SUPERCONDUCTING 8 CM CORRECTOR MAGNETS FOR THE RELATIVISTIC HEAVY ION COLLIDER (RHIC)*

A. Morgillo, J. Escallier, G. Ganetis, A. Greene, A. Ghosh, A. Jain, E. Kelly, A. Marone, G. Morgan, J. Muratore, W. Sampson, P. Thompson, P.J. Wanderer, E. Willen
Brookhaven National Laboratory, Upton, New York 11973-5000

RHIC will require 420 80 mm Corrector magnets. The magnets are made up of coils wound on a computer controlled wiring machine using ultrasonic power to bond the wire into an epoxy coated flat substrate. The coils are wrapped onto support tubes and concentrically assembled inside an iron yoke. These magnets are being built at Brookhaven National Laboratory (BNL) with more than 280 constructed by May, 1 1995. Design, construction and test results are presented.

I. DESIGN

A total of 432 80 mm aperture correctors, including 12 spares, is being built for the accelerator. Each is composed of up to four separate multipole elements. This large number of elements was the dominant consideration in the basic design, resulting in the following criteria.

1. Design was to have a minimum number of interchangeable parts. A completed corrector was to be achieved by assembly of concentric cylinders each containing one multipole. With this approach it is possible to build correctors with differing multipole selections and different choices of skew and normal multipoles out of "stock" tubes.
2. Low cryogenic load. Since these magnets are individually powered, the heat load of the current leads is an important consideration. This was reduced by choosing 50A as the nominal operating current. The cost of the numerous power supplies is also dependent upon the choice of operating current.

The nominal magnetic length (0.5m) was determined by the space available in the lattice. The strengths came from computer simulations of the accelerator with some additional margin added. Since the design, the simulations have been refined, and roughly 25% of the main arc dipoles and quadrupoles have been constructed and measured. In most cases the original design strengths are more than adequate for the accelerator as now simulated. The necessary strength and the 50A nominal current determine the number of turns required. A design with a superconductor short sample current limit three times this nominal current was chosen, which then determines the wire size. The multipoles required are a_0 / b_0, a_1 / b_1, b_3, b_4. The multipole elements are assembled radially in inverse order of their multipolarity (i.e., b_4 inner most et. seq.).

*Work supported by the U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

A. *Detailed Design*

To control the deflections produced by the Lorentz forces, it was necessary to use thicker walled tubes to support the dipole & quadrupole windings (4.4mm and 3.5mm respectively). The other support tubes are at the minimum economic wall thickness (1.7mm). Because of the large number of turns (as many as 600 in the dipole windings) it was decided to bond the wires onto a flat substrate with a computer-controlled wiring machine. The maximum wire diameter for this technique is 0.33mm which limits the dipole quench margin to 150%; all other windings retain the desired 300% margin. To successfully wrap the winding pattern around the support tube, the OD of the latter must be machined to a precise diameter, with a tolerance of 0.16mm. Experimentation showed that it is possible to wind two layers of wires onto a substrate, the turns of the second layer nesting above the spaces in the first layer. The required field strengths are obtained by one such double layer for all multipoles except the dipole which requires three double layers. To secure the windings against the Lorentz force, a pretensioned Kevlar overwrap is used. An iron yoke is used both as a return path and a mechanical support for the cylinders. This is composed of low carbon steel laminations whose diameter is that of the main quadrupoles. In RHIC, all the 80mm magnets have the same outside dimensions, which simplifies construction, cryogenics and electrical buswork.

B. *Field Quality Design*

In principle, this winding technique can produce any wiring pattern and hence arbitrarily good field quality. In practice, patterns are limited to coils made up of straight sections and 90E arcs, with the further restriction that each pole consists of a single continuous block of turns with uniform spacing. With these constraints, the coils extend from the midplane to 2B/(3·2*m*) angle, where 2*m* is the multipolarity number (=2 for dipole). This cancels the first harmonic allowed by symmetry in the straight section. The number of turns and the radius of the curves on the end are adjusted slightly to achieve a field purity of better than 0.4% at the good aperture radius of 25mm. For the dipole windings, the second allowed harmonic does not fall off very rapidly with radius and it is necessary to adjust the three double coils to produce acceptable cancellation in the complete package. In production it has been found that the errors in wrapping the substrate around the tube, and the positioning of the tube within the magnet iron, contribute comparable field errors. Since the dipole correctors have a strength of 0.9% of the main dipoles, and the other correctors have less than 0.14%, a 1% field error in the correctors is less than 1×10^{-4} referenced to the main magnets. Thus 1% errors in the correctors are acceptable.

