

# MICE: THE INTERNATIONAL MUON IONIZATION COOLING EXPERIMENT

Y. Torun\*, Illinois Institute of Technology, Chicago, IL 60616, USA  
for the MICE Collaboration

## Abstract

The MICE Collaboration has designed an experiment in which a section of an ionization cooling channel is exposed to a muon beam. This channel includes liquid-hydrogen absorbers providing energy loss and high-gradient rf cavities to re-accelerate the particles, all tightly packed in a solenoidal magnetic channel. It reduces the beam transverse emittance by  $>10\%$  for muon momenta between 140 and 240 MeV/c. Spectrometers placed before and after the cooling section perform the measurements of beam transmission and emittance reduction with an absolute precision of  $\pm 0.1\%$ .

## INTRODUCTION

A Neutrino Factory based on a muon storage ring is the ultimate tool for studies of neutrino oscillations, including possibly the discovery of leptonic CP violation [1, 2]. It is also the first step towards a  $\mu^+\mu^-$  collider. Ionization cooling of muons has never been demonstrated in practice but has been shown by end-to-end simulation and design studies to be an important factor for both performance and cost of a Neutrino Factory. This motivates an international program of R&D, including an experimental demonstration. The aims of the International Muon Ionization Cooling Experiment are:

- To show that it is possible to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
- To place it in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of cooling

A proposal [3] has been submitted to Rutherford Appleton Laboratory (RAL) to mount the experiment at ISIS.

## EXPERIMENT LAYOUT

The main components of MICE are outlined in Fig. 1. Cooling is provided by one lattice cell from the 201 MHz cooling channel of "Study-II" [4] with some components modified for cost savings and compliance with RAL safety requirements. The incoming muon beam first encounters diffusers to generate a large tuneable input emittance. In this section, a precise time measurement and particle identification are performed. Next comes an input spectrometer consisting of tracking devices within a uniform-field

solenoid to measure the phase space coordinates of each particle. This is followed by the cooling section, with hydrogen absorbers, rf cavities and superconducting coils. One additional absorber finishes the cooling section, both for symmetry and to protect the trackers against dark currents emitted by the rf cavities. The momentum, position and angles of the outgoing particles are measured in a second spectrometer, identical to the first one. At the downstream end of the experiment, another time-of-flight (TOF) measurement is performed, and particle identification by means of a Cherenkov counter and a calorimeter eliminates muons that have decayed in the apparatus. To avoid emittance growth, the magnets in these two cells are matched to the spectrometer solenoids using two sets of matching coils.

## MEASUREMENT TECHNIQUE

To allow precision measurement of transmission and emittance, one muon at a time will be tracked through the apparatus and detected using standard particle-physics techniques, which are much more precise than those typically used in beam instrumentation. A "virtual bunch" formed in offline analysis will be used to demonstrate how an actual bunch would have behaved had the beam intensity been orders of magnitude higher.

Momentum measurement requires a magnetic spectrometer. Ease of matching into and out of the cooling section and the need to keep a large-emittance beam in a small physical volume has led to the choice of solenoid magnets on each side of the cooling channel.

Each detector measures, at given z positions, the coordinates x and y of every incident particle, and the time. Momentum and angles are reconstructed by using several measurement planes. For the experimental resolution not to affect the emittance measurement significantly, the rms resolution of the measurements must be better than about 10% of the rms beam size at the equilibrium emittance in each of the six dimensions. An essential aim of MICE is to measure the equilibrium emittance precisely. For each incident particle it will be possible to determine whether it was lost in the channel or went through successfully. Therefore, losses can be separated clearly from cooling. Except for possible collective effects such as space charge, this technique is equivalent to full-beam measurements, but offers several advantages. Correlations between parameters can be easily measured. The role of each beam parameter (energy, transverse momentum, rf phase, etc.) can be studied using selection cuts in the ensemble of tracks without mak-

