IONIZATION COOLING IN MICE STEP IV

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Abstract

The international Muon Ionization Cooling Experiment (MICE), under construction at RAL, will test and characterize 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 a relative accuracy of 1% by measuring muons individually. These include two scintillating fibre trackers embedded within 4 T solenoid fields, TOF counters and a muon ranger. Step IV of MICE will begin in 2012, producing the experiment's first precise emittance-reduction measurements. Multiple scattering in candidate Step IV absorber materials was studied in G4MICE, based on GEANT4. Equilibrium emittances for low-Z materials from hydrogen to aluminium can be studied experimentally in Step IV of MICE, and compared with simulations.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) [1] is a test of a prototype muon cooling channel. It is an integral part of the worldwide research effort towards the 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, which are transverse coordinates to the beam, and E the muon energy. 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:

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

as derived in [3]. β is the particle velocity, $\beta_\perp$ is the optical beta function, X_0 the absorber radiation length, and $< dE/dz >$ the mean energy loss rate. The first term represents cooling, which describes the reduction of beam size in phase space. The second term represents the heating contribution which increases the emittance, due to multiple scattering in material. Ionization cooling is defined as a net reduction in beam emittance across an absorber.

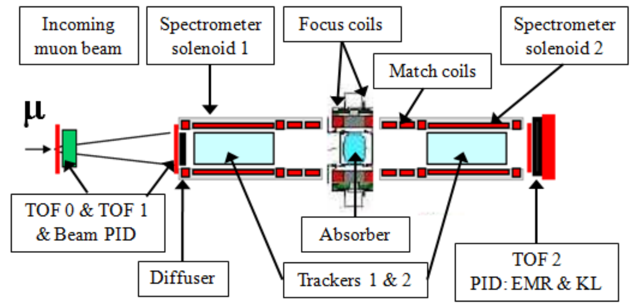

Figure 1: Step IV configuration of the MICE Experiment.

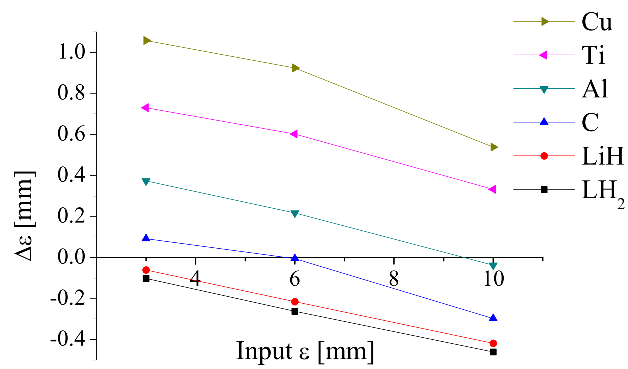

Figure 2: Change in emittance $\Delta\epsilon$ for Step IV using various absorbers, simulated in G4MICE. "Input ϵ" denotes the nominal transverse emittance of the input beam.

Step IV involves an Absorber Focus Coil (AFC) module between two spectrometer solenoids, as shown in Figure 1. The AFC module houses the absorber, a pair of focusing coils and the cryogenic system for the LH_2. A list of candidate absorber materials is given in Table 1, including lithium hydride (LiH) and LH_2. Absorber thicknesses, Δz, were selected to remove 10 MeV of energy from the beam, where the z axis runs parallel to the beamline.

Step IV was simulated using G4MICE [4] 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 2 shows the change in emittance in Step IV using input beams with normalized emittances of 3 mm, 6 mm and 10 mm, for six absorber materials. Heating will be observed with 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.

