STATUS OF THE MICE MUON IONIZATION COOLING EXPERIMENT*

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Abstract

Muon ionization cooling is the only solution to prepare high brilliance muon beams necessary for a Neutrino Factory or Muon Collider. The International Muon Ionization Cooling Experiment (MICE) is under development at the Rutherford Appleton Laboratory (RAL). A dedicated beam line generates a range of input emittances and momenta, with time-of-flight (TOF) and Cherenkov detectors to ensure a pure muon beam. A first measurement of emittance is performed in the upstream magnetic spectrometer with a scintillating fiber tracker. A cooling channel follows, alternating energy loss in liquid hydrogen with acceleration in RF cavities. A second spectrometer and particle identification system measure the outgoing emittance. By fall of 2009, the beam and first set of detectors will be commissioned, and a first emittance measurement will be made. An extensive plan of emittance and cooling measurements will then follow.

INTRODUCTION

The Neutrino Factory and Muon Collider[1] have each been proposed as a facility to understand fundamental questions in particle physics. In the Neutrino Factory, stored muons decay to produce a well-understood high intensity beam of muon, and uniquely, electron neutrinos to study the Golden oscillation channel: $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$. These key processes enable study of leptonic CP violation, the neutrino mass hierarchy, and unitarity, along with a rich program of neutrino interaction physics.

A Muon Collider would provide collisions with unique features, from low energy (100-1000 GeV) precise studies of Higgs or Higgs doublets, to exploration of center-of-mass energies reaching up to 4 TeV. Both accelerators require high brightness muon beams, and cooling is central to producing this intensity.

Due to the short muon lifetime, 2.2 μs, traditional beam cooling techniques, such as stochastic cooling, cannot be used. Ionization cooling, where the muon beam passes through liquid hydrogen (LH_2) absorbers followed by accelerating RF cavities, is the only viable option for such facilities. The beam loses both longitudinal and transverse momentum in the absorbers, but only longitudinal momentum is restored by acceleration in the RF cavities. This reduces the transverse emittance and cools the beam.

MICE[2] is an experimental program whose goal is to construct, commission, and test a fully engineered section of an ionization cooling channel based on the Feasibility Study-II[3] design. A 140-240 MeV/c muon beam will undergo a 10% reduction in transverse emittance, to be measured with a precision of 1%. The incoming beam can be tuned from 2 to 10 π mm-rad transverse emittance using beam optics and a variable thickness lead diffuser. The emittance will be precisely measured before and after the cooling channel by identical spectrometers, and the details of operating a cooling channel will be known.

MICE is an international collaboration with over 100 particle and accelerator physicists and engineers from Belgium, Bulgaria, China, Italy, Japan the Netherlands, Switzerland, the UK, and the US contributing to build this unique experiment and meet the challenges involved.

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MICE OVERVIEW

The MICE experiment is under construction at RAL on a dedicated muon beamline (see Fig. 1) at the ISIS 800 MeV proton synchrotron. A titanium target (UK) is dipped into the ISIS beam at the end of the 20 ms beam cycle at a rate of ~0.4 Hz [4].

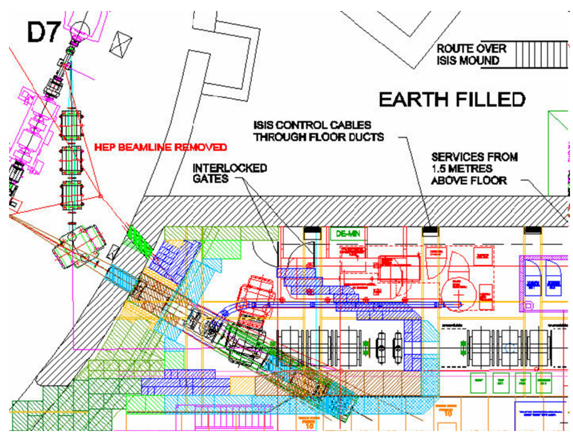

Figure 1: MICE beamline off the ISIS proton synchrotron at RAL.

Pions from interactions in the target are captured by a first quadrupole triplet and then momentum-selected by a dipole magnet. Following this dipole is a 5 m long, 5T superconducting decay solenoid to contain pions and their decay muons. The next dipole magnet is set to a lower momentum than the first to select a pure beam of muons. The muons are transported by quadrupoles to particle identification detectors (PID). These include a pair of time-of-flight (TOF) detectors (Italy) and two aerogel threshold Cherenkov counters (US-Belgium) which together provide π/μ separation up to 300 MeV/c. This particle identification ensures muon beam purity to better than 99.9%. The last quadrupole triplet leads into the MICE cooling channel (see Fig. 2).

