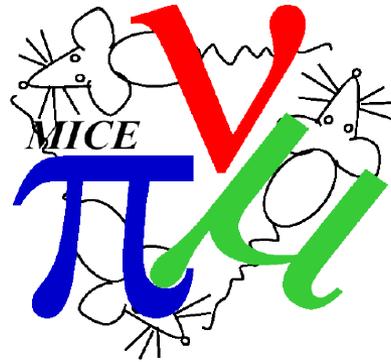


UK Overview and MICE Update



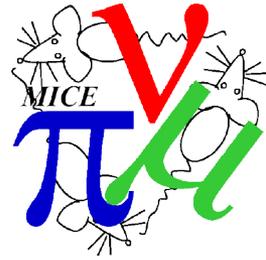
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ISIS

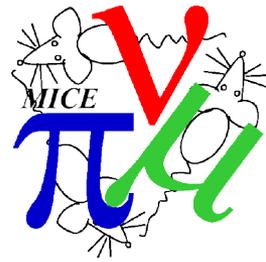
UK Overview and MICE Update



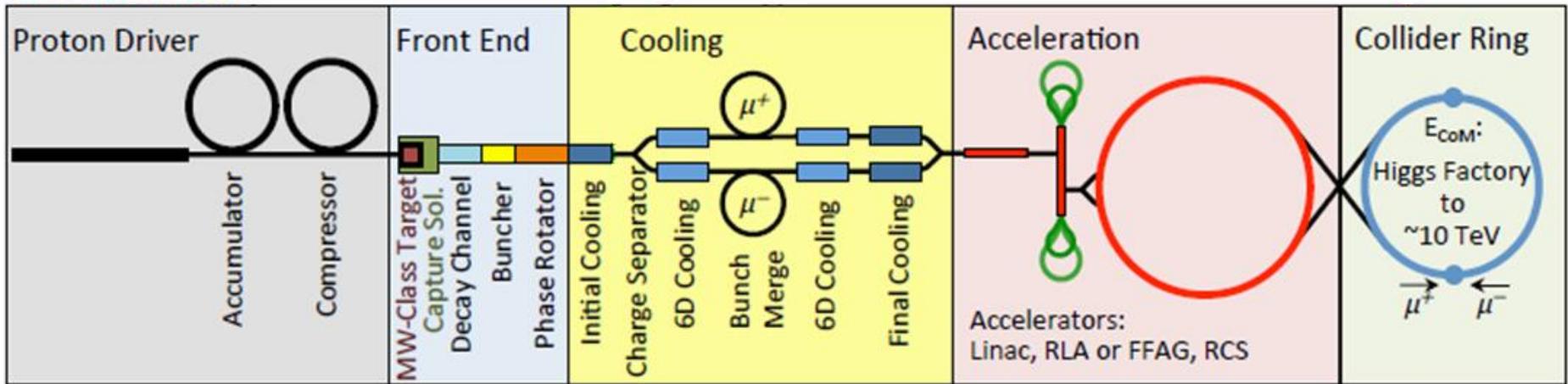
- UK has strong history of muon accelerator R&D
 - Neutrino factory design studies
 - EMMA prototype FFA for muon acceleration constructed at Daresbury lab
 - Muon Ionisation Cooling Experiment (MICE) hosted at RAL
- Continuing work
 - Analysis of MICE data
 - NuStorm design
 - Vertical FFA design/prototyping



Muon Collider (US MAP)

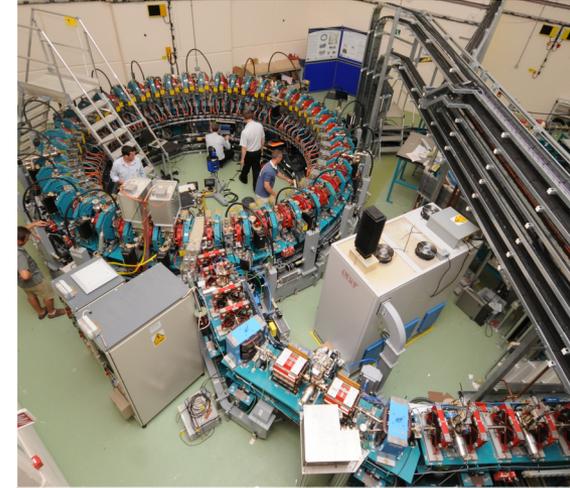
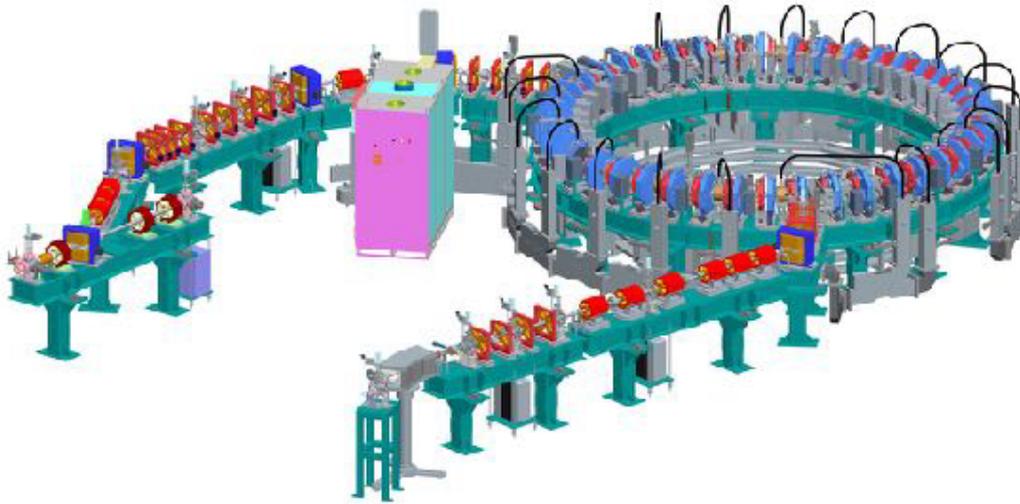
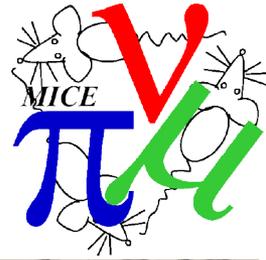


