STATUS OF THE MICE TRACKER SYSTEM

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Abstract

Tracking detectors based on 350-μm scintillating fibers have been developed to measure the emittance of muon beams at the Muon Ionization Cooling Experiment (MICE), which has been constructed to demonstrate ionization cooling by constructing a part of the cooling channel designed for a Neutrino Factory. The upstream and downstream trackers have been constructed at the Rutherford Appleton Laboratory (RAL) by 2009. The mechanical design and construction procedures with quality assurance adopted for trackers are described in this paper. The result of cosmic-ray tests performed at RAL is also presented.

INTRODUCTION

A Neutrino Factory based on a muon storage ring is the ultimate tool for studies of neutrino oscillations, including possibly the discovery of leptonic CP violation. Optimization by phase-space compression (cooling) of the muon beam is required to accelerate intense muon beams prior to a storage ring. Due to the short muon lifetime (2.2 μs), a novel method such as ionization cooling, proposed more than 20 years ago by A.N. Skrinsky [1], must be used. In ionization cooling, transverse phase-space is compressed in such a way that both longitudinal and transverse momentum of incoming muons are reduced in an absorber, then only the longitudinal momentum is restored by a following radio-frequency (RF) cavity. The Muon Ionization Cooling Experiment (MICE) [2] at the Rutherford Appleton Laboratory (RAL) has been constructed to demonstrate ionization cooling by building a section of a cooling channel.

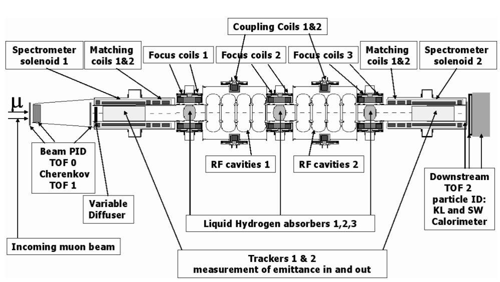

Figure 1: Schematic layout of the MICE experiment at RAL. The cooling section is located between two spectrometers to measure momentum and position of each incoming particle. The other detectors for particle identification are also shown.

The MICE cooling channel is comprised of three liquid hydrogen absorbers and eight 201-MHz RF cavities with a field gradient of 8 MV/m. All components are tightly packed within a magnetic focusing lattice (Fig.1). The emittance before (after) cooling is measured by a tracker instrumented in a 4T magnetic spectrometer located upstream (downstream) of the cooling channel. The emittance defined as a covariance matrix of six coordinates (x, y, t, x'=p_x/p_z, y'=p_y/p_z, t'=E/p_z), is determined by measuring these parameters for individual muons (single-particle method).

In MICE, an emittance reduction by 10 % is expected at the equilibrium. To determine it with a precision of 1 %, which corresponds to an absolute measurement with 0.1 % precision, it is required that the amount of material in the trackers is small to reduce the effect of multiple scattering. Also, stable running in the presence of X-rays from neighboring RF cavities is required. In order to meet these requirements, a tracking detector based on 350-μm scintillating fibers has been selected for use in MICE.

The detectors for particle identification are located upstream and downstream of spectrometers. The upstream detectors consist of Time-Of-Flight stations and Cherenkov counters, while the downstream ones consist of a Time-Of-Flight station and electro-magnetic calorimeters. The detectors aim to reduce pion and electron contamination to a level of 0.1 %.

THE SCIFI TRACKER

Requirements

In order to minimize the effect of multiple scattering, Scintillating Fiber (SciFi) Tracker consisting of fine scintillating fibers with a diameter of 350 μm are used in the spectrometers. A photon detector with high quantum efficiency is required to detect the low light yield from such a fine fiber. Visible Light Photon Counters (VLPCs) [3, 4] are employed for the SciFi Tracker. The maximum quantum efficiency of a VLPC is more than 85 % at a wavelength of 520 nm (green). Hence, a secondary dopant of 3HF (3-Hydroxyflavone), for which the emission peak is at 520 nm, is added as dopant to the scintillating fibers. Clear-fiber light-guides transport scintillation photons to the VLPCs.

Layout

A tracker is composed of 5 stations, which are located with an optimized spacing (Fig.2). A station is made of a carbon-fiber frame of 40-cm diameter, and three scintillating-fiber doublets are glued with 120 degree angular spacing. A fiber doublet is formed by two layers of scintillating-fiber, in which scintillating fibers with 350-μm diameter are aligned with 427-μm pitch (Fig.3). Optical connectors are connected at the station frame and internal light-guides are attached to transport light to a patch panel. Scintillation light is then transported to VLPCs via external light-guides, which are shielded with light-tight flexible tube. The VLPCs are mounted at the bottom of a module with front-end readout electronics boards. The temperature on the VLPCs is stably maintained at 9 K using a cryocooler and an external temperature controller. The number of readout channels for two trackers is 6400.

