THE MICE EXPERIMENT

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Abstract

Ionization Cooling is the only practical solution to preparing high brilliance muon beams for neutrino factory or muon collider. The muon ionization cooling experiment (MICE)[1] is under development at the Rutherford Appleton Laboratory (UK). The muon beam line has been commissioned and shown to produce adequate beams for cooling measurements. First measurements of emittance with particle physics detectors have been performed. Cooling measurements with liquid-hydrogen and lithium hydride absorbers are planned for 2013. A full cell of the ionization cooling channel, including RF re-acceleration, is under construction, aiming at operation by 2016. The design offers opportunities for tests with various absorbers and optics configurations. Results will be compared with detailed simulations of cooling channel performance to ensure full understanding of the cooling process.

MICE PRINCIPLES AND CHALLENGES

The MICE experiment, its principle and its motivation are described in the MICE proposal[2], and the Technical Design Report. A recent status of the experiment can be found in [3]. The MICE collaboration is international and assembles contributions from continental Europe, Japan, UK and the US. The principle of ionization cooling is similar to radiation damping in an electron storage ring: starting with a beam of muons with large transverse emittance and energy spread, absorbers reduce the momentum of the particles in all three dimensions by dE/dx, and RF cavities re-accelerate the particles only in the longitudinal direction. Thus, emittance is reduced asymptotically to an equilibrium between cooling generated by dE/dx and heating by multiple scattering, leading to a preference for low Z absorbers such as hydrogen or lithium hydride situated at a low value of the optical Twiss parameter β. Cooling increases the brilliance of the muon beams, allowing higher intensities – essential for the neutrino factory -- to be accelerated or stored in an accelerator of given aperture, and is critical for the muon collider luminosity.

The practical realization requires operating high gradient cavities in vicinity of hydrogen absorbers and within a magnetic field. There are several technical challenges to this, in particular to reach high gradient in RF cavities embedded in magnetic field. This point, which is common to all of the early muon beam preparation system in a neutrino factory or muon collider, is the object of the MUCOOL R&D program at Fermilab [4]. Testing the concept requires construction of a full section of cooling channel and measuring its cooling effect in a variety of configurations. This is the goal of MICE.

The change of emittance in a cell being around 10%, and the direct measurements of beam emittance being limited to a similar precision, the method adopted by MICE is to work with a beam of limited intensity where particles can be measured individually using scintillator-based detectors. Time-of-flight hodoscopes measure the passage of particles with an accuracy of 50ps, two trackers embedded in spectrometer solenoids measure the space coordinates and angles as well as the momentum (x,y,x’,y’,p) with a resolution better than 10% of the width of the distribution at equilibrium emittance in each phase space dimension. Two identical spectrometer and time measurements are situated upstream and downstream of the cooling section. The distribution in all coordinates and the 6x6 correlation matrix between them can thus be extracted with a precision allowing a measurement of the emittance change to 1% of its value: $\Delta[(\varepsilon_{in}-\varepsilon_{out})/\ \varepsilon_{in}]\sim1\%$. The layout of the experiment is described in *Figure **1***.

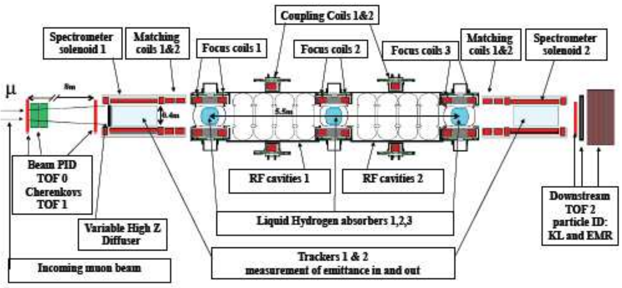

Figure 1 Layout of the Muon ionization cooling experiment MICE

MICE will be executed in steps, *Figure **2***, determined by the staged availability of effort and hardware, but designed in such a way as to commission at each step an important element towards the final measurements.

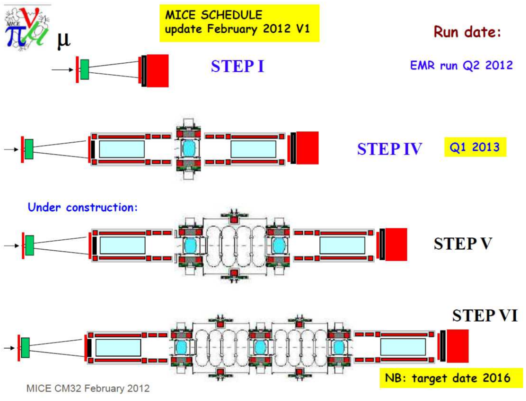

Figure 2 MICE implementation in steps

Step I is already executed and has provided the commissioning of the beam and beamline detectors. It also allowed first measurements of beam parameters distributions and emittance using particle physics detectors. In step IV (in 2013) the commissioning of precise emittance measurement and measurement of cooling effect in various absorbers will be performed. Finally step VI will integrate the RF system to test a fully realistic cooling cell, which reaccelerates the particles and thus coold be used in a real machine. Every element of MICE is either commissioned, or under construction. The target date is to begin running step VI with beam in 2016.

