Quality Control Testing of Cables for Accelerator Magnets

M. Garber and W.B. Sampson

BNL--42047

Brookhaven National Laboratory*, Accelerator
Development Department, Upton, New York 11973

DE90 001018

ABSTRACT

A large number of cables have been tested for the CBA, HERA, and SSC Projects. The short sample test procedures and apparatus are reviewed. A simple rule for estimating cable performance from measurements on strands taken from the cable is described. By using this "rule of thumb" cable vendors can make reliable estimates without having to invest in the substantial equipment required for full cable testing. Extracted strand tests should be checked periodically by full scale tests on complete cables.

INTRODUCTION

Short sample testing of superconducting cables used in accelerator magnets is required in order to ensure that the individual strands have not been unduly degraded during cabling. Occasionally this can be quite large; an example of this is given below. Another factor is the large increase in critical current density which has been achieved in recent years¹, which has made wires with perfectly reproducible properties difficult to manufacture. Mixing and matching of strands is used to produce constancy in cable properties, but this must be verified by short sample testing.

The first large scale program of short sample cable testing was undertaken for the erstwhile ISABELLE-CBA Project about ten years ago.² Test methods have been improved continuously since then. The development of cables carrying currents of order 10 kA at 6T, 4.2K, more than double the current of a decade ago, has led to the need for special mounting procedures and careful self field corrections to the measured results. An earlier paper reviewed the important features of the BNL cable test methods.³

Further details have been given in several conference papers. As indicated in the following sections, a large investment in equipment and refrigeration is required to test high current superconducting cables.

*Work performed under the auspices of the U.S. Department of Energy.

The straight line in Fig. 1 is drawn with a slope of 7×10^4 ohms. This corresponds to constant resistivity of 10^{-12} ohm cm. The intersection of this line with the V-I curve of the sample is the critical current, I_c . In practice the quantity $\rho = VA/Il$ is plotted vs I on a log-log plot. This curve is usually well approximated by a straight line, and I_c can be read off with good accuracy from the point whose ordinate is 10^{-12} ohm cm. The slope of this line, n , measures the steepness of the superconducting-normal transition, which depends on the uniformity of the NbTi microfilaments. Low n -values generally lead to low I_c 's other things being equal.

I_c is often referred to as the "short sample" current in discussions of the performance of magnets made of the given cable. This is because it is a fact of experience that the magnet quench current is usually within a few percent of I_c (either more or less). The correlation is not exact, however, because of such things as variation of I_c along a cable, heating at cable joints in the magnet, variations in heat flow to the cable, etc. In any case, the quench current, I_q , in a short sample test is usually significantly greater than I_c , typically by about 10%. In general, the greater the Cu/SC ratio the greater the ratio of I_q to I_c .

In addition to the field, the temperature of the measurement must be reported. The sample and dipole magnet are placed in a helium bath. High current gas cooled leads necessarily require a bath pressure greater than standard atmospheric. As a result the temperature of measurement is about 0.2K above the normal boiling point of helium. It is desirable to refer measured values to a common reference temperature. This is done by means of the so-called Lubell formula.⁷ A reference temperature of 4.22K is frequently chosen, although this is not necessary. The HERA project, for example, specifies 4.6K as reference temperature for short sample data. In order to distinguish between measured critical current values and those referred to some reference temperature we use the following notation: I_l is the critical current as measured at the helium bath temperature, T ; I_r is the critical current at the reference temperature.

CABLE CLAMP ASSEMBLY

In order to observe V-I curves like that of Fig. 1, it is necessary to prevent any cable motion which would be generated by the large Lorentz forces which occur at high currents. Figure 2 shows the method by which this is done. A bifilar sample is used (two such are shown in the figure). The thin and thick edges of keystone cables are placed as shown so that the top and bottom surfaces are parallel and the applied stress is uniform. The net Lorentz force on the assembly is zero. However, the perpendicular field produces forces on the members of the bifilar pair which try to make them slide apart in a shear like fashion. (The perpendicular field is oriented relative to the current direction so that the sum of the applied and self fields is a maximum at the thinner edge of the cable. This produces a tendency to shear apart rather than together. Cf reference 4.) In order to prevent this motion, a large compressive stress is required. The value required varies inversely with Cu/SC ratio. However, in order to standardize the procedure, a value of 10 kpsi is used for all cables. This is adequate for most of the cables commonly tested. Further details on the stress dependent behavior are discussed in reference 6.

Although the separation between cables in the bifilar pair is small, the couple created by the shear forces is enough to produce significant twisting of the assembly unless otherwise prevented. To do this the ends of the assembly are locked in position relative to the magnet bore tube by a key-slot arrangement.

