THE EFFECT OF SELF FIELD ON THE CRITICAL CURRENT DETERMINATION OF MULTIFILAMENTARY SUPERCONDUCTORS*

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Abstract

In determining the short sample critical current of conductors of large cross section or high current density the self field produced by the transport current must be taken account in order to obtain a "true value" for the critical current. A simple model calculation for determining this effect is described. Measurements on wires, cables, and monoliths show the validity and self consistency of the procedures.

Introduction

It has been known from the earliest days of superconductivity that the self field plays a role in the determination of the transport critical current, I_c . Since the self field is proportional to the current it is especially important in connection with modern high current conductors. Frequently, little account is taken of this in the reporting of critical current data. This is probably due to the fact that modern conductors are complicated configurations of twisted filaments and/or wires, and an exact calculation of the self field would be formidable if not impossible. In an earlier paper¹ we described a simple model calculation of the self field of an accelerator magnet (Rutherford type) cable. Since then experience has shown that the application of this simple procedure gives currents which are self consistent in a number of ways. For example, the results are independent of the short sample test geometry. This is important in reporting results for quality control purposes. Likewise, comparison of short sample results with magnet performance is found to be in much better agreement.

In this paper we describe the application of our method to several multifilamentary NbTi conductors: wires, SSC type cables, and a monolithic conductor of rectangular cross section. In each case the magnetic field in a plane normal to the direction of current flow is calculated assuming the current to be distributed uniformly over the entire cross section of the conductor. In the case of the cable the cross section is taken to be the trapezoidal figure enclosing all the wires. The magnitude of the peak field resulting from the sum of the applied field, B_a , and the self field is called B_p . An important assumption we make is that the proper field to be used with the measured critical current is the peak field, B_p , rather than the applied field or the average field.

The critical current is defined as the 10^{-12} ohm cm value at $T = 4.222$ K. The experimental method for determining I_c is described elsewhere.^{2,3,4} A preliminary discussion of the self field correction was given at the 1986 ICFA meeting.²

Multifilamentary Wires

Wires are generally measured in the form of coiled samples with relatively wide spacing between turns. The peak field at the wire surface is, to a good approximation:

$$B_p = B_a + 4 \cdot 10^{-4} I / D$$

$$= B_a + \pi \cdot 10^{-4} J D / (1+x) \quad (1)$$

where B is in tesla, I in amperes, and D , the wire diameter, is in mm. J is the current density in the superconductor in A/mm^2 , and x is the copper-to-superconductor ratio. Figure 1 shows the application of this formula to critical current data for a multifilamentary wire of the type used in SSC cables.⁵ The lower curve shows the I_c data plotted versus B_a -values; the upper solid curve is a plot of the

same data versus the B_p -values. The open circles in Figure 1 show the results of magnetization measurements of J_c at a number of fields. The experimental details of the magnetization measurements are given in reference 6. J_c is calculated by means of the Bean-London formula:

$$J_c = 1.9 \cdot 10^6 \cdot (1+x) \Delta M / d \quad (2)$$

where ΔM is the width of the magnetization loop in tesla and d is the filament size in μm . The magnetization data agree well with the self field corrected transport data. Filament sausing is small in this wire so that differences between the transport and magnetization currents mentioned by Wilson⁷ are not discernible in this sample. The high field differences are attributed almost entirely to the self field effect. The dashed curve in Figure 1 is an extension of the critical current curve into the low field region where it is not accessible to transport current measurements because of the self fields.

Fig. 1. Critical current density in a wire with $D = 0.65$ mm, $C/S = 1.8$, filament dia. = $5 \mu m$, n -value = 25 at 5T.
(- - -) transport J_c plotted against B_a .
(—) transport J_c plotted against B_p .
(O O O) J_c calculated from D.C. magnetization.

Equation 1 shows that the self field effect is proportional to D and J_c . this is illustrated in Figure 2 for a range of values common in practice. The ratio of self field corrected critical current density, J_{sf} , to the uncorrected value, J_a , is plotted against J_a for wires of diameter 0.1, 0.5, and 1.0 mm. The copper to superconductor ratio is assumed to be 1.5 and the ratio of J_c at 5T to J_c at 6T is assumed to be 1.25. For fine wires the correction is negligible but for wire sizes of the order of 1 mm the correction is considerable. An illustration of the size effect is shown in Figure 3. Results are shown for a group of wires which were drawn down as part of a J_c -maximization study. The critical current density is plotted against true strain after the last heat treatment. The larger conductors show relatively lower currents when no self field correction is made. After making the correction J_c varies smoothly with strain. Not only is it more difficult to produce high J_c 's in larger wires, but an additional penalty is paid in reporting the results if the self field correction is omitted.

