PROCEEDINGS OF SCIENCE

MICE Results

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The Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory is an experiment designed to measure ionization cooling of muons, essential for future muon accelerator facilities, such as a Neutrino Factory or a Muon Collider. The experiment took data between 2015 and 2017, collecting about 350 million muon events traversing a liquid hydrogen (LH2) or a lithium hydride (LiH) absorber after passing through a series of superconducting focusing magnets in a variety of optical configurations. Measurements of the muon beam upstream and downstream of the absorber are used to characterise multiple Coulomb scattering and energy loss of muons in the absorber material and enable the measurement of ionization cooling for the first time.

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1. Introduction

The Muon Ionization Cooling Experiment (MICE) at the Rutherford Appleton Laboratory in the UK was designed and built to demonstrate the concept of ionization cooling [1] for the first time [2]. Ionization cooling is essential in the design of a future Neutrino Factory [3] or a Muon Collider [4]. Muons are produced from the decay of pions, but the muon beam generated has a very large emittance that needs to be reduced in order to be able to accelerate the muons efficiently. Ionization cooling is the only technique capable of reducing the beam emittance within the short lifetime of the muon. This is achieved by passing the muon beam through a low density absorber inside focusing magnetic fields, and re-accelerating the muons using RF cavities to restore the longitudinal momentum. The change in four-dimensional (4D) transverse emittance ε_T is:

$$\frac{d\varepsilon_T}{dz} = -\frac{\varepsilon_T}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m_\mu c^2 \beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}, \tag{1.1}$$

where $\beta = v/c$, E_μ and m_μ are the muon energy and mass, $\beta_\perp$ is the Twiss transverse beta function and X_0 is the radiation length. The best cooling is achieved with a low-Z absorber, such as liquid hydrogen (LH2) or lithium hydride (LiH) where X_0 is maximised, inside a strong focusing field in which $\beta_\perp$ is minimised. The aim of MICE is to measure transverse emittance reduction for muon beams with emittance between 3 mm rad and 10 mm rad and momenta 140–240 MeV/c. The only known way of performing this measurement at the accuracy required is by reconstructing individual muon trajectories inside a tracking magnetic spectrometer and recreating virtual beams offline.

2. The Muon Ionization Cooling Experiment

The configuration of the Muon Ionization Cooling Experiment is seen in Figure 1. It consists of two scintillating fibre trackers upstream and downstream of an absorber inside a focus-coil magnet. Each tracker contains five scintillating fibre triplet planes in helium gas. The absorbers are either a 350 mm thick vessel filled with liquid hydrogen ($X_0 = 890$ cm) or a 65 mm thick LiH solid absorber ($X_0 = 102$ cm). Aluminium windows separate the helium volume from the vacuum containing the liquid hydrogen absorber. A solenoidal magnet consisting of five superconducting coils surrounds each of the trackers. A time-of-flight (TOF) system, consisting of three detectors (TOF0 and TOF1 upstream and TOF2 downstream of the cooling channel), a Cherenkov detector, a pre-shower system (named KL) and an Electron-Muon Ranger (EMR) are used for particle identification and for particle energy measurements. The MICE beam is shown in Figure 2 and

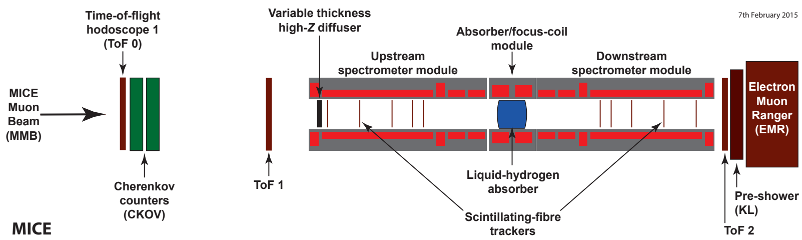

Figure 1: Schematic diagram of the MICE cooling channel.

is described in [5]. The beam line delivers a muon beam with a normalised transverse emittance range between 3 mm rad and 10 mm rad, and with mean momentum selectable between 140 and 240 MeV/c. Pions produced by the insertion of a titanium target into the 800 MeV ISIS proton synchrotron are captured in a quadrupole triplet (Q1–Q3). A dipole magnet (D1) selects the momentum of the pions and these decay in a 5 T superconducting decay solenoid (DS). The muons from pion decay are momentum-selected by a second dipole magnet (D2) and transported by two quadrupole triplets (Q4–Q6 and Q7–Q9). A pneumatic "diffuser", with different material thickness at the entrance of the cooling channel generates the range of emittances. Between 2015 and 2017 the MICE beam delivered about 350×10^6 muons to MICE.

