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THE MUON IONIZATION COOLING EXPERIMENT*

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for the MICE collaboration

Abstract

The Muon Ionization Cooling Experiment (MICE) is designed to demonstrate a measurable reduction in muon beam emittance due to ionization cooling. This demonstration will be an important step in establishing the feasibility of muon accelerators for particle physics. The emittance of a variety of muon beams is measured before and after a "cooling cell", allowing the change in the phase-space distribution due to the presence of an absorber to be measured.

Two solenoid spectrometers are instrumented with high-precision scintillating-fibre tracking detectors (Trackers) before and after the cooling cell which measure the normalized emittance reduction.

Data has been taken since the end of 2015 to study several beams of varying momentum and input emittance as well as three absorber materials in the cooling cell, over a range of optics. The experiment and an overview of the analyses are described here.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) is a collaboration of over 100 scientists from 10 countries and 30 institutes around the world. Based at the Rutherford Appleton Laboratory in the UK it is designed to demonstrate a measurable reduction in emittance in a muon beam due to ionization cooling.

Ionization cooling [1] is the process of reducing the beam emittance (phase space) through energy loss in ionization as particles cross an absorber material, this combined with restoration of the longitudinal momentum of the beam through re-acceleration (using RF cavities) makes sustainable cooling.

Muon colliders and neutrino factories are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies and precision measurements of parameters of the Higgs boson and the neutrino mixing matrix. Ionization cooling is the only practical solution to preparing high intensity muon beams for use in these facilities. Muon ionization cooling is necessary for a Muon Collider or neutrino factory [2,3], as the short lifetime of the muon ($\tau_\mu \sim 2.2\,\mu$s) and the large emittance of muon beams (as muons are tertiary particles) means that traditional beam cooling techniques which reduce emittance cannot be used and ionization cooling is the only viable technique to reduce the emittance of the beam within their lifetime.

MICE is currently the only experiment studying ionization cooling of muons.

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MUON IONIZATION COOLING

Muon cooling can be characterized by the rate of change of the normalized emittance (phase space occupied by the beam). Where the muons lose both longitudinal and transverse momentum through ionization energy loss as they pass through the absorber, a proportion of the lost longitudinal momentum can then restored using accelerating RF cavities that follow the absorber. Along with this cooling, however, there is a heating effect produced as a result of multiple scattering through the system, therefore, the net cooling is a balance between these two effects. This is described in Eq. (1), where the first term on the right hand side represents the cooling effect and the second term the heating effect:

$$\frac{d\epsilon_n}{ds} \sim -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014\text{GeV})^2}{2E_\mu m_\mu L_R} \qquad (1)$$

$\frac{d\epsilon_n}{ds}$ is the rate of change of normalized-emittance within the absorber; β, E_μ and m_μ the ratio of the muon velocity to the speed of light, muon energy, and mass respectively; $\beta_\perp$ is the lattice betatron function at the absorber; and L_R is the radiation length of the absorber material.

The effect of the heating and cooling terms defines an equilibrium emittance:

$$\epsilon_{n,eq} \propto \frac{\beta_\perp}{\beta X_0}\langle\frac{dE_\mu}{ds}\rangle \qquad (2)$$

below which the beam cannot be cooled. However, as input emittance increases, beam scraping results in increased beam loss and so the two must be balanced.

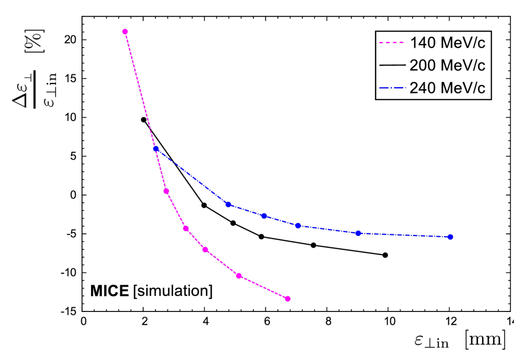

Figure 1: Change in emittance in percent vs. input emittance for a range of MICE beam momenta.

