THE MICE MUON BEAM LINE AND HOST ACCELERATOR BEAM BUMP

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Abstract

The international Muon Ionization Cooling Experiment (MICE) is designed provide a proof of principle of the technique of ionization cooling, that is the reduction of the phase space of a muon beam via ionization energy loss in absorbers. Subsequent reacceleration is then provided by RF cavities ("sustainable cooling"). Ionization cooling represents an important step toward future facilities based on stored muons beams, such as a future Neutrino Factory or Muon Collider.

The MICE Muon Beam begins with the decay of pions produced by a cylindrical titanium target dipped into the circulating proton beam of the 800 MeV ISIS synchrotron at the Rutherford Appleton Laboratory, U.K. This generates a pion shower which is captured and subsequently decays producing the muon beam. A secondary effect of the MICE target is to cause an increase in the number of protons lost from the ISIS beam. It is important that this effect be minimized.

An overview is presented here of the MICE Muon Beam, including the results of a study in to the effect of raising the vertical position of the ISIS beam (a "beam bump") in the vicinity of the MICE target.

THE MICE MUON BEAM LINE

The MICE cooling channel will consist of three absorber modules, used to reduce transverse and longitudinal beam momenta, interspersed with two RF cavities, used for longitudinal reacceleration. It is required to produce an $\sim$10% reduction in beam emittance, and measure that change to 1% accuracy (an absolute emittance measurement of 0.1%) via scintillating fibre trackers at either end of the channel. The MICE Muon Beam line is to supply the muon beam to the cooling channel, with tunable emittance of 1 - 12 π.mm.rad.

The current layout of the MICE Muon Beam line is shown in Figure 1. The ISIS synchrotron serves as a proton driver, supplying $\sim$800 MeV protons to a cylindrical titanium target. The target is pulsed into the circulating beam towards the end of the 10 ms ISIS injection-extraction cycle using a magnetic drive, to a dip depth chosen by the user. Hadronic interactions between the protons and the titanium nuclei lead to a pion shower, part of which is captured by a quadrupole triplet, set at an approximately 25° angle to sector 7 of ISIS (where the target is located). Following this

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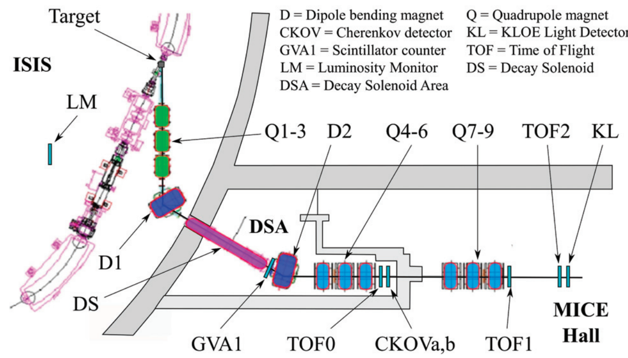

Figure 1: The MICE beam line. Adapted from [1].

first triplet a dipole is used to perform a first momentum selection on the beam and direct it into the MICE experiment hall. The beam then traverses a 5 T superconducting decay solenoid, increasing the pion path length, and so the muon content downstream. After the solenoid a second dipole performs a second momentum selection and again redirects the beam. Two final quadrupole triplets provide focusing as the beam approaches the cooling channel.

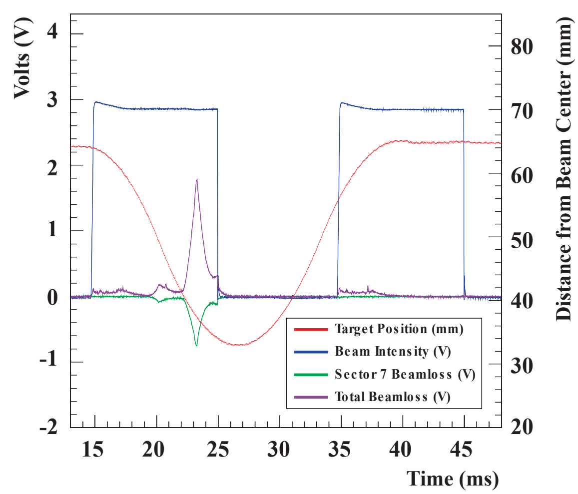

Figure 2: Diagram of two consecutive ISIS cycles, the first of which is intercepted by the MICE target. The ISIS beam intensity is shown, together with the target dip profile, and the instantaneous beam loss around the whole ring, and in sector 7 only.

Positioned at various points along the beam line are various detectors, including a scintillator counter (GVA1), two threshold aerogel Cherenkov detectors (CKOVa,b), three time-of-flight stations (TOF0-2), and a pre-shower detector similar to that used by the KLOE experiment[2]. The cooling channel is to be positioned between TOF1 and TOF2. A detailed description of the MICE beam line, including the various detector systems, can be found in [3].

