

## Progress Report on the g-2 Storage Ring Magnet System\*

G. Bunce<sup>a</sup>, J. Cullen<sup>a</sup>, G. Danby<sup>a</sup>, M. A. Green<sup>b</sup>, J. Jackson<sup>a</sup>,  
L. Jia<sup>a</sup>, F. Krienen<sup>c</sup>, R. Meier<sup>a</sup>, W. Meng<sup>a</sup>, W. Morse<sup>a</sup>, C. Pai<sup>a</sup>, I. Polka<sup>a</sup>,  
A. Prodella<sup>a</sup>, R. Shutt<sup>a</sup>, L. Snyderup<sup>a</sup>, and A. Yamamoto<sup>d</sup>

a. Brookhaven National Laboratory, Upton NY 10973, USA,

b. Lawrence Berkeley Laboratory, Berkeley CA 94720, USA

c. Boston University, Boston MA 02215, USA

d. KEK Laboratory, Japan

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## A Progress Report on the g-2 Storage Ring Magnet System\*

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C. Pai<sup>a</sup>, I. Polk<sup>a</sup>, A. Prodell<sup>a</sup>, R. Shutt<sup>a</sup>, L. Snodstrup<sup>a</sup>, and A. Yamamoto<sup>d</sup>

a. Brookhaven National Laboratory, Upton NY 10973, USA,

b. Lawrence Berkeley Laboratory, Berkeley CA 94720, USA

c. Boston University, Boston MA 02215, USA

d. KEK Laboratory, Japan

**Abstract**--The 3.1 GeV muon storage ring for the g-2 experiment at Brookhaven National Laboratory has three large solenoid magnets that form a continuous 1.451 tesla storage ring dipole with an average beam bend radius of 7.1 meters. In addition to the three storage ring solenoids, there is an inflector dipole with nested dipole coils that create very little stray magnetic field. A superconducting shield on the inflector gets rid of most of the remaining stray flux. This paper reports on the progress made on the storage ring solenoid magnet system and the inflector as of June 1995. The results of cryogenic system tests are briefly reported.

### I. BACKGROUND

An experiment to measure the value of g-2 for the muon is under construction at the Brookhaven National Laboratory in Upton New York, USA[1,2]. The g-2 experiment magnet system consists of three large superconducting solenoid magnets that form a storage ring, a superconducting inflector magnet for injecting the muon beam into the storage ring, and a string of conventional bending and quadrupole magnets that are used to carry a decaying pion beam from a fixed target at the Brookhaven 33 GeV Alternating Gradient Synchrotron (AGS) to the storage ring that is located in a building some distance from the AGS.

The focus of this report is the storage ring with its three large superconducting solenoids and the superconducting inflector dipole. There are two 24 turn inner solenoids that have a coil diameter of 13.4 meters and a single 48 turn outer solenoid that has a coil diameter of 15.1 meters. The three solenoids are the largest diameter superconducting solenoids that have been built to date. The current in the two inner solenoids will be run in opposition to the current in the outer solenoid creating the storage ring dipole field. An iron return yoke in the shape of a C returns the magnetic flux. Separate iron pole pieces control the quality of the 1.451 tesla induction in the gap. The integrated induction around the storage ring must be good to 1 ppm within a 90 mm diameter region that contains the muon beam[3].

The open part of the C points inward so the electrons that result from the decay of the muons (muons at rest have a decay half life of about 60 microseconds) will spiral inward to the detectors for the experiment. The beam enters the storage ring from the outside through a hole in the outer solenoid between the two 24 turn coils that are mounted on the outer solenoid cold mandrel. An artists conception of the storage ring and g-2 experiment detectors system is shown in Figure 1

At the ring entrance, a superconducting DC inflector will locally cancel the field of the main storage ring magnet so that the muon beam enters, as closely as possible, tangentially to the equilibrium orbit of the storage ring. The inflector magnet is designed to "eat" its own flux so that stray field from the inflector is greatly reduced. In addition the inflector has a superconducting shield so that virtually all of the remaining stray field from the inflector is eliminated.

