Submitted to 1994 Applied Superconductivity Conference
Boston, MA - October 16-21, 1994

Conf-941013--17
BNL-60991

The Large Superconducting Solenoids for the g-2 Muon Storage Ring

G. Bunce, J. Cullen, G. Danby, J. Jackson, L. Jia, R. Meier
W. Morse, C. Pai, I. Polk, A. Prodell, R. Shutt, L. Snydstrup
Brookhaven National Laboratory, Upton, N.Y. 11973

M.A. Green
Lawrence Berkeley Laboratory, Berkeley, CA 94720

A. Yamamoto
National Laboratory for High Energy Physics, Tsukuba, Japan

***Abstract*--The g-2 muon storage ring at Brookhaven National Laboratory consists of four large superconducting solenoids. The two outer solenoids, which are 15.1 meters in diameter, share a common cryostat. The two inner solenoids, which are 13.4 meters in diameter, are in separate cryostats. The two 24 turn inner solenoids are operated at an opposite polarity from the two 24 turn outer solenoids. This generates a dipole field between the inner and outer solenoids. The flux between the solenoids is returned through a C shaped iron return yoke that also shapes the dipole field. The integrated field around the 14 meter diameter storage ring must be good to about 1 part in one million over the 90 mm dia. circular cross section where the muons are stored, averaged over the azimuth. When the four solenoids carry their 5300 A design current, the field in the 18 centimeter gap between the poles is 1.45 T. When the solenoid operates at its design current 5.5 MJ is stored between the poles. The solenoids were wound on site at Brookhaven National Laboratory. The cryostats were built around the solenoid windings which are indirectly cooled using two-phase helium.**

I. INTRODUCTION

An experiment is being built at Brookhaven National Laboratory[1] to measure the value of g-2 for the muon to an accuracy of 0.35 ppm, which is a factor of 20 better than the present experiment accuracy of 7.3 ppm measured at CERN[2]. The principle piece of equipment used in the experiment is a superferric storage ring. The storage ring is required to produce a dipole field which is homogeneous to 1 ppm and stable to 0.1 ppm. This report discusses the fabrication of superconducting coils and cryostats used in the construction of the storage ring.

A cross section of the storage ring is shown in Fig. 1. The iron yoke has a C shaped cross section with the opening of the C facing the center of the magnet ring. This allows decay electrons which spiral inward to be seen by detectors. The ring is comprised of twelve 30 degree steel sectors placed end to end each weighing 56,800 kg. At each of the twelve interfaces where the sectors come together, the sectors are supported on a common 76.0 mm thick steel plate bolted and grouted to the floor. Each sector is constructed using three plates. The middle spacer plate is sandwiched between the upper and lower yoke plates. The assembly is held together by 8 high strength steel bolts 44.5 mm in diameter and pretensioned to a load of 779 kN. When assembled on the support system and leveled, the lower yoke plates were coplanar within ±0.1 mm and the assembled gap between lower and upper yoke plates were uniform to ±0.2 mm. The final gap tolerance between the poles, when installed, will be ±0.05 mm.

Manuscript received October 16, 1994. This work was supported in part by the U.S. Dept. of Energy under Brookhaven National Laboratory contract number DE-AC02-76CH00016.

II. TOOLING

Several major pieces of tooling were developed to help in the manufacture of the coils and cryostats due to the critical dimensional requirements imposed by the required field uniformity and the need to manufacture very large circular components that fit to one another.

An accurate stable base was needed to perform the functions of assembly table, machining fixture, coil winder, and measurement jig. These properties were designed into one machine called the coil winding fixture shown in Fig. 2. The

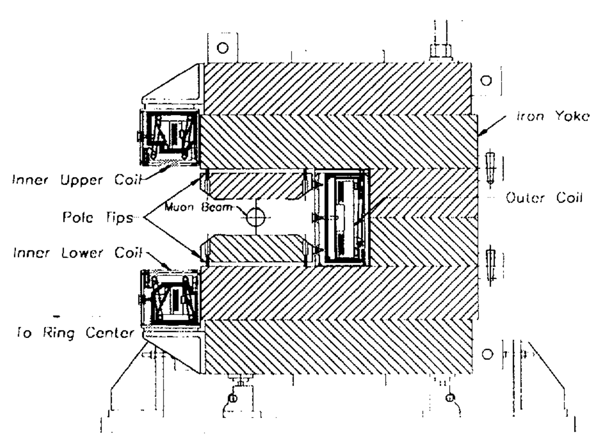

Fig. 1 A Cross-section View of Storage Ring

radial and vertical runout was 0.6 mm and 0.8 mm, respectively. After inspection the mandrel was secured on the support stands and the winding machine was reconfigured in preparation for winding.

