MICE OPERATION AND DEMONSTRATION OF MUON IONIZATION COOLING*

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on behalf of the MICE collaboration

Abstract

The international Muon Ionization Cooling Experiment (MICE) will demonstrate ionization cooling, the only technique that, given the short muon lifetime, can reduce the phase-space volume occupied by a muon beam quickly enough. MICE will demonstrate cooling in two steps. In the first one, Step IV, MICE will study the multiple Coulomb scattering in liquid hydrogen (LH_2) and lithium hydride (LiH). A focus coil module will provide focusing on the absorber. The transverse emittance will be measured upstream and downstream of the absorber in two spectrometer solenoids (SS). Magnetic fields generated by two match coils in the SSs allow the beam to be matched into flat-field regions in which the tracking detectors are installed. This paper will present preliminary results and present plans for data taking of MICE Step IV, together with the design of the MICE Cooling Demonstration Step (Step DEMO), which requires addition of RF systems in the current setup.

INTRODUCTION

A stored muon beam is capable of producing a high intensity, precisely known, flavor-pure neutrino beam, and can provide a source for a multi-TeV muon collider [1–3]. The muon beam is generated from pion decay, where the pion beam is produced by bombarding a target with a high-power proton beam. Muons generated in this way occupy a large phase space volume, which is hard to accept using traditional accelerator components. In order to increase the acceptance, the beam must be cooled before acceleration. Because of the short lifetime of muons, traditional cooling methods do not suffice. In ionization cooling, all components of the muon momentum are reduced when the beam passes through an absorber. The longitudinal momentum is then restored with re-acceleration [4]. The dependence of the normalized transverse emittance of a muon beam passing through a medium is given by:

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

where ϵ_n is the normalized transverse emittance, $\beta = v/c$, E_μ the energy in GeV, $\beta_\perp$ the transverse Courant-Snyder betatron function, m_μ the muon mass in GeV/c^2, and X_0 the radiation length of the material. MICE will be the first experiment to demonstrate the reduction of the transverse phase space volume of a muon beam at a momentum useful for neutrino factory and muon collider applications.

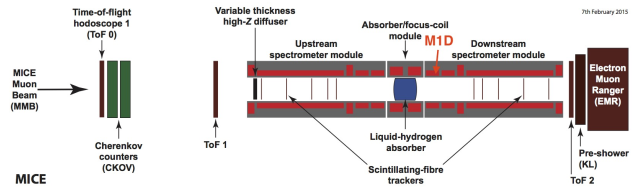

Figure 1: The schematic drawing of the MICE Step IV beamline configuration. The red label marks the position of M1D, which will stay powered off during Step IV due to a failure in Sep. 2015.

Step IV of MICE will make detailed measurements of multiple Coulomb scattering and energy loss of muons in the absorber materials over a range of momenta from 140 to 240 MeV/c. The collaboration also seeks to measure transverse normalized emittance reduction in a number of lattice configurations [5]. A schematic drawing of MICE Step IV is shown in Figure 1. The phase space volume of the beam is measured in the upstream and downstream spectrometer solenoids (SSU and SSD) using scintillating-fiber (Scifi) trackers. Time-of-flight (TOF) detectors upstream of SSU and downstream of SSD are used for particle identification. There are twelve coils in the channel. Three coils, E-C-E, in each of the SSs provide constant fields within the trackers. Two coils, M1 and M2, in each of the SSs provide matching into the focus coil (FC) module, and two coils in the FC module provide beam focusing onto the absorber. MICE Step IV will be operated in both flip and solenoid modes, where the direction of longitudinal magnetic field, B_z, flips across the absorber in flip mode and stays the same in solenoid mode.

In the next and final step of MICE, which is the demonstration of the ionization cooling, or Step DEMO, RF cavities and two additional absorber modules will be introduced. In this step, the unnormalized transverse emittance of the beam will be reduced with RF re-acceleration. The goals of MICE Step IV and Step DEMO are described in Table 1.

MICE STEP IV STATUS

MICE Step IV has completed its construction. Currently all the detectors described above are in place and working. MICE has developed its own comprehensive simulation software package, the MICE Analyses User Software (MAUS). MAUS was organized and written to combine the simulation requirements: to not only perform Monte Carlo (MC) simulations based on Geant4 core packages, but also to provide online monitoring and offline reconstruction of experimental data. MAUS has developed rapidly over the years and now is in version 2.6.0. In parallel, a G4beamline [6] simulation en-

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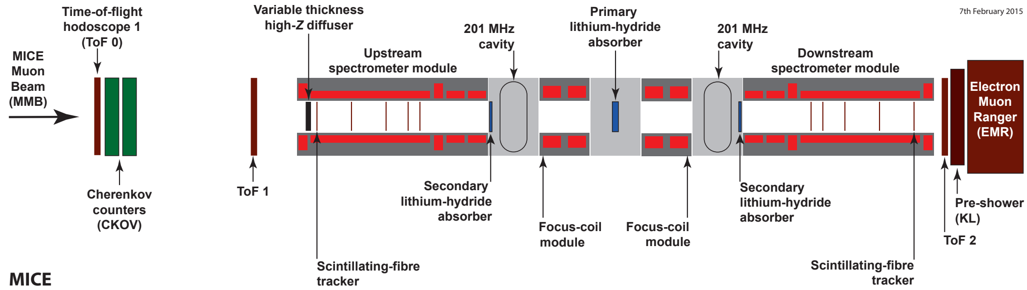

Figure 2: The schematic drawing of the MICE Step DEMO beamline configuration.