II. Construction Details

The coils are wound using a 0.33 mm diameter superconducting wire coated with 50% overlap of 25μ thick Kapton insulating film and coated with 12μ thick bondall coating. The wire is wound with a 0.15 mm spacing between wires onto a flat epoxy coated substrate consisting of 0.076 mm thick Kapton base with 0.20 mm thick of a b-staged epoxy filled with glass fibers. A second layer of wire is wound on top of the first nested between wires. The wire is bonded to the substrate or bondall coated first layer using an ultrasonic welding process on a computer-controlled wiring machine. A resonant stylus, with a tip formed to capture the insulated wire is excited at 25 KHz, transferring the ultrasonic power through the wire to the underlying substrate material, causing the wire to bond to the epoxy coated substrate. The wiring machine is computer-controlled in a closed loop allowing flexibility in the selection of the wiring pattern, the number of layers, the wire size, and the speed of the wiring. Five wiring machines are operated simultaneously by two operators. Each machine is connected to a common local area network. Production wiring files are electronically transferred from the magnet design group to the production group. Modifications or design changes to the wiring files can be converted into finished coils quickly.

The earlier coil design consisted of cornered ends with 45 degree angles [1]. These 45 degree bends proved to be a source of wire damage where the stylus would stop and rotate to the next path. This would cut the Kapton insulation and damage the copper coating of the wire with occasional damage to the superconducting strands. Bonding problems were also encountered in the earlier design between the first and second layers because the second layer wires were laid directly on top of the first layer wires. The design was revised to rounded ends and nested wires to alleviate these problems. Nomex coil supports are installed into a wound flat coil to act as a filler where the wires are not located thus making the thickness constant throughout the assembly. The coil assembly is bonded to stainless steel support tube with epoxy supported with fiberglass cloth. The quadrupole, octupole, and decapole tube assemblies are then coated with epoxy and butt wrapped with a single layer fiberglass cloth and a double layer of Kevlar yarn at 32 turns per inch at a tension of 22 lbs. The dipole tube assembly is coated with epoxy and butt wrapped fiberglass cloth and a single layer of Kevlar yarn. Second and third layers of dipole coils are placed onto the assembly in the same fashion. The assembly is coated with epoxy, fiberglass cloth and a double layer of Kevlar (see Fig. 1). The dipole coils are spliced in series as one assembly. The four different coil assemblies are assembled concentrically as shown in Fig. 2. The support tubes are supported by Ryton molded yoke keys inside the iron yoke.

The iron yoke is made up of punched 1.52 mm thick low carbon steel half laminations pinned together into yoke modules with the weight carefully controlled. The yoke modules are keyed and welded together at the 0E and 180E seams.

Table 1 lists the correctors completed to datae.

Table 1. Construction Status as of April 25, 1995

Corrector Type	Number Required	Number Produced to Date	Coil Configuration
CRB	100	79	b_0,b_1,b_3,b_4
CRC	136	67	a_0,a_1,b_3,b_4
CRD	78	66	b_0
CRE	78	50	a_0
CRF	40	19	b_0,a_1,b_3,b_4
Total	432	281	

