CONF-740957--16

TITLE: ADJACENT CONDUCTOR FIELD CORRECTIONS TO HIGH CRITICAL CURRENT
SHORT SAMPLE MEASUREMENTS

AUTHOR(S): Gilbert A. Miranda and John D. Rogers

SUBMITTED TO: Applied Superconductivity Conference, Oakbrook,
Illinois, September 30-October 2, 1974.

MASTER

By acceptance of this article for publication, the publisher recognizes the Government's (license) rights in any copyright and the Government and its authorized representatives have unrestricted right to reproduce in whole or in part said article under any copyright secured by the publisher.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the U. S. Atomic Energy Commission.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

We have measured the critical current of several superconductors to 24 kA in magnetic fields to 4.5 T. The samples were hairpin shaped with the straight section under test in a perpendicularly applied field. The proximity of the straight parts causes the field of the current in one leg to change the applied field in the other leg. We have corrected the measured results for this adjacent conductor field (ACF). These corrections result in data for uniform applied fields. One conductor was used in a 300 kJ magnet. This single-layer, edge-wound coil was rated near 9.8 kA using the uniform field data. Under test the magnet reached 12.5 kA giving no sign of approaching the critical current. The "excess current" is due to the field gradient across the conductor in this coil. One contribution is due to the variation of j_c with the field value within the conductor. A second contribution results from the position dependent anisotropy of the filaments. A third possibility is to change the definition of I_c . We have chosen the definition to be the current at which the sample generates an electric field of 3.5 $\mu\text{V/m}$. If 46 $\mu\text{V/m}$ were chosen, I_c would rise approximately 0.86 kA at 17 kG.

I. INTRODUCTION

We have measured the critical current of several large, twisted, multifilamentary NbTi superconductors to 24 kA in fields to 4.5 T. A one-shot flux pump and a dipole magnet similar to that described by Purcell and DesPortes¹ were used. In this apparatus the samples are hairpin shaped and the applied field (B) is perpendicular to the straight section of the conductor.

The proximity of the straight parts causes the field of the current in one leg to change the field in the other leg. This adjacent conductor field (ACF) shifts the I_c curves an amount which depends on the conductor spacing, the critical current, and the direction of the ACF relative to B.

For isotropic conductors there are three measured curves; one each when the ACF aids or opposes B, and the third when the ACF is perpendicular to B. Rectangular conductors have two principal sets of these curves. This is caused by anisotropy of the conductor.

We used a rectangular conductor to build a nominal 300 kJ magnetic energy transfer and storage (METS) coil. This magnet was edge-wound with a single layer of conductor. In this configuration there will be a large field gradient within the conductor and a consequent variation with position of j_c . To predict the performance of this coil one cannot use the uniform field data directly, but must sum the currents in the filaments. The results of such a calculation are discussed in a later section.

II. MEASUREMENTS

We present data for two of the largest superconductors which we have tested. These conductors were made by Magnetics Corporation of America (MCA) and contain 2640 NbTi filaments in a six to one copper matrix. The first sample was a round pre-production specimen with a diameter of 7.94 mm. The second specimen (Kryo 210) was the same material as the first

sample and was rectangular with dimensions 5.08 mm by 10.16 mm. These samples have approximately the same cross section area and differ in shape only. A photomicrograph of Kryo 210 is shown in Fig. 1. Note the position dependent deformation of the filaments.

Fig. 1. Cross section of Kryo 210. The conductor is 10.16 mm by 5.08 mm with a six to one copper matrix. Note the deformations of the filaments and matrix spacing.

The samples were formed into 60-cm long hairpins in which the smallest radius of curvature was greater than 1 cm. The magnetic field was applied perpendicular to the long portion of the hairpin. The bend at the end of the hairpin and the soldered connections to the flux pump experienced much weaker fields than the section of sample under test. The length of this test section is determined by the field profile of the magnet, which has a field nonuniformity of $\pm 2\%$ in a distance of approximately 36 cm dropping rapidly beyond that. The effective sample length is then approximately 71 cm.

We chose I_c to be that current at which the electric field along the sample increases to 3.5 $\mu\text{V/m}$. This electric field value is set mainly by experimental considerations and corresponds to a potential of 2.5 μV across the sample. For the range of currents measured here, these conditions correspond to superconductor resistivities of 1 to $5 \times 10^{-13} \Omega \text{ cm}$. Voelker² recommends $10^{-12} \Omega \text{ cm}$ for a design maximum resistivity.

The data for the round sample are shown in Fig. 2. The upper curve was obtained with the ACF opposing the applied field, giving a smaller total field and higher I_c 's. The lower curve was taken with the ACF aiding the applied field, giving a larger total field and lower I_c 's. The center curve results when the sample is oriented so that the ACF is perpendicular to the applied field. This curve is closest of the three to the "true" I_c , although it is shifted slightly towards lower fields. The coil fields shown on the figure are for the METS 300 kJ coil made from rectangular conductor and are for later comparison. The notation on the figure with respect to "inner" and "outer" filaments denotes the location of the filaments in the conductor itself relative to its center.

