PROCEEDINGS OF SCIENCE

Emittance Measurement in the Muon Ionization Cooling Experiment

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The Muon Ionization Cooling Experiment (MICE) collaboration will demonstrate the feasibility of ionization cooling, a technique to produce a small emittance muon beam for a future neutrino factory and/or muon collider. The emittance is measured on a particle-by-particle basis. Measurements are made before and after the cooling cell using a high precision scintillating-fibre tracker in a solenoidal field. A pure muon beam is selected using a particle identification (PID) system that can efficiently reject pions and electrons. The emittance of a muon beam has been measured particle-by-particle for the first time. The analysis techniques required for this precision measurement are presented.

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1. Introduction

Future muon-based accelerators, such as a neutrino factory or muon collider will require an intense muon beam that occupies a small volume of phase space [1], i.e has a small emittance, ε. Muons produced from pion decay occupy a large phase space volume, which must be reduced before they can be efficiently accelerated.

Conventional cooling techniques are not possible for muons due to their short lifetime. One possible technique is ionization cooling, where muons pass through a low-Z absorbing material (e.g. LiH) and lose energy by ionisation. This reduces all momentum components, cooling the beam. RF acceleration then restores longitudinal momentum, resulting in transverse emittance reduction. Several orders of magnitude in 6D cooling has been achieved in simulation [2].

The Muon Ionization Cooling Experiment (MICE), shown in Figure 1, will demonstrate ionization cooling by studying emittance change as a function of absorber material, beam and magnetic lattice properties. The MICE Muon Beamline (MMB) [3] at the Rutherford Appleton Laboratory, UK, transports muons through several particle identification detectors (TOF0, TOF1, CKOV) to the Cooling Channel. This consists of three, 3–4 T, superconducting solenoid magnets, each with several coils, followed by further particle identification detectors (TOF2, KL, EMR). Two, five-station, scintillating fibre tracking detectors sit in a uniform magnetic field to measure the position and momentum of individual muons crossing the Cooling Channel.

Particles were measured in the upstream tracking detector, during the 4 T field commissioning of the upstream solenoid magnet, in October 2015. The normalised transverse emittance of the set of accepted muons is reported here.

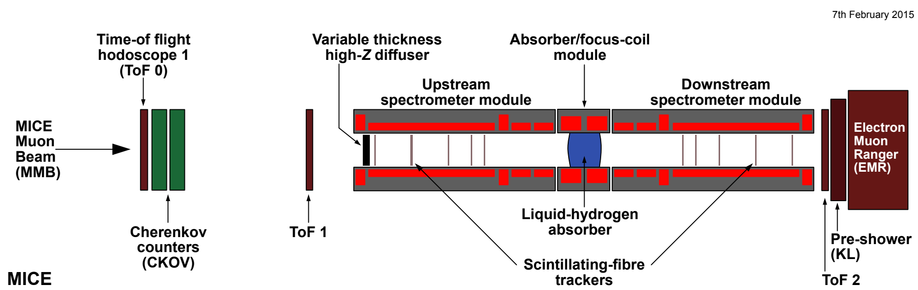

Figure 1: Muons are transported through PID detectors to the Cooling Channel. The position and momenta of individual muons are measured before and after crossing an absorber (LiH or liquid H_2) by a scintillating fibre tracker immersed in a 4 T uniform field.

2. Particle selection and measurement

The MMB delivers a high-purity muon beam with less than 1.4% [4] pion contamination. Two time-of-flight hodoscopes, TOF0 and TOF1, are used to determine the travel time of particles immediately upstream of the Cooling Channel. Particles accepted as muons for this analysis required a time-of-flight of 27–32 ns. Rejected particles were identified as electrons. The time-of-flight of accepted muons is shown in Figure 2 (left).

Particle selection required only one particle in each of: TOF0; TOF1; and the upstream Tracker, per trigger. A further requirement was imposed on the momentum lost between TOF1 and the upstream Tracker to remove particles that pass through the annulus of the high-Z diffuser (Figure 1), which was present but not in use at the time of taking data. This corresponds to a requirement that muons were within a radius of $\simeq 100$ mm of the reference beam axis at the entrance to the Cooling Channel.

After entering the Cooling Channel, muons crossed a 4 T field region that enclosed the upstream scintillating fibre Tracker. The Tracker consists of 5 stations, each with three planes of 350 μm thick fibres oriented at 120° to each other, giving a transverse position, (x, y), at each station. A Kalman filter, which allows for multiple scattering and energy loss in estimating the helical track parameters, provides the best estimate of position and momentum for each particle [5]. Figure 2 (right) shows the measured total momentum of accepted muons crossing the upstream Tracker and their time-of-flight between TOF0 and TOF1. The dotted (red) line corresponds to an ideal muon losing the mode momentum between the two detectors.

