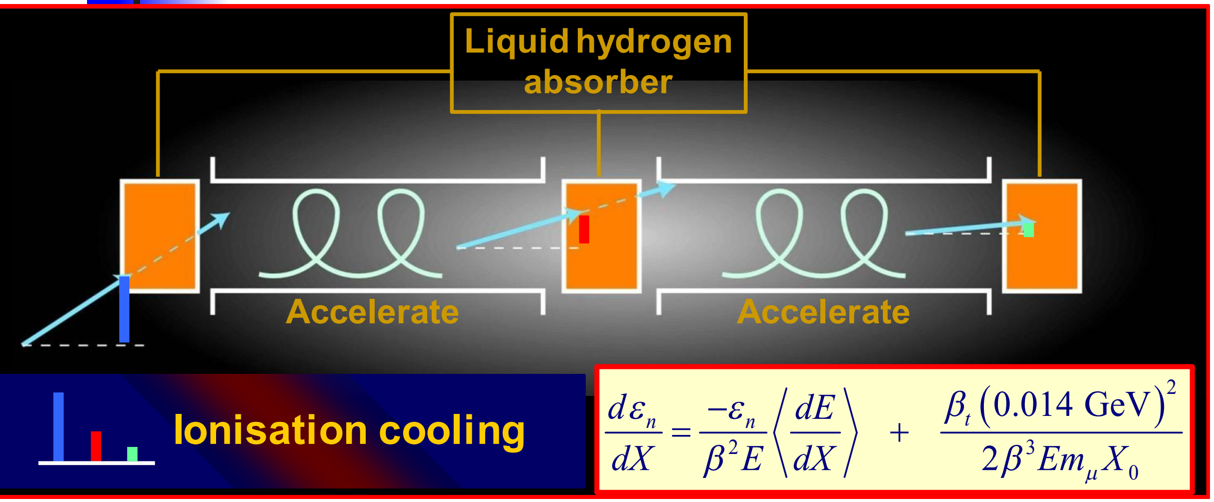
Muon Front End





- Looked at high power targetry e.g. fluidized powder jet
- Developed solenoid chicane and proton absorber concept
  - Clean the beam following target
- Detailed studies on transverse ionization cooling line for initial cooling; and hardware prototyping
  - Muon ionization cooling experiment

4D Ionisation Cooling



$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014\ \text{GeV})^2}{2\beta^3 E m_\mu X_0}$$

	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

- Competition between
  - Ionisation energy loss (dE/dx) **cools** the beam
  - Multiple Coulomb Scattering off atomic nuclei **heats** the beam
- For best cooling
  - Low Z → more dE/dx and less scattering
    - Liquid hydrogen is best
  - Tight focus and large acceptance → scattering less significant
    - Require a compact magnetic lattice

