

THE ALIGNMENT OF THE MICE TRACKER DETECTORS*

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Abstract

The Muon Ionization Cooling experiment (MICE) has been designed to demonstrate the reduction of the phase-space volume (cooling) occupied by a muon beam using the ionization-cooling technique. This demonstration will be an important step in establishing the feasibility of muon accelerators for particle physics. The emittance of the beam will be measured before and after the cooling cell using a solenoidal spectrometer. Each spectrometer will be instrumented with a high-precision scintillating-fibre tracking detector (Tracker). The Trackers will be immersed in a uniform magnetic field of 4 T and will measure the normalised emittance reduction with a precision of 0.1%. A thorough knowledge of the alignment of the Trackers is essential for this accuracy to be achieved. The Trackers are aligned: mechanically inside the spectrometer solenoids, with respect to the MICE experimental hall, to one another, and to the magnetic and beam axes. These methods are described here.

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE), in preparation at the Rutherford Appleton Laboratory in the UK, aims to demonstrate ionization cooling for the first time. Ionization cooling is the process of reducing the beam emittance (phase space) while maintaining the longitudinal momentum of the beam. Muons are produced with a large emittance, which must be condensed before acceleration. Muon beams are produced at the front end of a Neutrino Factory (NF) [1] with an emittance of 15–20 mm.rad, which must be reduced to 2–5 mm.rad. A Muon Collider [2] requires further cooling, reducing the emittance to 0.4 mm.rad in the transverse plane, and 1 mm.rad in the longitudinal plane. Due to the short muon lifetime, synchrotron radiation and stochastic cooling techniques are unsuitable for muon beams, and hence ionization cooling is the only process that can efficiently reduce the emittance of a muon beam within its lifetime.

The MICE experiment shown in Figure 1 will pass a muon beam through a low-Z material (absorber), where the muons lose both longitudinal and transverse momentum through ionization energy loss. A proportion of the lost longitudinal momentum is then restored using accelerating RF cavities that follow the absorber. Along with this cooling, however, there is a heating effect produced as a result of multiple scattering through the system, therefore, the net cooling is a balance between these two effects. This is described in Eq. 1, where the first term on the right hand side

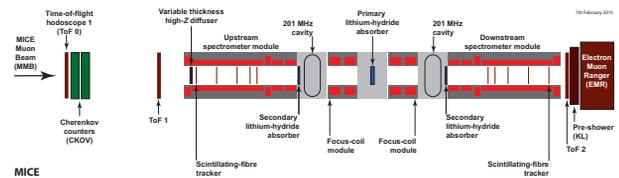


Figure 1: Schematic of the International Muon ionization Cooling Experiment (MICE), with the beam entering from the left.

represents the cooling effect and the second term the heating effect:

$$\frac{d\epsilon_n}{ds} \sim -\frac{1}{\beta^2} \left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta_\perp (0.014 \text{ GeV})^2}{2E_\mu m_\mu L_R} \quad (1)$$

$\frac{d\epsilon_n}{ds}$ is the rate of change of normalised-emittance within the absorber; β , E_μ and m_μ the ratio of the muon velocity to the speed of light, muon energy, and mass respectively; β_\perp is the lattice betatron function at the absorber; and L_R is the radiation length of the absorber material.

MICE aims to reduce the normalised emittance of the muon beam by a few percent and to measure the reduction with a precision of 0.1%. To do this each muon will be measured individually by an upstream and downstream high precision scintillating fibre tracking detector (Tracker). The Trackers are contained within super-conducting spectrometer solenoids (SSs) which produce a uniform 4 T field. The muon beamline has been commissioned and the beams produced have been shown by direct measurement with MICE particle detectors to be adequate for cooling measurements. The beam was experimentally studied paying particular attention to the rate, particle composition and emittance; the Trackers are built, fully tested, installed and are undergoing commissioning and calibration. MICE is surrounded by a partial return yoke (PRY) so as to minimise any stray magnetic field from the experiment.

MICE Step IV, shown in Figure 2 will begin data taking this year [3]. It will test the full system but without RF cavities to re-accelerate the beam (and will have only one absorber). Step IV can reduce normalised beam emittance but it will not restore longitudinal momentum and so it will not allow for a demonstration of sustainable cooling.

The final stage (see Figure 1), the Demonstration of Ionization Cooling will include the RF cavities and additional absorber modules and its construction is scheduled for completion in 2017.