\* torun@iit.edu

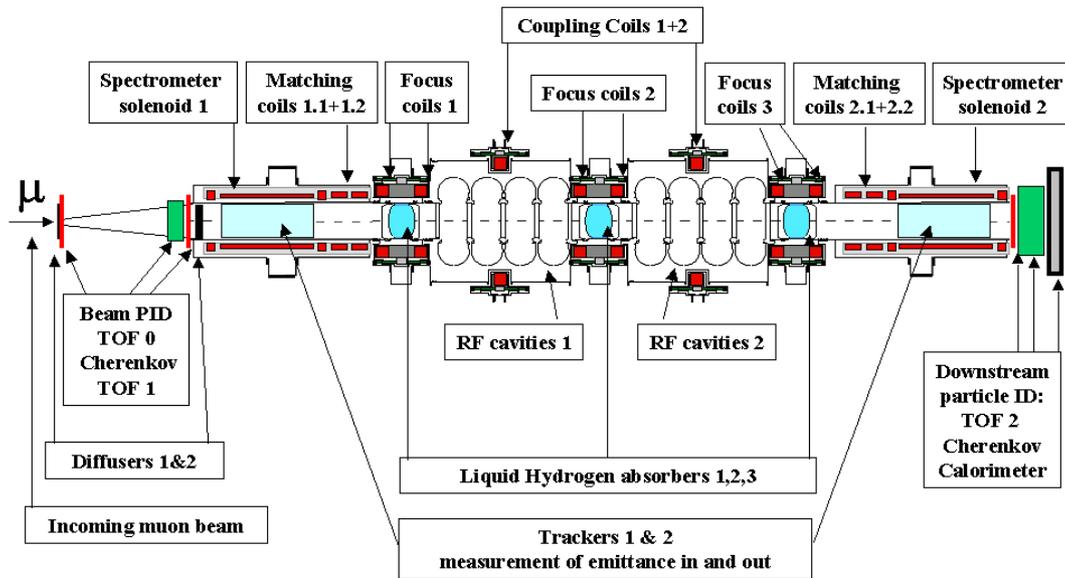


Figure 1: MICE layout.

ing changes to the beam parameter settings. Software cuts based on the incoming beam make it possible to derive a variety of results with different input beam conditions from a single data set. Any desired input beam conditions can be reconstructed by appropriate weighting or culling of the observed particles.

## RF BACKGROUND

The layout described above has one major drawback: the detectors will be exposed to a large dark current and x-ray background generated by the nearby high-gradient rf cavities. The understanding of this problem is well underway [5]. Several factors contribute to protect the tracking detectors: i) the rf cavities will be operated at a moderate gradient of 8.3 MV/m, due to the limited availability of rf power; ii) most dark-current electrons are deflected by the field flips [6]; iii) the electrons must also pass through the liquid-hydrogen absorbers, which are thick enough to absorb them completely, letting through x-rays only; iv) the detectors are built of low-Z material and are well able to distinguish muon hits from those generated by x-rays. Thus, it appears that the performance of the detectors will not be affected.

## POSSIBLE EXPERIMENTS AND TIMELINE

Many different cooling experiments can be performed with the proposed apparatus. First, beam momentum can be varied since the magnets have been designed to allow exploration of momenta as high as 240 MeV/c. The Super-FOFO lattice used here has the property that the beta function at the absorber can be changed by adjusting the currents in the focusing and coupling coils. Different rf volt-

ages and phases can also be used. Another important part of the experimental program will be testing various absorbers. It will be straightforward to replace the liquid hydrogen with liquid helium. The mechanical assembly of the liquid hydrogen absorbers will also allow replacement of one of the absorber windows by a structure supporting solid absorbers [7].

Since all detectors and parts of the equipment will not be ready at the same time, one can foresee a development of the experiment in time, to allow a number of preparatory stages. This leads to the scenario presented in Fig. 2. First (step I), the beam can be tuned and characterized using a set of TOF and particle ID detectors. In step II, the first spectrometer solenoid allows a first measurement of 6D emittance with high precision and comparison with the beam simulation. This should allow a systematic study of the tracker performance. In step III, the two spectrometers work together without any cooling device in between which allows the study of systematic errors. Step IV, with one focusing pair between the two spectrometers, should provide experience with operating the absorber and a precise understanding of energy loss and multiple scattering in it. Several experiments with varying beta-functions and momenta can be performed with observation of cooling in normalized emittance. Starting from step V, the real goal of MICE, which is to establish the performance of a realistic cooling channel, will be addressed. Only with step VI will the full power of the experiment be reached.

