Journal of Physics: Conference Series

Measurements of muon multiple scattering in MICE

Neutrino2016 IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **888** (2017) 012212 doi:10.1088/1742-6596/888/1/012212

Measurements of muon multiple scattering in MICE

R Bayes

School of Physics and Astronomy, University of Glasgow,
University Avenue, Glasgow G12 8QQ, UK
For the MICE Collaboration

E-mail: ryan.bayes@glasgow.ac.uk

Abstract. Neutrino factories have been identified as the best facility for making precision measurements of neutrino oscillation physics. To fully realize this technology, a demonstration of the reduction of the phase space of a muon beam must be presented. The Muon Ionization Cooling Experiment (MICE) is tasked with providing such a demonstration. Ionization cooling uses the energy loss in a low Z material followed by acceleration in RF cavities to reduce the phase space of a beam on a time scale many times less than the time scale of muon decay. Multiple coulomb scattering (MCS) simultaneously inflates the muon beam and so the interplay between energy loss and MCS must be well understood. Unfortunately MCS is not well simulated in the materials of interest in the GEANT Monte Carlo program. A programme has commenced for MICE to measure MCS in several materials of interest including lithium hydride, liquid hydrogen, and gaseous xenon. The experimental methods and early results will be presented.

1. Introduction

The purpose of MICE is to measure emittance reduction in muon beams as they pass through low Z absorbers[1]. This is a necessary technology for the development of Neutrino Factories[2] and Muon Colliders[3]. Multiple scattering within the absorber material acts to increase the beam divergence even as energy loss potentially reduces the normalized transverse emittance. To make a prediction of emittance reduction in MICE a simulation of multiple scattering in the target materials must be validated. A previous measurement conducted by the MuScatt experiment[4] has shown that the implementation in GEANT (v4.7.0) overestimates the scattering.

The emittance change of a muon beam is given by the expression

$$\frac{d\epsilon_n}{dz} \approx -\frac{\epsilon_n}{p_\mu \beta}\langle\frac{dE_\mu}{dz}\rangle + \frac{\beta_\perp p_\mu}{2m}\frac{d\sigma_{\theta^2}}{dz} \tag{1}$$

where ϵ_n is the normalized emittance of the muon beam, $\beta_\perp$ is the transverse extent of the beam, and σ_{θ^2} is the RMS width of the scattering distribution. This width was estimated by Greisen and Rossi such that

$$\frac{d\sigma_{\theta^2}}{dz} = \left(\frac{13.6\ \mathrm{MeV/c}}{p_\mu \beta}\right)^2 \frac{1}{X_0} \tag{2}$$

where X_0 is the radiation length of muons in the material of interest. More detailed evaluation of the behaviour of the emittance will depend on the precise shape of the scattering distribution. GEANT4 uses a compact representation of a Lewis distribution to represent the scattering. MICE can compare the data collected from field off runs with and without an absorber to validate this model of the scattering. An atomistic model of scattering using a screened nucleus cross-section to provide the behaviour of the muons through a material has been developed within the MICE collaboration and will also be compared to the data[5].

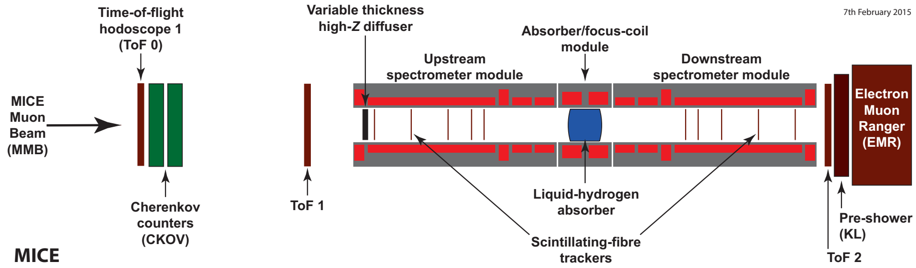


Figure 1: A schematic representation of the current MICE layout

2. The Muon Ionization Cooling Experiment

MICE currently consists of a system of particle identification detectors and two tracking detectors to measure and characterize muon beams passing through a central absorber. The tracking detectors are contained in a 3 Tesla superconducting solenoid to measure the muon momentum. The absorber is also contained in a superconducting coil to reduce the transverse size of the beam as it passes through the absorber material. Three scintillator plane hodoscopes are placed before the last quadrupole triplet of the muon beam line, before, and after the cooling channel to act as time of flight detectors. Cherenkov light detectors, a lead pre-shower calorimeter and a totally active scintillating detector are present but not used in this analysis. The current MICE setup is shown in Fig.1.

3. Muon Multiple Scattering Studies

Data were collected by MICE in 2015 and 2016 that may be used for the purpose of simulation validation. At that time the magnetic field was not available so the tracking detectors were used These data included $7{\times}10^5$ particle triggers collected with muons scattering in a Xenon filled absorber vessel and $3.7{\times}10^6$ particle triggers collected with muons scattering in a lithium hydride disk which was taken at three different beam settings accessing different ranges of momenta. Smaller data samples were collected to measure the resolution and scattering in absence of the scattering material using the same beam settings.

