TEST RESULTS FROM THE COMPLETED PRODUCTION RUN OF SUPERCONDUCTING CORRECTOR MAGNETS FOR RHIC*

J. Muratore, A. Jain, G. Ganetis, A. Ghosh, A. Marone,
A. Morgillo, W. Sampson, P. Thompson, P. Wanderer
Brookhaven National Laboratory, Upton, New York 11973, USA

Abstract

The production run of all 432 superconducting 8 cm corrector magnets required for the Relativistic Heavy Ion Collider (RHIC) has been completed at Brookhaven National Laboratory (BNL). All have been tested at 4.35 K for quench performance and at room temperature for magnetic field quality. In addition, magnetic field measurements at 4.35 K have been done for a 20% sample of these. Summaries of the harmonic and quench test results are presented. A comparison of the quench performance for magnets made with different coil preload tensions is also shown.

1 INTRODUCTION

All 432 superconducting 8 cm aperture corrector magnets have been manufactured and tested at Brookhaven National Laboratory (BNL) for the Relativistic Heavy Ion Collider (RHIC), now under construction at BNL. These correctors will provide magnetic field corrections to random and systematic errors in the main dipole and quadrupole magnets and be used to help determine beam dynamics in the two superconducting collider rings. A previous paper[1] has described in detail the design and construction features of these magnets and presented test results available for the 65% of the magnets that had been tested up to that time. The present paper summarizes the final test results for quench performance and field quality for all the 8 cm correctors at the end of the successful production run, and compares the quench performance of correctors which were made with different coil prestress loads.

2 GENERAL MAGNET DESCRIPTION

For details of the design and construction features of RHIC 8 cm correctors, our previous paper[1] should be consulted. Only a brief description of these features will be presented here. Each corrector may include either one (a_0/b_0) or four (a_0/b_0, a_1/b_1, b_3, b_4) multipole elements, where a_n denotes a skew, and b_n a normal, multipole; and the subscript n = 0, 1, 3, 4 refers to dipole, quadrupole, octupole, and decapole symmetries, respectively. Each multipole element is constructed by winding 0.33 mm diameter multifilament Cu/NbTi (ratio 2.5:1) wire in flat winding patterns (one racetrack-shaped winding for each pole) on a kapton/epoxy/fiberglass substrate by a technique known as the Multiwire process, using a computer-controlled stylus. The wires are wound in double layers, with the top layer wires nested in between the wires of the bottom layer. The coil substrate is then wrapped around and epoxy-bonded to a cylindrical stainless steel support tube. Next, the mounted coil windings are wrapped with a single layer of epoxy/fiberglass cloth and a double layer of Kevlar yarn at a specified tension in order to provide mechanical clamping and minimize movement of the wires by Lorentz forces during magnet excitation. The dipole coil consists of three double layers of windings and the other multipole coils have one double layer.

The four completed coil-tube assemblies are mounted concentrically in order of decreasing multipolarity with the highest order harmonic (decapole) at the innermost, smallest diameter and the lowest order harmonic (dipole) at the outermost, largest diameter. This is shown in the magnet cross-section of Fig. 1. The two outermost tubes have thicker walls to withstand the stronger Lorentz forces of the higher field strengths of the dipole and quadrupole coils. In order to provide mechanical stability and a return path for the magnetic flux, the finished multiple tube assembly is surrounded by a laminated iron yoke with the same outer configuration and diameter as the other 8 cm magnets. Each corrector is then assembled with a main quadrupole and trim sextupole, or trim quadrupole, magnet in a combined assembly, where they share a common cold beam tube and outer helium-containment/support shell. These so-called CQS units are then installed in their own cryostats and subjected to various diagnostic tests before acceptance and delivery to the collider rings.

3 EXPERIMENTAL PROCEDURE

Because of the stresses imposed on the thin superconducting wires during the coil winding process, it was considered necessary, as part of the acceptance procedure, to cold-test all individual correctors before insertion into CQS assemblies. This would screen out any coils that may have sustained wire damage which could lower the maximum current limit. Cold-testing was performed by fitting the yoked coil assemblies with temporary support shells and hanging them in vertical dewars filled with liquid helium at 4.35 K (nom). The magnets and test system were instrumented to provide data for quench and electrical analysis. Among experimental parameters which were monitored during testing were dewar temperature and pressure, coil and lead voltages, power supply current and voltage, and quench detector signal data.