Table 1: MICE Physics Program Goals for Step IV and Step DEMO (Fig. 2)

Step IV:	Material properties of LiH and LH_2 that determine the ionization cooling performance Observation of the normalized transverse emittance $\epsilon_{\perp}^{n}$ reduction
Step DEMO :	Observation of transverse emittance $\epsilon_{\perp}$ reduction with re-acceleration Observation of $\epsilon_{\perp}$ reduction and $\epsilon_{\parallel}$ evolution Observation of $\epsilon_{\perp}$ reduction and $\epsilon_{\parallel}$ and angular momentum evolution

vironment with simplified MICE geometry was developed to simulate the muon beam in solenoidal field. The preliminary comparison of the two simulation tools showed good agreement. The comparison between the MC and measurement is continuing.

Both the upstream and downstream spectrometer solenoids have been tested at currents required by the design optics, However, the first downstream matching coil (M1D) was damaged and will remain inoperable throughout Step IV. The SSU magnet was tested and run at its full current in 2015, which provides a longitudinal magnetic field of B_z $\approx$4 T in TKU. In the summer of 2016, MICE successfully operated SSU, FC, and SSD together for the first time, providing B_z $\approx$3 T in both TKU and TKD. MICE also did a series of studies to find an optimized cooling channel optics without the M1D [7]. Using a Genetic Algorithm (GA) optimization on the coil currents, the Step IV optics was shown to be robust even without the M1D. The GA can also work as a tool to optimize the optics based on the measured input beam, and also to fit the data to a MC simulation. The applications of algorithms like the GA are being investigated.

In 2015 and 2016, MICE has taken initial Step IV data for tracker reconstruction validation and emittance measurement. Data were also taken for absorber material physics studies, including for an empty absorber (air in the absorber module), Xe and Lithium Hydride (LiH) absorbers. MICE is taking data to validate the optics design step by step, which includes untangling the effect of the upstream matching coils by using data taken with and without them energized. The preliminary qualitative comparison with the MC simulations shows that the beam behaved as expected in the channel. Detailed quantitative studies are under way. Data taken with SSU, FC and SSD on and an empty absorber is currently being analyzed. During runs in 2017, material physics data will be collected with a Liquid Hydrogen (LH_2) absorber, and data with LiH and LH_2 absorbers will be taken for measuring the normalized transverse emittance change in the cooling channel. A preliminary analysis showing the measured beam emittance and transverse phase space are shown in Figure 3.

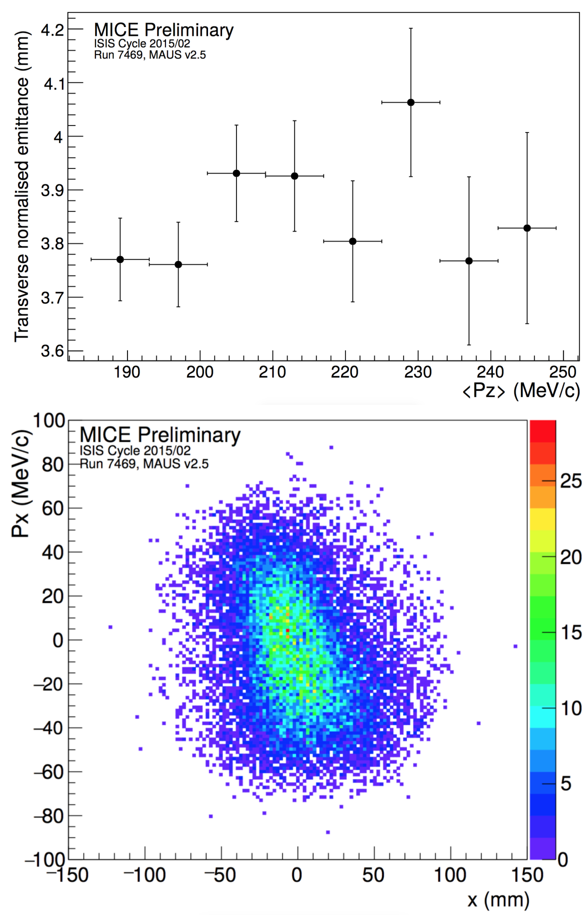

Figure 3: Measured emittance of the muon beam at TKU (upper) versus P_z and phase space distribution at TKU (lower).