### II. PROGRESS ON THE g-2 SOLENOID MAGNETS

Construction of the g-2 solenoids and their cryostats is complete[4]. The outer solenoid has been mounted on the lower part of the iron yoke. The iron back leg of the C and the upper part of the iron yoke has been mounted around the outer solenoid cryogenic vacuum vessel. The two inner solenoids have been mounted on the iron yoke as shown in Figure 2. The basic parameters of the three solenoids mounted in the iron is given in Table 1.

TABLE I PARAMETERS OF THE g-2 SOLENOID MAGNETS IN THE IRON

Iron Height (mm)	1570.
Iron Width (mm)	1394
Iron Mass for the Ring (metric tons)	681.6
Nominal Beam Bend Radius (m)	7.112
Number of Solenoid Packages	3
Pole Width (mm)	560.0
Nominal Gap between the Poles (mm)	180.0
Dipole Central Induction (T)	1.451
Number of Turns	48
Coil Current* (A)	5300
Magnet Self Inductance (H)	0.39
Storage Dipole Stored Energy* (MJ)	5.50
Total Solenoid Cold Mass (metric tons)	-6.2

\* at the design central induction

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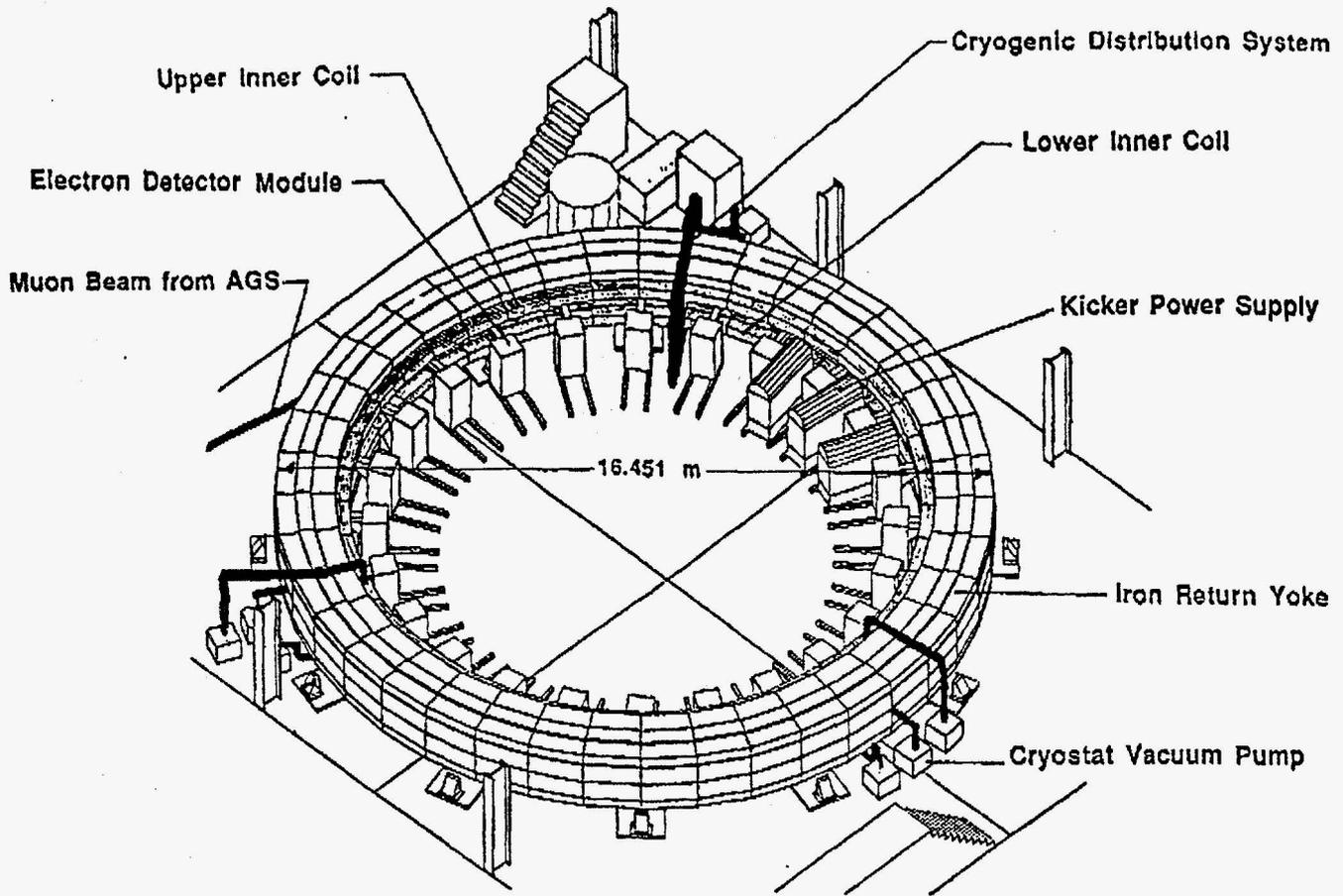


