FIRST RESULTS FROM MICE STEP IV

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on behalf of the MICE Collaboration

Abstract

Muon beams of low emittance provide the basis for the intense, well characterised neutrino beams of a neutrino factory and for multi-TeV lepton-antilepton collisions at a muon collider. The international Muon Ionization Cooling Experiment (MICE) will demonstrate ionization cooling, the technique by which it is proposed to reduce the phase-space volume occupied by the muon beam. MICE is being constructed in a series of steps. The configuration currently in operation at the Rutherford Appleton Laboratory (called Step IV) is optimised for the studying the properties of liquid hydrogen (LH2) and lithium hydride (LiH). Preliminary results from ongoing analysis will be described.

INTRODUCTION

Muon colliders and neutrino factories will require stored muons with high intensity and low emittance [1]. Muons are produced as tertiary particles ($p + N \rightarrow \pi + X$, $\pi \rightarrow \mu + \nu$) inheriting a large emittance (volume of the beam in the position and momentum phase space). For efficient acceleration, the phase-space volume of these beams must be reduced significantly ("cooled"), in order to be accepted by traditional accelerator components. Due to the short muon lifetime, ionization cooling is the only practical and efficient technique to cool muon beams [2]. In ionization cooling, the muon beam loses momentum in all dimensions by ionization energy loss when passing through an absorbing material, reducing the RMS emittance ($\varepsilon_{\mathrm{RMS}}$) and increasing its phase space density. Subsequent acceleration though radio frequency cavities restores longitudinal energy, resulting in a beam with reduced transverse emittance. A factor of 10^5 in reduced 6D emittance has been achieved in simulation with a 970 m long channel [3].

The rate of change of the normalized transverse RMS emittance ε_{N} is given by the ionization cooling equation [4]:

$$\frac{d\varepsilon_{\mathrm{N}}}{ds} \simeq -\frac{\varepsilon_{\mathrm{N}}}{\beta^2 E_\mu}\left\langle\frac{dE}{ds}\right\rangle + \frac{\beta_{\mathrm{t}}(13.6\ [\mathrm{MeV}])^2}{2\beta^3 E_\mu m_\mu X_0} \quad (1)$$

where βc is the muon velocity, $\langle dE/ds\rangle$ is the average rate of energy loss, E_μ and m_μ are the muon energy and mass, β_{t} is the transverse betatron function and X_0 is the radiation length of the absorber material. The first term on the right can be referred as the "cooling" term given by the "Bethe equation", while the second term is the "heating term" that uses the PDG approximation for the multiple Coulomb scattering.

A schematic drawing of MICE Step IV is shown in Fig. 1. MICE is instrumented with a range of detectors used for particle identification and position-momentum measurement: a scintillating fibre tracker upstream and downstream of the absorber is placed in a strong solenoid field to measure the position and the momentum (with a spatial resolution around 0.3 mm) and a series of particle identification detectors, including 3 time-of-flight hodoscopes (ToF0/1/2, with a time resolution around 60 ps), 2 threshold Cherenkov counters, a pre-shower calorimeter and a fully active scintillator.

MICE is currently taking data (in the Step IV configuration) in order to make detailed measurements of multiple Coulomb scattering and energy loss of muon beams at different momenta and channel configurations, with lithium hydride and liquid hydrogen absorbers. The collaboration also seeks to measure the reduction in normalized transverse emittance [5].

MEASUREMENTS OF SCATTERING DISTRIBUTIONS

Though multiple Coulomb scattering is a well understood phenomenon, results from MuScat [6] indicate that the effect in low Z materials is not well modeled in simulations such as GEANT4 [7]. MICE will therefore measure the multiple Coulomb scattering distribution to validate the scattering model and understand the heating term in Eq. 1, in order to make more realistic predictions of the emittance reduction.

