THE MUON IONIZATION COOLING EXPERIMENT

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ABSTRACT

MICE is a demonstration experiment to prove the feasibility of cooling a beam of muons via ionization cooling for use in a neutrino factory and/or muon collider. MICE is in progress at the Rutherford Appleton Laboratory in the UK, and includes a dedicated beamline and a cooling cell sandwiched between two spectrometers. The first MICE step was completed in 2010: commissioning and characterizing the muon beam and detectors. Results reported include a first measurement of beam emittance.

1. Introduction

Muons, for a neutrino factory or muon collider$^{1,2)}$, are produced as tertiary particles in reactions $p+N \rightarrow \pi + X$ with subsequent decay $\pi \rightarrow \mu\nu$, and hence have too large an inherent emittance (beam spread in the 6D position and momentum phase space) for cost-effective acceleration. They must therefore be “cooled” to reduce the beam spread both transversely and longitudinally. Due to the short muon lifetime, the only feasible technique is ionization cooling, which has as yet been studied only in simulation. The international **M**uon **I**onization **C**ooling **E**xperiment (MICE), at the ISIS accelerator at Rutherford Appleton Laboratory, will demonstrate the feasibility of muon ionization cooling with a variety of beam optics, momenta (140-240 MeV/c), and emittances.

MICE will measure a 10% emittance reduction with 0.1% emittance resolution, making it a precision experiment in which systematic errors must be well understood and minimized. For this reason, as well as budget constraints, MICE is staged, with the parameters of the beam, detectors, and cooling-cell components studied in detail at each step. MICE is comprised of a dedicated beam line (Fig. 1) to generate a range of input muon momenta and emittances, and a cooling cell sandwiched between particle identification detectors (PID) and scintillating fiber spectrometers (Fig. 2). Particle-physics techniques are used to tag muons upstream and ensure that the muon has not decayed downstream of the channel. Kinematic properties of individual muons are measured in both trackers to reconstruct the “before” and “after” beam emittances. The cooling cell will consist of low-Z absorbers immersed in magnetic fields, with RF cavities to restore the longitudinal component of muon momentum.

Emittance is given by $\varepsilon = \sigma_r \sigma_p/(mc)$, where σ_r and σ_p are the RMS spatial and momentum spread, respectively, and mc is the product of the particle mass and speed of light$^{1,3)}$. The *normalized* emittance $\varepsilon_n = \varepsilon\gamma\beta$, where γ and β are the usual

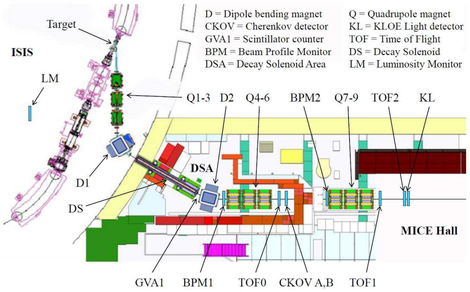

Figure 1: MICE beamline schematic.

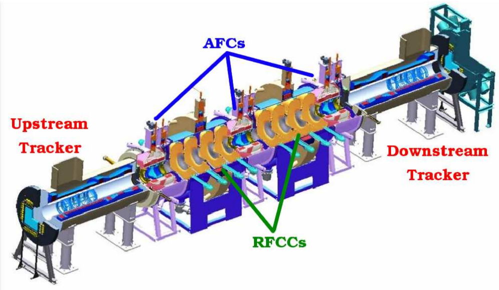

Figure 2: MICE trackers and cooling section.

relativistic factors, is used to remove the energy dependence (a higher energy beam has smaller emittance due to boosting).

