MICE OVERVIEW – PHYSICS GOALS AND PROSPECTS

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Abstract

Ionization cooling, a technique in which a muon beam is passed through a series of absorbers and followed by RF-acceleration, is a proposed method for cooling muon beams, i.e., phase-space reduction. The international Muon Ionisation Cooling Experiment (MICE), which will construct and operate a realistic cooling channel and measure the beam cooling performance, is the first essential step towards realization of neutrino factories and eventually muon colliders based on intense muon sources. The MICE experiment has been approved to be constructed at the Rutherford Appleton Laboratory (RAL) and the fist beam commissioning is scheduled for 2007. The physics goals and future prospects of the MICE experiment, together with the beamline and the instruments which are now being built are described.

INTRODUCTION

Muon storage rings have been proposed for use as sources of intense high-energy neutrino beams and as the basis for a muon collider. To avoid loss of muons during acceleration and subsequent injection into the storage ring, the beam emittance must be reduced. Due to the short lifetime of muons, cooling must be done quickly. Ionization cooling is therefore employed in the Neutrino Factory (NF) design studies. As described in the NF design study-II [1], ionization cooling can make significant contributions to both the performance (transverse emittance reduction from 12 to ~2.7 mm-rad) and cost (as much as 20%) of the accelerator complex. However, ionization cooling of muons at minimum-ionizing energy has never been realized in practice. The international Muon Ionization Cooling Experiment (MICE) collaboration [2] was formed in 2001 and aims to carry out this demonstration. The project achieved full scientific approval by CCLRC, and has authorization to construct the first phase of MICE at the Rutherford Appleton Laboratory.

PHYSICS GOALS

To perform ionization cooling, muons are injected into an absorber, where they lose both longitudinal and transverse momentum. The longitudinal momentum is restored using RF cavities following the absorber. However, as well as the cooling from the energy loss, there is also heating coming from multiple scattering. The net cooling effect is a delicate balance between these two effects. The MICE project aims to show that it is possible to engineer a realistic section of a cooling channel and to understand the behavior of a muon beam in the cooling channel by injecting well-controlled muon beams. The results from these studies can be fed back into the design of the NF cooling channel.

The normalized emittance of the outgoing muon beam, ε_{out}, from the cooling channel is a function of the initial emittance of the beam, ε_{in}, as shown in Figure 1 (full transmission for a normalized emittance of less than ~6π mm-rad). The effect of cooling is ~10% for a muon beam with large initial emittance, while heating is dominant for a small emittance beam. To achieve sufficient knowledge of the cooling technique, measurement with accuracy of 10^{-3} in emittance reduction $\varepsilon_{out}/\varepsilon_{in}$ is necessary.

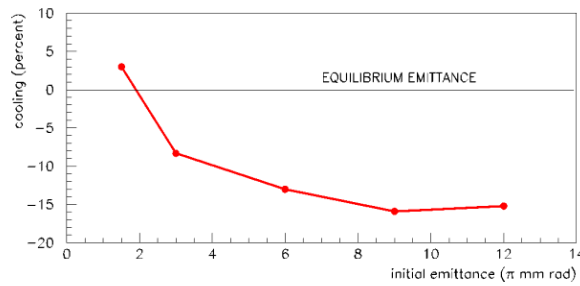

Figure 1: Expected emittance reduction as a function of the normalized input beam emittance.

Tracking of each muon passing through the cooling channel is employed to measure momentum at the entrance and exit. The beam emittance can be reconstructed by accumulating these individual measurements. Using the measured correlations between the cooling effect and the beam parameters (energy, transverse momentum, RF phase and so on), the expected performance in a NF cooling channel can be studied in the analysis.

LAYOUT OF THE EXPERIMENT

The layout of the MICE cooling channel and detectors are shown in Figure 2. The total length of the setup from the entrance of the first spectrometer solenoid to the exit of the second spectrometer solenoid is approximately 12 m. MICE consists of a cooling section between upstream and downstream particle spectrometers, and will be exposed to a 200 MeV/c muon beam.