Muon Collider



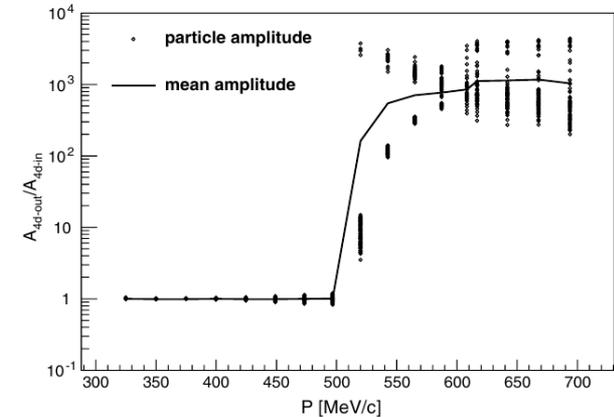
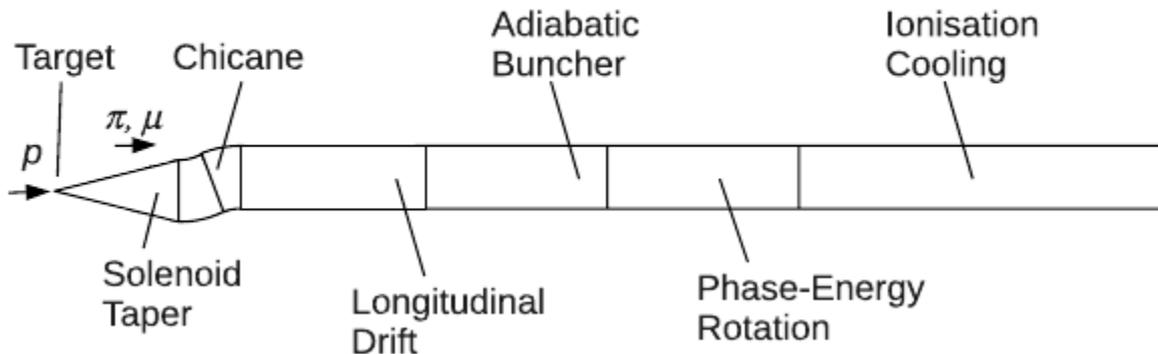
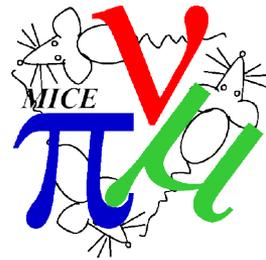
- UK has invested significant effort in
 - Proton driver R&D
 - Front end and initial cooling
 - Acceleration (esp FFA-based)
- Addressing the challenges of muon accelerator
 - Short lifetime
 - Large initial emittance

EMMA FFA Prototype



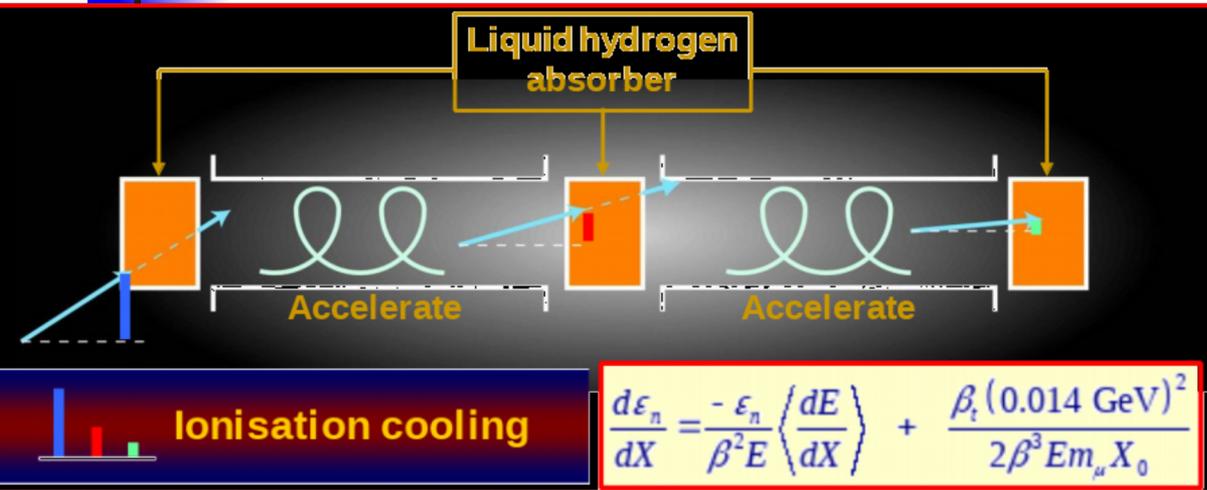
- Electron model of a non-scaling FFA
- Non-scaling FFA \rightarrow resonance crossing
- Fast fixed-frequency “gutter” acceleration