Questions

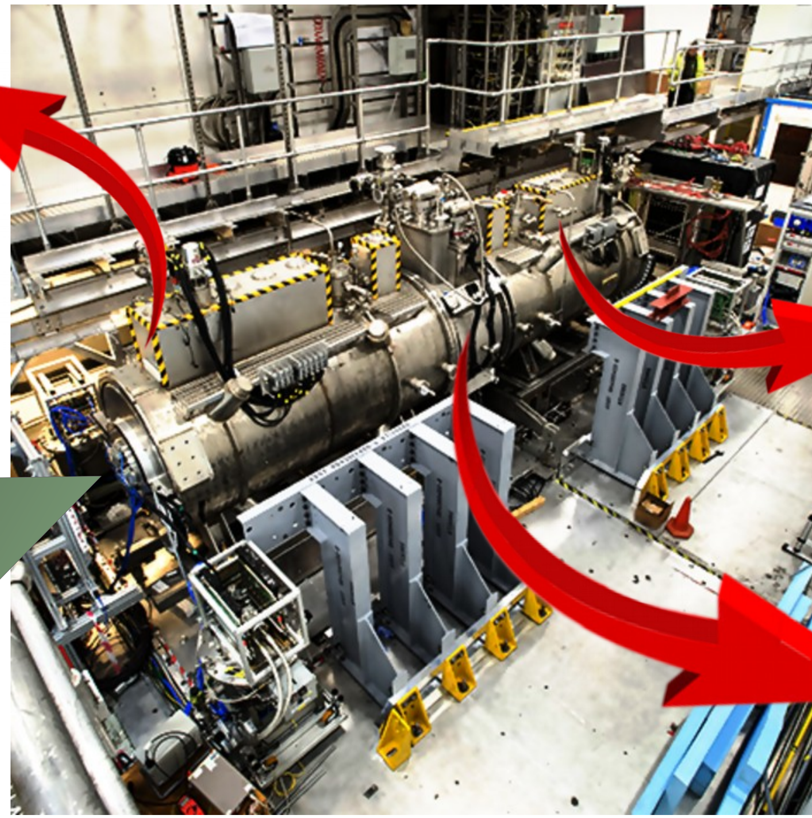
- Can we safely operate liquid hydrogen absorbers?
- Can we operate such a tightly packed lattice?
- Do we see the expected emittance change?
- Do we see the expected transmission?

