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Test Methods for Cable Critical Currents and Normal State Resistance

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A. Short Sample Test Method for Determination of Critical Currents of RHIC Cables.

1. Introduction

The sections which follow describe the test method used at BNL to determine transport critical currents of cable short samples. The measurement of critical currents of order 10^4 A is more difficult than the corresponding measurement for a wire carrying several hundred amps for a number of reasons. Large power supplies are required and sensitive voltage measurements must be made in the presence of much noise. Forces on the samples are large and care is required to restrain mechanical motion. Finally, self-field effects are large and must be carefully corrected. This paper describes the methods and procedures which have been developed at BNL over a number of years. These procedures have proven suitable for production testing.

2. Relation Between Wire and Cable Critical Currents

For a multifilamentary composite wire, the critical current Icw, may be written as

$$Icw = Jc\ (\pi\ d^2/4)/(1+x)$$

where Jc = critical current density in superconductor, A/mm^2

d = wire diameter, mm,

x = copper/superconductor volume ratio (or more generally non-SC/SC ratio).

The quantity Jc provides a figure for comparing wires of different diameter or of different copper/superconductor ratios. (The intrinsic current density of the NbTi may be larger than Jc since the latter is reduced somewhat by variations in cross-section of the filaments.) Present manufacturing art is such that we may expect to obtain, in multifilamentary composite wires of diameter 0.1 to 1 mm

$$Jc > 2600\ A/mm^2\ (T = 4.22\ K,\ B = 5\ T).$$

This value serves as the basis for a wire specification. For a RHIC wire, for example,

$$d = 0.648\ mm\ (= 0.0255\ in.)$$

$$x = 2.25$$

and we may expect

$$Icw > 264\ A.$$

$V/I = 10^{-12}/(N\pi d^2/4)$

where
V = voltage drop per cm
I = current in amps
N = no. of wires in cable

For purposes of numerical illustration let d = 0.0648 cm (=0.0255 in.), N = 30, and I = 7000 A; then V = 0.071 μV/cm. It is desirable, therefore, that test lengths of order 1 m be used when the measuring sensitivity is of order 0.1 μV.

The shape of the V-I curve is of the form

$$\rho = \text{constant} \cdot I^n$$

where $\rho = (V/I)(N\pi d^2/4)$. The quantity n is routinely measured as described below. Large n-values are indicative of uniform filaments. The n-value is, therefore, a useful diagnostic for monolithic conductors and individual wires although less so for cables. It is sometimes required that n exceed a specified value for some types of conductor.

The quench current is dependent on T and B in a way somewhat analogous to the critical current. Unlike the critical current, however, it is also dependent on several external factors: insulation, ramp rate, mechanical security. These affect the characteristic feature of quench current behavior, viz., training. This is the increase in quench current upon successive applications of current until, except in pathological cases, a limiting or plateau value is reached. This value is referred to as Iq. Temperature and field corrections are not generally made for Iq. The number of training quenches is minimized in short sample testing by using bare cable samples and by strong mechanical clamping as discussed below.

Iq is generally greater than Im and, as it provides a measure of the ultimate current carrying capability of the cable, it is routinely recorded. If Iq is less than Im, the latter may be determined by extrapolation provided there is enough of the V-I curve to permit this. However, in cases where Iq < Im the latter has no functional meaning.

4. Magnet: Temperature Bath: Power Supplies

The sample probe is located in a dipole magnet which is 48 in. long and has a 3 in. diameter bore. The maximum field is 6 T at a current of approximately 3 kA. The sample test length is 70 cm; over this length, the field homogeneity is about 1/1000. The magnet is equipped with a superconducting persistent switch which is very useful for keeping the field constant in time and noise free.

6. Electrical Instrumentation

Primary instrumentation consists of the following:

- 5 voltage taps and a thin foil heater element for each sample. These are contained on the G-10 strips shown in Fig. 1. The voltage taps work by the pressure contact of a copper wire across the width of the sample; the leads run out through a fine groove in the G-10. The heater element is a strip of stainless steel foil, 0.0005 in. thick x 1/8 in. x 1/4 in., which is located in a shallow well formed in the G-10 strip.

