MUON IONIZATION COOLING EXPERIMENT Step VI

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

Abstract

In the Muon Ionization Cooling Experiment (MICE) the transverse emittance of the muon beam is reduced (muon cooling) by passing the beam through a low-Z material and then through RF cavities to compensate for the loss in longitudinal momentum. Transverse emittance reduction of the muon beam will be demonstrated for the first time in MICE Step IV using liquid hydrogen absorbers as well as a variety of solid absorbers. Current status and efforts towards Step IV are summarized, including hardware fabrication and testing, and track reconstruction algorithms.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) [1, 2, 3] sited at the Rutherford Appleton Laboratory (RAL) is aimed at building and testing one full cell of a realistic cooling channel for future Neutrino Factories and Muon Colliders. Liquid hydrogen (LH_2) or solid absorbers will be used to reduce the emittance of the muons and RF cavities will be used to re-accelerate the particles and restore the longitudinal momentum lost in the absorbers. A 10% reduction in emittance will be measured with a relative precision of 1%. The beamline and most of the the particle identification detectors were commissioned (Step I) in 2010 [4] and analysis of the data is in progress. Step IV, scheduled for 2014, will make the first cooling measurements, and finally RF cavities will be added and the full cooling cell will be assembled and tested in Step VI [6] by 2019. The planned schedule of the experiment is shown in Fig. 1.

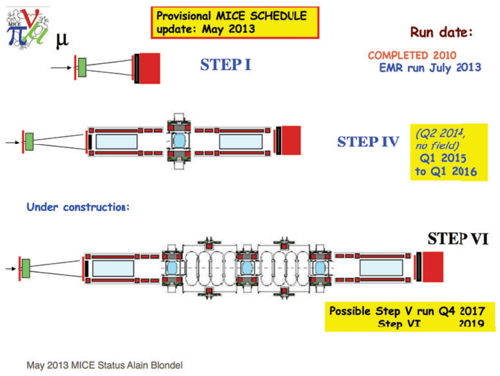

Figure 1: MICE schedule. Step I was completed in 2010 and the analysis is being refined.

STEP IV

The first experimental demonstration of transverse muon cooling will be made in Step IV of MICE. As shown by the layout of the Steps in Fig. 2, Step IV will add two scintillating fiber trackers immersed in a solenoidal field and placed upstream and downstream of an absorber-focus-coil (AFC) module which houses the absorbers. In addition to the particle identification detectors already commissioned (time-of-flight, KL sampling calorimeter), an electron-muon ranger (EMR) will be added to enhance and complete the particle identification. Assembly is expected to be complete by the second quarter of 2014 and data taking is planned to start from the first quarter of 2015.

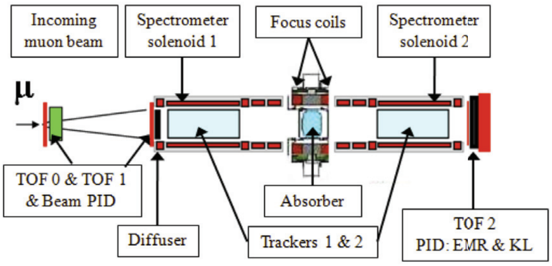

Figure 2: Schematic layout of MICE Step IV.

Spectrometer solenoids

The two spectrometer solenoid magnets which house the trackers are superconducting 4 T magnets each consisting of five coils wound on a common aluminum mandrel. A cross-sectional view of the magnet assembly is shown in Fig. 3. The two match coils and the first end coil act as a triplet to match the beam with the adjacent cooling channel. The center coil along with the end coils provide a uniform field over a 1 m long, 30 cm diameter volume. The magnets, shown in Fig. 4, were built by Wang NMR in Livermore, California in collaboration with Lawrence Berkeley National Laboratory (LBNL). The first magnet has been successfully trained to target currents and the cold mass is being held at liquid helium temperature in preparation for magnetic field mapping. The assembly of the second magnet is nearly complete after which it will be evacuated, cooled down, and trained. Both magnets will then be shipped to RAL this summer.