MICE will study this in order to obtain a complete experimental characterization of the cooling process, see Figs. 1 and 2. The cooling equation will be studied in detail for a variety of input beams, magnetic lattices and absorbers to demonstrate the feasibility of this technique. Since a typical

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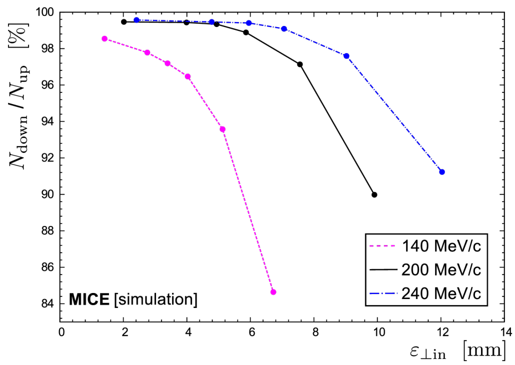

Figure 2: Change in transmission (in percent) vs. input emittance for a range of MICE beam momenta.

cooling channel will employ dozens to hundreds of cooling lattice cells, the precision with which the tails of distributions can be predicted will have important consequences for the performance of the channel.

MICE

The MICE experiment shown in Fig. 3 passes a muon beam through a low-Z material (absorber), where the muons lose both longitudinal and transverse momentum through ionization energy loss.

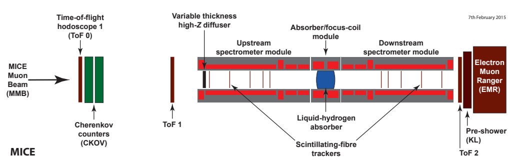

Figure 3: Schematic of the International Muon Ionization Cooling Experiment (MICE), with the beam entering from the left.

The muons produced in the MICE Muon Beam line first pass through the upstream particle identification (PID) detectors, are sampled and tracked upstream and downstream of the absorber by scintillating fibre trackers, before passing through the downstream PID detectors.

MICE is a single-particle experiment, meaning that there is no "beam" as such, instead, particles go down the beam line one by one. At each DAQ cycle, a single particle track is recorded and subsequently tracks are bunched at the analysis level. It is from this sample that the emittance is computed, see Fig. 4

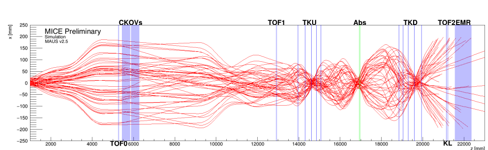

Figure 4: MICE is a single-particle experiment as particles go down the beam line one by one and are bunched at the analysis level.

The MICE Muon Beam

The MICE Muon beam is produced using the ISIS 800 MeV proton beam [4], which delivers 4 µC of protons in two 100 ns long pulses, with mean current of 200 µA. A titanium target is dipped into the ISIS beam, producing pions (π^+) which then decay into muons. MICE uses a decay solenoid to enhance the initial pion to muon decay process, dipole magnets for momentum selection and quadrapole magnets for beam focusing (Fig. 5).

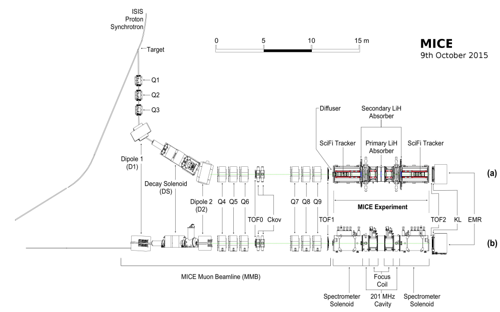

Figure 5: Schematic of the ISIS proton synchrotron and the MICE beam extraction magnets.

The MICE beam can be prepared as a π beam or μ beam with momentum between 140-450 MeV/c. The dip rate is 1 dip/1.28 s giving a maximum particle rate of: $\mu^+ \sim 120\ \mu$/dip and $\mu^- \sim 20\ \mu$/dip. The final muon beam is a 3 ms wide spill, in two 100 ns long bursts every 324 ns.

The MICE muon beamline delivers a high purity beam with less than 1.4 % pion contamination [5].

The MICE Instrumentation

The MICE cooling channel (as shown in Fig. 6 consists of: two spectrometer solenoids which produce a magnetic field up to 4 T. Each has five coils: a central coil which surrounds the Trackers, two end coils on either side of the central coil and two matching coils nearest the absorber. All coils are wound onto the same bobbin and have a core temperature of 4 K and an operating pressure of 1.5 bar. In-between the solenoids is the absorber focus coil (surrounding the absorber). This "cooling channel" magnet chain can operate in flip or solenoid mode. The absorber is modular to allow a range of cooling materials to be used (liquid-hydrogen, lithium-hydride, xenon and empty).

