Investigation of superconducting filament non-uniformities by an electrical method

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An electrical method of investigating non-uniformities of superconducting filaments and multifilamentary composites is described. It is based on the measurement and analysis of the recovery part of the current–voltage characteristic. As an example, results obtained on a Nb–Ti filament 11 μm in diameter are presented. The influence of some artificial inhomogeneities on the recovery part of the current–voltage characteristics of a 36 μm Nb–Ti filament is also demonstrated.

Keywords: measuring methods; multifilamentary wires; materials characterization

The non-uniformities of superconducting filaments in NbTi multifilamentary composites are currently the subject of intensive theoretical and experimental studies[1-3]. The non-uniformities of critical current density and cross section of individual filaments as well as along them are considered to determine the form of the current–voltage characteristics observed on multifilamentary composites[4-7]. On the other hand, analysis of the current–voltage characteristics allows an evaluation of the uniformity of superconducting filaments in composites.

To study geometrical non-uniformities of filaments various methods can be used. The most conventional is scanning electron microscopy. But this method does not allow investigation of the non-uniformity of electrical properties, such as critical current or normal state resistivity variations along the filaments.

This paper presents a new electrical method for investigating the non-uniformities, based on the analysis of the recovery part of the current–voltage characteristics. It is also shown that by this method geometrical non-uniformities, as well as non-uniformities of electrical properties and heat transfer, can be evaluated. The method is based on the analysis of steps on the recovery part of the current–voltage characteristic caused by normal zone localization on non-uniformities (see the theory in the Reference 8).

Theory

Consider a superconducting filament including non-uniformities of its parameters along the sample length. The parameters mentioned may be of different physical nature. Generally, non-uniformities may be caused by variation of the critical current density, the filament cross section, the normal state resistivity, the critical temperature and so on. Experiments have shown that the variation of the local critical current density manifests itself in the normal state resistivity variation[9]. The local critical temperature depends on the local material composition, which influences the normal state resistivity.

Suppose then that the non-uniformities of different physical nature manifest themselves in the variation of the normal state resistance per unit length r along the superconducting filament.

As an example, in *Figure 1* the parameter r is shown as a function of x (the x axis is identical with the filament axis). The characteristic length of the non-uniformity is l. If the whole filament is normal, the voltage U is given by

$$U = I \int_0^a r(x)\mathrm{d}x \tag{1}$$

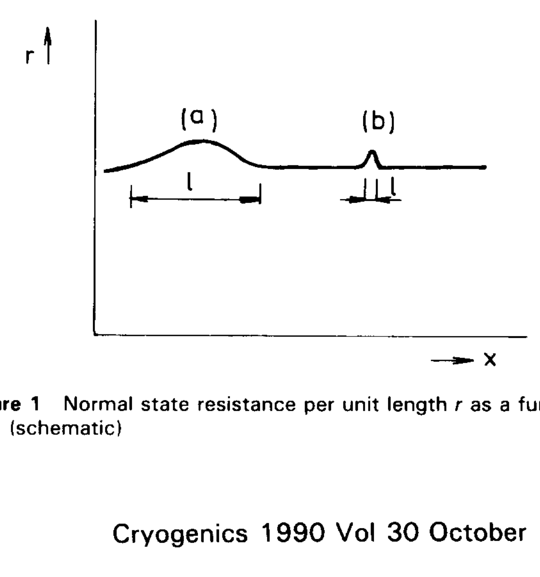

Figure 1 Normal state resistance per unit length r as a function of x (schematic)

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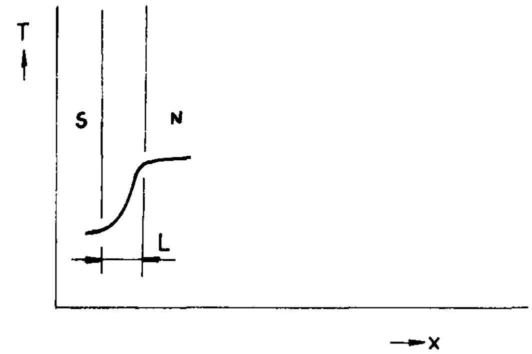

Figure 2 Temperature distribution along the N – S boundary

where a is the filament length and I is the current. While the current decreases, the process of normal zone disappearance starts at a certain value of I and the voltage U becomes proportional to the total length of the normal zone regions. Note that in an inhomogeneous sample several normal zone regions may exist simultaneously.

