MICE SPECTROMETER SOLENOID MAGNETIC FIELD MEASUREMENTS

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Abstract

The Muon Ionisation Cooling Experiment (MICE) is designed to demonstrate ionization cooling in a muon beam. Its goal is to measure a 10% change in transverse emittance of a muon beam going through a prototype Neutrino Factory cooling channel section with a 1% accuracy, corresponding to an absolute measurement accuracy of 0.1%. To measure the emittance, MICE uses two solenoidal spectrometers. The Spectrometer Solenoids are designed to have 4 T solenoidal fields, uniform at 3 per mil level in the tracking volumes. Planned and initial magnetic field measurements of the Spectrometer Solenoid magnets, and analysis for extracting precise values of positions, angles, and radius of the coils for input into magnet models will be discussed.

INTRODUCTION

The MICE experiment [1] located at Rutherford Appleton Laboratory consists of a dedicated beam line, which generates muons in a range of input momenta and emittances, and a cooling cell sandwiched between particle identification detectors (PID) and Spectrometer Solenoids (SS) equipped with scintillating fiber trackers, see Fig. 1. The cooling cell is designed to reduce the transverse emittance of a passing muon beam by about 10% using the ionization cooling principle. It is a prototype of a cooling channel section for use in a Neutrino Factory or a Muon Collider. Key to demonstrating the emittance reduction is the accurate measurement of the "before" and "after" beam emittances, which is achieved by measuring kinematic properties of individual muons in the two trackers.

Each spectrometer consists of a 4 T superconducting solenoid, with field designed to be uniform at the 3 per mil level in the tracking volume, and a tracker [2] composed of five planar scintillating-fibre stations, whose pacing has been chosen to optimize the performance of the reconstruction (track-finding efficiency and parameter resolution). Together, the spectrometers are required to determine the expected relative change in transverse emittance of approximately 10% with a precision of ±1% (i.e. 0.1% measurement of the absolute emittance). Therefore, the fields in the tracking volume should be known with high accuracy.

The MICE SS were built at Wang NMR (Livermore, CA, USA). A schematic representation of the magnet (not drawn to scale) is shown in Fig. 2. The cryostat consists

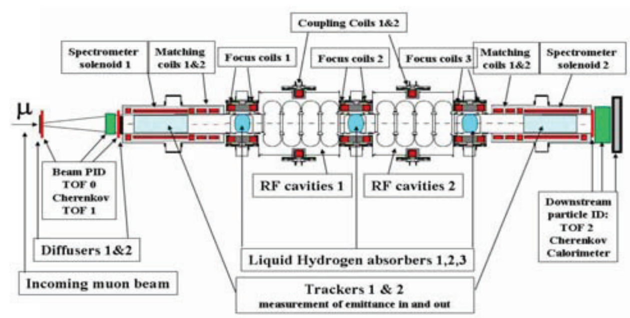

Figure 1: Layout of the MICE cooling cell.

of a liquid helium vessel, an 80 K thermal shield, cold mass supports and a stainless steel vacuum vessel with 40-cm diameter bore. Each solenoid consists of five superconducting Nb-Ti coils wound on a single aluminum mandrel. Two Matching coils (M1, M2) match the muon beam in the Spectrometer Solenoids to the beam in the cooling cell. Two End coils (E1, E2) positioned around a Center coil (C) are designed to generate a uniform 4 T field over a 110-cm-long and 30-cm-diameter volume. The currents given in Fig. 3 [3] are the maximum currents expected when the tracker solenoid is run for muons with an average momentum of 240 MeV/c and a β-function at the center of the absorbers of 420 mm.

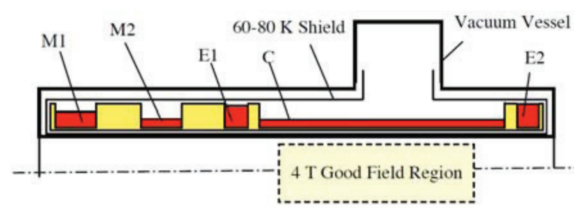

Figure 2: Top half of a schematic cross-section of one of the MICE SS.

	Match 1	Match 2	End 1	Center	End 2
Inner Coil Radius (mm)	258	258	258	258	258
Coil Thickness (mm)	46.165	30.925	60.905	22.125	67.783
Coil Length (mm)	201.268	199.492	110.642	1314.30	110.642
Current Center Axial Position* (mm)	124.00	564.00	964.00	1714.00	2464.00
Current Center Radial Position* (mm)	281.083	273.463	288.453	269.063	291.891
Coil Average J (A mm^{-2})	137.67	147.77	124.28	147.66	127.09
Number of layers per Coil	42	28	56	20	62
Number of Turns per Layer	115	114	64	768	64
Total Number of Turns	4830	3192	3584	15360	3968
Design Current (A)**	264.83	285.60	233.68	275.52	240.21
Coil Self Inductance (H)^	12.0	5.0	9.0	40.0	11.3
Coil Stored Energy (MJ)**	0.42	0.20	0.26	1.55	0.32
Peak Field in Coil (T)**	5.30	4.32	5.68	4.24	5.86
Temperature Margin at 4.2 K (K)**	~1.6	~1.8	~1.5	~2.0	~1.5

* Based on Z = 0 is at the match coil end of the magnet cold mass. (The center of MICE in these coordinates is at Z = -3487 mm.) R = 0 is the axis of the magnet (the MICE axis).
** This is at the maximum design current, which is based on the worst-case currents for the five coils.
^ The inductance of the two end coils and the center coil in series is about 74 H.

