THE MICE MUON BEAMLINE AND INDUCED HOST ACCELERATOR BEAM LOSS

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Abstract

The international Muon Ionisation Cooling Experiment (MICE) is designed to provide a proof of principle of ionisation cooling to reduce the muon beam phase space at a future Neutrino Factory and Muon Collider. The MICE Muon Beam is generated by the decay of pions produced by dipping a cylindrical titanium target into the proton beam of the 800 MeV ISIS synchrotron at the Rutherford Appleton Laboratory, U.K. Studies of the particle rate in the MICE Muon Beamline and its relationship to induced beam loss in ISIS are presented, using data taken in Summer 2010. Using time-of-flight to perform particle identification estimates of muon rates are presented and related to induced beam loss.

INTRODUCTION

The MICE experiment is designed to demonstrate the feasibility and performance of *ionisation cooling*, an accelerator physics technique to reduce the normalised emittance of a muon beam. Ionisation cooling was first proposed in the 1980's [1] as a means of reducing the emittance of muon beams, as traditional beam cooling techniques, such as stochastic cooling, are too slow to be effective due to the short muon lifetime of 2.2 μs. Applications include the Neutrino Factory, a proposed future neutrino source offering the best coverage of the oscillation parameter space [2], which will require cooling in order for the muon beam generated by the Neutrino Factory front-end to fit efficiently within the acceptance of downstream acceleration components [3]. Also a future Muon Collider, a facility proposed to offer a route to multi-TeV lepton - anti-lepton collisions, and which holds many technologies in common with a Neutrino Factory, would require even more stringent beam cooling [4, 5].

Ionisation cooling involves passing a beam through an absorber medium such that through ionisation energy loss the momentum of the particles is lost in all three spatial directions, causing a reduction in the beam emittance. This lost momentum is then replaced in the longitudinal direction only by means of RF cavities (known as *sustainable cooling*).

MICE is designed to evaluate the performance of a single cell of the Neutrino Factory cooling-channel lattice described in [6]. The channel is to consist of three absorber modules, initially containing liquid hydrogen, and two sets of four 201 MHz RF cavities, with a target emittance reduction of $\sim$10%. Two scintillating fibre trackers, each contained in a 4 T superconducting solenoid, are to be positioned before and after the cooling channel in order to measure the emittance with a precision of 1 in 10^3.

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BEAMLINE

The MICE Muon Beamline took first beam in Spring 2008 and is designed to supply the cooling channel with a muon beam of variable emittance in the range 1 to 12π mm rad over a momentum range of 140 MeV/c to 240 MeV/c. MICE is hosted by the Rutherford Appleton Laboratory, U.K., using the 800 MeV ISIS synchrotron as a proton source for the beamline. A schematic of the beamline is shown in Fig.1.

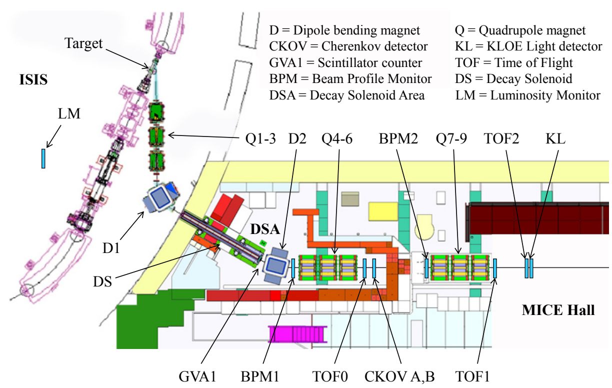

Figure 1: The MICE Muon Beamline as of Summer 2010. The future cooling channel is to be placed between TOF1 and TOF2.

A cylindrical titanium target, of inner radius 4.55 mm and outer radius 5.95 mm, is pulsed into the circulating proton beam close to extraction using a 24 coil stator drive [7]. Hadronic interactions in the target generate a pion flux which is captured by a quadrupole triplet. These are then transported to a 5 T decay solenoid to allow conversion to muons, before being further transported down the MICE beamline and so to the cooling channel.

Various detectors for beam characterisation are also placed along the beamline including a scintillator counter (GVA1), two scintillating fibre beam profile monitors (BPM1 and BPM2), three 50 - 60 ps resolution time-of-flight (TOF) stations, two Cherenkov light counters (CKOVA and CKOVB) and a calorimeter (KL) [8]. Their positions are shown in Fig.1. A luminosity monitor (LM) is also present in the synchrotron vault consisting of four photomultiplier tubes with some polyethylene plastic shielding [9].