The situation depends on the ratio l/L, where L is the width of the superconducting – normal zone boundary (see *Figure 2*). The value of L is given by[7]

$$L = (\kappa A/Ph)^{1/2} \tag{2}$$

where κ is the thermal conductivity of the filament, A is the area and P is the perimeter of its cross section, and h is the heat transfer coefficient to the coolant. For simplicity consider here two limiting cases: $l \gg L$ and $l \ll L$ (see *Figures 1* and *2*). The main results of the theory[8] for these two cases are summarized briefly as follows.

In the first case ($l \gg L$) it is possible to calculate the value of the minimum propagation current I_p at each point along the filament length. The inhomogeneity of filament parameters leads to the variation of I_p (see *Figure 3a*). Thus, for example, I_p is lower in the regions where $r(x)$ is higher and vice versa. Starting from the normal state and decreasing the transport current, the value of U is given by the sum $U = \Sigma_{i=1}^{n} U_i$, where U_i is the voltage on each normal zone region

$$U_i = I \int_{a_i(I)}^{b_i(I)} r(x)\mathrm{d}x$$

where $a_i(I)$ and $b_i(I)$ are the roots of the equation

$$I = I_p(x) \tag{3}$$

The graphical solution of this equation is given in *Figure 3a* for a general case of smooth inhomogeneities. As seen in this figure, the parameters a and b depend on I.

The corresponding current – voltage characteristic is shown in *Figure 3b*. It was assumed that for increasing current the normal zone first originates in point A. The normal zone length monotonically increases up to $I = I_+$, after which the left normal zone boundary jumps to point C. Thus, the monotonic dependence $I_p(x)$ leads to stepwise and non-linear current – voltage characteristics with hysteresis.

Note that a special case of rectangular inhomogeneities may exist when normal zone lengths are practically independent of I (see insert in *Figure 3a*). The corresponding current – voltage characteristic consisting of several linear parts is shown in the insert in *Figure 3b*.

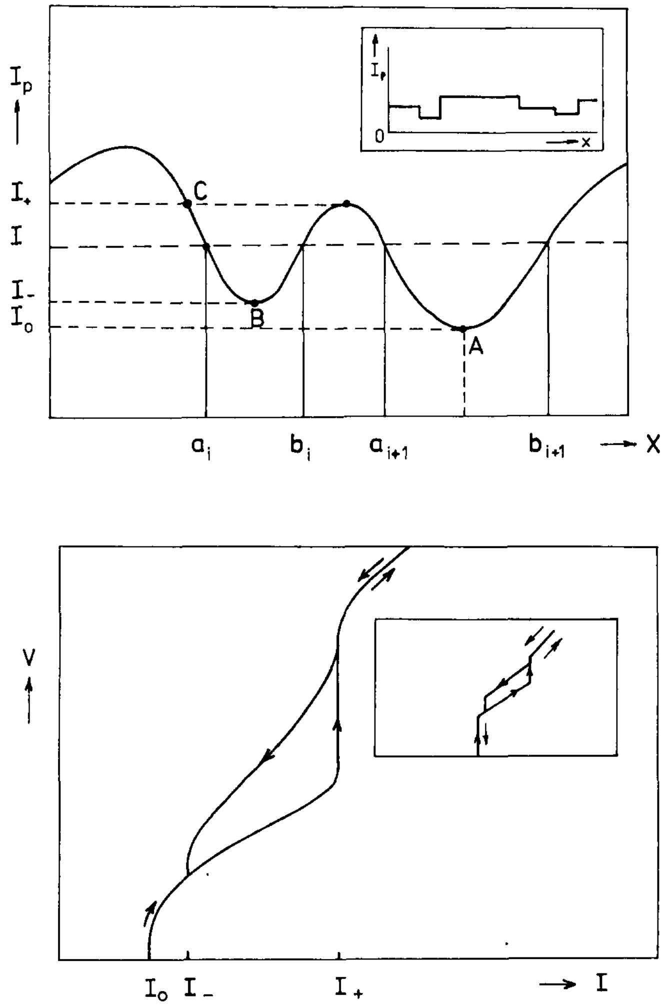

Figure 3 (a) Graphical solution of the equation $I = I_p(x)$. The regions $a_i < x < b_i$ and $a_{i+1} < x < b_{i+1}$, where $I > I_p(x)$, are in the normal state. Insert, special case: rectangular inhomogeneities. (b) Current – voltage characteristics corresponding to a filament with minimum propagating current distribution shown in (a). Insert, current – voltage characteristic for rectangular inhomogenities