Tracker

There are two scintillating fiber trackers in MICE, one upstream and one downstream of the absorber, to measure the coordinates, angles and momenta of particles. The

---

* durga@fnal.gov

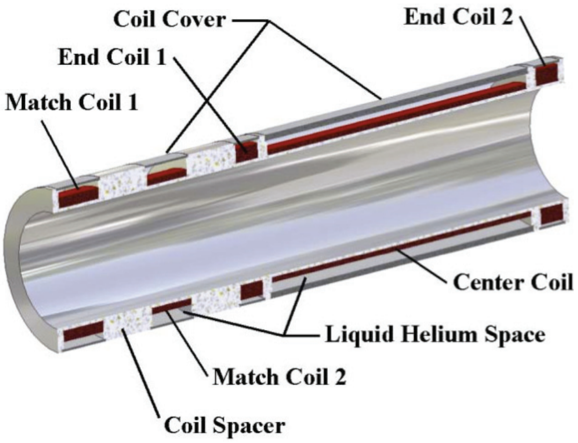

Figure 3: Cross section of a spectrometer solenoid magnet.

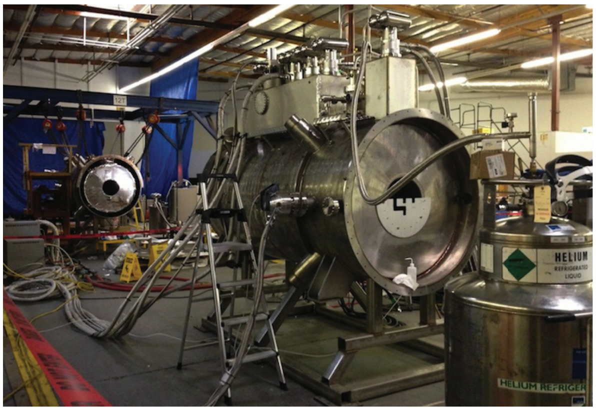

Figure 4: MICE spectrometer solenoids magnets. The magnet in the foreground has been trained and the one in the background is being assembled.

trackers cover an active 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. The trackers are read out by VLPCs and are measured to provide a spatial resolution of 470 μm.

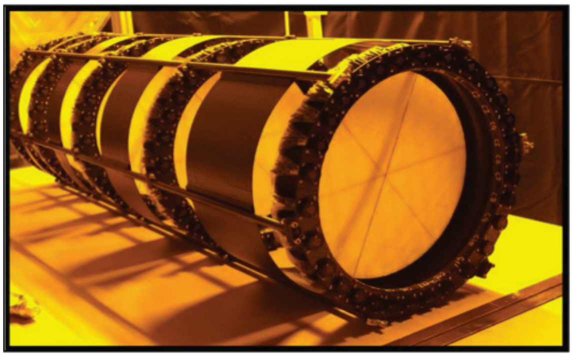

Figure 5: Photo of a scintillating fiber tracker.

Both trackers have been tested with cosmic rays. Fig. 6 (left) shows a display of cosmic ray events in the trackers and the photoelectron yield is shown on the right. The average photoelectron yield is ~ 11 and consistent with design and simulations. In May 2012, a "single-station" test was performed where a spare plane was exposed to beam and the readout electronics was tested and integrated with the data acquisition system. The data taken were also used to test the reconstruction of space points. The track reconstruction software is progressing well. Space-point reconstruction and pattern recognition are complete and full reconstruction based on the Kalman filter algorithm is being tuned.

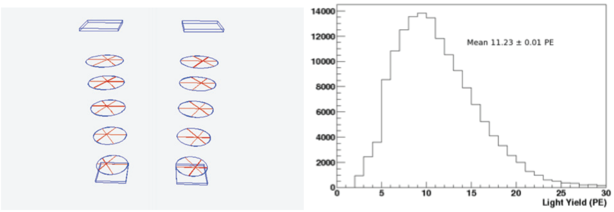

Figure 6: Display of a cosmic ray event in both trackers (left) and the light yield from cosmic ray tests (right).

AFC module

The Absorber Focus Coil (AFC) module sits between the two spectrometer solenoids and consists of two superconducting coils surrounding an absorber. As muons pass through the absorber their momentum is reduced in all three dimensions. The focus coils provide strong focusing to confine the beam and the coils can be operated with the same ("solenoid mode") or opposite ("flip mode") polarities. There will be one AFC module in Step IV, and two more will be added in Step VI for the full cooling cell. The magnets are fabricated by Tesla Engineering, UK. The first AFC magnet (Fig. 7) has been assembled and is being tested at RAL. It has reached the design current in solenoid mode and is being trained in flip mode after which it will be mapped and moved to the experimental hall. The assembly of the second AFC magnet is also nearing completion.