The detector suite consists of three Time Of Flight detectors:TOF0, TOF1 and TOF2, giving precise timing and time of flight measurements; 2 cherenkov threshold counters; a downstream calorimeter made up of the Electron Muon ranger (EMR), to separate muons from decay electrons in collaboration with the KL KLOE-Light detector. There are two scintillating fibre trackers, one upsteam and one downstream of the absorber, they measure normalised emittance reduction with a precision of 0.1% (beam emittance measured before and after cooling). This suite of detectors allow pion/muon separation up to 300 MeV/c.

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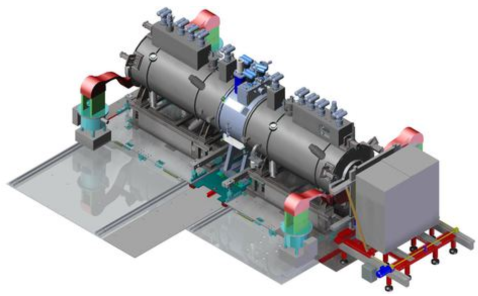

Figure 6: The MICE cooling channel showing the two spectrometer solenoids in grey and the absorber focus coil in blue.

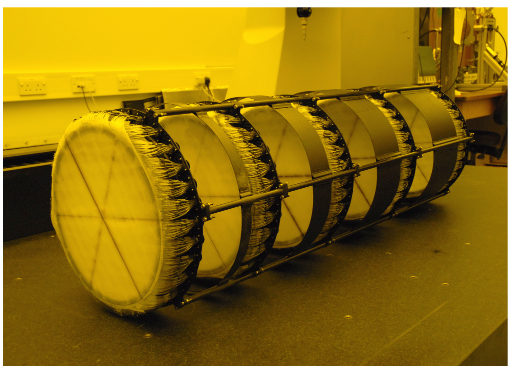

Figure 7: The MICE Tracker detectors showing the 5 stations each consisting of three planes of WLS fibres.

The Trackers (Fig. 7, each sit within a spectrometer solenoid producing a variable magnetic field up to 4 T. Each Tracker is 110 cm in length and 30 cm in diameter and consists of five 'stations' with longitudinal space separation varying between 20–35 cm (the varied separation distance between the stations allows the muon pT to be determined). Each station has three planes of 350 µm clear wavelength shifting fibres, each plane sits at 120 degrees to the next, providing a position resolution in the Trackers of 470 µm.

Data Taking

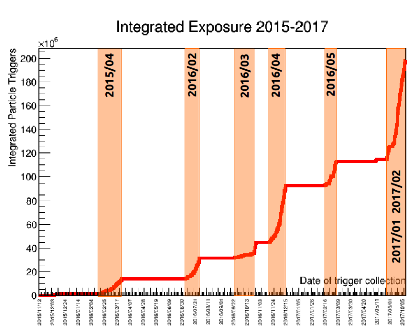

Figure 8: The MICE integrated particle triggers collected as a function of time. ISIS user cycles in which data were taken are highlighted in orange.

Mice has successfully taken data since December 2015. It has collected over 200 million integrated triggers over six ISIS user cycles with negligible down time. Figure 8 shows the MICE integrated exposure over time.

DIRECT MEASUREMENT OF THE MICE MUON BEAM EMITTANCE

The MICE muon beam has high purity with less than 1.4% pion contamination and 0.05% decay electrons [5]. The time of flight between TOF0 and TOF1 is used to further improve the beam purity by removing other sources of contamination, such as decay positrons, from the final analysis sample. Tracker reconstruction using pattern recognition and a Kalman filter provides the best estimate of the particle position and momentum.

The time of flight between TOF0 and TOF1 is represented as a function of the total momentum reconstructed in the Tracker, shown in Fig. 9. The dotted line represents the ideal time of flight for a muon (with momentum loss as described by the Bethe-Bloch formula) between entering TOF1 and reaching the Tracker reference plane (closest to the absorber).