Consider now the second case, $l \ll L$. This type of inhomogeneity will be called a 'point' inhomogeneity. The only type of point inhomogeneities considered will be those whose presence leads to a local temperature rise in the normal state ('hot' points). In addition the distance between the hot points is assumed to be $> L$. A possible distribution of normal and superconducting zones along a filament is shown in *Figure 4* for $I < I_p$, where I_p is constant between hot points. This distribution is metastable and originates as follows.

Begin from the normal state. When decreasing the current to a value $I < I_p$, some superconducting domains arise. In general, this process is of random nature, e.g. it starts from randomly distributed points. The propagation of superconducting zones may be interrupted near hot points, if the heat release is high enough. The condition for such a normal – superconducting boundary localization is given by the formula

$$I_p - I \leqq \Gamma I_p \tag{4}$$

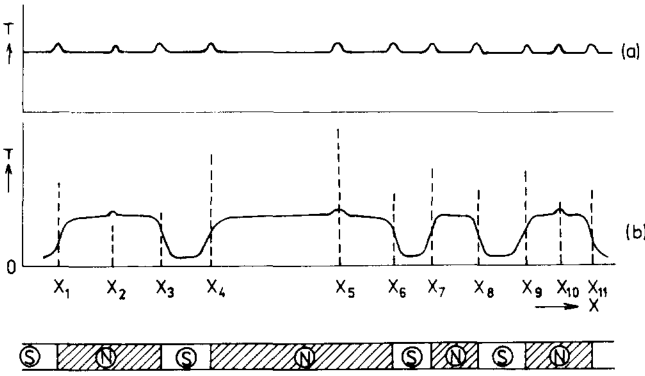

Figure 4 Temperature distribution along the superconductor with point inhomogeneities during the recovery of superconductivity: (a) $T(x)$ at $I > I_p$; (b) possible temperature profile $T(x)$ at $I < I_p$ and corresponding distribution of normal and superconducting zones along a filament. – – –, Positions of hot points. The length of each dashed line is proportional to the corresponding value of Γ

where Γ is a dimensionless parameter characterizing the additional heat release

$$\Gamma = \frac{1}{rL}\int_0^l [r(x) - r]\,\mathrm{d}x = \frac{\Delta rl}{rL} \tag{5}$$

where r is the resistance per unit length, which is constant between hot points, and the product Δrl is the additional resistance of a hot point.

Consider now the form of the recovery part of a current–voltage characteristic due to the existence of hot points. Begin, for example, from the normal–superconducting zone distribution shown in *Figure 4*. The total voltage U is given as

$$U = I\left[\int_{x_1}^{x_3} r(x)\mathrm{d}x + \int_{x_4}^{x_6} r(x)\mathrm{d}x + \int_{x_7}^{x_8} r(x)\mathrm{d}x + \int_{x_9}^{x_{11}} r(x)\mathrm{d}x\right] \tag{6}$$

Here the values x_i are determined by distances between point inhomogeneities, so they are independent of the current I. While I is further decreasing, the voltage U decreases linearly in proportion to I. At a certain value of I_i the difference between I_p and I_i becomes higher than necessary for localization of the normal–superconducting boundary on the inhomogeneity given by Equation (3). In the case being treated it occurs first at the point x_3 at $I = I_3$. Thus the normal zone between x_1 and x_3 disappears. The total voltage given by Equation (6) changes abruptly at $I = I_3$ and becomes equal to

$$U = I\left[\int_{x_4}^{x_6} r(x)\mathrm{d}x + \int_{x_7}^{x_8} r(x)\mathrm{d}x + \int_{x_9}^{x_{11}} r(x)\mathrm{d}x\right] \tag{7}$$

and so on.

