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The design, construction and performance of the MICE scintillating fibre trackers

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ABSTRACT

Charged-particle tracking in the international Muon Ionisation Cooling Experiment (MICE) will be performed using two solenoidal spectrometers, each instrumented with a tracking detector based on 350 μm diameter scintillating fibres. The design and construction of the trackers is described along with the quality-assurance procedures, photon-detection system, readout electronics, reconstruction and simulation software and the data-acquisition system. Finally, the performance of the MICE tracker, determined using cosmic rays, is presented.

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1. Introduction

Muon storage rings have been proposed for use as sources of intense high-energy neutrino beams in a Neutrino Factory [1] and as the basis for multi-TeV lepton–antilepton colliding-beam facilities [2]. To optimise the performance of such facilities requires the phase-space compression (cooling) of the muon beam prior to acceleration and storage. The short muon-lifetime makes it impossible to employ traditional techniques to cool the beam while maintaining the muon beam intensity. Ionisation cooling, a process in which the muon beam is passed through a series of liquid hydrogen absorbers interspersed with accelerating RF cavities, is the technique proposed to cool the muon beam. The international Muon Ionisation Cooling Experiment (MICE) will

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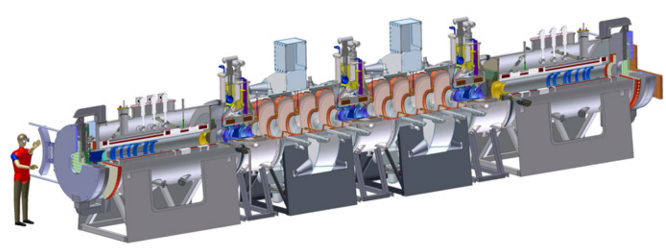

Fig. 1. Cutaway 3D rendering of the international Muon Ionisation Cooling Experiment (MICE). The muon beam enters from the bottom left of the figure. The instrumentation used for particle identification (PID) upstream of the first spectrometer solenoid (not shown) is composed of two time-of-flight hodoscopes (TOF0 and TOF1) and two threshold Cherenkov counters (CKOVa and CKOVb). The upstream spectrometer is followed by the MICE cooling channel, which is composed of three 20 l volumes of liquid hydrogen and two sets of four 201 MHz accelerating cavities embedded in a solenoidal transport channel. This in turn is followed by the downstream spectrometer, a third time-of-flight hodoscope (TOF2), and a calorimeter system (KL and EMR).

provide an engineering demonstration of the ionisation cooling technique and will allow the factors affecting the performance of ionisation cooling channels to be investigated in detail [3]. Muon beams of momenta between 140 and 240 MeV/c, with normalised emittances between 2 and 10π mm, will be provided by a purpose-built beam line on the 800 MeV proton synchrotron, ISIS [4], at the Rutherford Appleton Laboratory [5].

MICE is a single-particle experiment in which the position and momentum of each muon is measured before it enters the MICE cooling channel and once again after it has left (see Fig. 1) [6]. The MICE cooling channel, which is based on one lattice cell of the cooling channel described in Ref. [7], comprises three 20 l volumes of liquid hydrogen and two sets of four 201 MHz accelerating cavities. Beam transport is achieved by means of a series of superconducting solenoids. A particle identification (PID) system (scintillator time-of-flight hodoscopes TOF0 and TOF1 and threshold Cherenkov counters CKOVa and CKOVb) upstream of the cooling channel allows a pure muon beam to be selected. Downstream of the cooling channel, a final hodoscope (TOF2) and a calorimeter system allow muon decays to be identified. The calorimeter is composed of a lead-scintillator section (KL), similar to the KLOE [8] design but with thinner lead foils, followed by a fully active scintillator detector (the electron–muon ranger, EMR) in which the muons are brought to rest. For a full description of the experiment see Ref. [6].