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

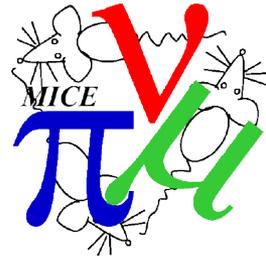
4D Ionisation Cooling



	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

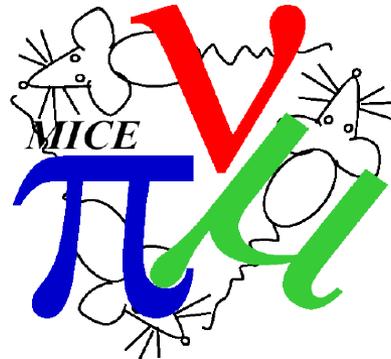
Questions



- 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?

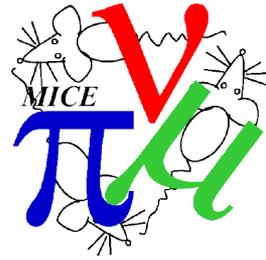


Muon Ionization Cooling Experiment



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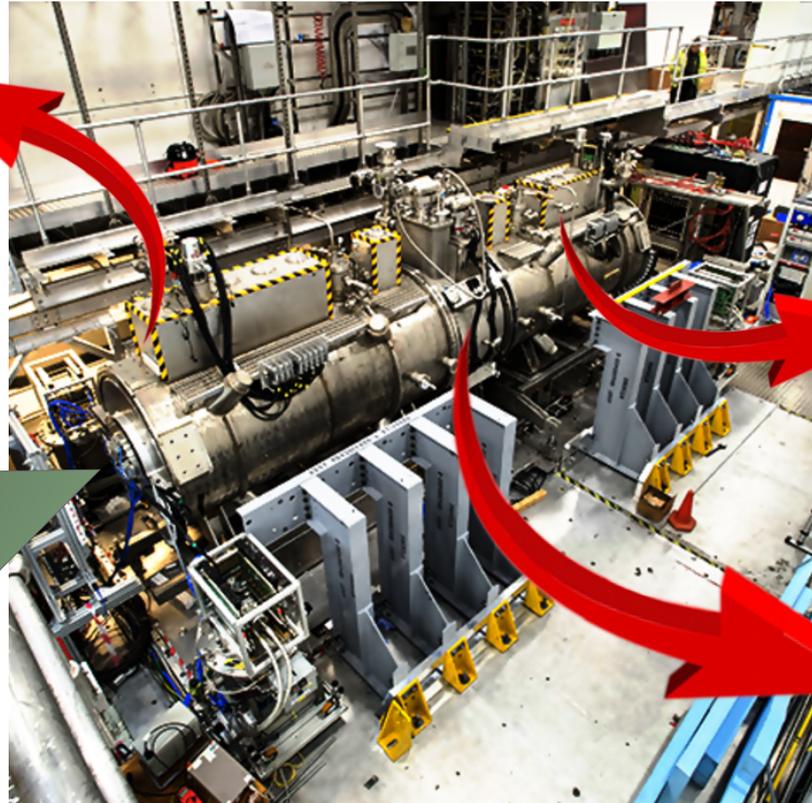
The answer - MICE



