ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO127

RECENT RESULTS FROM MICE ON MULTIPLE COULOMB SCATTERING AND ENERGY LOSS*

Jingyu. Tang†, Institute of High Energy Physics, CAS, P. R. China

J. Nugent, University of Glasgow, UK

Abstract

Multiple Coulomb scattering and energy loss are well known phenomena experienced by charged particles as they traverse a material. However, from recent measurements by the MuScat collaboration, available simulation codes (GEANT4, for example) are known to overestimate the scattering of muons in low Z materials. This is of particular interest to the Muon Ionization Cooling Experiment (MICE) collaboration that has the goal of measuring the reduction of the emittance of a muon beam induced by energy loss in low Z absorbers. MICE took data without magnetic field suitable for multiple scattering measurements in the fall of 2015 with the absorber vessel filled with xenon and in the spring of 2016 using a lithium hydride absorber. In the fall of 2016, MICE took data with magnetic fields on and measured the energy loss of muons in a lithium hydride absorber. These data are all compared with the Bethe formula and with the predictions of various models, including the default GEANT4 model.

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 accelerators. 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 (ε_{RMS}) and increasing its phase space density. Subsequent acceleration by 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_T is given by the ionization cooling equation [4]:

$$\frac{d\varepsilon_T}{dz} \cong -\frac{\varepsilon_T}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2mc^2\beta^3}\frac{(13.6\ \mathrm{MeV/c})^2}{E_\mu X_0}, \quad (1)$$

where E_μ is the muon energy, β the muon velocity, dE_μ/dz the magnitude of the ionization energy loss, m the muon mass, X_0 the radiation length, and $\beta_\perp$ the transverse beta function at the absorber. 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 [5] for the multiple Coulomb scattering.

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

MICE data taking was concluded in December 2017 (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 (LiH) and liquid hydrogen (LH_2) absorbers. The collaboration also sought to measure the reduction in normalized transverse emittance [6], comparing the emittance of a sample of muons selected in the upstream tracker with the emittance of the same sample measured in the downstream one, after passing through the absorber.

MEASUREMENTS OF SCATTERING DISTRIBUTIONS

Though multiple Coulomb scattering is a well understood phenomenon, results from MuScat [7-8] indicate that the effect in low Z materials is not well modelled in simulations such as GEANT4 [8]. MICE therefore measured 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.As MICE was designed to measure the emittance change to 0.1% level, precise measurements on multiple Coulomb scattering are required. Both data with field off and field on in the scintillating fiber tracker are available for MICE. While the field on data is still being analysed, the field off analysis is presented here.

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) and with a full and an empty liquid hydrogen absorber vessel (~22 litre). Here the LiH analysis is presented.

*on behalf of the MICE Collaboration

†tangjy@ihep.ac.cn

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO127

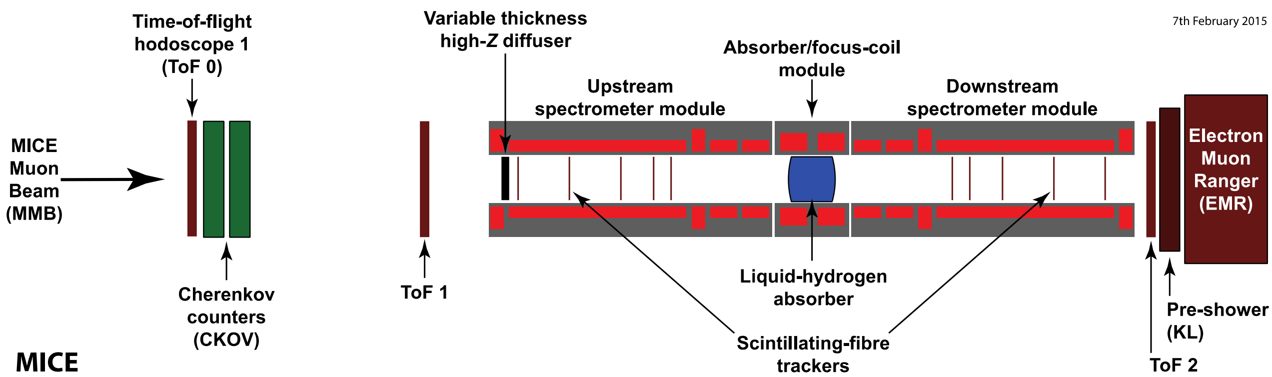

Figure 1: Schematic diagram of MICE in its final configuration (Step IV).

