First Demonstration of Ionization Cooling in MICE

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Probing the Nature of Matter with Muons

- First accelerators built in 1920s/30s
  - Accelerating protons, ions and electrons
- Antiproton acceleration in 1980s
  - Made possible by stochastic cooling
- Muon acceleration?
- Muon collider → excellent Higgs probe
  - Suppress synchrotron radiation
  - Strong coupling to Higgs
  - Potential for very high energy leptons
- Neutrino factory → Well-characterised neutrino source
  - Tunable energy
- Challenges
  - Muons produced as tertiary particle
  - Relatively short lifetime
Muon Collider and Neutrino Factory

- **Facility**
  - High power protons
  - Target → pions
  - Capture → muons
  - Cooling
  - Rapid acceleration
  - Storage ring
  - Rapid cooling → ionization cooling
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
- MICE
  - Demonstrate ionization cooling principle
  - Increase inherent beam brightness → number of particles in the beam core
  - “Amplitude”
Amplitude

- 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 \(\sim \text{"RMS emittance"}\)
Muon Ionization Cooling Principle

- Muons lose longitudinal and transverse momentum through ionization energy loss in an absorber
  - Non-conservative system
  - Normalised amplitude decrease
- Muons regain only longitudinal momentum in RF cavities
  - Overall, transverse momentum and amplitude is reduced
- Multiple scattering degrades the cooling effect
  - Mitigate by tight focussing
  - Mitigate by choice of low-Z absorber material
- Challenge to maintain tight focussing and high acceptance
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 ionization cooling principle and amplitude non-conservation
Muon Ionization Cooling Experiment

**Measure** muon position and momentum downstream

**Measure** muon position and momentum upstream

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

*Science & Technology Facilities Council*
Experimental Site

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

The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment, JINST 7, P05009 (2012)

Characterisation of the muon beams for the Muon Ionisation Cooling Experiment, EPJ C 73, 10 (2013)

Pion contamination in the MICE muon beam, JINST 11 (2016)
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

- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- $45^\circ$ polythene wedge absorber for longitudinal emittance studies
Scintillating Fibre trackers

- Tracks form a helix in spectrometer solenoids
- Position of particles measured by 5 stations of scintillating fibres
- Reconstruct helix in two phases
  - Pattern recognition to reject noise
  - Kalman filter to get optimal trajectory
- Yields momentum and position of particles at reference plane

- A scintillating fibre tracker for MICE, NIM A 659, 2011
- The reconstruction software for the MICE scintillating fibre trackers, J.Inst.11, 2016
High precision Time-of-Flight detectors
- Comparison of time-of-Flight with momentum enables rejection of impurities

Threshold Cerenkov detectors provide rejection of impurities near the relativistic limit

KLOE Light and Electron Muon Ranger provide calorimetry and rejection of decay electrons in downstream region

- Energy loss and multiple Coulomb scattering underlie ionization cooling emittance decrease
- Precision measurement of multiple coulomb scattering
  - See next talk
- Validation of energy loss model
- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision
Measurement of Beam Properties

- 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

MICE Data

\[ \sigma_{xx}^2 \]

\[ \sigma_{pxpx}^2 \]

\[ \sigma_{yy}^2 \]
Measurement of Emittance

- Measure four dimensional beam emittance (mean amplitude)
  - Including e.g. x-y coupling terms
  - Slice in $p_z$ to understand effect of dispersion
- No absorber → decrease in number of core muons
- With absorber → increase in number of core muons
  - Cooling signal
- \( R_{\text{amp}} \) is ratio of CDF
- Core density increase for LH2 and LiH absorber → cooling
- More cooling for higher emittances
Muon cooling is last “in-principle” challenge for neutrino factory or muon collider R&D

MICE has measured the underlying physics processes that govern cooling

MICE has made an unprecedented single particle measurement of particle trajectories in an accelerator lattice

MICE has made first observation of ionization cooling

Opens the door for high energy muon accelerators as a probe of fundamental physics