CRITICAL CURRENT TRANSITION STUDY ON MULTIFILAMENTARY NbTi SUPERCONDUCTORS HAVING A Cu, A CuNi OR A MIXED MATRIX.

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Abstract

Measurement of voltage-current characteristics in multifilamentary wires, showing the transition from the superconducting to normal state, provides information about the quality of the wires and their production techniques. In this paper several methods of describing this transition are discussed. In general, the so-called n-power law turns out to be adequate in the critical current region. The dependence of n on the magnetic field yields information about the inner structure of the wire, especially whether the limitation of the current is caused by intrinsic or extrinsic effects. However, when submicrovolt measurements are carried out on short-sample specimens with high-resistivity matrices, in several ranges of current other n-values can be distinguished. This can be caused by a current diffusion process. A different way of describing the resistive transition is by means of a critical current distribution function. Such a function can be found by calculating the second derivative of the voltage with respect to the current.

Introduction

More than 25 years after the introduction of composite superconductors for technical applications, it remains interesting and important to study the superconducting to normal transition. In order to improve the quality of the production techniques used for multifilamentary wires it is necessary to know what factors cause the limitation of the critical current. Moreover, it is sometimes important to gain knowledge about the longitudinal resistance of multifilamentary conductors, also far below the critical current. An example is the application of a large length of superconductor in persistent mode circuits as in NMR magnets.

In general, two effects can be distinguished that limit the maximum current in multifilamentary wires. The first is an intrinsic limitation, which is due to the microstructure of the superconducting material itself and its ability to perform flux pinning. However, most wires do not reach this limit because of a second effect. During the many stages of the production process of superconducting wires all kinds of irregularities on the surface of the filaments may arise. These defects, such as sausaging of the filaments, lead to an extrinsic limitation of the critical current.

In studies of the resistive transition it is important to know whether the lowering of the critical current is caused by microstructural effects or by sausaging. In principle, measurements of voltage-current characteristics can provide this information.

Characterization of the critical current transition

The easiest way to characterize the resistive transition in multifilamentary wires is to specify a single value for the critical current according to a certain criterion. On the basis of experimentally determined voltage-current characteristics (U-I curves) one can adopt the $10^{-14}\Omega$m criterion for example. This specifies the critical current as being that current at which the voltage drop across the wire corresponds to a resistivity of $10^{-14}\Omega$m. Another possibility is looking at the voltage drop per unit length of the wire. Values of 10^{-6} or 10^{-7} V/cm are commonly used to define the critical current.

However, as a result of these rather arbitrarily chosen criteria, specifying the thus found critical current value alone will not yield information about the way the transition from the superconducting to normal state takes place. Depending on the inner structure of the wire this transition can be very sharp or more gradual.

One possible way of describing the U-I curve is by adopting the so-called n-power law: $U \sim I^n$. Although this is an empirical formula, it turns out in practice, that for most wires this equation holds quite well in the current region where the relevant part of the resistive transition takes place. Consequently, the transition can be characterized by a constant power n: a large value for n indicates a sharp transition, whereas a gradual one results in a low value of n. Furthermore, n may be found to be dependent on the applied magnetic field. Intrinsically limited wires especially show large n-values for low magnetic fields, while having smaller values for higher fields. On the other hand, wires that are badly sausaged hardly show any dependence on the field.

By determining the n-value as a function of the magnetic field it is possible to detect the presence of extrinsic effects in a wire, although it is hard to express the extrinsical limitation of the current quantitatively.

A different approach for considering the resistive transition is by means of a critical current distribution function. According to this theory [1] each section along the length of a wire is supposed to have its own local critical current. When a current is flowing through this wire, only those sections that have a lower local critical current contribute to the voltage across the wire. This can be expressed by:

$$U(I) = A \times \int_0^I (I - I')\, f(I')\, dI' \,, \qquad (1)$$

where A is a constant and f(I') is the distribution function of the local critical currents. Obviously, for ideal intrinsically limited composites this distribution function is very peaked, whereas in the case of badly sausaged filaments it is broad. Note, that in equation (1) (first published by Baixeras and Fournet in 1967 [2]) the influence of the self-field has been neglected. Furthermore, it is assumed that the temperature remains constant during the increase of the current (isothermal conditions).

