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THE EFFECT OF FIELD ORIENTATION ON CURRENT TRANSFER IN MULTIFILAMENTARY SUPERCONDUCTORS*

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Abstract

Experimental data and discussion are presented on the current distribution along the length of a superconducting wire when subjected to multiple parallel and perpendicular magnetic fields. The experimental data were taken on a rectangular pancake coil with the applied magnetic field in the plane of the coil. These data indicate that significant current transfer occurs in the first and last perpendicular magnetic field sections and little transfer occurs between these two sections. The implication for superconducting magnet design will also be discussed.

Introduction

Results of recent measurements[1] on current transfer in hairpin and long straight critical current geometries showed curious effects in multiple parallel and perpendicular field sections on the current transfer in multifilamentary superconductors. These two critical current geometries are illustrated on Fig. 1. In the hairpin geometry, the sample axis changes along its length from parallel, to perpendicular, to a return parallel with respect to the relatively uniform applied magnetic field. In the long geometry, the sample traverses several magnetic field regions; from low, to gradient, to relatively uniform perpendicular, to gradient, and then to low again. All of the measurements reported and discussed here were made on the same material. A cross-sectional view of this material is given in Fig. 2. It is a commercial multifilamentary Nb_3Sn superconductor with a diameter of 0.7 mm, 2869 filaments, and a copper to non-copper ratio of 1.7. Its critical current is about 75 A at 8 T, 4 K using an electric field criterion of 1 nV/cm.

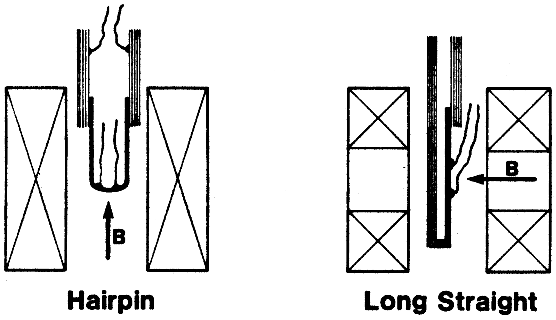

Figure 1. Schematic representation of the hairpin and long straight critical current measurement geometries.

The following experimental observations on the symmetry of current transfer were made on both the hairpin and the long straight geometries. The current contacts were made at the surface of the wire and the copper jacket ensured that the current entering the core of the conductor was nearly radially symmetric. The length of the sample in the parallel or low field region was long enough that the current transfer caused by the low or parallel field critical current density was essentially completed before the wire enters the perpendicular, high-field region. This was indicated by the profile of the current transfer electric field, E_t, with distance from the current contact, x. E_t close to the current contact was a few μV/cm and it had decreased to less than 2 nV/cm before the perpendicular high-field region was reached. Thus, assuming the E_t continues monotonically decreasing with x, and that there is a finite current density, J_c^*, below which the superconducting filament resistivity is zero, then the current distribution among the filaments must have essentially reached the distribution that the conductor would have in a parallel or low field if the current contact were an infinite distance away. This postulate only states that the effect would be observed and would have about the same magnitude if the current contact were an infinite distance away. The electric field profile of each end of the sample in parallel or low field was symmetric, implying that the transfer into the conductor occurs in the same way as the transfer out. In the absence of a perpendicular-field region, no additional transfer (in) would take place at this current. However, additional transfer does take place when the current enters the perpendicular, high-field region because the lower critical current density forces the current distribution among the filaments to be more uniform. This transfer results in E_t's as high as 100 nV/cm. These transfer electric fields were symmetric about the center of the magnetic field just as in the low or parallel field region. This implies that the current starts to transfer to the outer filaments on the other side of center, symmetric with the transfer in.

A logical extension of these results is to ask what would happen if there were multiple parallel and perpendicular field sections? Would the current transfer in and out among the filaments on every perpendicular field section? If it did, this would have a serious implications for superconducting magnet design in cases where the windings are such that the magnitude or angle of the magnetic field cycles many times. It would affect the persistence, refrigeration load, and the stability of the system. The experiment below was designed to answer these questions.