Figure 3: As built parameters of the second MICE SS.

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The experiment would use muon beams of momenta in a range between 140 and 240 MeV/c, with normalised emittances between 2 and 10 π mm. Since the currents in the Spectrometer Solenoid coils would be different for each momenta/emittance case, mapping the magnets for each possible configuration is impractical. Instead, a model of the solenoids will be used to simulate the fields for each case for use in MICE data analysis. The purpose of the magnetic field mapping is then to determine the precise coil geometry for the model, effects of magnetic material (detector shielding) on the field, and determine the SS magnetic axis.

INITIAL MAGNETIC FIELD MEASUREMENTS

The initial magnetic field measurements of the second MICE SS were performed at Wang NMR [4], before the magnet was fully trained, and without any magnetic material present near the solenoid. The apparatus used for the measurements is shown in Fig. 4. It consisted of a stainless steel guide tube that provided support for a 3D Hall probe within the warm bore. The guide tube was supported at both ends by aluminum plates, which were surveyed and mounted to the warm bore openings on both sides of the magnet. Measurements were performed along the central magnet axis, and with 100 mm horizontal and vertical offsets. The coils in the magnet were powered up to 150 A during testing, just above 50% of the design current values listed in Fig. 3. The measurement results were compared with Opera 3D simulation of the magnet shown in Fig. 5.

The main sources of systematic uncertainties were: the probe was positioned manually in the longitudinal direction and the position was read out from a ruler attached to the G10 shaft; the system was not surveyed in the longitudinal direction; the measurements are very sensitive to probe rotations, which were restricted only by a few centering bearings in the guide tube. There was some indication of instability in power supply regulation, visible in the shift in measured field for the circled points in Fig. 6. The observed shift of ~100 G corresponds to about 0.7 A current change. A ~3% discrepancy between measurements and simulations could be due to effects of fringe field on the Controls and Monitoring (C&M) equipment. The SS C&M Review [5] addressed some of these problems, for example, shunts were added to read out currents in the coils in addition to readout of power supply currents.

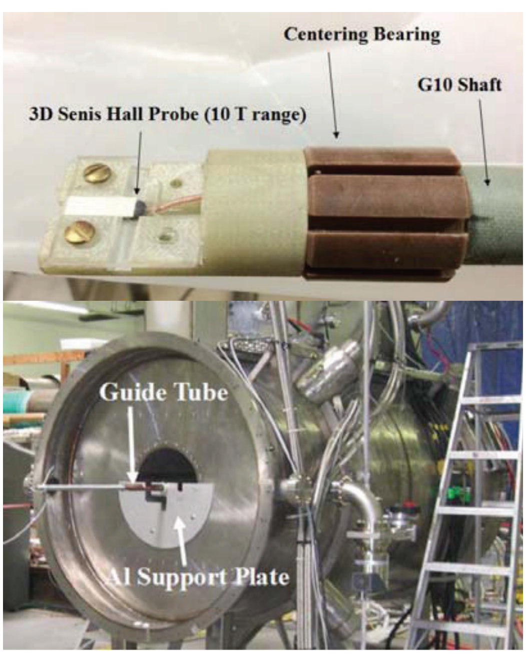

Figure 4: (Top) 3D Hall probe attached to a G10 shaft with centering bearing. (Bottom) Measurement apparatus, showing the stainless steel guide tube supported by aluminum plates.

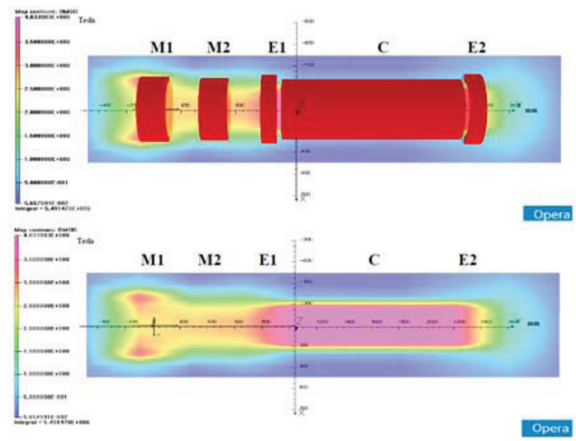

Figure 5: Opera 3D simulation of the magnet.