Muon Ionization Cooling Experiment

C. T. Rogers
Rutherford Appleton Laboratory

The answer - MICE

Measure muon position and momentum upstream



Measure muon position and momentum downstream

Muon Beam

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

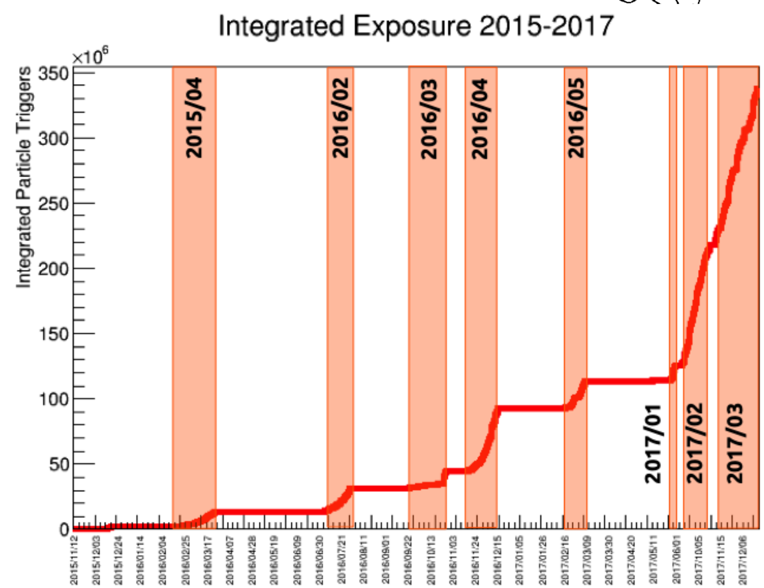
Collaboration

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

Science & Technology Facilities Council
ISIS

Data-Taking 2008-2017

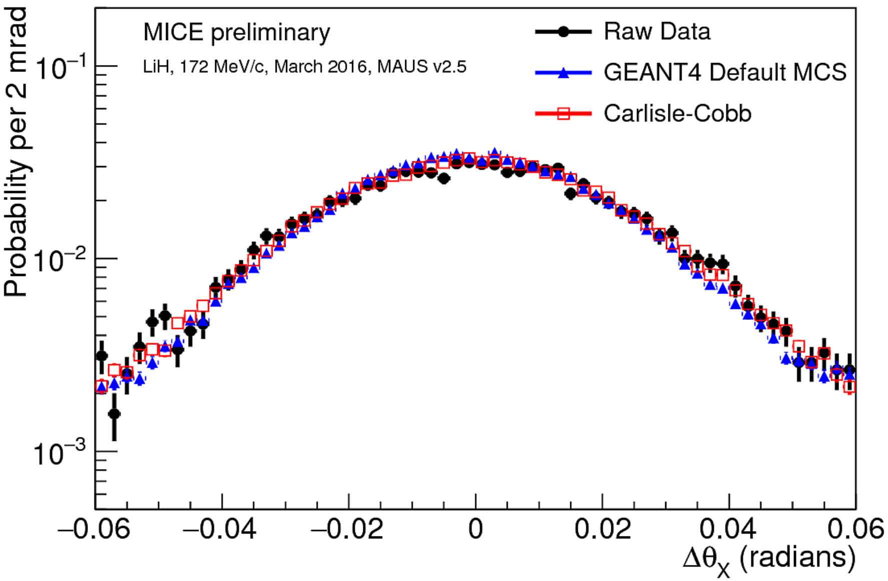
- Data was taken between 2008 and 2017
- Varied
  - Material
  - Input emittance
  - Energy
  - Degree of focussing
- Measured
  - Scattering
  - Energy loss
  - Emittance change

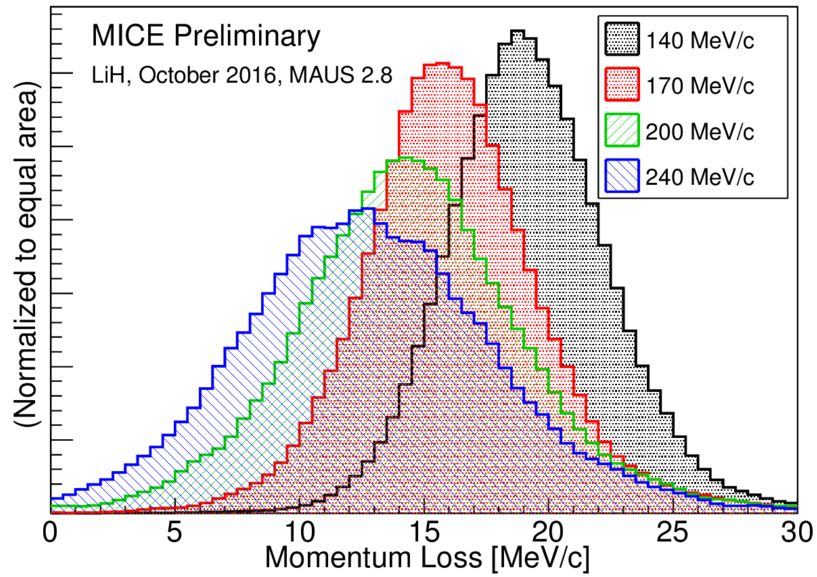


$$\underbrace{\frac{d\varepsilon_T}{ds}}_{\text{Emittance Change}} \approx \underbrace{-\frac{\varepsilon_T}{\beta_R^2 E}\left\langle \frac{dE}{ds} \right\rangle}_{\text{Cooling via dE/dx}} + \underbrace{\frac{\beta_T\,(13.6\text{MeV})^2}{2\beta_R^3 E m_\mu X_0}}_{\text{Heating via scattering}}$$