D. Winding

The kapton/fiberglass ground plane band was installed on the i.d. of the mandrel with a 0.08 mm layer of sticky B-staged epoxy film on both faces of the insulation. The winding of 24 turns proceeded at a rate of about 0.75 m per minute. The length of conductor on the 2.75 m diameter supply spool was sufficient for one coil. There were no joints in the superconductor used in each coil. A wrapping mechanism in the coil winding machine applied the three layers of turn-to-turn insulation as it was being fed into the mandrel. The conductor was pushed into the mandrel i.d. under a compressive load of 625 N in order to form the conductor to the coil radius and to provide solid contact with the mandrel through the ground plane insulation. In order to prevent buckling of the soft conductor while under compressive loading it was guided along its length through the winding device and clamped down in the mandrel with 230 automatically actuated pneumatic air cylinders. Upon completion of winding 4.7 mm G-10 and epoxy prepreg layers were placed on the inside diameter and top of the conductor stack, and the 3 meter coil covers installed.

E. Cure

Preparation of the coil for epoxy cure involved placing a carefully sized G-10 shim on top of the coil to set the coil compression, then the aluminum coil covers were installed. The pre-cure size of the coil was about 3 mm larger in height than its finished dimension due to thickness of B-stage epoxy in the conductor insulation tape. To accommodate this coil covers were installed using spring loaded clamps. The mandrel was fitted with silicone rubber electric heaters, insulated , and heated to cure the coils. Cure temperature was 130±5C for 90 minutes. When the B-stage epoxy liquified, the spring clamps compressed the conductor stack until the coil covers came to final position against the coil mandrel.

As coil assemblies were completed they were removed from the building using the lifting rig and stored outside. Removal of the outer coil from the building with the lifting rig is shown in Fig. 3.

IV. Cryostat Assembly

A. Vacuum Vessel Construction

A cross section of the outer cryostat is shown in Fig. 4. The coil winding machine is used as an assembly and measurement fixture during construction of the vacuum box. Curved aluminum U sections were used to build up the vacuum box. To make these U sections a bottom plate was machined with the curvature of the tank and side plates were rolled to the tank radius. Next, the bottom and side plates were clamped to form the U section and welded and trimmed to length. Sixteen U sections make up the outer vacuum chamber.

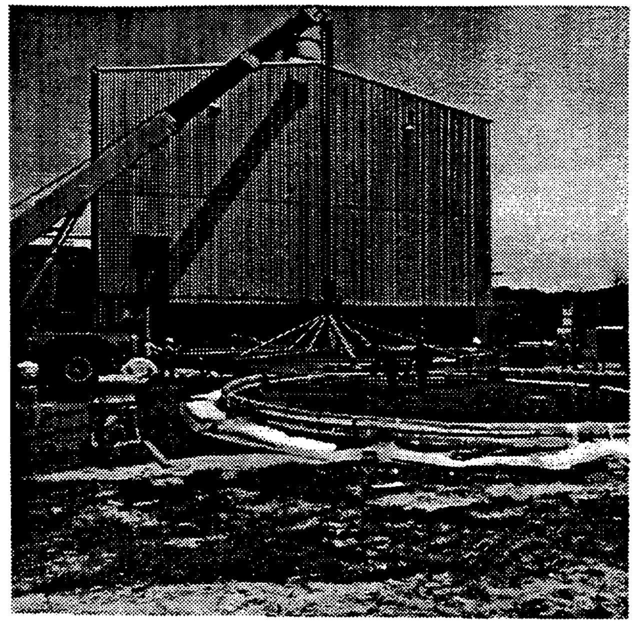

Fig. 3 Outer Coil is Removed From Building

Individual chambers were clamped onto the winding machine support stands and MIG welded with peening of the welds for stress relief.

B. Coil Assembly Preparation

In a parallel effort to the assembly of the vacuum vessel weldment the outer coil assembly was brought into the building, fixtured above the vacuum vessel, and prepared for insertion into the vacuum vessel. The coil leads and the intercoil connection between upper and lower coils were formed for mounting to the coil aluminum covers using G-10 mounting clamps. Helium cooling tubes were TIG welded directly to the leads. The intercoil connection was accomplished by lapping the conductors from the upper and lower coils for a length of 1 m and applying a TIG weld along one accessible edge of the conductor. Although this is a resistance joint it is directly cooled by an attached helium cooling tube over the entire length of weld. The effect of this TIG welding on the critical current of the superconductor was found to be negligible by testing.

The coil assembly is supported inside the vacuum vessel at 16 points around the ring using fiberglass straps which are not heat stationed. These straps are attached to the coil mandrel and vacuum vessel using a simple clevis and pin. Heat leak for one strap is calculated to be 0.14 W. The straps of the outer coil support the weight of the 3600 kg assembly since the opposing vertical magnetic forces of the coils are reacted in the mandrel. Inner coil assemblies use 48 pairs of straps due to high vertical magnetic load when powered. Both inner and outer coils are vertically adjustable.