In addition to creating the pion shower used to generate the muon beam, the action of the MICE target has the secondary effect of increasing the number of circulating protons lost from the ISIS beam, known as beam loss. This is illustrated in Figure 2, where two ISIS cycles are shown, one with the MICE target dipping, one without. Increased beam loss can clearly be seen when the target is present, correlated with the target dip depth. Increased beam loss levels are undesirable as increased losses can lead to machine activation, making hands on maintenance more difficult. It has been shown that particle rate in the MICE beam line increases linearly with target-induced ISIS beam loss [1]. Hence, it is important to achieve the most efficient means of creating beam in the MICE beam line for the minimum cost in beam loss in ISIS.

THE ISIS BEAM BUMP

Under normal operation the MICE target dips vertically into the circulating ISIS beam during the interval 6-10 ms of the cycle, depending on dip depth. However the actual muon measurement time of interest is only 9-10 ms, hence there is unnecessary beam loss and activation due to losses from 6-9 ms. Active control of the vertical beam position could mitigate this unwanted beam loss and could increase the relative target dip depth.

A vertical closed orbit bump generated using 4 steering magnets, 2 either side of the MICE target can be used to control beam position at the target. Some of these steering magnets are also used to produce a bump from 8-10 ms to facilitate extraction under normal operation. This adds a layer of complication onto operation of an acceleration cycle in which MICE operates but is within the power supply specifications. The closed orbit bumps for MICE, extraction and their sum are shown in Figure 3. A beam bump amplitude of 10 mm has been arbitrarily chosen.

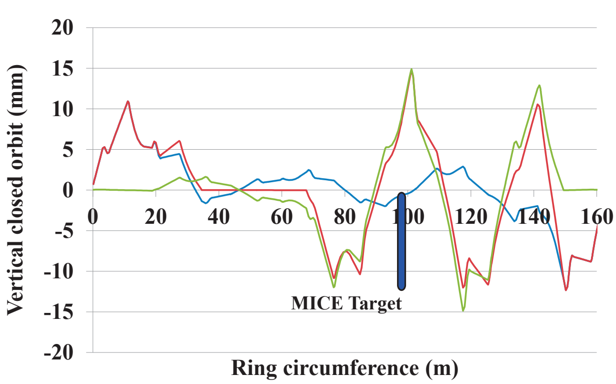

Figure 3: MICE operating trajectory (green), ISIS extraction trajectory (blue), the sum trajectory (red).

During commissioning a 2 mm bump was applied to the beam and the MICE target measured a 1.8 mm movement of the beam edge. Beam losses could be optimised by steering the beam away from the target from 6-8 ms (∼ -2 mm), towards the target from 8-9 ms and then holding beam position constant from 9-10 ms (+4 mm). Figure 4 shows this has reduced almost all ring beam loss from 6-8 ms.

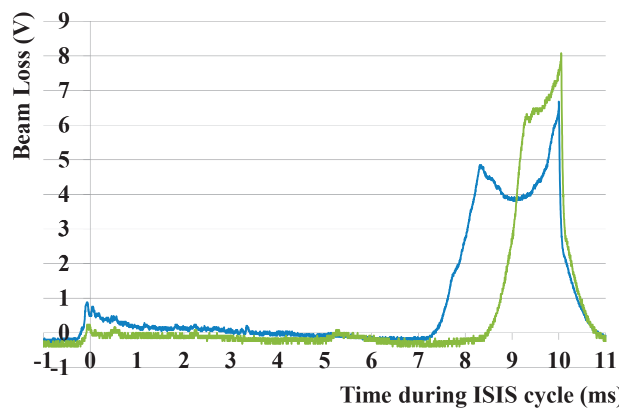

Figure 4: Total Ring beam loss bump off (blue), on (green).

The addition of recent power supply upgrades to vertical steering magnets and new control software will enable +/- 10 mm bumps to be applied as requested for any given target depth.

EFFECT OF THE BUMP ON MICE

To test and commission the beam bump, the orbit excursion and the target dip depth and timing were adjusted simultaneously to probe and optimise the beam. To observe the effects of the beam bump in MICE, the beam line was configured for a 260 MeV/c pion beam.

During the study the spill gate, the window in which the MICE Data Aquisition System (DAQ) records data from the detectors, was set to the present default value, covering the last 3 ms of the ISIS injection - extraction cycle. In the later steps MICE it is likely that the spill gate will decrease to 1 ms in order to accommodate the operation of the RF cavities. To assess the effectiveness of the beam bump with a smaller spill gate, the bump was optimised to occur during the last 2 ms of the ISIS cycle. The bump was not focused further than this (say, to 1 ms), as this would risk saturating the DAQ with a large instantaneous particle rate, due to the higher instantaneous beam loss.