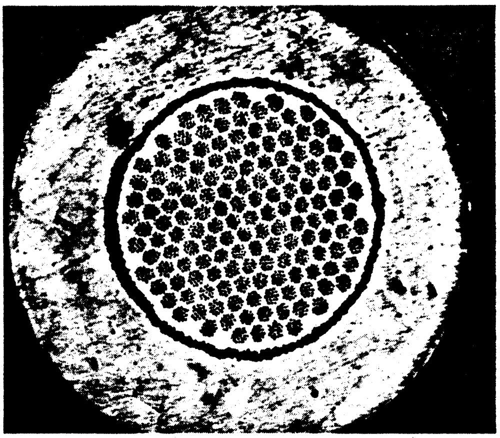

Figure 2. Cross section of the superconducting sample with an outer copper jacket separated by a tantalum diffusion barrier from the core of bronze, Nb, and Nb_3Sn.

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Experimental

The special shape sample for this study was formed prior to its reaction, in a rectangular pancake coil as illustrated in Fig. 3. The bends in the sample have a radius of curvature of about 2 mm. The results did not show any significant change in the superconducting properties due to the bends, except, perhaps, for some minor filament inhomogeneities and breakage. Measurements were made with the magnetic field in the plane of the coil, pointed down in the figure. The critical current at 1 μV/cm was measured for the seven pairs of adjacent voltage taps in perpendicular field-sections, and the resulting critical current data had a range of only 2% indicating a relatively uniform sample. This configuration has a number of sections that are essentially (within 10°) parallel or perpendicular to the magnetic field. The ends of the sample are in parallel field. These sections are sequentially numbered for reference on Fig. 3 so that all of the odd-numbered sections are in parallel field and the even-numbered in perpendicular field. The current contacts at each end of the wire were 0.5 cm long. The first and the last sections, 1 and 11, were 6.6 cm and 6.3 cm long respectively. As mentioned above, with a parallel field section this long, the current transfer due to the parallel field critical current density is essentially complete before the first perpendicular field section. Notice also the fact that the magnetic field at the ends of the sample is not exactly parallel with the sample (because of alignment and field profile) would only cause the effect in the first perpendicular field section to be smaller than if the ends were in a perfectly parallel field.

The data were taken by recording the voltage as a function of current as the current was ramped up and then down. The voltage was measured to an accuracy of 2% ±2 nV and the current to an accuracy of 0.5% ±0.2 A. The current ramp rate was relatively slow (a few minutes from zero to I_c), but there still were significant voltages induced in the voltage leads to the sample because of this ramp. These induced voltages were accounted for by using the recorded voltages, up and down, and the known current ramp rate. The resulting voltage-current curves were consistent with voltage-current points obtained by holding the current fixed (actually the current was still drifting, but at a rate at least 20 times less). Thus the final voltage-current curves were independent of ramp rate in the range tested and the observations are not the result of any inductive effect.

Evidence of the response of the current distribution to multiple parallel and perpendicular field sections is also given on Fig. 3. The measured voltage and tap separation of each adjacent pair of taps is indicated for a current of 75 A in a field of 8 T. The critical current (75 A) at 1 nV/cm was determined from a measurement of another specimen, so the small additional voltage on the inner configuration taps could be due to a difference in the critical current, the continuing transfer, or filament inhomogeneities. All of the voltages are positive. They changed sign and had the same magnitude (within the accuracy of the measurement) when the current direction was reversed. This indicates a symmetry of current transfer (in and out) with the direction of current flow. Furthermore there is a symmetry of current transfer voltage about the center of the configuration, section 6. Notice the similarity of the voltages seen on the following pairs of sections: 1 and 11; 2 and 10; 3 and 9; 4 and 8; 5 and 7.