Charged-particle tracking in MICE is provided by two solenoidal spectrometers. Together, the spectrometers are required to determine the expected relative change in transverse emittance of approximately 10% with a precision of $\pm 1\%$ (i.e. a 0.1% measurement of the absolute emittance). The trackers themselves are required to have high track-finding efficiency in the presence of background induced by X-rays produced in the RF cavities. Each spectrometer consists of a 4 T superconducting solenoid of 40 cm bore instrumented with a tracker composed of five planar scintillating-fibre stations (for a review of the use of scintillating fibres in charged particle tracking see Ref. [9]). Each station is composed of three doublet layers of scintillating fibres laid out in a 'u,v,w' arrangement. To reduce multiple Coulomb scattering of muons to an acceptable level, a fibre diameter of 350 μm is required. The scintillation light is read out via 1.05 mm clear-fibre light-guides. To reduce the cost of the read-out electronics seven 350 μm fibres are read out through each clear-fibre light-guide. The active area of each station is a circle of diameter 30 cm.

The concentration of the primary and secondary dopants within the scintillating fibre must be chosen to maximise the light yield while minimising the fibre-to-fibre optical cross-talk. Light-yield measurements using prototype stations led to the choice of 1.25% and 0.25% by weight for the concentrations of primary dopant, para-terphenyl (pT), and secondary dopant, 3-hydroxflavone (3HF), respectively [10].

The MICE trackers are read out using the DØ Central Fibre Tracker (CFT) optical read-out and electronics system [11]. The scintillation light is detected using Visible Light Photon Counters (VLPCs) [12,13]. These are low band-gap silicon avalanche devices that are operated at 9 K. The VLPCs have a high quantum efficiency ($\sim$80%) and a high gain that in some devices is in excess of 50 000. The VLPC signals are digitised using the Analogue Front End with Timing (AFE IIt) board developed by the DØ collaboration [14].

The solenoidal field in the tracking volume is designed to be uniform at the 3 per mil level. The MICE coordinate system is such that the z-axis is parallel to the beam, the y-axis points vertically upwards, and the x-axis completes a right-handed coordinate system. A muon therefore describes a circle in the x,y plane as it travels through the solenoid. The transverse momentum of the muon is obtained by determining the radius of this circle, while the number of turns determines the z-component. The station spacing has been chosen to optimise the performance of the reconstruction (track-finding efficiency and parameter resolution).

This paper is organised as follows. The mechanical design and construction of the trackers are described in Section 2. The photon-detection system and read-out electronics are presented in Sections 3 and 4, respectively. Section 5 contains a summary of the performance of the devices. Finally, a summary is presented in Section 6.

2. Mechanical design and construction

The layout of the MICE tracker is shown in Fig. 2. The five stations are held in position using a carbon-fibre space frame. The distance between neighbouring stations is such that each nearest-neighbour spacing is unique. This ensures that the azimuthal rotation of track position from one station to the next differs, this difference being important in resolving ambiguities at the pattern recognition stage. The station spacing, together with other key parameters of the tracker module, are presented in Table 1.

Each station consists of three 'doublet layers' of 350 μm scintillating fibres glued on a carbon-fibre station body. The doublet layers are arranged such that the fibres in one layer run at an angle of 120° to the fibres in each of the other layers as shown in Fig. 3a. The arrangement of the fibres within a doublet layer is shown in Fig. 3b. This packing arrangement ensures that there are no inactive regions between adjacent fibres. The configuration of the seven fibres ganged for read-out via a single clear-fibre light-guide is also indicated in Fig. 3b.

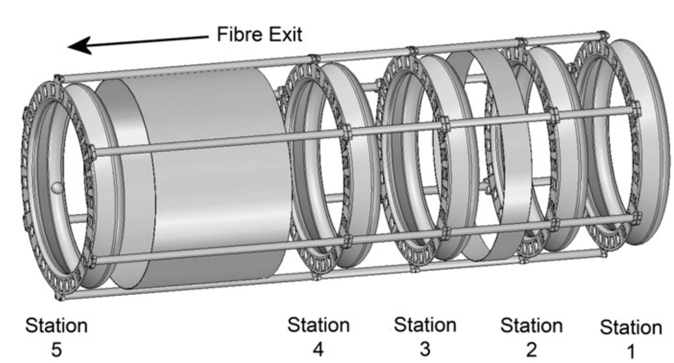

Fig. 2. Schematic diagram of the MICE tracker. The five stations are shown supported by the carbon-fibre space frame, with fibres omitted for clarity. The station numbering scheme is indicated together with the direction in which the clear-fibre light-guides leave the tracking volume.

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