NORMAL STATE RESISTANCE AND LOW TEMPERATURE MAGNETORESISTANCE OF SUPERCONDUCTING CABLES FOR ACCELERATOR MAGNETS*

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Abstract

The normal state resistivity of the superconducting NbTi cable used in accelerator magnets is usually specified by the resistance per unit length at room temperature (295 K) and the residual resistance ratio (RRR). Using these resistance parameters, the amount of copper in the multifilamentary wire can be calculated. This method is consistent with the traditional etch and weigh technique, and as such is an alternative and convenient way of specifying the copper to superconductor ratio. In principle the magnetoresistance can be calculated from the RRR and the "Kohler Plot", for copper. In practice however, measurements of magnetoresistance for a wide variety of SSC inner cables show considerable disagreement with calculation. In this paper the magnetoresistance data on cables with RRR ranging from 50 to 175 are analyzed taking into account the conductor geometry and the effect of the small interfilamentary spacing on the resistivity of copper.

Introduction

The electrical resistance of the multifilamentary NbTi wire which is used to make superconducting magnet cable is routinely measured at 295 K and 10 K. From these two measurements can be determined the amount and purity of the copper in the wire. Similar measurements are also made on the effect of transverse magnetic fields on the normal state resistance of the cable. These normal state resistances are relevant in determining quench propagation characteristics and the maximum temperature reached in the coil windings of a magnet during a quench. In the first part of this paper we discuss the relationship between the room temperature measurement and the amount of copper in the superconducting wire. The second part deals with the transverse magnetoresistance of SSC prototype cables.

Resistance and Copper to Superconductor Ratio, Cu/Sc

In this section we examine the quantitative relationship between the resistance and the copper to superconductor ratio, X . A study of CBA wires with a nominal X of 1.7 has been reported by Garber et al.¹ In the present report, wires from several sources with X values ranging from 1 to 3 were examined. Resistances and critical currents were measured on 75 cm long samples. Two 25 cm pieces were then cut from each sample for the mass determination as outlined below.

The copper to superconductor ratio is defined in terms of the volumes of the respective components. It can be calculated from four quantities: A , the area of cross section; m , the wire mass per unit length; m_s , the mass of NbTi per unit length, and δ_{cu} , the density of copper. The superconductor mass was determined by weighing after etching away the copper matrix. Each sample was weighed three times: before etching, after a 15 minute etch in 50% nitric acid solution and after a second 15 minute etch, to make certain that all the copper was removed. Weight readings before and after the second etch agreed to within ± 0.1 mg. This corresponds to $\pm 0.5\%$ in m_s . The copper to superconductor ratio, X_m , is calculated from,

$$X_m = \left(\frac{A \delta_{cu}}{m - m_s} - 1 \right)^{-1} \quad (1)$$

The room temperature resistance R_t is measured at ambient temperature ($^{\circ}\text{C}$), and the resistance at the reference temperature of 295 K is calculated from:

$$R = R_t / [1 + 0.0039 (t - 22)] \quad (2)$$

The low temperature resistance R_{10} is measured just above the transition temperature of NbTi. The residual resistance ratio r is then defined as

$$r = R/R_{10} \quad (3)$$

The room temperature resistance can be written as,

$$\frac{1}{R} = \frac{X}{(1+X)} \frac{A}{\rho_{cu}} + \frac{1}{(1+X)} \frac{A}{\rho_s} \quad (4)$$

or,

$$X = \frac{1 - RA/\rho_s}{RA/\rho_{cu} - 1} \quad (5)$$

where ρ_{cu} is the copper resistivity at 295 K and ρ_s is the resistivity of NbTi $\approx 60 \mu\Omega/\text{cm}$. Variations in ρ_{cu} due to impurities may be approximated by

$$\rho_{cu} = \rho_i \frac{r}{r-1} \quad (6)$$

where $\rho_i = 1.695 \mu\Omega\text{-cm}$ is the resistivity of pure copper.

If the low temperature resistance is not known a value of ρ_{cu} of $1.71 \mu\Omega\text{-cm}$ can be used which is equivalent to an RRR of approximately one hundred, a typical value for composite wire.

Figure 1 shows the copper to superconductor ratio X_R as derived from resistance measurements plotted against that obtained by mass determination X_m . For some samples $X_R < X_m$ probably due to variations in cross sectional area. This "sausaging" of the filaments has been observed in microstructural studies and is correlated with the low n -values indicative of non-uniform filaments.²

Fig. 1. Resistive determination of Cu/Sc, X_R , plotted versus mass determination, X_m .