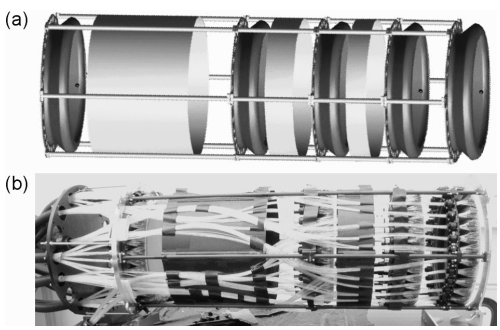

Figure 2: (a) Schematic view of a tracker. Five stations are installed with optimized spacing. Light-guides are not shown. (b) A photograph of the upstream tracker with internal light-guides installed.

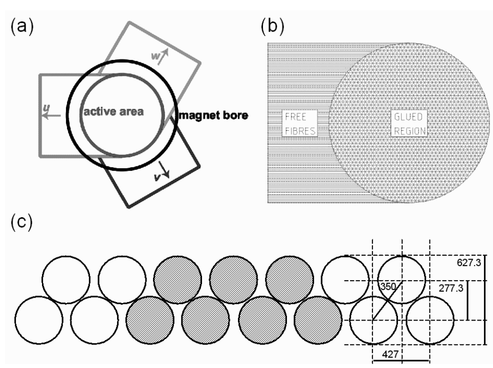

Figure 3: (a) Arrangement of the doublet layers in the scintillating-fiber stations. The magnet bore of 40 cm and the active area of scintillating-fiber station with the diameter of 32 cm are indicated with circles. The arrows indicate the directions that individual 350-μm fibers run in the u, v and w planes. (b) Schematic diagram of the scintillating-fiber ribbon. The circular area with the diameter of 32 cm, in which fiber canes are glued to form the doublet layer, is indicated by the dashed line. (c) Detail of the arrangement of the scintillating fiber in a doublet layer. The fiber diameter, the fiber spacing and the fiber pitch are indicated in the unit of μm. A cluster of seven fibers ganged for readout in a single clear-fiber light-guide is shown with shadowed circles.

Readout

Charges converted at VLPCs are transported via copper ribbons to an analog front end board (AFEIIt) [5] mounted on the top of the cryostat. Digitized charges are packaged with time information and are forwarded to back-end electronics, VME LVDS Serdes Buffer (VLSB) modules. FPGAs on an AFEIIt are programmed via VME MIL-1553 prior to readout by software based on the Experimental Physics and Industrial Control System (EPICS) [6]. Data stored in VLSBs are read out at every end of spills by software based on the Data Acquisition Test Environment (DATE) [7] which was developed by ALICE Collaboration.

Construction

Station The construction of scintillating-fiber stations has been performed at Imperial College London, UK in 2008. At first, visual inspection was applied for fiber doublets assembled at the Fermi National Laboratory (FNAL) in USA. Seven fibers were held together with a rubber tube, and then threaded through a hole of an optical connector. Once the bundling was finished, an LED scan was performed and CCD images were taken, which were analyzed with a computer to check that the number of fibers in each bundle was seven and all bundles were inserted in the correct holes. After verifying the bundling was correct, the fiber doublet with connectors attached was mounted on a vacuum chuck. The fiber sheet was aligned to match the center of the vacuum chuck by observing with a microscope. Once the alignment was verified, the air between the fiber doublet and the chuck was evacuated. The station frame with glue applied was then put on the fiber doublet and left until glue was cured. The remaining two doublets were glued in order, then, free optical connectors were fixed to the station. Glue was applied to each connector and the extended fibers were cut off. Finally, the surfaces of the optical connectors were polished with a diamond cutter.

The light yield of constructed stations has been measured using a radio-active source, ^{57}Co, emitting gamma-rays of 122 keV. The station to be tested was mounted in a light-tight box and light-guides were attached with grease applied. The source was mounted at the top of an arm, which was then fixed with a linear guide to control the location of the source. In order to illuminate all scintillating fibers, the source scanned 28 different points and 50,000 events were taken at each location. It takes eleven hours to fabricate a station and to take data. Light yields were analyzed by fitting each light yield distribution with a Gaussian. Fifteen stations including backups have been tested and more than 10 photo-electrons have been measured for all stations.

