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Superconducting Wire and Cable for RHIC

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Abstract—The superconducting dipole and quadrupole magnets in the RHIC accelerator ring are to be fabricated from 30-strand superconducting cable. The RHIC wire has a diameter of 0.65 mm, copper-to-superconductor ratio of 2.25, filament diameter of 6 μm and high critical current density. Primary emphasis during manufacturing has been on uniformity of materials, processes and performance. Near final results are presented on a production program which has extended over two years. Measured parameters are described which are important for design of superconducting accelerator magnets.

I. INTRODUCTION

A decade ago the principal concern of superconducting magnet design was to obtain wire with the highest possible value of the critical current density, J_c. Since then, due primarily to the work of Larbalestier and others [1], J_c values in the neighborhood of 3000 A/mm^2 have become more or less routine in production [2]. For machines like HERA and RHIC this is a comfortable level of current density and attention has turned to the equally important concern of magnet designers, uniformity of superconductor wire and cable. In two previous articles [3,4] the manufacturing objectives and procedures of the RHIC procurement program were described, and early test data were given. Now, nearly all wire and two-thirds of cables for the RHIC dipole and quadrupole magnets have been produced. In this paper we give a summary of the main performance results on this material.

A. Wire Data

The most important quantities in the RHIC wire specification [5] are the critical current at an applied field of 5 Tesla and a temperature of 4.2 K, I_c(5T, 4.2 K), the electrical resistance per meter at 295 K, R295, and the wire diameter, D. Together, these quantities determine J_c and the copper-to-superconductor ratio, C/S. Our reasons for preferring the above set of specifications have been discussed in detail elsewhere [6,7]. Another quantity, I_c(3T)/I_c(5T) or "3/5 ratio" is also specified. This quantity checks on control of metallurgical processing for the Nb-Ti superconductor as raw material and in wire processing and, as a consequence, on the low field magnetization.

1) Wire diameter: Wire diameters were measured by OST during final draw using on-line laser micrometry. Figure 1 shows the data for nearly the entire production of approximately 18 million meters of wire. The variation in D settled down considerably in the second half of the production run; it appears that a variation tolerance of $\pm 5 \times 10^{-5}$ inches (1.3 μm) would be feasible in the future. Wire cleanliness and surface integrity are checked by visual and eddy current inspection.

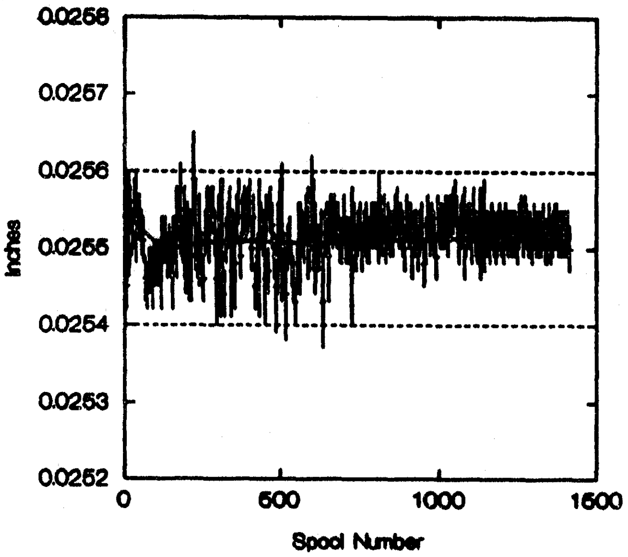

Figure 1. On-line laser diameters with two axes typically measured every meter. Average value for one-sixth of all spools, with ± 3 std. dev. vertical bars. Solid line is the running average.

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2) Wire I_c(5T, 4.2 K): Figure 2 shows the critical current data. The small but steady increase in I_c during the first half of production is not attributable either to diameter variation or to variation in C/S. Instead it appears to be associated with slight decreases in interfilament spacing which resulted from changes in assembly during the earlier billet set ups. Gregory et al [8] first showed that closer packing led to greater uniformity of filament cross section and, hence, increased J_c. Li et al [9] showed that this effect was active even for relatively small interfilament spacing decreases of order 0.1 μm. The present data were found to correspond to a decrease in interfilament spacing over the first half of production of about 0.07 μm as determined by photomicrography of the wire cross sections. The Quality Indices (n-values) from wire critical current measurements increased very slightly when interfilament spacing decreased.

