Fabrication and Test of Model Superconducting Inflector for g-2 at FNAL

S. Krave, V.S. Kashikhin, T. Strauss

***Abstract*— The new FNAL g-2 experiment is based on the muon storage ring previously used at BNL. The 1.45 T dipole magnetic field in the storage ring is required to have very high (1 ppm) homogeneity. The muon beam injected into the ring must be transported through the magnet yoke and the main superconducting coil cryostat with minimal distortions. The old inflector magnet shielded the main dipole fringe field inside the muon transport beam pipe, with an outer NbTi superconducting screen, and did not disturb the field in the area of circulating beam. Nevertheless, this magnet had coils with closed ends in which a large fraction of muon beam particles were lost. A new magnet is envisioned utilizing the same cross section as the original with open ends for improved beam transport. A model magnet has been wound utilizing 3d printed parts to verify the magnetic behavior of the magnet at room temperature and validate winding of the complicated geometry required for the magnet ends. Room temperature magnetic measurements have been performed and confirm the magnetic design.**

***Index Terms*—Accelerator, Dipole Magnet, Septum, Superconducting Magnet.**

I. Introduction

THE new Muon g-2 experiment at FNAL is based on equipment used in the earlier experiment at BNL [1]. The experiment has been transferred to Fermilab and is being upgraded to provide more sensitivity than previous results. The main part of the experiment consists of a large 15 m diameter superferric storage ring, producing a 1.45 tesla field [2]. One of the most challenging parameters of this experiment is to maintain an extremely high field homogeneity, on the order of a few ppm in the circulating beam area. To correct for errors, special iron shims are used.

The muon beam is injected tangentially into the closed orbit, passing through the main yoke, and cryostat. As the beam path traverses the main magnet fringe field, it should be shielded in this region. To solve this problem, a unique superconducting inflector was proposed [3] [4] [5]. The inflector is a self-shielding truncated cosine theta magnet designed to have minimal impact to external fields. In operation, it produces a 1.45 T field, cancelling the main magnet field without disruption. In order to even further reduce the impact of operating the inflector, it has an additional multilayer NbTi superconducting magnetic shield, designed to trap the storage ring flux in an undisturbed state [6].

During the first stage of the experiment, it will run using the BNL supplied inflector. Rather large beam losses occurred in simulation because of the closed end design of the current model inflector. An open ended inflector has been proposed [7], and is in the prototype stage.

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II. Old Inflector

The original inflector was designed as a truncated cosine theta superconducting magnet at KEK [8], [9]. It was built using an aluminum stabilized NbTi conductor of cross section of 2 x 3 mm. Wire was wound in a channel on extruded aluminum mandrels. A view of the magnet cross section can be seen below in Fig. 1 with magnet parameters located in TABLE I.

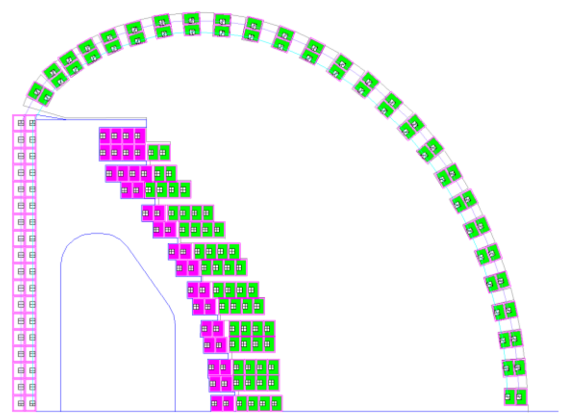

Fig. 1. Inflector Cross Section

TABLE I: OLD INFLECTOR MAGNET PARAMETERS

Parameter	Value
Dipole magnetic field in the beam pipe center (T)	1.45
Magnet effective length (mm)	1696.4
Coil length (mm)	1700
Total length (mm)	2045
Beam pipe width x height (mm)	18 x 56
NbTi superconducting screen width x height (mm)	103.2 x 154.6
NbTi superconducting screen length (mm)	1931
Coil current (A)	2850
Superconductor with Al stabilizer dimensions (mm)	2 x 3
Superconductor ratio (NbTi:Cu:Al)	1.0:0.9:3.7
Superconductor critical current at 3.5 T and 4.6 K (A)	3890
Inductance (mH)	2.0
Stored energy (kJ)	9.0
Overall cold mass dimensions (mm)	110x150x2025

In general, the original inflector performed very well and it will continue to be used in the first operation of the g-2 experiment at Fermilab.