Fig. 1. An Artists Conception of the g-2 Experiment with the Detectors in Place

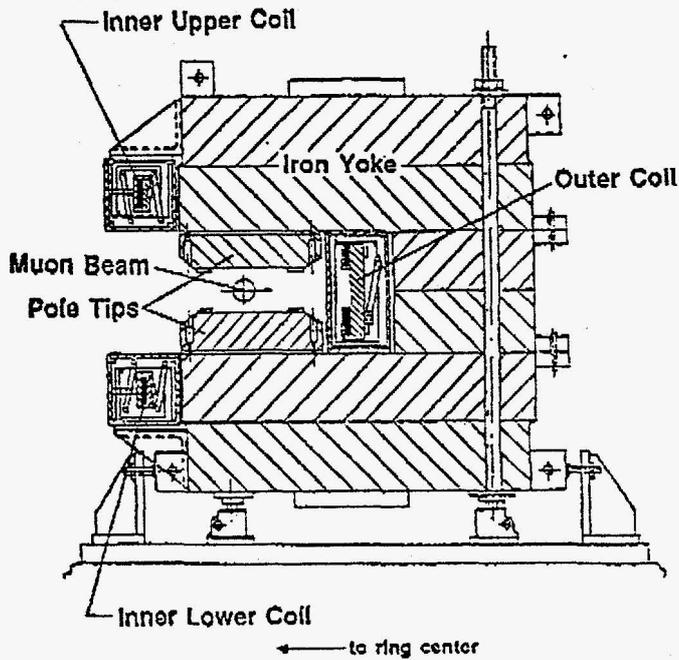


Fig. 2 A Cross-section View of the Storage Ring

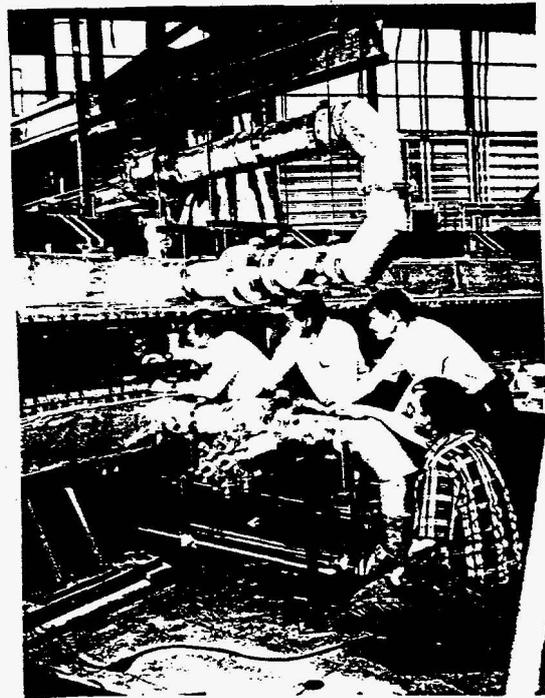


Fig. 3 The g-2 Storage Ring Dipole from the Inside

Fig 3 shows the assembled ring iron with the three solenoids mounted on the iron. The two inner solenoids are clearly visible in Fig. 3, and the pole pieces that shape the field have been installed. The outer coil cryostat is buried in the iron return yoke. The clearance between the iron poles and the outer solenoid cryostat is small (as small as 6 mm). This means that the outer coil cryostat vacuum vessel should not be too cold. In general, this is only a problem when the outer cryostat vacuum vessel is filled with helium at a pressure above 20 torr. The effect of cryostat vacuum vessel pressure on the temperature of the vacuum shell was measured during a cryogenic test of the outer solenoid.

