PARTICLE PRODUCTION IN THE MICE BEAMLINE*

L. Coney#, UC Riverside, Riverside, CA 92521, USA; A. Dobbs#, Imperial College, London, UK; Yordan Karadzhov#, University of Sofia, Sofia, Bulgaria for the MICE Collaboration

Abstract

The Muon Ionization Cooling Experiment (MICE) is being built at the Rutherford Appleton Laboratory (RAL) to test ionization cooling of a muon beam. Successful demonstration of cooling is a necessary step along the path toward creating future high intensity muon beams in either a Neutrino Factory or Muon Collider. Production of particles in the MICE beamline begins with a titanium target dipping into the ISIS proton beam. The resulting pions are captured, momentum-selected, and fed into a 5T superconducting decay solenoid which contains the pions and their decay muons. Another dipole then selects the final particles for propagation through the rest of the MICE beamline. Within the last year, the MICE target has been redesigned, rebuilt, and has begun operating in ISIS. The decay solenoid has also become operational, dramatically increasing the number of particles in the MICE beamline. In parallel, particle identification detectors have also been installed and commissioned. In this paper, the commissioning of the improved MICE beamline and target will be discussed, including the use of Time-of-Flight detectors to understand the content of the MICE beam between 100 and 444 MeV/c.

INTRODUCTION

The Neutrino Factory and Muon Collider[1] are both next-generation facilities designed to uncover answers to important questions in particle physics. Muons stored in a Neutrino Factory decay to produce a well-understood intense beam of electron and muon neutrinos that travel to remote detectors. This provides the opportunity to study neutrino oscillations, including $\nu_e \to \nu_\mu$ and $\overline{\nu_e} \to \overline{\nu_\mu}$, and investigation of the neutrino mass hierarchy, leptonic CP violation, and neutrino cross section measurements. A Muon Collider could be used for precision studies of the Higgs Boson or exploration of physics at high center-of-mass collisions. In order to provide the intended physics reach, both of these machines need high intensity muon beams which, in turn, requires beam cooling.

Unlike traditional proton beam cooling where stochastic cooling is acceptable, the short lifetime of the muon, 2.2 μs, motivates the search for a faster cooling method. Ionization cooling is the proposed solution. This is a technique where muons pass through liquid hydrogen (LH_2) absorbers and then immediately through accelerating RF cavities. In this way, the particles lose both transverse and longitudinal momentum in the absorbers, but recover only the longitudinal momentum in the RF cavities. This reduces the transverse emittance and cools the beam.

The MICE[2] experiment is designed to build and test a complete, engineered section of an ionization cooling channel where the transverse emittance of a 140-240 MeV/c muon beam will be reduced by 10%. Using scintillating fiber particle trackers, the beam emittance will be measured before and after the cooling channel with a precision of 1%. With the completion of MICE, the first demonstration of ionization cooling of a muon beam will be done, paving the way for continued design of future muon accelerators.

MICE BEAMLINE

MICE is being built at RAL at the ISIS 800 MeV proton synchrotron (see Fig. 1). Most beamline components upstream of the cooling channel section are already in place. Commissioning of the beamline and the particle identification detectors (PID) is well under way.

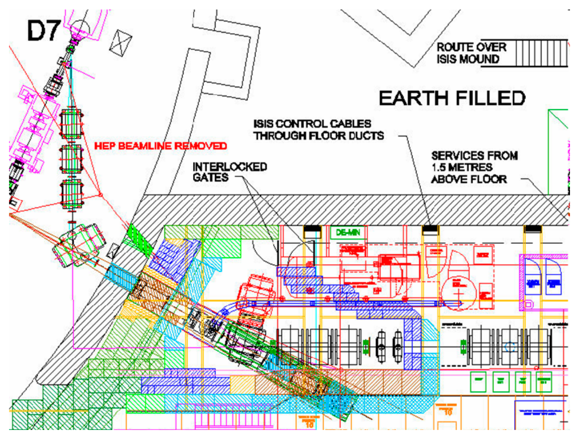

Figure 1: The MICE beamline is shown coming off of the ISIS proton synchrotron at RAL.

The muon beam begins with a titanium target that is dipped into the end of the 20 ms ISIS cycle at a rate of 0.4 Hz [3]. Pions from proton interactions in the target then pass through a quadrupole triplet, are momentum-selected by a dipole magnet, and are then transported through a 5 meter long 5T superconducting decay solenoid. This magnet captures the pions and their decay muons. The muons are sent into the rest of the beamline by a second dipole magnet set to a lower momentum than the first in order to improve beam purity. The muon beam is transported through two more quadrupole triplets to PID detectors, including three time-of-flight (TOF) detectors and two threshold Cherenkov counters. These provide pion-muon separation up to 300 MeV/c, and ensure high muon beam purity.