Due to the large aperture dipoles used to select the muon momentum distribution, the transported muon sample contains a large momentum spread, $\sigma_{p_z} \simeq 25.7$ MeV/c, for a mean longitudinal momentum of $p_z = 195.4$ MeV/c. The emittance of the particle sample does not accurately represent the volume occupied by the particles (phase space), as muons with different longitudinal momenta occupy different regions of transverse phase space due to the presence of dispersion. The effect of this dispersion is removed by splitting the sample into momentum-coherent 8 MeV/c bins.

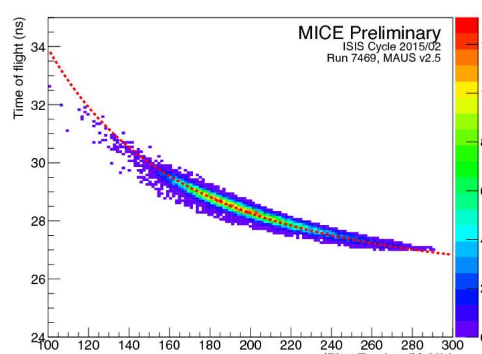

Figure 9: Time-of-flight distribution between TOF0 and TOF1 as a function of the total momentum measured in the upstream Tracker. The absence of other populations indicates selection of a pure muon sample.

The transverse normalised emittance was calculated for each 8 MeV/c bin as:

$$\epsilon_N = \frac{1}{m_\mu}\sqrt[4]{det\Sigma} \tag{3}$$

where m_μ is the muon mass and Σ is the 4D transverse phase space covariance matrix.

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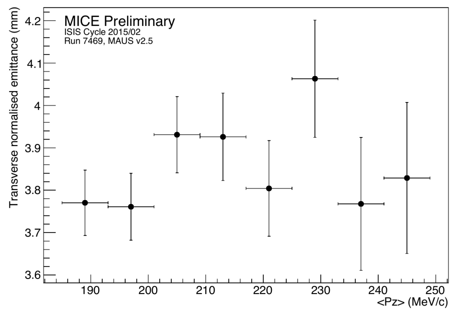

Figure 10: Transverse normalised emittance of 8 MeV/c longitudinal momentum bins.

The measured, momentum binned transverse normalised emittance is shown in Fig. 10. The horizontal error bars represent the limits of each momentum slice, while the vertical error bars are purely statistical errors on the measurements. A full systematics study is underway and preliminary results indicate that that they are small in comparison. The binned emittance values are consistent across the range of studied momenta. The mean measured transverse normalised emittance for the whole sample is 3.85 ± 0.04 mm.

EMITTANCE EVOLUTION IN MICE

In order to demonstrate emittance reduction, MICE has measured the amplitude distribution upstream and downstream of the absorber. The single particle amplitude for each muon was reconstructed for each of the upstream, downstream and scraped ensembles. Initial beam emittances of 3 mm and 6 mm nominal emittance have been analysed so far. The resulting amplitude distributions are shown in Fig. 11.

The first bin is at the beam centre and hence is least affected by scraping. The 3 mm nominal emittance beam shows a clear reduction in the number of reconstructed muons downstream to upstream within the first bin, significantly above any scraping effects, which is characteristic of an emittance growth, or heating. Likewise muons with low amplitude upstream of the absorber are observed to move to higher amplitude when measured downstream, as the sample emittance is below equilibrium. Muons sampled from 6 mm 140 MeV beam show negligible change between the upstream and downstream reconstruction consistent with equilibrium emittance (and supported by simulation).

A full description of Emittance Evolution in MICE can be found in the relevant section of these proceedings.

MULTIPLE SCATTERING MEASUREMENTS

Multiple coulomb scattering is a well known electromagnetic phenomenon experienced by charged particles traversing materials. However, recent measurements by the MuScat [6] experiment show that the available simulation codes, e.g. GEANT4 [7], overestimate the scattering of muons in low Z materials. This is of particular interest to MICE

