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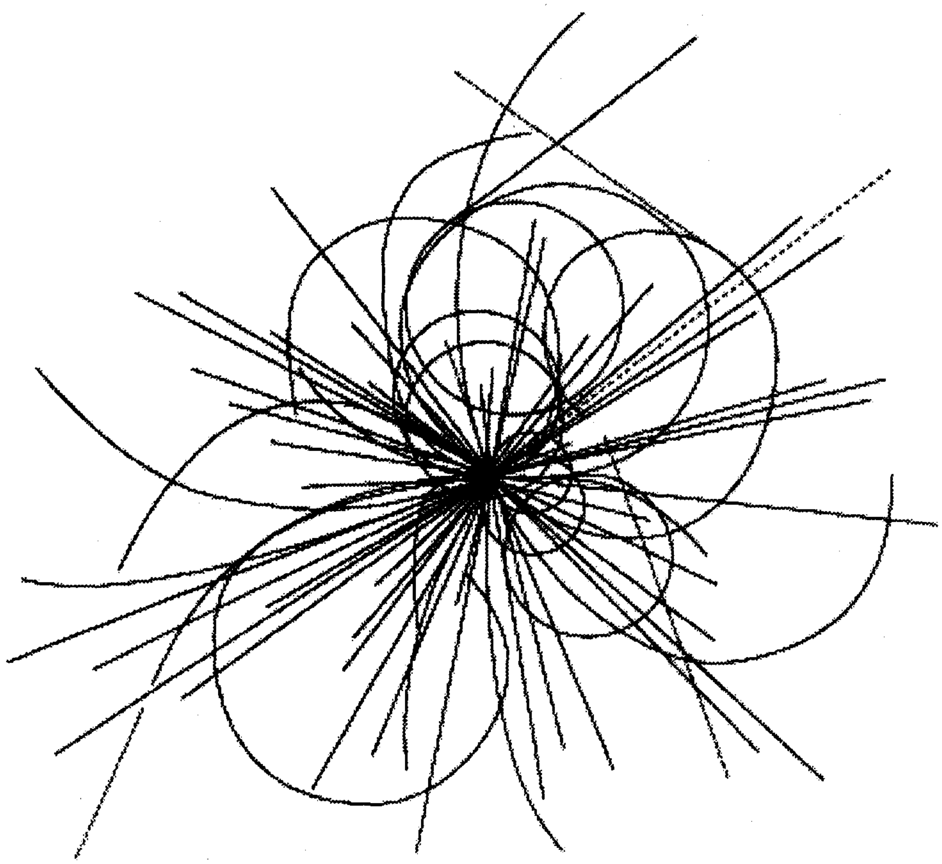

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EXTRACTED STRAND I_C AND STRAND I_C DEGRADATION FOR SSC CABLES

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INTRODUCTION

The performance testing of the large quantities of superconducting cables for SSC magnets is a daunting challenge, at best. In an effort to reduce the quantity of full cable testing required, an investigation is underway to evaluate the utility of determining the performance of the SSC cables using extracted strand testing. It is believed that the cable performance can be quite accurately determined by measuring the critical current (I_c) on strand samples removed, at random, from the manufactured cable.[1] These strand measurements are used to derive the cable critical current. The measured critical current (I_{ce}) are then compared to the virgin strands (I_{cv}) input into the cable to determine the degradation resulting from the cable fabrication. The advantage of this type of certification is two fold; firstly the manufacturer can certify the performance using existing strand measurement equipment. This allows for a reduction in the lead time between manufacture and delivery of the cable. Secondly, the SSC can perform random sampling, as opposed to 100% cable testing and still maintain adequate visibility into the performance of the cables. The following sections cover the techniques used and the results obtained for measurements of extracted strand I_c (I_{ce}) and field dependence of I_{ce} for more than fifty representative cables. The data for another five cables for which full cable I_c values were previously measured at Brookhaven National Laboratory are also presented and compared with full cable I_c results. The details of the full cable measurements performed at BNL are described elsewhere[2]. The SSCL full cable test facility will soon be in routine operation which will allow for precise verification of the validity of extracted strand testing in the determination of I_c in SSC cables.

