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 ultra-high intensity 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 beams have been shown by direct measurement with the particle physics detectors to be adequate for cooling measurements, in rate, particle composition and emittance. Measurements of beam cooling properties of liquid-hydrogen, lithium hydride and other absorbers are planned for 2014-2016. A full cell of the ionization cooling channel, including RF re-acceleration, is under construction, aimed at operation by 2017-2019. The design offers opportunities for tests with various absorbers and optics configurations. Results will be compared with detailed simulations of cooling channel performance for a full understanding of the cooling process.

MICE GOAL AND PRINCIPLE

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 with contributions from continental Europe, Japan, the UK and the US. For neutrino factories and muon colliders the high intensity muons beams are generated and prepared in a powerful magnetic 'bottle' generated by a string of axial coils and solenoids, from the target solenoid all the way to the last stages of cooling. MICE is such a magnetic bottle and addresses several challenges of the first stage of muon machines beyond cooling. There are several technical challenges to this, in particular to reach high gradient in RF cavities embedded in magnetic field, which 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 it 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.

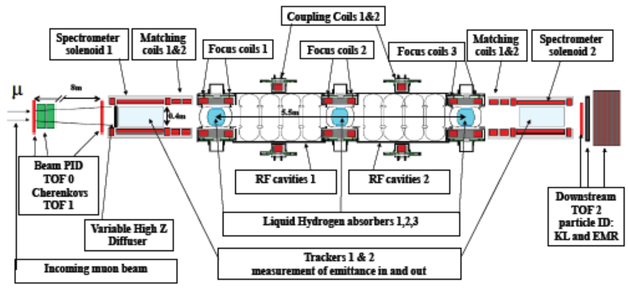

Figure 1: Layout of MICE.

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.

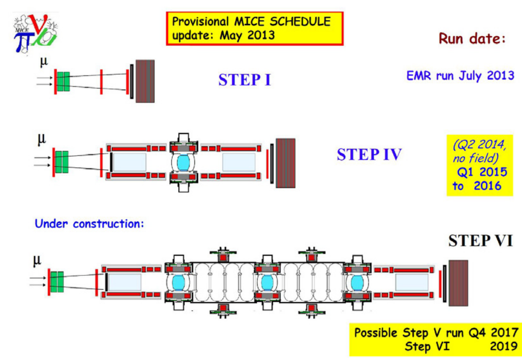

Figure 2: MICE implementation in steps.

STEP I RESULTS

Step I, commissioning of the beam and beam-line detectors, is complete, and led to several publications [6, 7, 8]. The beam-line description and commissioning results are given in [8]. The layout of the beam line is shown in Fig. 3.

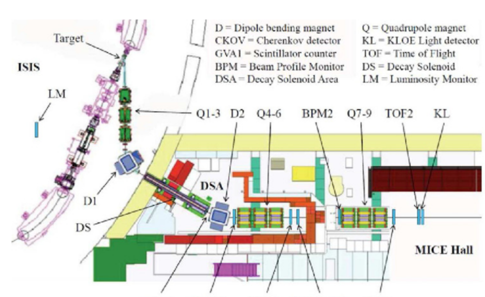

Figure 3: Layout of the MICE beam-line at ISIS.

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 brings the beam towards the target for this duration ensuring 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 ~ 0.6 P_1) or a 'pion beam' (P_2 ~ P_1) with momenta between 140 and 450 MeV/c, Fig. 4. The 'pion beam' contains electrons, muons and pions with a few % momentum spread. The 'muon beam' is a rather pure muon beam with a momentum spread of typically 25% Fig. 5. During a run in December 2011, the 'muon beam' purity was determined, by analysis of signals deposited in the KL detector, as compared with selected samples of pions and muons in the 'pion beam', to be around 99%, Fig. 6.

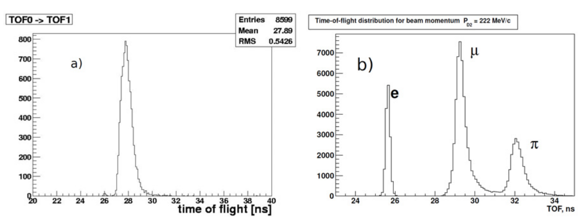

Figure 4: Time of flight (TOF1-TOF0) for (a) the 'muon beam' (P2 ~ 0.6 P1) and (b) a pion beam (P2 ~ P1).