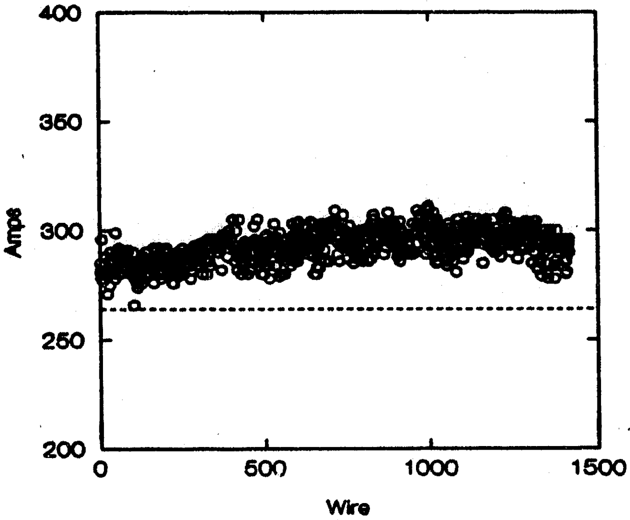

Figure 2. I_c(5T, 4.2 K). Mean value = 293 A; std. dev. = ±7 A (2.4%). Dashed line is RHIC minimum specification limit.

3) I_c(3T)/I_c(5T): Values of this quantity were determined by short sample tests at OST. These tests are also performed on approximately 15% of the wires by BNL. The I_c(5T) data generally agree within 1% (±1.5 A) with those at OST. The distribution of 3/5 ratios has remained very uniform throughout the entire production, thereby indicating very good control of the metallurgical processing of the source alloy and wire production. The mean value and standard deviation are 1.49 and 0.01, respectively. A graph of the 3/5 distribution is shown in Ref. [4].

4. R295: Figure 3 shows the R295 distribution. The method of calculating C/S is discussed in Refs. [6,7]. It is necessary to measure the residual resistance also. The value of RRR is typically between 40 and 44; the effect of this variation on C/S is 0.02 (1%). (In final RHIC magnets RRR increases to above 200 because the copper is annealed during coil curing.) The calculated C/S distribution has a mean value of 2.20 and standard deviation of ±0.06. This variation is largely due to billet processing. Since the electrical method of determining C/S is not practical during billet processing, the chemical method is used. The correlation of this value of C/S and the resistance of final size wire is subject to some uncertainty due to the resistance of interfilamentary copper and the resistance of barrier layers. It is necessary, therefore, to establish a correlation between billet assembly parameters and final size wire resistance.

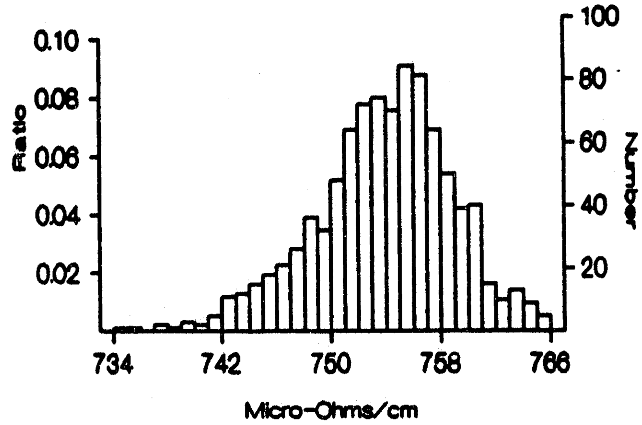

Figure 3. R295 distribution. Mean = 753; std. dev. = ±5.

5. Piece length: The RHIC specification calls for a minimum cabling spool length of 700 m and no cold welds. These conditions have proven to be very easy in view of the long piece lengths achieved by OST [4]. Since the earlier report, the average piece length has increased to 10.9 km, with greater than 98% of all drawn lengths in excess of 2 km.

B. Cable Data

1. Mid-thickness: Uniform, stable magnet performance depends critically on uniform cable dimensions. Cable mid-thickness is especially important as it directly affects critical current degradation and coil pre-stress. Figure 4 shows results for approximately 370 km or about 70% of total production. These measurements were made at NEEW using a Cable Measuring Machine (CMM) apparatus. Periodic checks are made by a 10-stack short sample method in order to insure the accuracy of this important measurement. The results are shown in Fig. 5. For the second half of production shown in the figure, CMM measurements were made at intervals of one foot and averaged for the exact 10-stack sample length.

2. Cable width and keystone angle: Measured values of these parameters are well within specified tolerances. The mean values and standard deviations are: cable width = 0.383 ± 0.0002 inches, and keystone angle = 1.18 ± 0.02 degrees.

3. Cable critical current: Figure 6 shows the short sample critical current results, which are obtained in BNL's test lab. The upward drift in the data follows that for the wires. Even with this variation the data fall well within specified tolerances. The nominal cabling degradation for the entire data set is 2%. It should be noted that cable test results are customarily corrected for the self-field effect [10], whereas wire data are not. The true degradation is, therefore, larger -- of order 7 or 8%. Degradation is caused by compaction during cabling. In the present design the cable thin edge is compacted to 82% of two wire diameters. Cabling degradation is known to be sensitive to this ratio.

