STATUS OF MICE: THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT

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Abstract

A key unanswered question in particle physics is why the universe consists only of matter. It is believed that CP violation in the lepton sector is the answer. The best tool to find this is a muon-based neutrino factory. Muons can also be used for an energy-frontier collider that would fit on an existing laboratory site. Since muons are produced as a tertiary beam, their phase space and energy spread are large and must be reduced (cooled) to create a usable beam. Ionization cooling, comprising momentum loss in material followed by RF reacceleration, is the only suitable technique. A transverse cooling channel is merely a linac with absorbing material in the beam path. To demonstrate an understanding of the physics and technology issues, MICE will test a section of cooling channel exposed to a muon beam derived from the ISIS synchrotron at RAL. The muon beam line is now installed and commissioning is under way. Fabrication of cooling-channel components and the required detector systems has begun. A successful demonstration will go a long way toward proving the value of muon beams for future accelerator-based particle physics experiments.

INTRODUCTION

Muon ionization cooling is the only practical method for preparing high-brilliance beams needed for a neutrino factory or muon collider. It reduces the transverse phase space of muons sufficiently to permit subsequent acceleration and storage in a practical acceleration system. This key enabling technology will be demonstrated experimentally for the first time in the Muon Ionization Cooling Experiment (MICE).

MICE is an experimental program to establish the feasibility and performance of ionization cooling. The approach is to measure precisely the emittance of 140–240 MeV/c muon beams both before and after an ionization-cooling cell. Implementing such a system will tell us about the subtleties of fabrication of the required components and, after comparing our results with detailed simulation predictions, will provide a validated tool for designing and optimizing the performance of a future neutrino factory and/or muon collider cooling channel.

The experiment is currently under construction at the Rutherford Appleton Laboratory (RAL) in the UK.

MICE BEAM LINE AND SCHEDULE

The secondary muon beam line at RAL's ISIS synchrotron is being built to meet the needs of MICE. The line will provide muon beams in the range of 140–240 MeV/c momentum, with normalized transverse emittance values in the range of 1–10 π mm-rad. The muon beam will be momentum-selected and transported to the MICE apparatus (see Fig. 1). Particle identification ensures better than 99.9% muon purity. Via magnet settings and a Pb diffuser of adjustable thickness, the transverse emittance of the input muon beam can be tuned. The input 6D emittance is measured [1] in a magnetic spectrometer comprising a five-station scintillating-fiber tracker mounted within a 4 T superconducting (SC) solenoid. The tracker determines x, x', y, y', and particle energy. The time-of-flight (TOF) counters measure the sixth phase space coordinate, t. The cooling cell consists of low-Z absorbers and normal conducting (NC) RF cavities, along with SC coils to provide strong focusing for the beam. The final emittance is measured in a second spectrometer system identical to the first one. Electrons from muon decay are eliminated from the data by calorimetry.

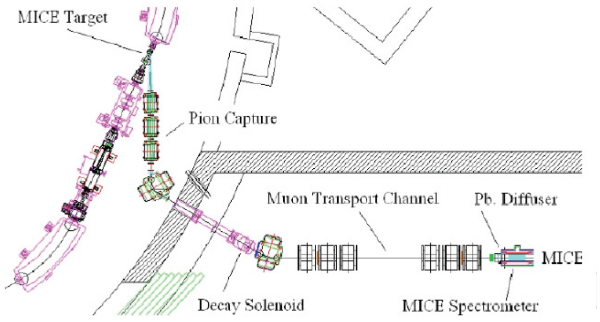

Figure 1: MICE beam line at ISIS, with two bending magnets and three quadrupole triplets.

The most important part of MICE is the cooling cell (see Fig. 2). It comprises three absorber–focus-coil (AFC) modules [2,3] and two RF–coupling-coil (RFCC) modules [4] (Fig. 3). Each hydrogen absorber contains about 20 L of liquid and is enclosed within a pair of room-temperature safety windows (Fig. 4) [5].

A pair of focus coils is employed to focus the muon beam, which results in a low equilibrium emittance for the channel. While hydrogen is best, for emittance far from equilibrium, a more practical absorption medium may be LiH, or Be. MICE is therefore designed to test both liquid and solid absorbers over a range of beta-function values. Critical hydrogen system issues are:

1. safety
2. use of the thinnest possible metal containment windows
3. hydrogen storage

A commercial metal-hydride storage system will be tested at RAL.

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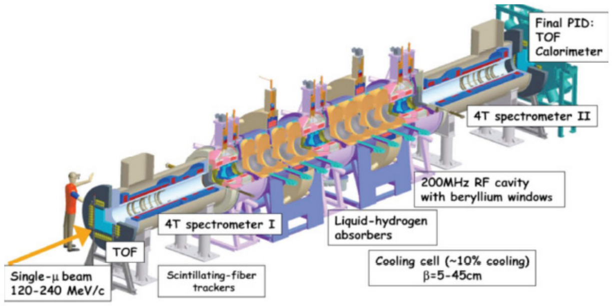

Figure 2: Cutaway view of the MICE cooling channel.