- Hazemeyer DCCT secondary current standard,

- Digital voltmeters, 6-1/2 digit, 0.1 μV sensitivity,

- Nicolet 12 bit, 4 channel digital oscilloscope,

- 2 calibrated carbon resistor thermometers, located at each end of the magnet,

- isolation preamplifiers, 1 μV noise level.

Secondary instrumentation consists of the following:

- quench current protection circuits for the magnet, the gas-cooled leads, and the samples,

- DC power supplies for persistent switch, and sample heater element,

- pulse power supply for sample heater element.

7. Measurement Procedure and Determination of Critical Currents and n-value

The cable samples are energized in pairs, either A-B or C-D in Fig. 2, and the V-I curves are determined simultaneously for each member of the bifilar pair. In the event that one member has a low Iq its partner may be unmeasurable in that set-up. The latter must be tested at another time with a partner having a comparable Iq - another piece of the same cable, for example. In situations like the preceeding, a minimum of 2 and perhaps 3 of the cable samples can be measured. In quality control tests of production cables, the match between samples is close enough that Ic's can be determined for all 4 samples. In the rest of this section we shall describe the procedure for testing one cable only, it being understood that a pair of samples are under simultaneous test.

The measurements are made with the helium bath level above the joint between the samples and the gas-cooled leads, and well above the top of the dipole magnet. The magnetic field is set to a desired value and locked in

The temperature sensors are monitored continuously. If the temperature varies more than ± 0.010 K during the taking of a V-I curve, the measurement is aborted. Efforts are then made to reduce the temperature variation. These include waiting for the helium bath to settle down, increasing the flow of gas through the current leads, and refilling the dewar. The last measure is generally unnecessary if the run is less than 3 hours. (The usual run duration is 2 hours.)

8. Temperature Calculation

The discussion in this section pertains to NbTi conductors of composition and metallurgical treatment appropriate for accelerator magnet applications.

Calculations of the critical currents at temperatures other than that at which Im is measured are made using a linear fit:

$$\frac{Ic}{Im} = \frac{Tref - Tc(B)}{T - Tc(B)}$$

where Im and Ic are the measured critical currents at T and Tref, respectively. Tc(B) is an effective critical temperature, i.e., the temperature at which the linear fit gives Ic = 0. The above equation is a good approximation in the temperature range of interest, viz., 2 K to 4.6 K. A good approximation for Tc(B) in the field range of interest, viz., 3 T to 8 T, is given by the following expression:

$$Tc(B) = 9.2 \left(1 - \frac{B}{14.5}\right)^{0.59}$$

where B is the field in tesla. B is determined as described in the following section.

9. Magnetic Field Correction

The magnetic field is the sum of the applied field produced by the dipole magnet and the self-field produced by the measuring current. The latter produces a substantial correction. However, its effect is difficult to assess because it is spacially non-uniform, it is hard to calculate exactly, and it depends upon the geometrical details of the bifilar sample. Experience has shown that the following assumptions give results which are self-consistent for a wide variety of geometries and which give reliable predictions of magnet behavior.

a) The critical current of the sample is determined by the peak magnetic field. This depends, of course, on the orientation of the applied field and the direction of the sample current. This important point will be discussed further in the next section.

11. Data Averaging Using I-B Graph; Degradation

The critical currents are plotted on a graph of I vs. B. A straight line is fit to the data (Ic generally follows a linear variation with field for B in the range 4 to 7 T and T between 2 and 4.6 K). In making this fit, the slope is adjusted to be the same as that determined in the wire measurements (multiplied by N), since the latter is more accurate than the value obtained for the cable data. This ratio should be the same for wire and cable unless there is a post-cabling heat treatment. In this case, the slope must be determined for wire samples taken from the cable.

The short sample value of Ic(B) is read off from this straight line for any field of interest. The degradation of the cable, as mentioned before, is $D = 1 - (Ic/\Sigma Icw)$. In practice, a few wires are measured and Σ Icw is estimated from this sample. In cases where questions arise as to whether D meets a specification, it is necessary to determine Icw for all the wires in the cable map.

We have hitherto ignored the fact that the critical current of a wire is also subject to a self-field effect. However, it has become general practice <u>not</u> to take account of this correction, notably in discussions of Jc in the literature. For cables it is not acceptable to ignore self-field corrections for the reasons given previously: sensitivity of measurements to sample configuration and comparison of data with magnet performance. As a result of this convention, the specified degradation is lower than the true degradation, which would take account of wire self-field effect and lead to a larger value of ΣIcw.

and averaged. The taps are relatively close to the heater in order to minimize the effect of current fall-off which results from the increase of normal state resistance as the quench propagates.