Measure muon position and momentum upstream

Measure muon position and momentum downstream

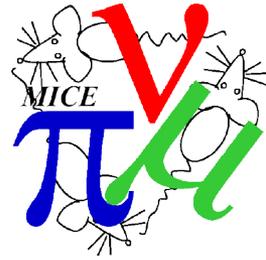
Muon Beam



Cool the muon beam using LiH, LH₂, or polyethylene wedge absorbers

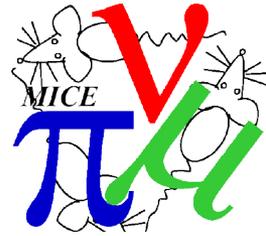


Collaboration

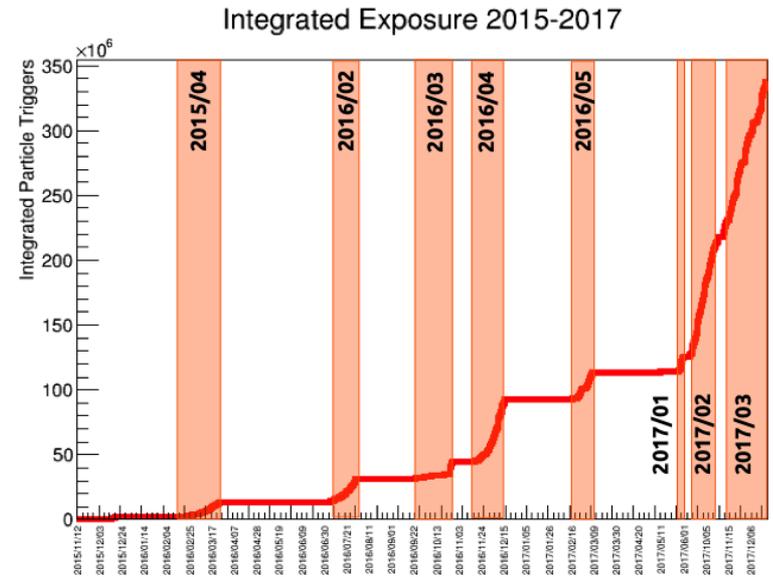


- Over 100 collaborators, 10 countries, 30 institutions
- Operated at Rutherford Appleton Laboratory 2008-2017
- Transport line bringing pions/muons from ISIS synchrotron

Data-Taking 2008-2017

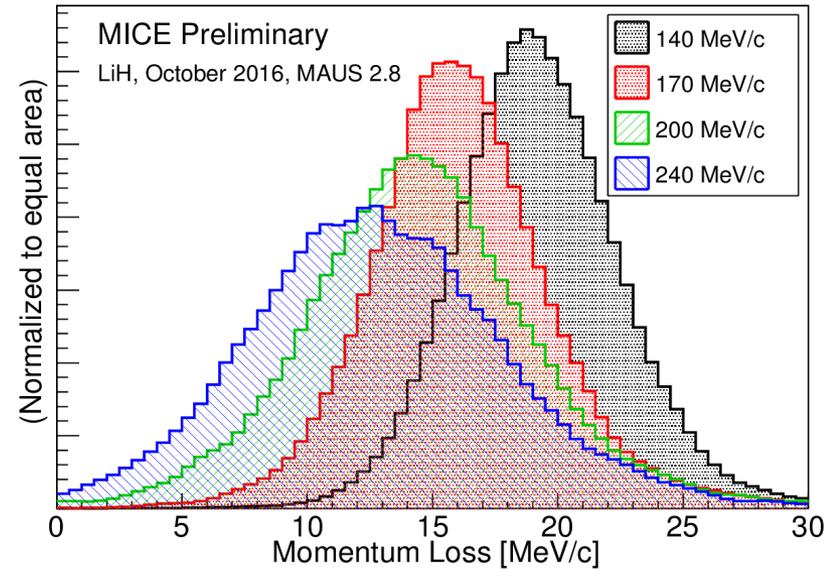
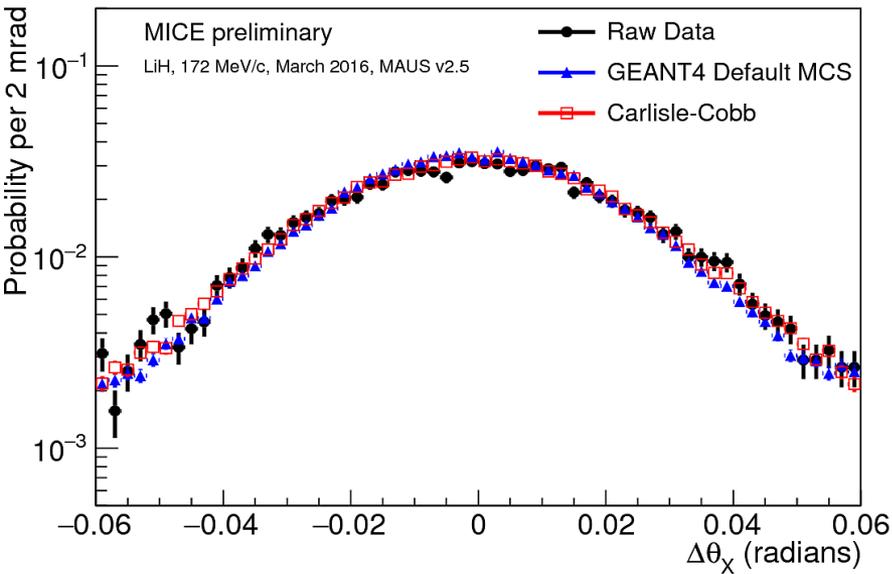
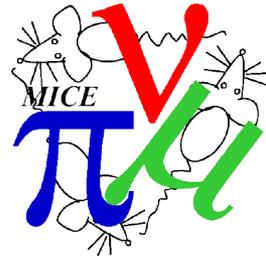


- Data was taken between 2008 and 2017
- Varied
 - Material
 - Input emittance
 - Energy
 - Degree of focussing
- Measured
 - Scattering
 - Energy loss
 - Emittance change



