# PARTICLE PRODUCTION IN THE MICE BEAMLINE*

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*Abstract*

The Muon Ionization Cooling Experiment (MICE) will test transverse cooling of a muon beam, satisfying a crucial demonstration step along the path toward creating high intensity muon beams in a Neutrino Factory or Muon Collider. In the last year, MICE has taken a record amount of data to commission the beamline and calibrate the particle identification (PID) detectors. Studies of the MICE beamline and target timing will be discussed, including the use of Time-of-Flight (TOF) detectors to understand the MICE beam content.

## INTRODUCTION

Given recent advances in neutrino physics and considering that the Large Hadron Collider is running smoothly, resources must be devoted to next-generation accelerator facilities. A very rich program of physics is promised by the Neutrino Factory and Muon Collider [1]. The Neutrino Factory would provide a well-understood beam of $\nu_\mu$ and $\overline{\nu_e}$ from the decay of muons in a storage ring, an ideal facility to study neutrino mass hierarchy and CP violation in the lepton sector. The Muon Collider ($\mu^+\mu^-$) would allow precision studies of the Higgs Boson and exploration of center-of-mass energies up to 4 TeV, with a small footprint for high energies. However, they both are complex accelerators with challenging designs.

These muon beams are produced by the decay of secondary pions from protons incident on a target. This creates a large spread in space, angles, and energy. To accomplish the beam intensity needed to reach intended physics goals, cooling of the muon beam is required; however, with the 2.2 μsec muon lifetime, traditional techniques fail. Ionization cooling can rapidly cool the muon beam by passing it through low Z absorbers followed by accelerating radio frequency (RF) cavities. The beam loses transverse and longitudinal momentum in the absorbers, and then regains longitudinal momentum in the RF cavities. In this way, the transverse emittance is reduced and the beam is cooled.

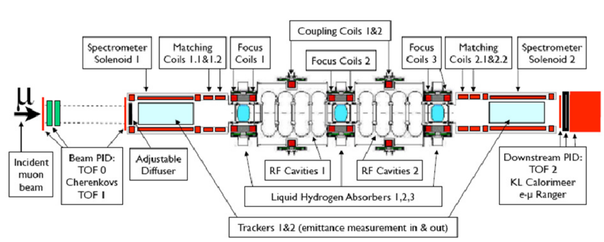


Figure 1: Schematic of MICE cooling channel.

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The Muon Ionization Cooling Experiment (MICE) is a program whose goal is the design and commissioning of a cell of the Feasibility Study-II ionization cooling channel [2]. The cooling cell will be composed of three liquid hydrogen absorbers and two sets of 201 MHz RF cavities (see Fig. 1). It is designed to produce a 10% reduction in transverse emittance for beams with momentum (140 to 240 MeV/c) and incoming emittance (3 - 10 π mm-rad). Two fiber trackers will precisely measure the beam emittance to 1%, and test ionization cooling.

## MICE BEAMLINE

MICE (see Fig. 2) is being built at the ISIS proton synchrotron at Rutherford Appleton Laboratory (RAL). A cylindrical titanium target is dipped into the beam at the end of the 20 ms beam cycle at ~0.4 Hz [3]. Pions created by target interactions are captured in a quadrupole triplet, momentum-selected by a dipole (D1), and passed through a 5-T superconducting solenoid where they decay to produce muons. Particles of defined momentum are selected with a second dipole (D2) for propagation downstream. Ionization cooling calls for muons; however, $\pi^{+/-}$ and $e^{+/-}$ beams are needed to understand the beamline.

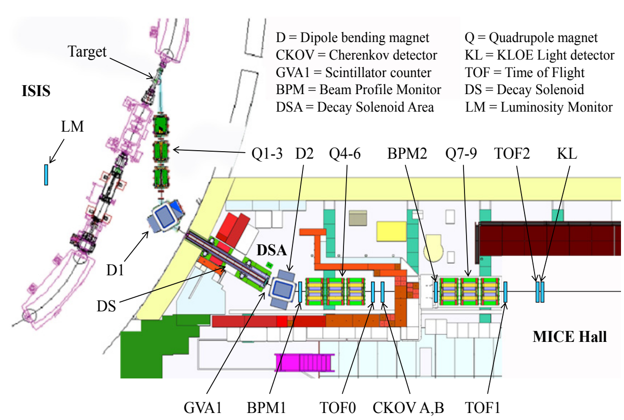


Figure 2: The MICE upstream beamline in 2010 configuration.

The MICE beamline up and down-stream of the cooling channel also includes beam characterization tools. Three time-of-flight (TOF) detectors [4], made of orthogonal planes of scintillating bars, and two threshold Cherenkov counters (CKOV) provide excellent π/μ separation up to 300 MeV/c (see Fig. 3). The TOFs and two scintillating fiber beam profile monitors (BPM) show spatial profiles of the beam. Downstream, a calorimeter identifies electrons produced by the decay-in-flight of muons in the cooling channel. The calorimeter is made up of a lead-scintillating-fiber composite layer (KL), followed by the Electron-Muon Ranger (EMR), a 1m$^3$ block of scintillator bars that measures muon momentum.

