THE STATUS OF MICE STEP IV

D. Rajaram*, *on behalf of the MICE collaboration*
Illinois Institute of Technology, Chicago, IL 60616, USA.

Abstract

Muon (μ) beams of low emittance provide the basis for the intense, well-characterised neutrino beams of the Neutrino Factory and for lepton-antilepton collisions at energies of up to several TeV at the Muon Collider. The International Muon Ionization Cooling Experiment (MICE) will demonstrate ionization cooling – the technique by which it is proposed to reduce the μ phase-space volume. MICE is being constructed in a series of Steps. At Step IV, MICE will study the properties of liquid hydrogen and lithium hydride that affect cooling. A solenoidal spectrometer will measure emittance up and downstream of the absorber vessel, where a focusing coil will focus muons. The construction of Step IV at RAL is nearing completion. Its status will be described together with a summary of the performance of the principal components. Plans for the commissioning and operation and the Step IV measurement programme will be described.

INTRODUCTION

Stored muon beams for facilities such as a Neutrino Factory or a Muon Collider originate from decays of pions from proton-target interactions, and occupy a large volume in phase space. For efficient acceleration the phase space volume (emittance) must be reduced (cooled) significantly. Due to their short lifetime, ionization cooling is the only practical technique to cool beams of muons.

In ionization cooling, a muon beam passes through an absorber material losing momentum in both transverse and longitudinal dimensions. Subsequently the muons are re-accelerated whereby the longitudinal momentum is restored thus resulting in a net cooling. The dependence of the normalized transverse emittance on path length in a medium is given by [1]

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

where ε_N is the normalized transverse emittance, β the velocity in units of c, E_μ the energy in GeV, $\beta_\perp$ the transverse betatron function, m_μ the muon mass in GeV/c^2, and X_0 the radiation length of the material. The first term on the right describes reduction of emittance per unit length ("cooling") while the second term describes the effect of multiple scattering ("heating"). Equilibrium emittance is reached when the terms are equal and an ideal cooling channel would provide the smallest equilibrium emittance.

The Muon Ionization Cooling Experiment (MICE) [2] sited at the Rutherford Appleton Laboratory (RAL) is aimed at being the first demonstration of muon ionization cooling. It is designed to build a cell of a realistic cooling channel and study its performance under different conditions. The experiment was designed to be built and operated in a staged manner. In the first stage (Step I) which ended in 2013, the muon beamline was commissioned [3] and characterized [4]. The next stage – Step IV – will study the change in transverse emittance using LH_2 and lithium hydride (LiH) absorbers under various beam and optics configurations. In the final stage – the MICE demonstration of ionization cooling – two rf cavities will be added to enable re-acceleration and demonstrate ionization cooling of muons.

* durga@fnal.gov

STEP IV

A schematic layout of MICE Step IV is shown in Fig. 1. An absorber (LH_2 or LiH) is placed within a superconducting Absorber/focus-coil (AFC) module. Up- and down-stream of the AFC module are situated two superconducting solenoid trackers to precisely measure the emittance of the muons before and after they pass through the absorber. Particle identification, to reject contaminating pions, upstream of the absorbers is performed using two time-of-flight hodoscope (TOF) stations, and two threshold Cherenkov (Ckov) counters. Downstream of the absorber, contamination from decay electrons is rejected using a TOF, a pre-shower calorimeter and a fully active scintillator calorimeter (EMR). More detailed descriptions and status of the components follow.

Diffuser

The diffuser is designed allow varying the input emittance by inserting material into the beam. It sits just inside the upstream end of the first spectrometer solenoid and consists of four independently controllable irises of different thicknesses, two made of brass and two of tungsten. In total they provide 3 X_0 of material in steps of 0.2 X_0.

Spectrometer Modules

Two superconducting spectrometer solenoid magnets, one upstream and the other downstream of the absorber, house the scintillating fiber trackers. Each magnet consists of five coils wound on a common aluminum mandrel. A cross-sectional view of the magnet assembly is shown in Fig. 2. The center coil along with the end coils provide a uniform 4 T field over a 1 m long, 30 cm diameter volume. The two match coils and the first end coil act as a triplet to match the beam with the adjacent cooling channel. The magnets, shown in Fig. 3, were built by Wang NMR in Livermore, California in collaboration with Lawrence Berkeley National Laboratory. Both magnets were trained to the designed operating current and their fields were mapped. They were then shipped to RAL where they are now installed in the MICE experimental hall.