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.

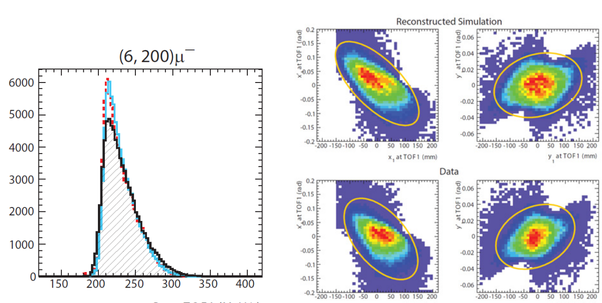

Figure 5: Left: beam momentum in the nominal MICE muon beam. Red, blue and black shaded distributions are simulation, reconstructed simulation and data respectively. Right: Horizontal (x,x') and vertical (y,y') trace space distributions at TOF1 for simulation (top) and data (bottom) in the MICE nominal muon beam [9].

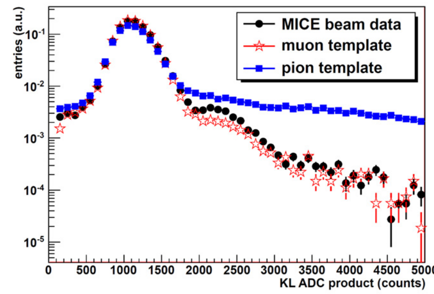

Figure 6: Determination of MICE muon beam purity using the KL detector. A pion contamination in the muon beam at or below the 1% level is determined [10].

The nominal muon beam (P_2 ~ 0.6 P_1) is very pure but offers a skewed momentum distribution (Fig. 5). Work towards a symmetric distribution is reported in [11].

TOWARDS STEPS IV AND VI

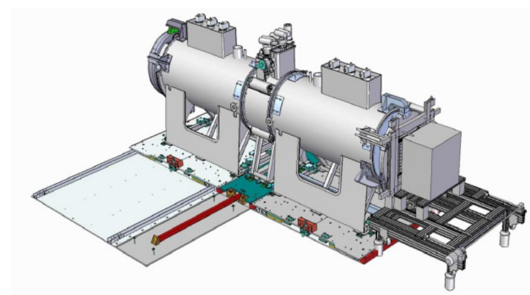

Figure 7: MICE Step IV (engineering drawing).

The components to be assembled for Step IV are:

-- two spectrometer solenoids, 2 m long magnets each comprise 5 superconducting coils [12], Fig. 8. They deliver a uniform field of 4 T in the tracker region of 1 m length, 40 cm bore, and tuneable coil for optics matching. They are built at Wang NMR, Livermore, CA; the first one is operational and waiting for magnetic measurements [13], the second one will be training in June 2013.

-- the first focus coil magnet is training at RAL.

-- a diffuser composed of four brass and tungsten irises

-- two completed trackers, tested with cosmics [6].

-- 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 both helium and hydrogen.

An important task to complete before running step IV is to prepare for the large stray magnetic fields generated by the magnets, which do not include a return yoke, Fig. 9. This has led to a careful relocation of a number of electronics racks and compressors, and for those elements that could not be moved, to the study of local shielding. In case this would not be completely feasible, a global return yoke has been study that would satisfy requirements for step IV and VI. A review is planned and decision will take place in September 2013. It is expected that the Step IV measurements will start in February 2015, with a possible run of the full assembly without magnetic field in early

ISBN 978-3-95450-122-9

summer 2014. Progress towards MICE step IV is described in [14].

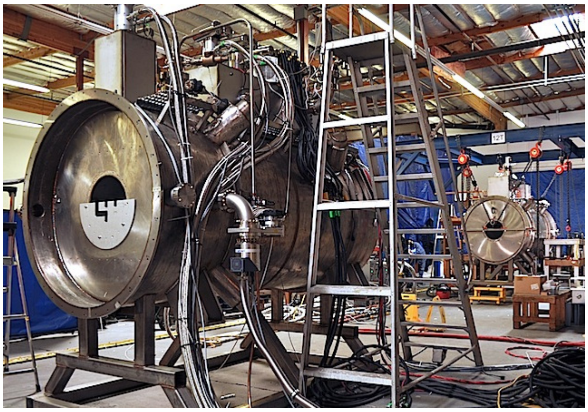

Figure 8: Spectrometer solenoids at Wang NMR, Inc. of Livermore, CA.