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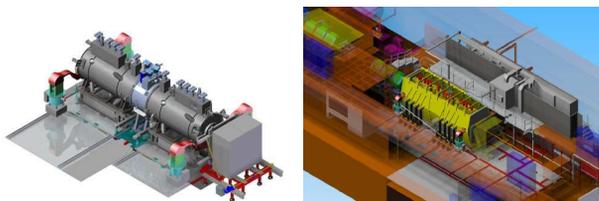


Figure 2: Left: Step IV of the MICE Experiment, showing the AFC absorber module (Central blue magnet) which contains the absorber, the two SS magnets either side (in grey) containing the Trackers and the DS PID detectors (Grey square). Right: Rendering of Step IV cooling channel in the MICE Hall including the PRY (yellow).

THE TRACKERS

The emittance of the MICE beam will be measured before and after cooling using two high-precision scintillating-fibre tracking detectors (Trackers), each sitting within a superconducting solenoid magnet (SS) which produces a uniform magnetic field of 4 T. They are designed to measure normalised emittance reduction with a precision of 0.1%.

The Trackers (one shown in Figure 3) are 110 cm in length and 30 cm in diameter. There are five stations per Tracker, held in position using a carbon-fibre space-frame, at varying separations in z of 20–35 cm. This ensures that the azimuthal rotation of track position from one station to the next differs, which allows us to resolve ambiguities in the rotation angle and hence determine the muon pT . Each Tracker is instrumented with an internal LED calibration system and four 3D Hall probes.



Figure 3: Photograph of one of the MICE Trackers, showing the 5 stations and the 3 doublet planes of scintillating fibres at 120° angles.

The Tracker stations consists of three ‘doublet layers’ of $350\ \mu\text{m}$ scintillating fibres, these layers are arranged such that each is at an angle of 120° to the next (as can be seen in Figure 3). This arrangement ensures that there are no inactive regions between adjacent fibres. Bundles of seven fibres are grouped into a single readout channel (this produces less multiple scattering than a single fibre with the same resolution). The Trackers have a spatial resolution

per doublet layer of $470\ \mu\text{m}$ and an expected light yield of ~ 10 photo-electrons.

TRACKER ALIGNMENT

In order for the Trackers to measure the beam emittance with the required precision, it is essential that their relative positions and those of their stations are well understood. To this end the Trackers are mechanically aligned inside the bore of each SS which in turn is surveyed into position in the MICE hall; the Upstream and Downstream Trackers must be aligned to one another, and to the magnetic and beam axes and the internal positions of the Tracker stations checked. All non-mechanical alignment will be carried out using a beam based analysis, where a beam of relatively straight muon tracks (no magnetic field) is measured traversing the Upstream Tracker and any deviation from their expected path in the Downstream Tracker is analysed to determine any misalignments.

Mechanical Alignment of the Trackers

Each Tracker is mechanically aligned inside the bore of its SS using a specifically designed ‘alignment jig’ (shown in Figure 4). The jig allows the Tracker to be positioned inside the bore, with respect to Tooling Ball Reflectors [4] (used as survey points mounted on the SS), to an accuracy of ~ 25 microns.

The alignment jig has a semicircular section with three reflectors mounted onto it to allow the central vertical fibre of the Tracker stations to be positioned in the true vertical plane, with no rotational offset which would affect particle track reconstruction. Once this is in place inside the bore, a long shaft section of the jig is used to allow the z position (along the beamline) of the Tracker to be fixed. Since the SS is a series of coils designed to create a homogeneous field in the region of the Tracker, it is essential that the Trackers are positioned in this appropriate region in z . The long shaft section of the jig is extended to the correct position in z and θ (already determined) and bolted into place. The jig, with the exception of the shaft, is then removed and the Tracker is inserted into the bore at the correct θ and z , now set by the jig shaft. The shaft of the alignment jig is then removed.

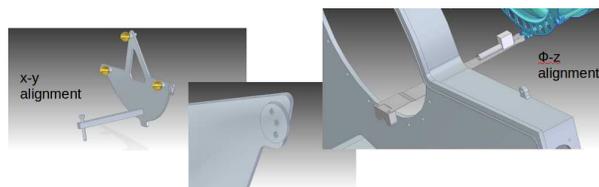


Figure 4: Technical drawing of the MICE Tracker alignment jig; showing the semicircular section for rotational (θ) alignment (far left); the shaft for positioning in z (far right) which determines how far into the bore the Tracker is inserted; and the mount for the survey balls (centre).

The SS magnets themselves are surveyed into position in the MICE experimental hall to ± 1 mm. Once in position, they can be moved in order to centralise the magnetic axis, by a maximum of 4 mm.

