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Multiple Scattering Measurements in the MICE Experiment

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Abstract

The international Muon Ionization Cooling Experiment (MICE), under construction at RAL, will test a prototype cooling channel for a future Neutrino Factory or Muon Collider. The cooling channel aims to achieve, using liquid hydrogen absorbers, a 10% reduction in transverse emittance. The change in 4D emittance will be determined with an accuracy of 1% by measuring muons individually. Step IV of MICE will make the first precise emittance-reduction measurements of the experiment. Simulation studies using G4MICE, based on GEANT4, find a significant difference in multiple scattering in low Z materials, compared with the standard expression quoted by the Particle Data Group. Direct measurement of multiple scattering using the scintillating-fibre trackers is found to be possible, but requires the measurement resolution to be unfolded from the data.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) [1] is a test of a prototype muon cooling channel, shown in Figure 1. It is an integral part of the worldwide research effort towards a Neutrino Factory or Muon Collider. MICE uses three, 35 cm, liquid-hydrogen (LH_2) absorbers to achieve a 10% reduction in emittance, and is based on US Study 2 [2]. Eight 201 MHz RF cavities, positioned between the absorbers, re-accelerate the muon beam.

Scintillating-fibre trackers within 4 T super-conducting solenoids make single particle measurements at each end of the cooling channel. Each tracker consists of five scintillating-fibre stations, shown in Figure 2, with an active diameter of 30 cm. Each station is composed of three doublet-layers of 350 μm scintillating-fibre. The trackers are designed to measure *x*, *y*, p_x, p_y, the transverse coordinates to the beam and *E* the muon energy. A pair of matching coils in each spectrometer tune the magnetic optics to match the muon beam into and out of the cooling lattice.

STEP IV

Step IV of MICE, shown in Figure 3, is due to start in 2013. It will make the first ionization cooling measurements of the MICE programme, with solid LiH ($\Delta z = 63$ mm) and LH_2 ($\Delta z = 35$ cm) absorbers. Absorber thicknesses were selected to extract 10 MeV of energy from the beam.

Step IV contains one absorber focus coil (AFC) module, with spectrometer solenoids at each end to study the beam

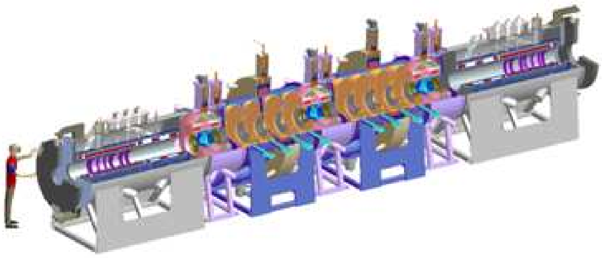


Figure 1: CAD Drawing of MICE.

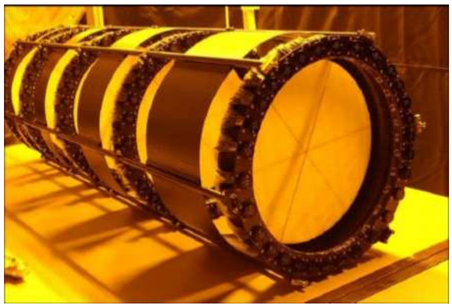


Figure 2: The MICE scintillating-fibre tracker.

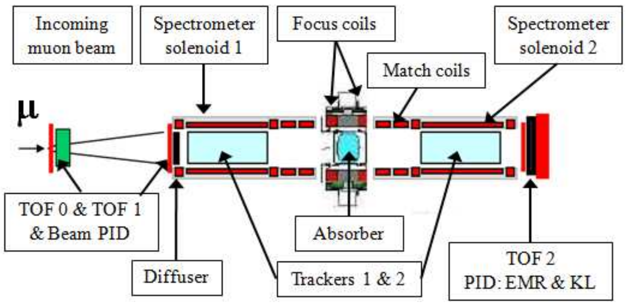


Figure 3: Step IV configuration of the MICE Experiment.

at input and output. The AFC module will house the absorber, the cryogenic system to cool the LH_2, and a pair of coils to bring the beam to a tight focus. In addition, two pairs of thin aluminium safety windows are present, one pair to maintain the vacuum and a second to provide redundancy.