The position and momentum of each muon is measured by the trackers along with the time-of-flight, the latter also provides particle identification. Selection criteria were imposed on each track to select a 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 [9], to the Molière model [10] as well as to a stand-alone scattering model developed by Carlisle and Cobb [11]. Data taken with LiH on a full range of beams, 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 $\Theta = 23.3 \pm 0.9 \pm 0.2$ mrad at 172 MeV/c, $\Theta = 17.9 \pm 0.4 \pm 0.5$ mrad at 200 MeV/c and $\Theta = 14.2 \pm 0.1 \pm 0.5$ mrad at 240 MeV/c in LiH. The preliminary analysis indicates that the PDG model overestimates [12]. The PDG recommended formula is:

$$\theta_0 = \frac{13.6\,\text{MeV}}{p_\mu c \beta_{\text{rel}}} Z \sqrt{\frac{\Delta z}{X_0}} \left[1 + 0.038 \ln \frac{Z^2 \Delta z}{\beta_{\text{rel}}^2 X_0} \right]. \quad (2)$$

Data were collected over a wide range of momenta. The data were then binned in momentum and the analysis repeated for each bin with the scattering width determined in each case. The angular distribution has been fitted with an expression with a $1/p\beta$ dependence of a similar form to the Rossi and Greisen expression for the RMS scattering recommended by the PDG [13] (Fig. 3).

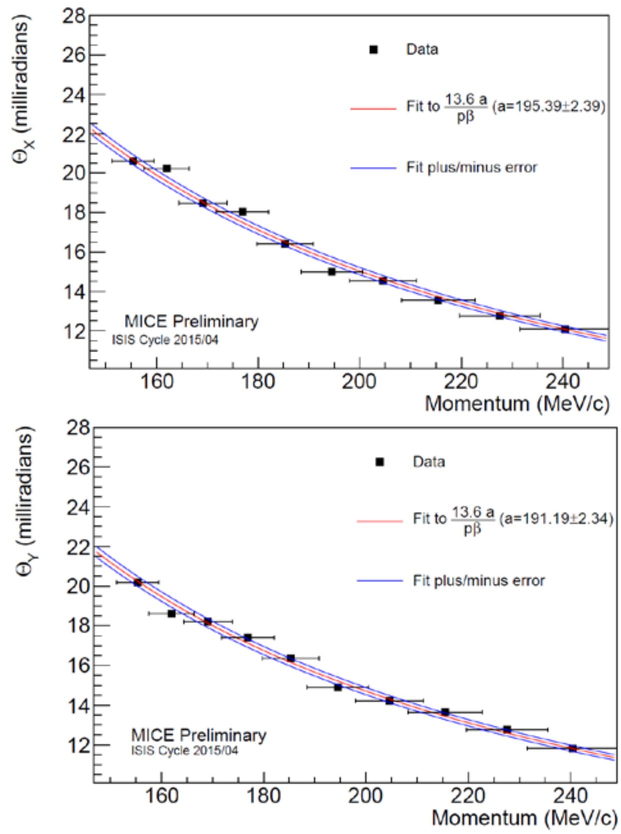

Figure 2: Results of the scattering analysis using data from all three nominal beam settings. Scattering widths are reported after application of deconvolution. Projected in the X-Z (top) and Y-Z (bottom) planes.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MOPO127

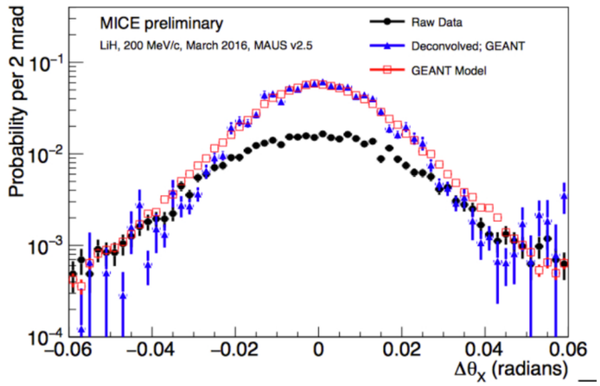

Figure 3: Scattering angular distributions in the X-Z plane, raw data and deconvolved data.

MEASUREMENT OF ENERGY LOSS

The mean rate of energy loss for relativistic charged heavy particles traversing matter is given by the "Bethe formula" [14]:

$$-\left\langle \frac{dE}{dX} \right\rangle = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right], \quad (3)$$

where the mean excitation energy, I, in hydrogen is known at the 5% level. Small differences are expected between the energy loss in LH_2 and in LiH.

