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Status of MICE

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Abstract

The Muon Ionization Cooling Experiment (MICE) is an experiment currently under construction at the Rutherford Appleton Laboratory (RAL) in the UK. The aim of the experiment is to demonstrate the concept of ionization cooling for a beam of muons, crucial for the requirements of a Neutrino Factory and a Muon Collider. Muon cooling is achieved by measuring the reduction of the four dimensional transverse emittance for a beam of muons passing through low density absorbers and then accelerating the longitudinal component of the momentum using RF cavities. The absorbers are maintained in a focusing magnetic field to reduce the beta function of the beam and the RF cavities are kept inside coupling coils. The main goal of MICE is to measure a fractional drop in emittance, of order -10% for large emittance beams, with an accuracy of 1% (which imposes a requirement that the absolute emittance be measured with an accuracy of 0.1%). This paper will discuss the status of MICE, including the progress in commissioning the muon beam line at the ISIS accelerator at RAL, the construction of the different detector elements in MICE and the prospects for the future.

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1 Introduction

The Muon Ionization Cooling Experiment (MICE) [1] is being built at the Rutherford Appleton Laboratory (RAL) in the UK to measure ionization cooling of a beam of muons traversing liquid hydrogen and other low Z absorbers (for example, lithium hydride, LiH). The MICE Collaboration includes about 150 collaborators from Belgium, Bulgaria, China, Holland, Italy, Japan, Switzerland, the UK and the USA. The aim of MICE is to measure a fractional change in emittance of $\sim 10\%$ for muons in the range 140-240 MeV/c, with a measurement precision of 1% (which assumes an absolute precision in the measurement of emittance of 0.1%). To achieve such a requirement, the experiment is designed as a single muon spectrometer.

The baseline design for a Neutrino Factory, as adopted by the International Design Study for a Neutrino Factory [2], includes a muon cooling channel of 80 m length. In order to achieve the design goal of 10^{21} muons per year at a Neutrino Factory, the transverse emittance of the muon beam needs to be reduced from 17π mm rad down to 7.4π mm rad required for the accelerating section [3]. This can be achieved with an 80 m long solenoid focussed cooling channel with radio frequency (RF) cavities of high accelerating gradient (15.25 MV/m) operating at 201.25 MHz, and LiH absorbers. MICE is a an essential experiment needed to demonstrate and measure the cooling performance of a realistic cooling channel with these characteristics. Measurement of the cooling performance as a function of input emittance is essential to validate the Neutrino Factory simulation codes. MICE will measure cooling for a variety of muon beams between 2π mm rad and 10π mm rad emittance and with momenta between 140 and 240 MeV/c.

2 Ionization Cooling

Cooling is achieved in a muon beam by allowing the muons to cross three low density absorbers (containing liquid hydrogen or lithium hydride) inside a focusing magnetic field. The muons experience a loss of total energy through ionization and the longitudinal component of the momentum is restored through eight 201 MHz RF cavities enclosed by two coupling coils. As the muons traverse the absorbers they are subject to energy loss (cooling term) and multiple scattering (a heating term). The interplay between these two terms determines the cooling performance. The change in emittance ϵ as a function of position along the cooling channel is given by:

$$\frac{d\epsilon}{dz} = -\frac{\epsilon}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m\beta^3}\frac{(13.6\ MeV)^2}{E_\mu X_0}, \tag{1}$$

where $\beta = v/c$, E_μ and m are the muon energy and mass, $\beta_\perp$ is the Twiss transverse beta function and X_0 is the radiation length. The ionization per unit density is proportional to Z (the atomic number), and the multiple scattering is inversely proportional to X_0, thus proportional to $Z(Z+1)$. Therefore, the best cooling is achieved with a low Z absorber, such as hydrogen or LiH.

The transverse emittance in the experiment is calculated from the fourth root of the determinant of the 4×4 matrix of covariances:

$$\epsilon_{4D} = \frac{1}{mc}\sqrt[4]{|\mathbf{V}|}, \tag{2}$$

where the elements of $\mathbf{V}$ are $V_{ij} = cov(x_i, x_j)$ with x_i being the four transverse phase-space coordinates x, p_x, y, p_y for each muon. Further information on the calculation of the fractional change in emittance and its associated statistical errors can be found in [4, 5].