* on behalf of the MICE Collaboration

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

mat'l	X_0 [g cm^{-2}]	dE/dz [MeV g^{-1} cm^2]	ρ [g cm^{-3}]	Δz [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

MEASURING EQUILIBRIUM EMITTANCE

The equilibrium emittance of a material ϵ_0 is defined as the point at which the heating and cooling terms of the cooling equation (Equation 1) are equal, i.e. when $\Delta\epsilon = 0$. Step IV will involve a broad study of different absorber materials to measure their equilibrium emittance, defined as:

$$\epsilon_0 = \frac{\beta_\perp (14\ \mathrm{MeV}/c)^2}{2\beta m_\mu X_0} \left\langle \frac{dE}{dz} \right\rangle^{-1}. \qquad (2)$$

No beam may be cooled to less than the equilibrium emittance of a material for a given $\beta_\perp$ and momentum. In beams where $\epsilon_n < \epsilon_0$ multiple scattering dominates and heating occurs. The figure of merit $X_0 < dE/dz >$ decreases with increasing Z, meaning that ϵ_0 increases with Z. In high Z materials large amounts of scattering will produce large increases in emittance and change the optical functions of the beam as they pass through an absorber.

G4MICE was used to find ϵ_0 in low Z absorber materials in Step IV, with beams as described in the previous section. For the purposes of this study, the AFC module was removed from the simulation geometry entirely, so that the absorber was the only physical volume in the channel. This allowed ϵ_0 to be measured without the additional scattering and energy losses that occur in the safety windows. The magnetic fields were input separately using a fieldmap. Whilst beryllium (Be) and lithium (Li) are unsuitable for use in MICE, they were included in the simulation study for completeness.

The equilibrium emittance for each material was extrapolated from Figure 3, and are listed in Table 2. Figure 4 compares the measured values of ϵ_0 in G4MICE with the predicted values. The measured values were significantly lower than expected for all absorber materials. This discrepancy had been observed previously in ICOOL simulations [5], and is therefore not restricted to GEANT4 based simulation code.

An alternative to studying multiple scattering as an increase in emittance, is to measure the change in the angular distribution of the muons after passing through an absorber, i.e. the scattering angle. The cooling equation (Equation 1) traditionally used to predict cooling assumes a Gaussian angular distribution according to Molière [6], which gives

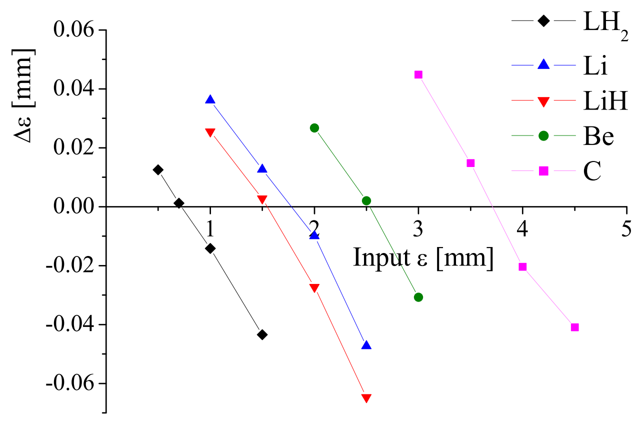

Figure 3: Cooling in Step IV in G4MICE, from which an equilibrium emittance can be extrapolated for each material.

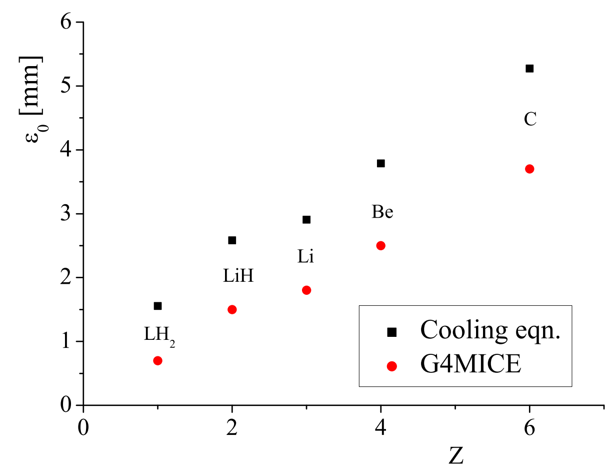

Figure 4: Equilibrium emittance ϵ_0 in G4MICE compared with the cooling equation, as a function of atomic number Z.

the projected angular distribution as:

$$\theta^{rms}_{plane} = \frac{13.6\ \mathrm{MeV}}{\beta c p} \sqrt{\Delta z/X_0} \Big[1 + 0.038 \ln(\Delta z/X_0) \Big] \quad (3)$$

and accurate to 11% or better for $10^{-3} < \Delta z/X_0 < 100$. θ^{rms}_{plane} is equivalent to $\sigma_x/\sqrt{2}$ for a symmetric beam. Δz is the thickness of the material and the remaining terms as defined earlier in the paper.