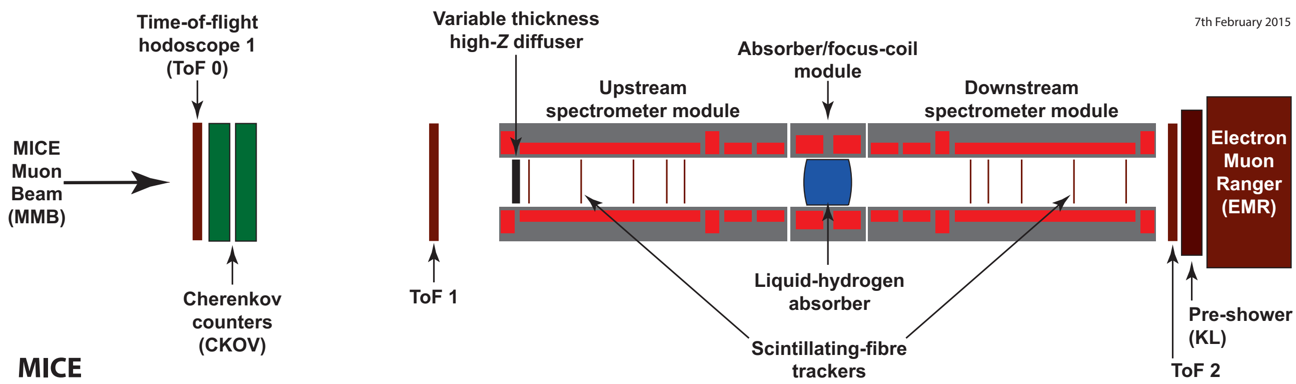

Figure 1: Schematic layout of MICE Step IV.

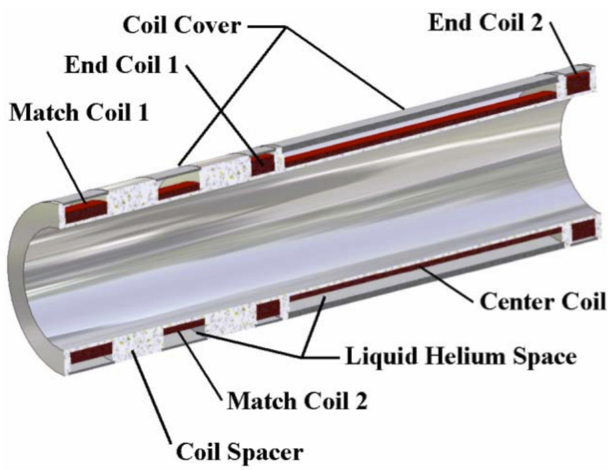

Figure 2: Cross section of a spectrometer solenoid magnet.

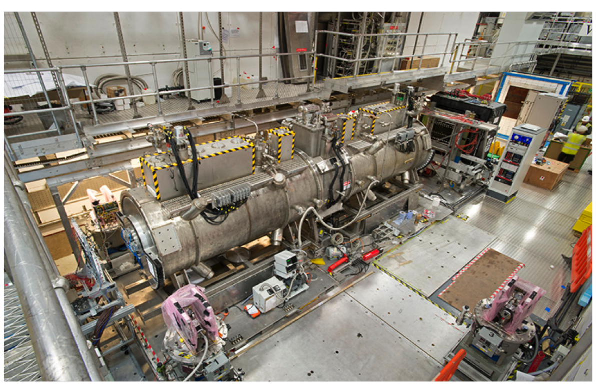

Figure 3: MICE spectrometer solenoids magnets installed in the experimental hall. The AFC module can be seen situated between the two solenoid modules.

AFC module

As can be seen from Eq. 1, lower equilibrium emittance is achieved by minimizing $\beta_\perp$ at the absorber. This strong focusing is provided by the focus-coil module which consists of two superconducting coils surrounding the absorber. The entire module connects to the adjoining spectrometer solenoids by means of bellows. The coils can be operated with the same ("solenoid mode") or opposite ("flip mode") polarities. Two magnets were fabricated by Tesla Engineering, UK. Both have been trained and their fields mapped in solenoid and flip modes. MICE Step IV will operate with one AFC module, which has been installed in the hall. The magnet will be commissioned in June-July 2015 in conjunction with the commissioning of the spectrometer solenoids.

Figure 4: The AFC magnet, before installation.

