

## THE STATUS OF THE CONSTRUCTION OF MICE STEP IV\*

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### Abstract

The International Muon Ionization Cooling Experiment will provide the demonstration ionization cooling. The experiment is being built in a series of Steps. Step IV, which consists of a tracking spectrometer upstream and downstream of an absorber/focus-coil module will be completed in early in 2015. In this configuration, the emittance of the muon beam upstream and downstream of the absorber will be measured precisely allowing the emittance reduction and the factors that determine the ionization-cooling effect to be studied in detail. Each tracking spectrometer consists of a scintillating-fibre tracker placed within a 4 T field provided by the superconducting spectrometer solenoid. The muon beam is transported to the absorber/focus-coil module: a 22 liter volume of liquid hydrogen placed inside a superconducting focusing coil. The properties of lithium hydride, and possibly other absorber materials, will also be studied. All the components of Step IV have been manufactured and integration of the experiment in the MICE Hall at the Rutherford Appleton Laboratory is underway. The construction and performance of Step IV will be described. A full study of ionization cooling will be carried out with Step V of the experiment which will include a short 201 MHz linac module in which beam transport is achieved with a superconducting “coupling-coil”. The status of the preparation of the components of Step V of the experiment will be described briefly.

### INTRODUCTION

The Muon Ionization Cooling Experiment (MICE) [1] is under construction at the UK’s Rutherford Appleton Laboratory (RAL). It will demonstrate for the first time the feasibility of ionization cooling of muons [2]. The MICE apparatus (Fig. 1) comprises two absorbers and a linac module sandwiched by the input and output spectrometers and particle identification and timing detectors that will be used to characterize the cooling process experimentally.

Ionization cooling is achieved in MICE by placing the absorbing material in the beam line. The absorbing material reduces beam momentum, which is replaced only in the longitudinal direction by acceleration in RF cavities, resulting in a net reduction of emittance. Overall, transverse emittance is reduced while longitudinal emittance stays the same or increases slightly due to stochastic processes in the energy loss. The process can beneficially continue until an equilibrium is reached between the cooling effect of ionization and the heating effect of multiple scattering. Ionization cooling works optimally for momenta near the ionization minimum,

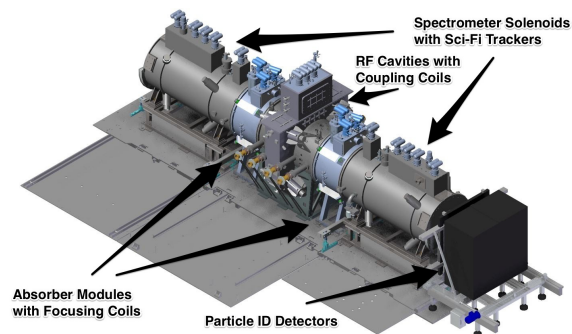


Figure 1: Engineering drawing of MICE Step V apparatus: two precision scintillating-fiber solenoidal spectrometers surround a cooling cell.

hence MICE is designed for the momentum range 140 to 240 MeV/c.

Once all the components are in place, a reduction in emittance will be measured with a relative precision of 1%. The beam line and the particle identification detectors were commissioned, and the results of analysis of the data presented [3,4]. Full results are expected by 2018, with analyses of some configurations available starting in 2015. Early results will include important validations of the models used in ionization-cooling simulation codes, as well as the first experimental test of muon transverse-longitudinal emittance exchange (needed for six-dimensional cooling, e.g., for a muon collider) in a wedge absorber.

### MICE STEPS

MICE was originally envisioned to be built in a series of six “Steps,” but due to technical considerations the abbreviated sequence was adopted shown in Fig. 2. Step I comprises of the pion-production target, pion-to-muon beam line, particle ID and time-of-flight detectors. Step I has already taken place, and the results are published. The last piece of equipment completing the list of detectors—the electron-muon-ranger (EMR)—was delivered to RAL in 2013, and tested with the muon beam.