Equation 1 can be rewritten to show that the change in emittance at the absorber is:

$$\frac{\Delta\epsilon}{\epsilon} = -\left(\frac{\Delta p}{p}\right)\left(1 - \frac{\epsilon_0}{\epsilon}\right),$$

where ϵ is the emittance of the beam and ϵ_0 is the equilibrium emittance. A 5% momentum loss in each absorber corresponds to cooling of less than 15% for a large emittance beam. The equilibrium emittance with liquid hydrogen is $\epsilon_0 \sim 2.5(\pi)$ mm rad.

3 Description of MICE

While the idea of ionization cooling is conceptually simple, there are a number of challenging difficulties that have to be overcome to demonstrate that ionization cooling can work in practice. In the cooling demonstration we aim to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory.

MICE will test one cell of the Feasibility Study 2 (FS2) cooling channel [6], which includes three Focus Coil modules with absorbers (liquid hydrogen or solid lithium hydride) and two RF-Coupling Coil (RFCC) modules, each containing four 201 MHz RF cavities per module (Figure 1). The cooling channel needs to be placed in a dedicated muon beam to measure its performance in a variety of modes of operation and beam conditions and to show that the design tools for a Neutrino Factory can reproduce the experimental results.

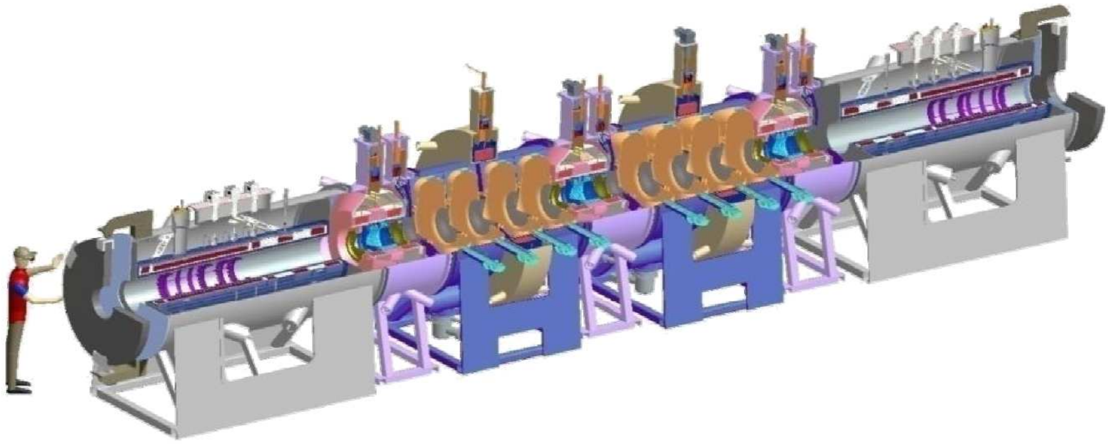

Figure 1: Three dimensional cutaway rendering of MICE.

Some of the experimental challenges include operating high-gradient (up to 16 MV/m) RF cavities of 201 MHz frequency in strong magnetic fields (up to 3 T). The design needs to take into account the safe operation of liquid hydrogen absorbers in the vicinity of the RF cavities. The small cooling effect ($\sim$ 10%) necessitates an emittance measurement with 10^{-3} precision. This can only be achieved in a single particle experiment, with two high resolution, low mass trackers embedded in 4 T solenoidal magnetic fields. Particle identification detectors, including a Time-of-Flight (TOF) system, two Cherenkov detectors and Electromagnetic Calorimeters, are used to identify pions, muons and electrons.

4 Status of MICE

4.1 MICE Target and Beam

The MICE muon beam will be derived from the ISIS synchrotron at the Rutherford Appleton Laboratory (RAL) in Oxfordshire, UK. Protons are injected in ISIS with a kinetic energy of 70 MeV and they are accelerated up to 800 MeV in an acceleration time of 10 ms at a frequency of 50 Hz.

