

MICE STEP I: FIRST MEASUREMENT OF EMITTANCE WITH PARTICLE PHYSICS DETECTORS*

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Abstract

The Muon Ionization Cooling Experiment (MICE) is a strategic R&D project aiming to demonstrate the only practical solution to prepare high brilliance beams necessary for a Neutrino Factory or Muon Collider. MICE is under development at the Rutherford Appleton Laboratory (UK). It presently comprises a dedicated beam line to generate a range of input emittance and momentum, with particle identification detectors (PID) to ensure a pure muon beam. In 2010, the beam line and detectors were fully commissioned and a first measurement of the emittance of a MICE muon beam with particle physics detectors was performed. This measurement is described, and the next steps of precise measurements of emittance and cooling are outlined.

INTRODUCTION

Next-generation intense muon beam accelerators such as the Neutrino Factory and Muon Collider [1] promise very rich programs of physics. The decay of muons in a storage ring produces a well-understood beam of ν_μ and $\bar{\nu}_e$, making a Neutrino Factory the ideal facility to measure the neutrino mass hierarchy and leptonic CP violation. A Muon Collider ($\mu^+\mu^-$) provides the route to multi-TeV lepton – anti-lepton collisions as well as to precision studies of the Higgs Boson. Both facilities are complex, share many technologies, and create muons from pion decay. This produces large initial muon beam emittance (ϵ) that, to varying degrees, necessitates cooling in order to accomplish the desired brightness.

Traditional beam cooling techniques fail due to the 2.2 μsec muon lifetime. This led to the development of ionization cooling which rapidly cools the muon beam by passing it through low Z absorbers alternating with accelerating radio frequency (RF) cavities. The beam loses longitudinal and transverse momentum in the absorbers, and regains the longitudinal component of the momentum in the RF cavities. As a result, the transverse emittance is reduced and the beam is cooled.

The goal of the Muon Ionization Cooling Experiment (MICE) is the construction, commissioning, and performance evaluation of a cell of the ionization cooling channel designed in Feasibility Study-II [2]. The cooling cell, made of three liquid hydrogen absorbers and two sets of 201 MHz RF cavities, is designed to produce a 10% reduction in transverse emittance for beams with momentum of 140 – 240 MeV/c and incoming emittance of 3–10 mm. Each muon will be precisely tracked by a scintillating fiber tracking spectrometer [3], both

upstream and downstream of the cooling cell. The beam emittance can then be reconstructed from a large sample

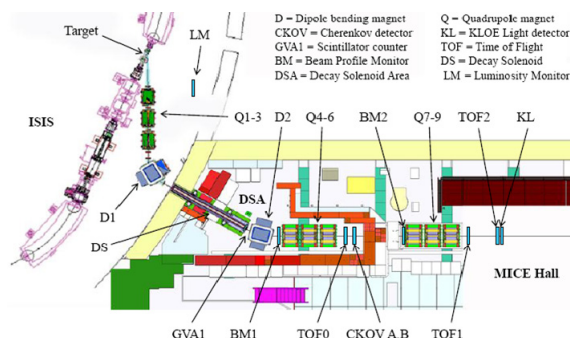


Figure 1: Schematic of MICE Step I beam line.

of particles and its reduction measured to 1%, thus demonstrating the feasibility of ionization cooling.

MICE STEP I

During 2010, Step I of MICE was completed. Goals for this stage of the experiment included calibrating the beam line detectors, understanding the beam, and preparing for future Steps with cooling. MICE will test cooling for a matrix of nine beam configurations, ie. optics points, each defined by its normalized emittance (ϵ_n) and longitudinal momentum (see Table 1). For clarity, the emittance which defines the beam is that found in the middle of the central absorber in the full MICE cooling cell. Muon beams (μ^+ or μ^-) for each point were reproducibly generated, and the beam line (see Fig. 1) and detectors were commissioned.

Table 1: MICE muon beam configurations (ϵ_n , p_z) with different emittance (mm) and momentum (MeV/c) values. The baseline beam is the central (6, 200) value.

3, 140	3, 200	3, 240
6, 140	6, 200	6, 240
10, 140	10, 200	10, 240

While muon beams are the main focus of MICE, pion (π^+, π^-) and electron (e^+/e^-) beams can also be produced. These were used to commission the three Time-of-Flight (TOF) detectors, two threshold Cerenkovs, and the Kloe-Light preshower detector. An intense data-taking campaign collected over 10^6 triggers, accomplished the Step I goals, and provided a wealth of data for studies.

EMITTANCE MEASUREMENT

The Step I data is being used to fully understand the MICE muon beam. Many analyses have been done on the

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data to study beam composition, muon rates, and data quality. In addition, it proved possible to use the TOF detector system to make a preliminary measurement of emittance for the MICE muon beams.