### MICE STEP IV

MICE Step IV will measure the factors that determine the ionization cooling effect, with results expected starting in 2015. In addition to the Step I components, Step IV requires the two scintillating fiber trackers mounted inside spectrometer solenoids (SS) and one absorber focus coil (AFC) module. The trackers have been completed for some time and tested with cosmic rays.

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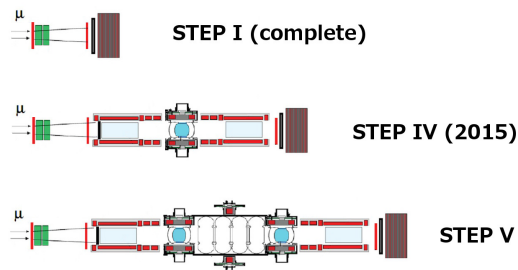


Figure 2: The Steps of MICE. Step I is complete, Step IV construction will be complete by 2015, Step V construction completion aim is 2017.



Figure 3: The first MICE spectrometer solenoid fitted with a fiber tracker is being moved to the MICE hall.

### Spectrometer Solenoids

Each SS is comprised of five superconducting coils: three to provide a 4 T field uniform to better than 1% over the 1-m-long, 40-cm-diameter tracking volume, and two to match the beam into or out of the cooling cell. The spectrometer solenoids have been built by Wang NMR in Livermore, CA, USA. Both SS were successfully trained to reach 102% of the operating current, field-mapped, and delivered to RAL (Fig. 3). Each SS will then be fitted with a fiber tracker before reaching the MICE experimental hall, a process already complete for one solenoid.

### Absorber Focus Coil

The Absorber Focus Coil (AFC) module shown in Figure 4 sits between the two spectrometer solenoids and consists of two superconducting coils surrounding an absorber. The focus coils have been built by Tesla Engineering Ltd., UK. 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”, requires lower currents in the coils) or opposite (“flip mode”, higher cur-

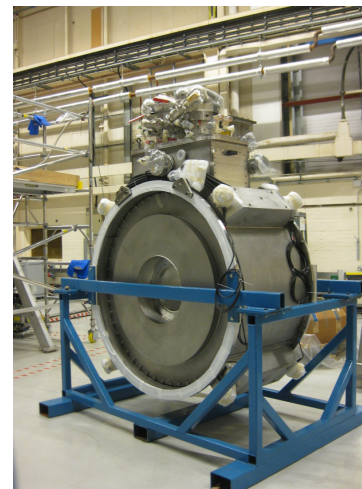


Figure 4: One of the MICE absorber focus coil modules at RAL.



Figure 5: Liquid hydrogen (left) and lithium hydride (right) absorbers.

rents) polarities. The first AFC has been trained to the full design current in “solenoid” mode, but has not reached the full current in “flip” mode. Nonetheless, at the moment it is the default magnet for Step IV, unless the second AFC shows performance superior to that of the first one and arrives on time, so that it can be swapped without affecting the schedule.

### Absorbers

The decrease in normalized transverse emittance will be observed and factors that determine ionization cooling effect studied in MICE Step IV, first with the liquid hydrogen (LH<sub>2</sub>) absorber shown in Fig. 5 (left), and then with a set of flat low-Z solid absorbers. The LH<sub>2</sub> absorber has a volume of 20.7 liters and is 35 cm along the beam axis with a radius of 15 cm. It was built at KEK and has since been delivered to RAL where the LH<sub>2</sub> delivery system has been tested with both LHe and LH<sub>2</sub>. The key solid absorber, a 65 mm thick LiH disk is shown in Fig. 5 (right). Both the disk and the support structure have been fabricated. While LiH will be the thickest solid absorber tested, the support includes spacers for mounting thinner disks made other materials. One of the aims of Step IV is to measure equilibrium emittance for different materials and experimentally test cooling theory predictions under a variety of conditions (different emittances, particle momenta and optics parameters).