Experimental

To demonstrate the influence of inhomogeneities on the recovery part of the voltage–current characteristic a sample of relatively thick (36 μm diameter) Nb–Ti monofilament was prepared, as shown in the insert in *Figure 5*. The recovery part of the voltage–current characteristic was very sharp, as shown in *Figure 5*. As the resistive parts of the voltage–current characteristics of this sample measured in external magnetic fields were very sharp too, the sample was supposed to be homogeneous.

Further, three types of artificial inhomogeneities were prepared successively and their influence on the recovery part of $A-V$ characteristics measured:

1 ≈5 mm of the filament length between the potential contacts was covered with a thin layer of General Electric varnish (heat transfer inhomogeneity);
2 the filament between the potential taps was etched slightly over a length of ≈2 mm; and
3 the filament was etched a little more over a length of ≈10 mm.

The recovery characteristics of the original sample and those of the same sample with the mentioned inhomogeneities are shown in *Figure 5*. Note that the magnetic field up to 1 T did not influence the measured recovery curves.

Experiments on thinner Nb–Ti filament extracted from a twisted multifilamentary composite, in which inhomogeneities can be expected, are now discussed. The filament was extracted from a multifilamentary Nb–Ti composite 0.524 mm in diameter containing 1045 filaments, each 11 μm in diameter, embedded in Cu/CuNi matrix. First, the matrix was etched off over a length of 25 mm. On both sides 1 cm of the composite was not

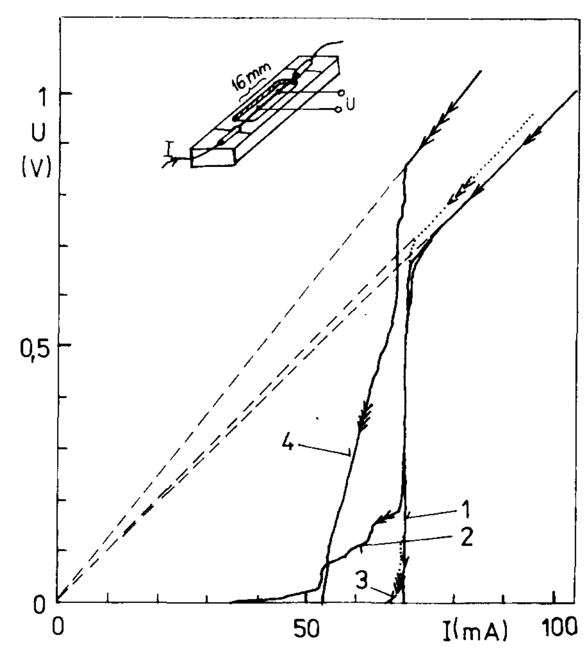

Figure 5 Recovery part of voltage – current characteristics of the bare 36 μm Nb – Ti filament: 1, original sample; 2, sample covered with thin layer of GE varnish over a length of ≈5 mm between the potential taps; 3, sample without GE varnish, slightly etched over a length of ≈2 mm; 4, sample without GE varnish, etched a little more over a length of ≈10 mm. Insert, sample and sample holder

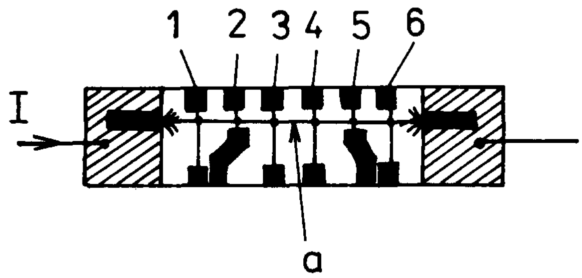

Figure 6 Sample of 11 μm Nb–Ti filament with six potential taps (1–6)

etched; these parts served as current contacts (see *Figure 6*). The distance between the neighbouring taps was ≈ 5 mm. *Table 1* gives the exact distances as well as the resistance and the mean filament diameter between the taps, measured by scanning electron microscopy (SEM).

The sample was supplied from an ordinary 4.5 V battery. A variable resistor for current control and another normal resistor for obtaining the signal proportional to the sample current were in series with the sample. The voltage–current characteristics were recorded with an $X-Y$ analogue recorder.

First, sensitive measurements of the voltage–current characteristics between all potential taps in a magnetic field of 5.46 T were made. They are shown in *Figure 7*. From these measurements critical currents corresponding to the electric field 0.1 μV cm^{-1} were estimated (*Table 1*). The lowest I_c value was measured between taps 3 and 4; this means that the 'weak spot' in I_c is situated between these taps.