The following preliminary approach to the MICE novel single-particle, muon-by-muon, method of emittance measurement was developed [4] and its results compared with simulation:

- Measure x , y , and t at the first two TOF stations (TOF0, TOF1).
- Identify muons using the time-of-flight.
- Use momentum-dependent transfer matrices to map the particle motion from TOF0 to TOF1.
- Make initial estimate of path length and longitudinal momentum (p_z). Use p_z and transfer map to improve path length estimate, and recalculate p_z . Iterate until it converges.
- Determine trace space (x , $x' = p_x/p_z$) and (y , $y' = p_y/p_z$) at TOF0 and TOF1.
- Calculate beam emittances.

Under normal circumstances, emittance would be determined using RMS beam size from three beam profile measurements. Since the transfer matrix is momentum-dependent, ($M_{ij} = M_{ij}(p_z)$), this is not possible in MICE where there is a large spread in p_z , approximately 100 MeV/c for a 250 MeV/c muon beam.

TOF Detectors

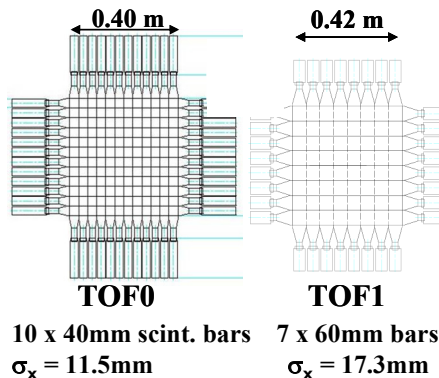


Figure 2: Schematic of TOF detectors showing the size and segmentation of the first two detectors.

The TOF detector system is designed to provide time-of-flight information which distinguishes muons from electrons and pions in the MICE beam. It is composed of three detectors (TOF0, TOF1, and TOF2), each with two orthogonal layers of scintillator bars (see Fig. 2). These detectors were commissioned during Step I data-taking, and have excellent timing resolutions of 51, 58, and 52 ps [5], respectively. For the ϵ measurement, a sample of good muons was selected using timing information from TOF0 and TOF1. Figure 3 shows the time-of-flight for a baseline μ^+ beam with the electron peak easily distinguishable from the muons in the larger, broad peak. A small pion contamination, $< 1\%$ as indicated by G4Beamline [6] simulations, is also present.

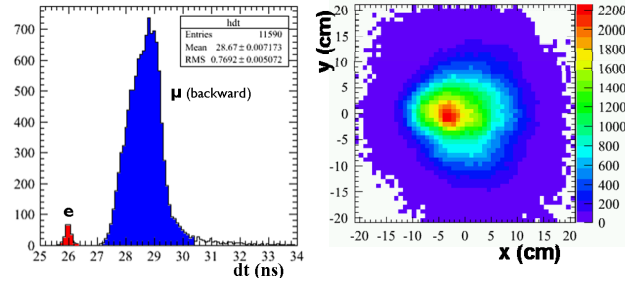


Figure 3: Time-of-flight profile of the (6,200) MICE μ^+ in the baseline muon μ^- beam with improved position resolution in TOF1.

In addition to time-of-flight, the precise timing information from the photo-multiplier (PMT) signals on both ends of each scintillating bar also provides excellent spatial resolution (~ 10 mm), much better than the segmentation of the bars themselves (see Fig. 4).

The TOF0 and TOF1 detectors provide the desired position and time information for each muon, thus completing the first two steps in the ϵ measurement.

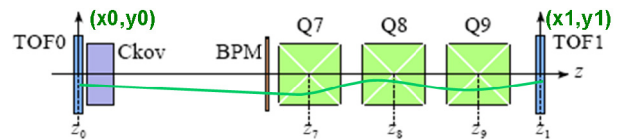


Figure 5: Muon path from TOF0 to TOF1 through drift spaces and quadrupole triplet.

Muon Path and Longitudinal Momentum

Once the initial and final particle positions are known, the muon path through the beam line is estimated. Each muon must traverse the CKOV detectors, several drift spaces, and the last quadrupole triplet in the MICE beam line while travelling the 7.71 m between TOF0 and TOF1 (see Fig 5).

$$\begin{pmatrix} x_1 \\ x'_1 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \quad (1)$$

A product of momentum-dependent transfer matrices (see Eq. 1), are used to map the particle motion through the drift spaces and quadrupole magnets. This is an iterative process where the first path estimate (s) is assumed to be a straight line. The muon momentum is estimated ($p_z/E = s/\Delta t$), the transfer matrix calculated, the particle tracked through each drift space and magnet using a thick edge quadrupole model, the change in path is found, and p_z is recalculated. This process is repeated until it converges. G4Beamline simulations show that ~ 5 iterations typically produce the true longitudinal momentum, and are also used to study scattering in material and detector effects.

