Conceptual Design of FNAL g-2 Superconducting Inflector Magnet

V. S. Kashikhin, N. Andreev, E. Barzi, S. Krave, H. Nguyen, C. Pooley, L. Roberts, D. Turrioni, A. Yamamoto, A. Zlobin

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 The new magnet is also self-shielded, but the magnet ends are open for beam transport, and it has a larger aperture for beam transport. All of these modifications are very critical for the success of the FNAL g-2 experiment. This paper describes the magnet conceptual design including the choice of superconductor, and the optimization of the coil geometry.**

***Index Terms*—Accelerator, inflector, magnet, muon, superconducting.**

I. Introduction

The new g-2 muon experiment at FNAL [1] is based on equipment used in the earlier experiment at BNL. It is being upgraded to provide greater sensitivity resulting in the ability to improve on previous results [2]. The main part of the experiment is the storage ring with the superconducting magnet. The unique 15m diameter superconducting coils generate a 1.45T magnetic field in the gap of a large circular iron dominated C-magnet. One of the main and most challenging parameters is an integrated field homogeneity in the circulating beam area which should be less than on the order of few ppm. Special iron shims and pole correction coils are used to improve the field homogeneity.

The muon beam is injected into the storage ring from the outer side about tangentially to the beam closed orbit, passing through a hole in the main magnet yoke, and the superconducting coil cryostat. Because the beam goes through the strong (1.45 T) main magnet fringe field, this area must be shielded from the field. For the previous experiment a very clever solution was found using a unique superconducting inflector magnet [3] – [6]. Several prototypes were built and the final magnet was based on NbTi aluminum stabilized superconductor. This magnet was designed as self-shielding, generating a 1.45 T field in the injected beam area to cancel the main magnet fringe field. During the first stage of experiment, the old magnet will be used. Rather large muon beam losses were found during simulations due to the superconducting coils ends crossing the beam aperture. The most recent simulations showed that about 50 % of muons might be lost. Another issue is the 18 mm width of the Inflector beam pipe which limits beam transmission through the magnet. The goal of this paper is to propose concepts for the improving the inflector magnet design and performance..

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V. S. Kashikhin#, N. Andreev, E. Barzi, S. Krave, H. Nguyen, C. Pooley, D. Turrioni, A. Zlobin are with the Fermi National Accelerator Laboratory, Batavia, IL 60510, USA (corresponding author# phone: 630-840-2899; fax: 630-840-6766; e-mail: kash@fnal.gov).

L. Roberts is with the Brookhaven National Laboratory…

A. Yamamoto is with KEK, Japan.

II. Old Inflector

Muon beam injection into the g-2 storage ring and storage ring operation strongly depends on the Inflector magnet performance. The old inflector was designed by the KEK team, fabricated by the TOKIN company, and will be in operation during the first phase of the experiment at FNAL. Nevertheless, it is very desirable to improve the performance of the new Inflector magnet. The new magnet should have both inner coil ends open for the muon beam, and an increase in the aperture of the transverse direction. It should be noted that it is very difficult to improve on the clever KEK magnet design which was based on the idea of a truncated double cosine theta dipole [3], a number of models, and cold tests [7]. The old magnet cold mass, and parameters with closed ends shown in Fig. 1, and Table 1.

Fig. 1. Inflector magnet cold mass.

A unique NbTi superconducting screen made by Nippon Steel, Japan [5] was used in the old magnet.. It is unclear at that time if such multilayer superconducting screen production technology exists. The space available for the magnet cold mass is very constrained, and cannot not be increased without major changes in the vacuum vessels, thermal shields, supports, etc...

TABLE I
OLD INFLECTOR MAGNET

Parameter	Units	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 bare 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

So, the following action items were chosen to proceed with the first step of new magnet design and fabrication:

- Disassembly of the old (repaired) Inflector magnet with the intention to use some of magnet parts;
- Measure part dimensions and produce a set of cold mass drawings;
- Make the magnetic design with open ends, and wider aperture;
- Fabricate and test the new magnet model.

At that time the magnet is fully disassembled and some magnet components are shown in Fig. 2. The 0.2 mm thick superconducting screen was glued to the surface of aluminum case. Fig. 3 shows the removed superconducting screen. One can see that the muon beam occupies a small area inside the inner coil sub-assembly, and crosses the layer of superconductors After disassembly, most of parts could be re-used for magnet model. The main goal for the model was to verify that the coil winding technology with open ends obtains reasonable end fringe fields.

The magnetic field of the Inflector with closed ends was simulated by OPERA3d code to investigate the magnet, superconductor, and superconducting shield main parameters. Good field quality in the beam pipe area, and less than 0.1 T fringe fields from the coils in the superconducting shield area were confirmed(See Fig. 4).