Further measurements were made with lower voltage sensitivity in order to be able to record the interesting part of the normal state voltage–current characteristic and the recovery of the sample into the superconducting state.

Starting from zero, current was increased up to a transition into the normal state. This part of the $I-V$ characteristic was not recorded. The recovery part of the characteristic was recorded. *Figure 8* shows the recovery characteristic measured between the taps 1 and 6 (whole sample length) and Figure 9 shows similar curves measured between taps 1 and 2 and 3 and 4. The stepwise form of the curves indicates the localization of normal (resistive) domains in the sample.

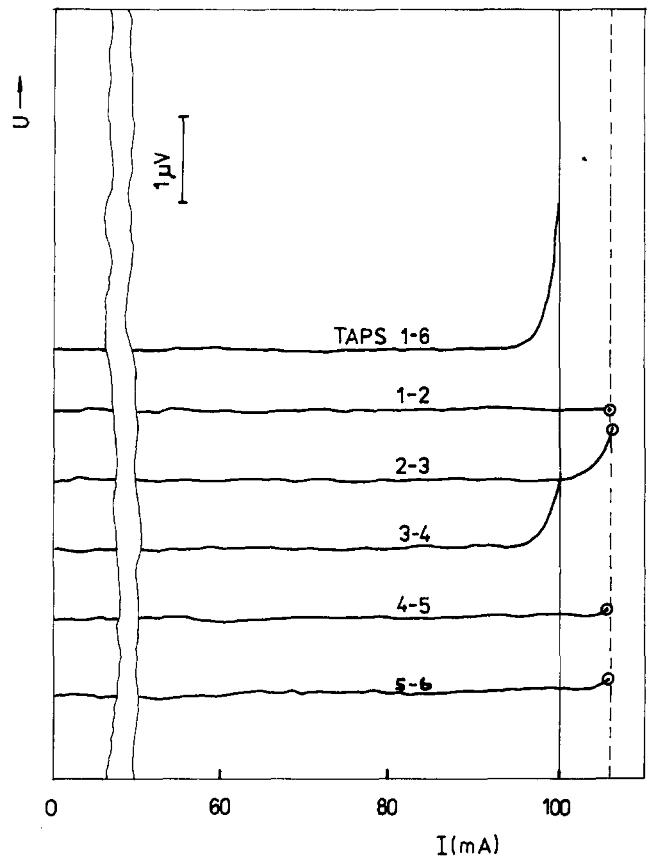

Figure 7 Current–voltage characteristics of the Nb–Ti filament measured between potential taps 1 and 2, 2 and 3, 3 and 4, 4 and 5, 5 and 6 and 1 and 6 (whole sample length) in magnetic field B = 5.46 T

Discussion

First, characteristic parameters of the sample are calculated. Assuming the filament diameter d = 11.2 μm, the thermal conductivity κ = 1 W cm^{-1} K^{-1}, and the heat transfer coefficient h = 1 W cm^{-2} K^{-1}, the thermal length L is given by

$$L = \frac{1}{2}\left(\frac{d\kappa}{h}\right)^{1/2} \approx 0.1-0.2 \text{ mm}$$

The Stekly parameter α for d = 11.2 μm, r = 92.5 Ω cm^{-1}, $P = \pi d$ = 34 μm, $T_c(B) - T_0$ = 2.4 K at B = 5.46 T, $I_c \approx 0.1$ A and h = 1 W cm^{-2} K^{-1} is

$$\alpha = \frac{rI_c^2}{Ph(T_c - T_0)} \approx 115$$

Because $\alpha \gg 1$, the minimum propagating current I_p can be calculated as (see, for example, References 7 and 8)

Table 1 Parameters of the sample made of 11 μm Nb–Ti filament

Potential taps	1–2	2–3	3–4	4–5	5–6	1–6
Distance between taps (mm)	4.64	5.05	5.55	4.68	4.70	24.62
Mean filament diameter (μm)	11.4	10.9	10.8	11.6	10.9	11
Resistance at 300 K (Ω)	44.6	48.8	51.0	43.6	40.8	228.8
Resistance per unit length r (Ω mm^{-1})	9.61	9.66	9.19	9.32	8.68	9.29
Critical current I_c (0.1 μV cm^{-1}) for B = 5 T (mA)	106	101	96.5	105	105	99

