Adv. in Cryo. Eng. - Mat'ls., Vol. 28, Eds. R. P. Reed and A. F. Clark, Proc. Int'l. Cryo. Mat'ls. Conf., San Diego, CA, August 1981, Plenum Press, New York (1982), pp. 571-580.

EFFECT OF TWIST PITCH ON SHORT-SAMPLE V-I CHARACTERISTICS OF MULTIFILAMENTARY SUPERCONDUCTORS*

L. F. Goodrich, J. W. Ekin, and F. R. Fickett

Electromagnetic Technology Division, National Bureau of Standards, Boulder, Colorado

INTRODUCTION

Precise determination of the critical current of practical superconductors requires measurement of the voltage-current (V-I) characteristic of the conductor at various magnetic fields. The measurement usually requires the detection of quite small voltages since very sensitive critical current criteria are necessary for the design of practical devices. Furthermore, most laboratories have only relatively small-bore solenoidal magnets, leading to the common use of very short sample lengths for routine critical current measurements. This situation may lead to some difficulties, as we show here.

Data taken on short samples of commercial multifilamentary superconductors have uncovered anomalous V-I characteristics. A voltage was detected at currents well below the sharp upturn in the V-I characteristic near I_c. It was apparently due to current transfer, but larger in magnitude than would be expected from previous current-transfer analyses.[1] Further data indicated that the voltage was strongly dependent on the voltage tap location. In fact, the voltage measured below I_c in the current direction between some taps was negative. In all cases, as I_c was approached, the V-I characteristic returned to "normal." Extensive experiments have shown that there are two extreme anomalous shapes of the V-I curves. These are illustrated in Fig. 1. Depending on the test geometry, the magnitude of many of these anomalous voltages can be on the order of commonly used critical-current criteria and may significantly affect the determination of I_c.

*Partially funded by the Department of Energy.

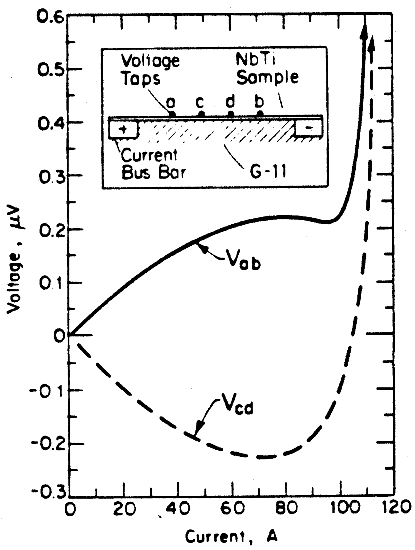

Fig. 1. Experimental data at 8 T showing anomalous V-I characteristic of short NbTi sample ($\ell_{ab} \approx 1.5$ cm, 2.5 filament twists between current contact centers). The horizontal dimensions of the inset are approximately to scale.

In this paper, the experimental investigation of the anomalous behavior and a phenomenological model developed to account for the observations are presented. Several techniques are discussed that minimize the effect and, thus, allow precise critical current determination in short samples.

APPARATUS AND SAMPLE PREPARATION

The apparatus used in this experiment was typical for a short, straight sample critical current measurement. It consisted of the following: a Dewar with a 9-T superconducting solenoid (3.8-cm bore), a cryostat with 600-A vapor-cooled leads, a series-regulated 600-A battery current supply, an analog nanovoltmeter, and an X-Y recorder. The magnetic field measurements were made to a precision of 0.1% with a calibration accuracy of 0.2%. The voltage and current measurements had an accuracy of 2% and 0.4% and a precision of 1% and 0.2%, respectively. Typical noise voltages were ±5 nV. Thermal voltages were checked at zero current and usually did not vary by more than ±10 nV. The sample holder was made of NEMA G-11 epoxy-fiberglass. Superconducting bus bar current contacts were set flush with one surface of the G-11 (see the inset in Fig. 1) such that the Lorentz force on the sample could be supported by the G-11, either directly or by a thin layer of varnish. Small slots were routed into the G-11 for voltage taps on the underside of the wire where needed.

The measurements were made principally on two samples: a twisted multifilamentary NbTi (twist pitch 1.27 cm, Cu:NbTi of 1.8:1, RRR of the copper ~70, 0.53 x 0.68 mm, 180 filaments) and an untwisted multifilamentary Nb_3Sn (0.70-mm diameter, 2869 filaments). The Nb_3Sn wire had an outer copper jacket separated by a tantalum diffusion barrier from the core of bronze, niobium, and Nb_3Sn.

