STATUS OF MICE, THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT*

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Abstract

Muon ionization cooling provides the only practical solution to prepare high-brilliance beams necessary for a Neutrino Factory or Muon Collider. The Muon Ionization Cooling Experiment (MICE) is thus a strategic R&D project for future muon facilities. It is under development at the UK's Rutherford Appleton Laboratory. It comprises a dedicated beam-line to generate a range of input emittance and momentum, with time-of-flight (TOF) and Cherenkov detectors to ensure a pure muon beam. Emittance will be measured in a first magnetic spectrometer with a scintillating-fiber tracker. A cooling cell will then follow, alternating energy loss in liquid hydrogen and RF acceleration. A second spectrometer identical to the first one and a particle-identification system will measure the emittance of the outgoing muon beam. In the 2010 run, completed in August, the beam and most detectors have been fully commissioned, and first measurements of input-beam emittance have been performed using the TOF detectors. The staged plan of emittance and emittance-reduction (cooling) measurements that will follow in 2011 and beyond is presented.

INTRODUCTION

A Neutrino Factory or Muon Collider will create unique opportunities both to discover new physics and to study it with precision. The Neutrino Factory muon storage ring will produce the purest, most intense and well-collimated, high-energy neutrino beams ever. These beams will enable precise measurements of the parameters of the neutrino mixing matrix, with the possible discovery of neutrino CP violation. A Muon Collider will enable precise study of any new physics discovered at the LHC. As an example, the masses, widths, and couplings of neutral Higgs bosons could be precisely measured via *s*-channel production [1]—an option not available at e^+e^- colliders. For both of these muon facilities, means must be developed to cope with the large initial emittance and energy spread of the muons at production. In order for the muon beam to be efficiently accelerated, its emittance must first be significantly reduced. Due to the short muon lifetime (2.2 μs at rest), the only practical cooling technique is ionization cooling.

The Muon Ionization Cooling Experiment (MICE) will be the first experimental demonstration of the feasibility of muon ionization cooling. The goals of MICE are to fabricate a section of cooling channel capable of giving the required performance for a Neutrino Factory, install it in a muon beam, and measure its performance in a variety of operating modes and beam conditions, thereby demonstrating ionization cooling and validating the cooling simulations used to design future muon accelerator facilities.

EXPERIMENT LAYOUT

MICE is under construction by an international collaboration at the UK's Rutherford Appleton Laboratory (RAL) on a purpose-built muon beam-line [2] (Fig. 1). A titanium target [3], dipped into the ISIS 800 MeV proton beam at an ≈0.3 Hz repetition rate, produces pions, which are focused by a quadrupole triplet and momentum-selected ($p \approx 400$ MeV/c) by a dipole magnet (D1). Those that decay within a 5-m-long, 5-T superconducting solenoid (DS) send muons into a second dipole (D2), which selects particles of ≈200 MeV/c momentum, ensuring >99.9% muon purity. The muon beam is focused by a second quadrupole triplet, arrival times are measured (with ≈55 ps resolution) by the first two TOF hodoscopes (TOF0, TOF1), and two Cherenkov detectors reject residual pions [4]. An additional TOF hodoscope further downstream (TOF2) also contributes to particle identification (PID).

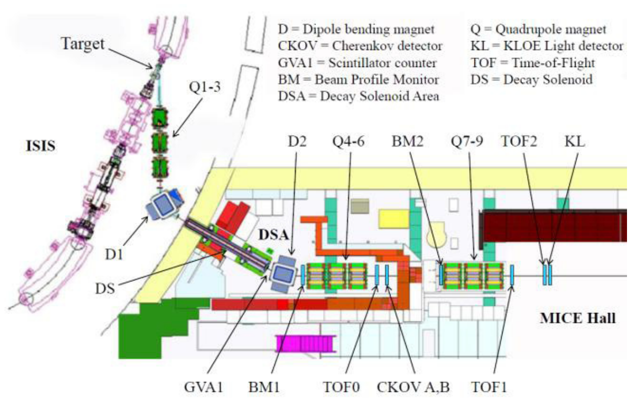

Figure 1: The MICE beam-line at ISIS [3].

Following the beam-line is a solenoidal spectrometer, which measures individual particle position and momentum using a scintillating-fiber tracker, then a 5.5-m-long section of cooling channel (see Fig. 2) [5]. Along with the quadrupole settings, a diffuser of adjustable thickness at the entrance of the solenoid helps generate a tuneable input emittance (3–10π mm.rad).

The full cooling section comprises three absorbers (liquid hydrogen, LH2, or solid lithium hydride, LiH) separated by two RF–coupling-coil (RFCC) modules. Each absorber is mounted within an absorber–focus-coil (AFC) module, with a pair of superconducting coils that provide strong focusing. Each RFCC module houses four normal-conducting, 201 MHz RF cavities within a solenoidal magnetic field.