The cooling channel is surrounded by TOF detectors and two 1.1m long, 20 cm radius, 5-station scintillating fiber trackers (UK-US-Japan) nested inside 2-m-long 4T superconducting spectrometer solenoid magnets (US).

The spectrometer magnets have four additional coils: two end coils to guarantee field uniformity and two coils to match optics with the cooling cells. The incoming and outgoing 6D emittances are measured by determining x, x′, y, y′, and particle momentum in the trackers, and by measuring t with the TOF counters.

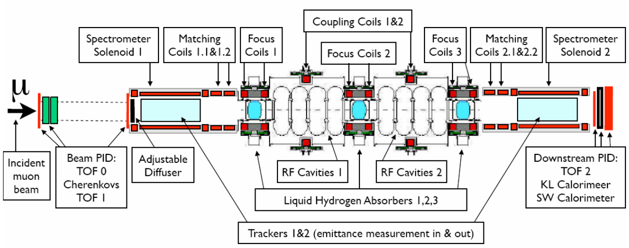

Figure 2: MICE cooling channel.

Liquid hydrogen absorbers alternating with normal conducting 201 MHz RF cavities provide the ionization cooling. The LH_2 absorbers are housed within an absorber-focus-coil (AFC) module with superconducting coils providing strong focusing at the absorbers. The RF cavities are low frequency because the beam size is large, and are normal conducting because they sit inside a focusing magnetic field. Two RF-Coupling Coil (RFCC) modules with three AFC modules make up the full cooling channel (see Fig. 3).

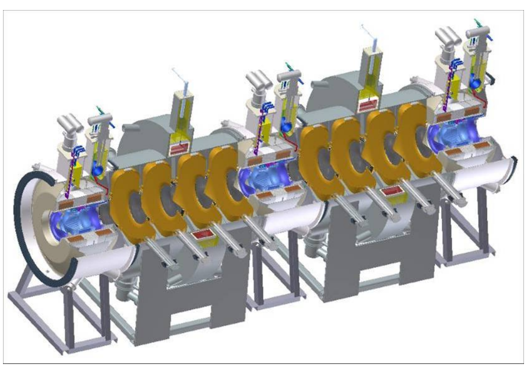

Figure 3: Full MICE cooling channel including three AFC modules and two RFCC modules.

Downstream PID is done using a third TOF detector and a calorimeter (Italy-Geneva-FermiLab) to distinguish between muons and decay electrons. The first part of the calorimeter is the KLOE-Like (KL) Pb-scintillating-fiber sandwich layer (Italy) which degrades electrons. It is followed by the Electron-Muon Ranger (EMR), a ~1 m^3 block of extruded scintillator bars. This fully active detector at the end of the MICE beamline will also measure muon momentum by range.

MICE STATUS

Beamline

Commissioning of the MICE beamline began in 2008 with first beam in March and data-taking to understand the conventional beamline magnet performance [5]. Protons, pions, positrons, and even muons could be seen clearly. These early commissioning data were taken without the decay solenoid; however, the magnet was recently ramped up to its full operating current. When data-taking resumes in September, the decay solenoid will increase muon rates by a factor of 10. A new target design has also been developed, parts are being fabricated, and the new system will be installed in ISIS in August.

Particle Identification Detectors

The first two TOF detectors were commissioned in the MICE beamline in the fall of 2008, and were found to have a timing resolution of ~55 ps [6]. Figure 4 shows the time-of-flight distribution for particles in a nominal 300 MeV/c π beam. The two threshold Cherenkov detectors used for π/μ separation at higher momentum are in the beamline and were commissioned. Figure 5 shows a typical signal from one Cherenkov PMT. The KL detector has been commissioned with cosmic rays, and exposed to pion and positron beams.

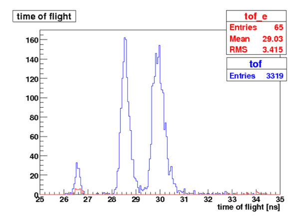

Figure 4: TOF distribution showing e^+, μ^+ and π^+ in a 300 MeV/c pion beam.

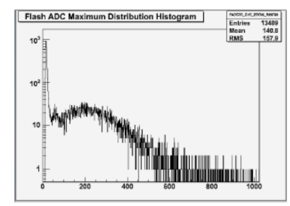

Figure 5: Light from a PMT on one of the Cherenkov detectors.

Spectrometers

Both scintillating fiber particle trackers are completed. Tracker 1 was tested using cosmic rays, and the same will be done for Tracker 2. Tracker 1 performed as designed with an average light yield of 11 photoelectrons (see Fig. 6), less than 0.1% dead channels, and position resolution consistent with the design goal of 430 μm [7].