All detectors are installed except for the EMR and trackers.

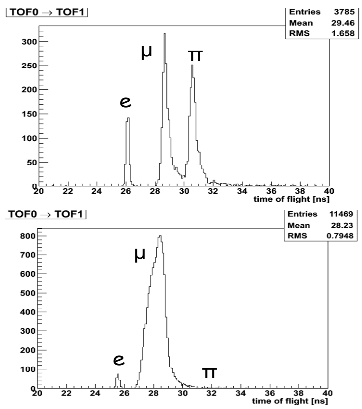


Figure 3: TOF distributions for 300 MeV/c π (top) and 200 MeV/c μ (bottom) beam with separation of $e^+$, $\mu^+$, $\pi^+$.

## MICE 2010 DATA TAKING

With dedicated periods of beam from June to August of 2010, MICE took data for Step 1, the first stage of the experiment. The target dipped more than 335,000 times into the ISIS beam, and over 13 M particle triggers were recorded. The goals for Step 1 were:

- Fully commission all beamline detectors.
- Commission the MICE target and beamline magnets.
- Take data for each ε-p setting in the MICE design.
- Compare data to simulation of the beamline.
- Prepare for Steps with cooling - produce μ beams.

Data designed to complete these goals were taken and will be described here briefly. Each analysis is well under way and Step 1 data-taking is complete. When the trackers are installed in MICE, the next steps will begin, starting with precisely measured beam emittance, muon cooling, and ultimately a test of sustainable cooling.

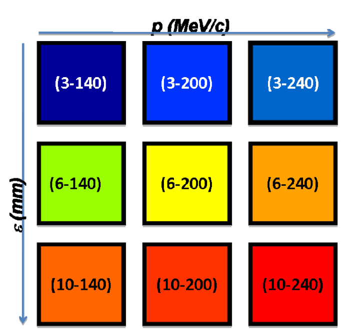


Figure 4: Emittance-momentum (ε-p) matrix of MICE beam configurations intended for cooling measurement.

### *Detector Studies*

A large portion of the data taken in 2010 has been used to commission the beamline detectors. Pion beams (π+ and π-) with initial momentum ranging from 200 – 300 MeV/c and e+/e- with momentum of 150 - 300 MeV/c were used to commission the TOFs, CKOVs, and KL detectors. While the standard MICE beam is reasonably focused at the TOFs, the commissioning beams had to be inflated transversely to populate the full detector surface. The KL calorimeter, designed to degrade electrons, required a variety of tightly focused electron beams for commissioning. The three TOF detectors and KL were all fully commissioned, with the TOF resolutions of 50-60 ps [4] matching design goals. Beam configurations were specifically tuned to produce the required particle type, momentum, and spatial distribution. For pions, D1 and D2 select particles of equal momentum. For muons, backward-going μ's enhance beam purity, so D2 selects particle momentum much lower than at D1. The three TOF detectors and KL were all fully commissioned, with TOF resolutions of 50-60 ps [4] matching design goals.

### *Beam Studies*

Many beam studies were done during the 2010 running, including a scan of the muon beam configurations needed for MICE cooling, the systematic optimization of the upstream beamline, particle rate vs. ISIS beam loss studies, a beam stability analysis, and the first measurement of muon beam emittance.

MICE is designed to measure cooling for different muon beam configurations, namely all combinations with an emittance of 3, 6, or 10 π mm-rad and a momentum of 140, 200, or 240 MeV/c. This leads to a 3x3 matrix of desired muon beam settings (see Fig 4) which must be studied to fully understand the beam dynamics involved. A good understanding of the upstream beamline when delivering these configurations is needed to prepare for the MICE steps with cooling. Each muon beam configuration was produced, studied, and optimized [5].

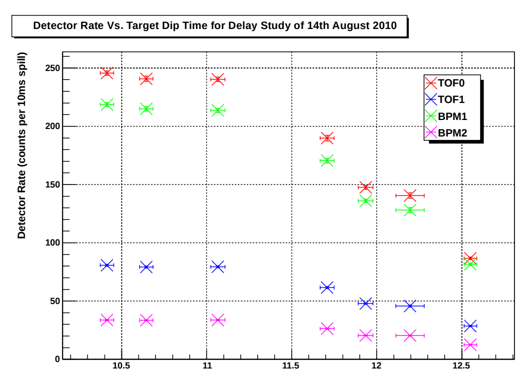


Figure 5: Particle rate in several beamline detectors as a function of target dip timing (nominal at 11.7 ms).

Using the central muon beam ε-p configuration of 6-200, an upstream beamline optimization was executed. Current scans in individual and triplet quadrupoles were done; downstream particle rates and beam profiles were studied and compared to simulation. This allowed understanding of upstream beam dynamics, and magnet currents for the 9 ε-p matrix points were optimized.

Particle rate as a function of beam loss in ISIS was also studied in depth [6]. Target timing was held steady while dip depth was varied to increase losses in ISIS and particle production in MICE. This was done at increasingly high beam loss intensity, up to 10 V, with both π and μ beams. A linear relationship was seen between rate and beam loss from 500 mV – 4700 mV.