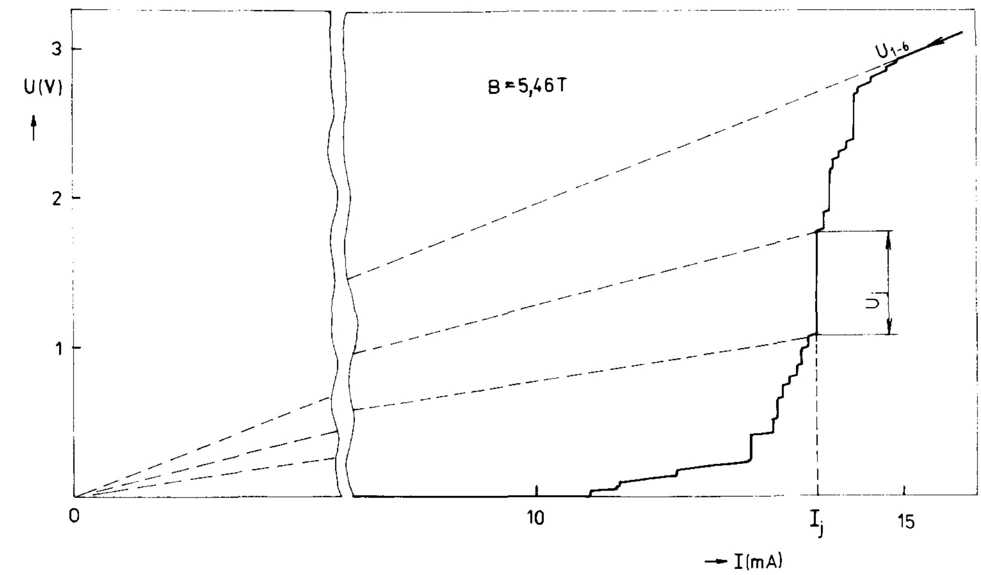

Figure 8 Recovery part of current – voltage characteristics measured between taps 1 and 6 in magnetic field B = 5.46T

$$I_p = I_c\left(\frac{2}{\alpha}\right)^{1/2} \approx 13.2 \text{ mA}$$

This value is approximately equal to the mean value of recovery current obtained experimentally.

The characteristic length of the normal zone jumps Δx_j can be estimated from the voltage jumps U_j occurring at the current I_j, which are caused by the abrupt change of the sample resistance, $R_j = U_j/I_j$. *Figure 8* shows that the jumps U_j are roughly 0.1 – 0.5 V and they occur in the current interval $11 < I_j < 15$ mA. Thus the resistance changes during jumps R_j are $10 < R_j < 50\ \Omega$. The corresponding length of inhomogeneities is $l = R_j/r$; substituting $r \approx 8\ \Omega\ \text{mm}^{-1}$ gives 1 mm $< x_j <$ 6 mm.

The characteristic value of the parameter Γ is of the order of $\Delta I/I_p$, where ΔI is the characteristic width of the current interval with stepwise recovery of superconductivity. One can see in *Figures 8* and *9* that $\Delta I \approx 3$ mA, which yields $\Gamma \leq 0.2$ up to 0.3, i.e. the non-uniformities of the sample are relatively weak.

Using the measured values of the currents I_j at which steps occur (taps 1 – 6, *Figure 7*) the corresponding values of the parameter Γ are obtained as

$$\Gamma_j = (I_p - I_j)/I_p \qquad (8)$$

The value of minimum propagating current I_p is assumed to be identical with the beginning of the recovery. The mean value of I_p obtained in this way between all pairs of potential taps is 14.15 mA. *Figure 10* shows the distribution function of Γ between potential taps 1 and 6. As seen from this figure there are two groups of hot points: 15 relatively weak non-uniformities with $\Gamma \leq 0.12$ and five relatively strong ones with $0.2 < \Gamma < 0.3$. A similar distribution function obtained from measurements between taps 3 and 4 is shown in *Figure 11*.