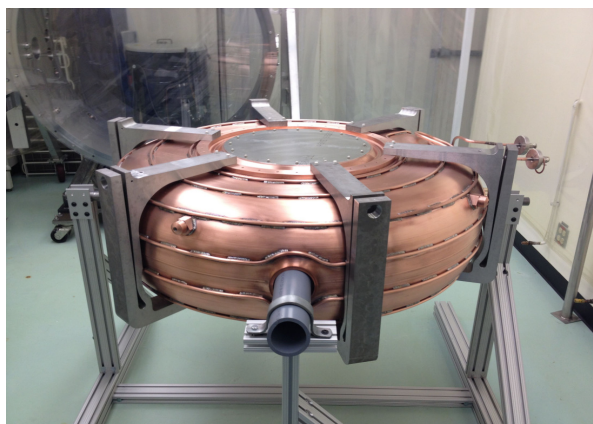


Figure 6: First MICE RF cavity being fitted with tuners at Fermilab.

## BEYOND STEP IV

MICE Step IV will allow the detailed characterization of ionization energy loss, multiple Coulomb scattering, and their effect on the ionization cooling process, and will thus validate the models used in muon ionization-cooling simulations. The goal of Step V representing the configuration shown in Fig. 1 is to test “sustainable” cooling with one full cell of the cooling channel. In Step IV particles lose momentum in all directions and the transverse emittance is reduced as they pass through the absorbers. The longitudinal momentum lost in the absorbers will be restored in Step V using re-accelerating RF cavities. By allowing a thorough exploration of the optics of ionization-cooling lattices, including those with periodic field flips and those with a modulated solenoid field, Step V will furnish a complete validation of the simulations.

### RF Cavity Coupling Coil

Step V requires (besides the components of Step IV) an additional AFC module and an RF-cavity-coupling-coil (RFCC) module containing four normal-conducting 201.25 MHz RF cavities with a guiding magnetic field provided by a large diameter coupling coil (CC) solenoid. All RF cavities have been fabricated and the first (Fig. 6) is being readied for testing in the Fermilab MuCool Test Area (MTA).

The 2.5 T superconducting CC magnets located around the RF cavity assemblies are the largest magnets in the MICE cooling channel and provide an additional longitudinal magnetic field to confine the beam between the absorbers. The coupling coil magnets and cryostats are designed by a collaboration between LBNL and the Harbin Institute of Technology (HIT), China. The first coil was wound at Qi-Huan Corp., China, and shipped to HIT. After preparation at LBNL it has been shipped to Fermilab where it is being tested and will be trained in the Solenoid Test Facility. Figure 7 shows the cold mass at Fermilab. During the first cold mass test



Figure 7: First CC cold mass at the Solenoid Test Facility at Fermilab after MLI rewrapping.

the heat load was too high, so numerous improvements were made to mitigate the issue. After that the CC has been tested and accepted. Fabrication of the needed cryostats and vacuum vessels (at LBNL, based on initial designs developed by SINAP) is also in progress, as is assembly of the RF control and power distribution systems by LBNL and Daresbury Lab.

## CONCLUSIONS

MICE Step IV construction is at an advanced stage. Both scintillating fiber trackers have been fabricated and tested. Both spectrometer solenoid magnets are at RAL. The first AFC magnet is being repaired, the second is being commissioned. The LH<sub>2</sub> absorber has been built and the delivery system tested. The construction of MICE Step V is progressing well. All RF cavities and windows for the RFCC module have been fabricated. An electropolished cavity is being outfitted for tests. The CC has been tested and accepted. Overall, MICE is progressing towards the first experimental study of muon ionization cooling. Step IV is planned for 2015 and the concluding Step V may be ready as soon as 2017. Once ionization cooling is established, the program leading to a neutrino factory with cooling could commence.

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