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Fig. 2. Self field correction as a function of J_a for various wire sizes. $C/S = 1.5$, $J_c(5T)/J_c(6T) = 1.25$.

Fig. 3. Critical current density vs strain for wires of different diameters: $\bullet$: J_c -(uncorrected values at 5T). $\circ$: J_c -(corrected values). The length of the vertical line for each wire is the self field correction. It is proportional to $J_c \times D$.

Cables

The higher currents in cabled conductors lead to a qualitative as well as quantitative difference in the technique of measurement. This is due to the large Lorentz forces which occur so that great care must be taken to constrain the cable samples. An advantageous way to do this is to make the sample straight and bifilar in form. It is then clamped in a stainless steel holder.^{2,3,4} The external field is supplied by means of a superconducting dipole magnet. A sample length of 1 m provides adequate sensitivity. Figure 4 illustrates the sample geometry. Usually, two sample pairs are assembled, as shown; measurements are made on one pair at time. Details of the electrical measurements and of the clamping fixture are given in references 2-4.

The applied field is usually oriented either parallel or perpendicular to the cable, i.e., to the wide dimension of the cable. In the parallel case the self field in the gap between the conductors either adds to the applied field, in which case B_p is located along the inner edge, or subtracts from the applied field, in which case B_p is located along the outer edge. This is illustrated in Figure 4 by the points labelled $B_p(II,+)$ and $B_p(II,-)$, respectively. In the perpendicular case the peak fields are located along the edges, where the self and applied fields are in the same directions. The direction of the current flow determines whether B_p is located along the thick or thin edges, see Figure 4.

Fig. 4. Arrangement of cable samples in a short sample test. The bifilar pairs are tested separately. The locations of the peak fields are shown for one cable.

$B_p(II,-)$: B_a and self field add on outside surfaces.

$B_p(II,+)$: B_a and self field add on inside surfaces.

$B_p(I,thin)$: B_a and self field add along thin edges.

$B_p(I,thick)$: B_a and self field add along thick edges.

M: 0.25 mm mylar separators.

G: 0.8 mm G-10 strips which contain instrumentation.

The self fields have been calculated using the complex variable method of Beth.⁵ Some results of these calculations are shown in Figures 5-7. Contours of constant field magnitude are shown superimposed on an outline of a bifilar cable pair for the (II,+) and (I,thin) cases in Figures 5 and 6, respectively. The quantity $(B_p - B_a)/I$ is referred to as the self field parameter, (B/I) for short. Figure 7 shows a plot of this parameter for the various geometries of interest. Since the peak field generally occurs at a point where the applied and self fields are simply additive the self field parameter is essentially constant over all but the lowest fields. For large gap separations the (B/I) values go to those appropriate for a monoilar conductor test.

Fig. 5. Constant magnitude field contours for a bifilar pair of SSC cables in the (II,+) configuration. $B_a = 6T$, $I = 10$ kA, dimensions in mm. See reference 5 for a detailed description of the cable.

Fig. 6. Constant magnitude field contours for a bifilar pair of SSC cables in the (I,thin edge) configuration. $B_a = 6T$, $I = 10$ kA, dimensions in mm. See reference 5 for a detailed description of the cable.

Fig. 7. Variation of the self field correction parameter, $(B_p - B_a)/I$, vs bifilar gap for SSC type cables. For gaps ≥ 100 the self fields are equivalent to those of monofilar samples.

Fig. 8. Critical current in a 30 wire SSC cable made from a single spool of wire with $D = 0.5$ mm, $C/S = 1.75$
 (a) Cable I_c vs B , parallel orientation. $\circ$: $(||, +)$ $\square$: $(||, -)$
 (b) Wire $I_c \times 23$ vs B , self field corrected.
 (c) Wire $I_c \times 23$ vs B , uncorrected.

All the wires in the cable pass repeatedly through the peak field region in a given experiment. As mentioned above, we hy-

pothesize that the critical current of the cable is determined by the properties of this region and the calculated peak field. An exception to this occurs if another region of the cable is sufficiently damaged that the critical current is limited by it even though the field is lower there; however, this does not happen under usual manufacturing practice.