Multiple Coulomb Scattering (MCS), which increases the beam emittance, plays a key role in the cooling equa-

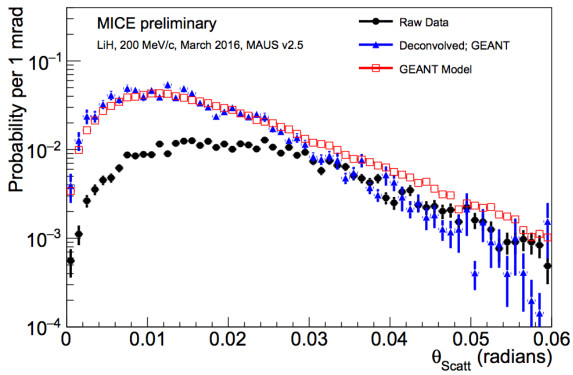

Figure 4: The comparison of $\theta_{scatter}$ given by MICE Step IV data and a Geant4 model with statistical errors only. The systematic errors of the measurements are being studied.

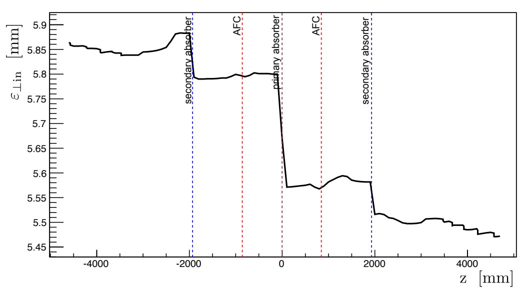

Figure 5: The Emittance reduction of an initial ϵ = 6 mm beam in the DEMO lattice with a 200 MeV/c beam setting.

tion. In order to understand MCS for low Z materials, data were taken with a LiH absorber at 172, 200 and 240 MeV/c beam settings. A Bayesian deconvolution was adopted to measure the scattering in an absorber material [8]. Preliminary analyses with statistical errors only yielded a Gaussian width of the projections of the scattering distributions of 15.6±0.1 mrad at 172 MeV/c, 12.8±0.2 mrad at 200 MeV/c, and 10.8±0.1 mrad at 240 MeV/c. The preliminary comparison of $\theta_{scatter}$ given by MICE Step IV data and the scattering model in Geant4 with a LiH absorber at 200 MeV/c is shown in Figure 4. The results indicate that Geant4 is inaccurate with low Z materials.

MICE STEP DEMO

The configuration proposed for the demonstration of ionization cooling is shown in Figure 2 [9]. Compared to Step IV, Step DEMO additionally requires two 201 MHz cavities and two secondary absorbers. The design parameters have been optimized to maximize the transverse emittance reduction and to minimize the beam loss. The emittance reduction of an initial ϵ = 6 mm beam in the DEMO lattice with the 200 MeV/c configuration is shown in Figure 5. The prototype RF cavity has been tested at Fermilab, and successful operation at MICE specifications has been demonstrated. The first production unit has been assembled at LBNL, and the assembly of the second unit is starting soon. Both units are scheduled to arrive at RAL by end of December, 2016.

CONCLUSION

MICE will demonstrate muon ionization cooling in two steps, Step IV and Step DEMO. Step IV construction is complete, and all the components are working. MICE has taken several sets of Step IV data, including emittance measurement data, material physics data for Xe and LiH absorbers, with straight tracks, and runs for optics validation with SSU, FC and SSD all powered on. The preliminary qualitative analyses showed that the measured optics agrees with the Monte Carlo simulations. Details about the measured optics are being studied. A prototype of the RF cavity required by the Step DEMO has been tested and met the MICE requirements. The assembly of the first production unit is done, while the second is being prepared. The cavities are scheduled to arrive at RAL by the end of December of 2016. MICE is taking more Step IV data for MCS measurements and to demonstrate normalized transverse emittance reduction.

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REFERENCES

[1] D. Adey *et al.* [nuSTORM Collaboration], “nuSTORM - Neutrinos from STORed Muons: Proposal to the Fermilab PAC,” arXiv:1308.6822 [physics.acc-ph].

[2] S. Geer, “Neutrino beams from muon storage rings: Characteristics and physics potential", in *Phys. Rev. D*, 1998, 57, 11, pp. 6989.

[3] C. M. Ankenbrandt *et al.* “Neutrino beams from muon storage rings: Characteristics and physics potential", in *Phys.Rev.ST Accel.Beams*, 1999, pp. 081001.

[4] D. Neuffer, “Principles and Applications of Muon Cooling", in *Proc PACart. Accel.*, 1983, 14, pp. 75.

[5] D. Rajaram *et al.* [MICE collaboration], “The status of MICE Step IV", `doi:JACoW-IPAC2015-THPF122`

[6] T. Roberts and Muons, Inc. “G4Beamline: a particle tracking simulation program based on Geant4", `http://www.muonsinternal.com/muons3/G4beamline`.

[7] A. Liu *et al.* [MICE collaboration], “MICE Step IV optics without the M1 coil in SSD", `doi:JACoW-IPAC2016-TUPMY006`

[8] R. Bayes *et al.* [MICE collaboration], “Measurements of muon multiple scattering in MICE", Proceedings, Neutrino 2016.

[9] J.-B. Lagrange *et al.* [MICE collaboration], “The MICE demonstration of muon ionization cooling", `doi:JACoW-IPAC2016-TUPMY004`