THE MICE MUON BEAM: STATUS AND PROGRESS*

A. Dobbs#, M. Apollonio, K. Long, J. Pasternak, Imperial College London, U.K.
D. Adams, STFC, Rutherford Appleton Laboratory, U.K.

Abstract

The international Muon Ionisation Cooling Experiment (MICE) is designed to provide a proof of principle of the ionisation cooling technique proposed to reduce the muon beam phase space at a future Neutrino Factory or Muon Collider. The pion production target is a titanium cylinder that is dipped into the proton beam of the Rutherford Appleton Laboratory's ISIS 800 MeV synchrotron. Studies of the particle rate in the MICE muon beam are presented as a function of the beam loss induced in ISIS by the MICE target. The implications of the observed beam loss and particle rate on ISIS operation and MICE data taking are discussed.

INTRODUCTION

The MICE experiment is designed to demonstrate the feasibility and performance of *ionisation cooling*, the process of reducing the phase space occupied by a muon beam by passing it through a series of absorbers and accelerating r.f. cavities. The technique was proposed many years ago [1] but has yet to be demonstrated – a necessary step towards a future Neutrino Factory or Muon Collider.

At the Neutrino Factory, the muon beam must be cooled to increase the number of muons which fall within the acceptance of the muon acceleration systems. For the Muon Collider, cooling is essential if the necessary luminosity in the colliding beams is to be achieved. The short muon lifetime precludes the use of conventional ring techniques to cool the muon beam.

The MICE collaboration will evaluate the performance of a single cell of the Neutrino Factory cooling-channel lattice described in [2]. The MICE Muon Beamline is required to provide a normalised emittance that can be varied between 1 and 12 π mm rad over a momentum range of 140 MeV/c to 240 MeV/c [3]. A 10% cooling effect is expected and the MICE spectrometer systems have been designed to measure this effect with a precision of 10^{-3} [4,5].

The experiment is hosted on the ISIS 800 MeV proton synchrotron at the Rutherford Appleton Laboratory, UK. The MICE Muon Beam, which was commissioned in the spring of 2008, is now routinely serving the first data taking phase of the experiment. A schematic of the beam line is shown in Figure 1 [6]. A cylindrical target [7] is dipped into the circulating beam. The depth at which the target is dipped is characterised by the 'beam centre distance' (BCD) which is the distance from the tip of the target to the nominal proton-beam axis at the target's maximum excursion into the beam. Pions produced in the target are captured by a quadrupole triplet and transported to a dipole magnet by which the pion momentum is selected. A 5 T super-conducting 'decay' solenoid follows the dipole, the additional pion path length in the solenoid increasing the muon-production efficiency. Following the solenoid, a second dipole is used to select the muon momentum and the beam is transported to MICE using a pair of large-aperture quadrupole triplets.

*Work supported by the Science and Technology Facilities Council
#a.dobbs07@imperial.ac.uk

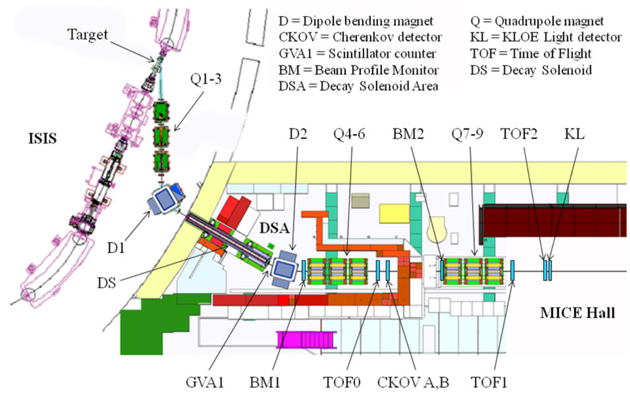

Figure 1: A schematic of the MICE beam line as of spring 2010.

