THE STATUS OF THE MICE TRACKER SYSTEM*

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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. MICE will reduce the transverse emittance of the beam by 10%, and spectrometers using particle physics techniques will measure the emittance reduction with an absolute precision of 0.1%. This will be done with scintillating fiber tracking detectors inside solenoid magnets on either side of the cooling channel. Each fiber tracker contains five stations with 3 layers of fibers rotated 120 degrees with respect to each other, thereby allowing reconstruction of hit points along the path of the muons. Light is carried from the active fiber volume by clear waveguide fibers where it is detected using Visible Light Photon Counters (VLPC). The details of the tracker commissioning using cosmic rays will be discussed in addition to the status and performance of the readout electronics.

INTRODUCTION

Neutrino Factories and Muon Colliders [1] require very intense muon beams. In order to optimize the performance of these facilities, it is necessary to cool the beam before acceleration. Due to the short muon lifetime, 2.2 μs, ionization cooling is the only viable option available for these accelerators. In ionization cooling, the muon beam is passed through several liquid hydrogen (LH_2) absorbers followed by accelerating RF cavities. In this manner, the beam loses both longitudinal and transverse momentum, but only longitudinal momentum is restored in the RF cavities. This reduces the transverse emittance and cools the beam.

The MICE Experiment

The goal of the MICE experiment [2] is to build and operate a realistic section of an ionization cooling channel based on the Feasibility Study-II [3] design. A 140-240 MeV/c muon beam will undergo a 10% reduction in transverse emittance through the cooling channel, to be measured with a precision of 1%. The incoming beam can be tuned from 2 to 10 π mm-rad transverse emittance using beam optics and a variable thickness lead diffuser. The emittance will be precisely measured before and after the cooling channel by identical spectrometers, and the practicalities of operating a cooling channel will be understood.

The MICE cooling channel is shown in Fig. 1. The full cooling channel is made up of three LH_2 absorbers and two sets of 201 MHz RF cavities contained within a series of superconducting solenoids which provide beam transport and strong focusing at the absorbers. Upstream of the cooling channel, particle identification detectors (PID) including a pair of time-of-flight (TOF) detectors and two threshold Cherenkov counters ensure muon beam purity to better than 99.9%. Downstream PID is done using a third TOF detector and a calorimeter to distinguish muons from background decay electrons.

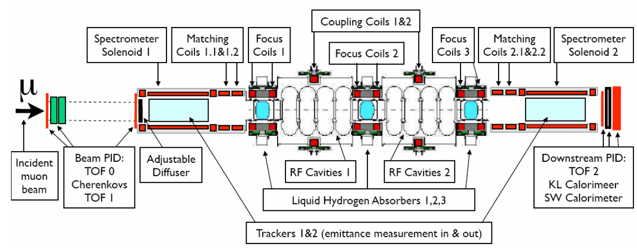

Figure 1: Layout of the MICE experiment with the cooling channel in the center flanked by input and output spectrometers and particle identification detectors.

Emittance Measurement

MICE is a single-particle experiment which will measure the position and momentum of each muon before and after it traverses the cooling channel. This particle tracking is done using two scintillating fiber detectors, each inside a 4 T superconducting solenoid. Each tracker has five stations with three planes of 350 μm fiber doublets to give an accurate point in space. The incoming and outgoing 6D emittance is measured by determining x, x′, y, y′, and particle momentum with the tracker, and measuring t using the time-of-flight detectors. The muon trajectories are circles in the x, y plane while passing through the solenoid. The radius of the circle determines p_T, while the number of orbits determines p_Z.

THE MICE TRACKERS

Tracker Requirements

The trackers are central to the main purpose of MICE, are essential to the success of the experiment, and must perform well. The trackers must be able to handle a high rate of 600 muons/msec when MICE is at full operational capability. The trackers must have a small amount of material in order to avoid multiple scattering of the muons, and must be able to operate in backgrounds from x-rays produced in the RF cavities.

