MICE SPECTROMETER SOLENOID MAGNETIC FIELD MEASUREMENTS

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Abstract

The Muon Ionization 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 an absolute measurement accuracy of 0.1%. To measure emittances, MICE uses two solenoidal spectrometers, with Solenoid magnets designed to have 4 T fields, uniform at 3 per mil level in the tracking volumes. Magnetic field measurements of the Spectrometer Solenoid magnet SS2, and analysis of coil parameters 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 between 140 and 240 MeV/c and emittances between 2 and 10 π mm, 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.

Each spectrometer consists of a 4 T superconducting solenoid, 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 of approximately 10% between the “before” and “after” beam transverse emittances with a precision of ±1% (i.e. 0.1% absolute measurement of the emittance). Therefore, the fields in the tracking volume should be known with high accuracy.

The MICE SSs 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 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 SSs 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 coil parameters

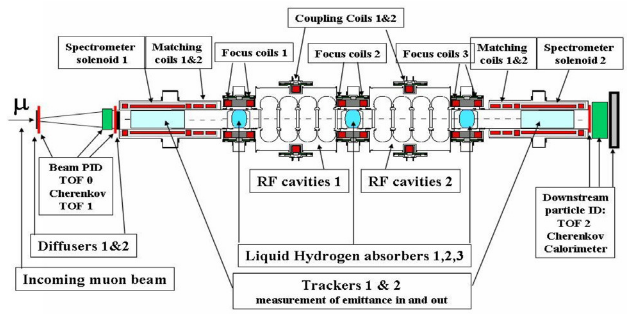

Figure 1: Layout of the MICE cooling cell. It is a prototype of a cooling channel section for use in a Neutrino Factory or a Muon Collider.

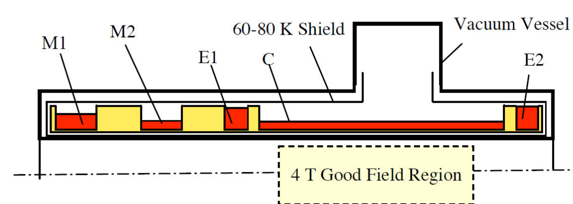

Figure 2: Top half of a schematic cross-section of one of the MICE SS.

	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 = 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.

given in Fig. 3 [3] are “as built”, which are different from the original design and design by vendor. Each coil layer was thicker than anticipated with fewer turns per layer, thus, the currents in the coils were adjusted accordingly.

A model of the solenoids (together with other magnets, equipment and structures in the MICE experimental hall) will be used to simulate the fields for each momentum/emittance case for use in MICE data analysis. Thus, the magnetic field mapping is important to verify the coil geometry for the model and effects of magnetic material (detector shielding) on the field.

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HIGH PRECISION MAGNETIC FIELD MEASUREMENTS

CERN Detector Technologies Engineering and Mechanics group built a dedicated system for mapping MICE magnets [4]. The system includes: a 5-m long support system, the chariot containing a detachable service module for an NMR probe, disk with seven 3D Hall probes, and the Data Acquisition system. The setup of the magnet measurement device is shown in Fig. 4.