Science & Technology Facilities Council ISIS

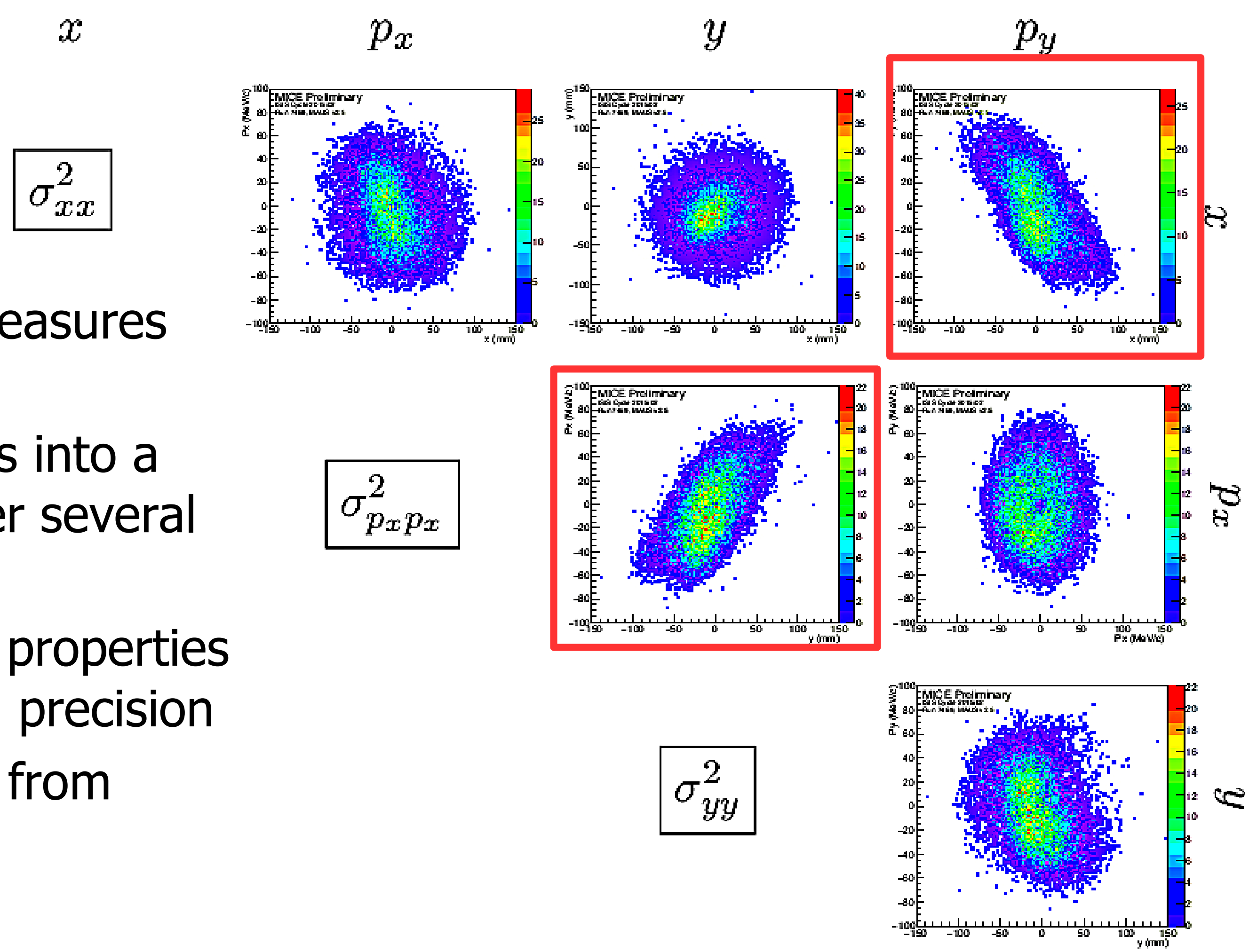
Measurement of Scattering





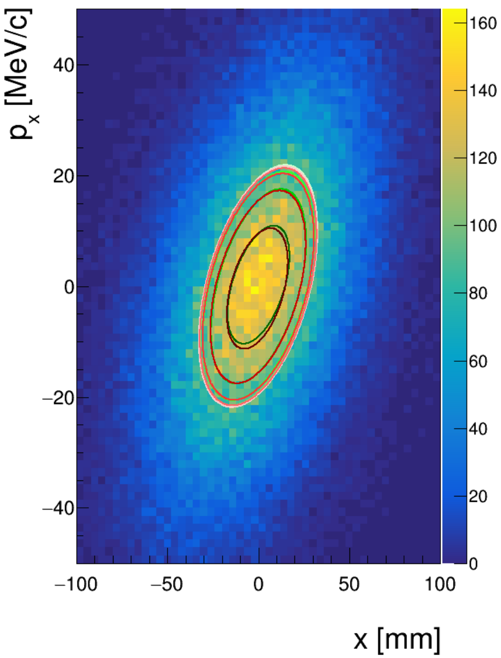
- Precision measurement of Multiple Coulomb Scattering
- Validation of energy loss model

