MICE Step 1: First measurements of emittance using particle physics detectors

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Abstract. The muon ionization cooling experiment (MICE) is a strategic R&D project intended to demonstrate the only practical solution to prepare high brilliance beams necessary for a neutrino factory or muon colliders. MICE is under development at the Rutherford Appleton Laboratory (UK). It comprises a dedicated beam line to generate a range of input emittance and momentum, with time-of-flight and Cherenkov detectors to ensure a pure muon beam. The emittance of the incoming beam is measured in the upstream magnetic spectrometer with a fibre tracker. A cooling cell will then follow, alternating energy loss in LH_2 absorbers and RF acceleration. A second spectrometer identical to the first and a second muon identification system measure the outgoing emittance. In the 2010 run the beam and most detectors have been fully commissioned and a first measurement of the emittance of a beam with particle physics (time-of-flight) detectors has been performed. The next steps of more precise measurements, of emittance and emittance reduction (cooling), that will follow in 2011 and later, will also be outlined.

Introduction

In order for a muon beam produced by the target of a neutrino factory to meet the downstream acceptance of the accelerator chain it must undergo a reduction in its emittance. Current methods of emittance reduction, or cooling, are too slow given the short lifetime of the muon. A new method is proposed in ionisation cooling [1]. An absorber material is used to reduce the total momentum of a muon, maximising energy loss against multiple scattering, and RF cavities restore momentum longitudinally. The net loss of transverse momentum results in a reduction in the transverse emittance.

MICE

The Muon Ionisation Cooling Experiment (MICE) [2] based at the Rutherford Appleton Laboratory (UK), aims to demonstrate ionisation cooling with a 10 % reduction in transverse emittance measured to within 1 %. A mechanical target dips into the ISIS proton synchrotron producing pions which decay into muons in the MICE beamline, formed from nine quadrupoles, two dipoles and a superconducting solenoid. The emittance of the beam will then be deliberately inflated with a diffuser of varying thicknesses; MICE will in this way be able to measure the emittance reduction for various emittance and momentum beams, ranging from 3 to 10 mm transverse emittance and 140 MeV/c to 240 MeV/c momentum.

Two scintillating fibre trackers [3] placed within 4 T superconducting solenoids will make precision measurements of the position and momentum of each muon, allowing for a measurement of emittance based on an ensemble of single particles. Time of flight detectors provide an accurate timing measurement for use in particle identification based on the known momentum and time of flight between detectors. A calorimeter-like detector, the electron-muon ranger (EMR), will add sensitivity to muons which have decayed in the MICE beamline. An additional KLOE-like (KL) scintillating fibre detector is placed in front of the EMR. Currently, all three TOFs, KL, Cerenkov PID detectors and luminosity monitors are installed. The trackers are due to be installed in 2012.

The absorber material chosen in MICE is liquid hydrogen, and some solid absorbers such as lithium hydride are under consideration. The acceleration will be performed by 8 MV 201 MHz RF cavities. The arrangement of the detectors, absorbers and RF cavities is shown in Figure 1.