Some rough values to illustrate the magnitude of the quantities involved are: I = 3000 A, V = 3 mV/4 cm, R = 0.25 μV/cm.

The usual specification is for zero magnetic field. The above measurement may be made in an external field, however, in order to determine the magnetoresistance effect.

4. Room Temperature Resistance Correction

Normally occurring room temperature variations produce significant variations in the measured resistance. Designating this resistance as Rm and the ambient temperature as t(^{o}C), the resistance at the reference temperature of 295 K is calculated as follows:

$$R295 = Rm / [1 + 0.0039 (t - 22)]$$

The effect of the NbTi is negligible for the purpose of this correction.

5. Reported Quantities

The manufacturer ID, wire diameter, nominal Cu/SC ratio, and number of wires are recorded for each test specimen. The following results are recorded:

R295 (μ ohms/cm)
R10 (μ ohms/cm)
RRR

Optional (if requested)

R10 for B = 5 T
RRR for B = 5 T

6. Copper/Superconductor Ratio

The Cu/SC volume ratio may be calculated from R295 and R10 by means of the formulae in Technical Note 385. In applying these formulae the cable resistance must first be multiplied by N, the number of wires. A length correction factor is also applied, viz., the ratio of the length of a piece of cable to that of each of the wires prior to cabling. It has been found that this correction leads to good agreement between wire and cable Cu/SC values.