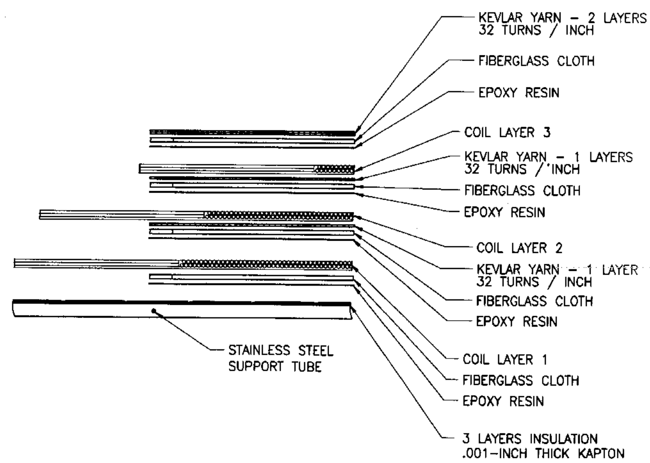

Fig. 1. Dipole concentric assembly section

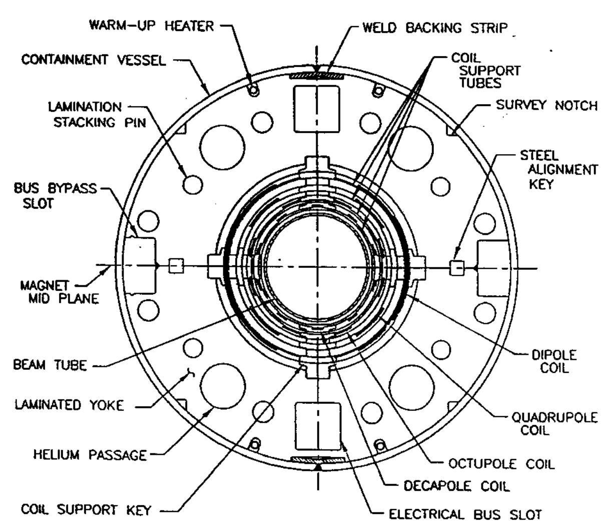

Fig. 2. Magnet cross section

III. HARMONICS TEST RESULTS

Warm measurements of field quality have been performed on all the corrector magnets built so far. The integral transfer function and other harmonic components at a reference radius, R_{ref}, of 25 mm are measured using a rotating coil of radius 35.6 mm (1.42 R_{ref}). These measurements are carried out at magnet current of 0.2A. The contribution from remnant fields is subtracted by making measurements at both positive and negative currents. The measuring coil is radially centered in the iron yoke using a well aligned fixture. The magnetic centers of the corrector layers (derived from feed down) are generally within 0.25 mm of the center of the iron yoke.

The results from the warm measurements in the correctors are summarized in Table 2. The integral transfer functions are expressed in T.m/kA at the reference radius of 25mm. The most dominant harmonic terms are typically below 1% of the fundamental field. These harmonic distortions are at an acceptable level for the accelerator.

The correctors are tested at liquid helium temperature for quench performance. Field quality measurements are also carried out on most of the correctors. There is good agreement between the warm and the cold measurements. The transfer functions increase slightly as a result of cool down, as indicated in Table 2.

Table 2. Corrector Field Quality

Layer Type	Transfer Function T.m/kA @25mm (Warm)	Std. Dev. In T.F.	Change in T.F. on Cool-down	Harmonics as fraction of the Fund. Field
b_0 / a_0	5.5514	0.11%	+1.0%	<0.3%
b_1	0.7630	0.07%	+0.7%	<0.5%
a_1	0.7569	0.07%	+0.7%	<0.5%
b_3	0.1920	0.45%	+0.8%	<1.5%
b_4	0.1495	0.30%	+1.2%	<1%

IV.QUENCH PERFORMANCE

As of April 18, 1995, 101 80 mm RHIC production correctors have been cold-tested. The design operating current for all corrector layers is 50A, and all have a conductor limit above 130A for all operating conditions at the RHIC temperature of 4.6K.

Because of the stress imposed on the thin superconducting wires during coil winding, it is considered necessary to cold-test all corrector coils as part of the acceptance process. Cold-testing is performed in vertical dewars filled with liquid helium at 4.4K (nom).

The minimum test procedure for any corrector is:

1. Ramp the dipole layer to +70A, then to -70A, and back to 0;
2. With the dipole at +70A, each of the other three layers is ramped to +100A, then -100A, then again to +100A, then back to 0.

If any layer quenches in the course of these ramp tests, the ramps for that layer are started over again and repeated until the three ramps can be performed without quench. Occasionally, magnets were subjected to more rigorous testing, with more bipolar ramps, one hour tests at maximum test current, and sometimes quench testing. The maximum test current of 100A for ramp tests was selected to provide 100% quench margin. This was reduced to 70A for the dipole layers to avoid quenches that might overheat the conductor wire. This was found necessary because of the high inductance of the dipole layers and the nature of the quench detection system being used.

The results are presented in Table 3 and are grouped according to layer type and performance category. For each type, the first column denotes 1) total layers tested, and the number of layers which 2) did not quench, 3) trained smoothly (monotonically), 4) trained erratically, 5) failed, and 6) had an initial quench below 50A but trained acceptably. A layer is rejected if its current limit is low due to conductor damage or if it does not train to the maximum test current.

As can be seen from the table, approximately half of the dipole layers (44%) and quadrupole layers (53%) did not quench at all during initial ramp testing, while 68% and 77% of octupole and decapoles, respectively, did not quench. All other layers except two dipoles and two quadrupoles trained satisfactorily, though a small number of them were slightly erratic.

Table 3. Quench Performance Results of RHIC Arc Corrector Layers (Multipole layer tested with dipoles @ +70A)

Performance	Dipole	Quad.	Octu.	Deca.
Total Tested	94	53	53	53
No quenches	41	28	36	41
Smooth training	46	19	12	6
Erratic training	5	4	5	6
Failed	2	2	0	0
I_{init} < 50A	10	0	2	1

V. Summary

The construction of corrector magnets required for RHIC is well underway. The design of these magnets is versatile and robust, allowing easy assembly into the many configurations required for the machine. Construction techniques have been adopted that ensure reproducible magnets while minimizing construction labor. Test results indicate that the magnets perform well beyond the level required for successful operation of the Collider.

V. REFERENCES

[1] G.H. Morgan, "Optimization of Multiwire Coil Ends Having 45 Degree Bends," Internal Report AD/RHIC-30, 1987; G.H. Morgan et al, "Geometry of an All-Multiwire RHIC Corrector, Magnet Division Note MDN-256-16 (RHIC-MD-68), 1988.