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The Characterization and Selection of Superconductor Wire and Cable for RHIC*

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ABSTRACT

This report describes the procedures used to select a single vendor for superconductor cable for the RHIC 80 mm dipole and quadrupole magnets, and some insertion dipoles with 110 mm aperture. Experience gained at BNL through involvement with the HERA and SSC Projects provided valuable learning experiences for this work. A performance specification was prepared and three qualified vendors were selected to complete a preproduction lot of 63,000 ft. of cable (approximately five multifilament billets). Samples were sent to BNL from every wire spool and from every continuous cable length. Mechanical, electrical and magnetization measurements were made to characterize the material. A data base was used to collect information, to compare BNL and vendor measurements and to study uniformity. Results are presented without specific identification of the vendors involved.

1. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) contains 1740 superconducting magnet elements, about one-third of which are arc dipoles and quadrupoles [1]. The operating field of the dipoles is 3.45 T. Thanks to improvements in the critical current density (J_c) of Nb-Ti in recent years [2], the plateau field of prototype dipoles is about 4.5 T. The coils are of single layer "cos θ" design, wound with keystoned Rutherford-type cable. The copper-to-superconductor ratio (C/S) and J_c are conservative: 2.25 and 2600 A/mm^2 (5 T, 4.2 K), respectively. Prototype dipoles exhibit little training: no quenches below operating current and a few below the quench current plateau. As R&D nears completion magnet production is being transferred to industry. However, procurement of conductors, i.e., superconducting wire and cable, will be done by BNL. The program which has been developed for this purpose is described in the following sections.

2. CONDUCTOR PROCUREMENT STRATEGY

The main emphasis of the program is on adherence to a uniform production method for the conductor rather than on peak performance. The goal is to have the magnet field behavior of all magnets in the RHIC accelerator be identical and, because of the effects of conductor magnetization and its possible time dependence, it is imperative that conductor be fabricated using materials with the same specifications, and that processes have the same steps, parameters and tolerances throughout. Therefore, the production phase of the procurement will be completed by one vendor with strict adherence to that vendor's process; no process changes will be permitted during the production phase. (Incidentally, similar procedures apply to magnet procurement – single companies will manufacture dipole, quadrupole and sextupole magnets.)

Conductor production for RHIC is modest by current standards. For the 80 mm dipoles and quadrupoles, it is about 50 tons (~ 140 billets), 30% of which is superconductor alloy. The total length of 30-strand cable is about 550 km (1.8×10^6 ft.). The entire production will be completed in about two years.

Vendor selection was based on a competition among three companies, each of which supplied wire and cable from about five billets (20 km each of cable). The products were judged by performance specifications. Manufacturing process details were not specified, but no changes were permitted during the competition.

While process changes were frozen during the competition, improvements based on experience gained will be introduced in the production phase. For example, methods for improving wire piece lengths were developed making it possible to specify no cold welds in production cables. Now that production has begun, however, no further process changes are allowed.

3. EVALUATION AND QUALITY CONTROL

In order to monitor adherence to technical specifications and product uniformity, a careful test and quality control program has been developed. A summary of the electrical specifications is given in Table I [3].

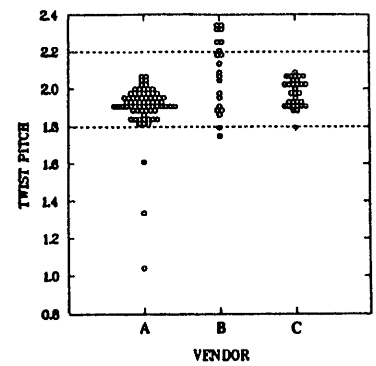

Figure 1: BNL-measured wire twist pitch (twists/inch) for the three vendors. Dashed lines show tolerance limites.

*This work is being done under the auspices of the U.S. Department of Energy.

Table I. Electrical Specification Requirements for RHIC Wire and Cable.

	Wire	Cable
Avg. $I_c(5T)$	> 264 A	> 7524 A
Range	< ± 10% Avg. I_c	< ± 6% Avg. I_c
$I_c(3T)/I_c(5T)$	< 1.6	– – –
R(295K)	< .0760 ohms/m	< .00266 ohms/m
RRR	> 38	> 38

Note: The cable consists of 30 strands of diameter .0255 ± .0001 inches (.648 ± .003 mm). The diameter and resistance specifications limit C/S to 2.25 ± 0.1. There are approximately 3500 filaments in each strand; nominal filament diameter is 6μm, minimum filament spacing is 1μm.

Instead of the more common C/S specification we advocate a resistance specification as indicated [4]. This test is simpler to perform, can be made on the identical sample used for critical current (I_c) determination, and provides a check on the wire diameter. The quantity $I_c(3T)/I_c(5T)$, or "3/5 ratio", is sensitive to the processing of the wire and serves as a control on it. It has been introduced also as an alternative to extensive low field magnetization testing. While the 3/5 ratio does not correlate exactly with low field magnetization, it does provide an adequate measure of control.

Mechanical specifications for wire are given in reference 3. Items covered are: nominal filament diameter and spacing, nominal copper-to-non-copper (or C/S) ratio, wire diameter, twist direction and pitch, sharp bend and springback tests, and surface condition. For cables items specified include: mid-thickness, width, keystone angle, lay direction and pitch, residual twist, a bend test, and surface condition.

During pre-production competition vendors were required to maintain QC records of the above items for samples from every wire spool. BNL performed comparison tests on 15% or more of the industrial samples. Cable dimensions were measured by the vendors continuously on-line by a Cable Measuring Machine (CMM) [5]. This was checked off-line by the 10-stack method [5], both by vendors and BNL. Other items were measured for samples from each end of every cable length. All cable electrical tests were performed at BNL, since they can be done conveniently only at our high current test facility.