MICE target operation produces an increase in beam loss levels around the synchrotron. This leads to an increase in activation of the accelerator which may have an impact on machine maintenance. It is therefore essential to optimise the particle production for MICE while minimising the generation of beam loss in ISIS. In this paper, a systematic study of the relationship between beam loss in ISIS and MICE particle rates will be presented.

In the next section, ISIS beam loss considerations and the effect of the MICE target are discussed in more depth. Then, the results of a particle rate versus beam loss study are presented. Finally, the implications are discussed together with plans for future work.

BEAM LOSS IN THE ISIS SYNCHROTRON

The MICE target is a 5.95 mm diameter hollow titanium cylinder with a wall thickness of 0.4 mm. The target intercepts the ISIS circulating beam over the last 3 ms of acceleration, equivalent to ~ 4000 turns, covering a proton energy range of 615 MeV to 800 MeV. Measurements show the full beam half-height is 43 mm. The target dips into the beam in the vertical plane on the ring central axis reaching its maximum depth towards the end of the 4000 turns. There are 39 beam loss monitors (BLMs) [8] placed around the inner radius of the synchrotron. These monitors detect neutrons produced by scattered protons that interact with accelerator components. The ionisation chambers that form the BLMs produce a voltage signal that is integrated over a particular time interval to give a measure of beam loss. Hence, the beam loss is presented in units of V.ms.

The ISIS synchrotron lattice has 10 'super periods', numbered from 0 to 9. The MICE target is situated in super period 7 (SP7). Each super period has four BLMs. The BLMs may be identified by a number running from 0 to 39, BLM 0 being in SP0 and BLM 39 in SP9. Alternatively, the BLMs may be identified by referring to the BLM number within a super period; for example the first BLM in SP8 is referred to as R8BLM1.

The integrated beam loss on each of the 39 monitors over the last 3 ms of acceleration for three BCD settings are shown in Figure 2. Two discernable regions are evident. The first, at the MICE target (BLMs 28–39) is due to high momentum-transfer scattering of the proton beam which peaks on R8BLM1 The second region in SP1-3 is associated with beam hitting the injection foil (BLM 3) and the collimators (BLM 5-12). The collimators are designed to collect beam loss during longitudinal trapping and acceleration, 70-250 MeV. Protons lost in the collimators in the last 3 ms of acceleration cycle have undergone small momentum-transfer scattering in the MICE target and have an emittance greater than the collimator acceptance. This loss is approximately 3 times the peak loss around the MICE target.

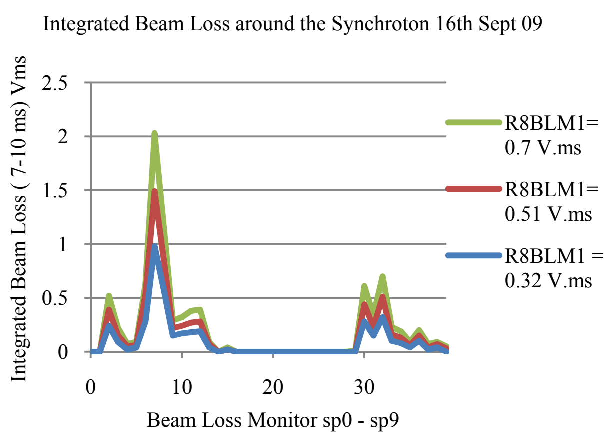

Figure 2: Integrated beam loss around ISIS ring for 3 target dip levels. Blue: R8BLM1 = 0.32 V.ms, Red: R8BLM1 = 0.51 V.ms, Green: R8BLM1 = 0.7 V.ms.

Under normal operation, beam loss in the ring is localised around the collimator system. At normal operating currents, 200 μA, the total integrated beam loss over the whole acceleration cycle, 0–10ms is 1.6 V.ms. Measurements of total integrated loss versus integrated loss on R8BLM1 are shown in Figure 3. A target dip depth with a BCD of 25 mm produces a 5 V.ms loss on R8BLM1; higher R8BLM1 losses relate to higher muon fluxes for the MICE experiment (see below). The equivalent integrated summed loss has increased to 57 V.ms. If MICE were to operate at 1Hz at this loss level then, assuming activation is proportional to beam loss, the machine activation would increase by 69%. Activation experiments when operating MICE at 0.3 Hz show measurable activation at 2 V.ms losses on R8BLM1.

