MICE: THE MUON IONISATION COOLING EXPERIMENT

Malcolm Ellis, Imperial College London, United Kingdom
for the MICE collaboration

Abstract

The provision of intense stored muon beams would allow the properties of neutrinos to be measured precisely and provide a route to multi-TeV lepton-anti-lepton collisions. The short muon-lifetime makes it impossible to employ traditional cooling techniques while maintaining the muon-beam intensity. Ionisation cooling, a process in which the muon beam is passed through a series of liquid hydrogen absorbers followed by accelerating RF-cavities, is the proposed cooling technique. The international Muon Ionisation Cooling Experiment (MICE) collaboration proposes to perform an engineering demonstration of ionisation cooling. The MICE cooling channel, the instrumentation and the implementation at the Rutherford Appleton Laboratory is described together with the predicted performance of the channel and the measurements that will be made.

INTRODUCTION

The ultimate tool for the study of neutrino oscillations, including the potential discovery of leptonic CP violation, is a Neutrino Factory [1,2]. A Neutrino Factory produces an intense beam of neutrinos from the decay of muons confined within a storage ring. The successful operation of a Neutrino Factory is also a potential first step towards a $\mu^+ \mu^-$ collider. Ionisation cooling of muons is a critical stage (both in terms of cost and physics reach) for a Neutrino Factory and has not been demonstrated in practise. The aims of the international Muon Ionisation Cooling Experiment (MICE) are:

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

A proposal [3] was submitted to the CCLRC for the experiment to be mounted at the Rutherford Appleton Laboratory (RAL) [4]. Following international peer review, the project has been granted full scientific approval by CCLRC.

Ionisation cooling is achieved by passing the muon beam through a series of liquid hydrogen absorbers, followed by accelerating RF cavities. This system cools the muon beam because both longitudinal and transverse momentum are lost in the absorber, while only longitudinal momentum is restored.

EXPERIMENTAL LAYOUT

The arrangement of the main components of MICE are shown in Figure 1. Cooling is provided by one lattice cell of the 201 MHz cooling channel designed in the "Study-II" Neutrino Factory feasibility study [5]. The muon beam first encounters a set of adjustable diffusers that allow the initial emittance of the beam to be tuned. A set of particle identification detectors (time of flight and cherenkov) will be used in the analysis to select muons entering the channel.

Following the input beam identification is a tracking detector inside a uniform-field solenoid, to allow the accurate determination of the phase space coordinates of each particle. This is followed by the actual cooling channel, consisting of a pair of 201 MHZ RF cavities placed between 3 liquid hydrogen absorbers.

A second spectrometer, identical to the first, is then used to measure the phase space coordinates of the particles leaving the cooling channel. This is followed by further particle identification (time of flight, cherenkov and calorimeter) to allow the selection of muons exiting the cooling channel during the analysis. To ensure that the spectrometer solenoids can be matched to the optics of the cooling channel, the tracker solenoid incorporates two sets of matching coils

MEASUREMENT TECHNIQUE

Standard particle-physics techniques will be employed to track individual muons through the experiment, as they are better able to cope with the beam intensity and provide a more precise measurement than the multi-particle techniques conventionally used in beam instrumentation. A "virtual bunch" will then be constructed during the analysis and used to demonstrate how an actual bunch would have behaved.

The parameters that must be measured are the position and momentum of each muon, as well as the time it passes a given reference surface. The tracking detectors will provide the position and momentum measurement, while matching the fitted track to the time of flight detectors will enable a time measurement with sufficient precision to determine the phase of the muon with respect to the RF system.

It has been determined that for the experimental resolution not to affect the resolution of the measured emittance, the RMS resolution of each of the measured parameters must not be greater than 10% of the RMS of that quantity at the equilibrium emittance.

With the exception of possible space charge effects, this analysis technique is equivalent to full beam measurements, however it has the advantage that correlations between parameters can be easily measured.