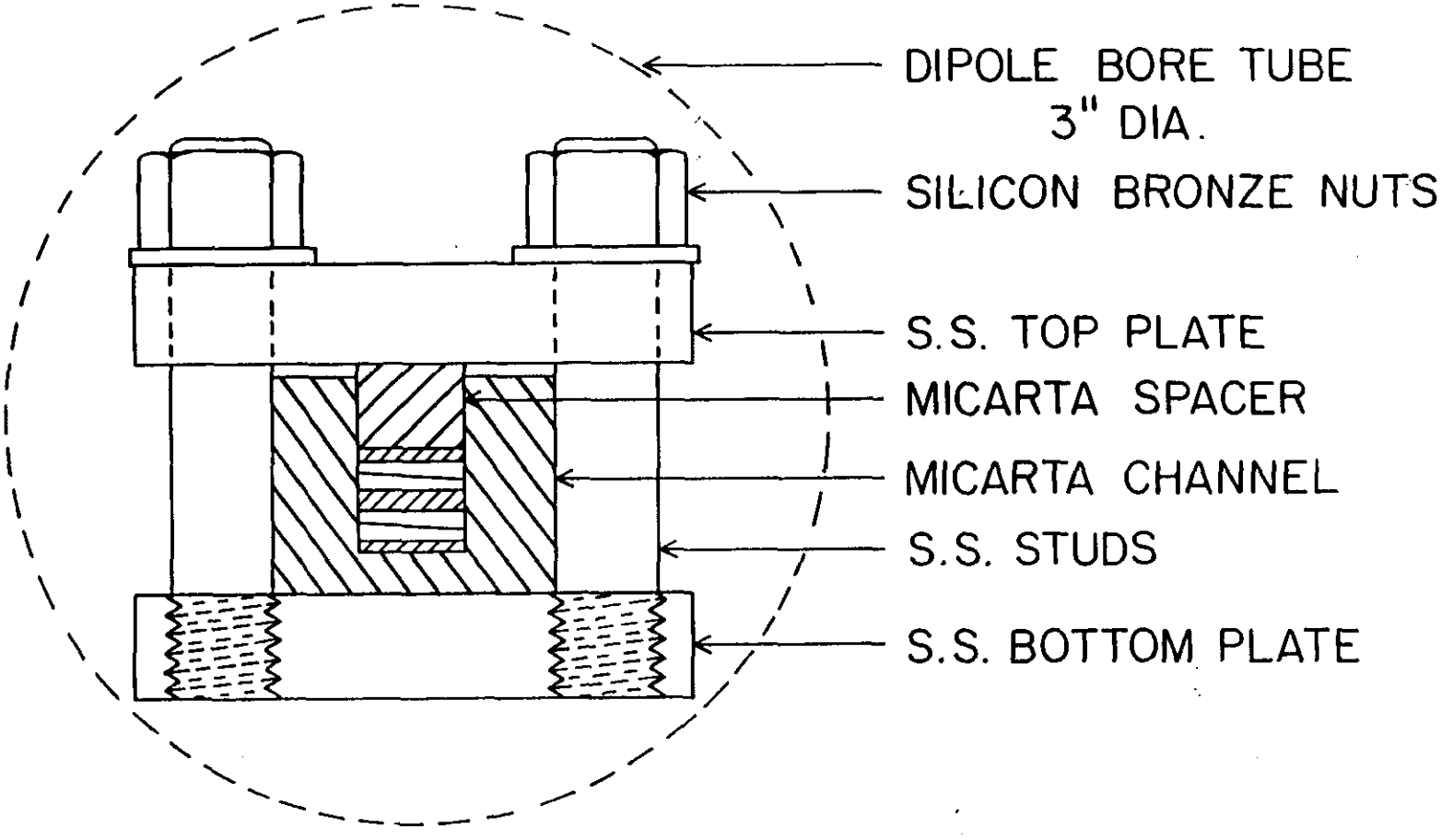

Figure 1. Mechanical Assembly.

Two bifilar pairs of keystoned 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 below, between, and above the bifilar pairs; thicknesses of the G-10 strips are 0.030, 0.130, and 0.030 in., respectively. The stainless steel studs are located 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.

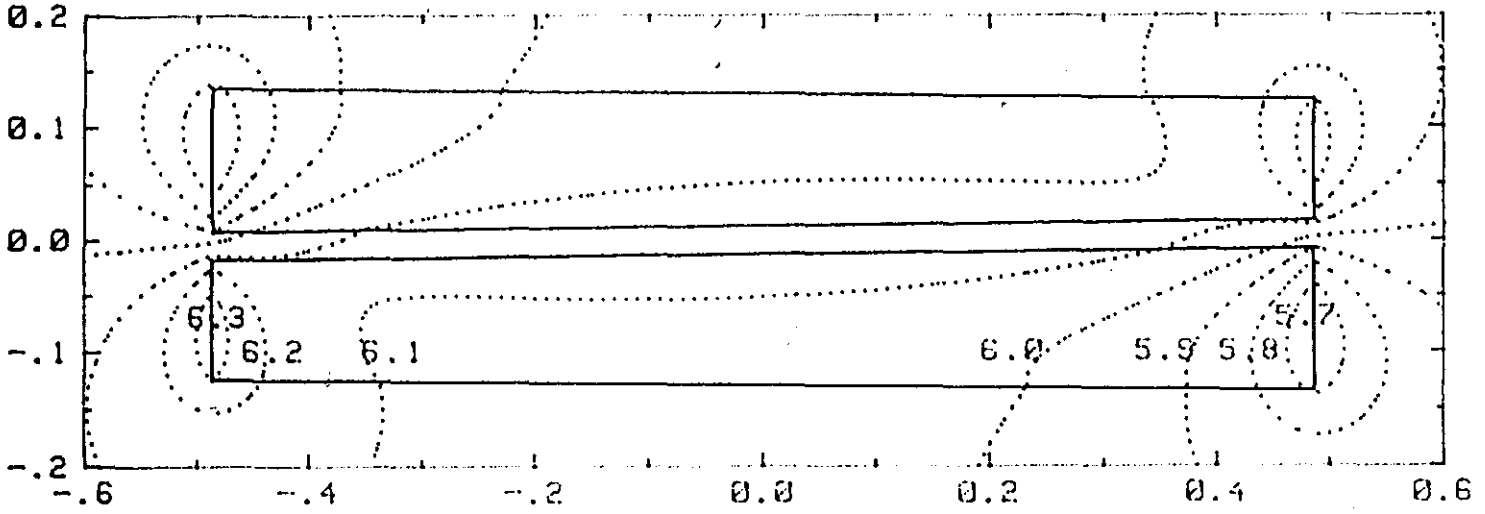

Figure 3. Contours of Constant Field Magnitude.

Calculated contours for perpendicular applied field of 6 T and current of 10 kA. The peak field is 6.4 T and occurs along the thinner edge of each conductor (left side of lower and right side of upper conductor).