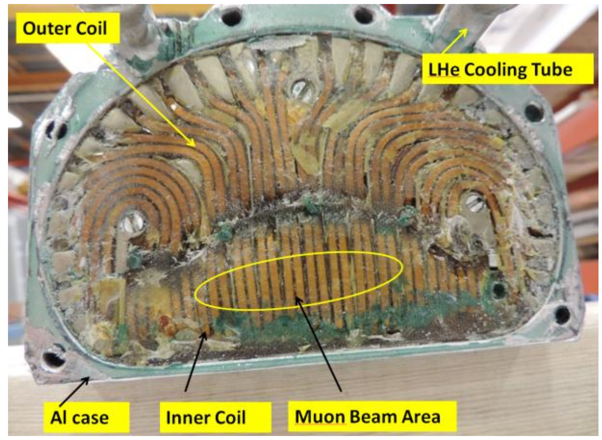

Fig. 2. Inflector magnet coil block before separation outer and inner coils.

Fig. 3. Two parts of superconducting screen after disassembly.

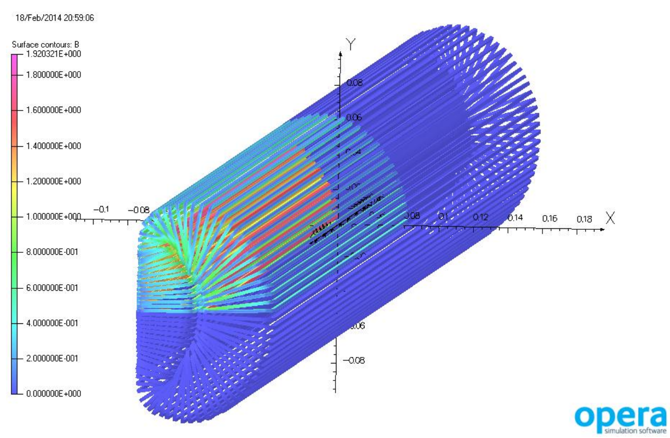

Fig. 4. The magnet coils geometry with closed ends. Coils superconductor peak field is 1.92 T without external field of 1.45 T.

III. NEW INFLECTOR CONCEPT

The first attempt for the new Inflector design with open ends explored the same magnet cross section as the magnet with closed ends (See Fig. 5). But the ‘bedstead’ configuration of inner coil ends substantially increased the peak field on the superconducting screen to 0.56 T. It confirmed the result obtained in [3] for the open ends configuration. The main reason for the larger field on the screen is the vertical bends of superconductor on both ends which generate the large normal field component in the screen area. The superconductor bends optimization is the most critical issue for the open end magnet approach.

The magnet inner turns geometry was optimized (See Fig. 5) to obtain a homogeneous magnetic field for the 10 mm wider aperture shown in Fig. 6.

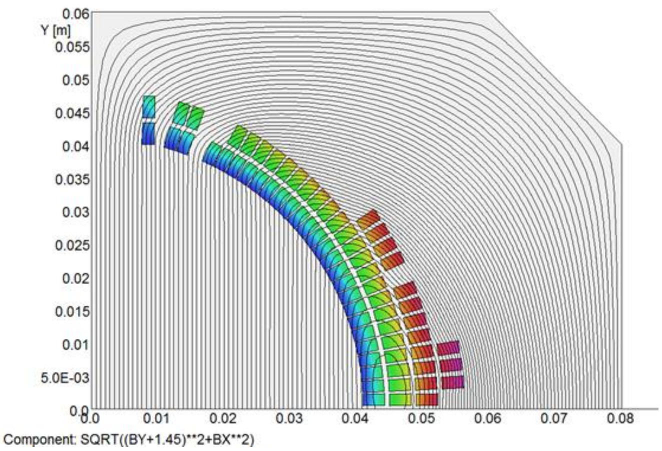

Fig. 5. Magnet model geometry, flux lines, and coil flux density. The coil peak flux density in the presence of main magnet field is 3. 97 T on the outer most turns.

The model assumed that the magnet was surrounded by an ideal superconducting screen. In reality, to reduce shielding currents in the screen, turns having an opposing direction of current to the inner turns should be placed along the screen inner surface.