A summary of the samples tested during the competition phase is given in Table II.

Table II. Summary of Vendor and BNL Wire and Cable Measurement Samples.

WIRE DATA

Vendor	Billets	Vendor Samples		BNL Samples		
		Mechanical	Electrical	Mechanical	Electrical	Magnetization
A	10	122	122	72	73	25
B	4	178	171	32	41	20
C	4	296	296	40	40	20

CABLE DATA

Vendor	Cables	Vendor Samples		BNL Samples		
		Mechanical	CMM	Mechanical	Electrical	Magnetization
A	18	16	15	18	30	20
B	8	6	8	15	15	14
C	12	6	9	17	17	17

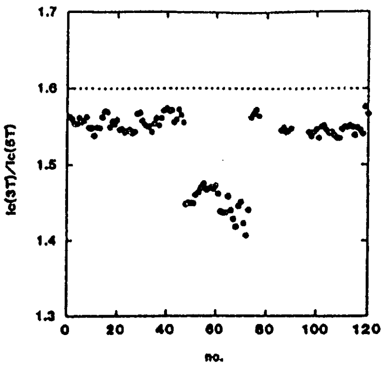

Figure 2a): Ratio of critical currents in RHIC wire at 3.0 and 5.0 T. The wire samples are from 10 billets produced alike.

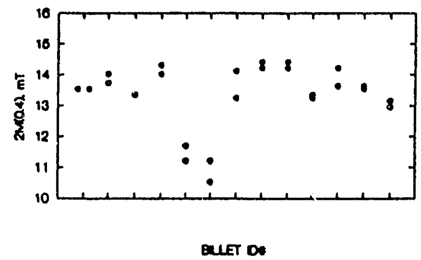

Figure 2b): Magnetization measurements at 0.4 T of a subset of the wire samples shown above. The different results are for the same billets with lower I_c ratio.

During production the manufacturer will be required to test wire samples from a minimum of four samples per billet or from 25% of all spools. If the average piece length is of order 2×10^4 ft. (6 km), the estimated number of wire samples to be tested by the vendor is about 700 for the entire 140 billet production. At BNL 30-50% of these will be tested as a control. Cable tests will be performed on one piece from every continuous length or minimum 15,000 ft. The estimated number of cable tests is 200-300.

4. RESULTS

At this time the vendor has been chosen [6] and full production is underway. In this section results obtained in the pre-production competition phase are given to illustrate each of the four QC types: mechanical and electrical of wire and cable. Test methods, procedures, and equipment used are carefully specified by BNL [3]. This has been done cooperatively with the manufacturers so that, in effect, a set of superconducting standards has been established.

Figure 1 shows a comparison of wire twist pitch measurements by BNL with vendors designated anonymously as A, B, and C. This property controls eddy current magnetization and is important because RHIC magnets are ramped at relatively fast rates (80 A/sec.); wire has been known to leave the manufacturer in an untwisted state [8]. Disparities between BNL and vendor measurements proved to be due to insufficient precision in the vendors' methods. The BNL technique has since been adopted by the vendors [9].

Figure 2. BNL measurements of the 3/5 ratio for wire supplied by one of the vendors are compared with low field magnetization. Magnetization measurements are not required, but are used by BNL to monitor superconductor and eddy current magnetization levels which reflect metallurgical processing and filament size, spacing, and twist. The 3/5 ratio is intended to serve as a production alternative to magnetization tests. In the illustration of Fig. 2 an unintended and undetected processing change produced the deviations in behavior shown. The correlation of measurements indicates that wire process control can be monitored by checking the ratio of critical currents at different fields.

Figure 3. CMM mid-thickness data obtained by one vendor are shown. The maximum, minimum, standard deviation, and mean values for all of the cable lengths produced are plotted. The mean thicknesses are well within the ± 6μm specified tolerance indicated by the dashed lines. Ten-stack measurements by the vendor and BNL are made to check the CMM results.

Figure 4. Cable critical currents are shown for one vendor. Dashed lines indicate the specification limit on the range, which is ± 6% of the mean value. Degradation is about 4% and is based on wire data which is not self-field corrected. True degradation is about 5% higher, or about 9% [10].

5. CONCLUSIONS

In recent years superconducting accelerator magnet production has evolved from laboratory to industrial fabrication. Properties of the conductor play a large role in the magnetic field behavior, and for this reason cable procurement for the RHIC Project has been kept under close BNL supervision. Cooperation between vendors and BNL during the pre-production phase of RHIC conductor procurement showed that this goal can be successfully achieved.

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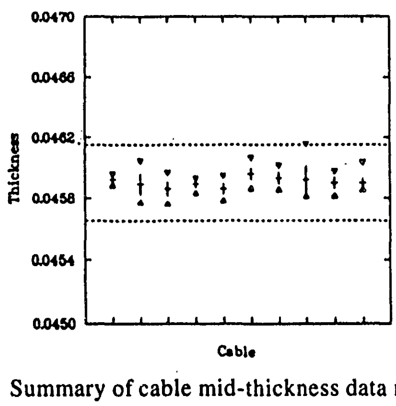

Figure 3: Summary of cable mid-thickness data measured by a CMM for several lengths produced by one vendor.

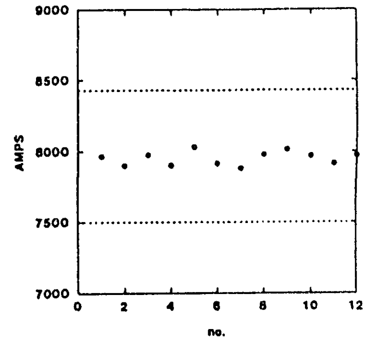

Figure 4: Cable critical currents at 5 T, 4.2 K for samples produced by one vendor.

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