Sample preparation was typical for short sample testing except for the two following techniques. A technique was developed to spot-solder a pair of voltage taps directly across the wire from each other to allow measurement of transverse voltages. The alignment of these taps was checked by measuring the room temperature resistivity and the voltage polarity of the pair and thus deducing the approximate misalignment. The worst case misalignment was ~0.2 mm, but more usually $\lesssim$ 0.1 mm. The other special technique was selective etching of the copper jacket from the Nb_3Sn wire. This was accomplished using an enamel insulating paint as a mask and a nitric acid etch. Small copper islands were left on the sample for ease in soldering voltage taps and current contacts.

EXPERIMENT

To investigate the anomalous voltage seen on the NbTi critical current sample as described in the Introduction, tests were made with two pairs of voltage taps spaced 0.5 and 1.5 cm apart. The V-I characteristics are shown in Fig. 1. Here the voltage definition $V_{ab} = V_a - V_b$ was used. These curves were reproducible and reversible to within 1%.

It was observed that both V_{ab} and V_{cd} changed sign when the current was reversed, but not when the field direction was reversed. There were slight differences (~10%) in the magnitudes of these voltages, especially close to I_c, as the direction of the current and the field were changed. These are attributed to the Hall effect and are discussed below, but they do not significantly affect the unusual shape of the V-I characteristics.

During the development of the phenomenological model, experiments were made using several unique sample configurations of both the twisted NbTi and the untwisted Nb_3Sn. These data and the voltage tap and current lead arrangements are presented in the appropriate places in our discussion of the model.

PHENOMENOLOGICAL MODEL AND SUPPORTING DATA

The unusually shaped V-I characteristics may be understood in terms of the interaction between current transfer and the twist pitch of the superconductor. Filaments nearest the current contacts carry current near their critical current density and exhibit a flux-flow resistivity. Conversely, filaments on the opposite side of the superconductor from the current contacts carry very little current because the resistive matrix separates them from the point of current injection. Therefore, it is possible for a voltage tap to be sampling either a resistive or nonresistive group of filaments and, thus, the voltage between taps may be quite different, depending on the relationship of tap spacing to twist pitch. Also, significant transverse voltages should be observed across the wire.

Results of transverse voltage measurements made on the NbTi sample are shown in Fig. 2. Notice that these curves are similar in shape and size to those in Fig. 1 except near I_c. As I_c is approached, the transverse voltage tends to go to zero as the current distribution among the filaments becomes more uniform. The distance between current injection points (approximately center to center) for the data shown in Fig. 2 was 2.6 times the twist pitch. Thus, the group of filaments nearest to the current bus bar on one end of the sample are not the same as the group nearest to the bus bar at the other end. Current must therefore transfer between the two groups of filaments by flowing through the resistive matrix material of the wire. This generates the large transverse voltages. The unusual V-I characteristics shown in Fig. 1 are simply the sum of the usual flux-flow V-I characteristic and

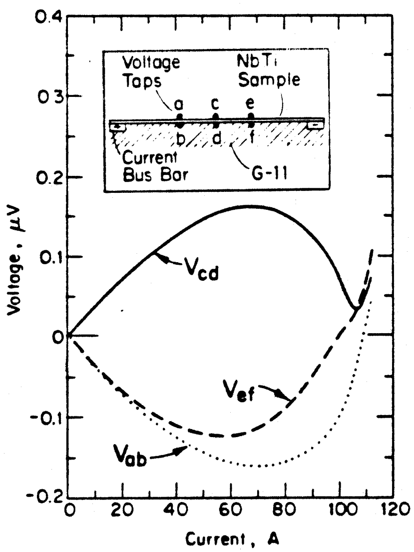

Fig. 2. Experimental data at 8 T on transverse voltages of short NbTi sample ($\ell_{ae} \approx 1.25$ cm, 2.6 filament twists between current contact centers).

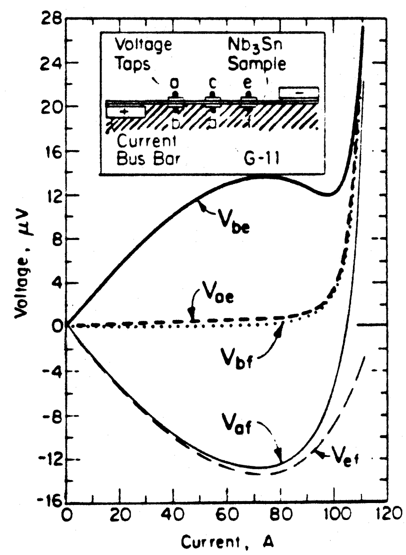

Fig. 3. Experimental data at 9 T on a selectively etched Nb_3Sn conductor ($\ell_{ae} \approx 1.25$ cm, no filament twists). Note the bus bar locations.

the transverse voltages caused by current transfer through the resistive matrix from one group of filaments to another.