Differentiating equation (1) twice with respect to the current yields the following expression:

$$d^2U / dI^2 = A \times f(I) \,. \qquad (2)$$

This equation makes it possible to calculate the distribution function from measured U-I curves. In this paper most attention is paid to the voltage-current dependence below the $10^{-14}\Omega$m criterion. This submicrovolt region is important to characterize the recently developed 50 Hz

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superconductors having very large numbers of filaments. In terms of a distribution function it means that mainly the low-current part of the function has been determined.

The superconducting chopper amplifier

In order to enable an accurate measurement of U-I curves, a superconducting chopper amplifier has been developed in our group. Its working principle was described extensively elsewhere [3]. This amplifier is sensitive enough to measure voltages as low as 1 nV per cm wire. As a consequence of such accurate measurements on short samples, misleading voltages can arise caused by a current diffusion process in the wire that is due to the connections and field inhomogeneities.

Current transfer length near input leads

When current is supplied to a multifilamentary wire by means of a soldered connection, this current will first be transported for the major part by the outer filaments of the wire. With increasing distance from the input lead the current gradually becomes more homogeneously distributed. This process of diffusion is mainly determined by the transverse resistivity of the matrix material and the longitudinal resistivity of the filaments. Therefore, the voltage drop along the wire is largest near the input leads, because here the current flows in the outer filaments. It is only when the final, steady-state current distribution has been achieved, as determined by the applied magnetic field, that the voltage measurements represent the properties of the wire rather than those of the connection. Consequently, before preparing a wire for an accurate voltage measurement, it is necessary to have knowledge about the diffusion length for the current.

Using a simple model one can derive a rule of thumb for calculating the current transfer length [4]. In this model the cross-section of the wire is divided into two zones of equal area, each having its own uniform current density. At the input lead all the current flows in the outer zone, whereas eventually both inner and outer zone have the same current (density). As a result of this model the following equation is found as being the characteristic length of the diffusion process:

$$l_{diff} = 0.25 \times R_w \times \sqrt{\frac{\rho_{tr}}{\rho_o}} \quad , \qquad (3)$$

in which l_{diff} is the current diffusion length, R_w the radius of the total wire, ρ_{tr} the resistivity of the wire in the transverse direction and ρ_o the desired resistivity measurement level. For example, to measure I_c at $\rho_o = 10^{-14}\Omega m$ for a wire with radius $R_w = 0.2$ mm and copper matrix with $\rho_{tr} \approx 5 \times 10^{-10}\Omega m$, the current diffusion length will be approximately 1 cm. However, when the same wire has a Cu30Ni matrix instead of a copper one with $\rho_{tr} \approx 3.7 \times 10^{-7}\Omega m$, this length is about 27 times longer! This implies, that a measurement of $10^{-16}\Omega m$ in a copper nickel matrix wire across 1 metre requires a sample length of at least 7 metres! Although this model is very simple, since it does not account for the fact that current diffusion already takes place in the soldered connection itself, it is clear, that the influence of the non-homogeneous current distribution caused by the input leads cannot be neglected. Especially in the case of high resistive matrices at moderate voltages or when very low voltages are measured in copper matrix wires, voltage taps should be connected well away from the input leads.

Besides the influence of the connections, the entire wire also has to be in a homogeneous magnetic field. Otherwise the current will redistribute between the filaments because the field-dependent critical current density determines the actual current density in the wire section. This means that a field gradient along the wire will affect a longitudinal voltage which can disturb the measurement of a U-I curve at very low voltage levels.

Table 1: Specification of investigated wires

no	manufacturer	diam. wire [mm]	N fil.	diam. fil. [μm]	sample length [cm]	ratio Cu/CuNi/NbTi	
1	Alsthom	0.12	14496	0.6	50.0	0.83/1.16/1	*
2	MCA	0.30	574	8.6	50.0	0/1.10/1	**
3	Alsthom	0.40	13068	1.8	34.4	1.89/1/1	***
4	MCA	0.20	367	7.0	100.0	1.25/0/1	
5	Vacuum-schmelze	0.20	24	14.0	40.0	7.0/0/1	

* for 50 Hz application, Cu30Ni around the filaments and a mixed central core.

