Manufacture and Testing of the Superconducting Wire and Cable for the RHIC Dipoles and Quadrupoles

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Abstract Production of superconducting wire and cable for RHIC dipoles and quadrupoles is now complete. This report presents final statistics generated during the manufacture and testing of this cable.

Albany (TWCA), with care being taken that all material underwent identical processing in order to achieve consistent results.

I. INTRODUCTION

In September of 1991, Oxford Superconducting Technology (OST) was awarded the production contract to supply superconducting cable for dipoles and 8 cm quadrupoles for the Relativistic Heavy Ion Collider (RHIC) project at Brookhaven National Laboratory. Some 566 km of 30 strand Rutherford cable ["dipole cable" below] were required. In January of 1993 a second contract for interaction region "quadrupole cable", 69 km of a 36 strand cable, was also awarded to OST. Progress reports on the execution of the first contract have been published previously [1],[2]. These references contain descriptions of the controls put in place to insure the uniformity of the final product, and the rationale for the data set chosen. Dipole cable deliveries to BNL began in the fall of 1992, and were completed on schedule by the end of 1993. Quadrupole cable was all delivered between January and April of 1994. Completion of the contracts enables this report to provide final performance statistics on the largest production run of superconducting accelerator magnet cable ever made.

Table 1 lists the primary specification parameters for both conductors [3],[4]. Metric units are shown, although the actual specifications used English units. Consistency as well as level of performance was a primary objective. A single stack, double extrusion process was used to manufacture the strand for both conductors, with 12.5" billets utilized in the second extrusion. NbTi alloy (47% Ti by weight) was sourced from Teledyne Wah Chang

TABLE I
RHIC CONDUCTOR SPECIFICATIONS

	30 Strand Cable	36 Strand Cable
Wire Characteristics		
No. of filaments	3510	4146
Filament diameter (μ)	6	6
Filament spacing (μ)	>1	>1
Cu / superconductor	2.25 ± 0.1	$1.80 \pm .1$
Wire diameter (mm)	$.6477 \pm .0025$	$.6477 \pm .0025$
Wire twist pitch (mm)	13 ± 1.5	13 ± 1.5
Wire minimum I_c (A)		
(measured at 4.2K, 10^{-14} Ω -m)	264 @ 5.0T	286 @ 5.6 T
Maximum Variation in I_c	$\pm 10\%$	$\pm 10\%$
Wire maximum R(295K) (Ω /m)	.0765	.082
Wire minimum RRR	38	36
Cable Characteristics		
Wires per cable	30	36
Cable mid-thickness (mm)	$1.166 \pm .006$	$1.156 \pm .006$
Cable width (mm)	$9.728 \pm .025$	$11.68 \pm .5/-0.0$
Cable keystone angle (degrees)	$1.2 \pm .1$	$1.01 \pm .06$
Cable lay pitch (mm)	74 ± 5	94 ± 5 mm
Cable minimum I (A)		
(measured at 5.0T, 4.2K)	7542	10100
Maximum Variation in I_c	$\pm 6\%$	$\pm 6\%$

II. DIMENSIONAL DATA

Tight control of strand diameter is the first step towards controlling cable dimensions, with the ultimate goal of achieving consistent magnet assembly and field quality. Two axis, on-line laser micrometers monitored the final

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draw at OST. Frequent cross calibrations with a dedicated laser micrometer in the die room enabled the process to be maintained within the specified $\pm 2.5 \mu$ tolerance. Figure 1 shows sampled data of the diameter variation throughout both the "dipole" and "quadrupole" runs.

Fig. 1. Strand diameter for dipole wire (left of arrow) and quadrupole wire (right of arrow). Measurements on every sixth spool are plotted. Vertical bars are mean $\pm 3 \sigma$ for that spool. Dashed lines indicate $\pm 2.5 \mu$ specified tolerance.

The previously reported success in obtaining long piece lengths for the dipole strand continued with the quadrupole wire. Figure 2 shows the piece length distribution for the entire quadrupole production run. More than half the material was produced in pieces longer than 35 km, enabling efficient allocation of strand to cables not permitted to have cold welds.

Fig. 2. Piece length distributions for the 36 strand production run.

Cabling of the strand was performed at New England Electric Wire Corporation. The most critical cable dimension is the mid-thickness. On line measurements

with a Cable Measuring Machine (CMM) were cross checked with stack measurements. The CMM results were reproducible to $.5 \mu$. Figure 3 shows cable mid-thickness results for the entire dipole production run.

Fig. 3. 30 strand cable thickness, as measured by CMM. Bars correspond to mean $\pm 3 \sigma$.

Similar on-line monitoring of other dimensions insured that the process remained under control. Statistics are given in Table II, where the mean and standard deviation for all conductor delivered under the contracts are given. We believe that the small variances indicated set a new standard for the industry.

TABLE II
DIMENSIONAL DATA, AS MEASURED

	Dipole Cable	Quad Cable
Wire diameter (mm)	$.6480 \pm .0007$	$.6472 \pm .0009$
Cable Mid-thickness (mm)	$1.166 \pm .001$	$1.156 \pm .001$
Cable width (mm)	$8.349 \pm .005$	$11.692 \pm .007$
Cable keystone angle (deg)	$1.18 \pm .02$	$1.00 \pm .01$

III. ELECTRICAL DATA

Critical currents measured in individual strands of both dipole and quadrupole cable are shown in Figure 4, and compared with their respective minimum specified values, and maximum variations. From these data, and the dimensional and Cu:s/c measurements, one can extract the strand critical current densities in the NbTi shown in Table III and the standard deviations. The current densities in NbTi show smaller variances than the strand currents, because the strand current is correlated with the local Cu:s/c ratio. Also shown in Table III are the measured cable critical currents.

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Fig. 4 Critical current for the dipole strand at 5.0T, 4.2K and for the quadrupole strand at 5.6T, 4.2K. The dashed lines are the respective minimum specified values. The arrows indicate the allowable + 10% variation.

TABLE 111
MEASURED STRAND CURRENT DENSITIES AND
CABLE CURRENTS

	OST <u>Measurements</u>	BNL <u>Measurements</u>
j_c in dipole strand @ 3T, 4.2K (a/mm^2)	4221 ± 67	4157 ± 56
j_c in dipole strand @ 5T, 4.2K (a/mm^2)	2834 ± 43	2807 ± 35
j_c in quadrupole strand @ 5.6T, 4.2K (a/mm^2)	2537 ± 69	2503 ± 30
I_c in dipole cable @ 5T, 4.2K (a)		8582 ± 175
I_c in quadrupole cable @ 5.6T, 4.2K (a)		10859 ± 162

Like the dimensional measurements, the electrical measurements on RHIC strand and cable show that a consistent product has been provided to the team building the accelerator magnets.

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