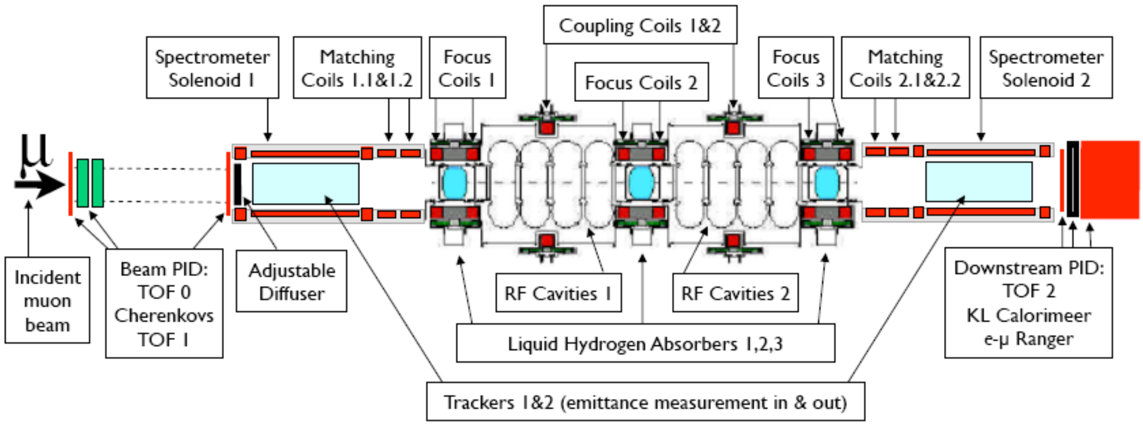

Figure 1. Layout of the Muon Ionisation Cooling Experiment, showing the full Step 6 MICE cooling channel.

Beam Rates

The rate of muon tracks seen in MICE is a consequence of the pions produced by the interactions of protons on the target. To maximise the muon rates the target would present maximum material to the proton beam. However, the resulting losses in the ISIS synchrotron are of concern, and so beam losses must be kept within set limits. A clear relationship has been shown [4] between the beam losses observed by ISIS and the number of tracks reconstructed as muons in the MICE hall. This is shown in Figure 2.

Time of Flight detectors

Three scintillating bar time of flight detectors with high time precision have been constructed for use in MICE [5]. The scintillating bars are arranged in an $x - y$ formation, with 10, 7 and 10 bars in each plane for TOFs 0, 1 and 2 respectively. The bars themselves are between 4 and 6 cm wide and approximately 2.5 cm thick. A calibration procedure accounting for time walk and other factors has produced a resolution of less than 60 ps for each time of flight detector. The resolutions are shown in Figure 3 and the individual resolutions are given in the caption. Using the $x - y$ geometry and the time difference measured between the photomultipliers at each end of the bars, a position measurement is also obtainable.

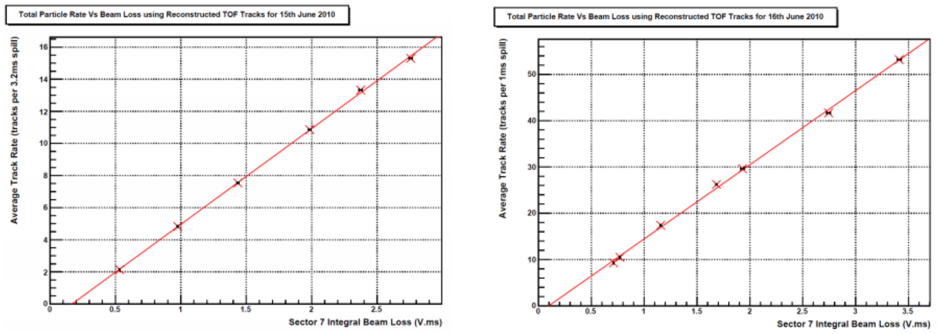

Figure 2. Reconstructed TOF tracks as a function of ISIS beam losses. Rates are shown for 1 ms (left) and 3.2 ms (right) spill gates.