Two sets of data for Kryo 210 are shown in Figs. 3 and 4 for the two orientations of B with respect to the broad face of the conductor. These data were taken on two different samples of the same conductor, one mounted face-to-face and the other edge-to-edge.

*Manuscript received September 30, 1974.

* Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico 87544

++Work performed under the auspices of the USAEC.

Fig. 2. Critical current data for the round preproduction sample.

Fig. 3. Critical current data for Kryo 210 with the field applied parallel to the broad face.

Fig. 4. Critical current data for Kryo 210 with the field applied perpendicular to the broad face.

The most notable feature of these data is the maximum in the upper curve at 0.5 T in Fig. 3. This is the point at which $B \approx ACF$ resulting in the overall cancellation of the applied field. The value for I_c at this maximum approaches the self-field critical current, and a change of B in either direction results in a higher total field and lower I_c .

A second typical feature is due to the anisotropy of the conductor. The value of I_c decreases by 24% at $B = 2$ T when B is applied perpendicular to the broad face (lower curve) instead of parallel to it (upper curve). Note that the I_c 's for B parallel to the face are approximately equal to I_c for the round conductor (Fig. 2). The rectangular specimen is thus hardly degraded from the round conductor for this direction of applied field.

The splitting (ΔB) between the upper and lower curves is larger for the face-to-face than for the edge-to-edge mounting. For Kryo 210, with aspect ratio 2 to 1 the ACF is about 6% stronger at the edge of the conductor than at the face. Further, due to anisotropy the ACF will have a stronger local effect on j_c in the edge-to-edge configuration. However, the ACF decreases faster with distance from the conductor in this arrangement than in the face-to-face mounting so the splitting of the curves is greater in the latter case. This argument also illustrates why the center and the lower curves merge at higher fields in Fig. 4.

We note, in passing, that in Figs. 2 and 3 there is a splitting between the data taken with the ACF pointing to the left and to the right relative to the applied field as shown. This splitting, however, is negligible for the face-to-face arrangement in Fig. 4. This appears to be a real effect and not an instrumental problem, since test runs under different conditions all gave consistent results. Several arguments, not presented here, which depend on the chirality of the twist, indicate that there should be no splitting. We have not found a satisfactory explanation for this incongruous result.

The coil fields shown in Fig. 4 are the maximum fields at the inner and outer filaments in the 300 kJ METS coil. This magnet was operated at a maximum of 12.5 kA at 2.26 T using a homopolar generator for the power source.³ Due to the noisy output of this generator, we could only measure d.c. potentials across the coil to within 10 mV. This corresponds to 46 $\mu\text{V}/\text{m}$ possible electric field along the conductor. Within this limitation the magnet showed no sign of approaching the transition to the normal conducting state. There were two limits on the maximum current in this test. The first was the short-term capacity of the vapor-cooled leads, and the second is the mechanical strength of the coil to withstand the Lorentz forces.

III. ANALYSIS

Short Sample Critical Currents

We want to determine the true I_c for the round conductor from the data. We assume a "true" I_c vs. B curve and calculate the ACF for each direction of I_c . The data are then shifted by amounts equal to their respective values of ACF.

The conductor is twisted, which means that the filaments within a given cylindrical layer will all see the same effective magnetic field. The effective field for each layer is the largest field applied to that layer. In determining the corrections to the data we treat only the contribution of the ACF and not the secondary effect of the redistribution of current among the filaments and the resultant change in the self field.

When the ACF aids the applied field, the maximum ACF at the inner and outer filaments are $\mu_0 I_c / 2\pi(2a+b)$ and $\mu_0 I_c / 2\pi(a+b)$ respectively, where a is the conductor radius and b is the spacing between the conductor surfaces. Typical values of the expressions are 0.34 T and 0.62 T respectively at $I_c = 15$ kA. If the ACF opposes B and if $B > \text{ACF}$, the maximum field at the filaments will occur between the conductor center and the surface furthest from the adjacent conductor. In this case the ACF at the inner and outer filaments are $\mu_0 I_c / 2\pi(2a+b)$ and $\mu_0 I_c / 2\pi(3a+b)$ respectively. At 15 kA, these expressions give respectively 0.34 T and 0.23 T.

Given the distribution of currents in the filaments and with an appropriate weighting factor for each filament one can calculate the average ACF. Lacking this, one can approximate the average ACF by equally weighting all filaments. With equal filament weighting the average when the ACF aids B is $0.80 \mu_0 I_c / 2\pi(a+b)$ or, 0.50 T at 15 kA. Similarly, when the ACF opposes B , the average is $0.77 \mu_0 I_c / 2\pi(2a+b)$ which gives 0.26 T at 15 kA. The total splitting (ΔB) at 15 kA is then 0.76 T. The value of ΔB measured from Fig. 2 for 15 kA is 0.58 T, which is 24% smaller than the calculated value. With the assumption that the relative values for the ACF are correct, the shifts for fields aiding and opposing would be approximately 0.66 ΔB and 0.34 ΔB respectively. These values for the corrections can be used whenever b is small compared to a .

