MICE: The Trackers and Magnets*

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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 colliders and Neutrino Factories for particle physics. The emittance of the beam will be measured before and after the cooling cell (or absorber) using a solenoidal spectrometer. Each spectrometer is instrumented with a high precision scintillating-fibre tracking detector (Tracker), which are immersed in a uniform magnetic field of 4 T. The cooling cell sits in an alternating focus coil magnet (AFC) which has two coils, axially aligned, that can be powered so that the fields oppose "Flip mode" or align "Solenoid mode", to a maximum B_z of ∼3 T. The status of the Trackers and magnets are described here.

INTRODUCTION: MICE

The Muon Ionization Cooling Experiment (MICE) [1–3], under development at the Rutherford Appleton Laboratory in the UK, aims to demonstrate ionization cooling of muons 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

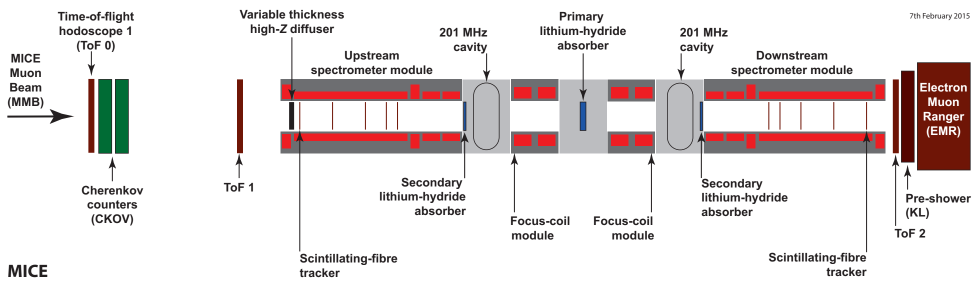

FIG. 1: Schematic of the International Muon Ionization Cooling Experiment (MICE), with the beam entering from the left.

a large emittance, which must be reduced before re-acceleration. Muon beams are produced at the front end of a Neutrino Factory (NF) [4] with an emittance of 15–20 mm·rad, which must be reduced to 2–5 mm·rad. A Muon Collider [5] requires further cooling, reducing the emittance to 0.00025 mm·rad in the transverse plane, and 70 mm·rad in the longitudinal plane [6]. Due to the short muon lifetime 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 (cooling). 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 represents cooling and the second term heating:

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

$\frac{d\epsilon_n}{ds}$ 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, energy, and mass respectively; $\beta_\perp$ 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 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 yolk (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. It will test the full system but without RF cavities to accelerate the beam (and will have only one absorber). Step IV will reduce overall beam emittance and measure it, but will not restore longitudinal momentum and so it will not allow for sustainable cooling demonstration.

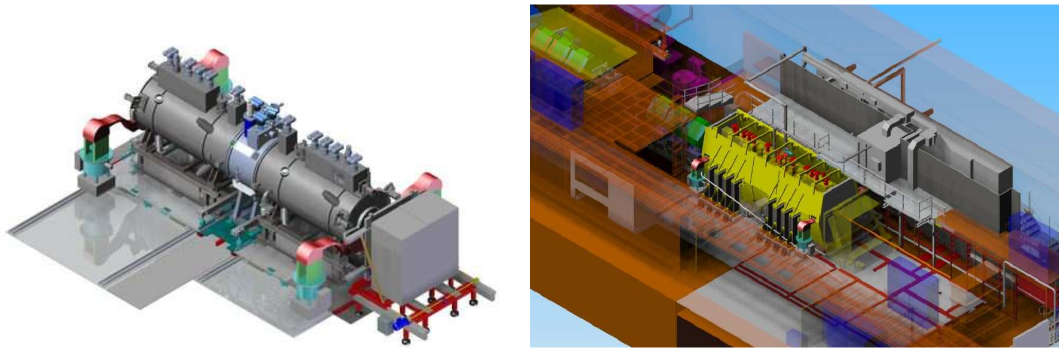

FIG. 2: Left: Step IV of the MICE Experiment, showing the AFC absorber module (Central blue magnet) which contains the absorbed, the two SS magnets either side (in grey) which contain the Trackers and the DS PID detectors (Grey square). Right: Rendering of Step IV cooling channel in the MICE Hall including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

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

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, this difference being important in resolving ambiguities at the pattern-recognition stage. Each Tracker is instrumented with an internal LED calibration system and four 3D hall probes.