Understanding of the effect is simplified considerably if the conductor used to obtain the V-I characteristics in Figs. 1 and 2 is untwisted. In this arrangement one current bus bar was placed on top, the other on the bottom to provide a half-integral number of twists between the current injection points. Data were obtained on the untwisted Nb_3Sn conductor in this geometry and are shown in Fig. 3. These data can be explained by the model shown in Fig. 4. Note that in multifilamentary conductors the equipotential lines at low currents are much more closely aligned with the conductor axis than in a conductor with an isotropic resistivity. The voltage between taps e and f starts from zero at $I \ll I_c$ (Fig. 4A), rises in magnitude as I increases (Fig. 4B), and decreases toward zero as all the filaments become resistive near I_c (Fig. 4C). Similarly, the voltage between taps a and f starts from zero at $I \ll I_c$ (Fig. 4A), rises in magnitude to a negative peak at an intermediate value of I (Fig. 4B), and then becomes positive as the entire conductor becomes resistive at $I \cong I_c$ (Fig. 4C). The voltage between taps b and e rises from a low value at $I \ll I_c$ to an intermediate high at an intermediate value of I, back to a low value as the

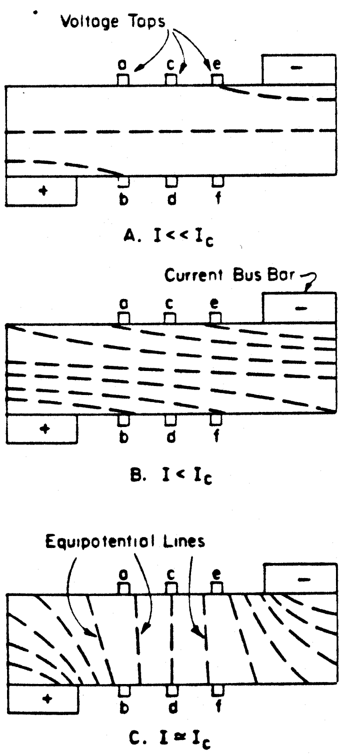

Fig. 4. Model of equipotential lines in a superconductor with an odd half-integral number of filament twists between the current contacts: (A) current much less than I_c; (B) intermediate currents less than I_c; and (C) current near I_c.

resistivity becomes more isotropic at $I \approx I_c$, and finally to a high value as I exceeds I_c. Note that the curves in Fig. 3 have about the same shape as those in Fig. 1.

In Fig. 3 it is easy to separate the anomalous V-I characteristics (V_{be}, V_{af}) into an essentially intrinsic characteristic (V_{bf}, V_{ae}) and an anomalous current-transfer characteristic (transverse voltages V_{ab}, V_{ef}). These separations, $V_{be} = V_{bf} - V_{ef}$ and $V_{af} = V_{ae} + V_{ef}$, were demonstrated experimentally with agreement of about 1% ±10 nV. So it is possible to have V-I characteristics with these shapes (and everything in between) depending on voltage tap location. Remember that this discussion and the data shown in Figs. 1, 2, and 3 correspond to a sample with a half-integral number of twist lengths between the points of current injection.

When there is an integral number of twist lengths between the points of current injection, the current transfer pattern is altered. Data obtained on the NbTi conductor with a current contact spacing of about two twist lengths are shown in Fig. 5. In this geometry, the V-I characteristic of the resistive filament,

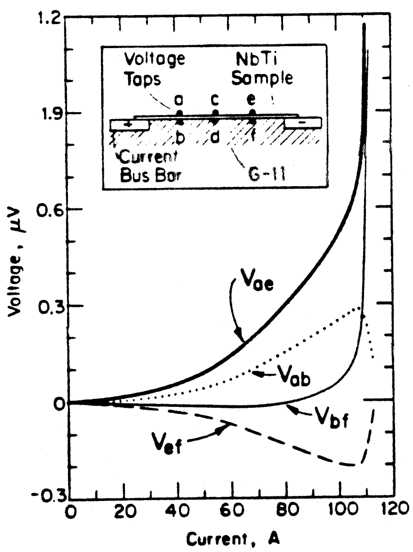

Fig. 5. Experimental data at 8 T on a NbTi conductor ($\ell_{ae} \approx 1.25$ cm, 2 filament twists between current contact centers).

