MICE Step I: First Measurement of Emittance with Particle Physics Detectors

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Abstract. A novel single-particle technique to measure emittance has been developed and applied to seventeen different muon beams for the Muon Ionisation Cooling Experiment. The mean momenta of these beams varies from 173 to 271 MeV/c, with emittances on the order of 2 to 4 mm.rad horizontally and 0.8 to 1.2 mm.rad vertically. The measured parameters of the beams and the results of simulations are in agreement.

Keywords: muon ionisation cooling, accelerator instrumentation
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INTRODUCTION

The Muon Ionisation Cooling Experiment (MICE) [1] will demonstrate the practicality of ionisation cooling, an essential technique for a future Neutrino Factory or Muon Collider. Muons are produced occupying a large volume of phase space that must be reduced for efficient acceleration. Ionisation cooling is the only technique that can reduce the emittance of these beams.

A beam of muons passing through low-Z material loses energy by ionisation. This reduces the beam divergence and the volume of occupied phase space. Longitudinal momentum is restored in accelerating cavities, maintaining the overall momentum of the beam, but its transverse emittance is reduced. A Neutrino Factory requires its large transverse emittance of $\varepsilon_N \approx 12 - 20$ mm.rad to be reduced to 2 – 5 mm.rad. These beams also possess a large momentum spread ≈ 20 MeV/c about a central momentum of 200 MeV/c. A Muon Collider would require more cooling.

MICE will measure the efficiency of one "SFOFO" lattice cell (Figure 1) based on the cooling channel design of the Neutrino Factory Feasibility Study [2], a superconducting lattice with a large momentum acceptance about 200 MeV/c. The lattice cell consists of two "focus" coil pairs that focus the beam onto low-Z absorbers, and two "coupling" coils surrounding two sets of four 200 MHz cavities. Single-particle measurements are necessary to explore the performance of the cooling channel as the expected reduction in emittance is $\approx 10\%$. Therefore, measurements of the beam before and after the cooling channel will be made with two scintillating fibre trackers contained in two superconducting solenoids known as the "spectrometer solenoids". Particle identification is provided by Cherenkov and time-of-flight (TOF) detectors, which also allow the muons to be timed with respect to the RF phase.

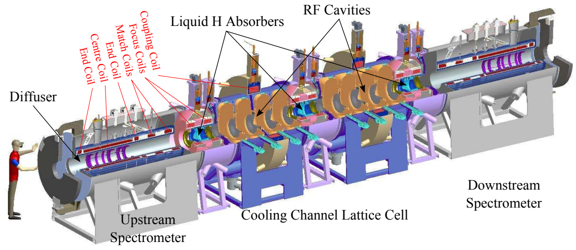

FIGURE 1. The MICE cooling channel lattice and detectors.

A realistic demonstration of cooling requires beams that closely resemble those expected at the front-end of a Neutrino Factory. These beams should cover a wide range of emittance so that ionisation cooling can be fully explored and understood. In MICE, the emittance range is obtained via a "diffuser", a variable thickness of high-Z material that can be inserted into the beam path upstream of the cooling channel. As cooling is a momentum-dependent process, it must be demonstrated over a range of beam momenta. MICE will demonstrate the cooling of 140 – 240 MeV/c beams with large momentum spreads using a selection of low-Z absorbers, including liquid hydrogen.

THE MICE BEAM LINE

Figure 2 shows the MICE beam line [3]. Muons are created and transported through a quadrupole triplet, Q4–6, and are incident on a TOF station (TOF0) and two Cherenkov detectors. The final quadrupole triplet, Q7–9, transports the beam to another TOF station (TOF1). In later steps of MICE the diffuser and cooling channel will immediately follow TOF1.

