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PHYSICS PROGRAMME OF NEXT MICE STEP IV

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Abstract

The International Muon Ionization Cooling Experiment is progressing towards a full demonstration of the feasibility of ionization cooling technology decisive for neutrino physics and muon colliders. Step IV should provide the first precise measurements of emittances and first evidence of cooling. The components required for Step IV, including spectrometer solenoids, muon trackers and absorber-FC (focus coil) modules have been assembled with data collection expected in 2015. The physics programme of this Step will be described in detail, which includes LiH and a few other promising absorber materials of different shapes.

INTRODUCTION

Results from atmospheric neutrinos at Super-Kamiokande [1] and from solar neutrinos at the Sudbury Neutrino Observatory [2], conclusively showed that neutrinos have a non-zero mass and oscillate between different neutrino flavours. A Neutrino Factory [3] is the only proposed facility with the capability to measure δ_{CP} with 5° accuracy and to perform measurements of the neutrino cross-sections. In the Neutrino Factory, neutrinos will be produced via boosted muon decay in a storage ring in the direction of a far detector site. Proposals include a facility with a baseline of 2000 km for a 10 GeV muon beam [4]. Before the muons are injected into the storage ring the phase-space volume of the beam must be reduced. This increases the number of muons that enter the acceleration channel (linac) and reduces the potential radiation damage. This is also important as it reduces the transverse contributions and systematic uncertainties of the neutrino beam. The only cooling technique which can act within the lifetime of the muon is ionization cooling. MICE is progressing towards a demonstration of this technology with its next Step IV providing the first measurement of transverse emittance reduction by ionization cooling. It relies on progress of the hardware being detailed in a separate paper. Demonstration of this technology is an essential part of the worldwide research effort towards building a Neutrino Factory.

IONIZATION COOLING

A muon beam crossing an absorber loses energy by ionization. This reduces the longitudinal and transverse momenta of the muons and hence the phase space occupied by the beam. A high gradient RF cavity is used to restore the longitudinal momentum of the beam.

The rate of change of normalised emittance in a medium of thickness X may be described as [5]:

$$\frac{d\varepsilon_N}{dX} \approx -\frac{\varepsilon_N}{\beta^2 E_\mu}\left\langle\frac{dE}{dX}\right\rangle + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}; \quad (1)$$

where ε_N is the normalised transverse (four-dimensional) emittance of the beam, X_0 is the radiation length of the medium, $\beta_\perp$ is the betatron function, E_μ and m_μ the energy and mass of the muons and $\beta = pc/E$. The first term on the right hand side of equation 1 describes the cooling effect and the second the heating due to multiple scattering. The emittance of the beam when these two effects are at equilibrium is:

$$\varepsilon_{eq} \approx \frac{\beta_\perp (0.014 GeV)^2}{2\beta m_\mu X_0}\left\langle\frac{dE}{dX}\right\rangle^{-1}. \quad (2)$$

The lower the equilibrium emittance the better the cooling channel. To achieve this, $\beta_\perp$ should be minimised which requires strong solenoidal focusing at the absorber and $X_0\left\langle\frac{dE}{dX}\right\rangle$ should be maximised. MICE will explore the parameter space using several low-Z absorbers, including liquid hydrogen, at a variety of $\beta_\perp$ functions.

MICE BEAM LINE

The MICE experiment is located at the Rutherford Appleton Laboratory (RAL) in the UK and operates parasitically on the ISIS proton accelerator [6]. MICE was designed to perform a high precision measurement of emittance using single particle events. MICE is staged in a number of Steps (see figure 1).

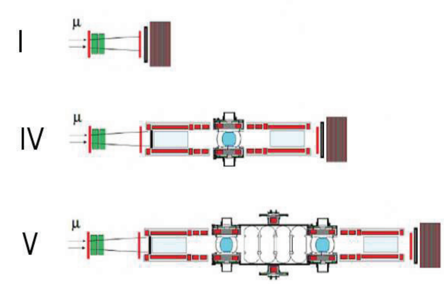

Figure 1: Schematic diagrams of the ‘Steps’ in which the MICE programme was conceived.

