

## PROGRESS AND STATUS OF THE MICE PROJECT

A. Blondel, DPNC University of Geneva, Switzerland  
P. Drumm, CCLRC Rutherford Appleton Laboratory, Oxfordshire, UK

### Abstract

The muon ionisation cooling experiment (MICE) at the Rutherford Appleton Laboratory (RAL) is a demonstration of muon cooling in a linear channel. A new muon beam and infrastructure for MICE are funded and under construction with expected availability in spring 2007. Construction of MICE itself will be staged over the following few years, ultimately including RF accelerating cavities and liquid hydrogen absorbers with focussing by solenoidal magnetic fields, with beam emittance before and after cooling measured in tracking spectrometers. The current status of the beam line, infrastructure and MICE components is presented.

### INTRODUCTION

Ionization cooling of intense muon beams is a key technology for high-performance Neutrino Factories or Muon Colliders. A Neutrino Factory based on a muon storage ring is widely regarded as the ultimate tool for the study of neutrino oscillations and leptonic CP violation. Muon Colliders offer extremely clean high-energy lepton-antilepton collisions due to the low level of beam-strahlung and synchrotron radiation, and allow precision studies of s-channel-produced Higgs bosons.

MICE is an experiment [1] in which the tuneable emittance of muon beams from 140–240 MeV/c is precisely measured before and after a section of cooling channel. The MICE collaboration comprises 140 accelerator and experimental physicists and engineers from Belgium, Bulgaria, China (joined recently), Italy, Japan, Netherlands, Switzerland, UK and the US. The experiment is approved to take place on ISIS at RAL, with project management ensured by RAL.

### THE MICE EXPERIMENT

Driven by both experiment methodology and realities of funding, the experiment is designed to proceed in stages as shown in Figure 1. An engineering view of the complete experiment is shown in Figure 2. A muon beam of central momentum between 140 and 240 MeV/c is generated from 800 MeV ISIS protons by the MICE beam line. A set of PID detectors ensures muon purity better than 99.9%. The input beam is tuneable between 1-12 $\pi$  mm.rad input emittance. The 6D emittance is measured in a 5-station scintillating-fibre tracker immersed in a 4T uniform magnetic field provided by a superconducting solenoid. The tracker provides measurements of  $x, x', y, y'$  and particle energy, while the TOF counters provide the sixth phase-space coordinate,  $t$ .

The cooling section consists of a succession of absorbers and normal-conducting RF cavities, with a series of coils providing an axisymmetric magnetic field

that focuses and contains the muons. The exiting beam emittance is measured in a second spectrometer system (tracker and TOF) identical to the first one. Electrons from muon decay bias the emittance measurement and are removed by a calorimeter.

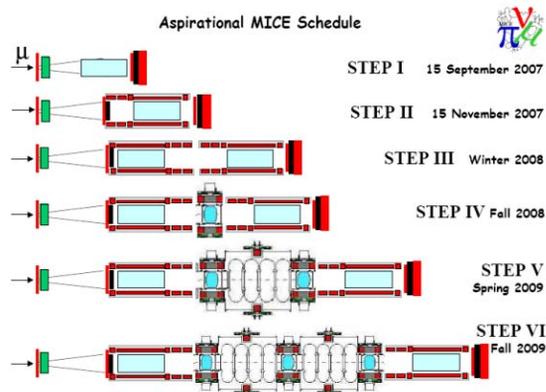


Figure 1: The MICE stages and aspirational schedule.

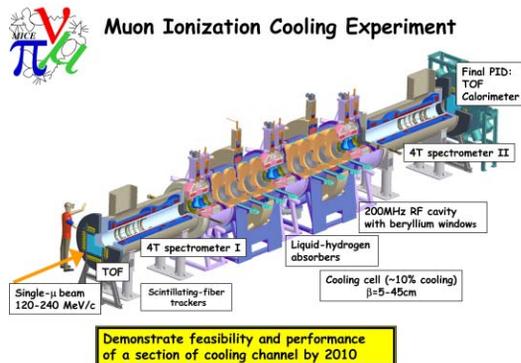


Figure 2: 3D engineering rendering of MICE.

In the current schedule, first beam will be available in mid-September 2007. At that point the main PID detectors will be ready as well as the tracker (without magnetic field). This will allow run-in of detectors and data acquisition and characterization of the beam composition (with an estimate of muon energy from the calorimeter). This 'Step I' will also be valuable for tracker alignment.

As soon as the first spectrometer solenoid becomes available, a measurement of particle momenta, and thus of emittance, will be possible, step II.

Step III is a crucial MICE step. By comparing directly two emittance measurements with high precision, it will allow a precise determination of the measurement biases and test the correction procedures. Steps I–III constitute the 'first phase' of MICE. With a caveat for the PID detectors (INFN), Phase I of MICE is fully funded.

Step IV will take place, assuming timely funding of the UK MICE Phase II bid, in fall 2008. A first measurement of cooling will be performed using the first absorber-focus-coil module. This will also allow a test of the focussing optics, both in flip (the pair of focus coils oppositely powered) and non-flip modes, for values of the optics  $\beta$  function from 5–42 cm.