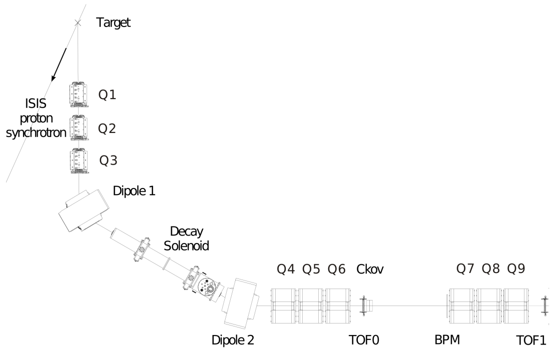

FIGURE 2. The MICE muon beam line.

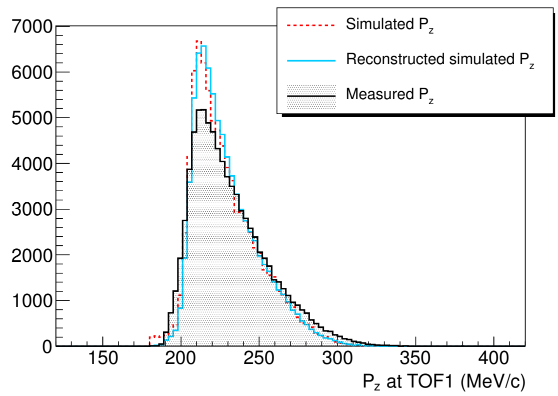

FIGURE 3. Longitudinal momentum, p_z, in simulation (red), reconstructed simulation (blue), and data (black) for a μ^- beam.

The TOFs [4] consist of two perpendicular planes of 1 inch thick scintillating slabs coupled to photomultiplier tubes. Their timing resolutions are $\sigma_{t0} = 51$ ps and $\sigma_{t1} = 59.5$ ps for TOF0 and TOF1 respectively. The difference in arrival times of light at the end of each slab are used to obtain transverse position measurements with resolutions of $\sigma_{x0} = 9.8$ mm at TOF0 and $\sigma_{x1} = 11.4$ mm at TOF1 [5].

The initial beam line design used TURTLE [6], assuming a 1 cm thick lead diffuser. Further beam line settings were obtained by scaling the magnet currents of the baseline case. These settings will transport muons of correct momenta to the cooling channel, but are not necessarily well-matched since the diffuser introduces large amounts of scattering into the beam and changes its optical parameters. As the β-function decreases by the same ratio as emittance increases, the final optics and diffuser thickness require knowledge of the inherent emittance of the input beams.

Data were taken during Step I of MICE to verify simulations and determine the characteristics of the muon beam, particularly its momentum distribution and emittance. Only the TOF stations, TOF0 and TOF1, were used for the measurement at this stage.

CHARACTERISATION OF THE MICE BEAMS

The beam line produces beams with large momentum spreads, and there is no single transfer matrix that applies to the entire beam. A new emittance measurement technique was developed to characterise each beam using single-particle measurements in the two TOF stations and tracking through the Q7–9 quadrupole triplet [5].

An initial estimate of p_z is made, assuming the muon travels on-axis between TOF0 and TOF1. The transfer matrix for the momentum estimate is calculated, and the trace-space vectors at each station can be determined from the position measurements by rearrangement of the transport equations:

$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix},$$

i.e. in the horizontal plane,

$$\begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}, \qquad (1)$$

where (x_0, x_0') and (x_1, x_1') are the trace-space vectors at TOF0 and TOF1 respectively. A new estimate of the muon momentum can be made along with corrections to its path through Q7–9, producing a further improved estimate of the trace-space vectors. This process is repeated several times, leading to measurement of the momentum distributions and trace-space covariance matrices, $\Sigma_{x,y}$ at the upstream side of TOF1 for each muon beam.

The efficiency of the reconstruction algorithm was determined by a Monte Carlo simulation. G4Beamline [7] tracked particles from the target to TOF0, then G4MICE [5] was used to track muons between TOF0 and TOF1. All simulations contained descriptions of beam line elements and materials, and the reconstruction smeared the simulated times and positions according to detector resolutions.

Figure 3 shows the agreement between measured and simulated momenta. The measured momentum distribution is shown in black (shaded). All distributions agree well in both shape and width, although the μ^+ distributions have a broader momentum spread due to the additional proton absorber in the beam path.

