MEASUREMENTS OF MUON BEAM PROPERTIES IN MICE

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Abstract

The *Muon Ionization Cooling Experiment* is one lattice section of a cooling channel suitable for conditioning the muon beam at the front end of a Neutrino Factory or Muon Collider. Scintillating fibre spectrometers and timing detectors provide a measurement of the six-dimensional phase space vectors of individual muons before and after cooling. Simulations based on measurements of the real muon beam show that it is well matched to the requirements of MICE.

INTRODUCTION

The *Muon Ionization Cooling Experiment* (MICE) collaboration is building a lattice element of the cooling channel of Neutrino Factory Feasibility Study-II [1] at the muon beam line of the ISIS proton accelerator at the Rutherford Appleton Laboratory in the UK.

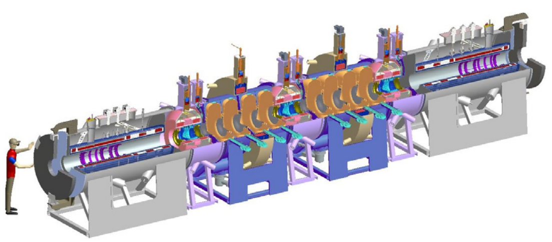

Figure 1: The MICE lattice cell and the upstream and downstream spectrometers.

MICE is designed to demonstrate that Ionization Cooling provides the emittance reduction required in a Neutrino Factory cooling channel. The analysis philosophy has three key features:

1. A fully engineered cooling channel lattice cell treated as a "black box";
2. An input muon beam with the transverse and longitudinal phase space distributions found along a Neutrino Factory cooling channel, and
3. The measurement of the phase space vectors of individual muons upstream and downstream of the lattice cell.

A previous paper by Rogers and Ellis [2] explained how measurements of the transverse phase space vectors $\vec{u}_\perp(z) = (x, p_x, y, p_y)$ of individual muons by the scintillating fibre trackers inside the upstream and downstream spectrometer solenoids may be used to measure the elements of the transverse covariance matrix of the beam. In this paper the first measurements of the new MICE muon beam are used to demonstrate that it is well matched to the requirements of MICE.

BEAM SELECTION

The MICE muon beam has been designed to approximately mimic the beam from the front end of a Neutrino Factory. It will however be necessary to increase the transverse emittance by scattering in a "diffuser" and to apply offline selections to generate the required longitudinal phase space distributions and transverse-longitudinal correlations. Some selection on transverse coordinates may be required to obtain an ideally matched beam.

The MICE beam line is a standard quadrupole focusing channel, however the MICE cooling channel uses a solenoidal lattice. Muons undergo decoupled oscillations in an analogous manner, but in the Larmor frame, precessing with angular frequency $\omega = \beta_z c\kappa = \beta_z cqB_{z0}/(2p_{z0})$ where κ is the focusing strength [3]. The transverse beta function defines the envelope within which the oscillations take place:

$$\beta_\perp = \frac{\left(\langle x^2\rangle + \langle y^2\rangle\right)\langle p_z\rangle}{2m_0 c\epsilon_N}. \tag{1}$$

It evolves according to the equation

$$2\beta_\perp\beta_\perp'' - (\beta_\perp')^2 + 4\beta_\perp^2\kappa^2 - 4 = 0. \tag{2}$$

In MICE the beam first encounters the uniform 4 Tesla field of the upstream spectrometer, where the transverse phase space vector is measured by reconstructing muons' helical paths through a scintillating fibre tracker. Matching coils then manipulate the focusing strength such that beam has the design beta function $\beta_\perp = 42$ cm in the first absorber focus coil [4]. The match condition $\beta_\perp' = 0$ in the upstream spectrometer is equivalent to the requirement $\beta_\perp\kappa = 1$. A mis-match may result in emittance growth, and a compromised measurement.

Beam re-weighting, may be required in the upstream spectrometer to select an appropriate "matched" beam which has the correlations between transverse phase space vector elements found in a Neutrino Factory lattice. The transverse tracker resolution of 0.4 mm and 1.1 MeV/c [6] will be more than sufficient to achieve this. Such a selection is consistent with treating the lattice cell as a "black box"; no such selection is made downstream [5].