Absorbers

In order to minimize heating effects from multiple scattering in the absorber, a low-Z material is optimal. MICE Step IV will study the cooling performance of both LH_2 and LiH absorbers. The LH_2 absorber has a volume of 20.7 liters and is 35 cm long in the direction of the the beam. It was built at KEK and then delivered to RAL where the LH_2 delivery stem was tested. The LiH absorber is a 65 mm thick disk of radius 225 mm. Fig. 5 shows photos of the absorbers.

Tracking

Two scintillating fiber trackers [5, 6] measure the coordinates and momenta of charged particles before and after they pass through the absorber. The trackers cover an active

Figure 5: LH_2 absorber (left) and LiH disk (right).

area 30 cm in diameter and sit in the bore of the spectrometer solenoids. Each tracker consists of five planes, and in each plane 350 μm scintillating fiber doublets are arranged in three views oriented at 120° to each other. Neighboring groups of seven fibers are bundled into a clear fiber light-guide read out by visible light photon counters (VLPCs). The trackers provide a spatial resolution of 470 μm and were tested with cosmic rays and a spare plane was exposed to beam and the data were used to test the reconstruction of space points.

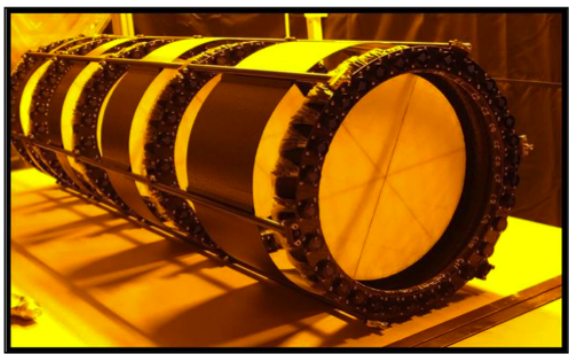

Figure 6: Photo of a scintillating fiber tracker.

Both trackers have been installed in the spectrometer solenoids. They have been instrumented and their electronics integrated with the data acquisition system. They will be commissioned with beam this summer.

Particle Identification

As described earlier, particle identification will be done using a combination of TOF, Ckov, KL and EMR detectors. Each TOF station consists of slabs of plastic scintillators arranged in horizontal and vertical views and provide a time resolution of 55 ps. The two Ckov detectors which sit just downstream of the first time-of-flight station have aero-

just downstream of the first time-of-flight station have aero-gel radiators with different indices of refraction. The KL pre-shower detector is a ~ $2.5X_0$ Pb and scintillating-fibers sandwich which degrades electrons. ~~Finally~~ at the downstream end of the experiment is the EMR [7] which is a fully active 1 m^3 volume consisting of 48 x/y planes with 59 scintillator bars in each plane. All the PID detectors have been installed and are being commissioned and calibrated with beam.

CONCLUSION

MICE Step IV will measure the cooling properties of liquid hydrogen and lithium hydride, and will also study emittance reduction with various beam and optics settings. Step IV construction is nearly complete. The spectrometer solenoid trackers as well as the Absorber/Focus-coil module have been installed in the beamline and will begin commissioning operations in June. The particle identification detectors are fully instrumented and have begun taking data for calibration. Preparations for the subsequent step with rf acceleration are on track [8] for MICE to demonstrate muon ionization cooling.

ACKNOWLEDGMENT

I wish to thank my colleagues in the MICE collaboration for their input.

REFERENCES

[1] D. Neuffer, 1987, "Multi-TeV muon colliders", AIP Conf. Proc **156**, 201.

[2] MICE website http://mice.iit.edu

[3] M. Bogomilov et al., 2012, "The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment", JINST **7**, P05009.

[4] D. Adams et al., 2013, "Characterisation of the muon beams for the Muon Ionization Cooling Experiment", Eur.Phys.J. C, **73**, 2582.

[5] M. Ellis, et al., "The design, construction and performance of the MICE scintillating fibre trackers", 2011, Nucl.Instrum. Meth. A **659**, 136.

[6] M.A. Uchida, 2015, "The Alignment of the MICE Tracker Detectors", these Proceedings.

[7] R. Asfandiyarov, "A totally active scintillator calorimeter for the Muon Ionization Cooling Experiment (MICE)", 2013, Nucl.Instrum.Meth. A**732**, 451.

[8] P. Snopok, 2015, "The MICE Demonstration of Ionization Cooling", these Proceedings.