** Cu30Ni matrix with Cu10Ni outer shell.

*** for low frequencies or pulsed operation, Cu around the filaments and CuNi barriers.

Experimental results

Measurements were carried out at 4.2 K on several wires (see table 1) in order to investigate the above mentioned aspects with respect to the critical current transition. Firstly, we checked in what current range the n-power law is valid for two wires with highly resistive matrices. Then we investigated the dependence of n on the applied field. For this purpose, we used both a wire with very thin filaments (these wires are generally extrinsically limited) and one with thicker filaments. Finally, from a U-I curve the critical current distribution was calculated.

A: Several n-values in one U-I curve

In figure 1 a measurement is shown that was taken on wire 1, at zero tesla. In this logarithmically scaled graph several values of n can be distinguished.

At low currents the transition is characterized by a very low value of n. This can be understood by realising that the sample has a highly resistive matrix between the filaments and that the voltage measurement is very sensitive. Therefore, the current transfer length near the input leads is very long and this means that the measured voltage increase is mainly due to the current diffusion process. It

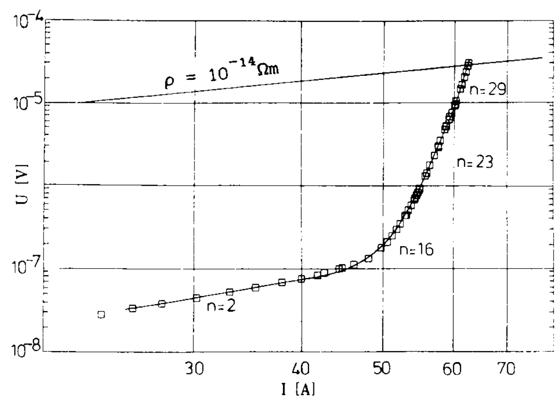

Fig. 1. Logarithmically scaled U-I curve of wire 1 at zero tesla, indicating several n-values.

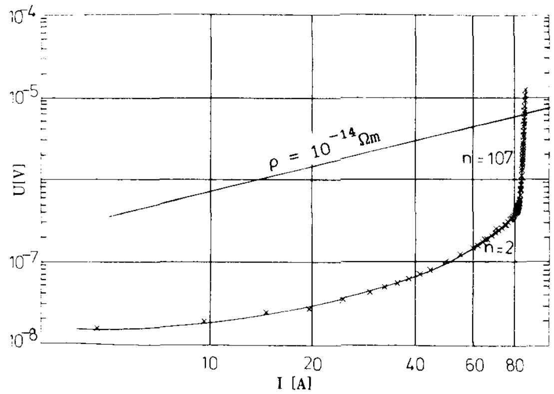

Fig. 2. Logarithmically scaled U-I curve of wire 2 at 4 tesla, indicating several n-values.

results in an n-value of about 2. It is not completely clear, whether the observed variation in the n-value in the subsequent stages of the U-I curve is still caused by the influence of the current diffusion process, or that it is due to properties of the wire itself. In the final stage, just before a quench occurs in the wire, the n value achieves its maximum of 29.

The same behaviour is shown in figure 2 with wire 2, having a copper nickel matrix. At four tesla the U-I curve starts with n-values that are even smaller than 2. After a gradual increase it achieves a maximum value of 107 at 82 A.

B: Dependence of n on the field

Plotting the n-value versus the applied magnetic field enables us to discriminate between intrinsic and extrinsic effects that limit the current. Therefore, we measured the U-I curves of two wires in several fields and calculated the n value in the current range around $I_c(10^{-14}\Omega m)$. The results of these measurements are shown in figure 3, 4 and 5. In general, a single n-value, being valid for a large current range, can be picked out from the graphs.