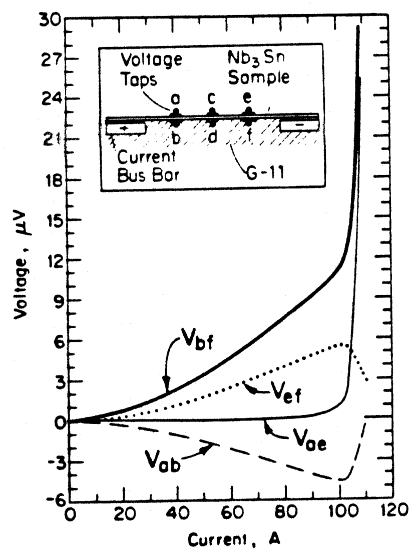

Fig. 6. Experimental data at 9 T on a selectively etched Nb_3Sn conductor ($\ell_{ae} \approx 1.25$ cm, no filament twists).

V_{ae}, is the sum of the V-I characteristics of nonresistive filaments, V_{bf} (essentially intrinsic characteristic), and the transverse voltages, V_{ab}, V_{ef} (anomalous current-transfer characteristic). The equation $V_{ae} = V_{bf} + V_{ab} - V_{ef}$ was demonstrated experimentally with an agreement of about 1.5% ±15 nV. Data obtained on the Nb_3Sn conductor in this geometry are shown in Fig. 6. Note that these curves are very similar in shape to the curves in Fig. 5 and can also be separated into an intrinsic V-I characteristic and an anomalous current-transfer characteristic, $V_{bf} = V_{ae} + V_{ef} - V_{ab}$, with experimental agreement of about 1% ±10 nV. The model for this configuration is shown in Fig. 7. The current is injected and extracted from the same group of filaments. The voltage between taps b and f is indicative of this group of filaments and rises much more rapidly than the voltage between taps a and e. Current does not transfer through the matrix to the far group of filaments sampled by taps a and e until I approaches I_c. In fact, the voltage taps on the top of the conductor remain at about the same potential until I reaches I_c.

TECHNIQUES TO MINIMIZE THE ANOMALOUS CURRENT TRANSFER VOLTAGE

Note from the above discussion that these unusually shaped V-I characteristics result from nonsymmetric current injection. If the

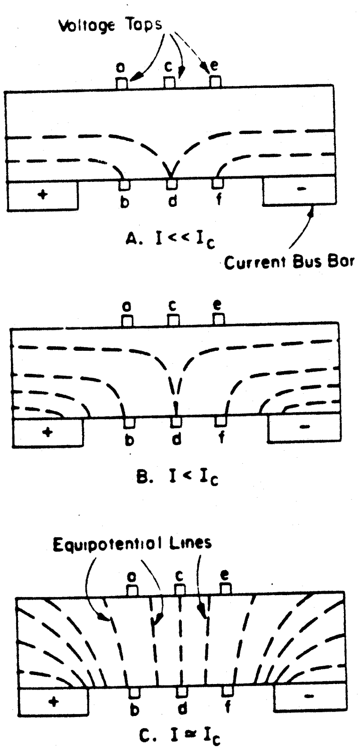

Fig. 7. Model of equipotential lines in a superconductor with an integral number of filament twists between current contacts: (A) current much less than I_c; (B) intermediate current less than I_c; and (C) current near I_c.

current is uniformly introduced around the circumference of the superconductor, the current transfer voltage should be independent of twist pitch considerations and reduced in magnitude.

There are at least two possible methods of making the current injection symmetric in short sample testing. One method is to make the solder joint at the current contact longer, at least one twist length, so that the current is introduced into all of the outer filaments. In the second method, current injection is made more uniform by having a symmetric current contact. Both of these techniques have been shown experimentally to reduce the anomalous voltages greatly, thus permitting a more accurate determination of the critical current.