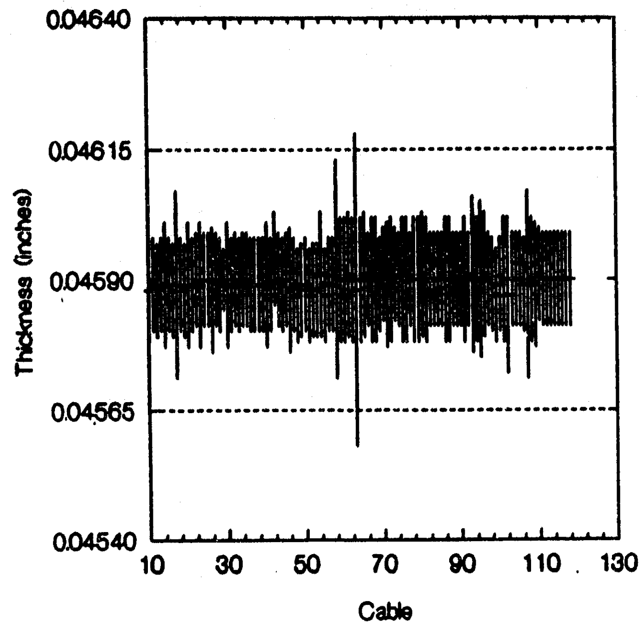

Figure 4. Cable mid-thickness. On-line CMM measurement. Mean values of typically 700 points per cable are plotted. Vertical bars represent 3 std. devs. Dashed lines are RHIC tolerances.

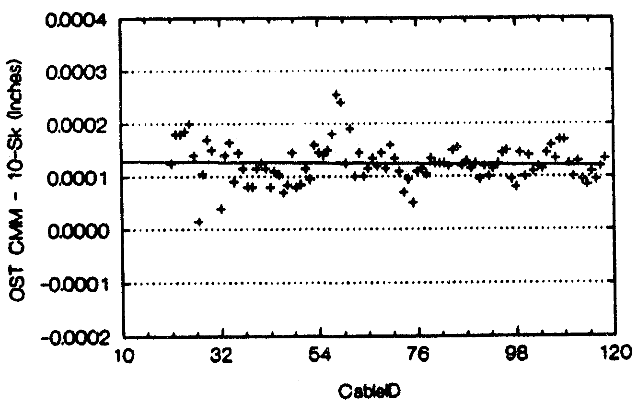

Figure 5. Comparison of CMM and 10-stack mid-thickness data. CMM values are higher by 3 μm with std. dev. of 1 μm.

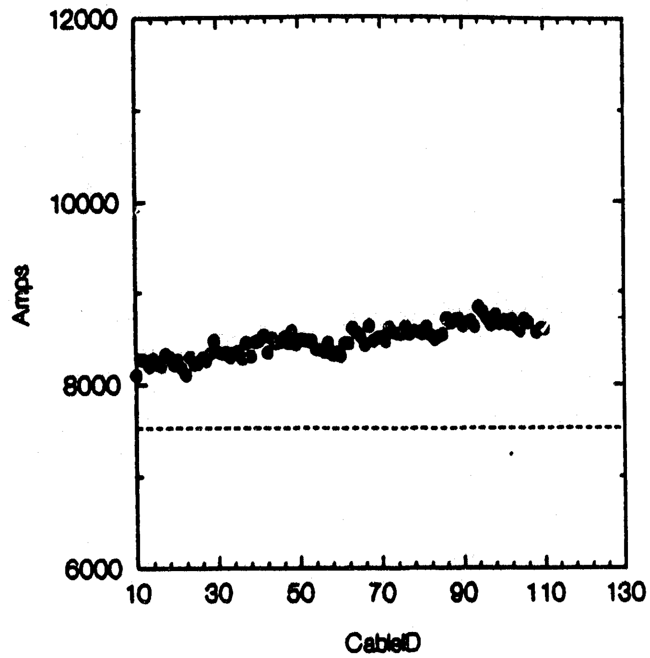

Figure 6. Cable short sample I_c (5T, 4.2 K) results. The mean value is 8475 A, std. dev. = ±163 A (1.9%). The dashed line is the specification minimum.

II. CONCLUSIONS

The RHIC dipole and quadrupole order is the largest single quantity of superconductor procured to date in the U.S. It has been manufactured with high product uniformity. This was the result of close cooperation between BNL, NEEW, OST, and TWCA.

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