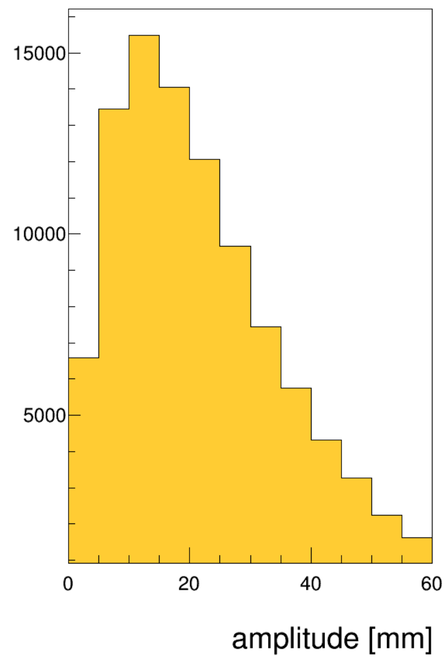
Phase space reconstruction



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

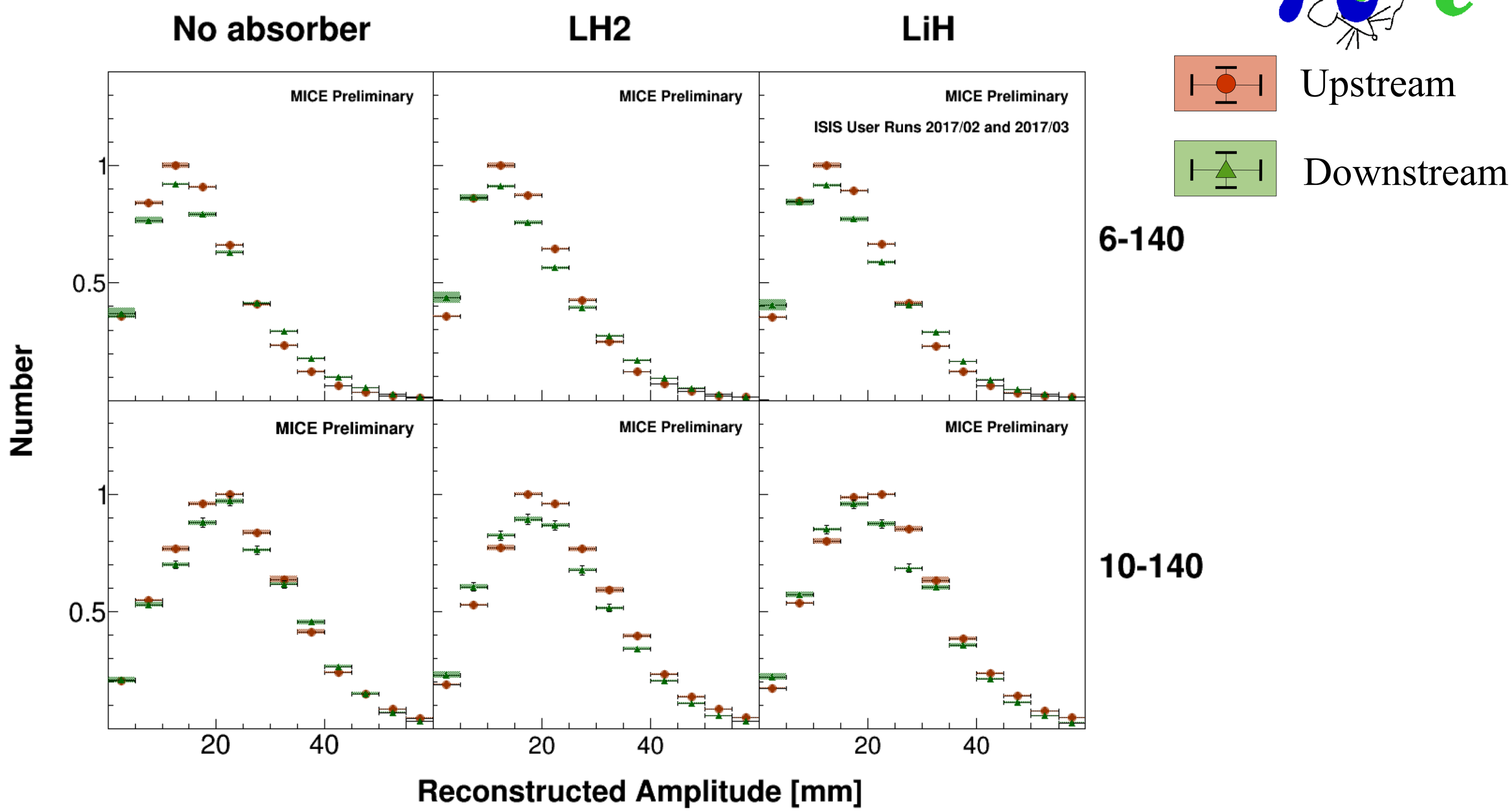
Amplitude reconstruction





- Phase space (x, p_x, y, p_y)