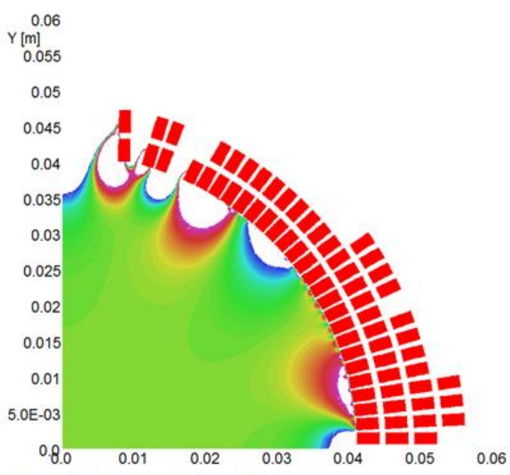

Fig. 6. Magnetic field with ± 1 % homogeneity area.

The 4 T superconductor peak field, in the presence of external 1.45 T field from the main magnet, is well above the 2.5 T field of the stand-alone magnet. The 4 T peak field drives the superconducting cable design to much higher values. Since only the outer coil will be in the high field area, two different cables for inner and outer coils will be used. It should be noted that further aperture width increase drives the superconductor peak field to 5 T.

Fig. 7 shows the 3D model geometry for magnetic field simulations, and the peak flux density on the superconductor combined with 1.45 T external field.

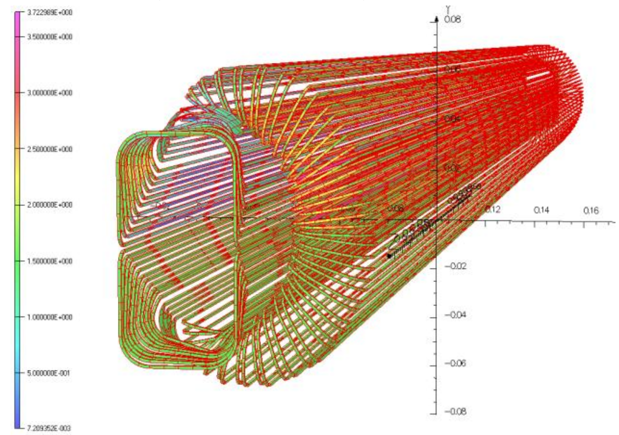

Fig. 7. Magnet geometry with open ends, and 10 mm increased aperture width.

The most critical parameter for the open ends magnet design is the normal field component, which in the magnet main part is less than 0.1 T. This value is acceptable for the superconducting screen. But at the magnet ends, this value is larger and further coil end optimization is needed. There are several options to resolve this issue: put the screen at several millimeters further from the coil, reconfigure the coils ends to compensate the normal to the screen field component, add to the magnet end field corrections coils.

The new Inflector cold mass will have the same external dimensions, and operating parameters close to shown in Table I.

IV. Superconductor Choice

The conductor of the original inflector had bare dimensions of 2 mm x 3 mm. In an optimized design for the new inflector, a Cu stabilized conductor has been developed aiming at a similar conductor size. The cable should work at higher fields but has about the same dimensions. The cable was made using FNAL's Technical Division Cabling Facility. This facility includes a compact cabling machine with 42 spools and electronic synchronization for lay angle control, a re-spooler, sets of forming fixtures, mandrels and measuring devices, and has been used to develop and fabricate (relatively) wide Rutherford-type cables for dipole and quadrupole accelerator magnets. To fabricate the small cables required by the new inflector design, the idea was developed of flat-rolling a composite round cable, or 6 around 1, made of seven 0.8 mm wires.

The next step was that of producing superconducting NbTi cable to measure the effect of plastic deformation on the strand superconducting properties. A 0.804 mm wire with Cu/SC Ratio of 1.34 from Oxford Superconducting Technology was used from TD inventory.

The critical current I_c of strands extracted from the cables above was tested at 4.2 K and up to 5 T. Some of the results are shown in Fig. 8, which displays the cross sections of cables Id1 and Id2. In these NbTi cables, the central strand suffered much less than the outer strands, which showed instead considerable I_c degradation and very low *n-values*, which is an indication of superconductor damage as well.

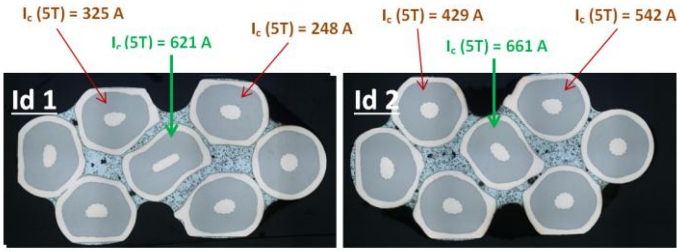

Fig. 8. Cross sections of NbTi cables made with seven 0.8 mm superconducting strands and showing I_c data at 5 T (Pictures by Marianne Bossert).