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

Measurement of Scattering



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

Phase space reconstruction



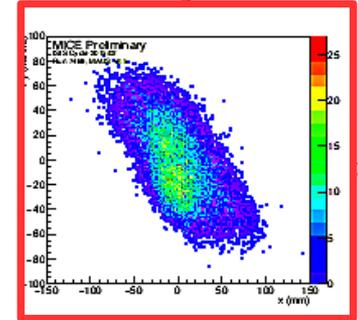
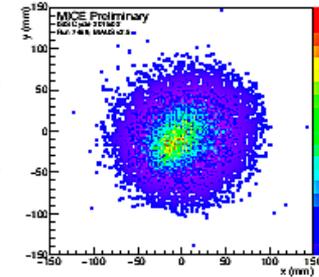
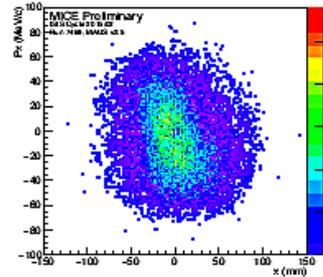
x

p_x

y

p_y

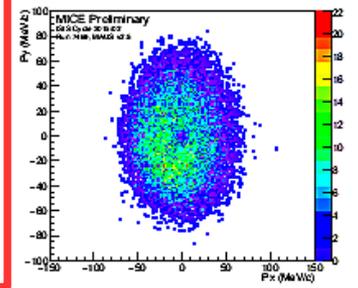
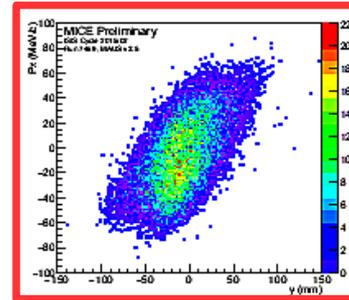
$$\sigma_{xx}^2$$



x

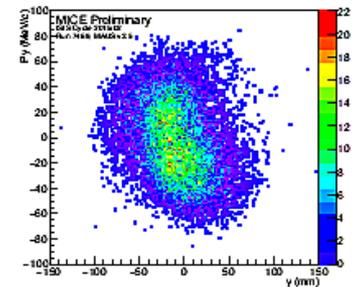
- MICE individually measures every particle
- Accumulate particles into a beam ensemble over several hours
- Can measure beam properties with unprecedented precision
- E.g. coupling of x-y from solenoid fields

$$\sigma_{p_x p_x}^2$$



x

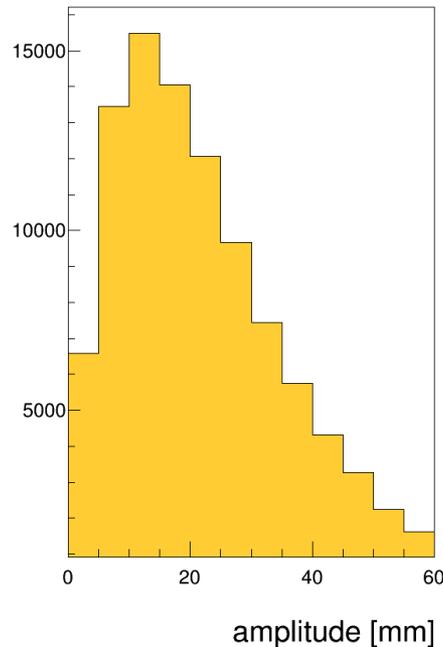
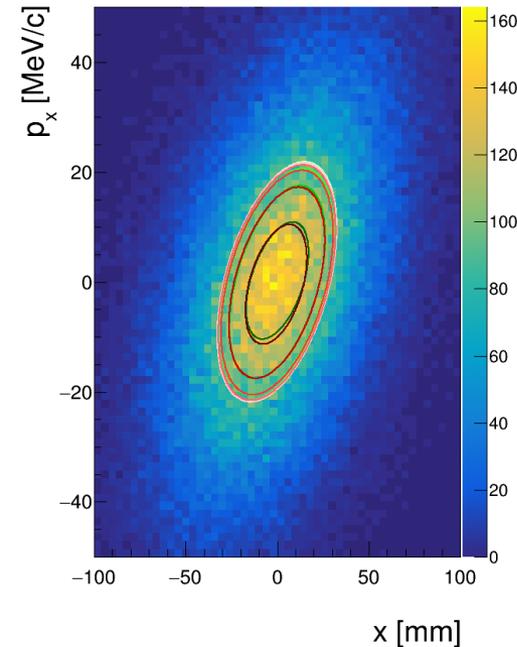
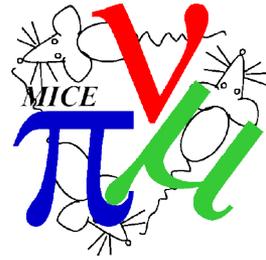
$$\sigma_{yy}^2$$