Figures 4 and 5 compare the trace-space distributions between simulation (left), reconstructed simulation (middle), and measured data (right). The effect of smearing is apparent in reconstructed trace-space, however, the

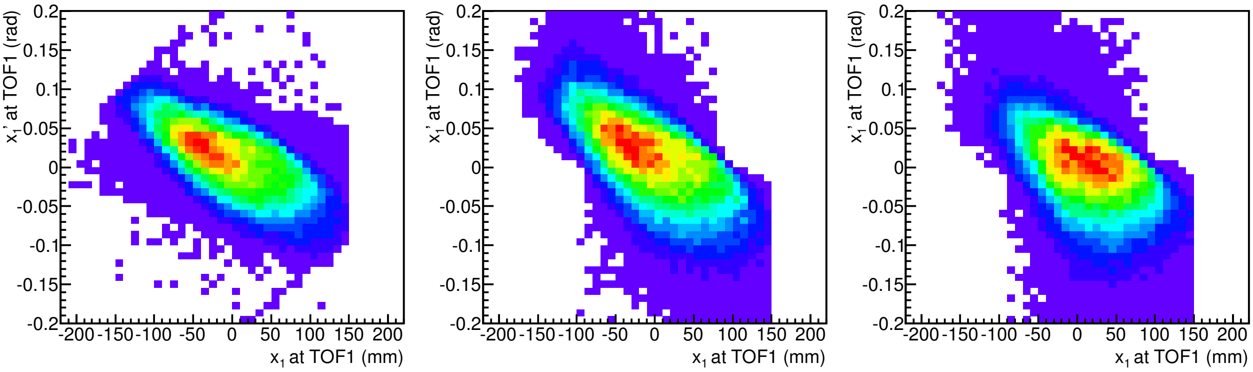

FIGURE 4. Horizontal trace space as measured at TOF1: (left) Simulation, (middle) reconstructed simulation, (right) data.

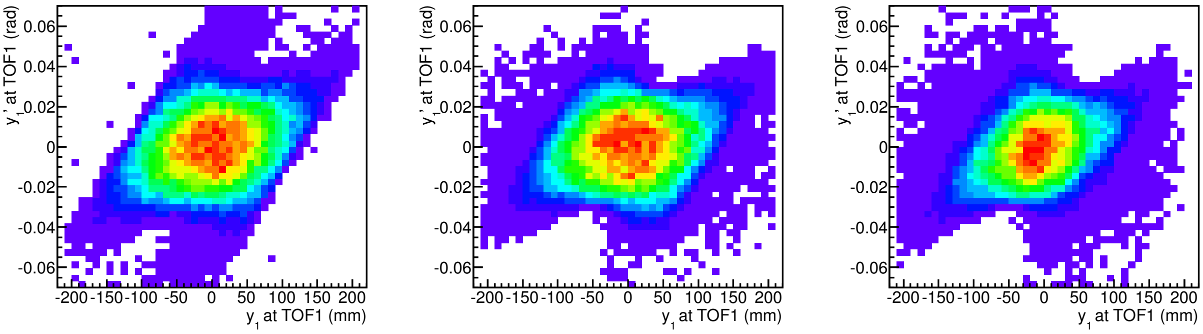

FIGURE 5. Vertical trace space as measured at TOF1: (left) Simulation, (middle) reconstructed simulation, (right) data.

simulations reproduce many of the characteristics of the measured beam. The boundaries of the distributions represent the quadrupole apertures translated to TOF1.

The amplitude of a muon can be expressed in terms of χ^2, where

$$\chi^2 = \begin{pmatrix} x-\bar{x} \\ x'-\bar{x'} \end{pmatrix} \Sigma_x^{-1} (x-\bar{x}, x'-\bar{x'}) = \frac{A_x}{\varepsilon_x},$$

A_x is the amplitude of the muon and $\varepsilon_x = \det \Sigma_x$ is the emittance of the beam. The χ^2 distribution is demonstrated in Figure 6, where the values for data (black, shaded) and reconstructed simulation (blue) are compared. The beam has a quasi-Gaussian core and non-Gaussian tail. High amplitude muons are outside the acceptance of the cooling channel; these were removed from further analysis by applying a cut at $\chi^2 = 10$.