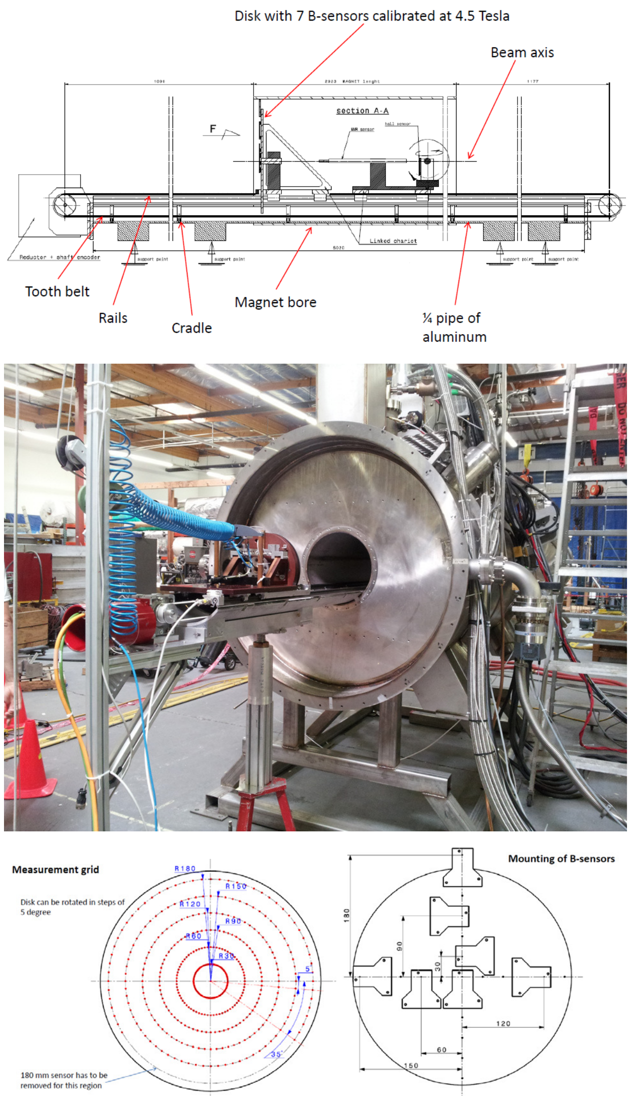

Figure 4: (Top) Magnet measurement device setup. (Center) Photo of the system in use for SS2 magnet. (Bottom left) Measurement grid of the device. (Bottom right) Mounting positions of the seven 3D Hall probe sensors on the disk.

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 rotated in steps of 5°. The probe at 180 mm radius needs to be dismounted for rotation angles between 225° and 355° 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; < 0.5 mm longitudinal position; and ± 2 mT magnetic field measurement in 1 to 4 T region.

Magnetic measurements of MICE SS2 magnet were performed for two setups: without any magnetic material present near the solenoid, and with steel (US1010) plate and cage, mounted on the E2-coil side of the solenoid for shielding detectors present in MICE channel.

For each setup, a series of measurements were done for two coil current configurations: "Solenoid Mode" and "Flip Mode", corresponding to the two MICE cooling cell magnetic field configurations when operating with muons with an average momentum of 240 MeV/c and a β-function at the center of the absorbers of 420 mm. Figure 5 shows an example of one set of measurements; measurements for all 3D Hall probes at different radii are plotted (0 mm – 18 mm), thus, the scatter in the points.

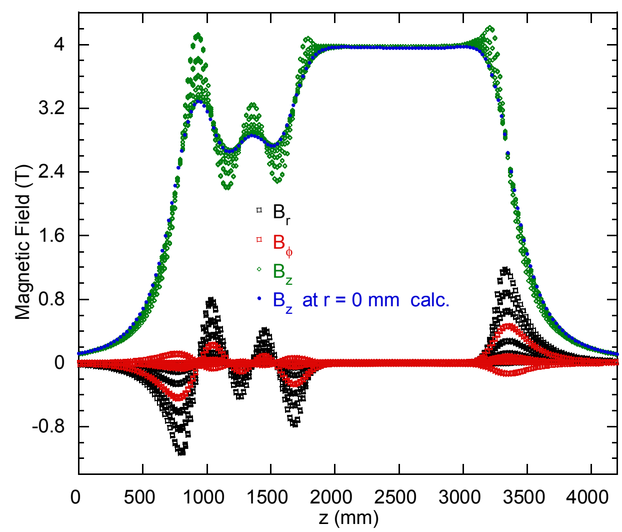

Figure 5: Measured field components for all probes, and a numerical calculation of the longitudinal field on magnetic axis using "as-built" coil parameters.

The typical measurement format was with 2 cm longitudinal steps and 20° disk rotation steps. There were additional faster measurement sets at currents adjusted to various percentage of a full current configuration to check linearity of field with current and study the hysteresis effect in the field (due to introduction of material in shielding plate). For these, the measurement format was with 5 cm longitudinal steps at only four disk rotation angles (0°, 40°, 180°, 220°). There were also additional studies to check for systematic uncertainties introduced by probes mounting on the disk (only 5 longitudinal positions, but with 5° disk rotation steps). We also measured coils powered at low current of 30 A: coils M1, M2, E1 and E2 individually, and coils E1-C-E2 together; the measurement format had varying longitudinal steps and 30° disk rotation steps.