- 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



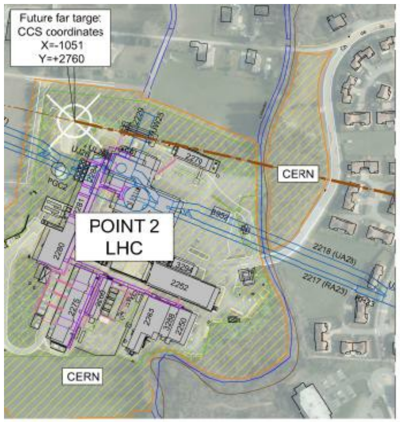
- No absorber → decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal

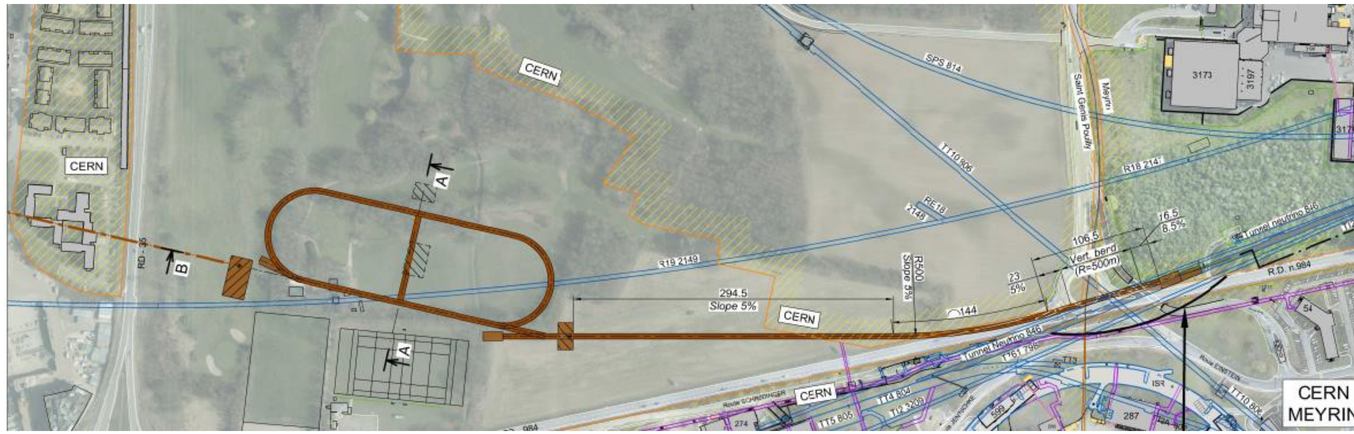
Science & Technology Facilities Council ISIS