y

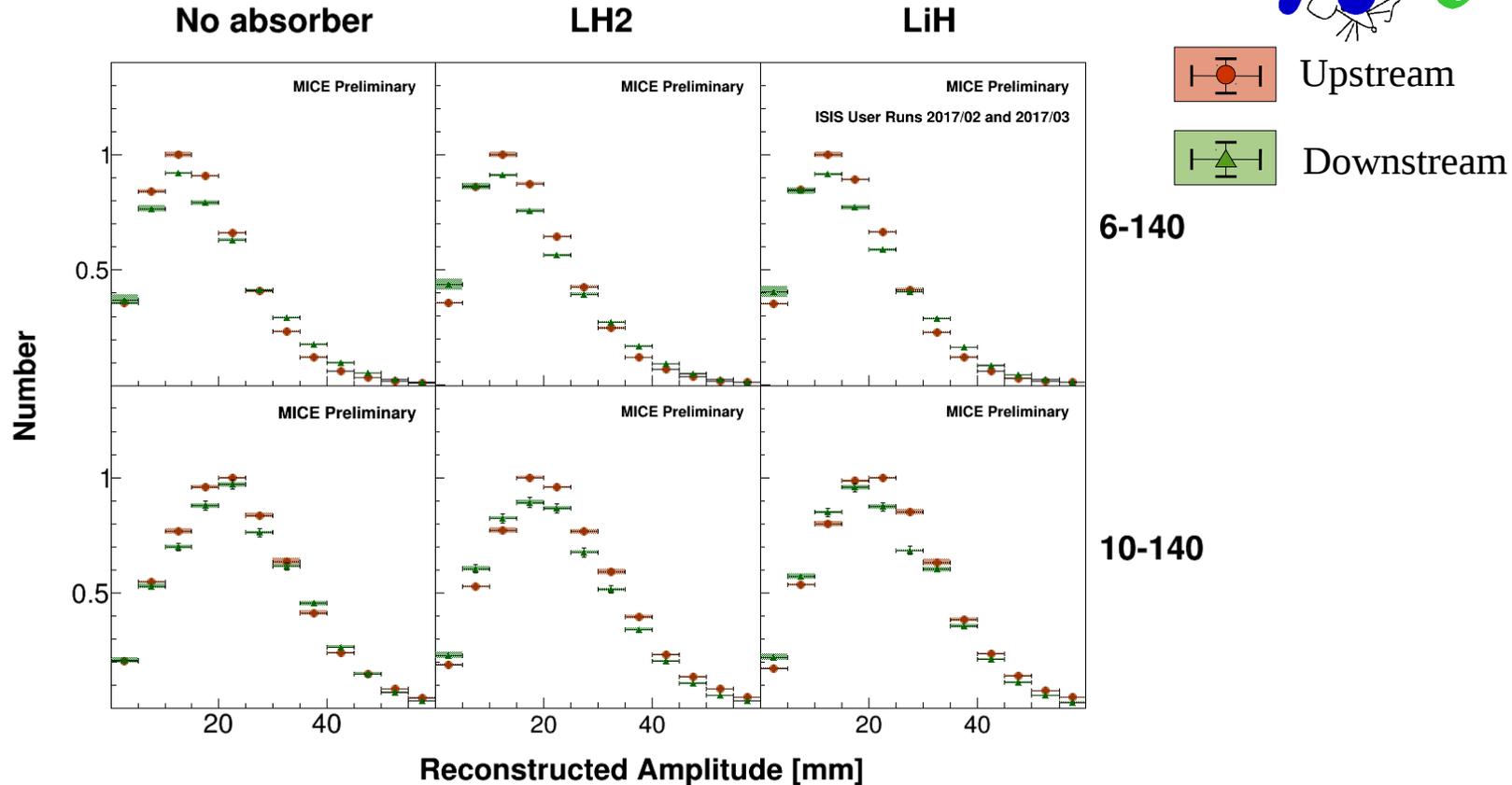
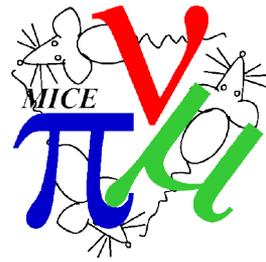


Amplitude reconstruction

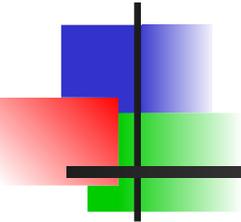


- Phase space (x, p_x, y, p_y)
- Amplitude is distance of muon from beam core
 - Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread
 - Reduces amplitude
- Mean amplitude \sim “RMS emittance”