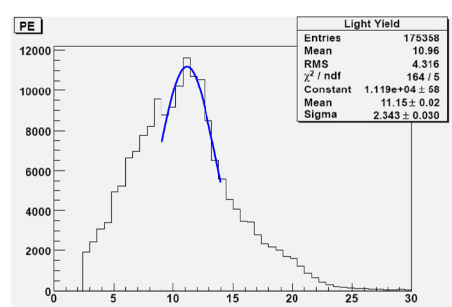

Figure 6: Light yield in first tracker determined using ~10,000 cosmic ray tracks.

Final assembly of the first spectrometer solenoid is complete [8]. The magnet has been cooled down to superconducting temperature. Preparations are under way to introduce current into the magnet and begin training the five coils simultaneously. After magnetic field mapping in May, the solenoid will be shipped to RAL where the TOF, diffuser, tracker, and magnet will be integrated and the entire spectrometer unit will be installed in the beamline. The second spectrometer solenoid will be delivered three months after the first.

Cooling Channel

The first LH_2 absorber has been fabricated at KEK and will soon be tested with liquid hydrogen. The thin aluminum windows for the absorber are made at the University of Mississippi. The absorber focus coils are manufactured in the UK with delivery expected in 2010.

The final design review of the MICE RFCC modules was done in 2008. The Harbin Institute of Technology in China has designed the coupling coils and will oversee their fabrication. LBNL is responsible for the design and fabrication of the cavities and will integrate the coils with the RFCC modules. The copper has been procured for the first five cavities, the material is being formed into half shells, and delivery will be made at the end of 2009. Fabrication of the coupling coils is under way in China, and the first unit will be delivered in summer 2010.

The MICE cavities each require ~1 MW of RF power in a 1ms pulse at a rep rate of 1 Hz. This is provided by four sets of amplifiers including Burle 4616 drive amps and 2.5 MW Thales TH116 main amplifiers donated by LBNL and CERN. These are being refurbished and tested at Daresbury Laboratory (UK) [9]. The first 4616 circuit has been completed and successfully tested. The first TH116 has been cleaned and repaired, and the RF surfaces have been silver plated. It is in the final stages of the rebuild and will be tested in summer 2009.

MICE SCHEDULE

MICE is proceeding in a staged manner (see Fig. 7) to ensure an accurate understanding of the experiment and to match funding profiles. The beamline is in place, and the experimental hall infrastructure is nearly complete for the first three steps. Step I, commissioning of the beamline and PID detectors, began in 2008 and will resume in September. With the decay solenoid operational, characterization of the muon beam will be possible. In November 2009, for Step II, the first tracker and spectrometer solenoid will be installed in the beam. At this point, a precise measurement of the incoming MICE emittance will be possible.

In the winter of 2010, the second spectrometer solenoid will arrive at RAL. During Step III, the emittance will be measured twice, and the tracking detectors can be compared and calibrated. This comparison will allow a precise determination of measurement biases and will test correction procedures. Step III.I involves the addition of a solid LiH disk between the two tracking spectrometers to test muon interaction with a different absorber material. While hydrogen is best for cooling, the LH_2 system comes with several challenges including use of very thin (~120 μm) aluminum containment windows, satisfying safety regulations, and hydrogen storage. Therefore, MICE has built in the capability to test other absorber materials.

In Step IV, the first liquid hydrogen absorber-focus-coil module will be installed and a first measurement of muon cooling will be performed in the summer of 2010. Step V will follow in 2011 when the first RF coupling coil module is installed and MICE will test sustainable cooling, where particle momentum lost in the absorbers is restored in the RF cavities.

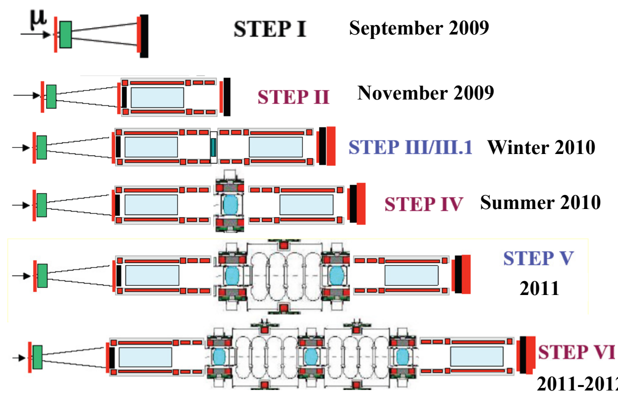

Figure 7: MICE schedule.

Finally, Step VI, running in 2011–2012, will meet the ultimate goal of MICE by operating a full cooling channel. Different configurations of the focusing optics in the central absorber will be fully tested. Information from these studies will inform the design of future muon accelerators, provide a practical understanding of the challenges involved in operating an ionization cooling channel, and present solutions to these challenges.

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