Absorbers

MICE will take data with liquid hydrogen (LH_2) and solid lithium hydride absorbers in Step IV with the possibility of adding other materials.

The LH_2 absorber, shown in Fig. 8 (left) has a volume of 20.7 liters and is 35 cm along the beam with a radius of 15 cm. It was built at KEK and has since been delivered to RAL where the LH_2 delivery stem has been tested with both LHe and LH_2. The LiH disk has been manufactured and was shipped to Fermilab where it has been measured and is now awaiting shipment to RAL. In addition to the LiH disks, we also plan to take data with LiH wedge absorbers (45° and 90° opening angles) to test longitudinal emittance reduction through emittance exchange. The wedges and absorber supports have been designed and are awaiting fabrication.

Figure 7: The first AFC magnet at RAL.

Figure 8: LH_2 absorber (left) and LiH disk (right).

EMR

The EMR is a 1 m^3 fully active scintillator calorimeter that will be located at the downstream end of the experiment. It is designed to stop all particles and the distinct shapes of the showers from $e^\pm, \mu^\pm, \pi^\pm$ will enhance the particle identification in MICE. The fabrication at the University of Geneva is nearly complete and an "EMR run" is planned for this summer. A prototype has been tested with cosmic rays and the simulation and reconstruction software are advancing. Fig. 9 shows a simulation of the interactions of $e^\pm$, $\mu^\pm$ and $\pi^\pm$ in the detector.

Software

MAUS – MICE Analysis and User Software – is the reconstruction and simulation framework for MICE. The primary goals of MAUS for Step IV are to provide 1) particle identification, 2) track reconstruction, 3) online reconstruction and monitoring, 4) simulation of the Step IV geometry, and 5) software tools for physics analyses. The tracker reconstruction is advancing and the Kalman-fitting algorithm is being polished. Reconstruction software for the particle identification detectors (time-of-flight, KL calorimeter) are in place. Once the tracker reconstruction is finalized, the information from the detectors will be combined to form "global" tracks with PIDs. The Monte Carlo simulation is based on Geant4. Geometric description and digitization of most of the detectors have been completed. A thorough test of the simulation and reconstruction software chain is planned for early 2014 to prepare for Step IV data-taking and analysis.

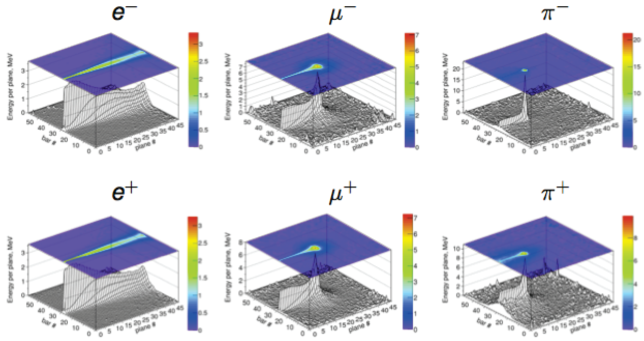

Figure 9: Simulation of 200 MeV/c $e^\pm, \mu^\pm, \pi^\pm$ in the EMR.

CONCLUSION

MICE Step IV construction is at an advanced stage. Both scintillating fiber trackers have been fabricated and tested. The first spectrometer solenoid magnet has been trained and the second is nearing completion. The first AFC magnet is on site and being trained. The LH_2 absorber has been built and the delivery system tested. Simulation and track reconstruction are progressing well. Step IV offers a rich experimental program with different absorbers and optics configurations and will provide the first demonstration of muon ionization cooling.

ACKNOWLEDGMENT

The authors wish to thank their colleagues in the MICE collaboration for their input and support.

REFERENCES

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

[2] G. Gregoire et al., 2003, Proposal to the Rutherford Appleton Laboratory, http://mice.iit.edu/mnp/MICE0021.pdf

[3] A. Blondel, 2013, "Progress of MICE, the International Muon Ionization Cooling Experiment", these Proceedings.

[4] 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.

[5] S. Virostek, 2013, "Assembly and Test of a Modified Spectrometer Solenoid for MICE", these Proceedings.

[6] D. Rajaram and P. Snopok, 2013, "Muon Ionization Cooling Experiment Step VI", these Proceedings.