Tracker Construction

With these requirements in mind, the MICE trackers were designed using scintillating fiber based technology. Each MICE tracker is a 1.1 m long detector with five

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separate stations perpendicular to the muon beam (see Fig. 2). There are three planes, rotated 120 degrees with respect to each other, in each station. The planes are made of 350 μm scintillating fiber doublets, where the active area has a 30 cm diameter. The fibers were mirrored on one end and have 75% reflectivity with a 4% rms. These very small fibers were chosen specifically to satisfy the requirements for MICE since they minimize the amount of material encountered by the muons as they pass through the trackers. The potential down-side to these small fibers is that there may be an unacceptably low light yield. Bundles of seven neighboring fibers are ganged together to form channels and fed into a single 1.05 mm clear waveguide fiber. This reduces the number of readout channels and satisfies the required position resolution of approximately 1 mm. Light from the scintillating fibers is carried out of the active tracker volume by these waveguides.

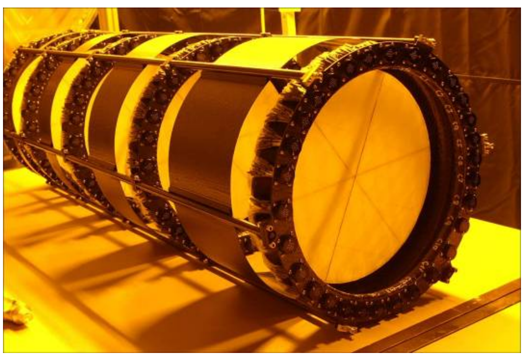

Figure 2: A MICE scintillating fiber tracker.

TRACKER READOUT

The clear waveguide fibers connect to VLPCs, solid state photo-detection devices [4], which convert the light to an electrical signal. VLPCs have high quantum efficiency (QE) of ~80%, high gain (~50,000), and low noise with the ability to handle high rates. They operate at 9 K and are housed in cassettes inside cryostats near the trackers. Each tracker has two cryostats with two VLPC cassettes, each of which has eight modules of 128 channels and can therefore read out 1024 channels. Signals from each VLPC are read out using AFEIIt (Analog Front End with Timing) boards, from the D0 experiment, mounted on top of each cassette. Data are read out with nine VLSB (VME LVDS SERDES (Serializer/Deserializer) Buffer) modules: one master to control timing and eight slaves to take data from the boards. The AFEIIt boards also control VLPC bias voltage and temperature controls.

All eight cassettes for each tracker have been characterized using LED pulser data to determine the optimal operating bias voltages for the VLPCs. Full data readout for each tracker system has also been tested.

COSMIC RAY TEST

The first MICE tracker was placed inside a carbon fiber cylinder and oriented with the beam axis vertical (see Fig. 3). Trigger scintillators were positioned above and below the tracker, and four inches of lead was placed below the tracker to select higher energy cosmic rays. Cosmic ray data were taken continuously from July – November of 2008. These data were used to measure the light yield for the tracker, to determine the tracker efficiency, and to calculate the tracker resolutions. This is the final testing done before the tracker is integrated with the spectrometer solenoid and installed in the muon beamline.

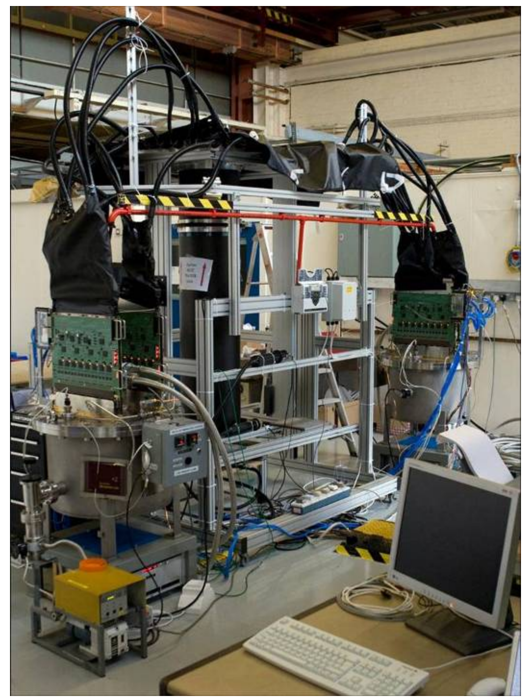

Figure 3: Tracker 1 in the cosmic ray test setup.