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Resistance Specification for Superconducting Wires

Using eq. (5), the resistance of wires of different diameters can be calculated as a function of Cu/Sc ratio. This is shown in Fig. 2 for the wires used in SSC cables. The range of acceptable values of R is determined by the Cu/Sc ratio and wire diameter tolerances. The above calculations can be extended to cables. In applying these formulae the cable resistance is multiplied by N , the number of wires and a length correction factor applied.

Fig. 2. Plot of resistance per cm for SSC inner and outer wires as a function of copper to superconductor ratio.

Transverse Magnetoresistance of Superconducting Cables

In this section we present magnetoresistance data on some SSC cables. We show that the measurements on conductors with very small NbTi filaments agree with the magnetoresistance of bulk copper provided size effect enhancement of the copper resistivity in the interfilamentary region is taken into account.

Test Procedure for Cables

The room temperature resistance measurement is made using a DC current of 1 A, and voltage contacts 70 cm apart (see Fig. 3). A thermocouple device of 0.1°C accuracy is used to determine the ambient temperature. Temperature correction to 295 K is made using eq. (2).

Fig. 3. Electrical wiring schematic experimental arrangement for determination of cable resistance.

The low temperature measurement is a dynamic one, made by inducing a quench when the cable is carrying current. Referring to Fig. 2, a quench is triggered in cable A, for example, by means of heater HA. The resulting waveform observed at nearby voltage taps, A2-A3 or A3-A4, consists of three parts: a superconducting state baseline voltage, a linear ramp voltage corresponding to the passage of the superconducting-normal interface between the volt-

age taps, and a slowly increasing signal characteristic of the normal state resistance. The latter increases in time due to normal state heating. However, at first the voltage is almost constant and is due to the residual resistance of the copper. Thus, there is a kink in the voltage waveform at the beginning and at the end of the linear ramp portion. The voltage difference between these two points equals the current times the residual resistance of the section of cable between the voltage taps. The resistance per centimeter is determined for two pairs of taps (A2-A3 and A3-A4 in Fig. 3) 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.

The above measurement is made at zero field and in an external transverse field in order to determine the magnetoresistance effect. The longitudinal quench propagation velocity can be deduced from the same test.

Experimental Data

Like copper, the magnetoresistance of the cables was found to be linear with field in the range $1 < H < 6$ tesla. Figure 4 shows the data for some of the cables that were studied. Considerable variation in the low temperature resistance is possible even for cables with the same Cu/Sc. Cable SC368A is similar to SC368B except the former was annealed after cabling. Table 1 lists the cables and their relevant geometric parameters.

Fig. 4. Resistance per unit length of SSC prototype cables as a function of applied magnetic field.

From a magnet designer's point of view the quantity of interest is the resistance at field which is given in Fig. 5, as the ratio of the resistance of 6T to that at zero field plotted vs the measured RRR. The solid line reflects recent data at 4.2 K for oxygen-free copper as compiled by Fickett.^{3,4} Clearly, for the conductors which have filaments with diameters, $d \sim 5 \mu\text{m}$, the measured magnetoresistance is higher than that predicted by the bulk copper data.

Fig. 5. The ratio of resistance at 6 tesla and at 0 tesla of SSC cables as a function of the measured RRR. The solid line is Fickett's^{3,4} data for bulk copper.

Size Effect in Multifilamentary Superconducting Wires

The discrepancy between the predicted and measured values of magnetoresistance can be reconciled by taking into account the resistivity enhancement in copper due to the so called "size effect". This becomes important when the bulk electronic mean free path, ℓ , becomes comparable to some sample dimension. The boundary scattering of electrons in effect reduces the scattering length and thereby increases the resistivity. Brändli and Olsen⁵ have written a detailed review of this effect and more recently Cavalloni et. al.⁶ have presented experimental evidence for the existence of a size effect on the longitudinal resistivity of multifilamentary superconducting wires.