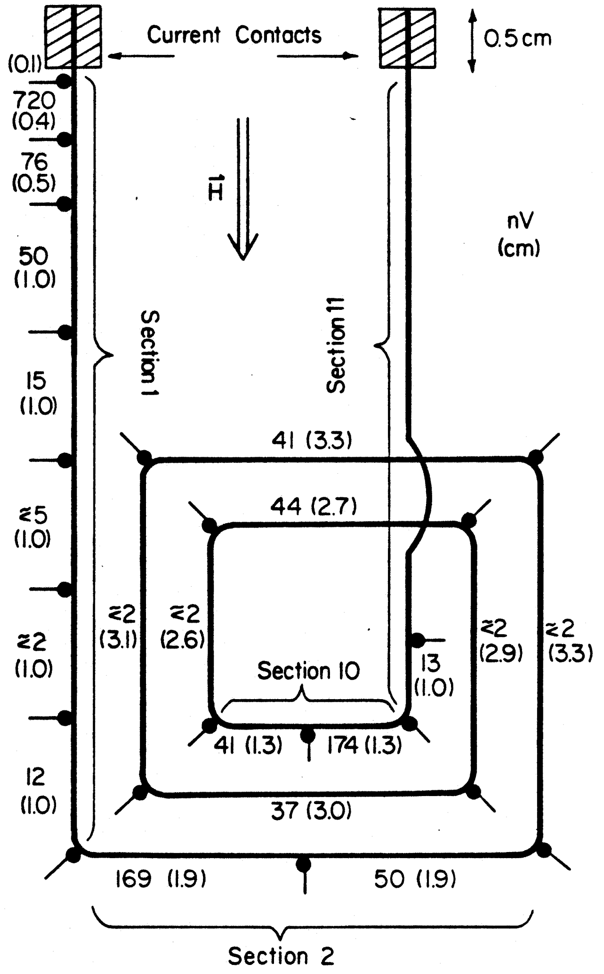

Figure 3. Rectangular pancake coil sample with voltage in nV (tap separation in cm) for each adjacent pair of taps at a current of 75 A with a field of 8 T in the plane of the coil.

Discussion

The above symmetry of current transfer voltage is somewhat surprising on first consideration. Notice that when the current reaches the first (for now assume electron current flow and section 1 is connected to the negative contact) perpendicular field section, 2, the current then will have to transfer into the inner filaments, since the reduced critical current density forces the current distribution among the filaments to be more uniform than that in the parallel field region, 1. The expected voltage profile due to this current transfer is observed along this perpendicular section, 2. Now consider the symmetric section, 10, here the voltage profile indicates that the current starts to transfer to the outer filaments in the same way that the current transferred to the inner ones in section 2. In fact, almost all of this transfer takes place in section 10, relatively little takes place around the corner in section 11, just as happened in section 1. Why does the current start to transfer out in section 10? If the current wants to transfer out before it reaches a parallel field section, why doesn't it transfer out at the end of sections 2, 4, 6, or 8? These results suggest that the presence of the current contact must be affecting the current distribution for a long length.

The effect of the current contact can be illustrated with equipotential lines as indicated by the data. A schematic diagram of the equipotential lines is given on Fig. 4. Using a time-reversal argument, these lines will be the same for current entering and leaving the superconductor. The outer copper jacket is not shown on this figure. The equipotential surfaces in the copper jacket should extend radially outward from the surface of the core, except near the current contact. The parallel and perpendicular field regions are treated here separately. The effect that the presence of the perpendicular region has on the parallel region is discussed in the appendix. The appendix also has a list of rules for qualitative construction of equipotential lines in superconductors and another example. The equipotential lines in Fig. 4 do take into account the interaction of these two regions; however, in the following discussion this interaction was omitted for clarity.

Consider first the easier case to imagine, that of the current entering the superconductor. The copper jacket on the superconductor will ensure that the current entering the core of the conductor at the current contact will be essentially radially symmetric.[2] The current is injected into the outer superconducting filaments at the joint and it starts to flow along these filaments. However, the current density is above the critical current density (except at the very low currents), and thus, a flux-flow voltage drop will occur along these filaments which will cause some of the current to transfer through the resistive interfilament material (bronze) into the next inner layer of superconducting filaments. This process continues until the current density in the outer filaments is essentially J_c^*, where J_c^* is the current density below which the superconducting filament resistivity is zero. I_c in parallel field is about four times I_c in perpendicular field, so it is expected that J will not be uniform throughout the conductor in parallel field, no matter the length, for any current less than the I_c measured in perpendicular field. There will be a low J in the inner filaments, thus all the inner filaments will be at about the same potential and there will be very little voltage drop along them. As the current enters the perpendicular field region, J_c drops and the outer filaments will again have a flux-flow voltage drop which causes more transfer. If the current is close to I_c, then the equipotential surface will eventually become flat and perpendicular to the axis of the conductor. Some transfer may occur due to inhomogeneities in the superconducting properties, but other than this, the equipotential surface will stay flat through the parallel and perpendicular regions until the last perpendicular region. The current will start to transfer out in the last perpendicular field region. This transfer out is a little harder to imagine because the presence of the current contact effects the equipotential surfaces in the multifilamentary superconductor a relatively long distance away, more than 6 cm or 150 times the diameter of the core. The extent of this long range effect has been observed before in this sample and in Cu-NbTi samples where anomalous voltages were reported.[2] The current starts to transfer out of the center filaments because these filaments are at a higher potential than the adjacent filaments. This transfer out will cause the outer filaments to have a flux-flow voltage drop, the inner filaments will be at about the same potential and there will be very little voltage drop along the inner filaments. Once the current has entered the parallel field region the flux-flow voltage drop along the outer filaments will become very low and very little transfer out will occur. As the current gets closer to the contact, the transfer out will increase and more and more flux-flow voltage will appear along the wire and ultimately the current will leave the conductor at the current contact.