The MICE target has been explicitly designed to cycle at $\sim$ 1 Hz, with the target only dipping into the beam for one pulse every 50 ISIS pulses. The intersection of the target with the outer part of the ISIS beam envelope is achieved during the last millisecond of the acceleration cycle (i.e., 9-10 ms after injection), when the protons have achieved an energy of nearly 800 MeV. To achieve this, the target requires acceleration of $\sim$ 80g. During the 2008 run the target was a titanium fin $10 \times 10 \times 1$ mm^3. The target insertion mechanism consisted of a linear motor with radial magnets, remote position sensing with laser quadrature readout to drive the commutator power to correct the 24 coil currents (Figure 2).

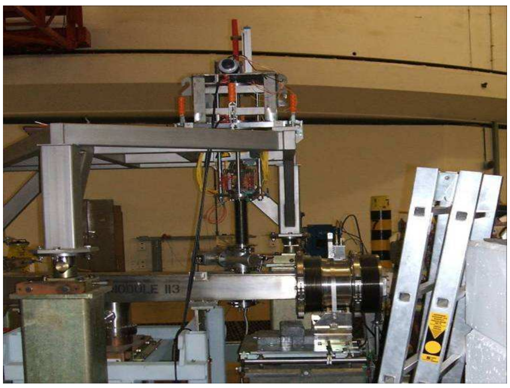

Figure 2: MICE target mechanism.

The target was operated successfully between March and December 2008, accumulating a total of about 180,000 pulses. The target showed very good stability and produced beam losses of the order of 50 mV (corresponding to 2.8×10^9 protons on target), the maximum then allowed by ISIS. However, the target was accidentally parked in the beam on 29 Nov 2008 and the target tip melted. The target mechanism jammed in December 2008 and it ceased to operate. As a consequence, there has been a complete redesign of the target system, with a new mechanism and a new target shaft with cylindrical geometry, diamond-like surface coating for increased durability and improved quality control. The new target was successfully installed in September 2009.

The MICE muon beam consists of an extraction region with three quadrupole magnets (Q1-Q3) and a dipole bending magnet for selection of pions with a determined momentum. This is followed by the pion decay region consisting of a superconducting solenoidal magnet, operating at a temperature of 4.5 K with a nominal magnetic solenoid field of 5 T, and a second dipole magnet for muon momentum selection. This magnet was supplied by the Paul Scherrer Institute (PSI) in Switzerland, and had to be refurbished before operation. It was successfully installed and achieved the design current of 870 A in April 2009. The final section of the beam consists of the muon matching section, with two quadrupole triplets (Q4-Q9), two Time-of-Flight counters (TOF0 and TOF1) and two Cherenkov modules (CKOVA and CKOVB). There is an additional scintillator counter (named GVA1) upstream of the second dipole and the Fermilab Beam Profile Monitoring system downstream of the second dipole, which are used for particle rate and position monitoring. All these beam elements have been installed and are fully operational. A fish-eye view of the MICE beam is shown in Figure 3. The final element of the matching section of the beamline is the diffuser, which consists of a rotating wheel with different thicknesses of material to blow up the beam for the case of large emittance beams. This device will be ready to be installed for the 2010 run.

Figure 3: Fish-eye lens view of the MICE beamline. The Decay Solenoid area is on the left, cryogenic vessels are seen in the middle and the last three quadrupoles (Q7,8,9) are on the right.

4.2 MICE Cooling Channel

Each MICE Absorber and Focus Coil (AFC) module (Figure 4) comprises a pair of superconducting Focus Coils and a liquid hydrogen absorber, designed such that it can be replaced by a solid absorber (for example lithium hydride). Two thin beryllium windows contain the liquid hydrogen to comply with the safety requirements. The first AFC is scheduled to be delivered in June 2010.