III. New Inflector Evolution

A new inflector was proposed with open ends and a larger aperture to increase the muon flux to the experiment [7]. The initial proposal used a somewhat different cross section than the existing inflector which would in turn require the redesign of a number of related components and a significant amount of optimization. It was therefore decided to base the new inflector on the existing cross section, but utilize an open ended design.

A few long lengths of wire-in-channel NbTi were located in Fermilab TD inventory with insulated dimensions of 2.56 mm x 1.77 mm which were suitable for using the original mandrel if wound 2 conductors deep. This conveniently allows the use of a large number of the original inflector parts from the first inflector. During optimization of coil end geometry, a saddle coil type geometry was decided on, with the first coil layer going one way, with the second going the other. An image of the modeled first layer is shown in Fig. 2.

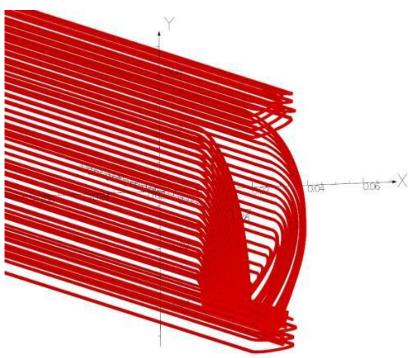

Fig. 2. First Layer End Geometry

This geometry allows the coil to be wound from one side to the other, with earlier turns defining later turns. Each layer started and finished with a small number of straight racetrack type coils to allow for tight packing.

IV. Model Inflector

A short model of the inflector has been wound based upon the open ended design and two layer inner and outer coils. The coil straight section and ends were 3d printed using ABS material on a Dimension 1200ES 3d printer. No additional ground insulation was necessary for the model as the plastic mandrels were non-conductive.

A. *Inner coil*

For the inner coil, a length of leftover wire-in-channel conductor was used. This conductor has cross section 2.56 mm x 1.77 mm including 135 µm braided polyester sleeve. The Cu/SC ratio of this particular conductor is 7:1 compared to the anticipated 5:1 that was expected to be used, but for this test, it provided a good analogue to the actual wire in channel conductor.

Winding took place on the 48 inch rotating table with tension provided by a calibrated tension system. The inner coil mandrel was fastened to the rotating mandrel support to allow for 2-axis control during manual winding (Fig. 3). Individual turns were clamped into place and held with cyanoacrylate glue (Fig. 4).

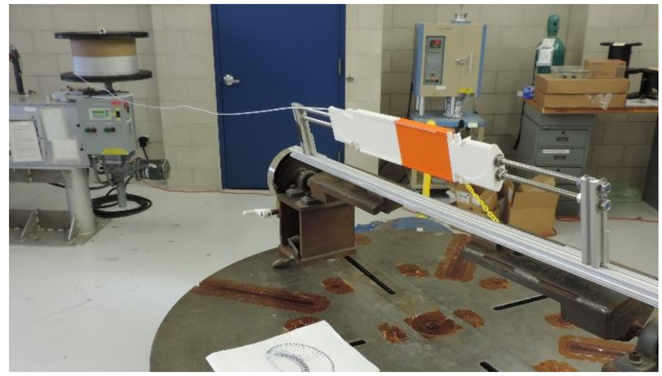

Fig. 3. Winding of Inner Coil

Fig. 4. Turn Placement on Inner Coil

Winding was completed from left to right, then right to left on top of the first layer of winding. During winding of the inner coil after each group of turns, it was examined for turn to turn shorts using a differential resistance technique. One short was detected and repaired where the polyester had frayed around a corner.