Thus, it is not feasible for each vendor to make these tests. However, a simple correlation exists between the current of strands taken from a cable and the full cable current. By utilizing this "rule of thumb", the vendor can obtain prompt, in-house feedback between the manufacturing process and short sample measurements. Examples are given below which show that a relatively small number of strands need be sampled in order to get a reasonable estimate of cable performance.

CABLE TEST METHOD

The V-I curve of a recently tested SSC cable is shown in Fig. 1. The sample is mounted in a dipole magnet with the field oriented perpendicular to the flat surface of the cable. The sample test length, i.e., that part which is in the uniform field region, is 700 mm long. Each half of the sample can be measured separately if, for example, it is desired to locate suspected flaws. The sample is long enough to provide adequate voltage compared with the DC noise resolution, which is about 0.2 microvolts. This sensitivity is achieved by means of a point by point determination of the V-I curve as follows. The current is incremented in steps. At each value the sample voltage is integrated for a time equal to 100 periods of line voltage, thus filtering power supply noise. The magnet is operated in the persistent mode so essentially no noise is contributed by the dipole field.

Fig. 1. V-I curve for an SSC inner type cable. Test length - 70.0 cm.
See Ref. 13 for physical description of the cable.

Fig. 2. Mechanical Assembly. Two bifilar pairs of keystone samples are assembled, as shown. The members of each pair are separated by Kapton, 0.010 in. thick. Instrumentation is located in G-10 strips placed in contact with each sample. The thicknesses of the G-10 strips are 0.030, 0.100, and 0.030 in., respectively. The stainless steel studs are spaced 1.5 in. apart along the 48 in. length of the fixture. The silicon bronze nuts are tightened to 200 in.-lbs. torque resulting in a mean pressure on the samples of approximately 10 kpsi.

CABLE TEST FACILITY

The sample holder discussed above is inserted in a dipole magnet which is 1.2m long and has a 75 mm bore. This is an early R&D dipole which is described in the literature.⁹ It has been used continuously for the last 12 years. The maximum central field is a little over 6T.

The liquid helium dewar is 2.8m long and has an inside diameter of 600 mm. Helium is supplied from a 10,000 l storage dewar, which is connected to a 100 l/hr liquefier. Gas recovery, storage, purification, and compression are handled by a central BNL plant.

Thus, the cable test facility consists of four separate areas:

- the gas handling plant
- refrigerator and storage room
- test dewars and power supplies - see Fig. 3
- electronic measurement and controls lab.

It would not be feasible to duplicate this investment in plant and operating cost at each cable vendor's facility. An alternative method of assessing cable performance, which is described below, can more economically serve to provide in-house short sample information to the superconductor manufacturer. Before doing so we describe two examples of quality control results, in the next two sections.

Fig. 3. Dewars and power supplies. 1-test dewar. 2-He fill and recovery lines. 3-sample probe. 4-15 kA power supply. 5-4 kA dipole power supply. 6-magnetization test dewar. 7-assembly area.

REPORTING OF CABLE RESULTS

Figure 4 is an example of the customary quality control report for a cable, in this case the one discussed earlier in connection with Fig. 1. Measurements are made at several fields. The first part of the report lists the peak field, the helium bath temperature, the critical current I_c , the quench current I_q , the quality parameter, n , and the critical current calculated for the reference temperature (4.22K in this case).

The next part lists the results of resistance measurements at room temperature and 10K. These are conveniently measured in the apparatus described. A complete description of the procedure is given elsewhere.⁵ The room temperature resistance, R_{295} , is an important element of the cable specification as it is determined by the Cu/SC ratio. Conversely, the Cu/SC ratio may be calculated from the measured resistances. This calculated value and the residual resistance ratio, RRR, are listed.

The last part of Fig. 1 gives critical currents determined by fitting a straight line to the measured I_c -B points. This is a good representation of the I_c -B dependence for fields between 5 and 7T, for multifilamentary NbTi wire of the type used (46.5 wt, % Ti). In making the fit to the cable data the slope is chosen to be the same as for the wire; wire data is usually more accurate since it is averaged over several wires. Special cable tests in which many points are measured and very great care is taken to reduce field and temperature errors confirm that wire and cable

slopes agree. For routine production cable testing it is more efficient to measure points at a few fields and utilize the wire slope value. The resulting accuracy is about $\pm 150\text{A}$.

Critical current densities are also listed. These are based on the specified or stated strand diameter and on the Cu/SC value determined from the resistance measurements.