EXPERIMENTAL DETAILS

The extracted strands are prepared by cutting a one meter length from each cable sample. Six strands are randomly taken from each cable sample for test. These strands are

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removed so as to not disturb the "zig-zag" imparted by the path of the wires through the cable itself. The sample rig is based on the successful design used at BNL for many years.[3] The sample holder consists of a G-10 barrel with grooves for three strand samples. The geometry of the 38 mm diameter barrel is such that each sample has a pitch of 12.7 mm. This combines to reduce, to minimal levels, the solenoidal contribution to the self-field on the sample during energization. The gage length between voltage taps is 579 mm. The samples are independently energized using three current leads and a single common lead so as to maintain the Lorentz forces inward during the I_c measurements.

During the mounting of these samples no effort is made to retain the original geometry of the wire pitch in the cable. The strands are pulled into the grooves of the sample holder, and straightened considerably, but not completely in the process. This is done to ensure adequate strand tension to avoid training behavior during the measurements. This sample mounting technique increases the possibility of introducing additional damage to the sections of the strand deformed at the edges of the cable. However, as the measurements show, apparently the additional movement introduced by hand is insignificant compared to the deformation imparted by the turkshead rollers during the manufacturing process.

The background field for the measurement is obtained using a 15 Tesla superconducting solenoid magnet with a 64 mm aperture, produced commercially by Oxford Instruments, Inc. The three samples reside, during the measurement, within the 1 % uniformity sphere defined by the magnet geometry.

The I_c measurements are performed using a computerized data acquisition system consisting of two Keithley 182 microvoltmeters, a Hewlett Packard 6464C DC power supply, a Hewlett Packard 6031A DC power supply, and a Dynapower zero flux current transformer. These instruments interface over an IEEE-488 bus. The system is operated using a LabVIEW virtual instrument called ICTEST running on a Macintosh computer with 5 Mb of RAM and a 40 Mb hard drive.[4] Data is collected at a rate of 2-3 Hz and full data reduction occurs within 3-5 seconds after measurement with typical data files of 200-300 data points. Typical noise levels in this system are 100-200 nV. I_c is defined using a $1 \times 10^{-14} \Omega$-m resistivity criterion. For a gage length of 579 mm, the criteria corresponds to 4-6 μV at I_c. Initial runs on the NIST Standard Reference Material ,[5] as well as the round robin testing certification procedures implemented for the VQP,[6] have shown compliance with required accuracy and repeatability levels. The repeatability, reproducibility, and accuracy variations are 1.31 %, 0.41 %, and 1.16 %, respectively. The total error of the Ic measurements is 2.23 %.

Six strand I_c measurements for each cable sample are averaged to produce a strand I_c value for the cable. No correction to the solenoid or the self-field of the wire is performed. The solenoid field produced by the strand is negligible (approximately 2.0×10^{-3} T). The maximum self-field for the outer and the inner wire (at 5.6 T and 7 T respectively) is less than 9.0×10^{-2} T. There is no necessity in self-field correction for comparison of virgin wire I_c and extracted strand I_c

The cable critical current is determined by the product of this average I_c and the number of strands in the cable. The average Ic for the virgin case and the extracted strand case is not corrected for self field and geometery effects. In addition to the cable I_c, the degradation of the strands as a result of the deformation during cabling is determined. The degradation is determined as the percent change of the average extracted strand I_c from the weighted average I_c of the virgin wires used in the cable manufacturing. The weighted average I_c of the wires used for the cabling was determined from the map of wire positions within the cable which is used to manufacture the cable. The weighted average I_c is the sum of the measured I_c of a wire times the fractional length of that wire in the cable divided by the number of strands in the cable.

RESULTS

Six cable samples were selected from the archive storage maintained within the SSC Magnet Systems Division Conductor R&D group. Three samples each of Inner and Outer cable were used. The critical current of these cables all had been previously measured at BNL. The cable samples selected, along with the relevant BNL results, are identified in Table 1.

Table 1. Relevant parameters of the BNL measured cables used for this paper.