Figures 8 and 9 show the validity of these ideas. The cable tested was made from a single spool of wire so that comparison with the properties of the pre-cabled wire could be made unambiguously. Curve (a) of Figure 8 shows $(||, +)$ and $(||, -)$ data for three applied fields. The I_c values are plotted vs the peak fields and fall on a single line even though the self field parameters are quite different. Note that points from the $(+)$ and $(-)$ configurations overlap. Curves (b) and (c) show how curve (a) compares with wire data. (c) is the critical current curve for the wire (multiplied by the number of wires in the cable) plotted without self field correction, i.e., vs B_a . It lies well below curve (a). However, the corrected curve, (b), lies just above (a). The small difference, about 1%, may be due to measurement inaccuracy, error in the method of correction, or degradation in the cable, but it is clear that these are all small. The wire in the flat region of the cable experiences very minor deformation and it is, therefore, very reasonable that cable and wire data agree. This behavior is found to be true for all wire and cable measurements when the wire data is known and can be averaged properly.

Figure 9 shows results for the two perpendicular configurations together with the parallel results. Since the wires experience consider mechanical deformation in the edge regions the critical

Fig. 9. Critical currents in a 30 wire SSC cable made from a single spool of wire with $D = 0.5$ mm, $C/S = 1.75$
 (a) Parallel field orientation
 (b) Perpendicular field; B_p is located on the thick edge
 (c) Perpendicular field; B_p is located on the thin edge

currents for these test configurations are generally lower. The thin edge deformation is the severest and I_c the lowest. For this reason, and because the maximum field in a dipole magnet winding occurs near the thin edge (see below), the $(\perp, \text{thin})$ value of I_c , curve (c), is

specified for predicting magnet performance. The difference between the wire I_c curve (b) of Figure 8, and this curve is the cable degradation. In the present example it is 11%. Often a degradation value is cited which is based on the as-measured, i.e., uncorrected, critical current of the wire. This value is always less than the true degradation (and even comes out negative sometimes). In the present example it is 7% or 4% less than the true degradation.

The $I_c(\parallel) - I_c(\perp)$ difference in a cable is thus attributable to the different regions which are sampled in the two measurements. It is not an anisotropy in the usual sense.

An interesting relationship has been observed between the critical currents of wires removed from a cable and the perpendicular thin edge current. When the uncorrected 10^{-12} ohm cm currents are summed for all the wires, a value which is very close to the true cable current is obtained. This "Rule of Thumb" appears to apply for all cables studied irrespective of the degree of degradation. Thus, it is possible to estimate the cable current by testing several wires taken from the cable. It should be noted that this rule works despite the complex voltage pattern along such wires which results from the severe kinking due to cabling. This is not the same I_c as is measured in virgin wires.

Table I lists results for two cables which illustrate the correlations discussed in this section. Although the Cu/SC ratios are the same the two cables are made of different wire and have different geometries. The solid lines indicate the correspondence between parallel cable and self field corrected wire I_c 's. The dashed lines indicate the rule of thumb just discussed, viz., as-measured I_c 's of wires removed from a cable agree with perpendicular cable values. This rule is seen to be obeyed even the degradations are rather different, 11% for the first, and 6% for the second cable. In the latter case, incidentally, use of the uncorrected wire I_c 's would lead one to calculate zero degradation.

Table I

Comparison of cable critical currents with wires before and after cabling. I_c values are given in parentheses. Cu/SC=1.8 B=5T T=4.22K

Wire Sum:	SSC Outer Type	Expt'l Inner
Self field corrected	10370 (2890)	11900 (2830)
Precabling, as meas'd	9990 (2780)	11110 (2650)
From cable, as meas'd	9300 (2590)	11100 (2650)
Cable:		
Perpendicular	9250 (2570)	11150 (2670)
Parallel	10300 (2870)	11960 (2850)

Monoliths

Multifilamentary monoliths of rectangular cross section are often used to make MRI magnets. I_c specifications usually refer to the parallel configuration because these conductors are wound into solenoidal coils. It is convenient to use the same measuring arrangement as for the cables. As the monoliths are somewhat smaller than the cables it is possible to vary the ratio of gap to conductor width over a greater range, and hence the self field parameter also. Figure 10 shows a plot of (B/I) for the monolith studied. Experimental results for two gap separations are shown in Figure 11. At each applied field I_c is determined four times: for the two gaps and two current directions. Four different (B/I) values correspond to the measured I_c 's. The self field corrections are indicated by the dotted lines in Figure 11. The points for all four configurations and for all of the applied fields fall nicely on a single I-B curve, which can be considered to be the characteristic curve for this orientation. Thus the self field corrections give consistent results for a wide range of currents and geometries.

