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MICE: the international Muon Ionisation Cooling Experiment

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Muon storage rings have been proposed for use as sources of intense high-energy neutrino beams and as the basis for multi-TeV lepton-antilepton colliding beam facilities. To optimise the performance of such facilities is likely to require the phase-space compression (cooling) of the muon beam prior to acceleration and storage. The short muon-lifetime makes it impossible to employ traditional techniques to cool the beam 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 technique proposed to cool the muon beam. The international Muon Ionisation Cooling Experiment (MICE) collaboration has been formed to carry out a muon-cooling demonstration experiment, and its proposal to Rutherford Appleton Laboratory has been approved. 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.

1. 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 in 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 are to show that it is possible to design, engineer and build a section of a coolling channel capable of giving the performance required for a Neutrino Factory and 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 held at the Rutherford Appleton Laboratory (RAL). 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 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.

2. Experimental Layout

The arrangement of the main components of MICE is shown in Fig. 1. Cooling is provided by one lattice cell of the 201 MHz cooling channel designed in the "Study-II" Neutrino Factory feasibility study [4]. 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.

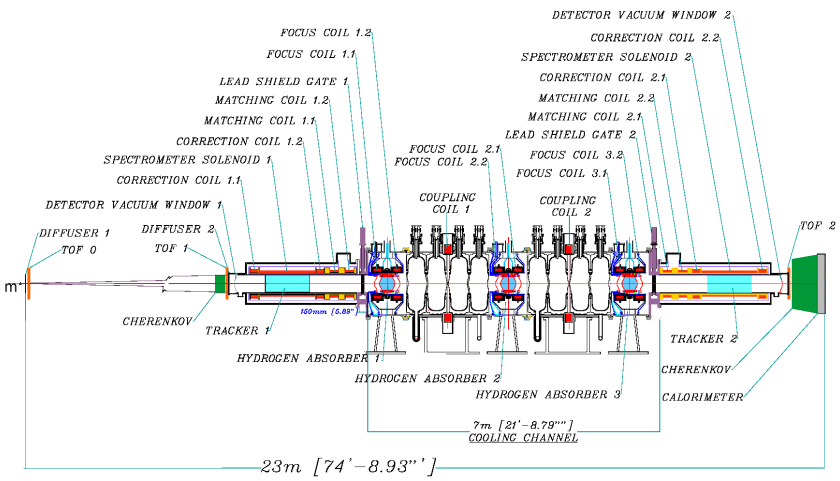

Fig. 1. Schematic layout of the MICE experiment.

3. 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 accurate 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 the 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 greated than 10% of the RMS of that quantity at the equillibrium 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.

4. RF Background

The design above imposes some constraints on the design of the tracking detectors (see 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 detectors.

The RF cavities will be operated at a moderate gradient of 8.3 MV/m, due to a limitation in available RF power. The electrons will need to pass through the liquid-hydrogen absorbers, which are thick enough to absorb them completely. Finally, the detectors are built of low-Z material and are well able to distinguish hits generated by muons from those generated by X-rays.

5. Detectors

The driving design criteria for the MICE detectors are robustness, in particular of the tracking detectors, to potentially severe background conditions in the vicinity of the RF cavities and redundancy in particle identification to keep contamination below 1%.

Three TOF stations equipped with fast scintillators are forseen. The first two, upstream of the cooling section and separated by about $3m$, will provide the basic trigger for the experiment in coincendence 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 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, deployed in three stereo views, with the fibres individually read out using cryogenic visible-light photon counters (VLPCs). A prototype detector 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 Cherenkov detectors and a calorimeter.

6. Cooling Channel

The MICE magnetic channel consists of seven magnet assemblies composed of eighteen superconducting coils spread over a length of nearly $11.5m$.

The baseline MICE channel operates with muons at an average momentum $p = 200MeV/c$ and $\beta = 42cm$ at the centre of the absorber. Eight 201 MHz RF cavities, in two 4-cavity assemblies are needed for the cooling section.

Hydrogen was chosen as the most suitable absorber material because of its large ionisation energy-loss rate and small probability of multiple scattering. The first prototype absorber module has been built at KEK and will be tested at Fermilab at the end of 2004.

7. Status

The MICE collaboration has brought together approximately 150 physicists and engineers from the world's accelerator and particle physics communities to tackle the challenges of ionisation cooling.

Together, they have designed an experiment to demonstrate the feasibility of muon cooling and, with enthusiastic support from the UK particle phsyics community, shown that it can be carried out at the 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 currently seeking funding from agencies around the world to realise 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 avaialable on the MICE collaboration website: http://www.mice.iit.edu/.
4. S. Ozaki *et al.*, *Feasibility Study-II of a Muon-Based Neutrino Source*, BNL-5263, June 2001.