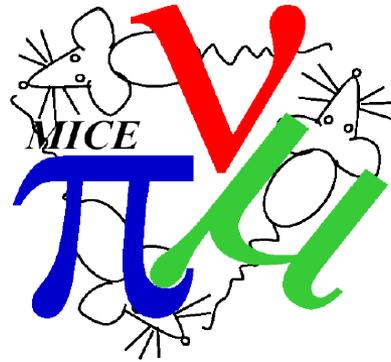
Change in amplitude distribution



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

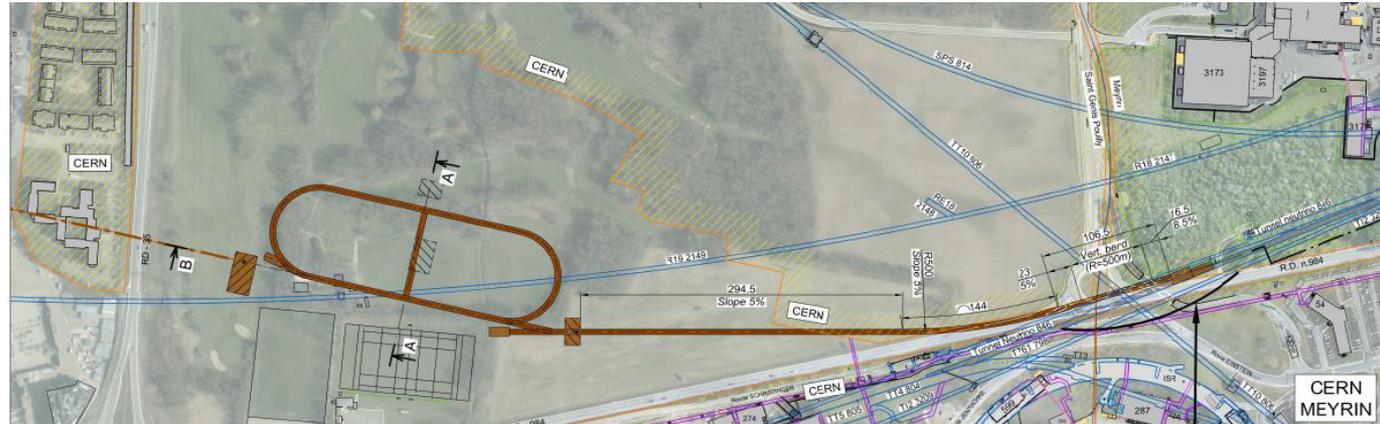
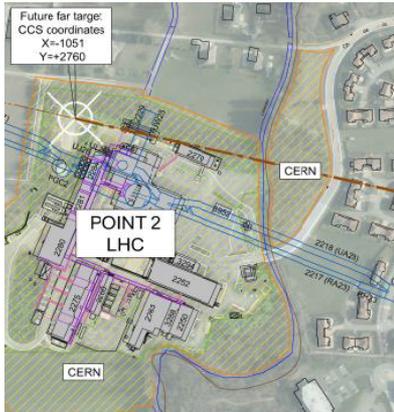
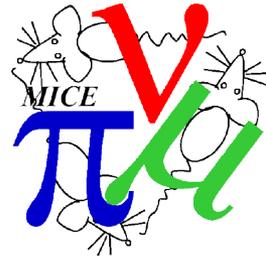


Ongoing UK Work



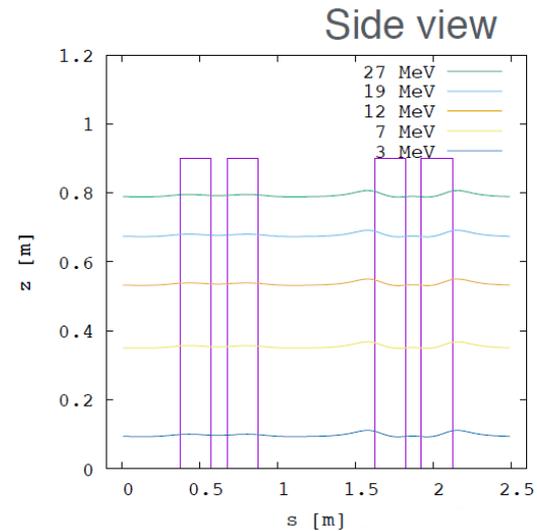
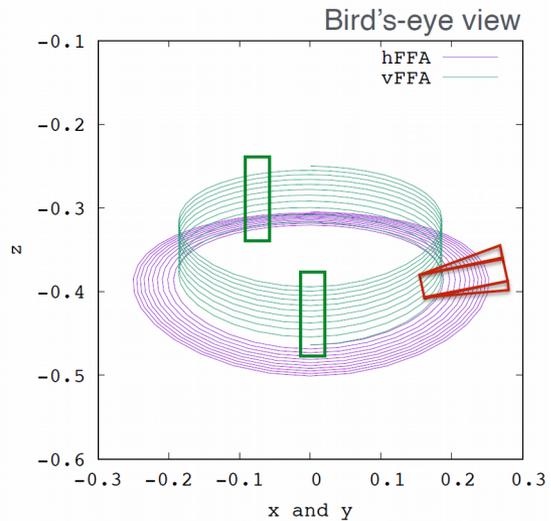
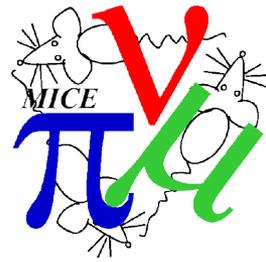
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Ongoing UK work - NuStorm