B. *Outer Coil*

After completion of the inner coil, an attempt to wind the outer coil was made using the same wire-in-channel conductor as above; however, the conductor was incredibly stiff and not well behaved. It was not possible to wind the outer coil with the plastic end parts as it was not strong enough to contain the-wire in-channel conductor with the tight bend radii (<3 mm) required. As a move to another conductor, as well as a more favorable end geometry were expected, the outer coil was wound using 16 AWG PVC insulated hookup wire. This wire choice allowed the possibility of making magnetic measurements, albeit at a significantly lower operating current. Using the PVC Wire, the outer coil was wound in a couple of days with no significant difficulty. It is shown below in Fig. 5.

Fig. 5. Outer Coil

With both coils completed, they were nested together and held in place using plastic brackets to allow for location adjustment of the inner coil relative to the outer. The completed magnet is shown in Fig. 6.

Fig. 6. Completed Model Magnet

V. Measurements

The completed model coil was measured at the Fermilab Magnet Test Facility [10]. It underwent a number of measurements, with particular focus on the septum as this region has the most significant effect on the circulating beam. The magnet transfer function was measured by inserting a hall probe down the bore of the magnet at currents up to 10 amps. The bore transfer function was found to be 10.3 G/Amp where the predicted value predicted was 10.65 G/Amp. The discrepancy can be attributed to a slight misalignment in the coils.

A hall probe scan was completed at a distance of ~4 mm from the septum. Two configurations were tested, the first where the inner coil ends are nested completely inside of the outer coil, and the second where the curved part of the inner coil extended beyond the outer coil. The test current was limited to 4 A to prevent magnet overheating.

The surface maps below are presented for the B_y component along X (Fig. 7). Measurement with no inner/outer coil shift are presented in Fig. 8.

Fig. 7. Coil Measurement Axis

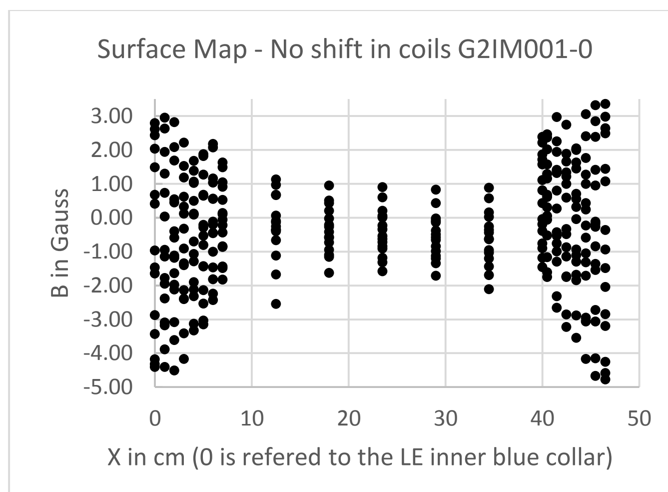

Fig. 8. Field Measurements with no coil shift

An additional set of hall scans was completed with the inner coil shifted relative to the outer coil as simulations had shown that some offset may help to reduce the flux present on the superconducting shield. Results of the hall scan for the shifted coil configuration are shown in Fig. 9.