Although there are several expressions for the resistivity enhancement the simplest one, by Nordheim,⁵ is the one we shall use. In the copper-stabilized wires there are usually two regions: (a)

those which are free of filaments and (b) those consisting of a array of NbTi filaments. The surfaces of the NbTi filaments act as boundary scatterers, and the copper in the interfilamentary region has a higher resistivity when ℓ is greater than the interfilament spacing, S . Assuming diffuse scattering at the NbTi interface, the resistivity of the copper can be represented by:

$$\frac{\rho_1}{\rho_0} = 1 + (1/K) \quad (7)$$

In this case $K \equiv S/\ell < 1$ and ρ_0 is the residual resistivity of (a) and ρ_1 the resistivity of (b). At 295 K, $\ell \ll S$ and the size effect is unimportant. Equation (7) can be written as:

$$\frac{r_1}{r_0} = \left(1 + \frac{\ell}{S}\right)^{-1} \quad (8)$$

where r_1 is the RRR of region (b) and r_0 is the RRR of the region (a). The mean free path can be calculated from $\rho\ell = 6.56 \times 10^{-12} \Omega \cdot \text{cm}^2$. From this the $\ell = 0.0387 r_0 \mu\text{m}$. Using this in eq. (8) we find that

$$r_1 = r_0 \left(1 + \frac{0.0387}{S} r_0\right)^{-1} \quad (9)$$

The interfilament spacing, S , is related to the local Cu/Sc ratio, X_L , by

$$X_L = 1.1(1 + S/d)^2 - 1 \quad (10)$$

where S and d , the filament diameter, are in microns. Using the geometric parameters X , X_L , and d , and the measured value of r , we can calculate r_0 and r_1 . These are given in Table I. For large filament conductors similar to those studied by Cavalloni et. al.,⁶ the ratio $(r_0/r_1) \sim 2$. However in fine filament conductors with small S values this ratio can be much higher. Thus if the RRR of the bulk copper is 100 the RRR of the copper between the filaments is only 20. Furthermore if the bulk copper is improved to 200 by annealing the interfilament copper ratio only increases to 23 for a conductor with a one micron filament spacing. A simple calculation leads to the residual resistivity ratio of the composite:

$$r = [(X - X_L) r_0 + X_L r_1]/X \quad (11)$$

and r is always less than r_0

Now if we assume that in field, the copper increases in resistivity in accordance with its respective RRR, then the ratio of the resistance at 6 tesla to that in zero field can be determined by reference to the bulk copper curve of Fig. 5. The dashed curve in Fig. 5 was calculated for $X = 1.5$, $X_L = 0.6$, $S = 1.2 \mu$ and $d = 6 \mu$,

Table I

Cable Sample	Wire Dia. mm	Cu/Sc, X	Filament Dia. μm	Local Cu/Sc, X_L	RRR				$S \mu\text{m}$	R(6T)/R(0T)	
					r	r_0	r_1	r_0/r_1		Meas.	Cal.
SC357	0.81	1.45	5	0.45	166	232	17.9	13.0	0.75	1.12	4.20
SC368A	0.81	1.2	6	0.50	125	198	22.8	8.7	1.0	3.32	3.47
SC368B	0.81	1.2	6	0.50	53	77	19.3	4.0	1.0	1.85	1.85
SC368B1	0.81	1.2	6	0.50	136	248	27.5	9.0	1.0	3.65	3.70
FG6218	0.81	1.28	4.7	0.45	116	171	16.6	10.3	0.7	3.20	3.26
SC363	0.81	1.6	20	0.45	79	94	46	2.0	3.0	2.01	2.14
SC347A	0.81	1.33	5	0.8	115	241	31	7.7	1.4	3.15	3.39
SC347A1	0.81	1.33	5	0.8	57	102	26.7	3.8	1.4	1.90	1.96
SC352	0.81	1.60	5	0.45	62	80	15.6	5.1	0.75	2.10	2.00
SC362	0.81	1.40	6	0.5	64	89	20	4.5	1.0	2.05	2.04
XT-12	0.81	1.3	23	0.8	69	86	58	1.5	6.9	1.90	1.94
SO118	0.65	1.8	15	0.6	84	104	44	2.4	3.0	2.20	2.25

the parameters for the SSC inner cable. Measured values of the R_0/R_n ratio for conductors of this type, the open points in Fig. 5, agree with the calculated curve to a remarkable degree. Conductors with larger filaments and therefore larger filament spacing, the solid points, are almost indistinguishable from bulk copper.

Conclusions

Resistance measurements which are routinely made on superconducting wires and cables for accelerator magnets can provide an accurate measure of the copper to superconductor ratio. Compared to the etch and weigh technique a resistance specification for Cu/Sc is preferable for monitoring of this parameter during wire and cable production.

Results shown here indicate that by using the 4 K magnetoresistance data of bulk copper and the size effect formula for the resistivity enhancement of copper, the measured RRR can be used to estimate the resistance at high fields.

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