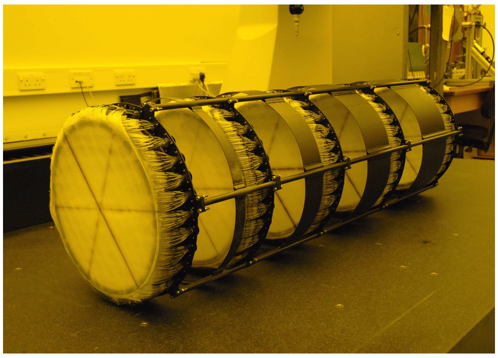

FIG. 3: Photograph of one of the MICE Trackers, showing the 5 stations and the 3 doublet planes of scintillating fibres at 120° angles (the central fibres of plane an be seen as darker lines traversing the station).

The Tracker stations consists of three doublet layers of 350 μm scintillating fibres, these layers are arranged such that each is at an angle of 120° to the next (as can be seen 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 reduces the number of readout channels, while maintaining position resolution). The Trackers have a spatial resolution per doublet layer of 470 μm and an expected light yield of $\sim$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 relative positions of the five Tracker stations were measured using a coordinate measuring machine (CMM) as part of the QA during construction and 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. The relative positions of the trackers are determined using through-going muons from data-taking without field.

Mechanical Alignment of the Trackers

Each Tracker is mechanically aligned inside the bore of its SS (superconducting solenoid) using a specifically designed 'alignment jig' (shown in Figure 4). The jig allows the Tracker to be positioned inside the bore, with respect to the SS (which is then surveyed in the hall), to an accuracy of ∼25 microns in theta and z.

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 at true vertical, 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 theta (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 theta and z, now set by the jig shaft (which is then also removed).

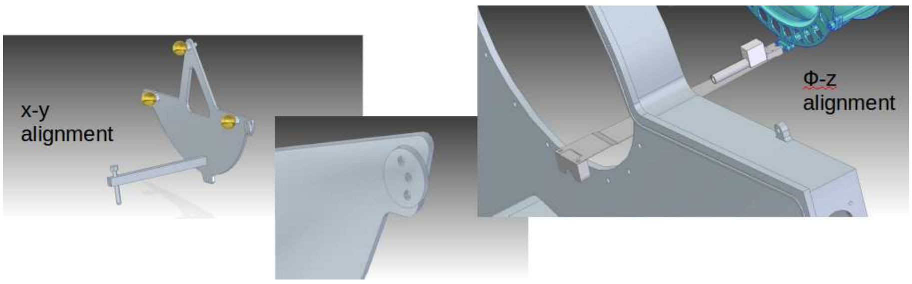

FIG. 4: Technical drawing of the MICE Tracker alignment jig; showing the semicircular section for rotational (theta) alignment (far left); the shaft for positioning in z (far right) which determines how far into the bore the Tracker is inserted; and the mount for the survey balls (centre).

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.

Upstream To Downstream Tracker Alignment

The relative positions of the Trackers are determined using a through going beam of straight track muons of a range of momenta and emittance (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 ($\sim$250 μm deflection between the first US tracker and the last DS Tracker planes for a 300 MeV/c beam and $\sim$300 μm for a 200 MeV/c beam), multiple scattering and fields due to 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. To reduce the effect of multiple scattering the absorber is removed.

Events with a single, five-point track in both the upstream and downstream Trackers are selected and the Tracker relative alignment is performed using the residuals between the downstream track parameters and the parameters of the upstream track extrapolated to the reference surface of the downstream Tracker. The Tracker-to-Tracker alignment residuals, based on data from the Kalman fit, are shown in Figure 5[7]. Multiple Coulomb scattering combined with the uncertainty on the extrapolated track parameters combine to yield a significant spread in track position residuals. The width of the residual distributions are consistent with expectations based on simulation.

THE MAGNETS

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 are installed and surveyed into the hall and commissioning has begun.

Field Mapping

The magnetic fields of each of the superconducting solenoids were measured ("mapped") to record the magnetic field and determine the alignment of the coils within the cryostats. The field was measured using a disc carrying seven three-axis Hall probes spaced by 30 mm apart radially. The disc was moved longitudinally and rotated within the warm bore of the

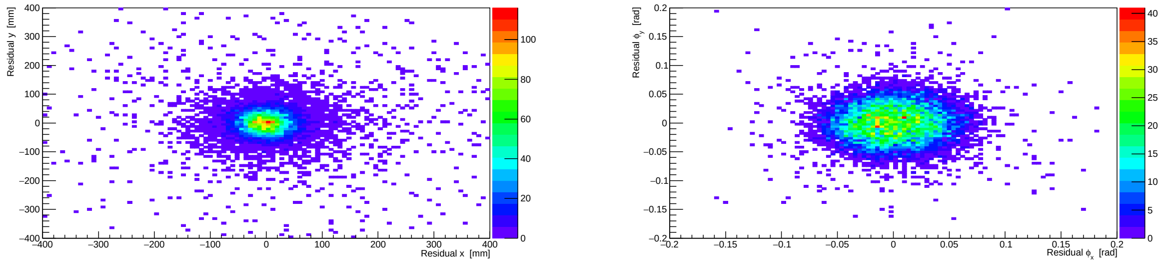

FIG. 5: Left panel: x, y position reconstruction residuals showing US to DS Tracker alignment performed using the MAUS Kalman filter. The residuals are calculated between propagated upstream tracks and the reconstructed downstream tracks. Right panel: The residuals for the ϕ_x-ϕ_y angles, where the ϕ_x angle describes the rotation in the x-z plane and ϕ_y shows the x-y plane. Performed using the MAUS Kalman filter between propagated upstream tracks and the reconstructed downstream tracks.