The design of the beam line at Rutherford Appleton Laboratory (RAL) for MICE is based on a conventional pion-decay channel. A target will intercept the halo of the ISIS 800 MeV proton beam to generate pions. The decay solenoid was obtained from the Paul Scherrer Institute.. The muons from pion decays are then transferred to the experiment by a large acceptance transport line consisting of a pair of quadrupole triplets. The muon beam first enters a matching section, where a lead diffuser generates a matched input emittance. A time-of-flight measurement is also performed to identify the incoming particles. The beam then enters the upstream spectrometer,

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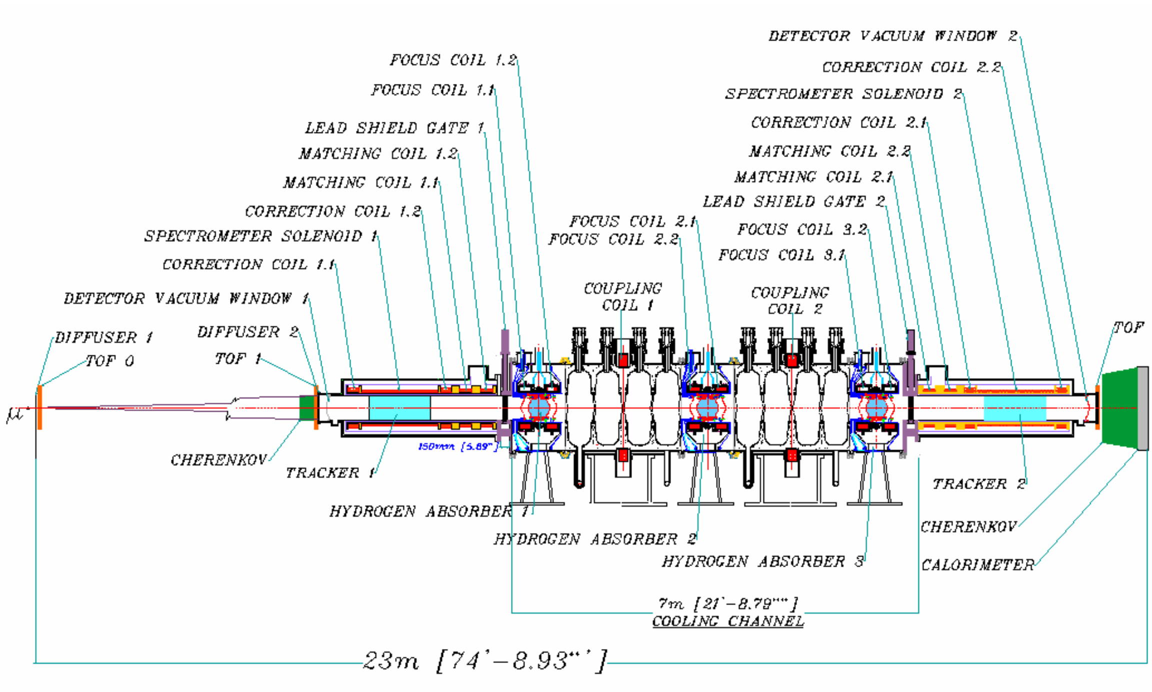

Figure 2: Layout of the MICE cooling channel and particle detectors.

where the momenta and spatial coordinates of each particle are measured by tracking detectors situated in a uniform solenoid magnetic field of 4 T for a length of 1 m. Incident particles pass through the cooling section and enter the downstream spectrometer. Finally, downstream of the second spectrometer, particle identification to reject pions and electrons produced from the decay-in-flight of the muons in the cooling section is provided by a second time-of-flight system and a calorimeter. The time measurements are also used to determine the phase of the electric field in the RF cavities experienced by the passing muon.

COOLING CHANNEL

The cooling section is designed based on the first part of the NF Study II [1] cooling channel. The designs of some components of the MICE cooling channel have been modified to effect practical solutions, to meet safety requirements, or to optimize costs. It consists of three liquid hydrogen absorbers spaced by 2.75 m. Each of the absorbers is surrounded by a pair of focus coils. Two sets of four 201 MHz RF cavities restore the longitudinal momentum lost in the absorbers. Coupling coils located around the cavity assemblies provide additional longitudinal magnetic field to confine the beam between the absorbers.

RF Cavity

The 201-MHz RF cavities are being developed in the MUCOOL collaboration [3]. The MICE cavities will operate at a field gradient of about 8 MV/m, and the MICE cooling channel will provide a maximum accelerating RF voltage of 21 MV. As the cavities must operate in a strong magnetic field, normal conducting technology must be utilized. In addition, to match to the large transverse size of the muon beam, a large aperture is needed. To achieve high shunt impedance, the beam aperture is terminated electromagnetically using thin, curved beryllium windows, which provide a good conducting boundary for the RF fields.