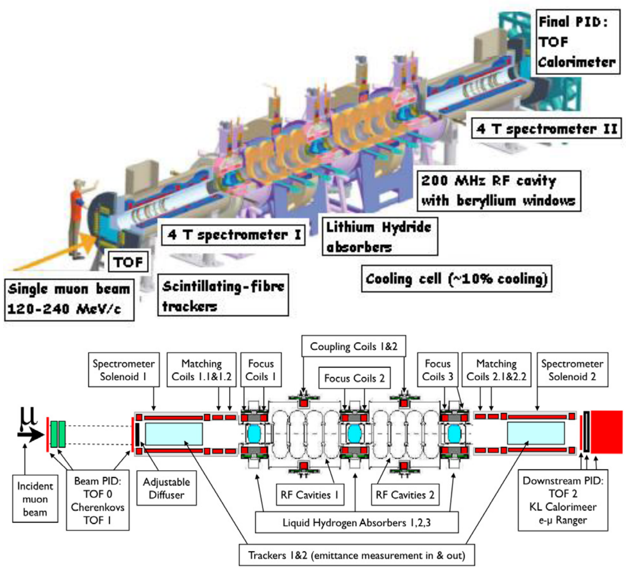

Figure 2: The MICE Cooling Channel: top, 3D cutaway view; bottom, 2D view.

After passage through the cooling section, the position and momentum of each muon are remeasured by a second spectrometer identical to the first. Finally, the TOF2 hodoscope together with a pair of calorimeters provide further time and PID measurements and reject background electrons from muon decay.

CURRENT STATUS

The MICE experimental program is planned to occur in steps (Fig. 3). Step I is underway and the preparation of the subsequent steps is in progress.

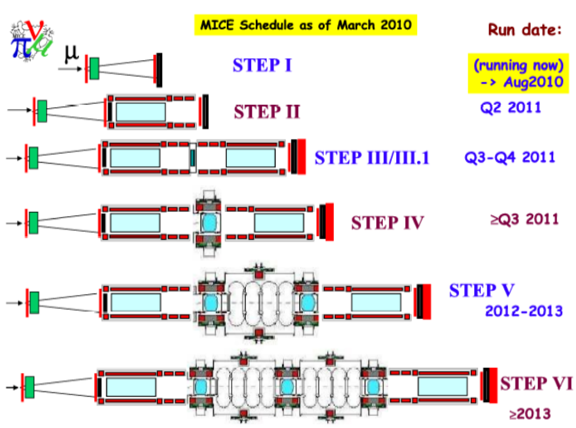

Figure 3: The MICE Steps.

Data Taking and Results

After a long break for component upgrading, installation, and repairs, including a redesign of the target and its bearings, MICE resumed data-taking in Sept. 2009 with all beam-line magnets operational. Since then, data-taking, on- and off-line event reconstruction, and analysis have been running routinely. Muon beams of positive and negative polarity have been studied (see Fig. 4) and first measurements of emittance using the TOF detectors have been performed.

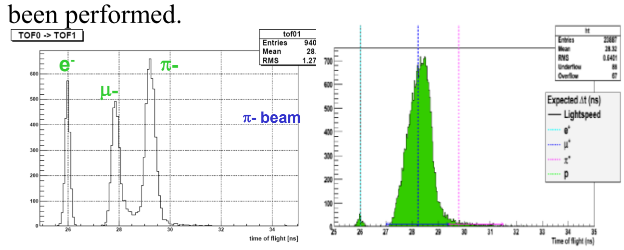

Figure 4: Time-of-flight (TOF) distributions for particles in (left) a pion beam and (right) a muon beam with a large energy spread (data taken Dec. 2009).

Target

The redesigned target has operated in ISIS for over 570k pulses with no sign of incipient failure (see Fig. 5) [6]. However, a second target, constructed in the same way as the first and operated in an assembly area, failed due to excessive bearing wear. An intense program of development has shown that plastic bearings can deliver in excess of 2.15M pulses with no evident wear. In diagnosing the behavior of the second target, attention is now focused on small asymmetries in the magnetic drive. Work continues with a view to producing two new targets by the end of 2010 [7].