For the mixed matrix wire (wire 3) there is no dependence of n on the field to be seen, so the wire is extrinsically limited. This could be expected because of the small size of the filaments of 1.8 μm. Therefore small irregularities already affect the filaments for a relatively large part.

On the other hand wire 4 with a copper matrix shows a clear negative slope in the n versus B curve. The n-value decreases at a rate of approximately 6 per tesla. Therefore, it can be concluded that extrinsic effects are of minor importance in the current limiting process.

C: Distribution functions

Calculation of the distribution function by differentiating measured U-I curves numerically is a mathematical process which becomes unstable quite easily. We performed the differentiation by taking a certain number of subsequent points from the U-I curve, through which the best fitting second order polynome was calculated. After this, calculation of a value of the distribution function is an easy task. This procedure was repeated with the same number of points but all shifted one to the right in the U-I curve. This method of differentiating becomes more stable when the curve fitting is done on more points. However, because of this smoothing process information about details in the distribution function is lost. Usually, 5 to 11 points were used to perform one differentiation.

In order to achieve quench currents that were well above $I_c(10^{-14}\Omega m)$, a wire was chosen containing only 24 filaments and a relatively large amount of copper (wire 5). Furthermore this composite was soldered to a brass strip (4 mm width and 0.075 mm thick) to obtain a further increase of the thermal stability. As a result of this extra stabilisation, the characteristic shifts to larger currents than found with the bare wire. In spite of the thick filaments the wire is extrinsically limited, as can be seen in figure 5.

In figure 6 the distribution function is shown for this composite at 4 tesla. Each differentiation was performed on 9 points of the U-I curve. The maximum in the distribution function is found at 46 A.

Conclusions

By means of the superconducting chopper amplifier it is possible to measure accurately U-I characteristics down to the submicrovolt range. These measurements are very useful to investigate the resistive behaviour of superconducting wires below

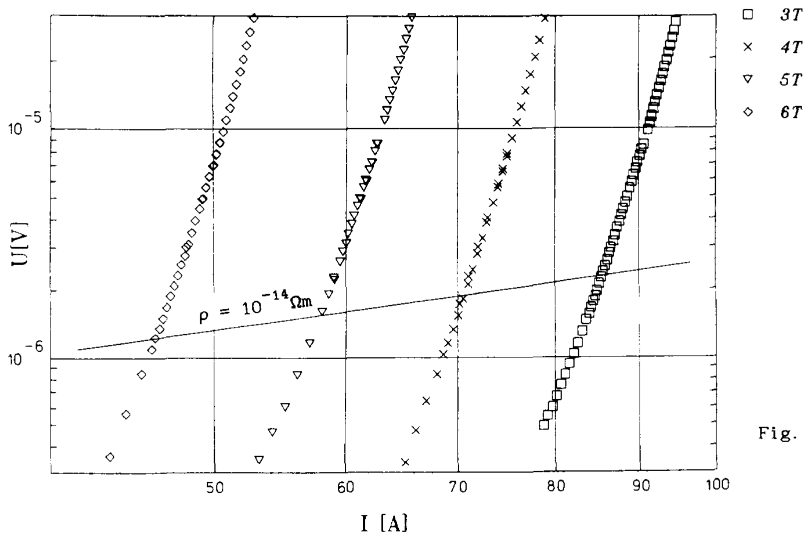

Fig. 3. Logarithmically scaled U-I curves of wire 3 at 3, 4, 5 and 6 T.