DISCLAIMER

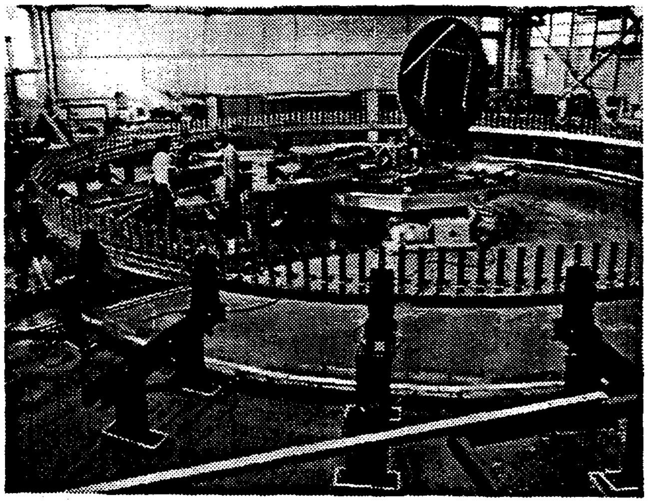

Fig. 2 Coil Winding Fixture

centerpiece of this fixture is a 4.88 m diameter motorized turntable having accurate bearings capable of repeatable circular rotation within 0.05 mm. Attached to this turntable is a platform which supports a milling machine, measuring equipment, or coil winding equipment as required for the operation at hand. The platform is supported at its end by machined wheels which bear on a precision ground track bolted to the floor and surveyed level. Support stands, 24 in all, with appropriate attachment hardware are placed in a circle around the outside of the floor plates for rigidly holding the coils or cryostats during machining, welding, and winding operations.

To assemble the coil mandrel weldments a strong, adjustable weld fixture was designed to hold 3.9 m long aluminum mandrel segments in perfect rigid alignment during the weld operations.

After assembly of coils a way to lift 14 m diameter coils and cryostats uniformly and with minimum shock was needed. To do this a lifting fixture consisting of a central hub having twelve 7 m radial arms was fabricated and is shown in Fig. 3. This allowed coils to be lifted gently.

III. Coil Construction

As can be seen from Fig. 1 there are three coil assemblies. The outer coil assembly supports two coils on one mandrel, while each of the inner assemblies consists of one coil. Construction of the outer coil assembly will be described in detail with significant differences in inner coil construction noted.

A. Conductor

Aluminum stabilized Niobium-Titanium superconductor was used to wind the coils. This is the same conductor used to wind the solenoid used in the Topaz detector for the Tristan storage ring at KEK[3]. Conductor properties are listed in Table I. The conductor was visually inspected for defects, measured, washed in inhibited detergent and dried prior to use in the winding operation.

TABLE I
Superconductor Properties

Superconductor	
Type	NbTi/Cu (Monolith)
Nominal dimensions	1.8 mm x 3.3 mm
NbTi/Cu ratio	1:1
Filament size	50 micron
Number of filaments	1400
Twist pitch	27 mm
RRR - Copper	120-140
Aluminum Stabilizer	
Type	Al extrusion
Purity	99.999% Al
Nominal dimensions	3.6 mm x 18 mm
(Al + Cu)/NbTi ratio	20:1
Location of superconductor	Centralized
RRR - Aluminum	2000-2500

B. Insulation System

1) Turn-to-turn: Three layers of kapton/fiberglass tape impregnated with B-staged epoxy 19.0 mm wide and 0.075 mm thick were helically wrapped with a gap spacing of 0.0-0.76 mm.

2) Ground plane: A 0.3 mm pre-cured band of three layers of epoxy bonded 0.05 mm kapton film sandwiched between two layers of fiberglass was used on the o.d. of the coil package. This thin construction served to minimize thermal resistance between the coil and mandrel. On the top, bottom, and i.d. of the coil package G-10 pieces provided electrical ground insulation.

C. Mandrel Construction

The mandrel shown in Fig. 1 is fabricated from 12 individual curved sections. Individual sections were rolled to shape, finish machined on the o.d. and bottom, and rough machined on the top and i.d. These sections were placed into a heavy weld fixture and joined using a combination of TIG and MIG welds for full penetration of the 50 mm thick mandrel. The weld was applied alternately to i.d. and o.d. with peening of the weld between passes to relieve stress and minimize distortion. At the completion of each weld the added section was inspected for correct radial, vertical, and azimuthal position upon release from the weld fixture. Radial variation could be adjusted by application of additional heat to the i.d. or o.d. Variation in azimuthal shrinkage was accommodated by installing spacer shims in the subsequent weld root.