A cryogenic test of the outer solenoid package was performed before the cryostat was buried. The outer coil was cooled from room temperature (294 K) to about 150 K using nitrogen gas mixed with liquid nitrogen boil off gas. At some point when the mandrel temperature was below 150 K, liquid nitrogen was used to cool the coil down to 80 K. It took about 115 hours to cool the outer coil package from 294 K to 80 K. The coil cool down from 80 K to the point where the outer coil became superconducting used liquid helium from dewars. It took 135 hours to cool the coil from 80 K until the magnet was superconducting.

The resistance of the coil dropped about a factor of 10 as the coil cooled from 294 K to 80 K. The coil resistance dropped another factor of 220 as the coil cooled from 80 K to 10 K. The RRR of the ultra pure aluminum matrix material has remained above 2000 despite the cold work induced in the conductor during winding. As the mandrel temperature dropped below 9.5 K, the coil became superconducting. The coil was fully superconducting when the average mandrel temperature reached 8.7 K.

The lowest temperature achieved in the outer coil was about 7 K. At that point, the liquid helium supply was exhausted. The measured heat leak into the outer solenoid mandrel was a little over 50 watts. This value is consistent with the heat leak calculations.

### III. PROGRESS ON THE INFLECTOR MAGNET

The inflector is a truncated dipole that is designed to cancel storage ring field so that the beam can enter the storage ring tangentially as closed as possible to the equilibrium orbit. The coil is a double cosine theta coil that minimizes the fringe field by cancellation of current distributions[5]. The field generated within the bore of the inflector is carried between the two coils. The cancellation of the fringe field is not complete, so a superconducting shield that remains superconducting within the storage ring field is used to cancel the rest of the fringe field generated by the inflector dipole. The g-2 inflector is 1.7 meters long. It operates at a current of 2850 A while in the field of the storage ring. The inflector stored energy at its full design current is about 9 kJ. A cross-section view of the inflector is shown in Fig 4

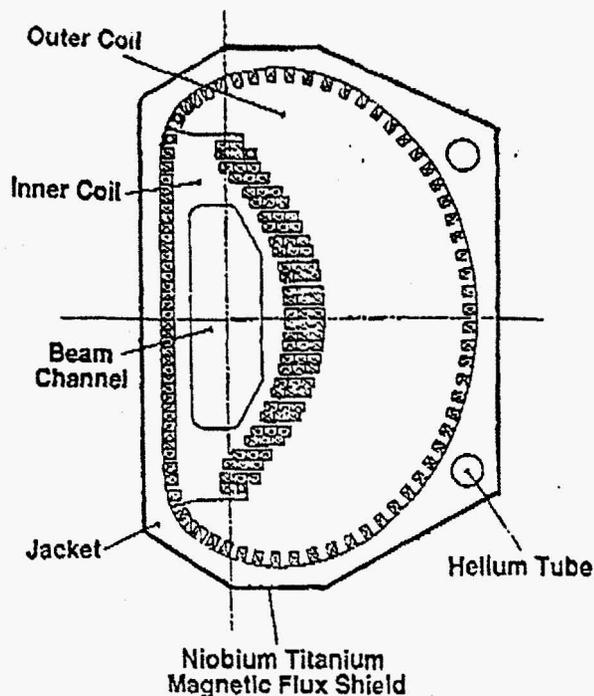


Fig. 4 A Cross-section of the g-2 Inflector Dipole

A one third length inflector was built at KEK in Japan using an aluminum based superconductor that was developed for a magnet used in a balloon astrophysics experiment. The g-2 inflector superconductor is also stabilized using very pure RRR = 750 aluminum. The one third scale model inflector was tested at KEK and Brookhaven with and without the superconducting shield. The test inflector operated at its design current in zero field and in a uniform background induction of 1.5 tesla.

The magnetic shield that consists of alternating layers of Nb-Ti, Nb and Cu successfully reduces the stray field that was generated by the inflector. If the proper cooling cycle is used on the inflector (The inflector is kept above 10 K while the storage magnet charges to its full design field. Then the inflector is cooled to 4.5 K.) the shields will keep the stray flux so low the integrated field error around the ring due to the inflector will be below one part in a million. Over the period of the inflector cold test, (over an hour), there was no recorded decay in the circulating currents in the shield.