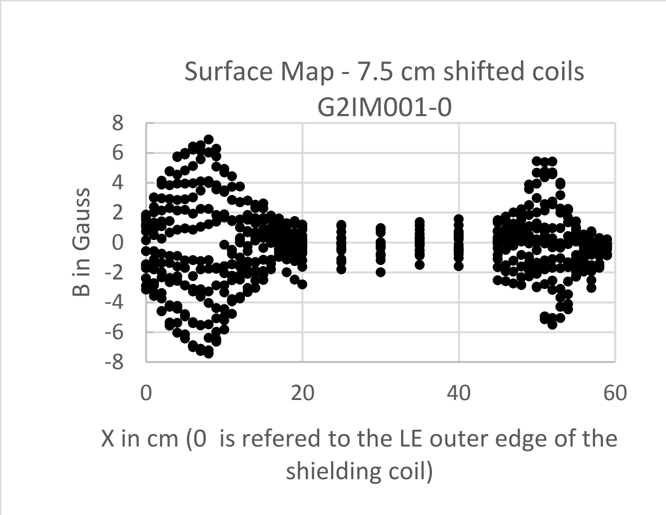

Fig. 9. Field Measurement with 75 mm coil shift

Overall the hall scan measurements agree well with the predicted results, though due to the low field strengths being measured, a great amount of noise was present in the measurements. The majority of the septum measured below 1.5 gauss at 4 A, or ~4% of bore field. When the inner coil remained nested inside of the outer coil, the peak fringe field transfer function was 1.0 G/A, or ~ 10% of the bore field. With a shift such that the inner coil extended 75 mm beyond the end of the outer coil, the peak fringe field transfer function was ~1.8 G/A.

An additional measurement of fringe field was made at the magnet surface around its circumference. While the septum area is most sensitive to leakage, the superconducting shield does surround the entire magnet and leakage needed to be verified. A plot of field along the outer surface of the magnet is shown below in Fig. 10. Zero indicates one edge of the septum, with points every 20 mm around to the other edge of the septum.

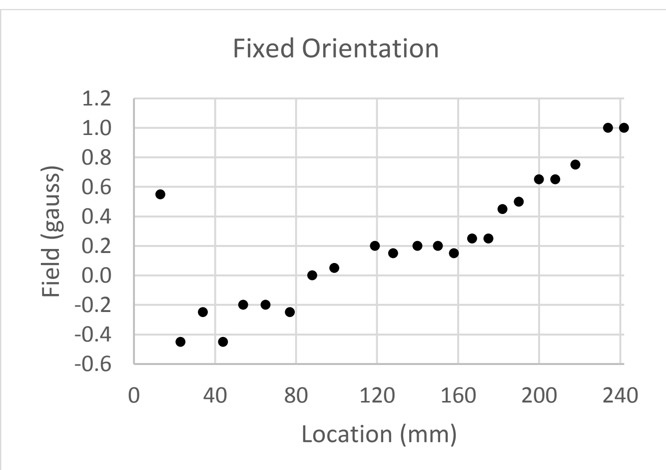

Fig. 10. Magnetic field around outer coil at 4 A applied current.

The field present outside of the outer coil is fairly low with a small step in field at the location of the misalignment of the inner to the outer coil.

VI. Path Forward

After fabrication of the first model, parts procurement began for longer lead-time items, including coil end parts and refined winding tooling. As the geometry of the coil end parts is rather complicated, they are to be fabricated out of an aluminum alloy, AlSi10Mg utilizing metal laser sintering [11]. A set of inner and outer coil end parts has been obtained for prototyping and can be seen below in Fig. 11.

Fig. 11. Laser Sintered Aluminum End Parts

The laser sintered parts allow for the required complicated geometries to be fabricated with good accuracy and fairly low cost. A geometry change has been made which will require a different version of parts, which will be fabricated in the same fashion. The first new inflector is to be wound using leftover original inflector conductor. The outer coil geometry will remain the same as the original, with the inner coil wound with conductor in channel. An image of the new planned end parts is shown below in Fig. 12.

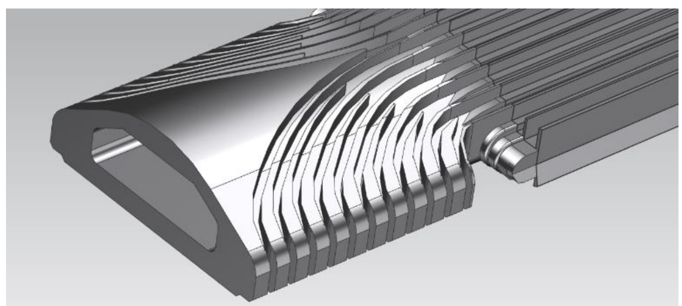

Fig. 12. Conductor in channel end parts for 2 x 3 mm conductor

Preparations for winding of the prototype inflector have begun and winding will start in the near future.

Acknowledgement

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