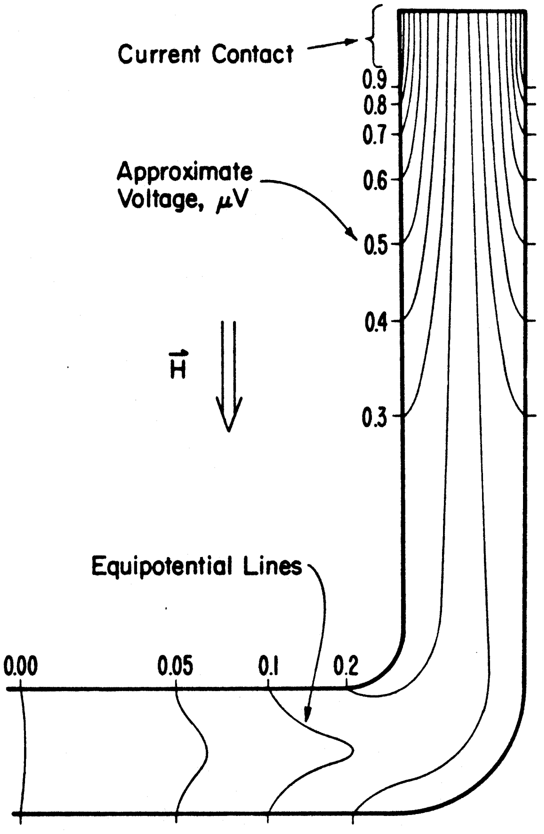

Figure 4. Schematic diagram of the equipotential lines in the core of the superconductor with the magnetic field pointing down the figure.

These data also indicate that the ultimate current distribution of a multifilamentary superconductor is not uniquely defined by the local conditions. Where the electric field is zero, the current density in a superconducting filament can be any value below J_c^*.[3] The value that it will have is determined by the boundary conditions (current contact) and the external magnetic field in regions where the electric field is non-zero. The voltage drops along the configuration's inner parallel field sections (3, 5, 7, and 9) indicate there is very little transfer occurring. The voltage drops along the configuration's inner perpendicular field sections (4, 6, and 8) could result in part from slight inhomogeneities and filament breakage at the bends. So the transfer that occurs here because of the field orientation change is at least eight times smaller than that of the first and last perpendicular field sections (2 and 10), if this transfer occurs at all. This suggests that the interfilament material, the bronze, is effectively isolating the superconducting filaments from each other.† This does not rule out the possibility that a transfer out would occur if the low or parallel field section were much longer. Conceivably, this could occur by means of selective transfer (toward the lower free energy state of the superconductor) at filament inhomogeneities and discontinuities. If this were to occur, the transfer back in would take place at the next perpendicular field section.

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† If the conductor were a monofilament, then the current distribution in the configuration's inner parallel field sections would not be as uniform as that for the configuration's inner perpendicular field sections because the free energy of the superconductor is lower for the current flowing in the outer area.