The perpendicular data are shown in Figure 12. They are not as interesting since the (B/I) values vary much less for the two

gaps. They are 15% lower than the parallel, probably due to a genuine anisotropy effect.

Fig. 10. Variation of the self field correction parameter $(B_p - B_a)/I$ vs the bifilar gap for a bifilar pair of monoliths.

Fig. 11. Parallel field critical current for a bifilar pair of monoliths for combinations of two gap separations and both directions of current. ●: critical current plotted at the applied field, B_a . ○: critical current plotted at the peak field, B_p . Horizontal dashed lines represent the self field correction.

Fig. 12. Perpendicular field critical currents for a bifilar monolith pair for gaps of 0.9 and 12.7 mm.

Fig. 13. Load line and cable short sample data, I_C , for a 1.8 m model SSC dipole magnet. I_Q is the quench current observed in the short sample test. Inset: schematic of one quadrant of the inner winding layer showing the location of the peak field in the magnet. The dipole axis is vertical.

Discussion

The self field corrections described in the foregoing sections enable the characteristic $I_C(B)$ curve to be determined consistently for a variety of geometries. This procedure is useful in materials studies such as I_C optimization and cabling degradation, in quality control and purchase specifications, and in comparisons of short sample data with magnet performance. It should be noted, however, that predicting the performance of a device such as a dipole magnet is more complicated than a simple comparison with the short sample I_C value. This is due primarily to the fact that the quench current, I_Q , is not related to I_C in a simple way. Figure 13 illustrates this for short sample measurements of SSC type cables. At high fields and relatively low currents the conductor can carry considerably in excess of the 10^{-12} ohm cm current, while at low fields quenching takes place before the relatively high I_C 's are reached. In addition, the peak field in a magnet does not occur exactly at the same point as in the short sample test set-up. The inset of Figure 13 shows a schematic of one quadrant of the inner winding of an SSC dipole. The calculated peak field is seen to occur near, but not quite at the thin edge of the polar turn. Thus a slightly higher performance may be expected than is indicated by the load line-short sample intersection.

The successful identification of measured I_C 's with the peak field has the important physical implication that current transfer between filaments is very small over lengths of order 1 m. Otherwise, I_C would reflect a dependence on the average fields in the conductor rather than on the peak fields. The same conclusion applies to current sharing between wires in a cable. It is indeed observed in our 1 m test apparatus that when an individual wire of a cable contains a cold weld splice the critical current of the cable is reduced by the amount that wire would normally carry.⁹

References

- [1] M. Garber and W.B. Sampson, "Critical Current Anisotropy in NbTi Cables", *IEEE Trans. Magn.*, Vol. MAG-21, pp. 336-338, March 1985.
- [2] 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, May 1986.
- [3] A.K. Ghosh, M. Garber, K.E. Robins and W.B. Sampson, "Training in Test Samples of Superconducting Cables for Accelerator Magnets", *Proceedings of 1988 Applied Superconductivity Conference* (this volume).
- [4] M. Garber and W.B. Sampson, "Test Methods for Cable Critical Currents and Normal State Resistance", SSC Technical Note No. 70, Brookhaven National Laboratory, March 1988. (unpublished)
- [5] "NbTi Superconductor Cable for SSC Dipole Magnets", SSC Material Specification No. SSC-MAG-M-402, June 1987.
- [6] A.K. Ghosh, K.E. Robins, and W.B. Sampson, "Magnetization Measurements on Multifilamentary Nb₃Sn and NbTi Conductors", *IEEE Trans. Magn.*, Vol. MAG-21, pp. 328-331, March 1985.
- [7] M.N. Wilson, *Superconducting Magnets*, Oxford Univ. Press, 1983. cf. p. 247.
- [8] R.A. Beth, "Evaluation of Current-Produced Two-Dimensional Magnetic Fields", *J. Appl. Physics* Vol. 40, pp. 4782-4786, November 1969. A Fortran program, "AFLD2", by G. Morgan was used.
- [9] M. Garber and W.B. Sampson, "Short Sample Results for Cable S/C 374. The Effect of Cold Welds", SSC Technical Note No. 74, Brookhaven National Laboratory, April 1988. (unpublished)