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#a.dobbs07@imperial.ac.uk, lconey@fnal.gov, yordan@phys.uni-sofia.bg

MICE BEAMLINE COMMISSIONING

The MICE target was redesigned and rebuilt in the first half of 2009[4], and installed in the ISIS beamline in August. Since that time, MICE has been an operating experiment, taking data to complete Step I of the experimental schedule[5]. The goals for this stage of the experiment include commissioning the new target, the decay solenoid, the conventional magnet beamline, and the particle identification systems.

Target

The redesigned target operating in the ISIS beamline has performed exceptionally well without problems since beginning operations in September 2009. The target has been used to run MICE as a stand-alone experiment and also parasitically during standard ISIS User Runs. Methods were developed to regularly monitor the stability of the target[3]. Target parameters are regularly checked, including beam center distance, a measure of how far into the beam the target dips.

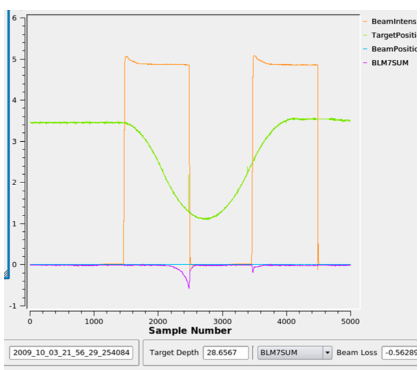

Figure 2: Target DAQ showing ISIS beam intensity (orange), MICE target position (green), and beam loss (V) in ISIS (blue) during timing study. Shows unwanted beam loss in ISIS cycle after that used by MICE.

Several target operation studies were done during commissioning in 2009. Dip timing with respect to the ISIS cycle was tested as a function of target delay (see Fig. 2). The edge of the beam at injection was found in order to define restrictions on the target outswing. Optimization of target timing and depth for different beam configurations continues as we improve run conditions.

Time-of-Flight Detectors

The time-of-flight system in MICE consists of three individual detectors (TOF0, TOF1, and TOF2) located along the beamline. The first, TOF0, is just downstream of the second quadrupole triplet, the second (TOF1) is located just after the third quadrupole triplet, and the last (TOF2) will sit downstream of the cooling channel.

For the analyses described in this paper, only TOF0 and TOF1 were used. Both detectors are composed of vertical and horizontal scintillating bars: TOF0 has ten 4cm-wide bars in each orientation, while TOF1 has seven 6cm-wide bars. Both detectors were calibrated during recent MICE running. TOF0 and TOF1 were found to have timing resolutions of 52 ps and 58 ps respectively. Figure 3 shows the time-of-flight distribution for particles in a nominal 300 MeV/c π beam. These detectors have proven to be invaluable during commissioning of the beamline.

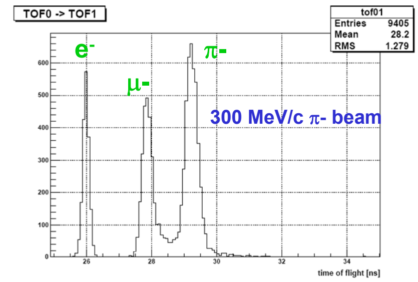

Figure 3: Time-of-flight distribution showing e^-, μ^- and π^- in a 300 MeV/c pion beam.

Decay Solenoid

The decay solenoid (DS) is an important part of the MICE beamline. It is designed to capture pions coming from the target and their decay muons. The magnet was fully functional during the MICE data-taking periods in the second half of 2009. This completed the MICE beamline upstream of the cooling channel, significantly increased the particle rate in the beam, and enabled the start of beam optics optimization and measurements[6]. Optimization of DS operation was begun by changing the magnetic field in 5% above and below the ideal value predicted by simulations for a 330 MeV/c π beam (See Fig. 4). Particle rate in the beamline and the beam profile in TOF0 were compared to predictions. These studies are ongoing and will be used to determine the final decay solenoid settings for each beam configuration.

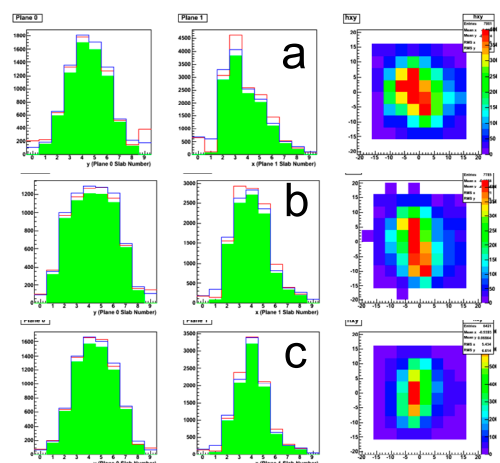

Figure 4: TOF0 y (left column) and TOF0 x (middle column) profiles for a) DS field raised 10%, b) nominal DS setting, c) DS field lowered 10% from ideal.