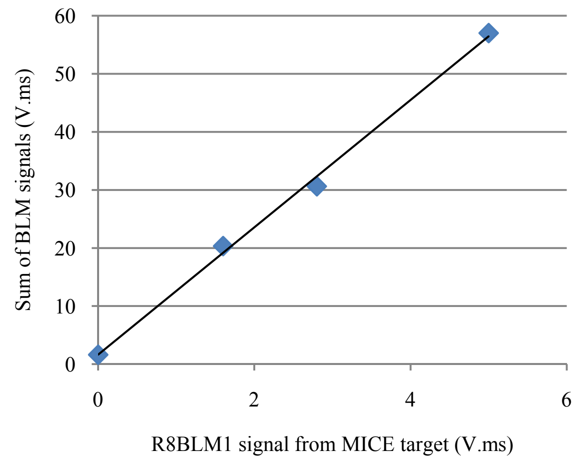

Figure 3: Sum Integrated beam loss versus R8BLM1.

BEAM LOSS VS. MICE PARTICLE RATE

Methodology

MICE receives three beam loss signals from ISIS: the summed losses from all the monitors in SP7, all the BLMS in SP8 (including R8BLM1) and the summed loss over the whole ring. For each of these signals, the losses are integrated over the whole ISIS acceleration cycle, and the integrated loss in SP7 used as the figure of merit for the beam loss produced by each target dip. This is illustrated in Figure 4.

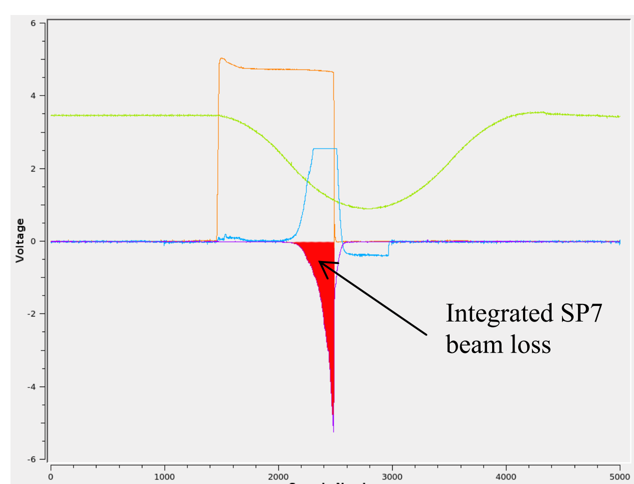

Figure 4: Screenshot from the MICE target DAQ showing one ISIS acceleration cycle with the MICE target present. The ISIS beam intensity is shown in orange, the target position in green, total beam loss over the whole ring in light blue, and the total beam loss in SP7 in purple. The red shaded area represents the integrated beam loss in SP7.

The corresponding particle rates are recorded by five detectors positioned along the MICE beam line. GVA1 is a scintillator slab readout by a photomultiplier tube (PMT). BPM1 and 2 are beam profile monitors, each consisting two planes of scintillating fibres, each plane being read out by a multi-anode PMT. Lastly TOF0 and 1 are time-of-flight stations, each consisting of two layers of scintillator bars, each bar being read out by a PMT at either end with a resolution of 50 – 60 ps [9]. The positions of the various detectors are shown in Figure 1.

Runs were taken with of order a hundred target pulses, each being at a fixed beam loss value. Several runs were performed for different beam loss values; the average values of the particle rates and beam loss over each run were calculated and the results plotted.

Results

The following results are taken from a study conducted on the 6th November 2009. The MICE Muon Beam was set to transport 290 MeV/c negative pions and the gate of the MICE DAQ system was set to 0.5 ms duration. Six runs were performed at various beam loss settings, ranging from approximately 0.5 V.ms to 4.7 V.ms (to date the highest beam loss levels achieved). The results are shown in Figure 5.

