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
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

- 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

**Cool** the muon beam using LiH, LH$_2$, or polyethylene wedge absorbers

**Measure** muon position and momentum downstream
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 focusing
- Measured
  - Scattering
  - Energy loss
  - Emittance change

\[ \frac{d\varepsilon_T}{ds} \approx -\frac{\varepsilon_T}{\beta_R^2 E} \langle \frac{dE}{ds} \rangle + \frac{\beta_T (13.6\text{MeV})^2}{2\beta_R^3 E\mu X_0} \]

- Emittance Change
- Cooling via \( \frac{dE}{dx} \)
- Heating via scattering
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

\[ \sigma_{xx}^2 \]

\[ \sigma_{pxp_x}^2 \]

\[ \sigma_{yy}^2 \]
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 \(\sim \text{“RMS emittance”}\)
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

Higgs factory cooling (simulated)

Long Emiss per bunch (mm)

Trans Emiss (mm)
Cooling test stand

- Collective effects $\rightarrow$ high beam intensity
  - Either nustorm-level muon beam
  - Or (low energy) proton beam $\rightarrow$ 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