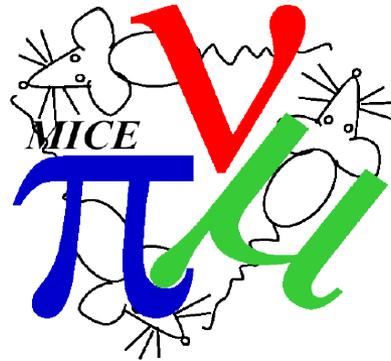
- Developing FFA option for NuStorm
 - Relatively high current, high energy muon beam facility
 - Excellent potential to support next generation of superbeams
 - Opportunity to develop capability for handling muon beams
- Alan Bross's talk later

Ongoing UK work - vFFA



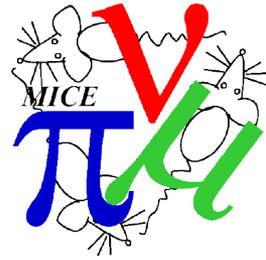
- VFFA → dipole field stronger higher in the magnet
 - Beam moves upwards with increasing momentum
 - Tune and optics is constant with increasing momentum
 - Isochronous in relativistic limit
- Applicable both to proton and muon acceleration
- Design underway
 - See Shinji Machida's talk later

What remains to be done (cooling hardware)?



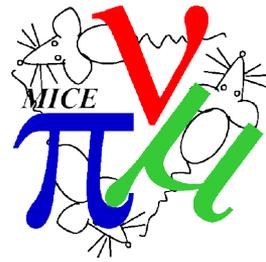
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Risks in ionization cooling

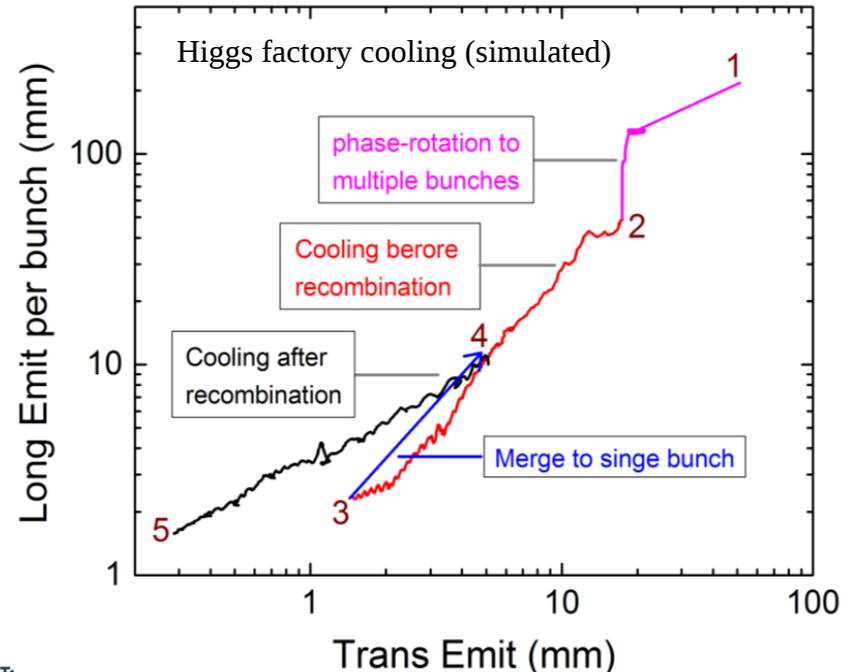
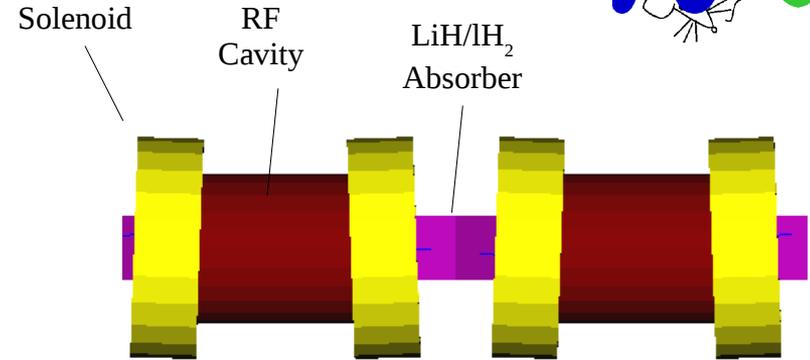


- MICE has demonstrated that transverse ionization cooling works
- What are outstanding risks → mitigations
 - Unforeseen collective effects → cooling test stand
 - Use protons to get sufficient intensity?
 - Uncertainty in energy straggling → cooling test stand
 - ~10 % uncertainty in FWHM in literature
 - 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?

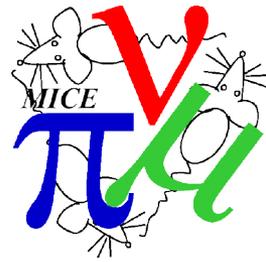
Cooling (6D)



- 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

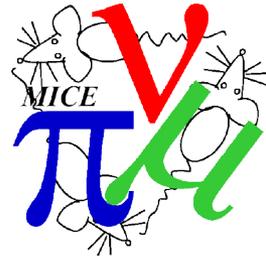


Cooling test stand



- 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