There are a number of challenges in MICE; those related to the cooling channel itself are as follows:

-- although the muon momentum is relatively low, 140 to 240 MeV/c, the realization of a short, large aperture optics requires strong solenoidal magnetic fields, up to 4T. This is realized with large superconducting magnets which have strong magnetic coupling with each other.

-- the best ionization cooling material is hydrogen; liquid hydrogen need to be contained and protected for safety in tanks with very two thin aluminium windows separated with vacuum.

-- the RF cavities must have a large aperture thus a relatively low (200MHz) frequency. In order to increase the efficiency, the cavities are closed with beryllium windows. The gradient in the cooling channel is normally limited by stable operation of the cavities in a magnetic field of locally more than 2T, to a level which has been surmised to be 16MV/m, but is presently unknown. For MICE a more practical limitation arises from the availability of RF power and from the need to protect the detectors against excessive exposure to dark current electrons and resulting x-rays. The MICE operational limit is 8MV/m, or, exceptionally at liquid nitrogen temperature, up to12 MV/m.

The measurement challenges are as follows:

-- to provide the requested resolutions in presence of potential RF induced backgrounds; the MICE tracker [5] embedded in the spectrometer solenoids with a field of 4T, was designed and tested to satisfy these requirements; the TOF hodoscopes[6] have been already operated since 2008 and provide the desired resolution of 50ps per station; for the TOF as well as for the trackers, the detector resolution is determined from the measurements themselves thanks to detector redundancy. This will allow unfolding of detector resolution in the extraction of the emittance without reliance on detector modelling.

-- a large emittance beam has to be generated with adequate properties. The beam line description and results of the commissioning are given in [7]. The layout of the beam line is given in *Figure **3***. The target is dipped in the ISIS proton beam when it is at the top of acceleration (up to 800 MeV), for ~2ms; an orbit bump which brings the beam towards the target for this duration ensures a clean beam delivery. Pions produced in the target are guided in a quadrupole triplet to dipole, D1, where a momentum P_1 is selected. Pions follow then a decay solenoid in which they can decay into muons of typically lower momentum. A second dipole (D2) operates a second momentum selection (P_2). The beam is then optically prepared by two quadrupole triplets to a given size and divergence in both planes. The beam can be prepared as ‘muon beam’ (P_2~ 0.6 P_1) or a ‘pion beam’ (P_2~ P_1) with momenta between 140 to 450 MeV/c. The ‘pion beam’ contains electrons muons and pions with a narrow (few %) momentum spread. The ’muon beam’ is a rather pure muon beam with a momentum spread of typically 15%. During a run in December 2011, the beam purity in the ‘muon beam’ was determined, by analysis of the pulse height in the KL detector left by particles in the ‘muon beam’ in comparison with selected samples of pions and muons in the ‘pion beam’, to be around 99%.

The maximum rate of particles obtained in ‘muon beam’ mode is ~120 muons per target dip, presently achieved at a rate of 1 dip every 2.56 s, for positive muons, and six times less for negative muons. This rate is sufficient to collect the ~ 10^5 muons necessary to perform a relative measurement of cooling with a precision of 1%, in about one hour. The rate is presently limited by the tolerance on irradiation caused in ISIS by protons and secondary particles produced in the MICE target.

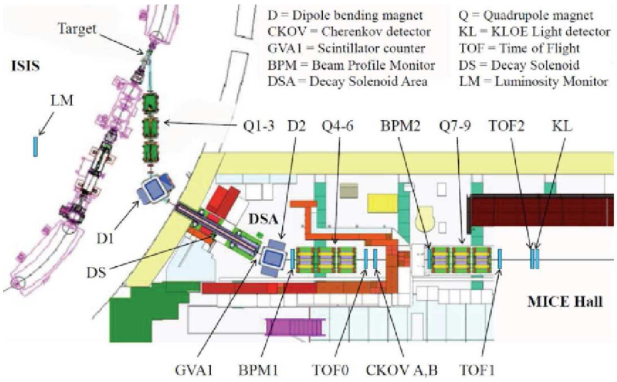

Figure 3 Layout of the MICE beam line at ISIS.