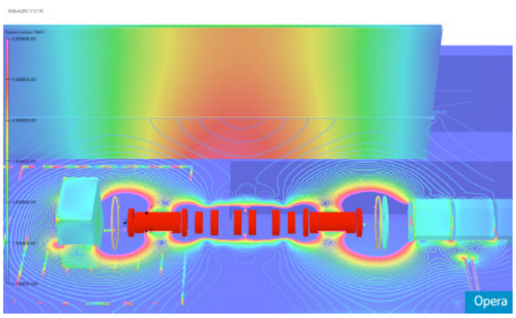

Figure 9: Stray magnetic field in the MICE hall, step VI.

Step VI requires in addition the construction of a full RF section [15] and two 'coupling coils'. A more detailed description of the Step VI construction can be found in [16]. The water cooled 200 MHz RF cavities have been spun, measured and electro-polished. The next step is their assembly with the couplers. A single-cavity module is constructed for tests in the MTA at Fermilab.

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 will be installed in the MICE hall in fall 2013. The layout of the RF system (Fig. 10) 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 is now fully organized. A first coil has been wound and is now ready for testing at FNAL. After this test is completed successfully, winding of another three coils will begin, while construction of the cryostats takes place and the integration of the magnets is prepared. The aim is that the first magnet will be ready in 2015 for testing of a single cavity in the full magnetic field, and the full experiment assembled for data taking in 2017-2019. It will be possible to test the experiment with one module of cavities ('step V') in 2017.

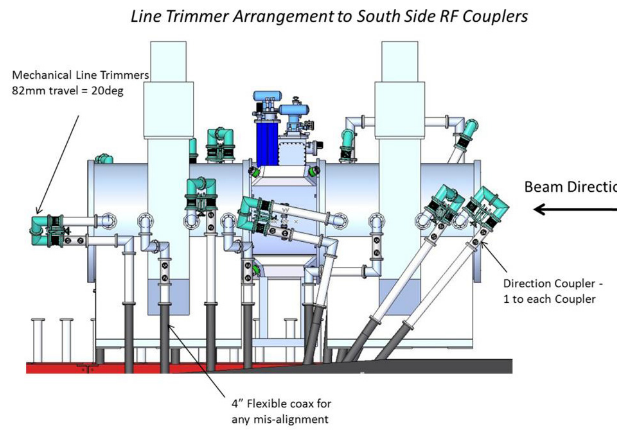

Figure 10: Sketch of MICE with RF power layout in the MICE hall with description of the phase trimmers for each pair of cavities.

REFERENCES

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

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

[3] MICE Technical Reference Document, http://www.mice.iit.edu/trd/MICE_Tech_ref.html

[4] A. Blondel, The MICE Experiment, IPAC 2012, http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/moeppb002.pdf Report to the MICE project board, MICE note 366

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

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

[7] 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.

[8] The MICE Muon Beam on ISIS and the beam-line instrumentation of the Muon Ionization Cooling Experiment, MICE collab., JINST 7 (2012) P05009, arXiv:1203.4089v2.

[9] MICE collab., Characterisation of the muon beams for the Muon Ionisation Cooling Experiment, in preparation

[10] MICE collab., Particle identification in the Muon Ionisation Cooling Experiment (MICE) beam, to measure its pion contamination, in preparation.

[11] O. Hansen et al, Towards a Symmetric Momentum Distribution in the Muon Ionization Cooling Experiment, IPAC13 TUPFI020.

[12] S.Virostek et al, Assembly and Test of a Modified Spectrometer Solenoid for MICE , IPAC13 THPME048.

[13] M. Leonova, Analysis of MICE Spectrometer Solenoid Magnetic Field Measurements, IPAC13 TUPFI054.

[14] D. Rajaram, MICE Step I, IPAC13TUPFI066.

[15] K. Ronald et al., The RF System for the MICE Experiment, IPAC13WEPFI066.

[16] D. Rajaram, MICE Step VI, IPAC13TUPFI065.