The performance of the MICE muon beam line

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Abstract. The *Muon Ionization Cooling Experiment* is one lattice cell of a cooling channel suitable for conditioning the muon beam at the front end of a Neutrino Factory or Muon Collider. The beam line designed to transport muons into MICE has been installed, and data was collected in 2010. In this paper the method of reconstructing longitudinal momentum and transverse trace space using two timing detectors is discussed, and a preliminary simulation of the performance of a measured beam in the cooling channel is presented.

Keywords: Ionization Cooling, Muon Beam, Transfer Lines, MICE
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INTRODUCTION

The *Muon Ionization Cooling Experiment* (MICE) collaboration is building a lattice cell of the cooling channel of Neutrino Factory Feasibility Study-II [1] at a muon beam line at the ISIS proton accelerator at the Rutherford Appleton Laboratory in the UK. In order to demonstrate cooling over a range of emittances and momenta, the beam line (Figure 1) must generate several matched beams with different optical parameters at TOF1.

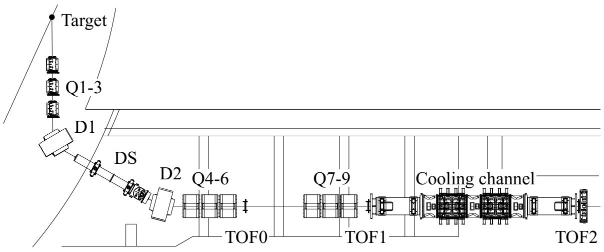

FIGURE 1. The MICE muon beam line. A titanium target intersects the ISIS proton beam, and dipole D1 selects and transports a beam predominantly composed of pions to the decay solenoid (DS). A muon beam is then selected by dipole D2 and transported into the cooling channel. Nine quadrupoles are tuned to generate a matched beam in the spectrometer solenoid at the beginning of the cooling channel. Timing detectors TOF0 and TOF1 are separated by 8 m.

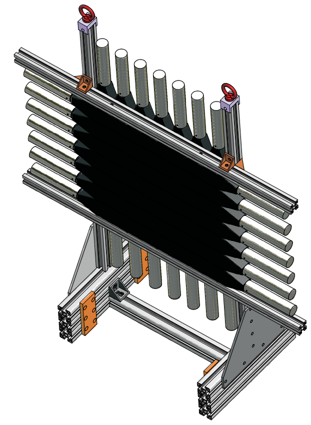

FIGURE 2. The design of the MICE timing detectors.

RECONSTRUCTION

Data from timing detectors TOF0 and T0F1 are used to analyze the performance of the MICE muon beam line. Both detectors are composed of two orthogonally oriented planes of scintillator slabs read out at each end by photomultiplier tubes (Figure 2), and measure time with resolution $\sigma_t = 50$ ps [2]. Particle species is determined by measuring the time of flight between TOF0 and TOF1. Longitudinal momentum may then be reconstructed using an iterative method. Figure 3 shows data for a baseline beam.[1] As the electron/positron peak is observed to be stable within 100 ps (Figure 4), systematic error is negligible, and p_z is measured with 5 MeV/c resolution and bias < 2 MeV/c at 250 MeV/c [3].

In order to evaluate the performance of the beam line the optical parameters of the beams are measured at TOF1. The transverse positions x and y are measured with resolution $2c_{\text{eff}}\sigma_t/\sqrt{2} \approx 1$ cm by the difference in arrival time of light signals in the photo-multiplier tubes

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[1] MICE uses beams with 140 MeV/c $< p_z <$ 240 MeV/c and 3 mm $<$ $\varepsilon_{\text{N}} <$ 10 mm. The baseline beam is designed to be composed of 200 MeV/c muons with normalized transverse emittance 6 mm after emittance inflation in the lead diffuser.