The results of the runs recorded during the beam bump commissioning are shown in Table 1, together with the beam bump settings.

Without a beam bump the target mechanism was limited to generating 0.7 V.ms of beam loss without inducing large early losses caused by scraping the ISIS beam or generating injection losses in the next spill. To reduce the early losses beam bumps 1-4 focused on moving the beam away from the target, allowing the target to enter the beam earlier. Entering the beam earlier also permits the target to penetrate

Table 1: Effect of different beam bump settings tried during commissioning, detailing the total beam loss and the fraction inside the MICE gate. Loss inside the 3 ms spill gate contribute to the particles recorded by the DAQ. The errors shown are the standard error on the mean calculated by the ROOT framework[4].

Beam Bump	Bump settings during ISIS cycle (mm)			Mean sector 7 beam loss (V.ms)	Mean rate in TOF1 (counts per spill) (3 ms gate)	Fraction of beam loss in spill gate	
	5 - 8 ms	9 ms	10 ms			3 ms bump	2 ms bump
None	0	0	0	0.71 ± 0.01	40 ± 1	0.89	0.67
1	-2	0	0	0.59 ± 0.01	38 ± 1	0.94	0.87
2	-4	0	0	0.67 ± 0.01	43 ± 1	0.97	0.95
3	-4	0	0	1.37 ± 0.02	99 ± 1	0.97	0.94
4	-6	0	0	1.80 ± 0.02	120 ± 2	0.99	0.97
5	-6	2	4	1.68 ± 0.02	116 ± 2	0.98	0.97

more deeply into the beam. This was tested in beam bumps 3 and 4 where the beam loss and particle rate increased significantly. During the runs the beam bump constrained the majority of the beam loss to the spill gate.

Once the early losses had been removed beam bump 5 focused on increasing and flattening the beam loss during the last 2 ms of the spill. This was accomplished by moving the beam upwards towards the target. During the last millisecond the beam was moved further towards the target in order to compensate for the target beginning to move out of the beam. This creates a more even distribution of beam loss across the spill gate, helping to lower the maximum particle rate which could saturate the DAQ.

Figure 5 shows the particle rate per unit beam loss induced in sector 7 of ISIS, using data recorded during the bump commissioning. This shows that as the beam bump was optimised the particle rate accepted by MICE increased per unit of beam loss induced in sector 7. This increased efficiency has enabled MICE to generate larger particle rates, while simultaneously reducing unwanted ISIS beam losses, which contribute to machine activation.

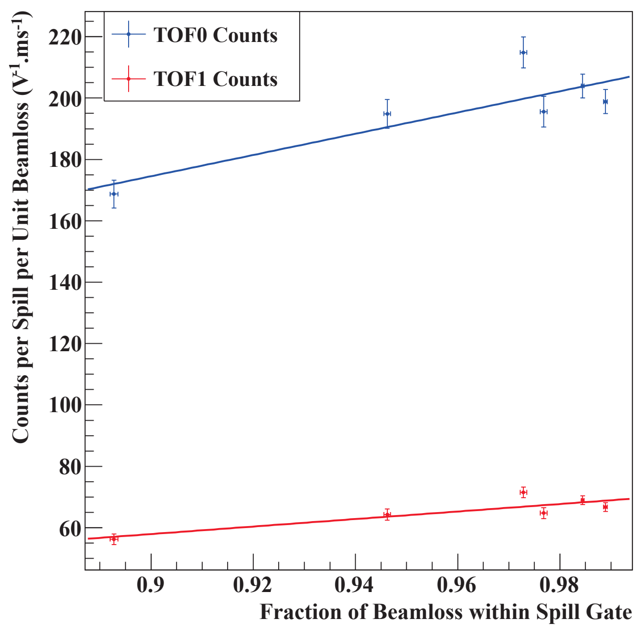

Figure 5: Particle counts measured in TOF0 and TOF1 per spill per V.ms of integrated sector 7 beam loss, plotted against the fraction of integrated sector 7 beam loss coinciding with the 3 ms spill gate.

CONCLUSION

Once commissioned the vertical beam bump has been enabled for all subsequent MICE shifts. This has allowed much simpler target operation and greater particle rates whilst reducing the total beam loss caused to ISIS. Additionally, since the beam bump compliments target operation, the particle rate can be adjusted with the target depth to meet the needs of the shift without modification from ISIS. This allows the present beam bump to assist MICE until the timing of the spill gate is adjusted at which point a re-commissioning shift will be required.

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