The full length inflector winding, potting and assembly of the two coils was completed by KEK in Japan in March of 1995. The inflector shield, developed by Nippon Steel Corporation was installed on the coil package in the spring of 1995. Shipment of the fully assembled inflector magnet in its cryostat to Brookhaven is expected in the summer of 1995. The inflector will be installed in the ring during the fall of 1995. The inflector will be tested along with the rest of the magnet system in early 1996. Final shimming of the storage ring magnet, with the inflector in place, will occur in the first half of 1996. The position of the end of the inflector in the storage ring is shown in Fig 5.

## V. THE CONVENTIONAL MAGNET SYSTEM

The conventional magnet system for the g-2 experiment consists of a string of bending magnets and quadrupoles that direct a beam of pion from the AGS target to the storage ring. The string of dipole and quadrupole magnets was installed during the spring of 1995. The beam transport system will be operable before the first pion beam is transported to the storage ring in early 1996.

## VI. CONCLUSION

The superconducting solenoids are fabricated and in place in the g-2 storage ring. The outer solenoid has been successfully cooled to 7 K using liquid nitrogen and liquid helium. The measured heat leak into the outer solenoid mandrel is very close to that predicted by calculation.

The one third length superconducting inflector was successfully tested. The superconducting shield performed well. Virtually all of the stray magnetic flux generated by the inflector was contained within the shield. When complete, the full length inflector will be shipped to the Brookhaven National Laboratory in the summer of 1995.

The g-2 refrigerator was tested and found to be satisfactory for the experiment. The cryogenic system hookup for the solenoids and the inflector will be complete in June of 1995. A full cryogenic system test will be finished in the summer of 1995.

## VII. ACKNOWLEDGMENT

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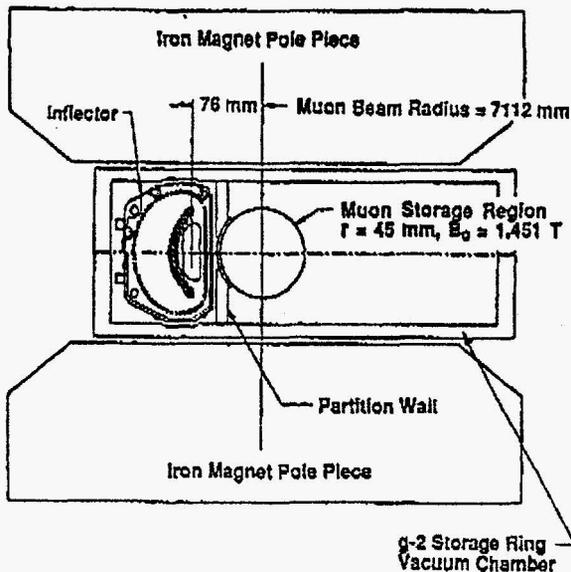


Fig 5. Inflector Cross-section in the Storage Ring (at the injection point)

## IV. CRYOGENIC SYSTEM TEST

The g-2 superconducting magnets will be cooled by a refrigerator built during the 1970s. This refrigerator was designed with a maximum capacity of 700 W when it is supplied with 120 grams per second of helium at a pressure of 1.8 MPa. The refrigerator was tested in 1994 using a single screw compressor that delivered 83 grams per second to the machine. The refrigeration and liquefaction were measured in a dewar located about 50 meters from the refrigerator. The refrigerator was connected to the load through a pair of unshielded transfer lines with bayonet joints about every 10 meters. The refrigerator delivered 450 watts of refrigeration to the load and it would liquefy over 4 grams per second of helium. The refrigerator performance appears to be more than satisfactory. With a pair of screw compressors that deliver 50 grams per second of helium at 1.6 to 1.8 MPa, the refrigerator should produce 625 watts (at the cold box). The expected heat load for the g-2 cryogenic system is from 350 to 420 watts depending on the safety margin used in the heat load calculations[6].

Construction and leak checking of the cryogenic distribution system used to cool the g-2 storage ring magnets and the inflector will be finished in June of 1995. A cryogenic test of the complete magnet system will be done during the summer of 1995. It is expected that the magnet system will be powered during the late summer of 1995. Magnet testing and shimming will occur in late 1995. The control system for the magnets and their refrigeration system will be installed in late 1995.

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