In ionization cooling, the muons lose energy traversing a low-Z absorber and have the longitudinal component of momentum restored in accelerating cavities, while being focused in a magnetic lattice. In passing through the absorber, muons lose energy in all directions–"cool"–while Coulomb scattering tends to increase emittance –"heat". The rate of change of ε thus has both a cooling and a heating term when traversing a path length s, as given in Eq. 1:

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(13.6\text{ MeV})^2}{2E_\mu m_\mu X_0} \quad\Rightarrow\quad \varepsilon_{n,eq} = \frac{\beta_\perp(13.6\text{ MeV})^2}{\beta\, m_\mu X_0\left\langle\frac{dE_\mu}{ds}\right\rangle}. \tag{1}$$

Here $\beta = v/c$, $\langle dE_\mu/ds\rangle$ is the average rate of energy loss, E_μ and m_μ are the muon energy and mass, $\beta_\perp$ is the transverse beta function (focal length) evaluated at the absorber, and X_0 is the radiation length of the absorber. Note that heating is reduced by strong focusing in the absorber (low $\beta_\perp$), and use of a low-Z absorber to increase X_0. The equation is also solved for the normalized equilibrium emittance $\varepsilon_{n,eq}$.

2. MICE Step I

The goals of the first step of MICE were to build and commission a muon beam line, to commission and calibrate the particle detectors, and to use them to measure the parameters of the beam. These goals were accomplished with the completion of Step I in August 2010, and the data are being analyzed.

The muon beam is created using a titanium target, dipped at ~ 1 Hz with acceleration ~ 90g into the ISIS beam during the last 3 ms of the acceleration cycle. The pions are transported to the MICE Hall and momentum selected using conventional quadrupole triplet (Q1-3) and dipole (D1) magnets. Muons from pion decay within the superconducting Decay Solenoid (DS) are then momentum selected and transported to the cooling cell with a dipole (D2) and quad triplets (Q4-6 & Q7-9).

PID is performed with two threshold Cherenkov counters and two time-of-flight scintillator hodoscopes (ToF0 & ToF1) surrounding the last triplet. Decayed muons are rejected using the last ToF plane (ToF2), KLOE-light calorimeter (KL), and

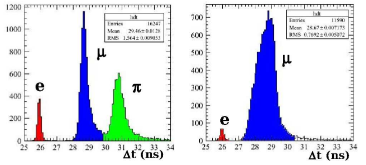

Figure 3: ToF0/ToF1 PID: forward μ selected (left), backward μ selected (right).

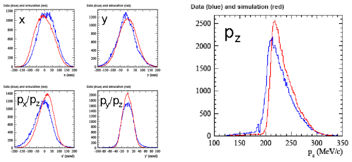

Figure 4: Comparison of kinematics distributions: data (blue) and simulation (red).

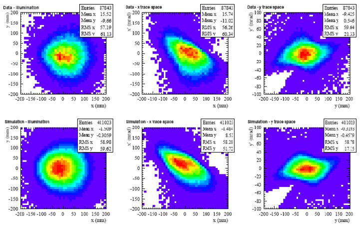

Figure 5: First emittance measurement: y vs x (left); x' vs x (middle), y' vs y (right).

electron-muon ranger (EMR) downstream of the cooling channel. Calibration data were collected for all detectors (except EMR). In what follows, only the ToF system will be considered. These detectors were calibrated to have time resolutions of 51 ps/58 ps/52 ps for ToF0/ToF1/ToF2, respectively$^{4)}$. In Fig. 3, one can observe the ability of the ToF system to identify particles and the tunability of the beamline.

3. First Emittance Measurement

Figure 4 compares kinematic measurements using the ToF detectors with simulation. Though small differences are evident, these preliminary results are promising. Figure 5 compares data and simulation (top and bottom) for y vs x, x' vs x, and y' vs y. This is the first beam emittance measurement made using single-particle detectors.

4. Conclusions

In 2010 MICE completed its first step: creating and characterizing a muon beamline, and commissioning and calibrating particle detectors. Early results are shown, including the first beam emittance measurement using particle physics techniques.

5. Acknowledgements

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6. References

1) C. Ankenbrandt *et al.*, Phys. Rev. ST Accel. and Beams **2**, 81001 (1999); M.M. Alsharo'a *et al.*, Phys. Rev. ST Accel. and Beams **6**, 81001 (2003).
2) "Feasibility Study-II of a Muon-Based Neutrino Souce," ed. S. Ozaki et al., BNL-52623, http://www.cap.bnl.gov/mumustudyii/FS2-report.html
3) D.M. Kaplan, Nucl. Instrum. Meth. **A453** (2000) 37.
4) R. Bertoni *et al.*, Nucl. Instrum. Meth. **A615** (2010) 14.
5) M. Rayner *et al.*, in preparation.