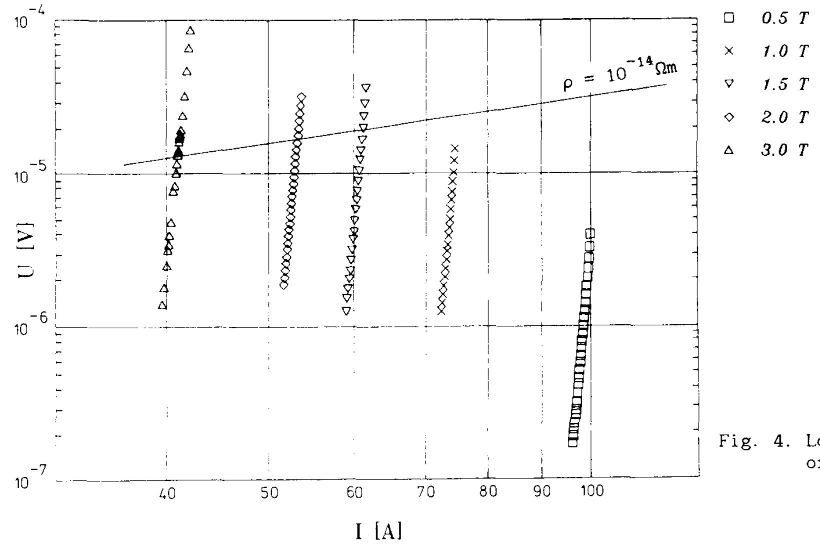

Fig. 4. Logarithmically scaled U-I curves of wire 4 at 0.5, 1, 1.5, 2 and 3 T.

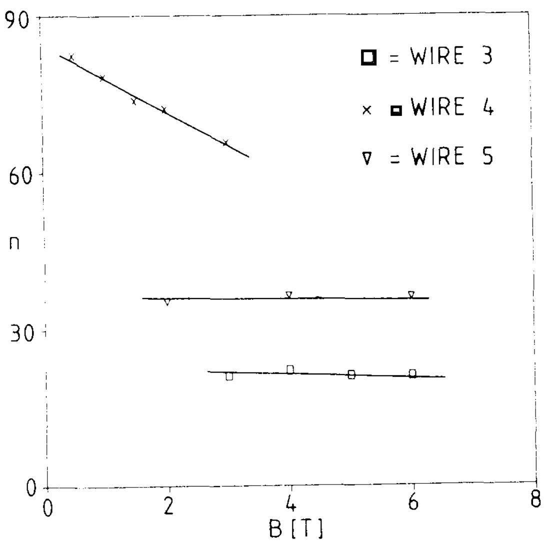

Fig. 5 Dependence of the n-value on the magnetic field for wire 3, 4 and 5.

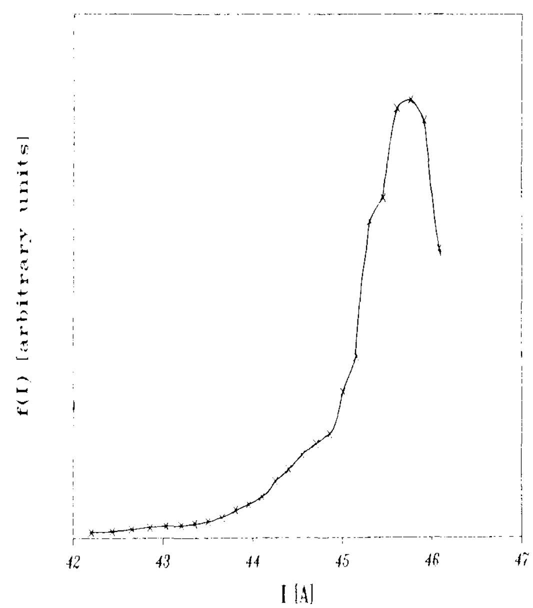

Fig. 6. Distribution function of wire 5 at 4 T.

$I_c(10^{-14}\Omega m)$. Moreover, they can be used to distinguish between extrinsic and intrinsic limitation effects of the current. This is done by adopting the n-power law to the U-I curves and considering the dependence of the n-value on the applied field. As a result of such sensitive voltage measurements on short sample specimens erroneous voltages can be found which are caused by current diffusion processes. This has been found especially for wires with high-resistivity matrices.

In order to calculate of the critical current distribution function from a U-I curve it is necessary to have a highly stable wire in order to achieve currents well above $I_c(10^{-14}\Omega m)$. However, soldering these wires to a normal conducting material shifts the whole curve to the right. More research is needed, especially to investigate in what way this procedure of adding extra stability to the wire affects the results with respect to the properties of the bare wire.

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