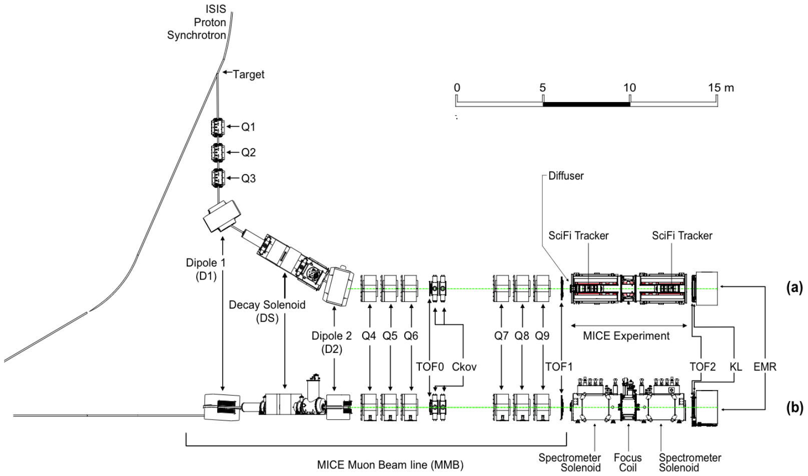

Figure 2: (a) Top view and (b) side views of the MICE muon beam and cooling channel.

3. Experimental Results

The Muon Ionization Cooling Experiment has delivered a comprehensive set of measurements in the momentum range of 140–240 MeV/c describing Multiple Coulomb Scattering (MCS) and energy loss in the absorber materials of MICE. The interplay between scattering and energy loss affects the cooling performance, as shown in equation 1.1. Experimental results of MCS of low-Z materials [6] have shown differences with GEANT4 [7] and other models, so new measurements are required to validate scattering models. Preliminary data of the projected MCS angular distribution transverse to the momentum vector for 172 MeV/c muons impinging on the LiH absorber, compared to GEANT4 and to a Monte Carlo model based on the Wentzel single scattering distribution by Carlisle and Cobb [8] is shown in Figure 3.

The 4D amplitude of a muon with phase-space coordinates given by $\vec{v} = (x, p_x, y, p_y)$ is defined

$$A_\perp = \varepsilon_T \left(\vec{v} - \langle\vec{v}\rangle\right)^T \Sigma^{-1} \left(\vec{v} - \langle\vec{v}\rangle\right), \tag{3.1}$$

where Σ^{-1} is the inverse of the covariance matrix of muon phase-space measurements and $\varepsilon_T = \sqrt[4]{\Sigma}/(m_\mu c)$ is the normalised 4D transverse emittance. MICE reconstructs the amplitude of each muon and the beam emittance using the upstream and downstream trackers. The signature of ionization cooling is an increase of the single-particle amplitude density in the core of the beam.

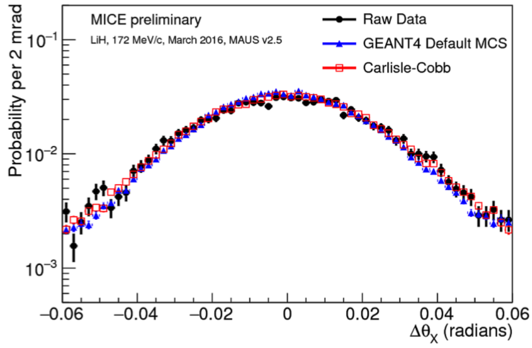

Figure 3: Projected MCS angular distribution from 172 MeV/c muons impinging on LiH measured in MICE.

