To be presented at the Fifth Annual 1993 International Symposium on
Super Collicer (IISCC) in San Francisco, California May 6-8, 1993

BNL-48178

A PROGRESS REPORT ON THE PRODUCTION OF 1.8 MILLION FEET OF SUPERCONDUCTING CABLE FOR THE RELATIVISTIC HEAVY ION COLLIDER PROJECT AT BNL¹

S. DelRe, G. Epstein, S. Hong, J. Lichtenwalner
Oxford Superconducting Technology, Carteret, NJ 07008
P. O'Larey, D. Smathers
Teledyne Wah Chang Albany, Albany, OR 97321
M. Boivin, R. Meserve
New England Electric Wire Corp., Lisbon, NH 03585
M. Garber, A. Ghosh, A. Greene, D. McChesney, A. Morgillo, R. Shah
Brookhaven National Laboratory, Upton, NY 11973

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) Project under construction at BNL will enable collisions between beams of nuclei as heavy as ^{197}Au , accelerated in two quasi-circular rings to a maximum energy of 100 GeV/u.^[1] The bending and focusing of the beams is done by dipole and quadrupole magnets constructed primarily from 30-strand Rutherford-type cable. This is a progress report on the manufacture of superconductor which is a key technical component for the accelerator.

A conservative specification was placed on the superconducting properties. Requested minimum J_c is 2600 A/mm² at 5T, 4.2 K and the copper-to-non-copper ratio (C/S) is designed to be 2.25. In order to provide a degree of control of the low field magnetization of the superconducting material, the quantity $I_c(3T)/I_c(5T)$ or "3/5 ratio" is specified for the wire. Table I summarizes some parameter requirements. Specifications on other mechanical properties are given in reference [2].

The production contract for RHIC superconducting cable was awarded to Oxford Superconducting Technology (OST) in September 1991 with conductor fabrication beginning in January 1992. Approximately 112,000 pounds (51 tonnes) of superconductor will be required to produce 1.86 M feet (566 km) of 30-strand cable. Approximately eighteen (18) months have been scheduled for conductor manufacturing with an overlapping period for cabling resulting in a total contract duration of two (2) years.

PROGRAM OBJECTIVES

Superconductor produced by OST for the RHIC contract was planned and is being manufactured with four primary objectives: overall process uniformity, proactive quality assurance, schedule adherence and thorough cost control.

¹Work performed under Contract No. DE-AC02-76CH00016 with the U.S. Department of Energy.

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

Parameter	Wire	Cable
Filament diameter	6 μm ; quantity 3510	
Filament spacing	> 1 μm	
Wire diameter	(0.0255 $\pm$ 0.0001) inch	
Wire twist pitch	(1.9 $\pm$ 0.2) twists/inch	same after cabling
I_c (5T, 4.2 K)	> 264 A	> 7524 A
Range	< $\pm$ 10% Average I_c	< $\pm$ 6% Average I_c
I_c (3T)/ I_c (5T)	< 1.6	
R(295)K	< 765 $\mu\Omega/\text{cm}$	< 26.8 $\mu\Omega/\text{cm}$
RRR	> 38	> 38

The most critical raw material component which must be controlled to minimize variation in the final product is Nb-Ti alloy. Negotiations with Teledyne Wah Chang Albany (TWCA) resulted in a concentrated "RHIC-only" campaign for Nb-Ti alloy where strict material and process conformance to a mutually agreed specification was maintained. Approximately 18 tonnes of alloy were melted and fabricated for the program. Statistical Process Control (SPC) monitoring was rigorously applied as well as use of dedicated crucibles, furnaces and fabrication equipment. This procurement of alloy was a landmark in communication and exchange of information between TWCA and OST, and resulted in Nb-Ti alloy with exceptionally uniform properties for use in the RHIC contract.

The next critical element for overall conductor uniformity was for OST to control the fabrication process. This was accomplished by specifically defining the critical process variables in advance of manufacture, and by expanding the process definition to include applicable machinery, manufacturing standards, operator instructions, lot sizes and testing procedures.

With the exception of some testing procedures, no process method was mandated by BNL. OST discloses to BNL on a continual basis all details regarding fabrication and testing. This open style of communication helps to identify potential sources of process nonuniformity and to correct them without adverse impact to the program.

Process and procedure uniformity are also maintained at the cabling facility at New England Electric Wire (NEEW) in Lisbon, NH. Detailed manufacturing and quality plans were established and agreed upon between OST and NEEW prior to commencing cabling and are monitored and disclosed on a regular basis to BNL. An OST representative is in "permanent" residence at NEEW to liaise among the three parties and maintain OST's substantial inventory on-site at NEEW.

OST's approach to Q.A. is intrinsically linked to ensuring process uniformity as well as providing a cornerstone for a productionized superconducting wire manufacturing facility. Detailed definition of Q.A. procedures, audits, testing methods and report formats were established prior to commencing manufacture. Both in-process and final superconductor test results are openly reviewed on a periodic basis with BNL to ensure that specified processes achieve anticipated results.