Run 2066

SC 398

10/25/88

Measurements

B	I	I_t	I_q	n	I_c
5.38	4.407	11547	12005	27	12371
5.79	4.406	10166	10826	25	10944
6.16	4.392	9356	9984	24	10064
R(295) = 25.5 uohms/cm			RRR = 69		
R(10) = .37 "			C/S = 1.42		

Calculated results for $T = 4.22$

B	I_c	J_c
5.0	13284	2730
5.6	11614	2387
6.0	10501	2158
7.0	7718	1586

**REPRODUCED FROM BEST
AVAILABLE COPY**

Fig. 4. Short sample test report (same cable as in Fig. 1).

AN EXAMPLE OF CABLE REJECTION

QC test results for several projects have been published.²⁹ From time to time cables are found to be below specification, necessitating diagnosis and correction of the underlying problem. An interesting example of one such case occurred during the production of cables for the HERA project. A detailed review of the complete run including test results for some 300 samples is given in reference 9. Early in the run the sequence shown in Fig. 5 was observed: a downward trend began at No. 28 and culminated in a clearly pathologic cable at No. 34. Fortunately the cabler was shut down at this point for other reasons. Thus, there was time for the manufacturer to investigate the cause, which turned out to be an improperly positioned mandrel. Gradual slippage of the mandrel led to increasing filament breakage and the observed steady decrease in I_c . After correcting this problem, no further difficulties arose during the remainder of the production run.⁹

Fig. 5. Critical currents of a sequence of cables during a production run for HERA (cf. reference 9).

ESTIMATION OF I_c FROM EXTRACTED STRAND DATA

Recently it was reported that a good estimate of the critical current of a cable is obtained by summing the critical currents of the strands extracted from the cable.⁴ In doing this, the measured strand currents are used with no account taken of wire self field effects (strand measurements are described in Ref. 10). This "rule of thumb" has been tested for cables in which the current, the Cu/SC ratio, and the residual resistance ratio have different values. The results are shown in Table 1. The first four columns list the cable number and the measured values of Cu/SC, RRR, and I_c . Column 5 lists the degradation, $D = 100 \times (1 - I_w/I_c)$, where I_w is the sum of the critical currents of the wires used to make the cable. In most of the cases, I_w is approximated by measuring between 8 and 12 wires. The average of these wire values is multiplied by the total number of cable strands to get I_w . In one case, cable 378, all 30 strands were measured because the value of Cu/SC varied considerably from strand to strand. In those cases where D values are not listed, pre-cabling wire samples were not provided. Two samples have zero or negative degradations. These come about partly from sampling error in determining I_w . In addition, neglect of self field effects in wires reduces I_w by a few percent.

The estimated critical current of the cable based on the extracted strand currents, I_{es} , is similarly determined from a sample of strands. In most cases a relatively small number of strands was tested. Column 6 lists the percentage difference between I_{es} and I_c , and column 7 lists the number of extracted strands, N_s . It appears from Table 1 that with $N_s \sim 4$ a reasonable estimate, good to about $\pm 2\%$, is obtained. Part of the difference between I_c and I_{es} is due to the accuracy of the cable measurement, which is between 1 and 2% also.

The procedure by which I_{cu} is determined is the same as that by which I_c is determined. By estimating the degradation from wire measurements, i.e., from I_c and I_{cu} , geometrical and other experimental conditions are nearly identical; this is an advantage over the method of comparing wire and cable results. The values of D obtained by comparing I_{cu} and I_c are approximately equal to the differences between the values listed in columns 5 and 6 of Table 1.

A quantitative calculation explaining the rule of thumb would be hard to formulate. For one thing, the magnetic field distributions are quite different for the two measurement configurations, cable vs strand. For another, the voltage distribution along an extracted strand, varying as it does between highly deformed, kinked regions and regions which are only slightly deformed, is rather different from that along the cable." It is fortuitous, therefore, that the rule works as well as it does.

Table 1. Comparison of Cable and Extracted Strand Data (B=5T, T=4.2K).

Sample	Cu/SC	RRR	I_c (amps)	D(%)	$100(I_{cu}/I_c - 1)$	N_c
RHIC Types ⁽¹²⁾						
106	2.26	66	6660	13.1	2.7	2
107	2.26	66	6880	10.2	1.6	2
SSC Inner Types ⁽¹³⁾						
351	1.50	34	11232	5.3	-0.6	8
351A	1.50	130	11621	-	-1.0	16
383	1.60	84	12828	4.0	0.8	3
395*	1.80	70	11130	0.0	-0.3	4
398	1.42	70	13284	-2.4	-1.5	4
399	1.54	82	13693	-	-2.9	4
6135	1.20	105	14160	-	-0.4	4
SSC Outer Types ⁽¹³⁾						
369	1.70	68	9600	6.9	1.9	3
378	1.70	74	9160	7.8	1.2	2
380*	1.71	65	9164	5.0	1.5	4
385**	1.59	66	8955	9.3	0.4	30
6136	1.73	110	9660	-	1.1	4
HERA Types ⁽¹⁴⁾						
L383	1.70	77	11973	-	0.0	4
1553	1.80	75	11397	-	-1.0	22

*These cables were made from a single continuous strand.