Track Reconstruction

Tracks in the detector are reconstructed using the G4MICE software package, an application of GEANT4 for the MICE detectors and beamline. Clusters are made from 1 – 2 channels with two or more photoelectrons (PE). Triplets, each of three planes per station, are found. The internal residual is calculated and determines if clusters belong together in a space point. Any clusters from different doublet layers in the same station that have not participated in a triplet are then collected as duplets. The pattern recognition algorithm uses a straight line track fit since the tracker is not yet in a solenoidal magnetic field. Sets of three points from different stations are then used to extrapolate to the other two stations and search for associated hits. These space points are passed to the Kalman filter which identifies a track.

Cosmic Ray Test Results

To calculate the light yield for Tracker 1, the distribution of light from clusters used in tracks was plotted (see Fig. 4). This measurement was made using approximately 175,000 hits corresponding to ~10,000 cosmic ray tracks. The average light yield for Tracker 1 is 11 PE meeting the design goal of 10.5 PE. This shows that despite the very small fiber diameter, the MICE trackers will be able to reconstruct the paths of muons through them with high efficiency.

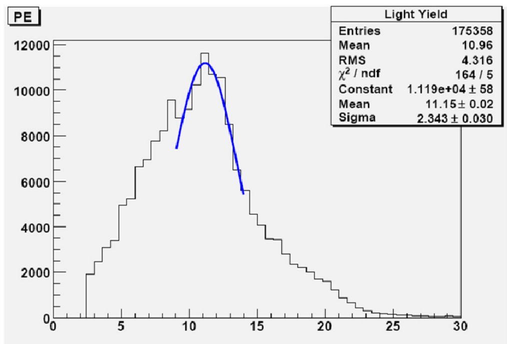

Figure 4: The distribution of light from clusters included in reconstructed cosmic ray tracks for Tracker 1.

To calculate the position resolution, tracks with five points (one for each station) were re-fit, removing one point at a time. The new tracks were then extrapolated to the station without a point. The difference between the extrapolated position and the original position is calculated as the resolution. The position resolution for the inner three stations is shown in Figs. 5 and 6 and is 583 µm in x and 597 µm in y. Because this includes extrapolation effects (multiple coulomb scattering), it is consistent with the design goal of 430 µm.

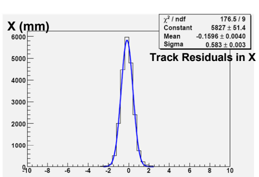

Figure 5: X resolution.

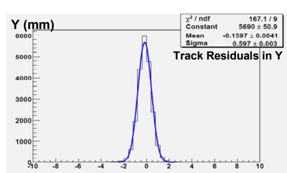

Figure 6: Y resolution.

Tracker efficiency is also very important to MICE. In this analysis, tracks were built using four of the five stations and a search was done for hits in the fifth station close to the extrapolation. The possibility of dead channels within the tracker was also a concern given the size of the fibers and their delicate nature. Fortunately, the cosmic ray test proved that there are only three dead channels in Tracker 1. This includes the entire readout chain from the fibers through the electronics and corresponds to less than 0.1% dead channels. This is an excellent result and handily beats the design goal of less than 0.2% dead channels.

CONCLUSIONS

Both scintillating fiber trackers for the MICE spectrometers have been successfully constructed. Tracker 1 was tested using cosmic rays and performed extremely well. A summary of the performance of Tracker 1 is given in Table 1. Light yield, tracker resolution and the number of dead channels all met or exceeded design goals. The second tracker readout system has been commissioned, and it is now set up to take cosmic ray test data. Tracker 2 will undergo the same studies as its predecessor. Readout for both trackers will be tested and integrated into the main MICE DAQ before moving to the MICE hall. In September 2009, the first tracker will be integrated with the first spectrometer solenoid and installed in the MICE beamline. Data taking in a muon beam will take place in November, and a precise measurement of the incoming beam emittance in MICE will be possible.

Table 1: Summary of the Tracker Performance

Station	Efficiency (%)	Resolution in X (mm)	Resolution in Y (mm)
1	99.47 ± 0.07	0.74 ± 0.01	0.77 ± 0.01
2	99.10 ± 0.09	0.56 ± 0.01	0.60 ± 0.01
3	97.99 ± 0.14	0.55 ± 0.01	0.58 ± 0.01
4	99.87 ± 0.04	0.57 ± 0.01	0.59 ± 0.01
5	98.39 ± 0.13	0.92 ± 0.01	0.90 ± 0.01

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