---

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

0-7803-4376-X/98/$10.00 © 1998 IEEE

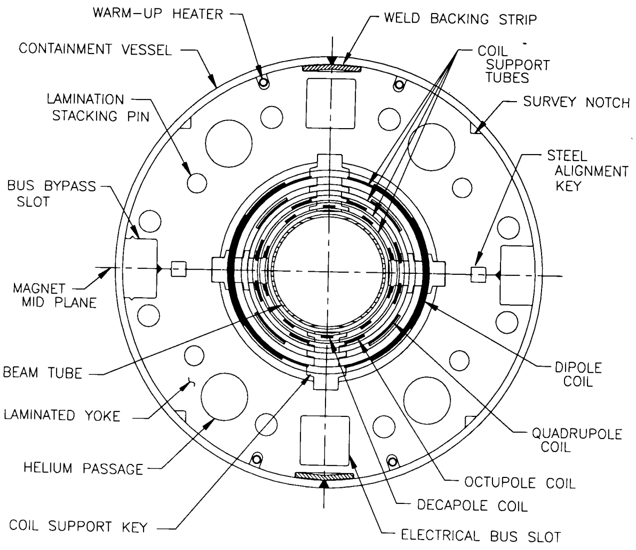

Figure 1: Cross-section of corrector magnet with four multipole coils.

All magnets were subjected to at least the following minimum test procedure:

1. Ramp the dipole coil to +70 A, then to -70 A, then back to 0; this is repeated at least two more times;
2. With the dipole at +70 A, each of the other three coils is ramped to +100 A, then -100 A, then back to +100 A, then back to 0.

If any coil quenched in the course of these ramp tests, the ramps for that coil were started over again and repeated until the above ramping scheme could be performed without a quench. In most cases, magnets were subjected to more rigorous testing, with more bipolar ramps, occasionally one hour tests at maximum test current, and sometimes ramps to quench. The maximum test current of 100 A for ramp tests was selected to provide 100% quench margin above the design corrector operating current of 50 A (nom). This was reduced to 70 A for the dipoles to avoid quenches that might overheat the conductor wire. This caution was necessary because of the high inductance of the dipole coils and the nature of the quench detection system being used. All corrector coils have a conductor limit above 130 A for all operating conditions at the RHIC temperature of 4.6 K.

4 QUENCH PERFORMANCE

It is convenient to discuss the test results grouped according to the four types of corrector coils regardless of the type of assembly. Also, in order to provide a uniform comparison among all the coils of each type, only performance during the initial test ramps, as described above in the minimum test procedure, will be shown. The initial tests were common to all magnets. Results from more extensive testing and quench tests will not be included here.

The results are presented in Table 1 and are grouped according to coil type and performance category. For each type, the first column denotes 1) total coils tested, and the number of coils which 2) did not quench, 3) trained smoothly (monotonically), 4) trained erratically, 5) failed due to wire damage, and 6) had an initial quench below 50A but trained acceptably. A coil was rejected if its current limit was low due to wire damage (Row 5) or if its quench behavior was judged to be too erratic.

Table 1: Quench Performance Results of RHIC Arc Corrector Coils (Multipoles tested with dipole at +70 A).

Performance	Dipole	Quadrupole	Octupole	Decapole
total	420	273	268	268
no quenches	288	207	197	226
smooth training	124	53	62	33
erratic training	6	11	9	9
failed	2	2	0	0
$I_{\rm init} < 50$ A	28	2	5	1

As can be seen from the table, 69% of the dipole coils and 76% of the quadrupole coils did not quench at all during initial ramp testing, while 74% and 84% of octupole and decapoles, respectively, did not quench. All other coils had one or more quenches but trained satisfactorily, except for two dipoles, four quadrupoles, and a decapole; each of these was removed from its corrector assembly and replaced by coils which tested satisfactorily.

The two dipoles and two of the quadrupoles which failed were conductor-limited at low currents, probably because of wire damage during winding. The other two rejected quadrupoles and decapole exhibited quench behavior judged too erratic. It should also be noted that one of the quadrupoles which quenched erratically was rejected on the basis of its performance in extended testing while one of the acceptable erratic decapoles was accepted because of extended testing results.

32 (2.6%) of the accepted coils exhibited some erratic quench behavior but were acceptable for collider operations. Also shown in the table are the numbers of each coil type where the first quench was below the RHIC maximum operating current of 50 A but trained acceptably afterwards. Of these 36 coils, 15 had initial quenches between 25 A and 40 A, while the others quenched above 40 A.