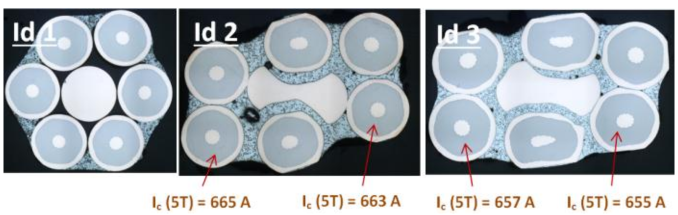

Fig. 9. Cross sections of NbTi cables made with six 0.8 mm superconducting wires around a central 0.8 mm Cu strand and showing I_c data at 5 T (Pictures by Marianne Bossert).

The critical current I_c of strands extracted from the cables above was tested at 4.2 K and up to 5 T. Some of the results are shown in Fig. 8 – Fig. 10, which also pictures the cross sections of various cables. In these NbTi cables, the central strand degraded much less than the outer strands, which displayed considerable I_c degradation and very low *n-values*, which is an indication of superconductor damage as well.

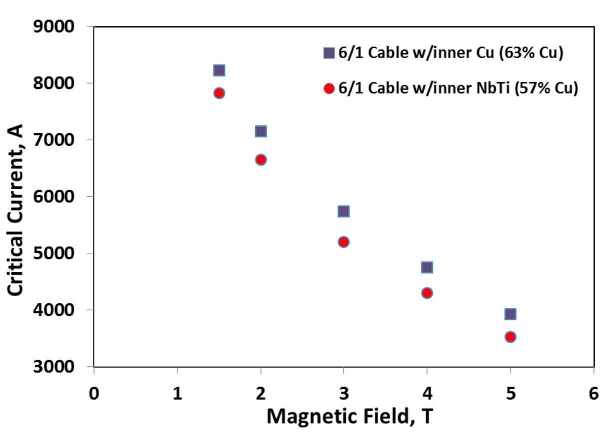

Fig. 10. I_c as a function of magnetic field B for the 6 around 1 cable made with only NbTi strands of 0.8 mm size and that made with a central 0.8 mm Cu wire.

The cable performance at the inflector operating temperature of 4.6 K is obtained by parameterizing and fitting the data acquired at 4.2 K. At 4.6 K and at the maximum field of 3.5 T seen by the inner coil of the magnet under design. The 6 around 1 cable made of six NbTi wires around a central Cu strand is expected to carry 4,800 A, which offers ~ 80% margin with respect to an operation current. A length of 60 m of such 1.8 mm x 3 mm cable was fabricated for magnet practice winding, and a length of round cable, which is sufficient to wind the whole magnet (~170 m) was also fabricated. This latter cable will be available to be used as-is if needed, or to be flat-rolled to size, according to the feedback produced by the practice magnet winding. Constraints associated with the winding technology will determine whether further cable R&D will be needed (for instance if cable twist were to be considered excessive for winding, solutions would have to be proposed).

To accommodate an inflector magnet design with a 10 mm larger aperture, which produces a larger maximum field of 4 T on the outer coil, a similar 6 around 1 study was carried out using 1 mm NbTi and Cu wires. The results on the effect of the central softer Cu wire were very similar (see Fig. 11) for all the produced cables, which again aimed at various thickness values. The superconducting properties of the NbTi peripheral strands were preserved with very good I_c retention with respect to the virgin wire. Based on the extracted strands I_c data, a cable of 2.3 mm x 3.85 mm is expected to carry 4,800 A at 5 T and 4.2 K. A sample of the latter cable was produced for magnet practice winding of the outer coil.

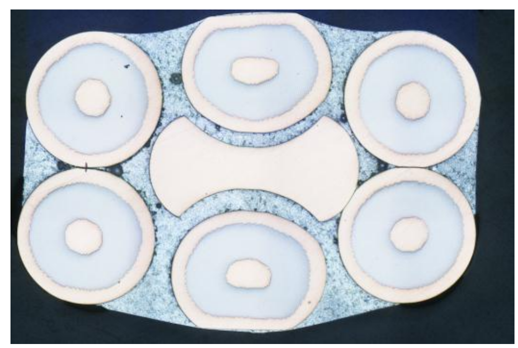

Fig. 11. Cross section of NbTi cable 2.3 mm thick made with six 1 mm superconducting wires around a central 1 mm Cu strand (Picture by Allen Rusy).

V. Conclusion

The Fermilab g-2 experiment will be more efficient by accommodating the new Inflector magnet with open ends, and increased aperture. Roughly a factor of two more muons should be transmitted through the new magnet. Both the old magnet design, and the concept for the new magnet have been discussed. The new magnet superconductor will operate at a higher field. Several NbTi cables with larger current carrying capacity were experimentally investigated. We have begun communications with industry for NbTi screen fabrication. The main conclusion is that it is possible to build the new Inflector magnet with substantially improved parameters.

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