Light-guide The light-guides have been constructed at Osaka University, Japan in 2008. First, clear-fiber wound on a spool was extracted and cut in 4m-long canes. A bundle of 225 fibers was then attached with test-cookies at both ends. The surface of each connector was exposed with a strobe light and a photograph was taken with a digital camera. Since the light propagating in a fiber can be reflected at a damaged location such as kinks or cracks, the damaged fiber can be identified by examining the photograph. Next, the bundle of clear-fibers was illuminated uniformly with LED light whose emission peak was close to that of 3HF. The uniformity of the light transported in each fiber was checked by taking a photograph of the surface of the connector at another end with a CCD camera. Clear-fibers with light yield below 90 % of the maximum value of 225 samples were rejected. Good fibers were then cut into two. One was used for the internal and the other for the external light-guides. Assembling with optical connectors, clear fibers were fixed with glue and the surfaces of connectors were polished. The quality of gluing and connection was inspected by eye, and then the reflection test and the transmission test were performed again. The bad-fiber fraction in all of the constructed light-guides was less than 0.1 %. Finally, light-guides were polished with a diamond cutter in FNAL.

Performance

Both of the upstream and downstream tracker have been constructed and performance of the trackers such as light-yields, residuals and efficiencies have been examined with cosmic-ray runs performed at RAL in 2008 and 2009 [8]. First of all, alignment of fiber doublets in the middle three stations was adjusted in such a way that the mean of the residuals between hit fiber (cluster) position and interpolated track from the outside two stations should be zero. Hit fibers were defined as the fibers in which the light yield was greater than 2.5 photo-electrons and hit positions were determined from triplets. The mean of the cluster light-yield distribution was 11.23 ± 0.01 photo electrons (PE) and the most-probable value was 9.37 ± 0.03 PE (Fig.4). The RMS of the residual distributions was 682 μm $\pm$ 1 μm as expected given a channel resolution of 470 μm and multiple Coulomb scattering in the doublet layers (Fig.5). The space-point efficiencies determined from the triplet residual were more than 99.7 % for each station.

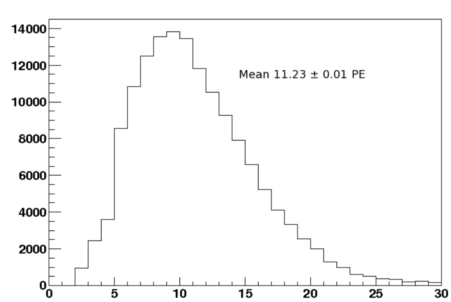

Figure 4: Light yield per doublet cluster from cosmic-rays, corrected for saturation effects in high-gain VLPCs.

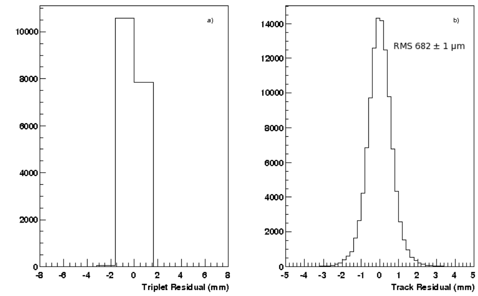

Figure 5: Performance of the MICE tracker evaluated using cosmic-rays. a) Triplet residual distribution, consisting of triplets made from single-channel clusters and used in full tracks. b) Track residual distribution. The RMS is noted on the figure.

CONCLUSION

SciFi trackers based on 350-μm scintillating fiber have been developed to measure the emittance of muon beam at MICE, in collaboration with Japan, USA and the UK. Both upstream and downstream trackers have been constructed and cosmic-ray tests have been performed at the Rutherford Appleton Laboratory by January 2009, which confirmed that both the trackers have the required quality for use in the MICE experiment.

REFERENCES

[1] A.N. Skrinsky and V.V.Parkhomchuck, Sov. Jour.Nucl. Phys. 12 (1981), p.3.

[2] MICE Collaboration, G.Gregoire et al., "An International Muon Ionization Cooling Experiment (MICE)", MICE Note 167 (2003), `http://mice.iit.edu/mnp/MICE0021.pdf`.

[3] M. Petroff and M. Stapelbroek, "Photon-Counting Solid-State Photomultiplier", IEEE TRANSACTIONS ON NUCLEAR SCIENCE 36 (FEB, 1989) 158162.

[4] M. Petroff and M. Atac, "High-Energy Particle Tracking using Scintillation Fibers and Solid-State Photomultipliers", IEEE TRANSACTIONS ON NUCLEAR SCIENCE 36 (FEB, 1989) 163164.

[5] P. Rubinov, AFEIIt Readout Format, November 2007, D0 Note 5520.

[6] R. Lange, EPICS: recent developments and future perspectives, in: Ninth International Conference on Accelerator and Large Experimental Physics Control Systems, October 13-17, 2003.

[7] ALICE Collaboration, DATE V5 User's Guide, Internal Note ALICE-2005-015, 2005.

[8] M. Ellis et al., arXiv:1005.3491 (2010), to be submitted to Nucl. Instrum. Meth. A.