Absorber

The heating effect on a muon beam is proportional to the mean deposited energy and is inversely proportional to radiation length. To minimize the heating, to the MICE absorbers use liquid hydrogen (radiation length X_0 = 8.7 m and energy absorption per unit length dE/ds = 30MeV/m). The hydrogen absorber and focusing solenoid magnet will be mounted within a single module of the Absorber Focusing Coil (AFC) module. The absorber thickness at the center is 350 mm and the aperture of the windows is 300 mm. The absorber body with the heat exchanger has a volume of 21L. It is designed to use natural convection, and a cryo-cooler will maintain the hydrogen in the liquid state during operation. The operating temperature will be between 15 K and 21 K and allows for a maximum of 15 W heat removal. The absorber design provides the ability to handle the assembly as a unit that can be inserted into, and extracted from, the bore of the focusing magnet for maintenance and for changing the experimental configuration. The prototype of the absorber was developed in KEK and has been tested with liquid hydrogen in the MuCool Test Area at FNAL.

DETECTORS

Particle Identification

In addition to the primary goal of measuring the space-time coordinates and the momenta of incoming (outgoing) muons in (from) the MICE cooling channel, the particle detectors should also be capable of identifying and rejecting residual pion and decay-electron contamination to the muon beam. For the required resolution on the emittance, pion identification will be achieved by means of a precise time-of-flight measurement over a 10 m distance prior to the first spectrometer solenoid. A 70 ps time resolution leads to a 99% pion rejection. The decay electrons can be identified by using the final calorimeter and can be rejected by a factor of 100.

Tracker

The MICE experiment requires the spectrometers to track individual muons as they enter the cooling channel and as they leave. In order to provide stable operation in a 4-Tesla solenoid magnetic field and under potentially high radiation background due to RF acceleration, a Scintillating Fiber (SciFi) tracker is employed as the tracker for MICE. The tracker consists of fine scintillating fibers with a diameter of 350 μm to suppress multiple scattering in the spectrometer. There are 5 stations in a spectrometer, and each station consists of 3 sets of fiber doublets at 120° to each other. The diameter of the sensitive region in the station is approximately 30 cm. Light from the scintillating fibers is transmitted to the photon detector through clear fibers. The light yield is expected to be very small for penetrating muons due to the small diameter of the scintillating fiber. In order to detect small signals from the SciFi trackers, Visible Light Photon Counters (VLPC) are used as they are photon detectors with high quantum efficiency (more than 80%) The secondary dye, 3-Hydroxyflavone (3HF), is used in the scintillating fibers because the VLPC has high sensitivity at around 520 nm which corresponds to the maximum emission wavelength of 3HF. A four-station prototype of the SciFi tracker was constructed and has been used to check the basic performance of the design with a 1-Tesla solenoid magnet in a KEK test beam in October 2005. A new cryostat for two 1024-channel VLPC cassettes has been developed and shown to be stable when cooled by cryo-coolers.

TIMELINE

The MICE experiment will proceed in a staged approach as shown in Figure 3. In the autumn of 2007, the first muon beam will be provided to the MICE channel and commissioning of the particle detectors will begin. In step I, the TOF system, the Cherenkov counter, the calorimeter and the tracker are exposed to the muon beam. The beam will be tuned using these particle detectors. In step II, the first spectrometer solenoid measures the 6D emittance of the beam with high precision. In step III, the systematic errors in the measurement of emittance reduction by the spectrometers are studied. The project up to this step has been funded. The first absorber with focusing magnets will be installed in step IV. To compare the energy loss and scattering in liquid hydrogen, solid absorbers could be inserted before this step. Measurements of the cooling effect will be performed under various beam conditions. From step V, restoring the longitudinal momentum is done with the RF cavities. The first demonstration of ionization cooling is realized in this step. The project will achieve the full cooling power in step VI.

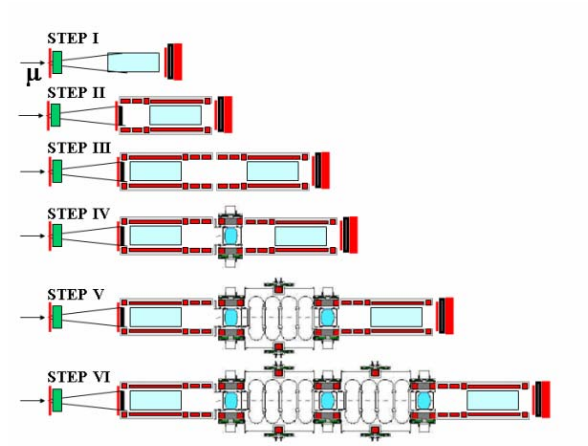

Figure 3: Staged approach of the MICE project

REFERENCES

[1] Feasibility Study-II of a Muon-Based Neutrino Source, ed., S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, BNL-52623 (2001). http://www.cap.bnl.gov/mumu/studyii/final_draft/chaper-5/chapter-5.pdf

[2] See http://mice.iit.edu/, for the MICE proposal and the MICE technical reference.

[3] MUCOOL expt. (Muon Ionization Cooling R&D), FNAL Proposal P904