ISIS BEAM LOSS

The action of the MICE target not only causes the pion shower used by the muon beamline, but also generates increased levels of beam loss in the ISIS accelerator. This has the potential to disrupt the beam for other users or more seriously to increase activation levels in the synchrotron vault making hands-on maintenance more difficult [10]. As such it is important that a systematic study be performed to investigate how the particle rate in the MICE beamline, in particular the muon rate, is related to the increased beam loss levels induced by the MICE target.

ISIS is divided in to 10 "super-periods" or "sectors" (S), which form the repeating cells of the ring. The layout of the ring, including the MICE target, is shown in Fig.2.

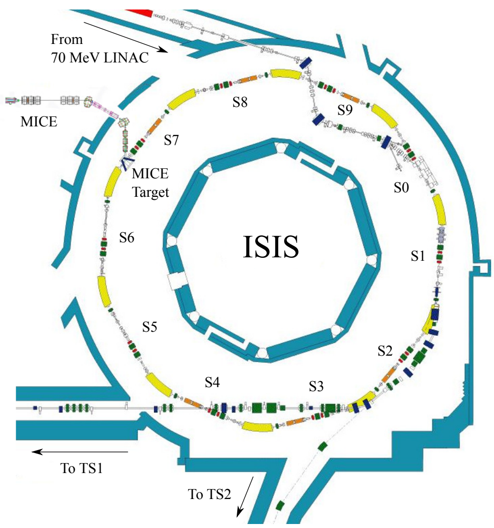

Figure 2: The ISIS 800 MeV proton synchrotron. TS1 and TS2 refer to the fixed target stations 1 and 2. The MICE target is present at the start of S7.

Injection into the ring occurs in S0 and the MICE target is positioned at the start of S7. Positioned around the inner radius of the ring are 39 beam loss monitors (BLMs), in the form of argon gas wire ionisation chambers [11]. The figure of merit used here to quantify the MICE induced beam loss will be the summed signal from the four BLMs in S7, integrated over the 10 ms period of the ISIS injection - extraction cycle (illustrated in Fig.3).

BEAM LOSS AND PARTICLE RATE

A dedicated study was performed on the 15th and 16th of June 2010 to observe particle rates in the MICE beamline as a function of ISIS beam loss (the results of a previous study from November 2009 can be found in [10]). The above definition of S7 integrated beam loss is used, together with the particle rates observed in the BPM2, TOF0 and TOF1 detectors. Runs were performed consisting of approximately 400 target pulses each, each run being taken at a fixed beam loss value. Between runs this value was altered by varying the target depth to create one data point

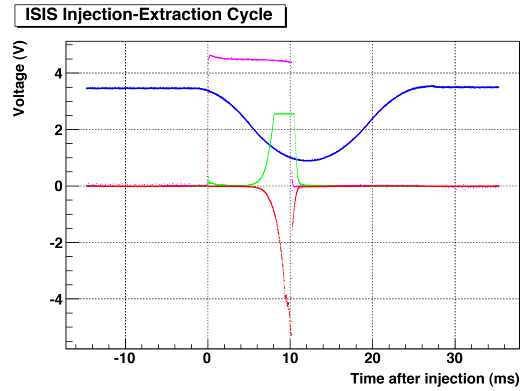

Figure 3: The ISIS injection - extraction cycle. The figure of merit used to quantify the beam loss induced by MICE target is given by the integral of the sector 7 (S7) beam loss curve, represented graphically by the area with a lower vertical bound given by the S7 beam loss curve, an upper vertical bound by the 0 V line, and with horizontal bounds of 0 - 10 ms.

per run. The 15th study used negative $\pi \rightarrow \mu$ beamline optics with a 3.2 ms spill gate per pulse, and the 16th a positive $\pi \rightarrow \mu$ beamline optics with a 1 ms spill gate per pulse. The results for the 15th and 16th are shown graphically in Fig.4 and Fig.5. Linear rate increases with beam loss are observed across all detectors, with the possible exception of the highest rate point for the 16th study in the TOF0 detector.