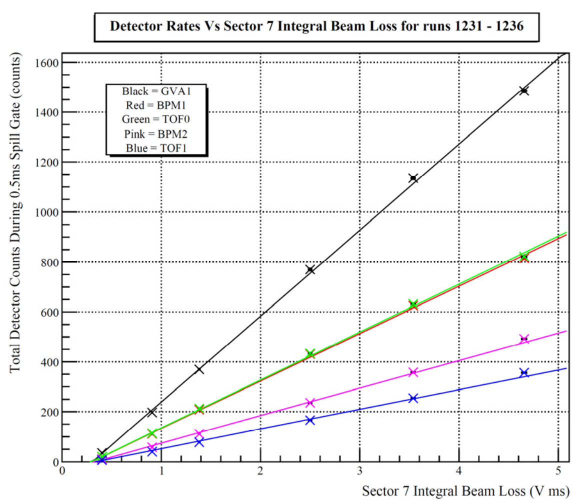

Figure 5: Particle rates in various MICE detectors as a function of beam loss induced in SP7 of ISIS, together with linear fits. Linearity can be seen to hold to a good approximation in every detector (with the possible exception of TOF1) over the whole beam loss range of ~ 0.5 V.ms to 4.7 V.ms. A constant offset is also observed for each detector, representing a background beam loss independent of the action of the MICE target.

DISCUSSION AND FUTURE WORK

There are a number of studies under way to improve particle rates per V.ms beam loss. Variations in target geometry and material could influence loss distributions and are under study using ORBIT [10]. A vertical orbit displacement of the circulating proton beam may also be able to limit beam losses to the last millisecond of acceleration, the period of interest for MICE. Replacing the ISIS collimators with a higher atomic number material would also improve collection efficiencies at higher energies but would generate more neutrons and produce more local activity.

Work to understand the particle beam in the MICE beam line is also on going, in particular to separate the beam into rates for individual particle species using the TOFs for particle identification. Achieving this should allow the muon rate to be extrapolated to higher beam losses (assuming the observed linearity continues to higher beam losses), and so be used to estimate the maximum muon rate achievable without producing unacceptable activation to the structure of the ISIS synchrotron.

ACKNOWLEDGEMENTS

We would like to thank the international MICE collaboration, which has provided the motivation for and the context within which the work reported here is being carried out. We also gratefully acknowledge the ISIS Division at the STFC Rutherford Appleton Laboratory for providing beam and essential support.

REFERENCES

[1] A. Skrinsky and V. Parkhomchuk, "Cooling methods for beams of charged particles", Sov. J. Part. Nucl. 12 (1981) 223, http://www.hep.princeton.edu/mumu/physics/skrinsky_sjpn 12_223_81.pdf.

[2] S. Ozaki et al., "Feasibility Study-II of a Muon-Based Neutrino Source", BNL-52623 (2001).

[3] D. M. Kaplan and K. Long, "MICE: The International Muon Ionisation Cooling Experiment", arXiv:0707.1915v1 [physics.acc-ph].

[4] V. C. Palladino and A. Alekou, "Status of MICE, the international Muon Ionisation Cooling Experiment", IPAC10.

[5] M. A. Rayner and J. H. Cobb, "Measurements of Muon Beam Properties in MICE", IPAC10.

[6] M. Apollonio et al., "Optimization of the MICE Muon Beamline", IPAC10.

[7] C. Booth et al., "MICE Target Hardware", IPAC10.

[8] M. A. Clarke Gayther, "Global Beam Loss Monitoring Using Ionisation Chambers at ISIS", EPAC94.

[9] M. A. Rayner and M. Bonesini, "The MICE PID Detector System", IPAC10.

[10] J. Galambos, "ORBIT – A Ring Injection Code with Space Charge", PAC99; http://www.JACoW.org.