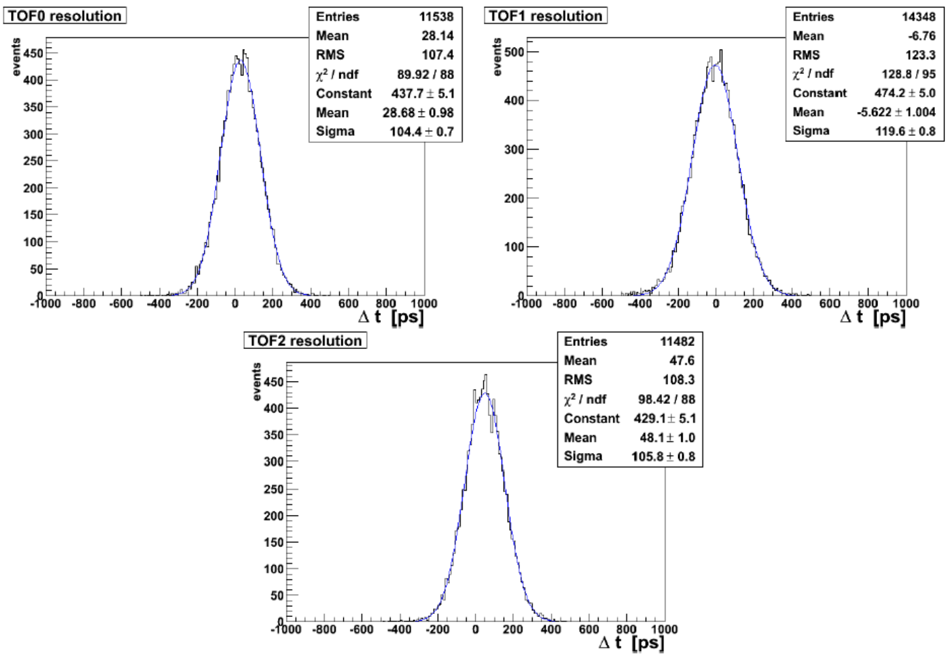

Figure 3. Timing resolution of the MICE time of flight detectors. Resolutions of 51 ps, 58 ps and 52 ps have been shown for TOFs 0, 1 and 2 respectively. The σ shown on the figures represents approximately twice the calibrated resolution, which is found from one plane only in each detector.

Measurements of emittance

Using the position and time information provided by the time of flight detectors, an iterative reconstruction method was developed [6] to calculate the single particle transfer matrix between two detectors, including the intervening quadrupole optics. In this manner, the optical functions of the beam were calculated. Based on an intensive period of running comprising Step 1 of MICE, the full range of operating modes, for both positive and negatively charged muons, were investigated. The reconstructed emittance and β functions for these modes are shown in Figure 4.

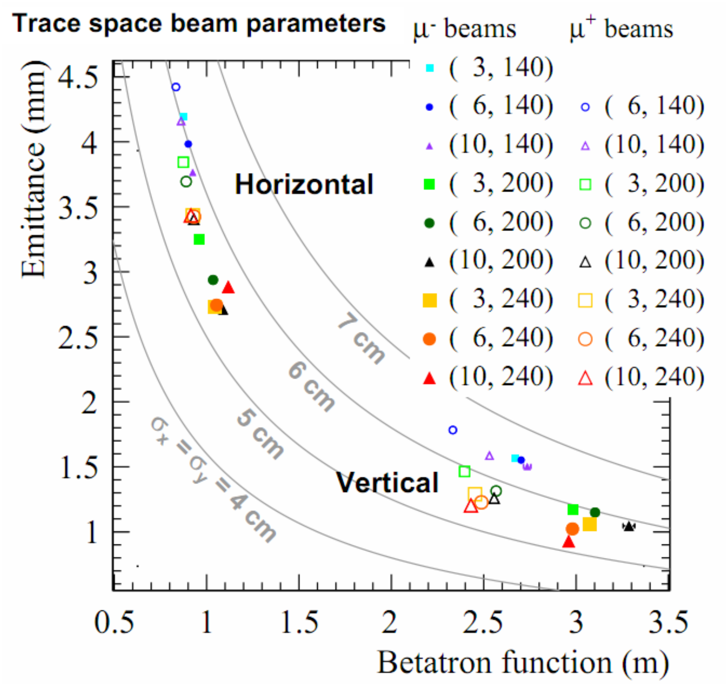

Figure 4. Reconstructed emittance (mm rad) and beta functions for the operating modes of MICE, including positive and negative polarity beamlines. The values in parentheses refer to the emittance (mm) and momentum (MeV/c) for which that beam is intended in the presence of the diffuser.

Conclusion

A run campaign during 2010, marking Step 1 of MICE, has provided data at each of the target operating modes for MICE. Using a new reconstruction method the emittance and betatron function of each of these beams has been calculated, although this measurement is preliminary based on the detectors available in the beamline. The full precision measurement of emittance will await the installation of the trackers. The MICE muon beamline has been commissioned, and the installed detectors shown to be operating to specification.

References

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