An increase in the cumulative amplitude is best observed by showing that the following ratio

$$R^N_{Amp} = \frac{\sum_{n=1}^{N} A_n^{down}}{\sum_{n=1}^{N} A_n^{up}} > 1, \tag{3.2}$$

where A_n^{down} and A_n^{up} are the amplitudes of the muons measured downstream and upstream of the absorber. Figure 4 shows that there is a migration of high amplitude muons to lower amplitude after traversing the LH2 and LiH absorbers ($R_{Amp} > 1$ at low amplitudes) for the high emittance 6 mm rad and 10 mm rad beams at a momentum of 140 MeV/c.

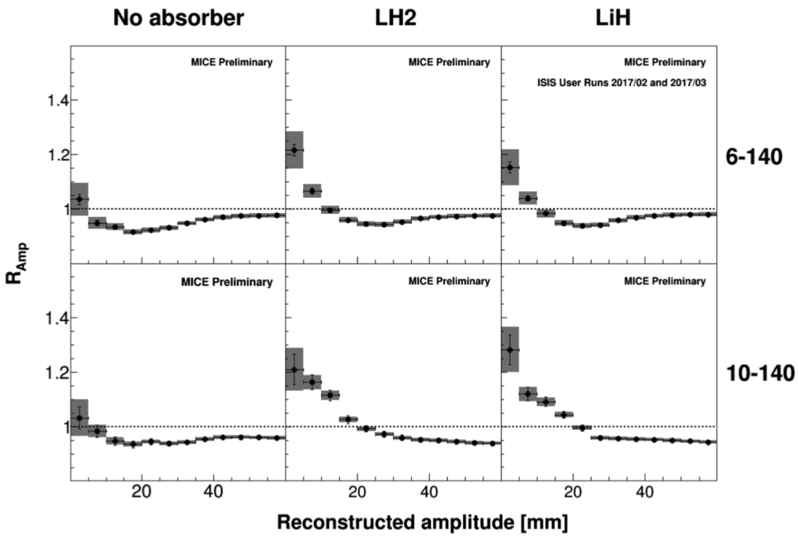

Figure 4: Demonstration of ionization cooling in MICE, showing that $R_{Amp} > 1$ in the core of the beam for high emittance beams of 6 mm rad and 10 mm rad at 140 MeV/c when the absorber is LiH and LH2.

The fractional emittance $\varepsilon_\alpha = \frac{1}{2}\left(\pi m_\mu c \varepsilon_T\right)^2$ is the phase-space volume occupied by a fraction α of the beam ($\alpha = 9\%$ corresponds to 1σ of the 4D phase space). Figure 5 shows the reduction in fractional emittance ε_9 for a beam of input emittance 6 mm rad and 140 MeV/c and a LiH absorber, also clearly showing ionization cooling [9].

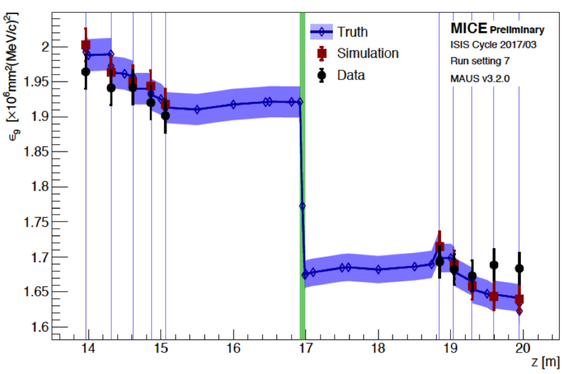

Figure 5: Reduction in fractional emittance ε_9 for a 6 mm rad, 140 MeV/c fmuon beam with LiH.

4. Conclusion

The Muon Ionization Cooling Experiment (MICE) was carried out at the Rutherford Appleton Laboratory and collected 350 million muon triggers during 2015 and 2017 to fully characterise ionization cooling. The data from MICE is being used to measure Multiple Coulomb Scattering and energy loss in LiH and liquid hydrogen absorbers. Ionization cooling is being studied in detail in the momentum range 140–240 MeV/c for an input normalised transverse emittance range between 3 mm rad and 10 mm rad. A preliminary analysis of the data shows ionization cooling for the first time for large input emittance of 6 mm rad and 10 mm rad beams. Therefore, this demonstrates the last remaining technological requirement to build the front-end of a Neutrino Factory.

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