MICE has collected data for muon beams at three different momenta, 172 MeV/c (in order to compare with MuScat), 200 MeV/c and 240 MeV/c with and without the LiH absorber in place (thickness 65 mm, $X_0 = 79.62$ g cm^{-2}), The position and momentum of each muon is measured by the trackers and the time-of-flight, the latter also provides particle identification. Selection criteria on the tracks were imposed to select a pure, well understood sample. Bayesian deconvolution was applied to the selected data in order to extract the scattering distribution within the absorber material and comparisons have been made to GEANT4 as well as to a standalone scattering model developed by Carlisle and Cobb [8]. Data taken with the 200 MeV/c beam, deconvolved using the GEANT model, are shown in Fig. 2. Different contributions to the systematic uncertainty have been considered: sensitivity to the thickness of the absorber, time of flight cuts used for momentum selection, alignment of the detectors and choice of the fiducial cuts. The time of flight systematics dominate. The scattering width taken from the scattering distributions projected in the X-Z and Y-Z planes are $\Theta = 20.3 \pm 0.2$ mrad at 172 MeV/c, $\Theta = 17.1 \pm 0.2$ mrad at 200 MeV/c and $\Theta = 13.8 \pm 0.1$ mrad at 240 MeV/c. The preliminary analysis indicates that GEANT4 underestimates the scattering width, while the PDG model overestimates it [9].

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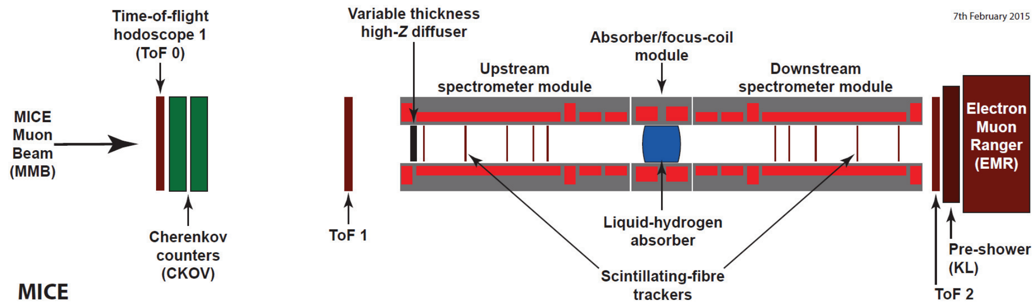

Figure 1: Layout of MICE Step IV configuration, showing the absorber, tracking spectrometers and detectors for particle identification.

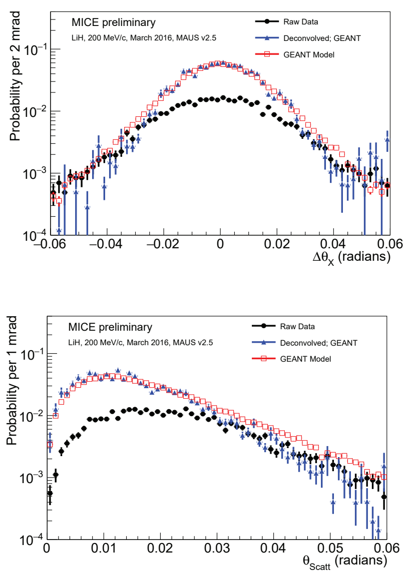

Figure 2: Projected (top) and 3D (bottom) scattering distributions of 200 MeV/c muons passing through the LiH absorber.

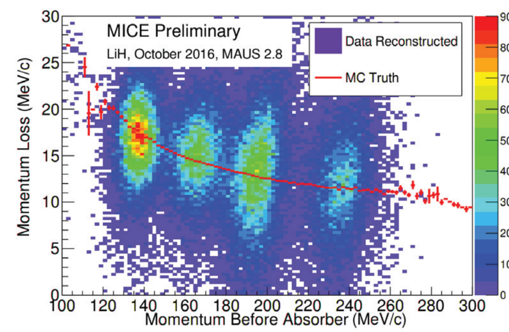

Figure 3: Distribution of the reconstructed momentum loss across the absorber for several different beams compared with the MC truth.

