THE EXPECTED PERFORMANCE OF MICE STEP IV

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Abstract

The international Muon Ionization Cooling Experiment (MICE), under construction at the Rutherford Appleton Laboratory in Oxfordshire (UK), is a test of a prototype cooling channel for a future Neutrino Factory. The experiment aims to achieve, using liquid hydrogen absorbers, a 10% reduction in transverse emittance, measured to an accuracy of 1% by two scintillating fibre trackers within 4 T solenoid fields. Step IV of MICE will begin in 2012, producing the experiment's first cooling measurements. Step IV uses an absorber focus coil module, placed between the two trackers, to house liquid hydrogen or solid absorbers. The performance of Step IV using various absorber materials was simulated. Multiple scattering in high Z absorbers was found to mismatch the beam with the lattice optics, which was largely corrected by re-tuning the MICE lattice accordingly.

INTRODUCTION

The MICE Experiment [1] is a test of a prototype muon cooling channel. It is an integral part of the worldwide research effort towards building a Neutrino Factory, the basis for which is found in US Study 2 [2]. MICE uses three 35 cm liquid hydrogen (LH_2) absorbers to achieve a 10% reduction in emittance and eight 201 MHz RF cavities to re-accelerate the muon beam. Trackers within 4 T solenoids make single particle measurements at each end of the cooling channel. Each tracker consists of five scintillating-fibre planes, measuring x, y, p_x, p_y and E. A pair of match coils in each spectrometer tune the magnetic optics to match the muon beam into and out of the cooling lattice.

STEP IV

The first cooling measurements of MICE will be made in Step IV which is due to start in 2012. This will be the first experimental verification of the theoretical predictions of the cooling equation:

$$\frac{d\epsilon_n}{dz} = \frac{-\epsilon_n}{\beta^2 E}\left\langle\frac{dE}{dz}\right\rangle + \frac{\beta_\perp (14\,MeV)^2}{2\beta^3 E m_\mu X_0} \quad (1)$$

where β is the particle velocity, $\beta_\perp$ is the optical beta function, E the muon energy, X_0 the absorber radiation length, and <*dE*/*dz*> the mean energy loss rate. The first term represents cooling and the second heating due to multiple scattering which increases the emittance. No beam may be cooled to less than the equilibrium emittance ϵ_0 of a material for a given $\beta_\perp$ and momentum. In beams where $\epsilon_n < \epsilon_0$ multiple scattering dominates and heating occurs.

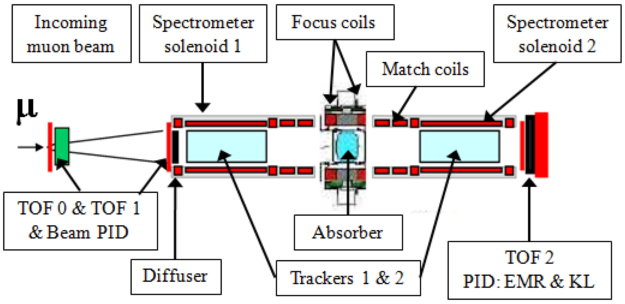

Figure 1: Step IV configuration of the MICE Experiment.

Figure 2: (*a*) 35 cm LH_2 absorber body and (*b*) the 63 mm LiH absorber .

Step IV involves an absorber focus coil (AFC) module between two spectrometer solenoids, as shown in Figure 1. Step IV will involve a broad study of different absorbers to measure their equilibrium emittances at different beam momenta, followed by a detailed study of one material. A list of absorber materials is given in Table 1, including lithium hydride (LiH) and LH_2 which are shown in Figure 2. The AFC module houses the absorber, a pair of focusing coils and the cryogenic system for the LH_2, and is shown in Figure 3a. The LH_2 absorber is currently undergoing testing at the KEK lab in Japan, as shown in Figure 3b. Absorber thicknesses Δx were selected to remove 10 MeV of energy from the beam.

Step IV was simulated using G4MICE [3], using beams of 10,000 muons, p_z = 207 MeV/c and σ_{p_z} = 1 MeV/c injected into the upstream spectrometer solenoid. Figure 4 shows the change in emittance in Step IV using input beams with normalized emittances of 3 mm, 6 mm and 10 mm, for six absorbers. Heating will be observed with

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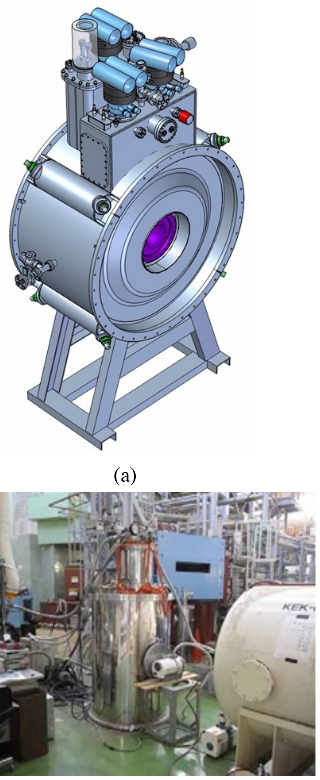
* on behalf of the MICE Collaboration


(a)

(b)

Figure 3: (*a*) CAD model of AFC module and (*b*) the LH_2 absorber being tested at KEK .