Ongoing UK Work

C. T. Rogers
Rutherford Appleton Laboratory

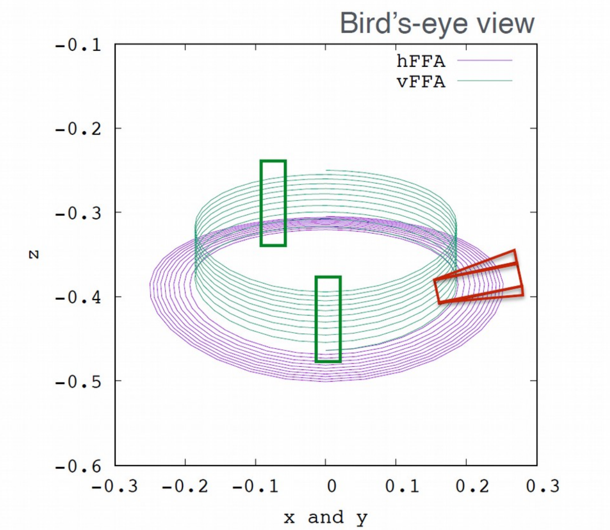
Ongoing UK work - NuStorm

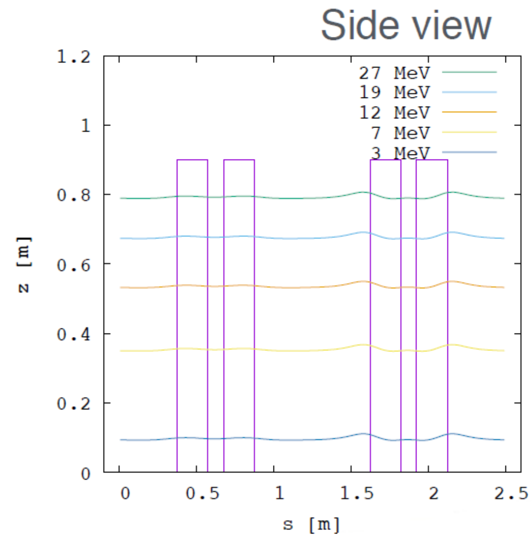




- Developing FFA option for NuStorm
  - Relatively high current, high energy muon beam facility
  - Excellent potential to support next generation of superbeams
  - Opportunity to develop capability for handling muon beams
- Alan Bross's talk later

Ongoing UK work - vFFA





- VFFA → dipole field stronger higher in the magnet
  - Beam moves upwards with increasing momentum
  - Tune and optics is constant with increasing momentum
  - Isochronous in relativistic limit
- Applicable both to proton and muon acceleration
- Design underway
  - See Shinji Machida's talk later

Science & Technology Facilities Council ISIS

What remains to be done (cooling hardware)?

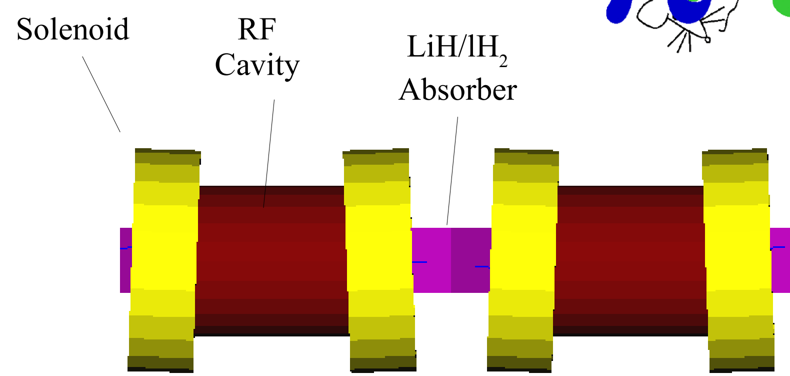
C. T. Rogers
Rutherford Appleton Laboratory