PARTICLES IN THE MICE BEAM

During commissioning of the beamline in 2009, many different types of beam configurations were run, including magnet currents designed to produce electrons, pions, and most importantly, muons. Beginning with a positive polarity beamline, data were taken with 300 MeV/c pions, 250 MeV/c pions, 200 MeV/c pions, 300 MeV/c positrons, and 150 MeV/c positrons. A muon beamline starting with 444 MeV/c pions and momentum-selecting

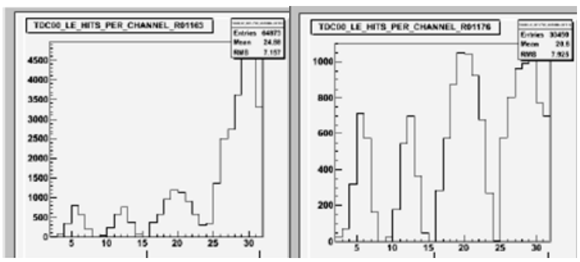

Figure 5: Particle hit profiles in x and y for TOF1 and TOF0. The peaks from left to right in each plot are TOF1 y, TOF1 x, TOF0 y, TOF0 x. The plot on the left is for a positive beam and shows the large number of protons ranging out in the most upstream layer of TOF0. The plot on the right is for a negative beam with no protons.

300 MeV/c muons was also run. As shown in Figure 5, there were a high number of protons in the muon beamline. This overwhelmed the trigger and obscured the muons. As a result, MICE changed magnet polarities and began running with negative particles.

Detector calibration and beamline commissioning continued with negative particles. The data taken include 300 MeV/c pions, 330 MeV/c pions, 300 MeV/c

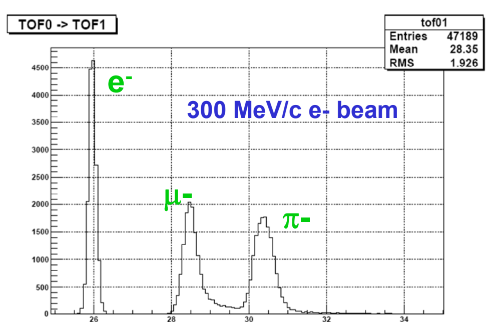

Figure 6: Time-of-flight distribution for a 300 MeV/c e^- beam.

electrons, 150 MeV/c electrons, and several muon beamlines. This was the first time significant statistics were taken with a muon beam. The TOF system was used throughout running to determine what kind of particles were in each beam configuration and with what relative populations (See Figs. 3, 6, 7, and 8). Different particle species, e^-, π^-, and μ^- can clearly be seen.

Interestingly, different methods for producing muon beams produce distinctly different distributions of particles (See Figs. 7, 8). For the different muon beams, there are two relevant momenta, the pion momentum coming from the target, and that of the selected population of decay muons. The second dipole in the MICE beamline is used to choose different populations of muons in an effort to improve muon beam purity and to create a beam designed for the MICE emittance measurement.

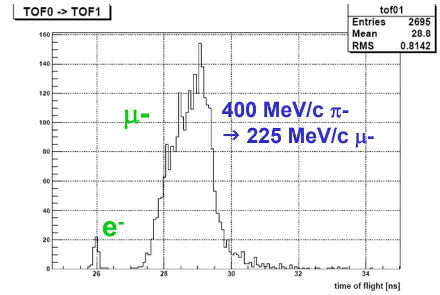

Figure 7: Time-of-flight distribution showing e^- and μ^- in a 225 MeV/c μ^- beam.

Analysis to fully understand the MICE beam continues, and the TOF system is proving to be an excellent tool for this process. Not only is it used to identify muons in the beamline, it also provides beam profile information for comparison with simulations. With the new target available, the decay solenoid operational, and the PID detectors working, Step I is well under way. Creation of muon beams in preparation for the MICE emittance measurement has begun in earnest.

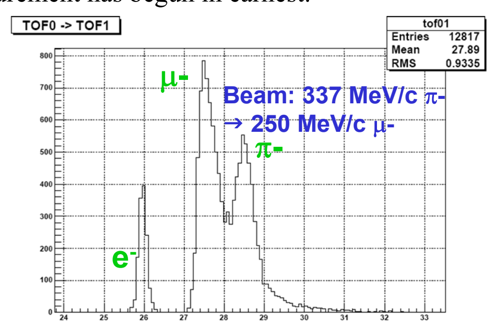

Figure 8: Time-of-flight distribution showing e^-, μ^-, and, π^- in a 250 MeV/c μ^- beam.

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