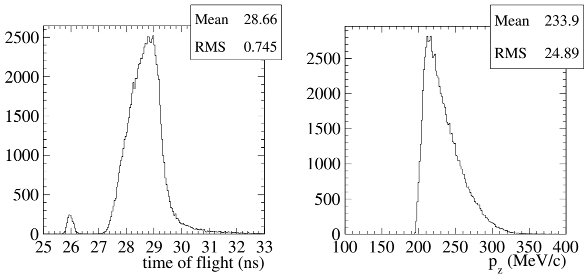

FIGURE 3. The time of flight between TOF0 and TOF1, and the longitudinal momentum of the muon component at TOF1 for a baseline MICE beam with negative polarity. The beam is dominated by muons, with a small electron component at 26 ns. A pion component would be expected at 31 ns.

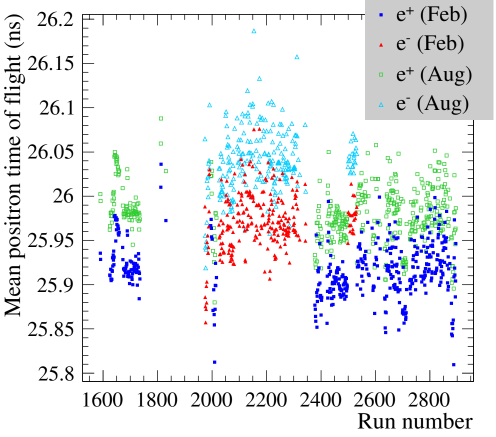

FIGURE 4. The mean position of the electron/positron peak in data sets from between May and August 2010 for independent detector calibrations performed in February and August of that year. The peak is expected to be stable as $v_z \approx c$. The former calibration is used in this paper.

at opposite ends of a scintillator slab, using an effective propogation speed $c_{\text{eff}} = 14$ cm/ns. In order to deduce the transverse momenta, consider that trace space vectors $(x, \mathrm{d}x/\mathrm{d}z)$ may be evolved from TOF0 to TOF1 using a product $\mathbf{M}(p_z)$ of transfer matrices through the drifts and quadrupole magnets lying between the two detectors. The angles x' and y' may then be deduced by noting that $\det(\mathbf{M}) = 1$:

$$\begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}.$$

The distribution of the baseline beam in trace space thereby deduced is shown in Figure 5. A comparison with simulation is in progress [4].

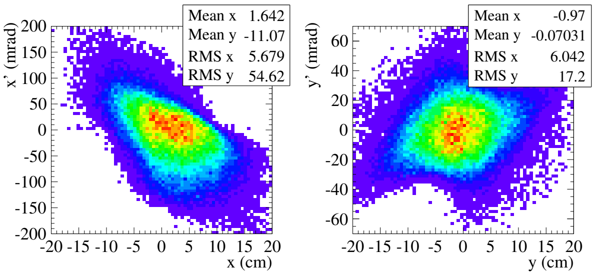

FIGURE 5. The reconstructed transverse trace space of the baseline beam at TOF1.

SIMULATION OF THE MEASURED BEAM IN MICE

A baseline beam, starting at TOF1 with the transverse distributions characteristic of the measured beam, was simulated passing through the MICE cooling channel lattice cell (Figure 6) using the G4MICE software package which includes all physics processes, in particular energy loss and scattering. The simulated beam was generated according to the measured covariance matrix of the four transverse phase space coordinates and therefore had the emittance and optical parameters of the real beam. A 7.5 mm thick lead diffuser was included to inflate the emittance to the nominal 6 mm.

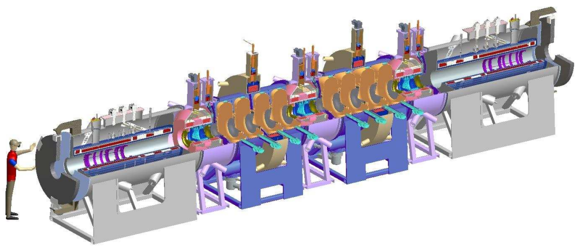

FIGURE 6. The MICE lattice cell and the upstream and downstream spectrometers. The emittance of a matched muon beam is reduced in three liquid hydrogen absorbers surrounded by focus coils, and lost longitudinal momentum is replaced by two quartets of RF cavities.

The evolution of the beta function of the simulated real beam in the cooling cell is shown in Figure 7. The optics of the beam are seen to be similar to the ideal optics derived from a matched numerical solution to the equation of motion. $\beta_\perp$ is minimum at the absorbers but some mismatch in the upstream spectrometer is evident.