Table 1: Step IV is designed to study cooling in a range of different materials.

mat'l	X_0 [g cm^{-2}]	dE/dX [MeV g^{-1} cm^2]	ρ [g cm^{-3}]	Δx [cm]
LH_2	63.04	4.103	0.07	35
LiH	79.62	1.897	0.82	6.3
C	42.70	1.742	2.21	2.6
Al	24.01	1.615	2.70	2.3
Ti	16.16	1.477	4.54	1.5
Cu	12.86	1.403	8.96	0.8

the Cu and Ti absorbers, as MICE can only generate beams of up to ϵ=10 mm, which is below ϵ_0 for materials with Z > 13 at input p_z = 207 MeV/c and β = 42 cm at the absorber. In high Z materials large amounts of scattering will produce large increases in emittance and change the optical functions of the beam.

The baseline coil tuning was adapted from the final Step VI configuration, documented in [4], and does not allow for energy loss and scattering in the absorbers. The rms size σ_x^2 of a beam through a thin absorber is constant, and as a result:

$$\sigma_x^2 = \beta\epsilon = const, \tag{2}$$

$$\Longrightarrow \beta_2 = \frac{\beta_1 \epsilon_1}{\epsilon_2} \tag{3}$$

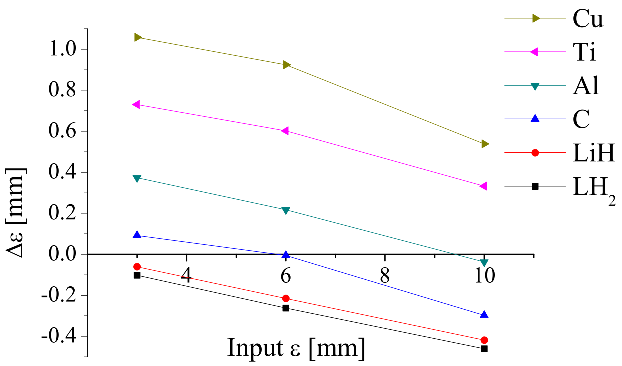


Figure 4: Change in emittance $\Delta\epsilon$ for Step IV using various absorbers, simulated in G4MICE with 10,000 muon events and σ_{p_z} = 1 MeV/c. "Input ϵ" denotes the nominal transverse emittance of the input beam.

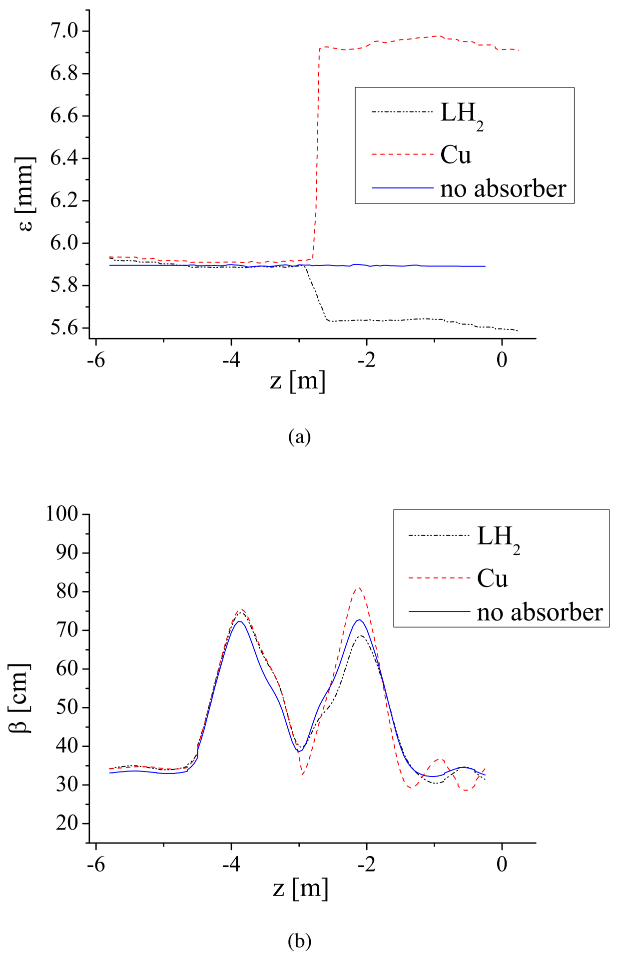
so there will be a sharp drop in β in the absorber. This causes the beam to be mismatched with the lattice optics downstream of the absorber and the beam envelope to fluctuate in size. Such mismatching could significantly hamper reconstruction performance in the downstream tracker and transmission through the channel. Figure 5 shows the change in emittance for three configurations of Step IV, and highlights the drop in β in the Cu absorber and mismatching downstream.

