RESULTS FROM STEP I OF MICE AND PHYSICS PLAN FOR STEP IV

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on behalf of the MICE collaboration

Abstract

The Muon Ionisation Cooling Experiment (MICE) will demonstrate ionisation cooling, an essential technology for a Neutrino Factory and/or Muon Collider, by measuring a 10% reduction in emittance of a muon beam. A realistic demonstration requires beams closely resembling those expected at the front-end of a Neutrino Factory, *i.e.* with large transverse emittance and momentum spreads.

The MICE muon beam line at ISIS, Rutherford Appleton Laboratory, was built to provide beams of different momenta and emittance so that the performance of the cooling channel can be fully explored. During Step I of MICE, a novel technique based on time-of-flight counters was used to establish that the beam emittances are in the range 0.6–2.8 π mm-rad, with central momenta from 170–280 MeV/c, and momentum spreads of about 25 MeV/c.

The emittances of the beams will initially be increased by scattering in high-Z material. Low-Z absorbers, such as liquid hydrogen and LiH will be used to reduce the emittance of the beam. The physics program of Step IV of MICE is discussed, including all stages necessary for a first demonstration of ionisation cooling.

INTRODUCTION

Muons produced at the front-end of a Neutrino Factory occupy a large area of phase space, which must be reduced before they are stored and accelerated. For example, the Neutrino Factory requires a large transverse emittance beam of $\varepsilon_N \approx$12–20 π mm-rad to be reduced to 2–5 π mm-rad. Conventional cooling techniques are inapplicable to reducing the emittance of muon beams due to the short muon lifetime. A different technique is required to maximise the muon flux delivered to a storage ring.

Ionisation cooling is the only possible method of reducing the emittance of a muon beam. Muons pass through a low-Z material, losing energy by ionisation, which reduces their momentum components. They are then re-accelerated, which restores longitudinal momenta, resulting in a net reduction in the divergence of the beam and therefore the transverse emittance. The reduction in emittance, $\frac{d\varepsilon_N}{ds}$, is given by

$$\frac{d\varepsilon_N}{ds} = \frac{\varepsilon_N}{\beta^2 E_\mu}\left\langle\frac{dE}{ds}\right\rangle + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}, \quad (1)$$

where ε_N is the normalised transverse emittance, β the relativistic velocity, E_μ the energy, $\frac{dE}{ds}$ the energy lost by ionisation, m_μ the mass of the muon, X_0 the radiation length of the absorber material, and $\beta_\perp$ the transverse beta function.

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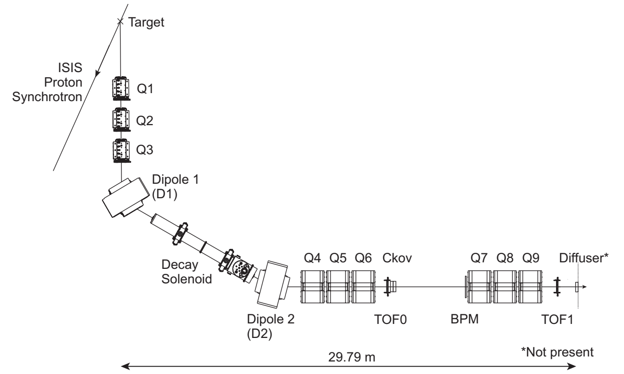

Figure 1: The MICE upstream beam line during Step I in 2010–11.

The first term describes "cooling" by ionisation, and the second describes "heating" by multiple scattering. Hence, a small $\beta_\perp$ and large X_0 are necessary features of an ionisation cooling channel.

The Muon Ionisation Cooling Experiment (MICE) will measure the cooling efficiency of one "SFOFO" lattice cell based on the cooling channel design of Neutrino Factory Feasibility Study 2 [1]. The cooling channel will accept beams with a momentum spread of $\approx$ 20 MeV/c about central momenta in the range 140–240 MeV/c, and transverse emittances of 3–10 π mm-rad. The beam will pass through a sequence of liquid hydrogen absorbers and RF cavities, contained within a solenoidal focussing channel, where its emittance is reduced by $\approx$ 10%. This reduction will be measured to 1% precision using single-particle measurements with scintillating fibre trackers inside a 4 T solenoid field (the "spectrometer solenoids"). Particle identification is provided upstream by threshold Cherenkov and time-of-flight (TOF) detectors, and by a pre-shower detector and muon ranger downstream.

CHARACTERISATION OF THE MICE BEAM LINE

A realistic demonstration of cooling requires beams resembling those expected at the front-end of a Neutrino Factory. The new muon beam line at the ISIS proton synchrotron, Rutherford Appleton Laboratory, has been designed to produce beams of variable emittance and momenta. The beam line is described in [2] and is shown in Figure 1. The ISIS proton beam is sampled by a titanium target, creating pions that are captured by the upstream quadrupoles (Q1–3). The pions are momentum-selected at the first dipole, D1, and transported to the Decay Solenoid which captures the decay muons.