TOWARDS STEP IV AND VI

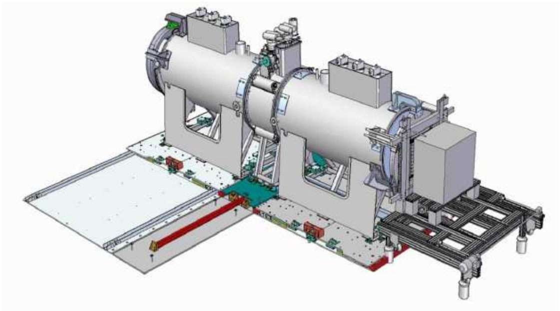

Figure 4 MICE step IV (Engineering drawing)

The components to be assembled for step IV are:

-- two spectrometer solenoids. These 2m long magnets comprise 5 superconducting coils. They deliver a uniform field of 4T in the tracker region of 1m long and 40cm bore, and tunable field adjustment for the matching with the cooling channel. They are in production in Berkeley, the first one is presently under vacuum pumping, before the final training.

-- the focus coils (two are being produced now) is also in the final step of testing before being shipped to RAL.

-- the diffuser is composed of four irises of brass of tungsten that will be used to adjust the radiation length of material placed at the entrance of the first tracking volume to allow emittance to be varied.

-- the trackers have been completed for some time and have been running with cosmics for two years. A tracker test in beam is taking place in May 2012 to integrate the detector in the MICE DAQ and control system.

-- liquid hydrogen absorbers have been fabricated at KEK (Japan) and their windows in Mississippi University; Lithium hydride absorbers have been provided. The liquid hydrogen system has been prototyped and tested with Helium; tests with hydrogen are imminent.

-- A fully active calorimeter, the EMR, is to be added at the downstream end of MICE for the rejection against electrons from muon decay, and to complement the momentum measurement of on-axis particles. This is under construction in Geneva with delivery in MICE in fall 2012.

It is expected that the step IV measurements will start in February 2013.

Figure 5 Completed spectrometer solenoid at Livermore.

Step VI requires in addition the construction of a full RF section and of the large magnets surrounding the RF cavities, called ‘coupling coils’. The water cooled 200 MHz RF cavities have been spun and measured. The next step is the electropolishing and assembly with the couplers. A single cavity RF module has been constructed for tests in the MTA at Fermilab towards the end of 2012.

Meanwhile the RF power amplifiers, refurbished from material donated by LBNL and CERN, are being assembled at Daresbury Lab. A total of 8MW will be available, each 2MW amplifier feeding 2 cavities. First RF amplifier should be assembled in the MICE hall in fall 2013. The layout of the RF system in the MICE hall has been drafted – there will not be too much space in the hall once step VI is installed!

Finally, the coupling coil construction will take place in collaboration with Harbin ICST (China). A first coil has been wound and is now at LBNL being prepared for testing at FNAL. After this test is completed successfully, winding of another three coils will begin, while construction of the cryostats and the integration of the magnets is prepared. The aim is that the first magnet will be ready in 2014 for testing of a single cavity in the full magnetic field, and the full experiment assembled for data taking in 2016.

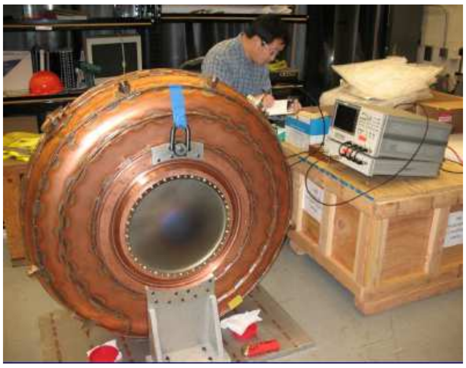

Figure 6 RF cavity with its Beryllium window being measured at LBNL.

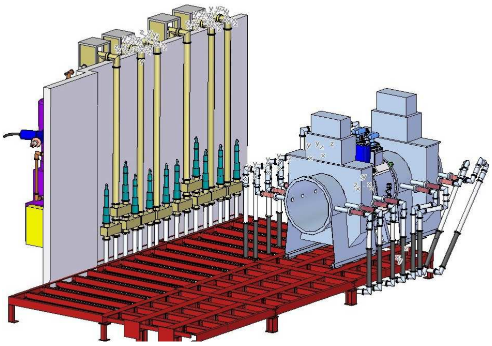

Figure 7 RF power layout in the MICE hall with sketch ot one RF module (two are necessary for step VI.

REFERENCES

[1] MICE experiment web site http://mice.iit.edu

[2] MICE proposal, MICE note 21, (2003)

[3] Report to the MICE project board, MICE note 366.

[4] http://www.fnal.gov/projects/muon_collider/cool/cool.html

[5] *The design, construction and performance of the MICE scintillating fibre trackers*. M. Ellis et. al. NIM A 659 (2011)136-153; arXiv:1005.3491v2

[6] *The design and commissioning of the MICE upstream time-of-flight system,* R. Bertoni et al, NIM A 615 (2010)14-26. arXiv:1001.4426v2

[7] *The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment,* MICE collab., arXiv:1203.4089v2 [physics.acc-ph] to appear in JINST.