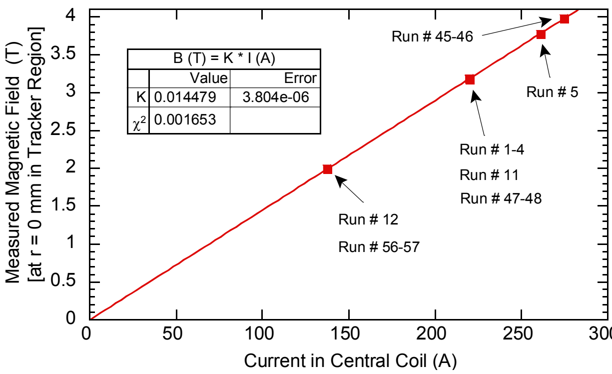

Figure 6: Magnetic field linearity study.

Figure 6 shows analysis of magnetic field linearity with current for a set of measurements without shielding plate, for "Solenoid Mode". There are several overlapping points at 80% current and 50% current, as indicated. The currents in coils were stable to ~0.05A (maximum variance) over ~2.5-hour measurement set, and set currents were reproducible to ~0.03A, as measured by the shunts installed to read coil currents directly [5]. The magnetic field is linear with current, with no indication of measurable offset at 0A.

Figure 7 shows zoom-in on the tracker region. Spread of the field measurements at each radial probe position comes from measurements at different disk rotation angles, and is due to shift of mapping device axis with respect to magnetic axis, as also indicated in Fig 8. An ~3% discrepancy between measurements and simulation was also observed in preliminary measurements [6], when we did not have a direct measurement of coil currents and precise survey of the mapping axis. These results together with the linearity

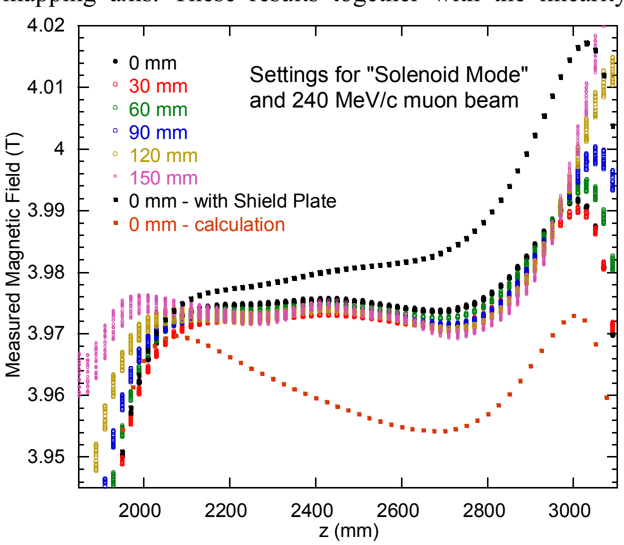

Figure 7: Longitudinal magnetic field component in the tracker region: measurements for 3D Hall probes at different radii for a case without shielding plate, measurements at 0 mm for a case with shielding plate, and a numerical calculation on axis (no shielding plate) using "as-built" coil parameters and measured coil currents.

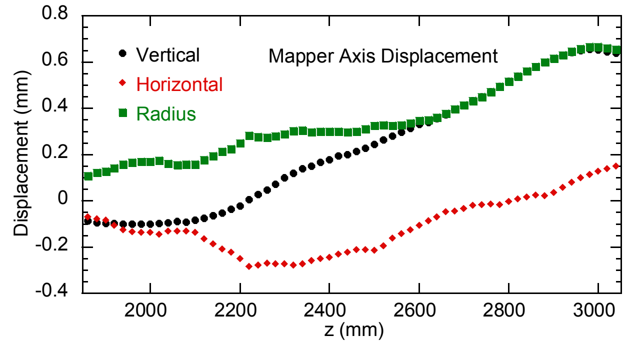

Figure 8: Survey of magnet measurement device axis (zoom-in on tracker region) in a coordinate system aligned to the cold mass axis.

studies indicate that this discrepancy does not come from control or measurement systems, but is due to the coils themselves. It is likely that the number of turns in coils E2, C, and possibly E1 are not as specified in [3], thus, the currents in the coils need to be adjusted to achieve the desired field configuration and uniformity.

The effect of shielding plate on magnetic field inside the solenoid agrees with the studies [7], indicating that reduction of current in the outer coil (E2) of ~2.5% is required to keep the desired magnetic field configuration. We plan to perform more field measurements around the shielding plate during the mapping of the MICE SS1.

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