The long current contact method was tested on the twisted NbTi wire. First the voltages were measured with the current contacts covering more than one twist length, then the wire was cut to shorten the current contact, and the same voltage taps were measured again. The current-transfer voltages were about a factor of 10 lower for the long current contacts and of a magnitude consistent with symmetric current-transfer analysis.[1]

Measurements on the Nb_3Sn wire with the copper jacket intact illustrate the second method. The copper jacket gives a more uniform injection of the current into the superconducting filament region because of the relatively high resistivity of the bronze in that region. The results are shown in Fig. 8. The magnitude of the current transfer voltage is reduced over that of V_{bf} in Fig. 6, again consistent with symmetric current-transfer analysis. Also, the voltage drop along the top filaments is about the same as that along the bottom filaments, which indicates a removal of the twist pitch dependence.

A COMMENT ON GALVANOMAGNETIC EFFECTS

Observations of strange voltages in a current-carrying conductor at low temperatures in a high magnetic field are often explained by arguments involving one or more of the many classical galvanomagnetic effects. It is our contention that, although several of these effects are present in our data, none of them cause the unusual shape of the V-I curves. Most of the effects are seen only in metals where the product of the cyclotron frequency, ω, and the electron collision time, τ, is quite large, usually ~100. Even in the copper stabilizer on our wires, $\omega\tau \lesssim 2.4$ at 4 K and 10 T. Furthermore, large effects are most common to single crystals and our metals are highly polycrystalline.

Two galvanomagnetic effects do appear in our data: the Hall effect and transverse magnetoresistance. Of these, only the former

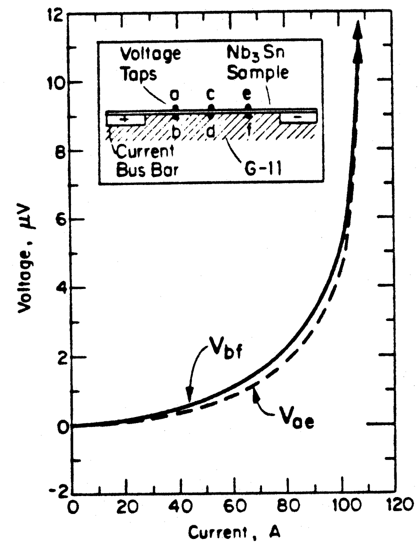

Fig. 8. Experimental data at 9 T on Nb_3Sn conductor with copper jacket giving uniform current injection ($\ell_{ae} \approx 1.25$ cm, no filament twists).

can be seen directly in I-V curves made at fixed field. The Hall voltages appear most strongly on the probe pairs transverse to the current. They reverse with both field and current and are developed almost entirely in the normal metal components of the wire. In the wires measured here, at currents well below I_c, we noted Hall voltages of ~10 nV in the NbTi at 8 T (on top of a ~200 nV current transfer voltage) and ~100 nV in the Nb_3Sn at 9 T (on top of a ~15 μV transfer voltage). These values appear to be consistent with the known Hall coefficients for the matrix materials[2] and the other parameters, but even an order of magnitude calculation requires a much more detailed model than we have space for. Suffice it to say that the Hall effect, although observable, represents only a small contribution to the measured transverse voltages.

Magnetoresistance is an even effect, it does not depend on current and does not reverse with field, thus it does not affect the shape of the V-I curves. It shows up most strongly in measurements on voltage taps along the sample as an increase in the resistance of the relatively pure copper stabilizer as the field is increased. For our wires this effect causes the zero field resistivity of the stabilizer at 4 K to increase by about a factor of 3 in going to 9 T.

CONCLUSIONS

Anomalous voltages may be observed in short sample critical current tests on multifilamentary superconductors. These voltages may in some instances even be negative, but in any case they can interfere with the correct determination of I_c (even for NbTi) especially when using sensitive (but realistic) electric field or resistivity criteria.

All of the observed behavior can be adequately explained by use of a model that considers the combined effects of the twist pitch of the filaments and the details of current injection and transfer within the sample.

The anomalous voltages can be reduced in short sample testing by insuring that the current is injected symmetrically into the conductor by long (at least one twist pitch) current contacts or by symmetric current contacts. The current-transfer voltages then will be independent of twist pitch and reduced in magnitude, making the usual methods of treating current-transfer voltages applicable.[1]

ACKNOWLEDGMENTS

The authors have benefited greatly from numerous discussions with A. F. Clark. E. Pittman has been most helpful in the care and feeding of the instrumentation. Ms. V. Grove prepared the manuscript--many times. Our thanks to them all.

REFERENCES

1. J. W. Ekin, J. Appl. Phys. 49:3406 (1978).
2. C. M. Hurd, "The Hall Effect in Metals and Alloys," Plenum Press, New York (1972).