MEASUREMENT OF ENERGY LOSS

The mean rate of energy loss for relativistic charged heavy particles traversing matter is given by the "Bethe equation" [10]:

$$-\left\langle \frac{dE}{dX} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (2)$$

where the mean excitation energy, I, in hydrogen is known at the 5% level but has never been measured in lithium hydride. Small differences are expected between the energy loss in LH2 and in LiH.

MICE measures the momentum upstream and downstream of the absorber using information from the trackers combined with measurements of the time of flight. Data has been analysed using central muon-beam momenta of 140, 170, 200 and 240 MeV/c in the presence of 3 T magnetic field, with and without the LiH absorber (Fig. 3). Preliminary results for 200 MeV/c muons in magnetic field traversing the LiH absorber show that the mean momentum loss is $\Delta p = 12.8 \pm 5.3$ MeV/c. Further studies are planned to deconvolve the energy loss measured without absorber from the measurement with the absorber in order to obtain the energy loss in the absorber. A final goal will be to measure correlations of energy loss with multiple Coulomb scattering.

DIRECT MEASUREMENT OF MICE MUON BEAM EMITTANCE

During commissioning of the solenoided cooling cell, muons were transported through to the upstream scintillating fibre tracker in a 4 T uniform solenoid magnetic field where the position and momentum of each individual muon were measured. This run was used to characterise the muon beam and validate the performance of track reconstruction.

The normalized transverse emittance is defined as:

$$\varepsilon_N = \frac{1}{m_\mu} \sqrt[4]{\det \Sigma}; \quad (3)$$

where m_μ is the muon mass and Σ is the 4D covariance matrix calculate on (x, y) and (P_x, P_y). In MICE the muon-beam emittance is measured on a single particle basis. Similar

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to the other studies presented here, the particles were selected after a series of cuts in order to obtain a pure and well reconstructed muon sample, as shown in Fig. 4. Particles were required to pass through the upstream and the downstream ToF detectors and the trackers, and were required to have a time of flight consistent with them being muons. Particles that scraped the magnet apertures in the channel were rejected.

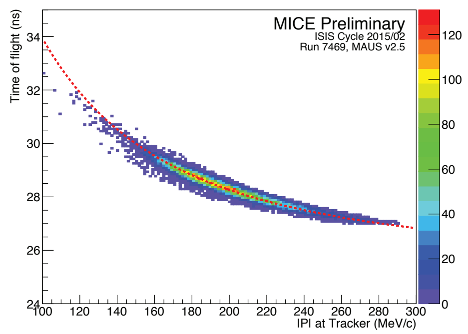

Figure 4: Time of flight between ToF0 and ToF1 detectors as a function of the total muon momentum; the red dotted line is the MC.

Figure 5 shows the calculated normalised transverse emittance measured at the last ("reference") plane of the upstream tracker in 8 MeV/c bins of longitudinal momentum (P_z). The emittance is uniform within errors across all samples. Errors are dominated in each bin by the statistical uncertainty.

CONCLUSIONS

MICE, at Step IV, will measure the properties of liquid hydrogen and lithium hydride that affect the performance of an ionization-cooling channel. The Step IV configuration will also be used to study the effect of channel optics and of the input beam momentum and emittance on the ionization-cooling. Step IV data taking commenced in 2016: scattering and energy loss measurements on LiH have been performed and similar measurements on LH2 are due in the upcoming runs. Emittance studies are in progress and results are in preparation for publication.

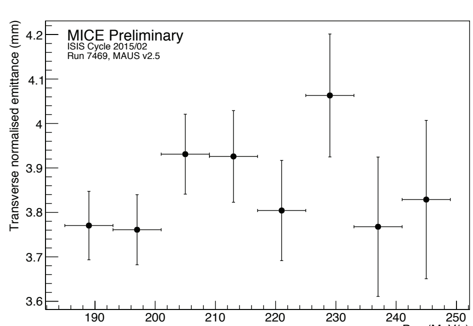

Figure 5: Normalised transverse emittance.

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