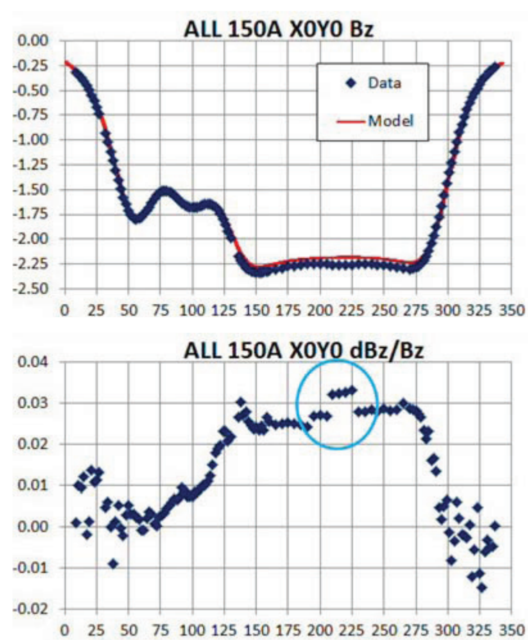

Figure 6: (Top) Axial components of the magnetic field (in T) vs. longitudinal position (in cm). On-axis; all coils were powered at 150 A. (Bottom) Normalized difference between the measured and simulated axial components of the field (in T) vs. longitudinal position (in cm).

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HIGH PRECISION MAGNETIC FIELD MEASUREMENTS

CERN Detector Technologies Engineering and Mechanics group built a dedicated system for mapping MICE magnets [6]. Two versions of the support system were built: 5-m version for SS magnetic measurements and a 2-m version for measurement of other smaller magnets in the MICE cooling channel. The chariot containing a detachable service module and a disk with seven 3D Hall probes, and the Data Acquisition system are common for the two device versions. The setup of the magnet measurement device is shown in Fig. 7.

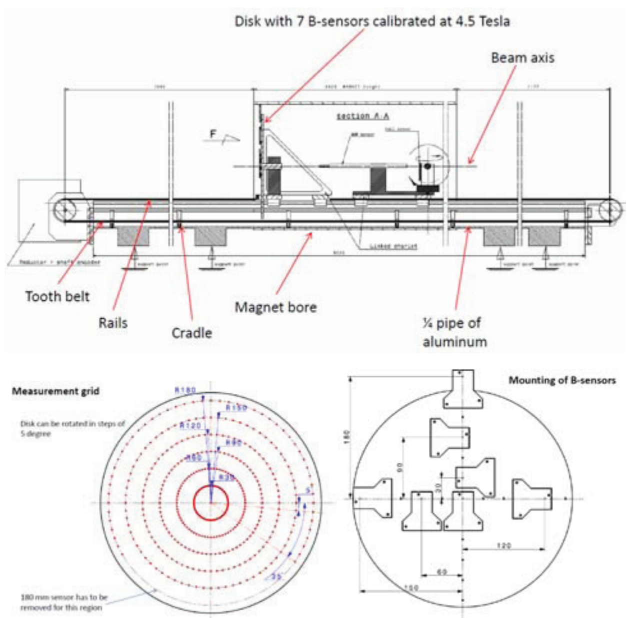

Figure 7: (Top) Magnet measurement device setup. (Bottom left) Measurement grid of the device. (Bottom right) Mounting positions of the seven 3D Hall probe sensors on the disk.

The support is made of ¼” aluminum pipe. Other components of the device are made of non-conducting materials to avoid eddy currents. The chariot is moved by a motor with reduction gear box and encoder on the outgoing shaft. The disk with seven 3D Hall probes can be manually rotated in steps of 5°. The probe at 180 mm radius needs to be dismounted for rotation angles between 125° and 240° due to interference with the chariot.

The system is characterized by the following uncertainties: ± 0.5 mm probe radial position; ± 1 mrad disk rotation angle, θ; < 0.5 mm longitudinal position; and ± 2 mT magnetic field measurement in 1 to 4 T region.

The system has been shipped from CERN to Wang NMR for Spectrometer Solenoid magnetic mapping at the vendor. Magnetic measurements of the MICE SS 2 are scheduled for May–June 2013, and of the MICE SS 1 for July–August 2013.

Magnetic measurements are going to be performed for two configurations: without any magnetic material present near the solenoid, and with steel (US1010) plate and cage, mounted on the solenoid side facing away from the MICE cooling cell (E2 coil side) for shielding detectors present in MICE channel.

The planned mapping studies will: establish mapping coordinate system and magnet’s position in it; check linearity of field with current; study the hysteresis effect in the field (due to introduction of material in shielding plate); and check for systematic uncertainties introduced by probes offsets, calibrations, etc. and try correct for them in the analysis.

The analysis of the magnetic measurements will determine magnetic axis of the SS magnets, and the precise coil geometries, for which the field simulation accurately reproduces the field measurements.

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