The cooling performance of Step IV has been studied previously [3] using G4MICE software [4], which is based on GEANT4.9.2. Muon multiple scattering was also investigated, the results of which found significant disagreement with the standard Particle Data Group (PDG) formalism. The PDG supply a straightforward expression to calculate multiple scattering, based on work by V. Highland [5]. It gives the projected angular distribution as:

* on behalf of the MICE Collaboration

Table 1: Tracker resolution in phase-space coordinates u_i.

u_i	$\sigma(u_i)$
x [mm]	0.54
y [mm]	0.44
p_x [MeV/c]	2.05
p_y [MeV/c]	1.52
p_z[MeV/c]	4.58

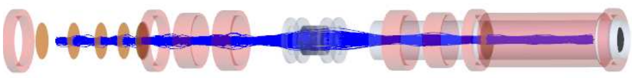


Figure 4: Simulation of Step IV in G4MICE software.

$$\theta_{rms}^{plane} = \frac{13.6\ \mathrm{MeV}}{\beta cp}\sqrt{\Delta z/X_0}\Big[1 + 0.038\ln(\Delta z/X_0)\Big], \quad (1)$$

said to be accurate to 11 % or better for $10^{-3} < \Delta z/X_0 < 100$. $\theta_{rms}^{plane} = \theta_{rms}^{space}/\sqrt{2}$. Note that the logarithmic term is ignored in the standard cooling formula for $\mathrm{d}\epsilon_n/\mathrm{d}z$, quoted in [3].

MULTIPLE SCATTERING MEASUREMENTS

A procedure was developed to investigate the ability of the trackers to measure multiple scattering with individual muons, in addition to beam emittance. In order to simulate the track reconstruction a Gaussian smear was applied to the coordinates of each muon, where the resolution for each phase-space variable is listed in Table 1, found in [6].

Four Step IV configurations were simulated in G4MICE: an empty channel, an AFC module (incl. Al windows, totalling $\Delta z = 0.7$ mm) without an absorber, an AFC with 35 cm LH_2 and an AFC containing 63 mm of LiH. Physical material in the spectrometer solenoids was removed from the simulation geometry. Muon beams were injected into a constant field region in the upstream spectrometer solenoid, matched according to the condition $\beta\kappa = 1$, given in Penn [8], where κ is the focusing strength. Step IV was simulated using beams of 10,000 muons (μ^-), with initial $p_z = 207$ MeV/c and $\sigma_{p_z} = 1$ MeV/c. Energy losses were turned off.

For each configuration, the procedure followed was:

1. The beam was tracked through the Step IV geometry, and the coordinates of each muon recorded at the position of the innermost scintillating-fibre plane, in each of the trackers ($z = -4.65$ m, -0.85 m). This produced an upstream and a downstream set of muon vectors.

2. The upstream muon vectors were re-injected into an empty Step IV geometry, and tracked to the downstream edge of the absorber.

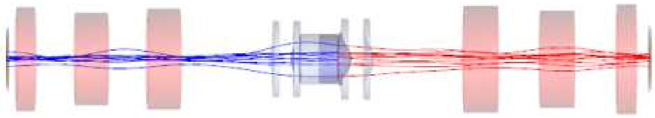


Figure 5: Muons tracked upstream (red) and downstream (blue) to the downstream face of the absorber.

3. The particle sign ($\mu^- \rightarrow \mu^+$) and momenta of the downstream muon vectors were flipped, and the muons tracked upstream to the absorber.

4. The 3D space angle between the upstream ($\vec{p}$) and downstream ($\vec{q}$) vectors was calculated at the downstream absorber face, using:

$$\cos\theta_{rms}^{space} = \frac{\vec{p}.\vec{q}}{|p||q|}. \quad (2)$$

5. Steps 2-4 were repeated, applying the Gaussian smear to represent the measured 6D muon vectors.

Figure 5 shows a visualization of the method, with the blue μ^- beam tracked to the downstream edge of the absorber, and the red, μ^+ beam tracked upstream to meet it.

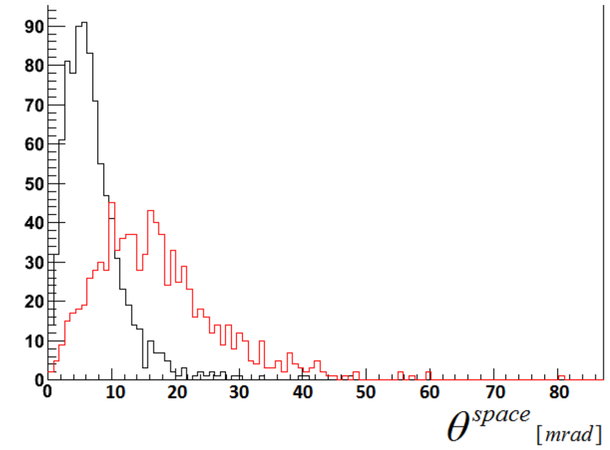
RESULTS

Figure 6 shows the rms space angle distributions for the Al windows in the AFC, and the LH_2 and LiH absorbers (incl. Al windows), with and without the tracker smearing. Table 2 lists the rms space angle predictions for the four configurations, from G4MICE simulations and the PDG formula. The empty channel run shows the accuracy of the tracking within GEANT4 ($\theta_{rms}^{space} = 0.06$ mrad), and the effect of the smearing, which limited the resolution to $\theta_{rms}^{space} = 23.37$ mrad.