Figure 8 shows the evolution of the emittance of the simulated real beam together with the evolution of the emittance of an ideal 6 mm beam launched in the spectrometer solenoid. The emittance of the simulated real beam is slightly higher than the nominal 6 mm but decreases as expected at the absorbers. The initial over-

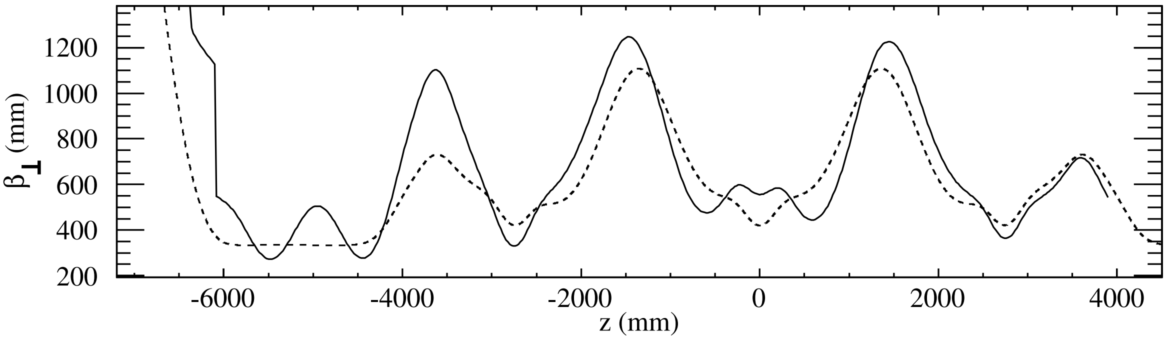

FIGURE 7. The baseline beam distribution measured in 2010 evolved through the final MICE lattice. The matched numerical solution to the equation of motion is shown dashed. The absorbers are located at $z = -2750$, 0, and 2750 mm. The uniform field region of the upstream spectrometer is between -5800 and -4500 mm, approximately.

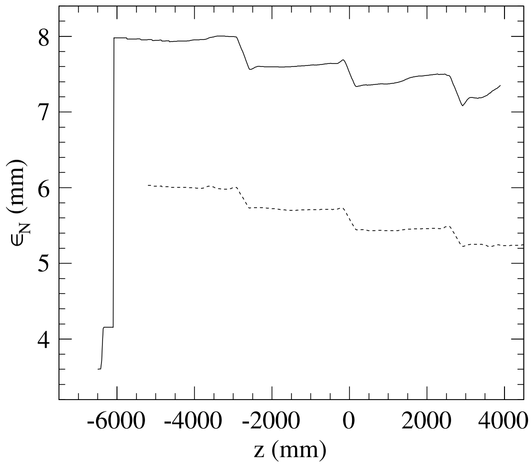

FIGURE 8. The baseline beam distribution measured in 2010 evolved through the final MICE lattice. The evolution of an ideal $\epsilon_N = 6$ mm beam is shown dashed.

inflation of the emittance to 8 instead of 6 mm may be corrected by the use of a thinner lead diffuser disc.

Despite no transverse selection or re-weighting having taken place, the optics of the beam behave tolerably well and the simulated real beam is seen to be cooled. It is anticipated that only a small re-weighting of the measured beam will be required.

CONCLUSION

The MICE collaboration intends to use beams with central momenta ranging from 140 MeV/c to 240 MeV/c, and normalized emittances between 3 and 10 mm. Several beams designed to have appropriate optical parameters were generated in a successful data taking campaign in 2010. Timing detectors of ~ 50 ps resolution confirm the generation of beams dominated by muons at the required momenta.

Distributions of the trace space vectors of individual muons have been reconstructed for the various beams, and promising agreement is observed with Geant4 simulations. The evolution through MICE of the optical parameters of a measured baseline beam has then been simulated; the beam is relatively well matched, and tuning magnet currents and diffuser thickness should be sufficient to generate a well matched beam. Work is currently under way to analyze the performance of measured beams over the full range of emittances and momenta, for beams of both polarities.

ACKNOWLEDGMENTS

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