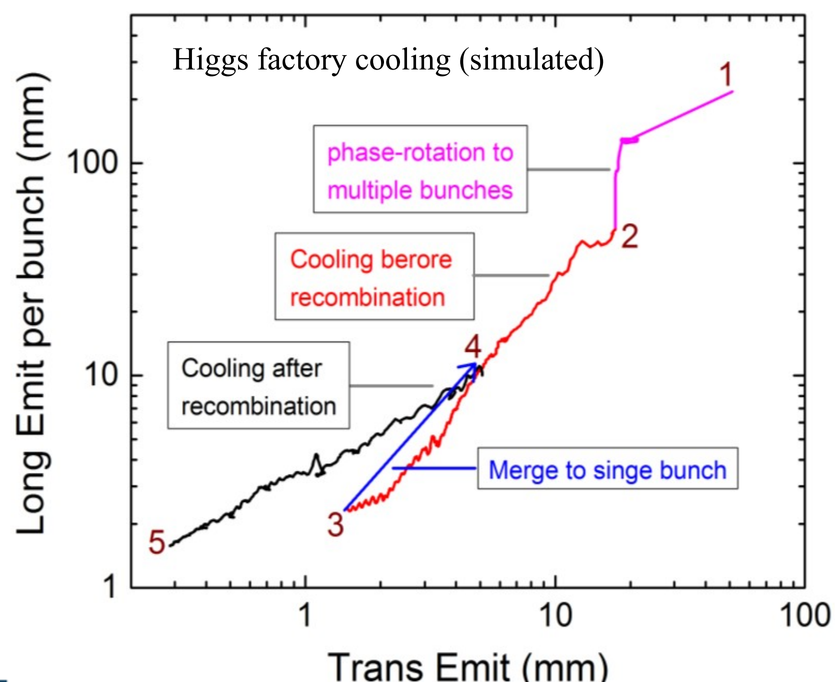
Risks in ionization cooling

- MICE has demonstrated that transverse ionization cooling works
- What are outstanding risks → mitigations
  - Unforeseen collective effects → cooling test stand
    - Use protons to get sufficient intensity?
  - Uncertainty in energy straggling → cooling test stand
    - ~10 % uncertainty in FWHM in literature
  - Engineering risks → engineering test stand i.e. no beam
    - Would need to be ready to commit to a lattice
- Job 1: Make a detailed assessment of potential issues
  - Done for MAP?

Cooling (6D)

- Why is energy straggling important?
- MICE demonstrated transverse cooling
  - Reduction in transverse emittance
  - Good for Neutrino Factory
- For a Muon Collider need longitudinal cooling as well
  - Use a dipole and wedge absorber to transfer emittance from longitudinal to transverse
- Energy straggling "heats" the beam longitudinally
  - Seek to characterise
  - Validate longitudinal effects





Cooling test stand

- Collective effects → high beam intensity
  - **Either** nustorm-level muon beam
  - **Or** (low energy) proton beam → Internal Target
- Energy straggling
  - **Either** very good energy resolution
  - **Or** multiple passes (i.e. ring)
- Fully correlated 6D phase space has only ever been measured twice
  - MICE (unpublished)
  - SNS Beam Test Facility
- Interesting – but challenging - to go to the next step!
  - Would need to carefully assess available resources and best application
  - Synergy with low energy muon beam community?
  - Exploit internal target applications?

Conclusions

- UK has a strong history in muon accelerator R&D
  - Design work
  - EMMA
  - MICE
- Ongoing programme
  - NuStorm
  - VFFA
- Further cooling R&D has interesting possibilities
  - Need to consider available resource