The beam line is composed of three quadrupole triplets, two dipole magnets, which select the momentum distribution of the muon beam, and the Decay Solenoid (DS), which increases the number of muons in the beam. A range of beam emittances can be created immediately upstream of the cooling channel via multiple Coulomb scattering in a high-Z diffuser. The particle identification suite consists of three time-of-flight detectors (TOFs), two Cherenkov detectors (Ckova and Ckovb), the KLOE-type sampling calorimeter (KL) [7] and the Electron Muon Ranger (EMR). Two

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scintillating fibre trackers will be used to measure space point and momentum information before and after the cooling channel to reconstruct the emittance before and after cooling.

MICE STEP IV

In MICE Step IV (figure 2) the first Absorber Focus Coil (AFC) module, which will house the liquid hydrogen (LH_2) or solid absorber, will be placed between two scintillating fibre trackers.

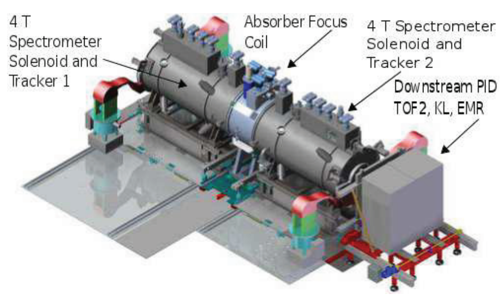

Figure 2: MICE Step IV cooling channel.

The two trackers are located within 4 T solenoids and perform 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.

First Measurement of Muon Ionization Cooling

MICE Step IV will provide the first measurement of emittance reduction by ionization cooling. The performance as simulated in MAUS is shown in figures 3 & 4.

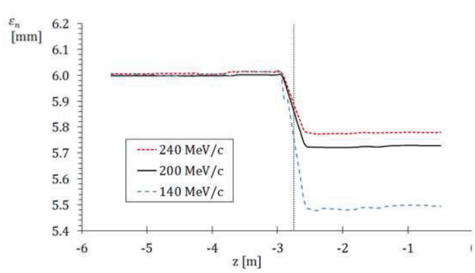

Figure 3: Maus simulations of a 6 mm emittance beam in Step IV with a 35 cm LH_2 absorber, showing the evolution of its emittance, ϵ_n, along the channel. The vertical dashed lines indicate the centre of the absorber [8].

The MICE program will study ionization cooling as a function of the initial emittance, ϵ_n, and momentum, $p = \beta E_\mu$, of the muon beam. It will also characterise the magnetic lattice of the cooling channel by varying $\beta_\perp$ at the absorber and determining the cooling performance for a variety of absorber materials.

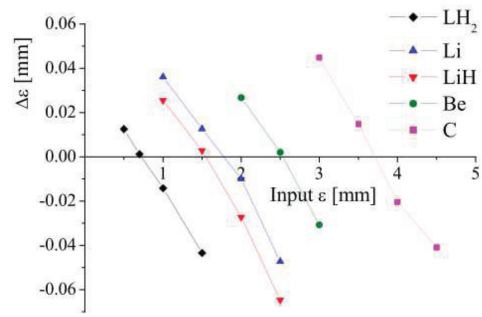

Figure 4: Cooling in Step IV in MAUS, from which an equilibrium emittance can be interpolated for each material [8].

Magnetic Lattice

The observed change in emittance depends, in part, on the parameters of the input beam and the optics of the cooling cell. MICE was designed to demonstrate cooling of a beam similar to that expected at a Neutrino Factory. Step IV will demonstrate transverse emittance reduction, with an expected reduction in emittance of 5%. Central momenta in the range of 140-240 MeV/c and emittance in the range 3-10 mmrad will be measured during Step IV, as this covers the range of possible neutrino factory momenta and emittances.

Matching Conditions

Each beam is matched into the upstream tracking volume, satisfying $\alpha_\perp = 0$, $\beta_\perp = 333$ mm at $p_z = 200$ MeV/c, figure 5 (where $\alpha_\perp$ & $\beta_\perp$ are the Twiss parameters). Matching into and out of the cooling cell will be examined by altering the tuning of the lattice and measuring the beams' optical parameters.