magnet. The axis of travel of the disc was surveyed with respect to fiducial marks on the cryostats. The positions of the Hall probes were known to about two tenths of a millimetre in the coordinate system defined by the magnet's fiducial marks.

The field components were measured typically every 20 mm to 50 mm longitudinally and every 20 to 45 degrees in azimuth. The probes recorded the radial, azimuthal and longitudinal field components in the coordinate system of the mapper disc. The Maxwell relation $\nabla \times \mathbf{B} = 0$ was used to correct the measured radial and azimuthal components for small radial misalignments of the probes (i.e. small rotations around the longitudinal axis). These components (and probe positions) were then converted to transverse Cartesian components in the mapper coordinate system. Figure 6 shows the fields measured in one of the spectrometer solenoids and one of the focus-coil modules.

The magnetic axis of each module was obtained by the implicit use of $\nabla \cdot \mathbf{B} = 0$. At each longitudinal position, z, simple linear fits of B_s versus s, where $s \equiv x$ or y in the mapper system, were made. The slopes, $k(z) = \partial B_s/\partial s \equiv -(1/2)\partial B_z/\partial z$, and intercepts, $B_o(z)$, from these fits were then used in a global fit over all longitudinal positions to find the equation of the magnetic axis in the mapper system:

$$B_o(z) = -k(z)s_o - \alpha k(z)z + \alpha_s B_z \; ; \tag{2}$$

where α_s and s_o are respectively the slope and intercept of the axis in the s–z projection

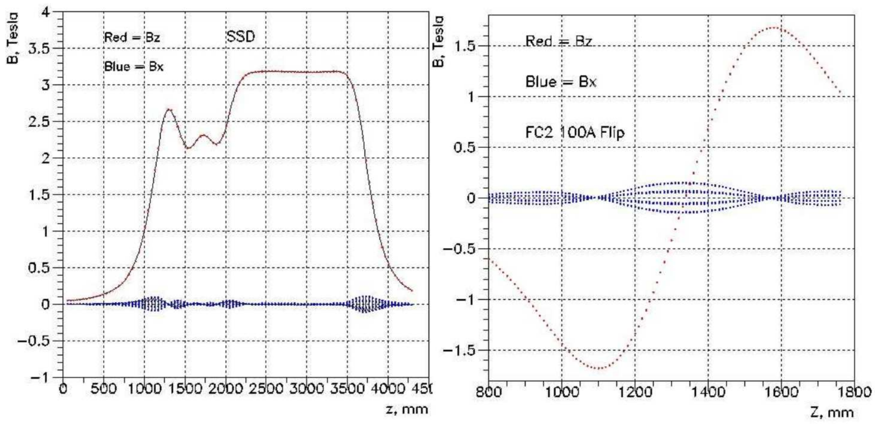

FIG. 6: Longitudinal, z, and transverse, x, fields in one of the spectrometer solenoids (left) and one of the focus-coil modules in flip-mode (right).

and the last term allows for the angle between the longitudinal mapper axis and the true magnetic axis.

The mapper survey was then used to transform the magnetic axis in the mapper system to the fiducial system of the the cryostat and finally, after the modules had been installed, into the MICE Hall coordinate system. The overall accuracy of this procedure was estimated to be better than 0.3 mm in each transverse coordinate.

CONCLUSIONS

MICE will demonstrate ionization cooling of a muon beam for the first time (reducing the beam emittance through ionization energy loss with partially restored longitudinal momentum by RF acceleration). The emittance of the beam will be measured before and after cooling using two Trackers positioned either side of the cooling channel. The Trackers sit in a 4 T magnetic field created by superconducting solenoid (SS) magnets. All magnets and detectors necessary for MICE Step IV are installed and are undergoing commissioning. It is essential to align all elements of the Tracker as precisely as possible. The Trackers are aligned mechanically to 25 microns and using through going straight track muon data. Initial results show that the Tracker alignment is consistent with expectations based on simulation. The magnetic fields of each of the superconducting solenoids were measured ("mapped") to record the magnetic field and determine the alignment of the coils within the cryostats.

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[7] This analysis was performed with data taken in October 2015 and hence was not included in the original conference talk, but is included here for completeness