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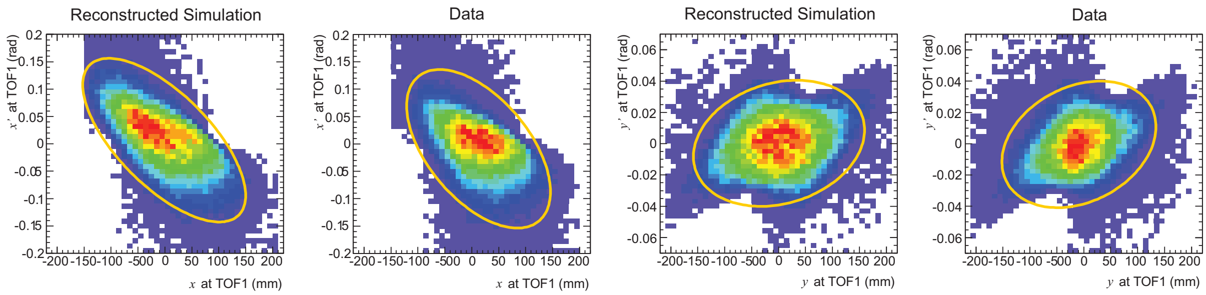

Figure 2: Reconstructed horizontal and vertical trace-space in simulation and data.

The second dipole, D2, can be tuned to select a high purity muon beam. Muons are transported through a final set of large aperture quadrupoles, Q4–9, to the cooling channel. The final component of the beam line is the "diffuser", a variable amount of high-Z material at the upstream end of the first spectrometer solenoid, which generates the full range of desired emittances. The diffuser was not present during Step I.

Particle identification is provided along the beam line by two aerogel Cherenkov detectors and a time-of-flight station (TOF0) after the Q4–6 triplet. A second time-of-flight station (TOF1) is located after the final Q7–9 triplet. Each TOF station consists of perpendicular planes of 25.4 mm thick scintillator slabs, where each end is coupled to a fast photomultiplier [2, 3]. The TOF0 and TOF1 detectors have measured timing resolutions of $\sigma_t = 55$ ps and $\sigma_t = 53$ ps respectively. Using the difference in arrival times of light at each end of a scintillating slab, transverse position resolutions of $\sigma_{x,y} = 9.8$ mm and $\sigma_{x,y} = 11.4$ mm, respectively, are achieved.

The beam line was commissioned during MICE Step I in 2010–11. Data were taken with TOF0 and TOF1 to determine the momentum distribution, emittance and dispersion of the beam line [4]. The trace-space covariance matrix, Σ, and the emittance, $\varepsilon = \sqrt{\det \Sigma}$, can be determined if the transfer matrices between the detectors is known. However, the beams have large momentum spreads and no single transfer matrix can be applied to the entire beam.

A method was developed [5] that first calculates an estimate of the muon momentum based on its time-of-flight. This gives the momentum-dependent transfer matrix, $M(p_z)$, for each muon. Using its known positions at TOF0 and TOF1, the trace-space angles, x'_0, y'_0, x'_1, y'_1, can be obtained by rearranging the transport equations,

$$\begin{pmatrix} x_1 \\ x'_1 \end{pmatrix} = M_x \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}, \tag{2}$$

i.e.,

$$\begin{pmatrix} x'_0 \\ x'_1 \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}. \tag{3}$$

The trace-space vectors, (x_0, x'_0, y_0, y'_0), are used to track the muon through the final Q7–9 triplet, leading to an improved estimate of its momentum. Iterating this procedure yields the final trace-space vector and momentum at TOF1. An example of the reconstructed horizontal and vertical trace space of one beam is shown in Figure 2, where the ellipse denotes an amplitude cut applied to the distributions prior to calculating the emittance of the beam.

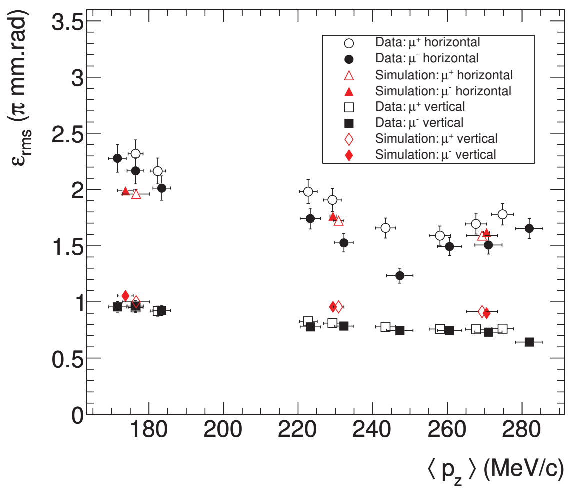

Figure 3: Horizontal and vertical RMS emittance in data and simulation.

Figure 3 shows the horizontal and vertical emittance of the 17 measured beams (black points) as determined from the reconstructed trace-space covariance matrices. Six simulated beams (red points) are also shown for comparison. The horizontal emittance of the beams is consistently larger than the vertical, forming two distinct bands. The positive muon beams have a higher emittance as they also pass through a polyethylene absorber designed to reduce the flux of protons on TOF0 in positive beam polarities. In general, the agreement between data and simulation is good, though the simulation overestimates the emittance in the vertical plane.