## COOLING CHANNEL

The MICE magnetic channel consists of seven magnet assemblies composed of eighteen superconducting solenoid coils spread over a length of nearly 11.5 m. The baseline MICE channel operates with muons at an average

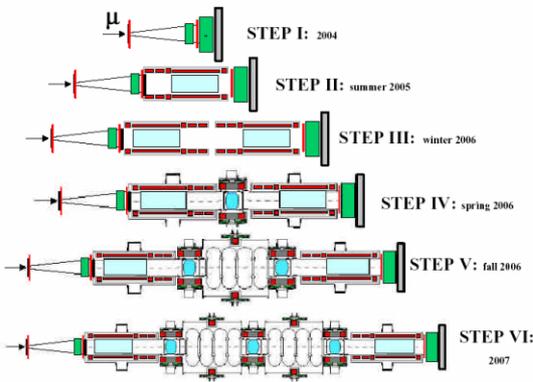


Figure 2: Six possible steps in the development of MICE

momentum  $p=200$  MeV/c and  $\beta=42$  cm at the center of the absorber. Eight 201-MHz rf cavities, in two 4-cavity assemblies, are needed in the cooling section. Due to the (financial) limitation of having only 8 MW of rf power available, the MICE cavities will operate at a gradient of about 8 MV/m (compared with the 16 MV/m specification for Study-II). The cavity shape chosen is based on a slightly reentrant rounded profile with a large beam aperture and a small nose cone [8]. To achieve high shunt impedance, the beam aperture is terminated electromagnetically using thin beryllium foils or thin-walled Al tubes. Hydrogen was chosen as the most suitable absorber material because of its large ionization energy-loss rate (“cooling”) and small probability of multiple scattering (“heating”).

## DETECTORS

The driving design criteria for the MICE detector systems are robustness, in particular of tracking detectors, to potentially severe background conditions in the vicinity of rf cavities and redundancy in particle identification (PID) to keep contamination below 1%. Three TOF stations equipped with fast scintillators are foreseen. The first two, upstream of the cooling section and separated by about 10 m, will provide the basic trigger for the experiment, in coincidence with the ISIS clock. These have precise timing (around 70 ps) and will provide muon identification as well as the muon timing (relative to the rf phase) necessary for the measurement of the input longitudinal emittance. The coincidence with a third station of similar nature, downstream of the second measuring station, will select particles traversing the entire cooling section. The baseline design for the tracking detectors is five sets of scintillating fiber planes per spectrometer, deployed in three stereo views, with the fibers individually read out using cryogenic VLPC photodetectors. An alternative design is also under investigation in which each spectrometer contains a time projection chamber with triple-GEM readout (TPG). Additional detectors will provide redundant particle identification to eliminate from the sample any residual pions in the incoming beam or muons that decay within the apparatus. These include time-of-flight scintillation counters, Cherenkov de-

tectors and a calorimeter. While these are standard ingredients for particle-physics experiments, measuring an emittance ratio with 0.1% precision has never been done and will require careful design of diagnostics and attention to system integration and calibration.

## STATUS

The MICE Collaboration has brought together 141 physicists and engineers from the world’s accelerator and particle physics communities to tackle the technical challenges of ionization cooling. Together, they have designed an experiment to demonstrate the feasibility of muon cooling and, with enthusiastic support from the UK particle physics community, shown that it can be carried out at Rutherford Appleton Laboratory. By measuring the parameters of each muon individually, MICE will measure the transverse emittance in each transverse plane with an absolute precision of 0.1%. The proposed cooling section will be operable with a variety of optical settings and absorber materials, allowing the cooling performance to be mapped out for a range of cooling-channel parameters and beam momenta and compared with the predictions of detailed simulations. By demonstrating that the technology of muon ionization cooling is not only technically feasible, but that its cost and performance are well understood, MICE will pave the way for the start of a Neutrino Factory construction project and will point the way to muon colliders in the longer term. The proposed schedule for the commissioning and operation of MICE will establish the technical feasibility of muon ionization cooling by 2007; we are seeking funding from agencies around the world to realize this schedule.

## ACKNOWLEDGEMENTS

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