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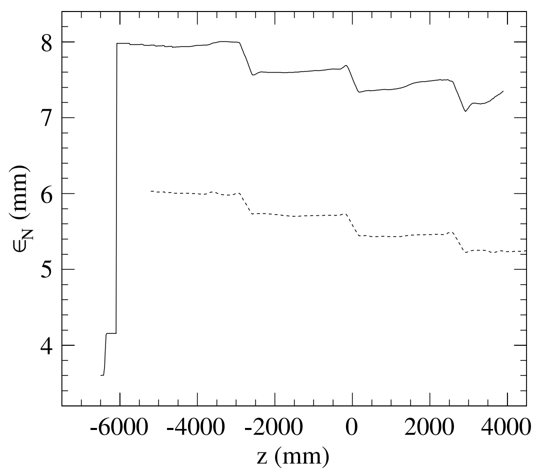

Figure 2: The beam distribution measured in December 2009 evolved through the final MICE lattice. The evolution of an ideal $\epsilon_N = 6$ mm beam is shown dashed.

SIMULATED REAL BEAM INTO SIMULATED MICE

MICE intends to use beams of momenta from 140 MeV/c to 240 MeV/c, and normalized emittances between 3 and 10 mm. In December 2009 the first measurements were made of the baseline $\epsilon_N = 6$ mm, $\langle p_z \rangle =$ 200 MeV/c input muon beam [7]. For this measurement, the MICE timing detectors, TOF0 and TOF1, which were the first detectors to be installed in the channel after the installation of the beam line, were used to measure the entire six-dimensional phase space of the upstream beam [8]. It is therefore possible to evaluate the performance of the beam line in generating a phase space distribution with the appropriate properties in the cooling channel.

A beam, starting at TOF1, with the transverse distributions characteristic of the measured beam was simulated 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.

The evolution of the beta function of the simulated real beam is shown in Figure 3. The optics of the beam are seen to be similar to the ideal optics derived from a numerical solution of Equation 2. $\beta_\perp$ is minimum at the absorbers but some mismatch in the upstream spectrometer is evident.

Figure 2 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-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

It has been demonstrated that the MICE muon beam line performs is well matched to the requirements of the experiment; it is expected that only a small amount of transverse beam selection will be necessary to obtain a well matched beam and observe cooling. Once longitudinally phased particles have been selected, it is anticipated that 100,000 muons will be required to make a 1% precision measurement of the fractional reduction in emittance of an $\epsilon_N = 6$ mm beam.

ACKNOWLEDGEMENTS

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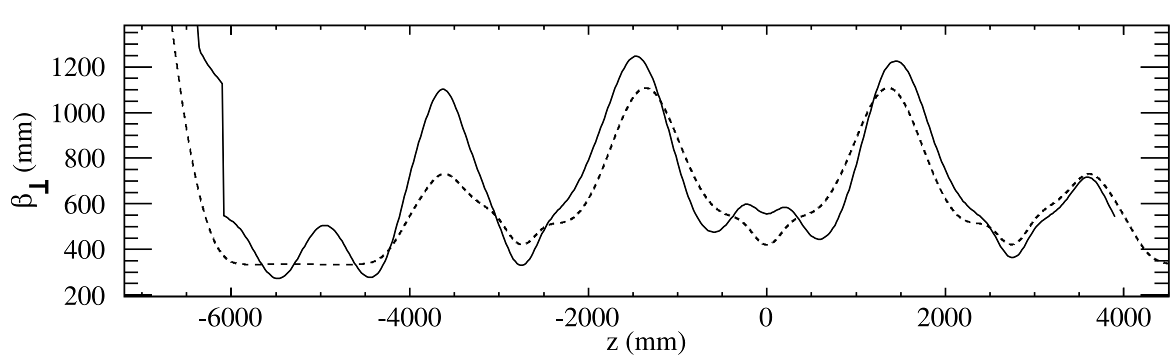

Figure 3: The beam distribution measured in December 2009 evolved through the final MICE lattice. The solution to Equation 2 is shown dashed. The absorbers are located at z =-2750, 0, and 2750 mm. The uniform field region of the upstream spectrometer is between -5800 and -4500 mm, approximately.

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