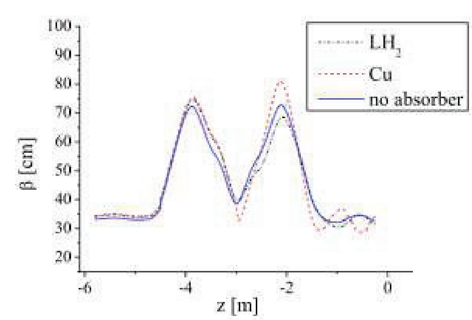

Figure 5: MAUS simulation of Beta function in MICE Step IV [8].

Absorber Material

Step IV is designed to study cooling in different materials, with a list of candidate materials given in table 1. While the Neutrino Factory requires cooling of only the four-dimensional transverse phase space to achieve the desired performance a Muon Collider must be cooled in all six phase-space dimensions. The MICE program incorporates a demonstration of longitudinal emittance reduction

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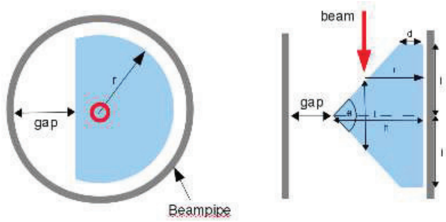

Figure 6: Schematic of wedge geometry, which is parameterised by the on-axis thickness t, opening angle θ and radius r[9].

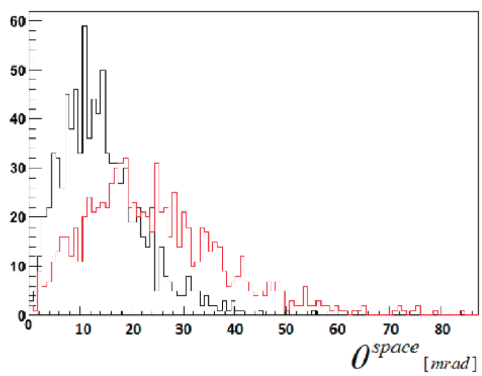

Figure 7: Space angle distributions for beams of 10,000 muons in MAUS, at the downstream face of the absorber position, for 35 cm LH_2. The black line represents Monte Carlo truth, and red the tracker reconstructed distribution [10].

via emittance exchange. This is achieved in MICE with a solid wedge absorber (figure 6) in Step IV. Muons with higher energy pass through more material and experience greater momentum loss. In this way longitudinal emittance of the beam can be reduced either in addition to, or even instead of transverse emittance reduction.

Table 1: Absorbers in the MICE Step IV Program

Material	X_0	dE/dX	ρ	Δz
	gcm^{-2}	$MeVg^{-1}cm^2$	gcm^{-3}	cm
LH_2	63.04	4.103	0.07	35
LiH	79.62	1.897	0.82	6.3

Multiple Scattering

MICE will measure multiple scattering in a variety of configurations; with and without absorber, with and without fields and for both LH_2 and LiH absorbers (figure 7).

MAUS simulations predicted scattering of 9.87 mrad in the AFC (Al windows), which was larger than the PDG value, including the 11% error [10]. MAUS scattering predictions with LiH and LH_2 absorbers however were significantly less than the PDG value. Step IV therefore provides an opportunity to directly measure multiple scattering and so quantify the precision of the existing Geant model and provide input to future refinements.

dE/dX

Current data on dE/dX and straggling are sparse. MICE is sensitive to the tails of the Landau distribution of dE/dX, information which will be needed to determine with confidence the muon collider luminosity. As with multiple scattering this will be measured for a number of materials.

CONCLUSION

MICE Step IV will provide the first measurement of transverse emittance reduction of muons by ionization cooling, a key milestone in the R&D effort to realise the Neutrino Factory. In addition to characterising and optimising a cooling channel Step IV will offer opportunities to develop an understanding of multiple scattering and dE/dX in a variety of materials all of which are critical to neutrino physics and muon colliders. Following this MICE Step V will perform the first demonstration of ionization cooling with re-acceleration.

ACKNOWLEDGMENT

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