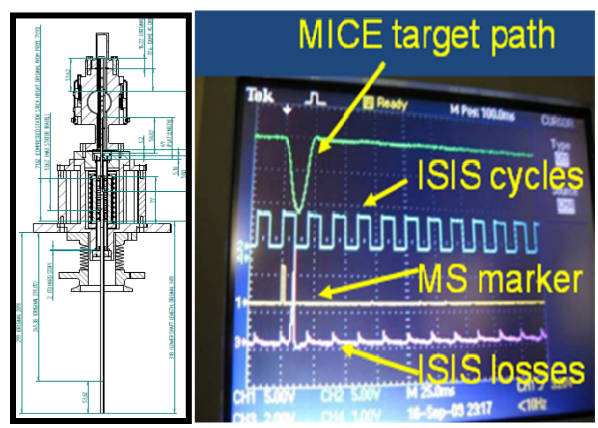

Figure 5: Left, target-assembly schematic diagram; right, on-line monitoring display of target operation.

Recent Progress

Both scintillating-fiber trackers have been completed and commissioned with cosmic rays. The construction of the Diffuser has made substantial progress (see Fig. 6). The final scintillation hodoscope, TOF2, was delivered to RAL in Nov. 2009 and is fully functional with a time resolution of 53 ps. An EMR (Electron-Muon-Ranger) module of the final design is under test in Geneva, and delivery of the complete detector is expected in early 2011. The on-line computer and monitoring systems have undergone continuous improvement in order to make operation of the experiment simpler and more reliable.

Cooling Component Progress

The LiH absorber, originally intended for Step III.1, has been resized so that it can also be used in the AFC module at Step IV. The LiH disk is now being manufactured, and a LiH wedge (for demonstration of emittance exchange [8]) is on order. The magnetic shielding plates have been produced and delivered to Fermilab. One liquid hydrogen absorber has been fabricated and successfully tested at KEK. To date, 11 absorber windows have been produced, two of which have been burst-tested at room temperature. The results of the burst test are consistent with the design specification. The design for the hydrogen delivery system in the MICE Hall is progressing. The cryostat and dummy absorber vessel required to test the system have been successfully commissioned with liquid helium.

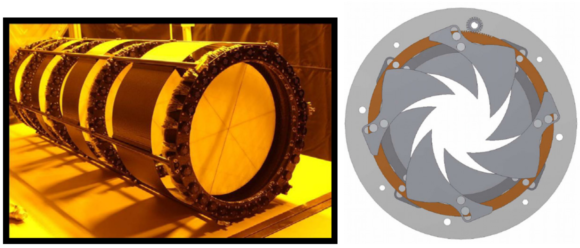

Figure 6: Left: Tracker. Right: Diffuser, new design, camera-iris type.

Fabrication of the first five RF cavities was completed in Dec. 2009. The beryllium windows are currently being manufactured (Brush Wellman Inc.), and three have been finished. Measurements of the electromagnetic properties of the cavities are in progress [9].

Solenoid Magnets

The fabrication of the spectrometer solenoids [10] is underway at Wang NMR under the supervision of LBNL. Although the construction of both magnets had been completed, the magnets failed during tests in 2008 and 2009. Since the other magnets in MICE have many features in common with the spectrometer solenoids, it is crucial to fully understand the problems with the spectrometer solenoids. After a detailed investigation, it was concluded that the HTS (High Temperature Superconducting) leads were insufficiently cooled and that the problem could be resolved by adding a single-stage cryocooler in the vicinity of the leads and making improvements to heat-conduction paths in this area.

The test results of the first spectrometer solenoid will be used to determine the final modifications to the second magnet. The first magnet was fitted with the additional cryocooler, equipped with a number of voltage taps, and kept cold in a state close to thermal equilibrium, allowing various measurements to be performed (see [10] for more details). The process to complete the necessary modifications to the magnets continues with a goal of retesting in early 2011.

The Focus Coil magnets are being manufactured by TESLA (UK). The first module will be delivered in Jan. 2011. The Coupling Coil magnets are in fabrication in China by Harbin Institute of Technology and Shanghai Institute for Applied Physics, with delivery expected in 2012.

MICE SCHEDULE

Due to the difficulties encountered in the commissioning of the spectrometer solenoids, the schedule for Steps II and III has slipped by about a year. It is anticipated that the first of these magnets will arrive at RAL in 2011, with the second to follow a few months later. Step I data taking ended in August 2010 with the start of a long ISIS shutdown. ISIS operation will resume in February 2011, by which time the full EMR detector, with 24 modules and magnetic shielding, is planned for installation in MICE. It is expected that a completed absorber will be assembled, tested and shipped to RAL by the end of 2010. Although there has been considerable progress on the construction of the RF cavities, the R&D on 201 MHz RF cavities in magnetic fields awaits delivery of the first coupling coil.

For this year the aim is to test a full high-power RF amplifier and to significantly advance design of the RF-power-distribution system in the MICE Hall [11]. Analysis of data taken during Step I will also continue in order to fully commission the MICE beam-line and detectors. The beam-line simulation will be optimized in preparation for the next steps of MICE, in which precise muon-beam emittance measurements will be made and muon cooling demonstrated.

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