Each MICE RF Cavity and Coupling Coil (RFCC) module consists of four normal conducting 201.25 MHz RF cavities (Figure 5) surrounded by one large diameter coupling coil that provides magnetic fields up to 3 T. Each cavity requires a pair of 0.38 mm thick, 21 cm radius precurved beryllium windows with TiN coating. The beta function of the module is 0.87 m. The cavity has a $Q_0 \sim 53,500$ and a peak input RF power of 4.6 MW per cavity providing a gradient of up to 16 MV/m. A test cavity has been successfully tested to 21 MV/m without any B field and to 10-12 MV/m with a B field of 0.4 T at the center of the cavity. In MICE the cavity will run at a nominal gradient of 8 MV/m. One of the key scientific issues is the ability of the cavities to withstand this gradient in the presence of a large magnetic field [7]. The design of the system is now complete and construction has started, following a successful Production Readiness Review.

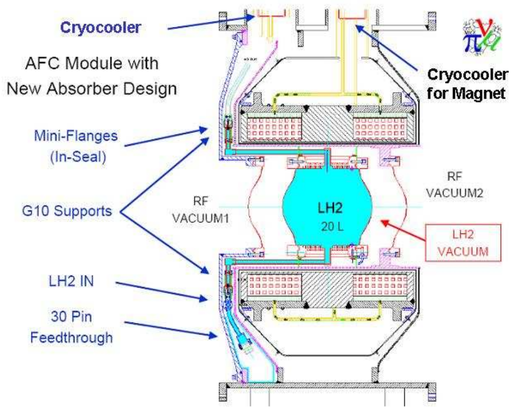

Figure 4: MICE Absorber and Focus Coil (AFC) module.

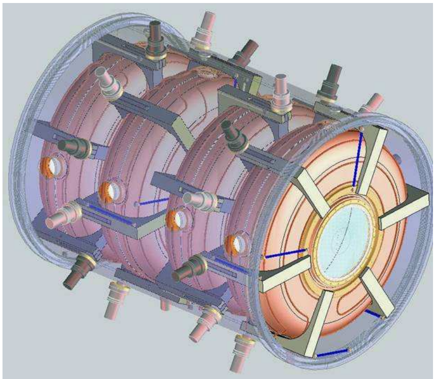

Figure 5: MICE RF Cavities for one RFCC module.

4.3 MICE Detectors

The particle identification systems for MICE consist of three Time-of-Flight (TOF) counters, two Cherenkov (CKOV) detectors, a KLOE-like (KL) Electromagnetic Calorimeter and an Electron-Muon Ranger (EMR). The three TOF counters have the double function of performing particle identification and measuring the RF phase (Figure 6). The difference between TOF0 and TOF1, which have already been installed, is used for pion-muon rejection, while the difference between TOF1 and TOF2 is used to separate muons from electrons at low momenta. The resolution of TOF0 has been measured to be 51 ps and of TOF1 to be 62 ps. Further pion-muon separation between 240 and 300 MeV/c is achieved with the help of two Cherenkov detectors, each read out by four photomultiplier tubes and each with an aerogel radiator of different refractive index (Figure 6).

Two scintillating fibre trackers have been constructed and are currently being calibrated using cosmic rays (Figure 7). Each tracker will be embedded in a 4 T solenoidal field and contains 5 scintillating fibre tracking stations. The spatial resolution requirement is less than 0.4 mm, while the measured resolution achieved using cosmics is $\sigma_x = 0.33$ mm and $\sigma_y = 0.36$ mm. The momentum resolution expected is 1.1 MeV/c in transverse momentum and 3.9 MeV/c in longitudinal momentum. The measured hit efficiencies per station are 99.38% and 99.86%, corresponding to only three dead channels. The measured photoelectron yield is 9.1 photoelectrons.

The MICE KLOE-Like (KL) lead-scintillating fibre Electromagnetic Calorimeter is dedicated to electron-muon separation downstream. It is a preshower consisting of 4 cm grooved lead foils with scintillating fibre readout. The KL has been installed and tested at RAL. The Electron Muon ranger (EMR) will consist of 50 planes of 1 m^2 made of 1.7 cm thick, triangular section scintillators, read out by wavelength shifting fibres attached on both ends to Hamamatsu R7600-00-M64 EG multi-anode photomultipliers (Figure 8). The total depth will allow range measurement for muons up to 300 MeV/c. The EMR is scheduled to be installed in July 2010.