Conclusion

The current will complete the transfer to a more uniform distribution in the first perpendicular magnetic field section. After the current has a uniform distribution, it will not transfer among the filaments everywhere the magnetic field changes. The current will start the transfer to the outer filaments during the last perpendicular magnetic field section. The implication of this for superconducting magnet design is that once the current has transferred to a uniform distribution among the filaments, it may stay in this distribution through low or parallel field sections until the last perpendicular field section. Thus, putting each end of the magnet wire through an external, high-field region would force the current into a uniform distribution that would remain for the whole length within the magnet.

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3. J. R. Clem, private communication.

Appendix

The presence of the perpendicular region has an effect on the equipotential lines in the parallel field region. First consider some rules for qualitative construction of equipotential lines in superconductors:

1) Equipotential lines can not cross a superconducting filament where J in that filament is less than J_c^*.

2) The potential of a superconducting filament where J in that filament is less than J_c^*, is determined at the first or last place where $J = J_c^*$.

3) If J in a superconducting filament is everywhere less than J_c^*, then the potential of that filament is determined by the potential of the adjacent material.

4) The current will flow toward a lower potential even if it is in a superconducting filament that is below its J_c^*.

5) The electric field in the superconducting filaments at any point along the wire will be larger for the outer filaments than for the inner filaments (except when zero or near inhomogeneities).

First consider the case where the whole superconductor is in a uniform magnetic field, either zero, parallel, or perpendicular, and the current is below I_c^* (the critical current equivalent to J_c^* in all of the filaments). A schematic diagram of the equipotential lines for this case is given on Fig. A1. The equipotential surfaces, shown in cross section as lines, are rotationally symmetric about the wire axis. The voltage for each equipotential surface will scale approximately with the current. The equipotential lines on each end will look like those on Fig. 4 from the current contact to the 0.3 line (the lines on Fig. 4 marked 0.00 to 0.2 will not be there). Notice that if the current is below I_c^* and the distance between the current contacts is long enough, then a region such as that between the two 0.0 potential lines will exist and the potential everywhere in this region will be the same. As the current approaches I_c^*, the space between the 0.0 lines (on Fig. A1) gets smaller (both along and across the wire) and ultimately meet at I_c^*.

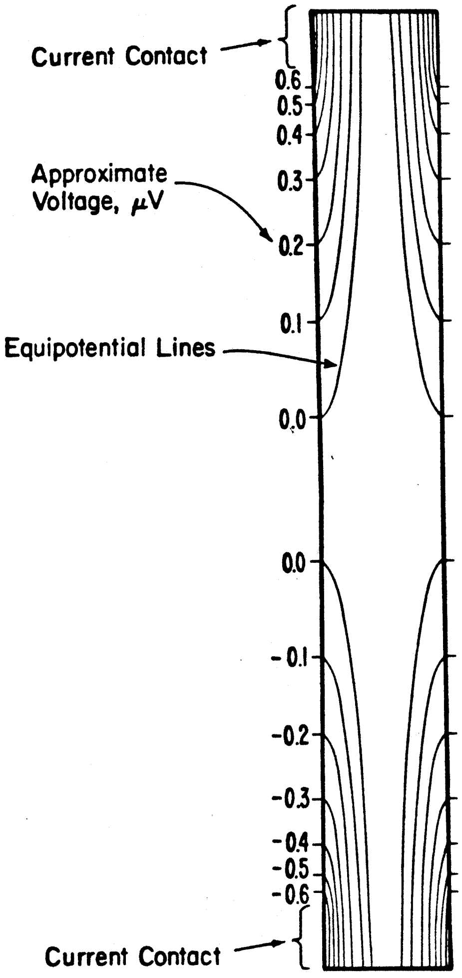

Figure A1. Schematic diagram of the equipotential lines in the core of the superconductor with a uniform external magnetic field.

Now consider the case represented on Fig. 4, where there are two regions of different I_c^*'s (parallel and perpendicular field regions in this specific case) with the second region having a lower I_c^*. The other end of the configuration will be an image of this end. The presence of the perpendicular field region will cause equipotential lines such as the 0.1 and 0.2 lines (in Fig. 4) when the current is above the I_c^* of the perpendicular field. When the current is below the I_c^* of the perpendicular field, a line such as the 0.2 line will be the last line before the image lines at the other end of the configuration. Notice that the center filaments in the parallel field region have a different potential because of the presence of the perpendicular field. This results in a radial electric field and, thus, some current transfer even though the filaments in this region are below their J_c^*.