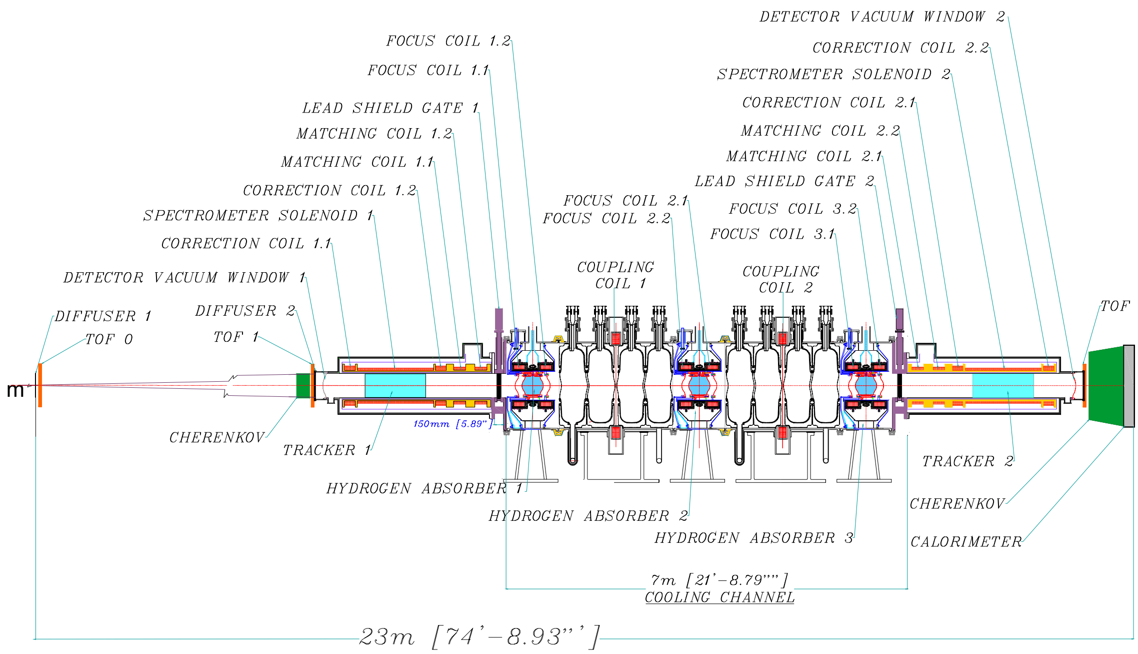

Figure 1: Layout of the MICE experiment.

In addition, the role of each beam parameter (energy, transverse momentum, RF phase, etc.) can be studied without making changes to the beam settings. Software cuts can be used to select any conceivable input beam by appropriate weighting and selection of the recorded events and study the effect that the cooling channel has on such an input beam.

RF BACKGROUND

The design above imposes some constraints on the design of the tracking detectors (described below). The detectors will be exposed to a very large dark current and x-ray background produced by the adjacent RF cavities. Several factors contribute to protect the tracking detectors:

1. The RF cavities will be operated at a moderate gradient of 8.3 MV/m, due to a limitation in available RF power.
2. Most dark-current electrons are deflected by the field flip.
3. The electrons must also pass through the liquid-hydrogen absorbers, which are thick enough to absorb them completely. As a result, only X-rays will penetrate as far as the tracking detectors.
4. The detectors are built of low-Z material and are well able to distinguish hits generated by muons from those generated by X-rays.

DETECTORS

The driving design criteria for the MICE detector systems are robustness, in particular of the 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 3 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 two tracking detectors will each consist of five sets of scintillating-fibre planes per spectrometer, deployed in three stereo views, with the fibres individually read out using cryogenic visible-light photon counters (VLPCs). A prototype detector using this technology, and to the MICE design has been built and operated at Fermilab.

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 detectors include time-of-flight scintillation counters, Cherenkov detectors and a calorimeter. While these are standard ingredients for particle-physics experiments, an emittance measurement with 0.1% precision has never been performed and will require careful design of diagnostics and attention to system integration and calibration.

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 momentum $p = 200$ MeV/c and $\beta = 42$ cm at the centre of the absorber. Eight 201-MHz RF cavities, in two 4-cavity assemblies, are needed in the cooling section. The MICE cavities will produce an accelerating gradient of 8 MV/m. By selecting muons passing through the cooling channel 'on crest' the desired cooling effect will be produced. The RF power will be provided by four 2 MW amplifiers, each amplifier serving two cavities. The cavity shape chosen is based on a slightly re-entrant rounded profile with a large beam aperture and a small nose cone. To achieve high shunt impedance, the beam aperture is terminated electromagnetically using thin beryllium foils or thin-walled aluminium 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').

The first prototype MICE absorber module has been built at KEK and is waiting to be shipped to Fermilab where it will be tested later this year.

TIMELINE

It is planned that the MICE experiment will develop in time to allow a number of preparatory stages to be carried out before the full MICE cooling cell is assembled. The proposed scenarios are presented in Figure 2.

First (step I), the beam can be tuned and characterized using a set of TOF counters and particle identification devices. This stage is expected to occur in 2006. In step II, the first spectrometer solenoid allows a first measurement of 6D emittance with high precision. Comparison with the beam simulation will allow a systematic study of the tracker performance to be made.

In step III, the two spectrometers work together without any cooling device in between which allows the study of systematic errors. Step IV, due in 2007, with one focus-pair/absorber assembly 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, in 2008, will the full power of the experiment be reached.

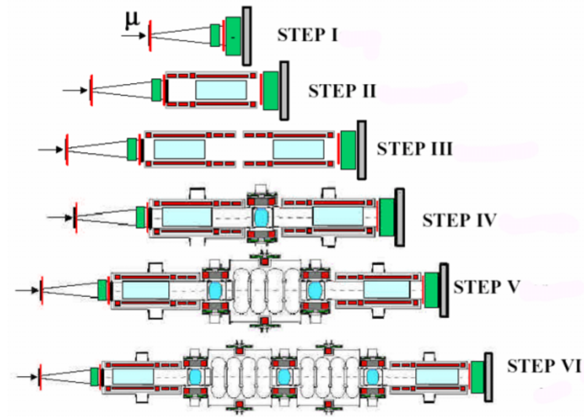

Figure 2: Proposed steps in the implementation of MICE.

STATUS

The MICE collaboration has brought together approximately 150 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.

The proposed schedule for the commissioning and operation of MICE will establish the technical feasibility of muon ionisation cooling by 2008; we are seeking funding from agencies around the world to realize this schedule.

REFERENCES

[1] C. Albright *et al.*, arXiv:hep-ex/0008064, May 2000.
[2] M. Lindner, arXiv:hep-ph/0209083, Sept. 2002
[3] A full description of MICE can be found in the proposal submitted to the Rutherford Appleton Laboratory: (http://mice.iit.edu/mnp/MICE0021.pdf), and more details are available on the MICE collaboration web site: http://www.mice.iit.edu/ .
[4] see P. Drumm, these proceedings
[5] S. Ozaki *et al.*; *'Feasibility Study-II of a Muon-Based Neutrino Source*', BNL-52623, June 2001.