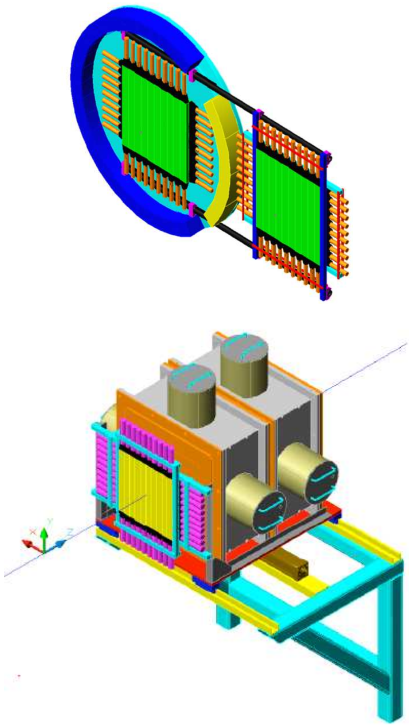

Figure 6: Design of the Time-of-Flight counters (top) and Cherenkov counters (bottom).

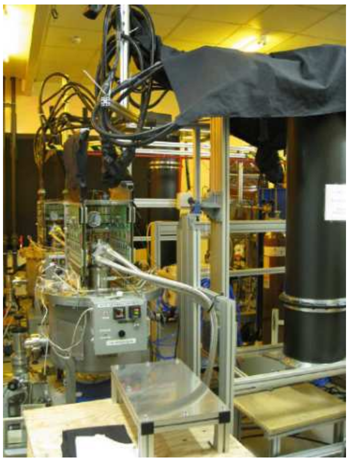

Figure 7: Scintillating fibre tracker undergoing cosmic ray calibration.

5 Conclusions and Outlook

The commissioning of the MICE beam commenced in 2008. The MICE target operated in the ISIS beam from March to December 2008. Particles were observed using the beam, TOF and CKOV counters. The beam counter rate was measured as a function of ISIS beam loss. However, the beam did not operate with the decay solenoid, so the particle rate was much lower than the nominal rate. For the 2009 run, all the beamline elements have been installed, including all quadrupole and dipole magnets, the superconducting decay solenoid and a newly designed target. All these elements are ready for MICE beam commissioning in Autumn 2009 (Step I of MICE). The spectrometer scintillating fibre tracker will be installed in 2010 and the first measurement of emittance (Step II of MICE) will be carried out during 2010. Steps III and IV (energy loss using a solid absorber and liquid hydrogen absorber respectively) will be carried out during 2010 and 2011. Step V, the first measurement of cooling with two hydrogen absorbers and one RF Coupling Coil (RFCC) module, is expected in 2012-2013. The final Step VI of MICE, a measurement of cooling with a full cooling channel consisting of three absorbers and two RFCC modules, will be carried out from 2013.

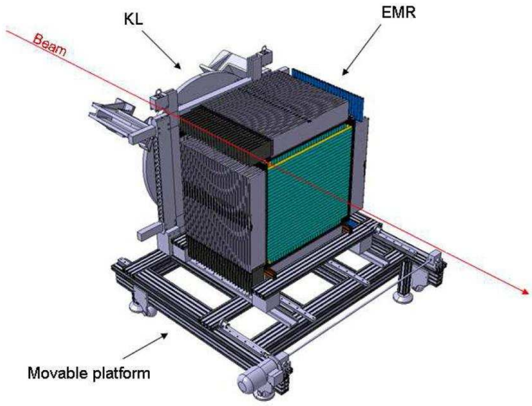

Figure 8: Electromagnetic Calorimeters of MICE, consisting of the KLOE-like (KL) calorimeter and the Electron-Muon Ranger (EMR).

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