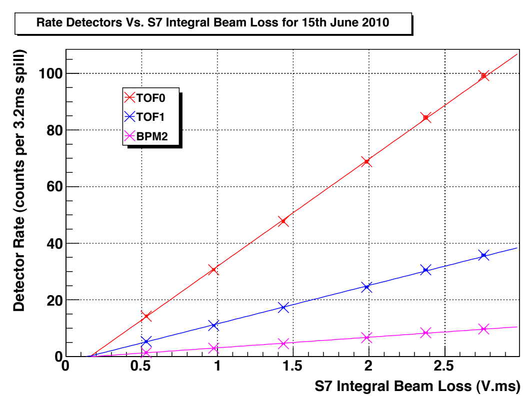

Figure 4: Results of the 15th June 2010 study showing absolute particle rate in three detectors as a function of integrated S7 beam loss. Linear fits are also shown.

By looking at the particle time-of-flight between the TOF0 and TOF1 stations particle identification (PID) may be performed to move from the absolute rate of all particles to an estimate of muon rate. Fig.6 shows an example TOF track spectrum from a 15th June run and the cuts used to define a muon track. The tracks are reconstructed by software from time-to-digital conversion data of photomultiplier tube (PMT) hits in the TOF stations, and so incur more inefficiencies than the previous rates which are derived from the more basic "scaler" hits defined simply by coincidences of PMT hits in individual detectors.

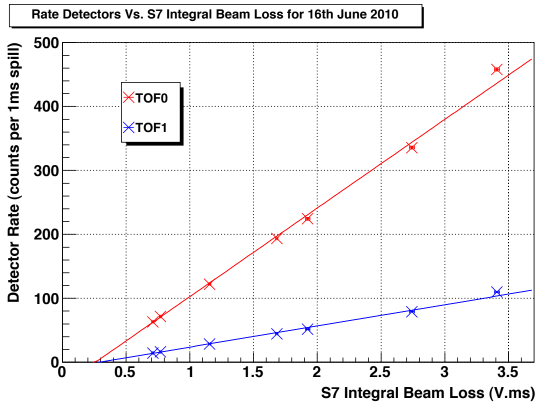

Figure 5: Results of the 16th June 2010 study showing the absolute rate in two detectors (BPM2 failed on the 16th) as a function of integrated S7 beam loss. Linear fits are also shown.

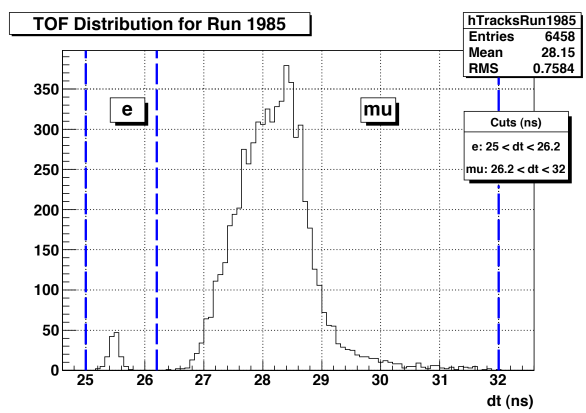

Figure 6: TOF spectrum for run 1985 taken during the 15th June study. The cuts used to define muons tracks are indicated. Small levels of pion contamination are expected in the right hand muon peak.

Once the reconstruction is performed, the muon track rate, averaged for each run, may then be plotted against beam loss. Fitting these plots with first order polynomials allows the evaluation of muon track rates as a function of beam loss, the results of which, including evaluations of the previous absolute particle rates, are shown in Tab.. This then provides an estimate of the number of usable muons present in the first two TOF stations of the MICE beamline.

In the case of a positive beamline the muon rate, in the range of tens of muons per 1 ms gate, is about an order of magnitude below the desired rate for MICE. Deeper target dip depths could be used but would result in ISIS beam loss levels which would probably be unacceptable. Various proposal are being considered to address this including adding a beam "bump" to the ISIS beam in the vicinity of the MICE target, extending the ISIS collimator system, altering the target material or geometry and increasing the target dip frequency.

Table 1: Summary of results for the June 2010 studies. "Scaler Hits" refers to the absolute rates for all particles shown previously. "Deriv." refers to the derivative of the function fitted to TOF tracks against beam loss distributions.

Conditions	Scaler Hits	All Tracks	Muon Tracks
15th Deriv. 3.2 ms	13.6	6.0	5.9
15th 1.3 V.ms 3.2 ms	15.6	7.0	6.8
15th 2 V.ms 3.2 ms	25.1	11.1	10.9
16th Deriv. 1 ms	31.1	16.4	16.4
16th 1.3 V.ms 1 ms	33.6	19.7	19.7
16th 2 V.ms 1 ms	56.8	31.2	31.1

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