The beams characterised during Step I of MICE have effective emittances of 0.6–2.8 π mm-rad with central momenta of 170–280 MeV/c and momentum spreads of approximately 25 MeV/c. The horizontal and vertical beta functions lie in the range 1.49 m$< \beta_x < 2.22$ m and 3.07 m$< \beta_y < 3.81$ m. Dispersion is introduced at D2, which is transformed by the final beam optics into disper-

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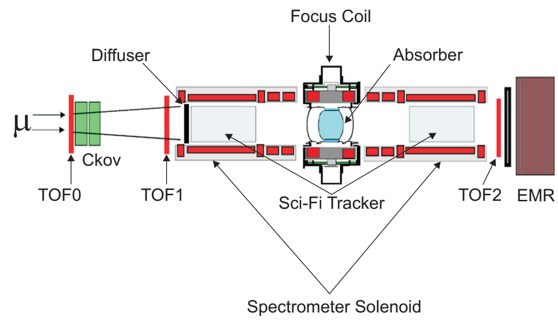

Figure 4: Schematic of MICE Step IV with the two spectrometer solenoids, diffuser, absorber and focus coil.

sion in x and x' at TOF1 of 90–189 mm and 0.03–0.11 rad respectively. Given these parameters, the beams are well suited for use in further steps of MICE.

PHYSICS PLAN FOR STEP IV

Step IV of MICE will use the above beams for the first demonstration of muon ionisation cooling without subsequent re-acceleration. A simplified cooling channel will be used, as shown in Figure 4, where spectrometer solenoids – containing scintillating fibre trackers – surround a low-Z absorber contained in a focusing solenoid ("focus coil"). The diffuser is located in the upstream section of the first spectrometer solenoid. The physics program, culminating in the ionisation cooling measurement, can be split into several stages.

The apparatus will be aligned according to the measured magnetic axes of the three solenoid magnets. The mechanical alignment of the channel will be understood by studying the zero-field case, *i.e.*, straight-line tracks through the scintillating fibre trackers and downstream particle identification detectors. The magnetic alignment of the channel will then be studied with the solenoidal field in its default configuration, generating helical tracks in the spectrometer solenoids that can be used for precise p_T measurements.

Once the magnetic alignment of the channel has been understood, matching the beam into the spectrometer solenoid will be explored. This requires scanning through the range of available momenta and fine-tuning the optics of the Q4–9 quadrupole triplets to present the best matched beam through the diffuser and into the first spectrometer solenoid. The transmission of the empty channel will be measured at various $\beta_\perp$. Repeating this with an absorber will demonstrate ionisation cooling.

The demonstration of muon ionisation cooling will be carried out with both a liquid hydrogen and solid LiH absorber (the proposed absorber for a Neutrino Factory cooling channel). The cooling performance of these materials will be studied at three nominal momenta, $p_z = 140, 200, 240$ MeV/c, three nominal emittances, $\varepsilon_N = 3, 6, 10\,\pi$ mm-rad, and beta functions, $\beta_\perp = 7, 15, 25$ and 42 cm. This allows for a full exploration of each material according to Equation 1 and the measurement of the "equilibrium emittance", where the reduction in emittance due to ionisation losses is equalled by the increase due to multiple scattering in the material. Direct measurements of multiple scattering are also possible. Other low-Z absorbers, such as aluminium or carbon, will be studied as well as a LiH "wedge" absorber that will exploit the dispersion in the muon beam to investigate emittance exchange and 6D cooling.

SUMMARY

The MICE muon beam has been characterised and found to have emittances in the range 0.6–2.8 π mm-rad with a momentum spread of $\approx$ 25 MeV/c and central momenta of 170–280 MeV/c. When used in combination with a diffuser, the beam line will generate beams similar to those of a Neutrino Factory, and therefore beams that are suitable for a demonstration of muon ionisation cooling. The physics program of Step IV of MICE has been outlined leading up to a first demonstration of muon ionisation cooling. Multiple scattering in low-Z materials will also be studied, along with a preliminary measurement of 6D cooling by exploiting the measured dispersion in the beam line.

REFERENCES

[1] S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo. Feasibility Study-II of a Muon-Based Neutrino Source. Technical report, 2001. BNL-52623.

[2] M. Bogomilov *et al.* The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment. *Journal of Instrumentation*, 7(5):05009, 2012.

[3] R. Bertoni *et al.* The design and commissioning of the MICE upstream time-of-flight system. *Nucl. Inst. Meth. A*, 615(1):14 – 26, 2010.

[4] The MICE Collaboration. Characterisation of the muon beams for the Muon Ionisation Cooling Experiment. *Submitted to Eur. Phys. J. C.*

[5] M. A. Rayner. PhD thesis, Oxford University, University of Oxford, Oxford, UK, 2011.

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