**This cable was made from strands in which Cu/SC varied from 1.24 to 1.71.

All strands, both before and after cabling, were measured.

SUMMARY

A large investment in equipment and refrigeration is needed for cable critical current tests. This makes it impractical for wire and cable manufacturers to undertake such tests themselves. Fortunately, a good estimate of cable critical current can be obtained from extracted strand measurements. A relatively small sample, ~4 strands, is adequate for this purpose. Thus, it is possible to monitor cable production with modest expenditures. Sample cables could be tested at a national facility such as that at BNL in order to ensure the validity of the extracted strand results.

ACKNOWLEDGEMENTS

We thank the cryogenic support group directed by D.P. Brown for their vital support. Many helpful suggestions have been made in the course of this work by K. Robins and A.K. Ghosh. We thank R.K. Maix and A.F. Greene for discussions concerning the HERA cables.

REFERENCES

1. P.J. Lee and D.C. Larbalestier, "Determination of the Flux Pinning Force of a-Ti Ribbons in Nb46.5 Wt% Ti Produced by Heat Treatments of Varying Temperature, Duration and Frequency", J. Mater. Sci., Vol. 23, pp. 3951-3957, 1988.
2. M. Garber, M. Suenaga, W.B. Sampson, and R.L. Sabatini, "Effect of Cu,Ti Compound Formation on the Characteristics of NbTi Accelerator Magnet Wire", IEEE Trans. Nuc. Sci., Vol. NS-32, pp. 3681-3683, October 1985.
3. W.B. Sampson, "Procedures for Measuring the Electrical Properties of Superconductors for Accelerator Magnets", Proceedings of the ICFA Workshop on Superconducting Magnets and Cryogenics, Brookhaven National Laboratory, Publication No. 52006, pp. 153-156, 1986.
4. M. Garber, A.K. Ghosh, and W.B. Sampson, "The Effect of Self Field on the Critical Current Determination of Multifilamentary Superconductors", IEEE Trans. Magn., Vol. MAG-25, pp. 1940-1944, March 1989.
5. W.B. Sampson, M. Garber, and A.K. Ghosh, "Normal State Resistance and Low Temperature Magnetoresistance of Superconducting Cables for Accelerator Magnets", IEEE Trans. Magn., Vol. MAG-25, pp. 2097-2100, March 1989.
6. A.K. Ghosh, M. Garber, K.E. Robins, and W.B. Sampson, "Training in: Test Samples of Superconducting Cables for Accelerator Magnets", IEEE Trans. Magn., Vol. MAG-25, pp. 1831-1834, March 1989.
7. M.S. Lubell, "Empirical Scaling Formulas for Critical Current and Field for Commercial NbTi", IEEE Trans. Magn., Vol. MAG-19, pp. 754-757, May 1983.
8. A.D. McInturff, W.B. Sampson, K.E. Robins, P.F. Dahl, and R. Damm, "Prototype and Proposed 'ISABELLE' Dipoles", IEEE Trans. Nuc. Sci., Vol. NS-24, pp. 1242-1244, June 1977.
9. R.K. Maix, D. Salathe, S.L. Wipf, and M. Garber, "Manufacture and Testing of 465 km Superconducting Cable for the HERA Dipole Magnets", IEEE Trans. Magn., Vol. MAG-25, pp. 1656-1659, March 1989.

10. M. Garber and W.B. Sampson, "Test Methods for Short Sample Critical Current Determination of Twisted Multifilamentary Superconducting Wire", SSC Technical Note SSC-MD-89, Brookhaven National Laboratory, January 1985 (unpublished).
11. L.R. Goodrich, E.S. Pittman, J.K. Ekin, and R.M. Scanlan, "Studies of NbTi Strands Extracted From Coreless Rutherford Cables", IEEE Trans. Magn., Vol. MAG-23, pp. 1642-1645, March 1987.
12. RHIC Specification RHIC-MAG-M-4142, NbTi Superconductor Cable for RHIC Dipole and Quadrupole Magnets.
13. SSC Specification SSC-MAG-M-4142, NbTi Superconductor Cable for SSC Dipole Magnets.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.