Upstream To Downstream Tracker Alignment

The relative positions of the Trackers are determined using a through going beam of straight track muons of 200 MeV/c (the magnets are off, thereby allowing the muons to follow straight tracks through the Trackers). The path of the muons will be affected by the Earth's magnetic field, multiple scattering and fields created by magnetic material along the experiment, and hence these effects must be accounted for when modelling the expected path (in the case of perfect alignment) of the beam through the Trackers. The partial return yoke (PRY), surrounding the experiment, which shields against stray magnetic fields leaking into the MICE hall, can also affect the muons' paths, in particular if the magnets are turned on at any point prior to straight track alignment (which can cause hysteresis effects in the steel PRY), and therefore, it must be carefully considered, modelled as far as possible and measured in situ (to scan for any areas of magnetism). To reduce the effect of multiple scattering the absorber is removed and a small emittance muon beam is selected. The muon tracks are then compared between the Upstream and Downstream Trackers, taking the Earth's magnetic field and the other effects described into account and any offset/divergence in the muon paths can hence be unfolded to understand the Tracker alignment.

A full Monte Carlo study is currently under way to determine and maximise alignment sensitivity. In the simulation the Downstream Tracker is physically offset to the Upstream at: rotational angles of 0–10 mm.rad, z displacements of 0–3 mm and twists (non-horizontal Tracker positions) of 0–10 mm.rad. There are 15 free parameters per Tracker (3 fibre planes x 5 stations) and hence, to achieve good statistics, 30,000 muons are simulated. Taking into account the effect of Earth's magnetic field, the ability of the reconstruction to unfold these offsets is determined and improved accordingly. Subsequently, the field strength of magnetic material around the path of the beam is estimated and where possible measured and included in the simulation to determine the best possible alignment sensitivity.

The Tracker alignment cannot affect the emittance of the beam only MICE's sensitivity to it. The expected muon rate calculated from earlier MICE runs is 60 μ /spill and it will be possible to obtain the muons required in less than one days running.

Internal Tracker Alignment

The process to understand internal Tracker alignment i.e. alignment of the stations of a Tracker with respect to one another, follows a similar method to that of Upstream to Downstream Tracker alignment. In this case the stations are rotated (θ), twisted (in θ and z) and offset in z, with respect to one another. Again the reconstruction software is used to

determine the sensitivity required, and where necessary, is improved to meet that requirement.

Magnetic Alignment

The Upstream SS magnet, followed by the absorber focus coil magnet(s) (AFC) (that surround the absorber(s)) and the Downstream SS combine to form the magnetic axis of the experiment. These magnets will be aligned along a common magnetic axis. To do this it may be necessary to offset the physical positions of the magnets so as to centralise the magnetic axis (as shown in Figure 5). A full study of the magnetic axis in each magnet is ongoing and will be confirmed with beam.

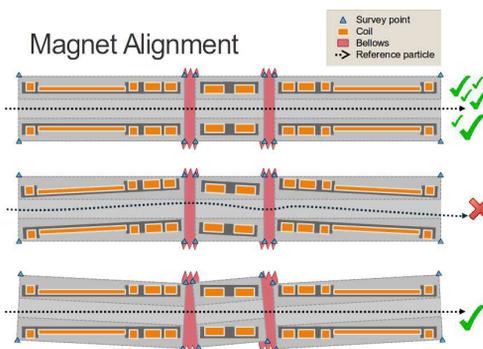


Figure 5: Diagram showing the MICE magnets and the magnetic axis they create. The magnets are shown as grey boxes with their coils in orange, and the magnetic axis is the black dashed line. If the magnetic axis is ideally situated through the centre of the magnets then no further alignment is necessary (top), if not however (middle), then the magnets will be aligned to correct this which may result in them being physically offset/angled with respect to one another (bottom). Image courtesy of V. Blackmore.

CONCLUSIONS

MICE will demonstrate the ionization cooling (reducing the beam emittance through ionization energy loss with partially restored longitudinal momentum by RF acceleration) of a muon beam for the first time. The emittance of the beam will be measured before and after cooling using two tracking detectors (Trackers) positioned either side of the cooling channel. The Trackers sit in a 4 T magnetic field created by superconducting solenoid (SS) magnets. Whilst the alignment of the Trackers cannot affect the beam emittance, misalignment can reduce the precision with which MICE can measure it. It is therefore essential to align all elements of the Tracker as precisely as possible. To this end the Trackers are aligned: mechanically to the SS bore (to ± 25 microns), the SSs are positioned with an accuracy of ± 1 mm, and the magnets are aligned to one another such that the magnetic and beam axes are overlaid and central to the Tracker volume. Any offset in the alignment of the Tracker stations and the Trackers themselves are measured and accounted for in the software.

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