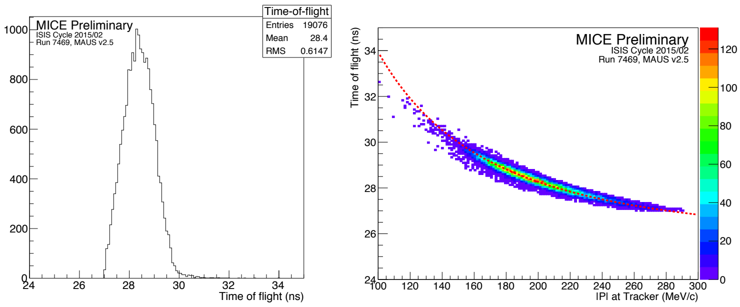

Figure 2: (Left) Time-of-flight of muons between TOF0 and TOF1. (Right) Muon momentum as measured in the upstream Tracker versus time-of-flight. The (red) dotted line corresponds to an ideal muon that suffers the mode momentum loss between TOF1 and the Tracker.

3. Emittance measurement

Position and phase space portraits for the selected muons are shown in Figure 3. The initial particle distribution transported through the MMB to the Cooling Channel contains dispersion in the horizontal plane. As is expected from the time-of-flight distribution, the selected muons have a large momentum spread of $\sigma_{P_z} = 25.7$ MeV/c at a mean longitudinal momentum, $P_z = 195.4$ MeV/c. Calculating the total volume occupied by the muons as shown in Figure 3 results in an overestimate of their emittance, as muons with different longitudinal momenta occupy different regions of phase-space.

The selected muons were divided into 8 MeV/c longitudinal momentum slices to account for dispersive effects. The emittance of each momentum slice was calculated as [6]

$$\varepsilon_N = \frac{1}{m_\mu}\sqrt[4]{\det\Sigma}, \tag{3.1}$$

where m_μ is the mass of the muon and Σ is the 4D covariance matrix,

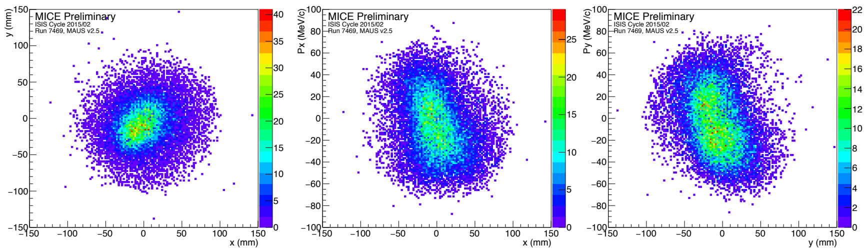

Figure 3: (Left) Transverse position, (middle) (x, P_x) and (right) (y, P_y) phase space as measured at the reference plane of the upstream Tracker.

$$\Sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xPx} & \sigma_{xPy} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{yPx} & \sigma_{yPy} \\ \sigma_{xPx} & \sigma_{yPx} & \sigma_{PxPx} & \sigma_{PxPy} \\ \sigma_{xPy} & \sigma_{yPy} & \sigma_{PxPy} & \sigma_{PyPy} \end{pmatrix}, \tag{3.2}$$

and the elements of Σ, σ_{ab}, are the covariances between phase space dimensions.

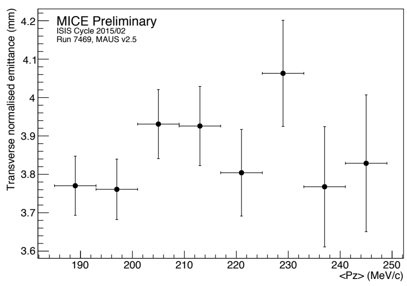

Figure 4: Transverse normalised emittance of 8 MeV/c longitudinal momentum slices.

The measured transverse normalised emittance of each momentum slice is shown in Figure 4. The horizontal error bars correspond to the width of the momentum slice, and the vertical correspond to the statistical error on the emittance measurement of that slice. Systematic error studies are in progress, but current estimates are that these errors are small in comparison. The emittance of muons measured in each momentum slice is consistent across the range of momenta. The mean measured transverse normalised emittance of all momentum slices is 3.85 ± 0.04 mm.

4. Conclusions

The position and momenta of a selected sample of muons were measured with a scintillating fibre tracker during the 4 T commissioning of the MICE upstream solenoid. The transverse normalised emittance of these particles was calculated in 8 MeV/c longitudinal momentum slices. The emittance of the beam is 3.85 ± 0.04 mm showing no evidence for variation with muon momentum.

References

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