The completely welded ring was allowed to come to its equilibrium position and then clamped in place on the support stands prior to insitu finish machining of the inner coil mounting diameter. The winding fixture was configured with a milling machine and the top and i.d. of the mandrel was brought to finished dimensions. After machining and releasing clamps the

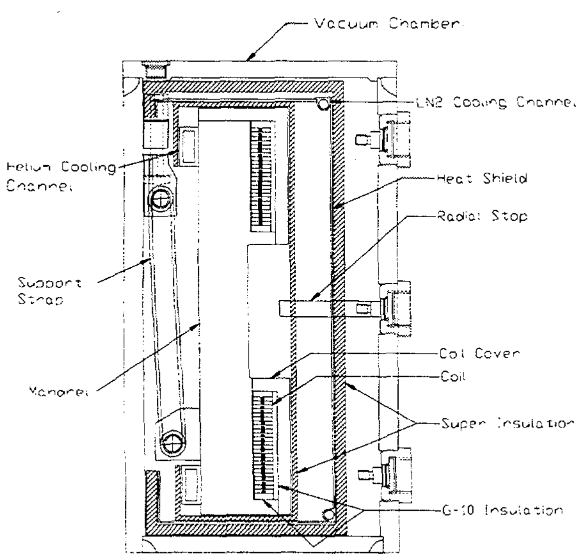

Fig. 4 Cross-section of Outer Cryostat Assembly

After application of superinsulation the heat shield was assembled around the coil. The LN2 cooled aluminum shield consists of two cooling tubes to which 0.75 m long right angle sections of sheet are attached forming a box structure. It is hung on the top of, and insulated from, the coil by 6.4 mm thick honeycomb pads and attached using G-10 insulated screws.

Prior to insertion into the vacuum chamber superinsulation was placed around the heat shield. During coil preparation voltage taps and temperature sensing silicon diodes were applied at pre-planned locations.

C. Cryostat Closure

Once the vacuum chamber was assembled and the coil preparation was completed the coil assembly was lowered into the vacuum chamber using threaded rods. The fiberglass support straps were attached to the vacuum chamber. The vacuum chamber top which consisted of 16 plates was welded into position using a TIG root pass and MIG filler passes.This welding of the outer cryostat alone consisted of 4 passes of 200 m of weld, accomplished by an automatic welding machine mounted on the rotating coil winding machine. The assembly was pumped down, vacuum leak checked, then moved out of the building to await magnet assembly.

IV. Coil Cooling

Cooling of the superconductors is accomplished indirectly via thermal conduction. The heat path consists of the following: from the helium, through the helium tube walls, weld joints of the tube, the mandrel, ground plane insulation, conductor insulation to the conductor. Two LHe cooling tubes (one tube for inner coils) are welded on the mandrel o.d. The coolant path starts at a point on the lower portion of the mandrel, travels clockwise around the mandrel, moves vertically to the upper portion of the mandrel, then returns counter clockwise to the starting azimuth on the mandrel. On inner coils the fluid enters, loops around once and exits.

The three g-2 solenoids and the superconducting leads between solenoids will be cooled by two phase helium which comes from a refrigerator bought by Brookhaven National Laboratory during the mid 1970's. The refrigerator has two piston expanders and receives its high pressure helium gas from a pair of screw compressors. The refrigerator cold box is capable of producing 700 W with liquid nitrogen precooling in the upper stages of the machine. At full output, the three g-2 solenoids can be cooled from room temperature to 4.4 K in just under two days. The available cooling from the g-2 refrigerator far exceeds that to keep the magnets cold and supply gas to a pair of 5300 A gas cooled leads for the solenoids and a pair of 2850 A gas cooled leads for a superconducting inflector magnet which will also be cooled by the refrigerator.[4]

V. Conclusion

As of October, 1994 all three coil/cryostat assemblies have been constructed. The lower inner coil and outer coils have been installed in the magnet yoke. Construction of the refrigeration system is approximately 50% complete. First power-up of the magnet is scheduled for Spring, 1995.

VI. Acknowledgement

This work was supported by the g-2 group at the Brookhaven National Laboratory and the U.S. Department of Energy under Brookhaven National Laboratory contract number DE-AC02-76CH00016.

References

[1] E821 Collaboration, "Design report, BNL AGS E821, a new precision measurement of the muon (g-2) value at the level of 0.35 ppm", Brookhaven National Laboratory Report, April 1994.

[2] J. Bailey, et al,"Title unknown", Nullear Physics, B150, 1979.

[3] M. Ikeda, S. Meguro, I. Inoue, and A. Yamamoto, "Aluminum stabilized superconductor for the topaz twin solenoid", Proc. of ICEC-11, Berlin-West, 676, 1986.

[4] M. Green, et al, "The g-2 superconducting magnet system", 13th Inter. Conference on Magnet Technology, Victoria, B.C., Sept 1993.