The standard absorbers for MICE, listed in Table 1, are scaled so ΔE = constant. As a result it was necessary to re-scale them to each produce the same amount of scattering, scaled to 63 mm of LiH, i.e. $\theta^{rms}_{plane} = 0.01685$ rad. Pencil beams were projected directly down the axis of the channel, i.e. $\sigma_x = \sigma_{px} = 0$ in 2D. $N_\mu = 10,000$ with initial $p_z = 207$ MeV/c, and $\sigma_{p_z} = 0$ MeV/c.

Table 2: Multiple scattering studied in low Z materials.

Z	mat'l	ϵ_0 [mm] Cooling eqn.	ϵ_0 [mm] G4MICE	θ^{rms}_{plane} [rad]	Δz [cm]
1	LH_2	1.6	0.7	0.0136	57.6
2	LiH	2.6	1.5	0.0156	63.0
3	Li	2.9	1.8	0.0156	10.0
4	Be	3.8	2.5	0.0167	2.3
6	C	5.3	3.7	0.0172	1.4
14	Al	10.3	n/a	0.0178	0.6
22	Ti	16.8	n/a	0.0179	0.2
29	Cu	22.3	n/a	0.0183	0.1

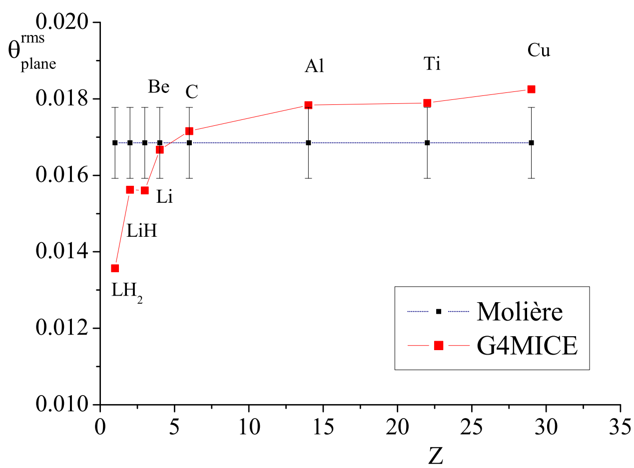

Figure 5: Measured scattering angle θ^{rms}_{plane} in G4MICE compared with predictions from Molière's theory of multiple scattering.

Figure 5 shows the scattering angles as measured in G4MICE compared with the straight line behaviour as predicted by Molière, where the error bars reflect the stated 11% accuracy of the theory. Scattering predictions at $Z < 5$ were significantly greater than measured in G4MICE, which corroborated with the deficit in the measured ϵ_0, shown in Figure 4. However the scattering angles for Be, C, Al and Ti were consistent with predictions, implying that the simulated and predicted ϵ_0 should indeed agree. The measured θ^{rms}_{plane} in higher Z materials were marginally higher than predicted.

CONCLUSION

Step IV of MICE will study ionization cooling in different absorber materials, and can directly measure the equilibrium emittance ϵ_0 in low Z materials, up to and possibly including aluminium ($Z = 14$).

When trying to predict ϵ_0 in absorber materials, Molière's Gaussian approximation for multiple scattering is typically used, and incorporated into the widely used cooling formula. Such predictions appear to significantly overestimate ϵ_0 at $Z < 6$ when compared with simulations in G4MICE, based on GEANT4. The measured scattering angle from simulations strongly disagreed with predictions, with a large deficit in LH_2 and LiH, both of which are to be used in Step IV. As a result, there lies considerable importance in finding a more accurate formalism with which to predict ϵ_0 and the scattering angle.

Step IV in 2012 will present an excellent opportunity to measure ϵ_0 and verify both the cooling formula and the multiple scattering processes inside GEANT4.

REFERENCES

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