During the course of the production testing run, quench experiments by Ghosh[2] on single multipole coils without iron yokes showed that quench performance could be improved by increasing the pre-tension of the Kapton yarn wrapping from the initial design specification of 97 kPa to at least 152 kPa, which then became the new loading specification for all coils built afterwards. 61% of the 1229 coils in Table 1 were made with the higher pre-tension loading, and if the results are separated into two groups for low and high pretension, significantly improved performance when using the higher tension can be shown. Table 2 shows the percentage improvement in each category for each coil type.

Table 2: Comparison of Quench Performance Results of RHIC Arc Corrector Coils Assembled with Low and High Tension Kevlar (Multipoles tested with dipole at +70 A).

Performance	Dipole		Quadrupole		Octupole		Decapole	
	LO	HI	LO	HI	LO	HI	LO	HI
no quenches	45%	84%	56%	89%	67%	77%	77%	89%
smooth training	51%	16%	36%	9%	26%	21%	16%	10%
erratic training	3%	0.4%	7%	2%	7%	1%	7%	1%
$I_{\text{init}} < 50$ A	12%	3%	1%	1%	3%	1%	1%	0

5 FIELD QUALITY MEASUREMENTS

All the corrector magnets were measured warm to determine the integral transfer function, various normal and skew multipoles, and the offsets of the magnetic centers of individual layers relative to the mechanical center of the iron yoke. These measurements were carried out using a rotating coil of radius 35.6 mm whereas the reference radius used for calculating the multipoles in these magnets was chosen to be 25 mm. All warm measurements were carried out at a current of 0.2 A. The contribution from remnant field is significant at such low excitation and was subtracted by making measurements at both positive and negative currents. The measuring coil was radially centered in the iron yoke using a well-aligned fixture. The magnetic centers are derived from feed-down and are generally within 0.25 mm of the center of the iron yoke.

The results of the warm measurements are summarized in Table 3. The integral transfer functions are expressed in T.m/kA at a reference radius of 25 mm. The standard deviations in the transfer functions are partly due to the use of several different winding patterns in the early stages of production. The largest harmonic error terms are well below 1% of the main harmonic for the dipole and the quadrupole coils and are below 2% of the main harmonic for the octupole and the decapole coils. These error levels are quite acceptable for the accelerator.

Table 3: Corrector Field Quality.

Layer Type	Transfer Function T.m/kA @25 mm (Warm)	Std. Dev. in T.F.	Change in T.F. on Cool-down	Harmonics as Fraction of the Fund. Field
b_0/a_0	5.5549	0.16%	+1.0%	<0.3%
b_1	0.7627	0.18%	+0.7%	<0.6%
a_1	0.7570	0.09%	+0.7%	<0.6%
b_3	0.1920	0.53%	+0.9%	<2%
b_4	0.1494	0.48%	+1.2%	<2%

The correctors were tested at liquid helium temperature for quench performance. Most of these cold tests were performed in a 2-in-1 dewar to reduce the test time. Field quality measurements on cold correctors could not be performed in this dewar. However, roughly 20% of the correctors were cold-tested individually in other dewars where field quality measurements using a rotating coil could be made. There is good correlation between the warm and the cold measurements. The only significant effect is a change in the transfer function as a result of cool down, as given in Table 3. The standard deviation of the warm-cold difference in the integral transfer function is less than 0.1% of the transfer function for the dipole and quadrupole coils and is ∼0.3% for the octupole and decapole coils.

6 CONCLUSION

The results and experience of the testing of 432 superconducting corrector magnets, roughly 2/3 of which consisted of four multipole layers, have shown how such a large production test run may succeed within an allotted time and budget and, more importantly, accomplish the two main goals of 1) acceptance testing of the magnets for use in a working collider, and 2) provide a set of parameters which characterizes the behavior of each magnet for efficient operation in the collider. The use of higher pre-tension for improved quench performance, as described above, is a good example of how, even during a production test run of a large number of magnets, when basic R&D testing has finished, improvements to the design and/or assembly process may still be implemented when careful monitoring of data is carried out during testing. This experience was also seen in the production runs of other types of magnets for RHIC. From the quench performance results, it can also be seen that, in the case of these particular magnets, the decision to cold-test all correctors was important in screening out those magnets, though few, which did not meet the acceptance criteria due to damage during the delicate but efficient winding process used for these wire coil magnets. Other types of magnets, such as the main dipoles and quadrupoles, whose coils were wound with cable in a very different process, did not require 100% cold-testing for the acceptance process.

7 REFERENCES

[1] A. Morgillo, *et al.*, “Superconducting 8 cm Corrector Magnets for the Relativistic Heavy Ion Collider (RHIC)”, Proc. 1995 Part. Accel. Conf., p. 1393 (1995).

[2] A. Ghosh, private communication.