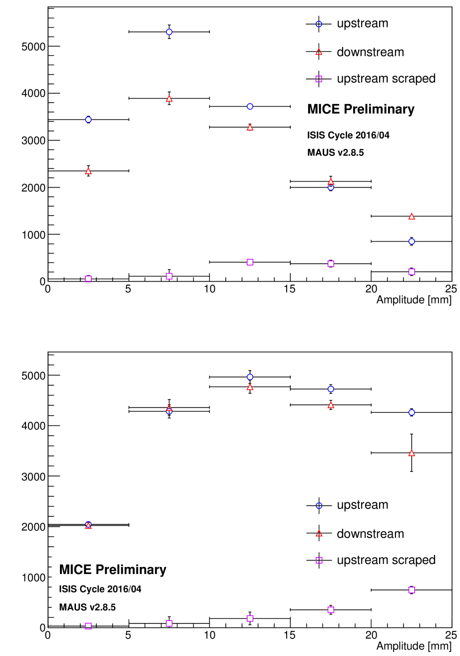

Figure 11: Change in amplitude distribution for the 3 mm 140 MeV configuration (above) and for the 6 mm 140 MeV configuration (below) are shown. Their transmission is ~90% and 80% respectively. Blue circles show the amplitude of upstream events, red triangles show the amplitude of downstream events while magenta squares show the amplitude of upstream events that are not observed downstream.

which aims to measure the reduction of muon beam emittance induced by energy loss in low-Z absorbers. Multiple scattering induces positive changes in the emittance in contrast to the reduction due to ionization energy loss. It is, therefore, essential that MICE measures multiple scattering in all absorber materials; lithium hydride, liquid hydrogen and xenon; and validates this multiple scattering against known simulations.

To make the scattering measurements data was taken for a range of beam momenta(172 MeV/c (in order to compare with MuScat), 200 MeV/c and 240 MeV/c) and with the absorber in and empty (to ensure scattering in the windows of the absorber module are accounted for). A strict track selection criteria was imposed to ensure a pure, well understood muon sample. Bayesian deconvolution was applied to the selected data in order to extract the scattering distribution within the absorber material and subsequent comparisons to GEANT4 were made, as well as to the standalone scattering model developed by Carlisle and Cobb [8].

Data taken with the 200 MeV/c beam and, with and without, the LiH absorber (thickness of 65 mm, X_0 = 79.62 gcm^{-2}) and deconvolved using the GEANT model, are shown in Fig. 12. All contributions to the systematic uncertainty have been considered including: sensitivity to the thickness of the absorber, the time of flight cuts used in the momentum selection, detector alignment and the choice

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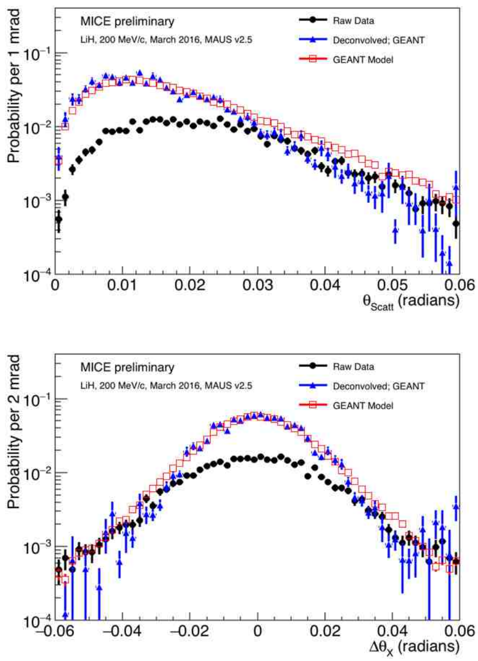

Figure 12: Projected (below) and 3D (above) scattering distributions of 200 MeV/c muons passing through the LiH absorber.

of fiducial volume cuts. The time of flight systematics are found to dominate. The scattering width taken from the scattering distributions projected in the X–Z and Y–Z planes are $\theta = 20.3 \pm 0.2$ mrad at 172 MeV/c, $\theta = 17.1 \pm 0.2$ mrad at 200 MeV/c and $\theta = 13.8 \pm 0.1$ mrad at 240 MeV/c.

This preliminary analysis indicates that GEANT4 underestimates the scattering width, while the PDG model overestimates it. A full discussion can be found in the MICE Multiple Scattering discussion in these proceedings.

CONCLUSIONS

MICE Step IV has been taking data since 2015. lithium hydride and xenon scattering data is complete and data taking with liquid hydrogen has begun. The cooling channel magnets have operated successfully taking data in flip and solenoid modes, throughout. The first direct measurement of emittance has been made in MICE, the dispersion effect is understood and there are several papers in preparation. The first emittance change measurements have also been made and are currently being finalised for publication. Multiple scattering results are progressing well and publication is also coming soon.

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