THE MICE EXPERIMENT

Alain Blondel , DPNC, University of Geneva, Switzerland, *on behalf of the collaboration*

Abstract

Ionization Cooling is the only practical solution to preparing high brilliance muon beams for a 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, aimed 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 Technical Reference Document [3]. A recent status update can be found in [4]. The MICE collaboration is international and assembles contributions from continental Europe, Japan, the 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 momenta 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 a neutrino factory – to be accelerated or stored in an accelerator of given aperture, and is critical for muon collider luminosity.

The practical realization requires operating high gradient cavities in the 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 every early muon beam preparation system in a neutrino factory or muon collider, is the object of the MuCool R&D program at Fermilab [5]. 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 use 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 50 ps, two trackers placed within spectrometer solenoids measure the spatial coordinates and angles as well as 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 distributions in all coordinates and the 6x6 correlation matrix among them can thus be extracted with a precision allowing a measurement of the emittance change to 1% of its value: $\Delta[(\varepsilon_{in}-\varepsilon_{out})/\ \varepsilon_{in}]\sim 1\%$. The layout of the experiment is shown in Fig. **1**.

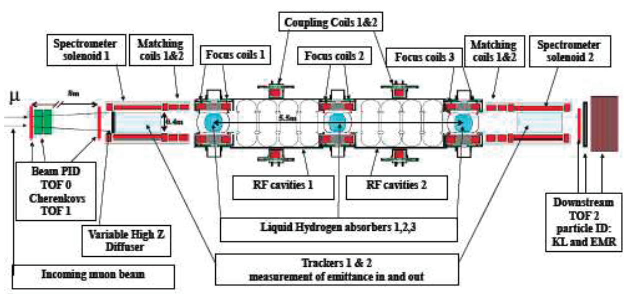

Figure 1: Layout of the muon ionization cooling experiment MICE.

MICE will be executed in steps (Fig. 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.

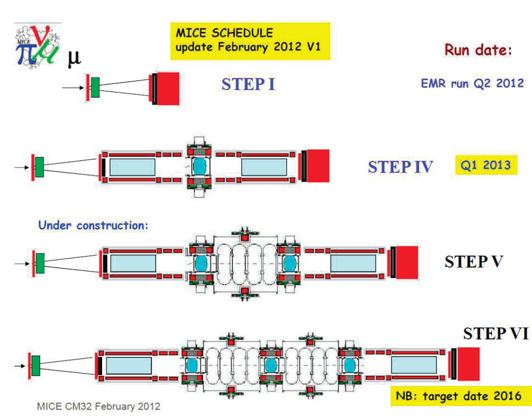

Figure 2: MICE implementation in steps.

Step I is complete and comprised the commissioning of the beam and beam-line detectors. It also allowed first measurements of beam parameters, distributions and

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emittance using particle physics detectors. In Step IV (in 2013) the commissioning of precise emittance measurement and measurement of the 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 could 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 short-focal-length, 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 must be contained and protected for safety in tanks with two pairs of very thin aluminium windows separated with vacuum.

-- the RF cavities must have a large aperture, thus a relatively low (200 MHz) frequency. In order to increase their electrical 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 to 12 MV/m.

The measurement challenges are as follows:

-- to provide the requested resolutions in the presence of potential RF induced backgrounds; the MICE trackers [6] within the spectrometer solenoids with a field of 4T, were designed and tested to satisfy these requirements; the TOF hodoscopes [7] have been operated since 2008 and provide the desired resolution of 50 ps 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 must be generated with suitable properties. The beam-line description and commissioning results are given in [8]. The layout of the beam line is shown in Figure **3**. The target is dipped into the ISIS proton beam at the top of the acceleration cycle (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 then enter a decay solenoid in which they can decay into muons of typically lower momentum. A second dipole (D2) implements 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' ($P_2 \sim 0.6\ P_1$) or a 'pion beam' ($P_2 \sim P_1$) with momenta between 140 and 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 'muon beam' purity was determined, by analysis of the pulse height deposited in the KL detector, as compared with that for 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.

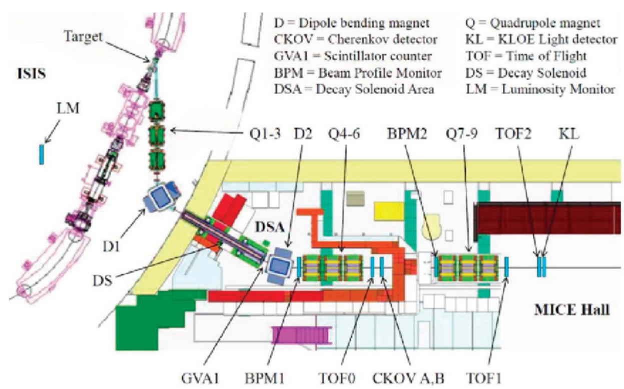

Figure 3: Layout of the MICE beam-line at ISIS.

TOWARDS STEPS IV AND VI

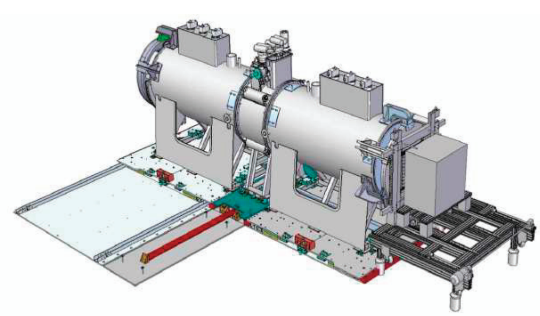

Figure 4: MICE Step IV (engineering drawing).

The components to be assembled for Step IV, Fig. 4, are:

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

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-- the first focus coils (of which two pairs are now in production) are also in the final stage of testing before being shipped to RAL.

-- a diffuser composed of four irises of brass or tungsten will be used to adjust the thickness in radiation lengths of material placed at the entrance of the first tracking volume in order to allow emittance to be varied.

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

-- liquid hydrogen absorbers have been fabricated at KEK (Japan) and their windows at the University of Mississippi; lithium hydride absorbers have also 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 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 Wang NMR, Inc. of Livermore, CA.

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 their 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 Laboratory. A total of 8 MW will be available, each 2 MW amplifier feeding 2 cavities. The first RF amplifier should be installed in the MICE hall in fall 2013. The layout of the RF system in the MICE hall has been drafted – there will be little free 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. See Figs. 6 and 7.

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

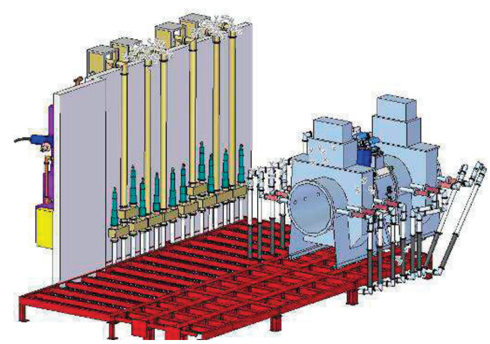

Figure 7: RF power layout in the MICE hall with sketch of one RF module (two are necessary for Step VI).

REFERENCES

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

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

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