These values are used in a paragraph below to approximate ACF corrections to the critical current for rectangular conductors.

To calculate the shift when the ACF is perpendicular to B we must first add the ACF and B vectorially and calculate the magnitude. The maximum magnitude within each layer of filaments is then determined and an average is taken similar to that calculated earlier. For the conditions at $I_c = 15$ kA and $B = 1.4$ T the upper and lower limits on the shift are 0.26 T and 0.04 T. The average value is 0.17 T. Using the corrected data at 15 kA, we find the shift is 0.05 T, which is 71% smaller than the calculated average. It is clear that the redistribution of current plays a significant role in these measurements.

The analysis of the data for rectangular conductors follows a similar pattern. It is complicated by the difficulty of calculating the ACF in the immediate vicinity of a rectangular conductor and by the position dependent anisotropic deformation of the filaments. It is probably more sensible to use a graphic method to approximate the "true" I_c .

One graphical method is to plot ΔB vs. I_c and draw a line through the points and the origin. From this ΔB curve and for corresponding I_c values, one then shifts the lower and upper curves toward each other by a proportionate amount of 0.66 ΔB and 0.34 ΔB , respectively. These correction factors are based on the round conductor results discussed above.

300 kJ METS Coil

The 300 kJ solenoid has an i.d. of 56.3 cm and a length of 73.0 cm. There are 122.5 turns of Kryo 210 conductor edge-wound into a single layer. If one naively uses the data in Fig. 4 and the maximum coil field on the inner edge of the conductor, this coil would be expected to have a maximum current of only 9.8 kA. To predict more accurately the performance of the coil, the field within the conductor at the coil mid-plane was calculated by treating the magnet as having a uniform current density filling the entire winding space. Although the actual current distribution is not uniform, this approximation is sufficiently accurate for our purpose. The field varies linearly from the maximum at the inner surface of the winding to -16% of maximum at the outer surface. Since this conductor is twisted, the lowest field seen by the filaments is the maximum value occurring at the inner filaments of the conductor and is 63% of the maximum field value.

Calculation of the maximum coil current is made difficult by the position dependent anisotropy of the filaments. This is further complicated by the twist of the conductor since each filament sees a variation of both field and anisotropy with position. It is more reasonable instead to calculate the upper and lower limits for the maximum coil current.

The lower limit is calculated by assuming that all filaments follow a j_c - B curve typified by the I_c of the conductor with B perpendicular to its broad face. The filaments are grouped into layers, each at a different field with the appropriate j_c . These currents are summed giving the lower limit on the coil maximum.

Calculation of the upper limit uses the round conductor as a basis. It is isotropic and therefore gives upper limits on j_c for the Kryo 210 filaments which have the least distortion. The calculation is simplified by the observation that if the filaments in the round wire were placed in the same position within the magnet as the Kryo 210 filaments they would have j_c 's 20% higher. The upper and lower limits are then 12.7 kA and 10.6 kA, which compare favorably with the actual performance.

It is possible that the magnet may have slightly exceeded the critical current indicated from our short sample measurements. As mentioned above, there was a possible 46 $\mu\text{V}/\text{m}$ electric field along the conductor during coil operation. The V - I curves from the critical current measurements show that at 46 $\mu\text{V}/\text{m}$ the coil conductor carried 0.86 kA over the current at the 3.5 $\mu\text{V}/\text{m}$ sensitivity level. The current carried by the copper matrix under these conditions is negligible.

This simply indicates that with a very small potential across the coil and with a slight superconductor resistivity an appreciable extra current above the basic critical value could flow under stable conditions.

IV. CONCLUSION

We have obtained reasonably accurate uniform field, short sample critical current data from measurements made on hairpin-shaped samples of large, high current

conductors. The measurements are shifted from the "true" I_c curve by the adjacent conductor fields (ACF) resulting in three curves for round conductors, and six principal curves for rectangular (anisotropic) conductors. Each curve is generated depending on whether the ACF aids or opposes or is perpendicular to the applied field. The shifts of the ACF "aids" and "opposes" curves for round conductor are 66% and 34%, respectively, of the splitting (ΔB) between them.

We have related the uniform field I_c data for the rectangular conductor (Kryo 210) to the single-layer, edge-wound configuration of our 300 kJ magnetic energy transfer and storage (METS) coil. The calculated upper and lower limits of the maximum magnet current are 12.7 kA and 10.6 kA respectively. This coil has been operated at 12.5 kA and showed no signs of approaching the transition to the normal conducting state.

ACKNOWLEDGMENTS

The authors wish to thank D. U. Doehling and W. F. Stewart for their assistance and C. G. Hoffman for the photomicrograph.

REFERENCES

1. J. R. Purcell and H. DesPortes, Rev. Sci. Instrum. 44, 295 (1973).
2. F. Voelker, Particle Accel. 1, 205 (1970).
3. C. E. Swannack, D. J. Blevins, C. R. Harder, J. D. G. Lindsay, J. D. Rogers, and D. M. Weldon, 1974 Applied Superconductivity Conference, Oakbrook, Illinois.