Straight tracks collected in these data sets are reconstructed using the tracker planes and the time of flight detectors. The trackers provide the direction and the position of the particle trajectories, while the particle velocities are measured from the time of flight between stations 1 and 2. A selection criteria based on the detection, time of flight, and position of a track was devised to select an unbiased sample of particle trajectories using only information upstream of the absorber. This satisfies the normalization criteria for the definition of the measured scattering distributions as probabilities. The scattering is characterized using the gradients $x' = dx/dz$ and $y' = dy/dz$ by considering the changes in the x and y projections across the absorber

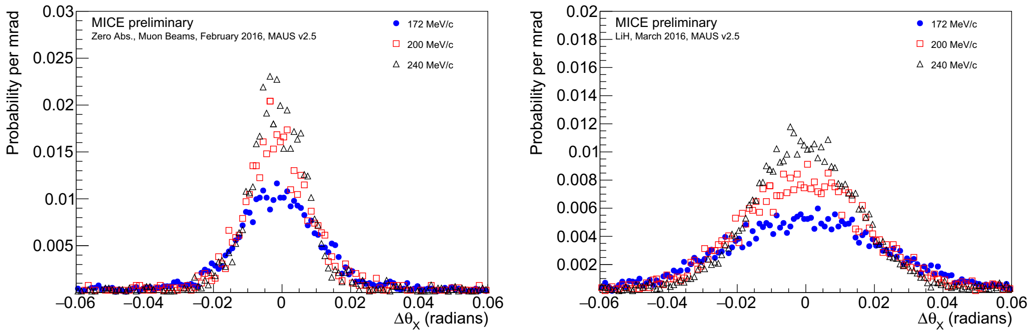
$$\Delta\theta_X = \arctan y'_{US} - \arctan y'_{DS}, \Delta\theta_Y = \arctan x'_{US} - \arctan x'_{DS} \tag{3}$$

or the change in the 3D scattering angle of the muon across the absorber

$$\theta_{Scatt} = \arccos\left(\frac{1 + x'_{US}x'_{DS} + y'_{US}y'_{DS}}{\sqrt{1+(x'_{US})^2+(y'_{US})^2}\sqrt{1+(x'_{DS})^2+(y'_{DS})^2}}\right) \approx \sqrt{\Delta\theta_X^2 + \Delta\theta_Y^2}. \tag{4}$$

The particle momentum is inferred from the time of flight so this selection criteria is particularly important for the verification of the scattering implementation as a function of momentum. The scattering distributions projected on the Y-Z plane for the three beam settings with no absorber are shown in Fig.2a and with the lithium hydride absorber are shown in Fig.2b.

Further analysis compares data and simulation to evaluate models. To facilitate these comparisons, different time of flight regimes have been defined for each of the three different



(a) Scattering in channel without absorber. (b) Scattering in channel with LiH Disk.

Figure 2: Multiple scattering distributions from the three different beam settings

data sets so that the momentum selection is matched between data and the simulation. These comparisons involve convolving models of the scattering in the absorber with the empty absorber data or alternatively applying a deconvolution algorithm to the data to remove the effect of external scattering and measure only the scattering in the absorber material. A deconvolution procedure has been adopted that relies on the Bayes theorem to measure the scattering in the absorber material[6]. This method uses the simulation in conjunction with the empty AFC scattering data to produce a conditional probability that a particle is measured at a particular angle θ_j^{rec} given a true scattering angle in the absorber material θ_i^{abs}, $P(\theta_j^{rec}|\theta_i^{abs})$. Application of the Bayes theorem yields a conditional probability that may be used to provide an estimate of the number of events at θ_i^{abs}, given a number of events $n(\theta_j^{rec})$, $n(\theta_i^{abs}) = \sum_{j=1}^{n_E} n(\theta_j^{rec}) P(\theta_i^{abs}|\theta_j^{rec})$. Iterating this method by updating the prior probability with this number for further applications of the Bayes theorem result in a distribution that approaches the true data distribution. The method is independent of the scattering model. The preliminary application of this deconvolution yields a gaussian width of the projections of the scattering distributions of 15.0 $\pm$0.1 mrad at 166 MeV/c, 12.9$\pm$0.2 mrad at 206 MeV/c and 10.9$\pm$0.1 mrad at 244 MeV/c assuming statistical uncertainties only. The evaluation of systematic uncertainties is in progress.

Multiple scattering is an important component to ionization cooling that must be well determined by the MICE collaboration. Measurements of the scattering of muons in the MICE absorber materials has been done and the systematic uncertainties are currently being analyzed. These systematic uncertainties must be understood before the difference between data and simulation, and therefore between predicted and measured emittance growth in MICE, can be properly quantified.

The work described here was made possible by grants from U.S. DOE and NSF, Italian INFN, U.K. SFTC, the European Community under the European Commission Framework Programme 7, The Japan Society for the Promotion of Science and the Swiss National Science Foundation. We are grateful to the staff of ISIS for the its reliable operation. We acknowledge the use of Grid computing resources deployed and operated by GridPP in the UK. http://www.gridpp.ac.uk/.

4. References

[1] Adams D *et al.* (MICE) 2013 *Eur. Phys. J.* **C73** 2582 (*Preprint* `1306.1509`)
[2] Bogomilov M, Matev R, Tsenov R, Dracos M, Bonesini M *et al.* 2014 *Phys.Rev.ST Accel.Beams* **17** 121002
[3] Stratakis D and Palmer R B 2015 *Phys. Rev. ST Accel. Beams* **18**(3) 031003 URL `http://link.aps.org/doi/10.1103/PhysRevSTAB.18.031003`
[4] Attwood D *et al.* 2006 *Nucl. Instrum. Meth.* **B251** 41–55 (*Preprint* `hep-ex/0512005`)
[5] Carlisle T 2013 *Step IV of the Muon Ionization Cooling Experiment (MICE) and the multiple scattering of muons* Ph.D. thesis Oxford U. URL `http://mice.iit.edu/phd/TimCarlisle-thesis.pdf`
[6] D'Agostini G 1995 *Nucl. Instrum. Meth.* **A362** 487–498