MICE beam stability was also examined over this prolonged data-taking period [7]. Particle production was done using 6-200 (ε,p) muon beams with constant trigger condition, DAQ settings, and target depth, delay, and pulses. These reference runs were taken every day.

Finally, the first muon beam emittance measurement at MICE was made [8] with the TOFs. Good muons were defined with timing information, then their positions were calculated using TOF0 and TOF1 as (x,y) stations. Given the beamline transfer matrix, the initial muon path length was assumed. Each particle was tracked, the momentum was estimated, and then x' and y' were inferred to give (x,x') and (y,y') and the phase space parameters.

### *Target Studies*

The MICE target was also commissioned during the recent Step 1 data-taking campaign. Target tests were run each day and all hardware was found to be stable [3]. Particle rate and beam loss were studied as a function of target depth and when changes in target dip timing were made. Ideally, target timing would optimize muon production across the spill gate while minimizing the impact on ISIS.

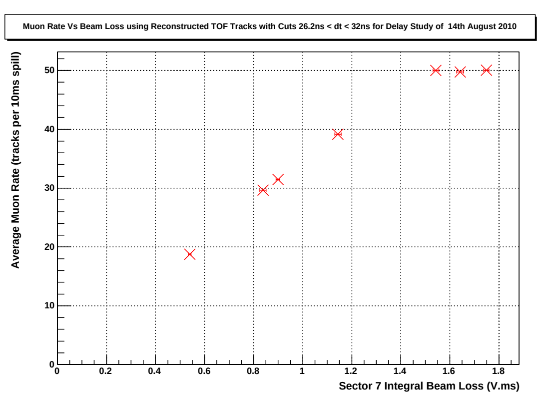


Figure 6: Muon rate as a function of target dip timing with nominal dip time at 11.7 ms.

The standard 6-200 muon beam was used for this study, and the dip depth of the MICE target was held constant while the time at which the target intersected the ISIS beam was changed. The trigger condition (TOF1), number of target dips (200), and DAQ spill gate (10 ms) were also held constant. Data was initially taken using the reference run timing, and then the target dip time was increased and decreased in steps of several hundred microseconds. Figure 5 shows the particle production rate in the TOFs and BPMs for different dip times. Figure 6 shows muons as a function of dip time. Integrated beam loss in ISIS as a function of dip time is shown in Fig. 7.

As the dip time moves earlier in the ISIS cycle, particle rates and muons/spill increase and then plateau. The beam

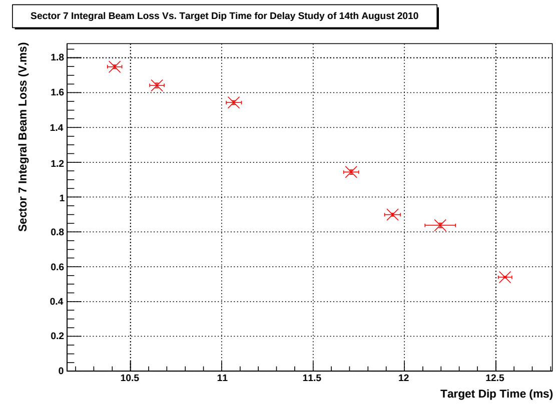


Figure 7: ISIS integrated beam loss vs. target dip timing with nominal dip time at 11.7 ms.

loss seems to continue to increase as we catch more of the beam cycle. These effects may be a function of the shape of the ISIS beam; however, more analysis is required. It would be interesting to see the distribution of particle triggers within the DAQ window to see if the plateau effect is due to triggers arriving too close to one another, but that data is not yet available. It is clear that earlier dip times produce more muons, but further study is warranted before an optimal timing is declared.

## CONCLUSIONS

Major progress has been made recently in MICE as Step 1 data were taken. The target, beamline, and detectors have been commissioned. Particle production of π, e, and μ beams has become routine in preparation for the arrival of the fiber trackers and the beginning of precision emittance measurements at MICE. Soon we will test ionization cooling and learn more of the practical challenges inherent in building a muon accelerator.

## REFERENCES

[1] S. Geer, "Neutrino Beams from Muon Storage Rings: Characteristics and Physics Potential," *Phys.Rev.* **D57**, 6989 (1998); V. Barger, "Overview of Physics at a Muon Collider," *AIP Conf. Proc.* **441**, 3 (1998).

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

[3] P.Hodgson *et al*, "MICE target hardware," IPAC10 Proceedings, 2010, WEPE063.

[4] R. Bertoni *et al.*,"The design and commissioning of the MICE upstream time-of-flight system," Nucl. Instr. Meth, A615 (2010) 14.

[5] M. Apollonio, "The MICE Muon Beam Line," NuFact2010 proceedings.

[6] A. Dobbs *et al.*, "The MICE Muon BeamLine and Induced Host Accelerator Beam Loss," MOP021, these proceedings.

[7] S. Blot, "Stability of the MICE Muon Beam Line," MOP061, these proceedings.

[8] M. Rayner, "Performance of the MICE Muon Beam Line," NuFact2010 proceedings.