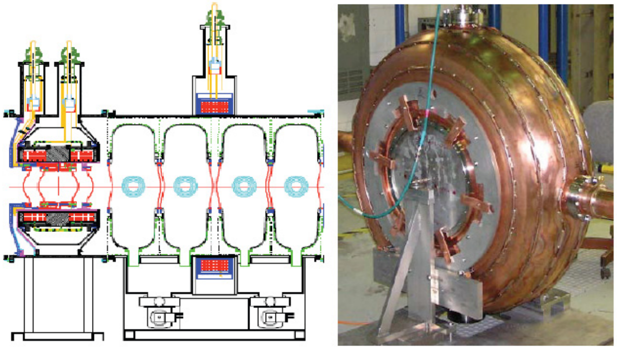

Figure 3: (left) Schematic diagram of AFC module connected to RFCC module, with cavities closed by curved Be windows; (right) a photo of the 201 MHz prototype cavity.

Since the beam to be cooled is large, the RF frequency must be low; due to the focusing magnetic field, NC cavities must be used to restore the energy lost in cooling. The eight 201 MHz RF acceleration cavities are very similar to the prototype cavity being tested in the MuCool Test Area (MTA) at Fermilab, and each will have Be windows on the beam apertures to close the cavity electro-magnetically. This is acceptable in a muon channel since the muons only interact weakly with material in their path. Compared with an open-cell cavity design, this method greatly improves the accelerating gradient of the cavity and is able to achieve ~18 MV/m in the 201 MHz cavity and ~40 MV/m in an 805 MHz ¼-scale prototype cavity with no magnetic field.

Although conceptually simple, both ionization cooling and its experimental verification pose challenges:

1. Operation of high-gradient (≈16 MV/m), low-frequency (201 MHz) RF cavities in strong (1–3 T) magnetic fields.
2. Safe designs employing substantial amounts of LH_2 near potential ignition sources.
3. The small effect (≈10%) of an affordable cooling device that leads to the goal of 10^{-3} emittance precision, requiring single-particle measurements rather than standard beam instrumentation.

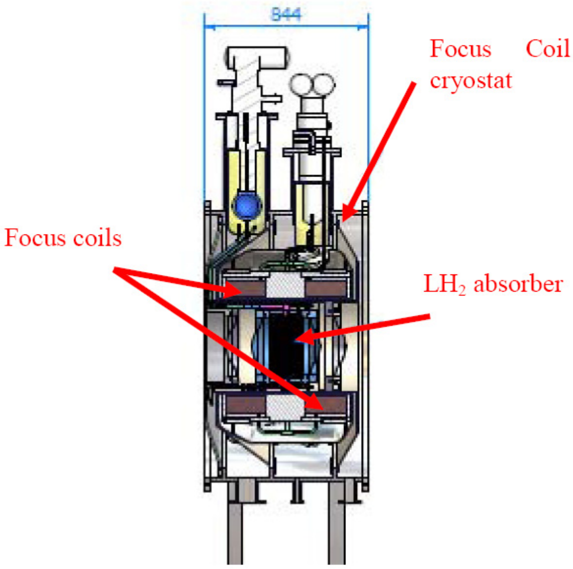

Figure 4: Side view of absorber–focus-coil module.

The staging of MICE (Fig. 5) allows careful calibration at each step and also reflects funding realities. Beam characterization and data acquisition have begun. Measurements of particle momenta and emittance will be possible once the first spectrometer solenoid is available. In Step III, up- and downstream emittance measurements will be precisely compared, which allows a precise determination of biases and testing of the required correction procedures. Step V will test "repeatable" cooling, in which the momentum lost in the absorbers is restored in the RF cavities. Step VI will test the full cooling cell.

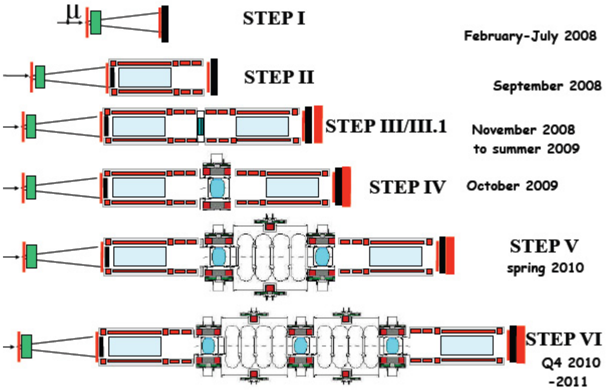

Figure 5: The planned stages of MICE.