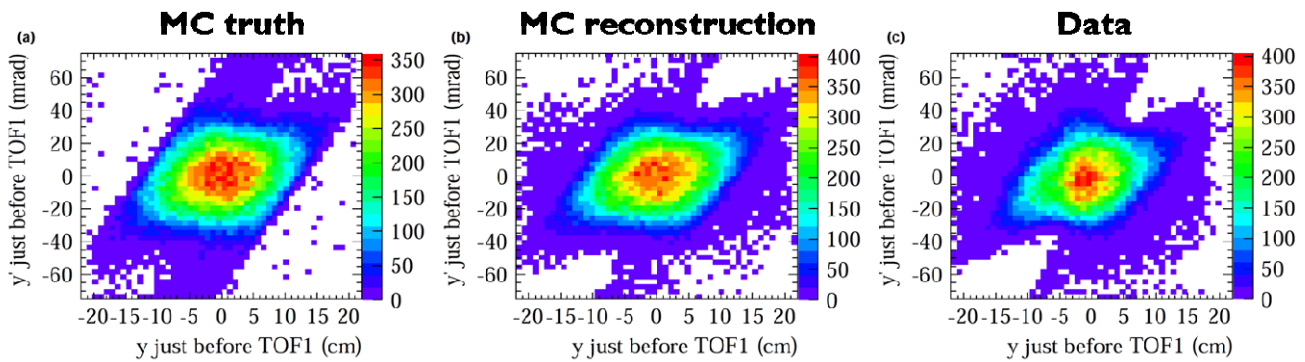


Figure 6: Vertical transverse trace space is shown for a baseline (6 mm, 200 MeV/c) μ^- beam configuration. All beam parameters are calculated at the upstream face of the TOF1 detector. Panel (a) shows simulation truth, (b) shows reconstructed simulation, and (c) shows reconstructed MICE beam data.

Trace Space and Emittance Calculation

Once the true p_z and appropriate transfer matrix $M(p_z)$ are known, and given that the $\det M \equiv 1$ for conservative systems, Equation 1 can be manipulated to give Equation 2. The phase space angles (x' and y') can then be deduced from the initial and final muon positions, the horizontal and vertical trace space (x, x') or (y, y') distributions can be plotted, and the transverse beam emittances (ϵ_x, ϵ_y) can be calculated.

$$\begin{pmatrix} x'_0 \\ x'_1 \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} \quad (2)$$

Figure 6 shows the vertical trace space (y, y') for the baseline (6 mm, 200 MeV/c) μ^- beam calculated for both data and Monte Carlo (MC) simulation. When comparing reconstructed MC with truth, it is clear that the reconstruction method skews the true distribution on the edges of the beam where nonlinear effects are non-negligible. The distribution in data is similar to that in simulation, and displays the same skewed shape for high amplitude particles. The RMS x and y emittances measured at TOF1 for this beam are $\epsilon_x = 2.94$ mm and $\epsilon_y = 1.15$ mm. The transverse normalised emittance is then given approximately by $\epsilon_n \approx (p_z/m_\mu) \sqrt{\epsilon_x \epsilon_y}$.

This emittance measurement technique was applied to all of the MICE muon (μ^+ and μ^-) beam configurations. However, the (3 mm, 140 MeV/c) matrix element did not have a large enough muon sample to give an unambiguous result, and will be re-run at a later date.

Future Emittance Measurements in MICE

This first measurement of emittance in MICE is only the beginning. Next, the two tracking spectrometers will be installed in the MICE beam line on either side of the cooling station, which will in turn evolve from a single absorber into a full cooling cell. Each 1.1m long tracker has five stations with three planes of 350 μm fibers, and will rest inside a 4T superconducting solenoid magnet. The trackers have taken cosmic ray data, have a measured

track residual of 661 ± 2 μm with 470 μm space point resolution, and will measure the x and y momentum of each particle to < 2 MeV/c. They will precisely measure x, x', y, y' , and p_z for each particle and will measure beam emittance into and out of the MICE cooling station.

CONCLUSIONS

In an important step toward the demonstration of ionization cooling technology, the MICE muon beam line has been successfully commissioned. In addition, the first measurements of the muon beam emittance have been made for all (ϵ_n, p_z) beam settings with a technique uniquely developed for MICE using the TOF detector system. Soon, the next steps will begin, starting with a high precision 0.1% beam emittance measurement using the trackers, followed by a measurement of the cooling effect of the absorber, and ultimately, with RF stations in place, the final 1% measurement of the full sustainable cooling performance of the Study II cell.

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