TUNING STEP IV

High Z absorbers clearly introduce mismatching between the beam and the magnetic optics. This can be corrected by first adjusting the upstream match coils to match the beam into the absorber (α=0), and then tuning the downstream match coils to achieve a flat beta function in the downstream tracker. MINUIT was used to find matched solutions in Step IV with Cu, for a 3 mm beam of p_z = 207 MeV/c on input. For each iteration of currents (M1, M2) the magnetic field on axis was recalculated using the standard expression for the field on the axis of a thin current carrying conductor, following the method described in [4]. The beta function was then evolved numerically for the given magnetic field using

$$\beta' = -2\alpha' - \frac{\beta^2 PD}{\epsilon_N 2 m_\mu c} \tag{4}$$

where *P* is the total momentum of the beam, *D* is the scattering term, ϵ_N the normalized emittance, m_μ the muon mass, and prime denotes differentiation with respect to z. Multiple scattering and energy loss were both considered, according to the Penn formalism [5]. The quality of the optics was calculated at the centre of the downstream spectrometer using the following function:



(a)

(b)

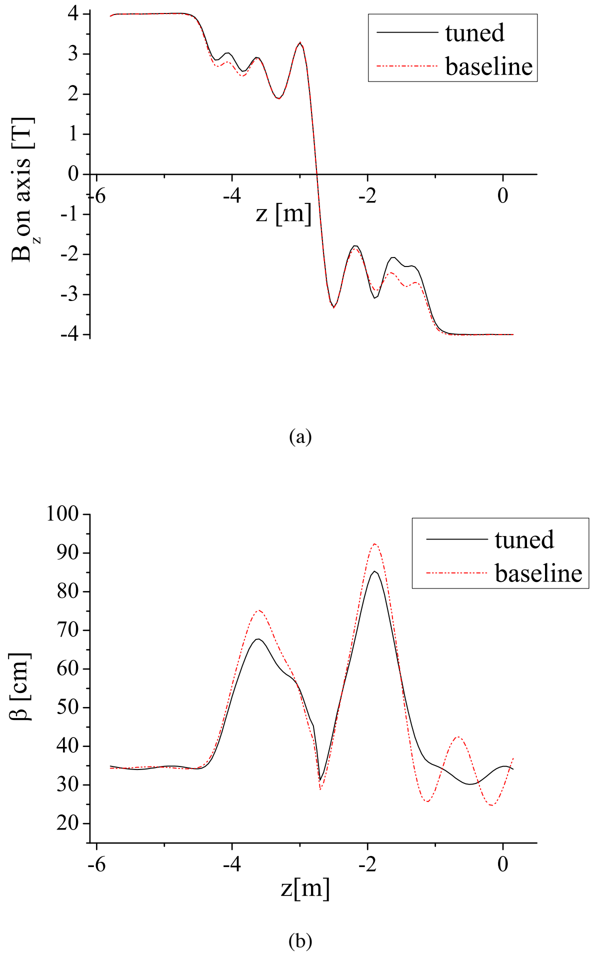
Figure 5: (*a*) Change in emittance and (*b*) beta function, for G4MICE simulations without material (p_z = 200 MeV/c), and with LH_2 & Cu absorbers (p_z = 207 MeV/c) centered at z=-2.75 m. A 3 mm emittance beam was used.

$$F \;=\; (\alpha - \alpha_0)^2 + (\beta - \beta_0)^2 \qquad (5)$$

where β_0 = 32.16 cm and $\alpha_0 = 0$. The new optics were simulated and significantly reduced mismatching downstream of the Cu absorber, shown in Figure 6. Further work remains to improve the optimization routine to tune the optics better and obtain a matched beam in the downstream spectrometer.

CONCLUSIONS

Step IV of MICE involves the first experimental verification of ionization cooling. It will make cooling measurements using LH_2 and solid absorbers including LiH. MICE will only be able to measure heating with the high Z Ti and Cu absorbers due to large multiple scattering. Simulations of Step IV using G4MICE have highlighted the need to retune the magnetic optics when using high Z absorbers to achieve a matched beam in the downstream spectrometer. An optimization procedure using MINUIT was used to find new operating currents for the match coils for a 3 mm beam through an 8 mm Cu absorber. The new optics appeared to significantly improve the quality of the match, but are not yet optimal and left room for improvement.



(a)

(b)

Figure 6: (*a*) Magnetic field on axis and (*b*) beta function using baseline and tuned Step IV optics, for a 3 mm emittance beam.

REFERENCES

[1] G. Gregoire et al., MICE Proposal, RAL (2004); http://www.mice.iit.edu/.

[2] S. Ozaki et al., BNL-52623, June 2001; M.M. Alsharo'a et al., Phys. Rev. ST Accel. Beams 6, 081001 (2003).

[3] Documentation on the G4MICE software suite is to be found at: http://mice.iit.edu/software/software.html.

[4] M. Apollonio & H. Witte, Optimizing the MICE matching coil currents for the production spectrometer solenoids, MICE Note 153, 6 November 2006.

[5] G. Penn, Beam Envelope Equations in a Solenoidal Field, MuCool Note 71, January 2000.