Optical functions and emittances were determined from the covariance matrices as

$$\varepsilon_x = \det \Sigma_x$$

$$\beta_x = \frac{\Sigma_{x,11}}{\varepsilon_x}$$

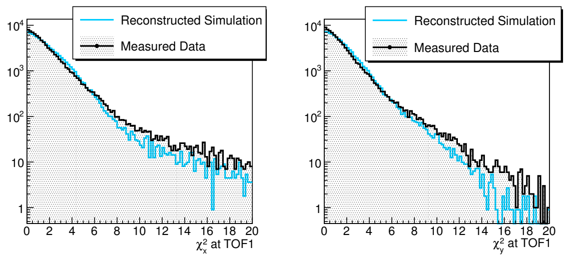

FIGURE 6. χ^2 distributions in x (left) and y (right). Measured data in black (shaded), reconstructed simulation in blue.

$$\alpha_x = -\frac{\Sigma_{x,12}}{\varepsilon_x}$$

and similarly for y. However, the beams have a large momentum spread and simulations show that α and β vary with momentum across the whole beam. The measured optical parameters are, therefore, effective parameters that describe the distributions in trace-space. Figures 7 and 8 compare the measured rms-emittance, in x and y respectively, to the available simulations. The agreement is good in the horizontal plane, but the measured verti-

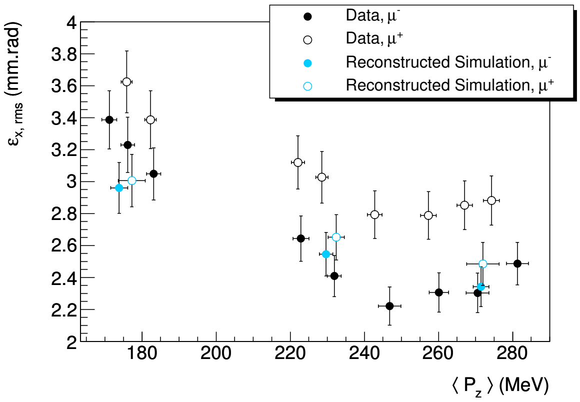

FIGURE 7. Emittance versus p_z at TOF1 for (black) data and (blue) reconstructed simulation in the horizontal plane.

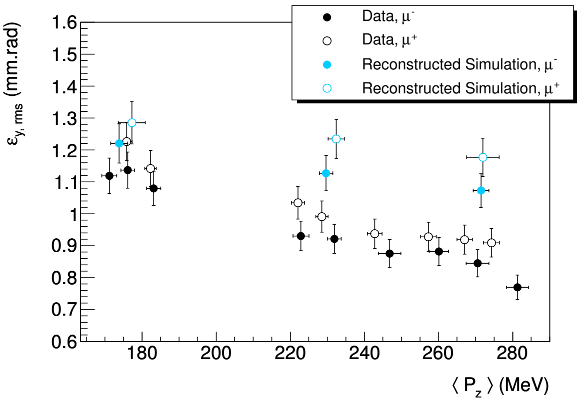

FIGURE 8. Emittanceversus p_z at TOF1 for (black) data and (blue) reconstructed simulation in the vertical plane.

cal emittance is consistently smaller at higher momenta, possibly due to scraping in the final quadrupole triplet.

SUMMARY

A single-particle method using two TOF detectors has been demonstrated to measure the properties of the MICE muon beams. Momentum measurements using this technique will be complementary to measurements using the spectrometer solenoids. Trace-space distributions at the entrance to MICE were also determined, and emittances of ≈ 2 to 4 mm.rad horizontally and 0.8 to 1.2 mm.rad vertically were measured.

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