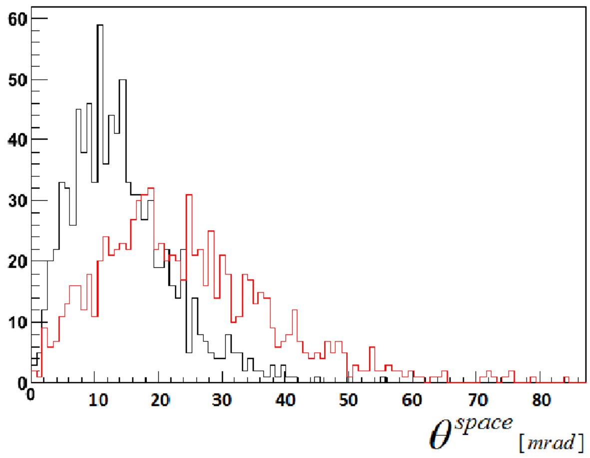
G4MICE simulations predicted scattering of 9.87 mrad in the AFC (Al windows), which was larger than the PDG value, including the 11 % error. G4MICE scattering predictions with LiH and LH_2 absorbers however were significantly less than the PDG value. These findings were consistent with previous work [3], which found a strong Z dependency (particularly at low Z) in the PDG expression when compared with GEANT4. The Al windows of the AFC were included in the PDG prediction for $\theta_{\mathrm{plane}}^{\mathrm{rms}}$

Table 2: rms multiple scattering space angle predictions, from theory and G4MICE.

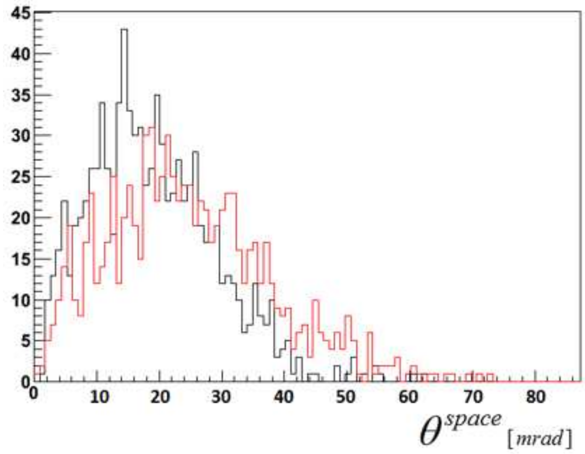
Configuration	θ_{rms}^{space} [mrad] PDG theory	No Smear	Smear
empty channel	n/a	0.06	23.37
Al windows	7.78	9.87	25.61
Al windows + LH_2	20.41	16.26	28.26
Al windows + LiH	25.74	21.55	32.82



(a)



(b)



(c)

Figure 6: Space angle distributions for beams of 10,000 muons in G4MICE, at the downstream face of the absorber position, for (*a*) Al windows only (AFC), (*b*) 35 cm LH_2 and (*c*) 63 mm LiH. The black line represents Monte Carlo truth, and red the tracker reconstructed distribution.

in LH_2 and LiH, calculating x/X_0 for the combined scatterer (absorber + Al), as given in Lynch & Dahl's paper [7]. The Monte Carlo prediction for the multiple scattering in LH_2 was $\theta^{space}_{rms} = 16.26$ mrad, 20 % less than the PDG value. In LiH $\theta^{space}_{rms} = 21.55$ mrad, 16 % less than the PDG prediction. The data were unfolded by subtracting the smear errors in quadrature. Whilst the scattering in the Al windows was apparent in the Monte Carlo (when compared with the empty geometry), the scattering appeared too small to measure. Unfolding the LH_2 and LiH datasets however provided sufficient resolution to observe the difference between the Monte Carlo and PDG scattering predictions. As a result the trackers were considered able to directly measure multiple scattering in the LH_2 and LiH absorbers.

CONCLUSION

Step IV of MICE will make the first measurements of ionization cooling, and is due to begin operation in 2013. It will measure cooling in 35 cm LH_2 and 63 mm LiH absorber materials, along with plastic and Al. Scintillating-fibre trackers will make precision measurements of the transverse emittance of the muon beam.

Simulations in G4MICE (Monte Carlo) indicated 20 % less multiple scattering than predicted by the PDG expression. A procedure was developed to ascertain whether Step IV of MICE could shed light on this discrepancy. A Gaussian smear was added to the muon positions and momenta recorded in the tracker, to imitate the tracker resolution. In an empty channel, with no scattering material, the smear resulted in an error of 23.37 mrad. As a result it will be necessary to unfold the smeared data to achieve sufficient resolution to address the difference between the Monte Carlo and PDG predictions. Step IV therefore provides an opportunity to directly measure multiple scattering.

REFERENCES

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