MICE measured the momentum upstream and downstream of the absorber using information from the trackers combined with measurements of the time of flight. Data has been analyzed using central muon-beam momenta of 140, 170, 200 and 240 MeV/c in the presence of 3 T magnetic fields, with the LiH absorber (Fig. 4). 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. The final goal will be to determine the correlation between energy loss and multiple Coulomb scattering.

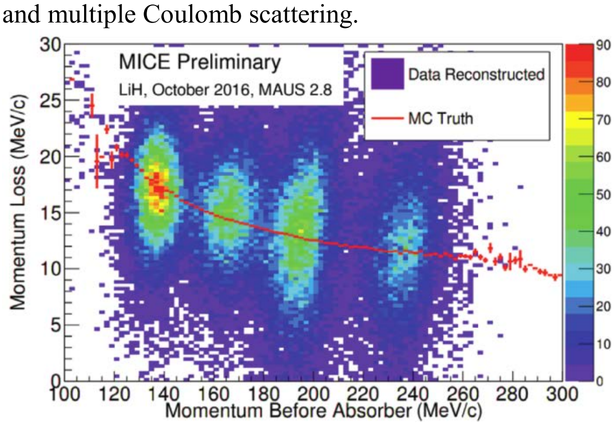

Figure 4: Distribution of the reconstructed momentum loss across the absorber compared with the MC truth.

CONCLUSION

MICE, at Step IV, has successfully collected all the required data in order to measure the properties of liquid hydrogen and lithium hydride that affect the performance of an ionization cooling channel. Step IV data taking commenced in 2015 and concluded at the end of 2017: scattering and energy loss measurements on LiH and LH_2 have been performed. 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. Several studies are in progress and results are in preparation for publication.

ACKNOWLEDGEMENTS

MICE has been made possible by grants from funding agencies from ten participating countries. We acknowledge the support of the staff of the STFC Rutherford Appleton and Daresbury Laboratories, and the use of Grid computing resources deployed and operated by GridPP in the U.K., http://www.gridpp.ac.uk/. The author acknowledges the support from China-US collaboration fund on High-Energy Physics jointly by CAS and IHEP.

REFERENCES

[1] S. Geer, "Neutrino beams from muon storage rings: Characteristics and physics potential". *Phys. Rev. D*, vol. 57, p. 6989, 1998.

[2] D. Neuffer, "Principles and applications of muon cooling", *Part. Accel.*, vol. 14, p. 75, 1983.

[3] D. Stratakis and R. Palmer, *Phy. Rev. ST Accel. Beams*, vol. 18, p. 031003, 2015.

[4] R. C. Fernow and J. C. Gallardo. "Muon transverse ionization cooling: Stochastic approach". *Phys. Rev. E*, vol. 52, p.1039, 1995.

[5] C. Patrignani *et al.*, (Particle Data Group), *Chin. Phys. C*, vol. 40, p. 100001, (2016, 2017 update).

[6] V. Blackmore, "Recent results from the study of emittance evolution in MICE", presented at IPAC'18, paper TUPML067.

[7] MuScat Collaboration, W. J. Murray, "Comparison of MuScat data with GEANT4", *Nucl. Phys. Proc. Suppl.*, vol. 149, p. 99-103, 2005.

[8] D. Attwood *et al.*, "The scattering of muons in low Z materials", *Nucl. Instrum. Meth.*, B251 (2006) 41.

[9] GEANT4 Collaboration, S. Agostinelli *et al.*, "GEANT4: A Simulation toolkit", *Nucl. Instrum. Meth. A*, vol. 506, p. 250-303, 2003.

[10] G. Moliere. Theory of the scattering of fast charged particles. 2. Repeated and multiple scattering. Z. Naturforsch., A3:78–97, 1948.

[11] T. Carlisle, "Step IV of the Muon Ionization Cooling Experiment (MICE) and the multiple scattering of muons". PhD thesis, Oxford U., 2013.

[12] R. Bayes, "Measurements of the Multiple Coulomb Scattering of Muons by MICE", NuFact16, 2016.

[13] B. Rossi, K. Greisen, "Cosmic-Ray Theory", *Rev. Mod. Phys.*, vol. 13, p. 240, 1941.

[14] S. Peter, "Particle penetration and radiation effects". Springer Series in Solid State Sciences, 151. Berlin Heidelberg: Springer-Verlag.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.