Cable sample	Vendor ave. virgin Ic (A)	SSCL ave. extracted strand (A)	SSCL cable calculation (A)	BNL cable measurement (A)	SSCL measured degradation (%)	Difference SSCL vs. BNL (%)
Inner						
3-I-00044	368	343	10290	10764	6.80	-4.4
3-I-00054	n/a	341	10286	10904	n/a	-6.0
3-I-00064	n/a	343	10290	10799	n/a	-4.9
Outer						
4-K-00025	318	302	10872	11188	5.1%	-2.9
4-K-00026	319	306	11016	11207	4.0%	-1.7

The average I_C, n (at 5.6T and 7.0T), dI_C/dB, and degradation data for 29 SSC Outer cables are presented in Table 2. The average I_C, n (at 7.0T and 8.0T), dI_C/dB, and degradation data for 17 SSC inner cables are presented in Table 3.

Table 2. Average I_C, dI_C/dB, n, and degradation for extracted Outer strands

Vendor		Ic (5.6 T)	n (5.6T)	Ic (7.0 T)	n (7.0 T)	Degradation (%)	dI_C/dB (A/T)
AISA	Ave.	288.3	37.7	196.0	32.0	1.6	-66.2
	Std dev.	1.1	0.9	0.8	1.3	1.2	0.7
FEC	Ave.	292.1	34.3	190.5	29.8	0.8	-72.7
	Std dev.	2.8	2.8	2.4	1.4	0.8	0.7
HIT	Ave.	282.8	40.1	188.6	34.1	6.0	-67.3
	Std dev.	3.1	2.6	2.1	1.4	1.1	0.9
OTU	Ave.	303.0	42.0	203.6	35.0	3.5	-71.1
	Std dev.	2.7	3.8	1.6	2.4	1.0	1.2
OST	Ave.	292.2	47.1	198.5	37.6	4.1	-67.0
	Std dev.	2.7	6.1	1.2	2.5	0.8	1.3

Table 3. Average I_C, dI_C/dB, n, and degradation for extracted Inner strands

		Ic (7.0 T)	n (7.0 T)	Ic (8.0 T)	n (8.0 T)	Degradation (%)	dI_C/dB (A/T)
IGC	Average	369.58	38.01	243.89	30.48	3.51	-125.70
	Std dev.	5.44	2.58	3.56	3.49	0.70	2.79
SEI	Average	356.89	36.88	237.49	31.80	3.64	-123.71
	Std dev.	9.23	1.01	3.01	3.59	1.07	1.91

DISCUSSION

The BNL value for the cable has a self field correction for their test configuration, according to Garber et. al.[2] They have developed a strand correction of $B_p = B_a + \pi * (10^{-4}) * J * D / (1 + x)$, where B_a is the applied field, J is the critical current density, D is the strand diameter, and x is the copper to superconductor ratio. Using a J slope of 29 % per Tesla, these corrections are 5.5% for Inner and 5.3 % for Outer strand. In addition, they have a field profile calculation for the cable cross section in their test rig which results in a correction about 1 % lower (i.e. 4 %) than the strand self field correction. This comes from figure 7 in the Garber paper for B perpendicular to the cable face and adding to the cable narrow edge. In the BNL case, the gap between the cables in the sample holder is 0.8 mm and the cable type is 40 mm (23 strand) Inner. Therefore, the uncorrected self field values with the SSCL extracted strand measurement are about 4-5 % lower than the self field corrected values of BNL procedure.

The difference between BNL and SSCL critical current values is as predicted by the self field correction. Based on this data and the round robin work performed on strand, it is felt that SSCL and BNL data are in agreement to better than 2 %. It is felt that the agreement are not likely to be better than this value because the strands in the cable are not exposed to a homogeneous field.[6] A single linear self field correction only approximates the situation of the strand in the cable. More in depth consideration of magnetic field and geometry corrections in SSC cables will be made when full cable measurements are made on the cables already characterized by extracted strand testing in this work.

The extracted strand n values are approximately 10-20 % lower than those on the virgin strands reported by the vendors. This reflects the extended superconducting to normal transition and Ic degradation found in the extracted strand.

It is noted that the degradation of the Phase IB cables is generally low, averaging about 3 % for Inner and Outer cables. Cabling result of SSC VQP Phase IB cable is discussed in more detail elsewhere.[7]

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