With Step V begin tests of “sustainable cooling”, momentum lost in absorbers being restored in RF cavities.

Finally with Step VI, a full cooling cell will be tested.

### THE CHALLENGES OF MICE

While ionization cooling appears at first sight to be straightforward, its realization poses several challenges:

1. Operating RF cavities of relatively low frequency (201 MHz) at high gradient (16 MV/m) in strong inhomogeneous magnetic fields (1–3 T) can produce intense dark currents, heating the LH2 absorbers or causing cavity breakdown. This is under active development in the US MUCOOL program at Fermilab

2. Hydrogen safety with substantial amounts of LH2 in proximity to RF cavities.

3. The small cooling effect produced by an affordable device ( $\approx 10\%$ ) requires precision emittance measurement: MICE is designed for  $10^{-3}$  emittance measurement precision. This requires a highly segmented, low mass, precise tracker with low multiple scattering and high redundancy to fight dark-current-induced background and a complete set of PID detectors.

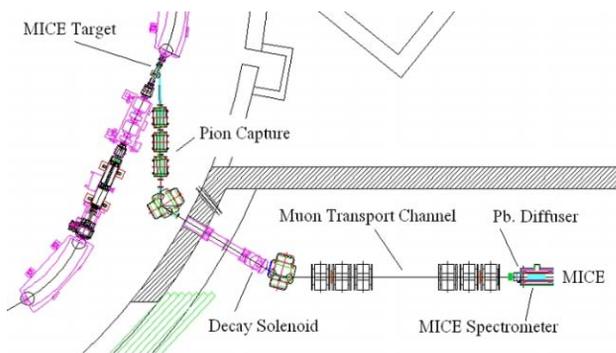


Figure 3: The MICE beam line at ISIS.

### STATUS OF THE PROJECT

#### Beam line

The MICE beam line is sketched in Figure 3. A pion beam is generated by dipping a small target into the proton halo during the 2 ms 800 MeV ISIS flat-top. The target design (Sheffield) is in process and an on-beam test is foreseen in October 2006. Issues are reproducibility and temperature stability of the mechanical system.

The pions are captured by a quadrupole triplet and momentum-selected by a dipole, all situated inside the ISIS vault. The design of this part of the beam line is complete and the beam elements are available. Pions decay within a 5-m-long, 12-cm-bore, 5T solenoid

provided by PSI in Switzerland. Refurbishing and warm testing of the solenoid are complete and the cryogenic plant has been purchased.

The pion-decay muons are momentum-selected in a second dipole. This second momentum is about half of the first (backward pion decay) ensuring excellent muon purity. In order to have a large momentum bite, the second bend angle is half the first. Matching of the beam and verification of its composition are performed in the last beam section, consisting of two quadrupole triplets. Tuning and alignment schemes are still under review. The first TOF station, a double-layer scintillator hodoscope (Italy), and the beam Cherenkovs (Belgium-US) are situated between the two triplets (see Figure 4). A second TOF at the entrance to the first MICE spectrometer, with 50ps resolution, complemented by the beam Cherenkovs, provide  $\pi/\mu$  separation up to 300 MeV/c. The TOF is prototyped to demonstrate the time resolution, with beam test in July 2006. The Cherenkov is in final design for beam test in summer 2006.

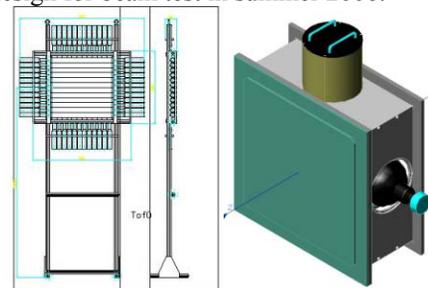


Figure 4: The upstream particle-ID detectors.

The beam emittance is generated by tuning the quadrupoles for beam size and generating the matched beam angular divergence in a variable-thickness beam diffuser. The diffuser has been designed as a re-entrant mechanism inside the first solenoid, automatically changeable in a few minutes from 0 to  $4X_0$  (Oxford).

#### Spectrometers

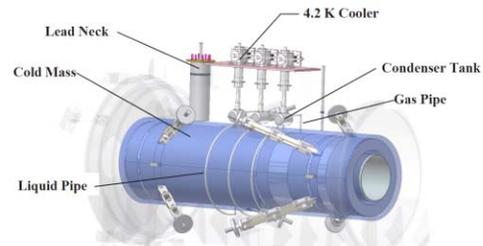


Figure 5: The MICE spectrometer solenoid.

The 2-m-long spectrometer solenoids (US) are required to provide 4-T field in a 1-m-long, 20-cm-radius, tracking volume. A main coil flanked by two correcting coils ensure the field uniformity; two additional coils on the downstream end provide matching optics into the cooling channel. These magnets are in the purchasing process with delivery expected in 2007, followed by measurement at Fermilab and shipment to RAL for installation in fall 2007. Magnet sensors (NIKHEF) will monitor the field during the many foreseen variations of MICE optics.