CURRENT STATUS

The beam line is now operational. The pions from a small, movable Ti target grazing the ISIS proton beam during its 2 ms flattop are captured by a quadrupole triplet and momentum-selected by a dipole magnet. Muons from pions decaying within a 5 T solenoid of 5 m length and 12 cm bore are momentum-selected in a second dipole at a momentum about half that of the pions. Two aerogel

Cherenkov counters and TOF0 (Fig. 6) are placed between quadrupole triplets 2 and 3. Three two-layer scintillator-hodoscope TOF stations each provide 50 ps resolution.

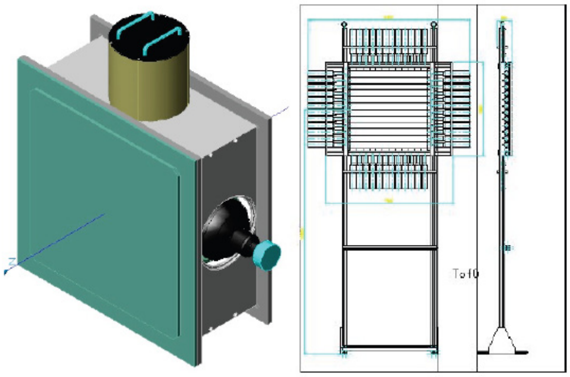

Figure 6: MICE upstream (Cherenkov and TOF) particle ID detectors.

The 2-m-long spectrometer solenoids (Fig. 7) will provide 4 T over a 1-m-long, 20-cm-radius tracking volume. Two end coils ensure <1% field non-uniformity and two matching coils at one end match optics in and out of the cooling cell. The magnets are on order for late-2008 delivery. This will be followed by field measurement and installation at RAL. Magnet sensors will monitor the field. Scintillating-fiber tracker 1 is completed and undergoing cosmic-ray testing and tracker 2 is in final assembly.

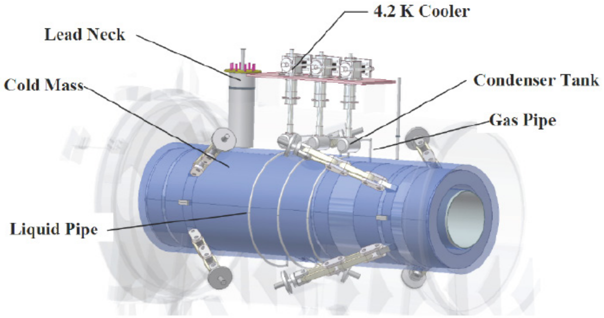

Figure 7: Schematic of spectrometer solenoid.

Downstream particle ID comprises TOF2 and a calorimeter to distinguish muons from decay electrons. A Pb–scintillating-fiber sandwich layer precedes a ≈1 m^3, fully sensitive, segmented scintillator block. The sandwich layer degrades electrons; the scintillator block precisely measures muon range. Prototypes have been tested and assembly of final detectors is in progress.

Currently, a CERN-refurbished 4 MW RF power source plus two 2-MW RF sources donated by LBNL give 8 MW in total, allowing 23 MeV of acceleration in MICE Step VI. The coupling coils are being constructed at the Institute of Cryogenics and Superconductivity Technology (ICST) of the Harbin Institute of Technology in China, in collaboration with LBNL. Crucial high-magnetic-field cavity tests await delivery of the first coupling coil.

MICE will run at ≈ 1 Hz and record up to 600 muons in each 1 ms beam burst. RF amplitude and phase, absorber mass, and other parameters must be precisely known for comparison with predictions and simulations. State-of-the-art instrumentation will monitor and record the relevant parameters.

MICE beam line commissioning started in February, 2008. The production rates of various particles, such as protons and pions, have been measured and particle identification has been made by means of Cherenkov light and time-of-flight measurements. Some representative results are given in Fig. 8, which demonstrates particle identification of both protons and pions.

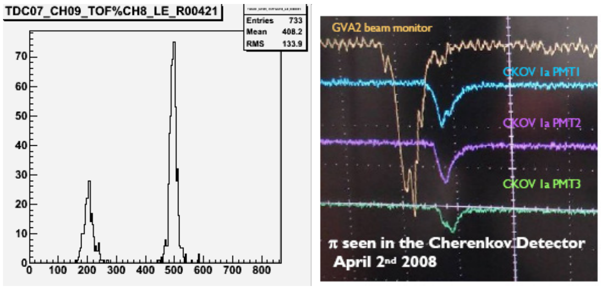

Figure 8: Representative MICE results. (left) Pions and protons separated through the time-of-flight with 414 MeV/c proton momentum at the first bending magnet; the left peak is pions, and the right peak is protons. (right) Cherenkov photomultiplier tube signals in coincidence with pulses from the second scintillating paddle indicating the passage of pions [6].

ACKNOWLEDGMENTS

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