OST is achieving the RHIC program schedules that were originally defined; these schedules are being reported to BNL on a regular basis. Schedule conformance is important in terms of maintaining a continuous flow of conductor to the cabling facility, efficient lot sizes and achieving contractual commitments.

OST accepted the RHIC contract on a fixed price basis; therefore, control and monitoring of cost are rigorously reviewed. The demonstrated success in terms of uniformity, overall quality, schedule and yield has resulted in a program that has met all measured cost criteria.

WIRE MANUFACTURING

Conductor produced under this contract has been standardized as a double extrusion, 4% barrier, high- J_c optimized fabrication process. RHIC conductor is actually very similar to SSC Outer Dipole conductor. First extrusion monofilament materials are identical to the SSC conductor and differ only in procurement specifications and the cut lengths of hexed monofilament rods. Second extrusion multifilament materials are fundamentally similar with necessary modifications for specified Cu center core size and C/S. Superconductor manufacturing steps for RHIC parallel very closely those of SSC outer conductor and are identical in terms of reaction heat treatments and fabrication equipment.

Piece length performance is important for monitoring process, yield and cost impact. Figure 1 represents actual piece length distribution for about 30 tonnes of superconductor completed. Average piece length is 10,127 meters (33,277 feet).

The distribution is significantly skewed towards longer piece lengths; pieces in excess of 5,000 meters must be cut for loading onto cable reels. Greater than 90% of all wire produced is in excess of 5,000 meters. Less than 0.3% of all conductor produced has been below the minimum length criteria of 670 meters. Because of this performance, the BNL requirement for no cold welds in cable was easily met.

Uniform wire diameter is necessary to enable production of uniform, mechanically stable cables; also, control of superconductor content, or C/S ratio, depends on keeping both the wire resistance and diameter constant.^[2] Wire diameters are measured and accurately controlled by OST on line during the final draw using laser micrometers with internal SPC software. Correlation of measurements between OST and BNL data is within about $\pm .00002$ inches. Figure 2 shows OST data for all of the wire spools produced to date. All wire is eddy current tested at final size to check for inclusions which could disrupt performance uniformity or cause wire breakage during cabling.

Figure 3 shows the distribution of critical currents for 486 wire samples. Measurements were made at BNL on half of the samples to check these results. Agreement with OST data is within 1.5%. The standard deviation is $\pm 2.3\%$, well within the specification requirement of $\pm 10\%$ of the running average. Small variation from a Gaussian distribution is caused by improved uniformity during production start-up and adjustments in wire cropping. The 3/5 ratio shown in Figure 4 has remained extremely uniform indicating no process variation.

The superconductor volume fraction is confirmed by monitoring R(295) and wire diameter. For specification purposes an upper limit is set upon R(295) so that the copper fraction may not get too low. The I_c specification ensures that copper fraction does not get too high. BNL and OST have worked to ensure agreement and accuracy of R(295) measurements to a level of about 0.3%. For 486 samples R(295) values have a standard deviation of 0.65% of the mean. Implied C/S variations are within 2.5% of the mean.

Figure 1. Wire piece length distribution.

Figure 2. Wire diameter for every sixth spool with $\pm 3\sigma$ bars, running average line and specified range.

Figure 3. Wire $I_c(5T, 4.2 K)$ distribution.

Figure 4. Wire "3/5 ratio" distribution.

CABLE FABRICATION

About 650,000 ft. of cable have been produced; the remainder will be completed within seven months. Coil pre-stress and ease of assembly are critically dependent on cable mid-thickness. Keystone angle and width are also important, but generally fall well within tolerances. Figure 5 shows mid-thickness data for cable produced so far at NEEW. The measured variation of mid-thickness along produced cables is about 50% of specified limits.

Critical current data for production cables are shown in Figure 6. The cable I_c average is 10% above the minimum critical current requirement and well within the allowed variation of $\pm 6\%$. The slight upward trend in Fig. 6 is due both to smoother operation of the cabling facility giving reduced degradation, and to a small increase in wire performance mentioned above. The standard deviation in I_c for all cables produced is about half of that seen in the wire, and can be attributed to selection of wire for use in cable. The degradation of recent cables is about 1%.

Figure 5. Cable mid-thickness with $\pm 3\sigma$ bars and specified range.

Figure 6. Cable $I_c(5T, 4.2 K)$ with lower limit and specified range.

SUMMARY

The RHIC production contract is in the final stages of strand manufacture at OST; cabling will be completed, on schedule, by December 1993. This contract has offered a unique opportunity to demonstrate that a significant quantity of SSC type superconductor can be manufactured with high uniformity, reliable schedules and effective cost control. OST would like to acknowledge the efforts of many individuals at BNL, TWCA, NEEW and other contributors and subcontractors who are helping to make this program a success.

REFERENCES

- [1] RHIC Conceptual Design; BNL publication 52195, May 1989.
- [2] RHIC Specification No. RHIC-MAG-M-4141.