### Trackers

Development of the MICE trackers is in itself an international collaboration among Japan, UK, and US. A first four-station prototype has been constructed and tested first in a cosmic test bench in 2004, then in a beam test at KEK in 2005 with magnetic field.

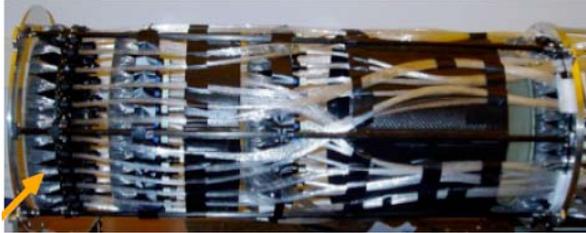


Figure 6: Four-station prototype of the MICE tracker.

The prototype showed alignment capabilities at the level of 5–10  $\mu\text{m}$  and 440- $\mu\text{m}$  resolution. The resolution achieved by the tracker in  $x$ ,  $x'$  is less than 10% of beam sizes at equilibrium emittance, ensuring unfolding of detector resolution from the emittance measurement with small systematics. Full production is expected starting fall 2006, with a careful QC process to avoid any loss of light yield or efficiency. The first tracker will be in place for the first beam in fall 2007.

### Downstream Particle ID

This features a TOF station and a calorimeter. The calorimeter separates muons from decay electrons. The design features a first layer of lead-scintillating fibre sandwich, similar to the calorimeter of the KLOE experiment in Frascati, followed by a fully sensitive segmented scintillator block of about  $1\text{m}^3$ . The calorimeter degrades electrons while the scintillator allows a precise measurement of muon range. First modules of the calorimeter have been built and will be tested in July 2006 in the Frascati BTF. The final setup, including shielding for magnetic field, is still under design, to be finalized and reviewed in October 2006.

### Controls and monitoring

Among the most interesting parts of MICE is the design of data acquisition and its connection with the control and monitoring system (CH, Japan, UK, US). MICE will run at 1Hz and record in one burst of 1ms up to 1000 muons. RF amplitude and phase, liquid hydrogen mass and many other parameters must be known so as to compare precisely the measured cooling effect to predictions. State of the art instrumentation will be constantly monitored and relevant parameters recorded in the data stream.

### The cooling cell: absorber-focus pair

The absorber focus-pair module integrates two functions of the cooling channel. An absorber reduces the muon momentum in all dimensions, and a pair of focusing coils reduces the beta function to ensure a small equilibrium emittance. The best absorption medium is hydrogen, but for large emittance far from equilibrium, a slightly less efficient but more practical medium may be

He or a solid such as LiH or Be. MICE is designed to test liquid or solid absorbers for a range of beta-functions. (Figure 7)

Critical issues with the hydrogen system are i) containment with metallic windows as thin as possible, ii) safety and iii) hydrogen storage. Absorber bodies and thin windows are under test in the MUCOOL programme at KEK and Fermilab. A prototype hydrogen system using metal-hydride beds as storage is under development at RAL. Safety reviews have been passed successfully—both internally and by the RAL safety office. Construction of the final system of absorber focus-pair modules will begin upon approval of the MICE-UK Phase II funding bid. R&D on these critical items is well advanced.

### Cooling channel: RFCC module

The MICE RF system requires relatively low frequency to handle the large beam, and must be located in a magnetic field, precluding use of SC cavities. A large ‘coupling’ coil surrounds the RF cavities. A sketch of a combined RF-coupling coil module is shown in Figure 7, together with the prototype 201-MHz cavity that has been powered at Fermilab up to 16 MV/m without magnetic field. Crucial high-magnetic-field tests await procurement of a coupling coil. RF power sources up to 4 MW are being refurbished at CCLRC Daresbury from used systems donated by Berkeley, and CERN has earmarked parts for another 4 MW system, allowing operation of MICE with a total acceleration of 23 MeV in Step VI.

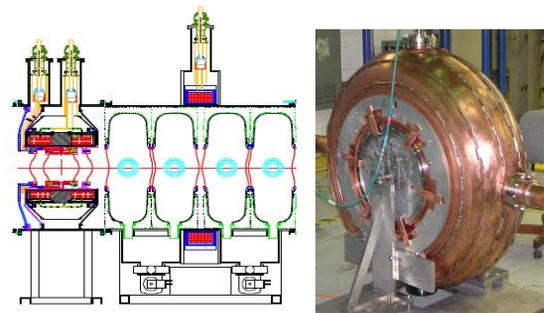


Figure 7: Engineering sketch of the RFCC module connected to the AFC module; the cavities are closed by violin-shaped Beryllium windows. Right: a 201-MHz cavity built at LBNL and Jlab.

Until recently funding for the MICE coupling coils was expected to cause significant delay to the experiment; encouraging signs have come recently for the MUCOOL coupling coil, and with the recent proposal by ICST Harbin (PR China) to join MICE with a contribution of two coupling coils. Realization of these proposals would allow MICE to follow the script of Figure 1.

## REFERENCES

- [1] The MICE web site, <http://mice.iit.edu> offers very complete documentation, links and references.