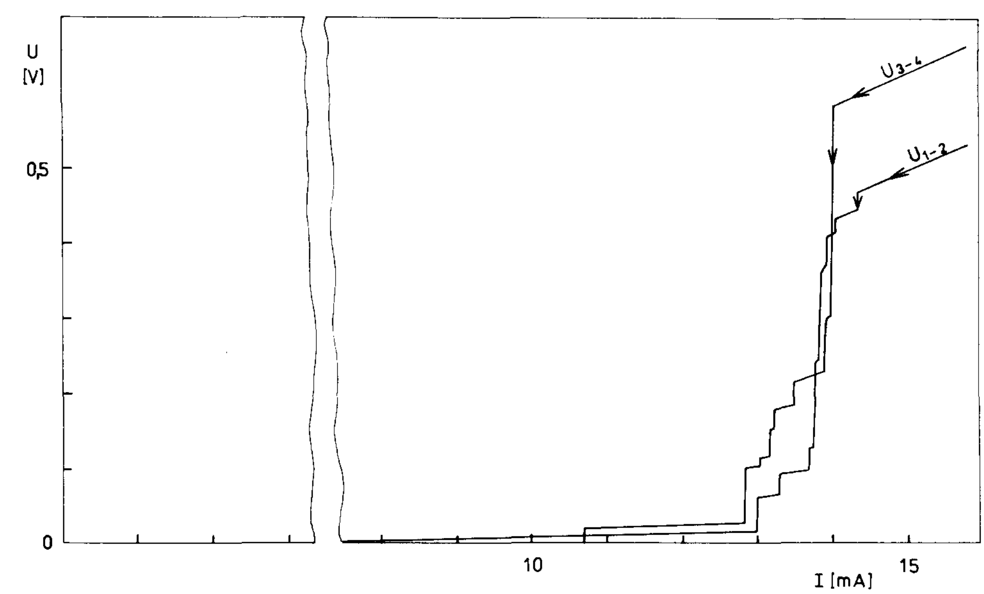

Figure 9 Recovery parts of current – voltage characteristics measured between taps 1 and 2 and 3 and 4

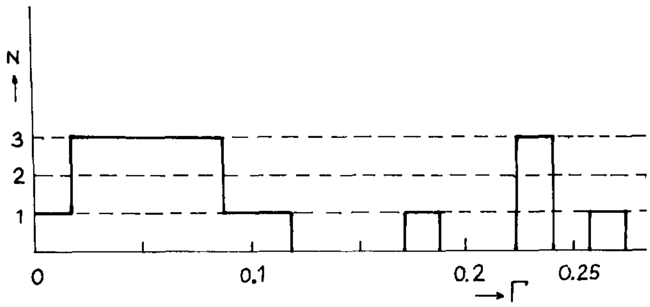

Figure 10 Distribution function of Γ between potential taps 1 and 6

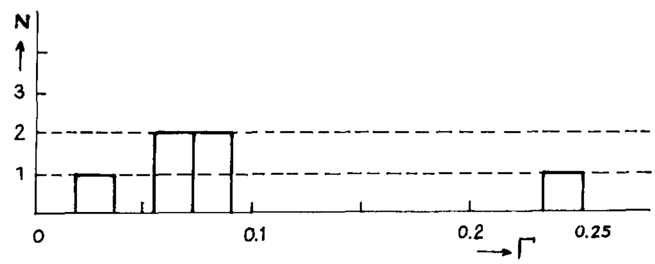

Figure 11 Distribution function of Γ between potential taps 3 and 4

Up to now, it has been assumed that only point inhomogeneities exist in the measured filament. But direct measurements of critical current and normal state resistance show these varying slowly along the filament (see *Table 1*). Similar results were obtained for variations of filament diameter using SEM. Thus both smooth and point inhomogeneities exist simultaneously in the filament. This evidently leads to weak non-linearity of the current–voltage characteristic and to the fact that some 'quasilinear' parts of the observed current–voltage characteristics between the jumps can not be extrapolated to the point $I = 0$.

Conclusions

The electrical method presented above allows investigation of the non-uniformities of a superconducting filament or wire (composite) by analysis of their $I-V$ characteristics. This method was demonstrated on one Nb–Ti filament ≈ 11 μm in diameter. It was shown that the recovery part of its $I-V$ characteristic is stepwise. The parameters of steps in measured voltage can be used to evaluate the distribution of the non-uniformities along the measured filament. Measurements on the Nb–Ti sample 36 μm in diameter with three types of artificial inhomogeneity demonstrated their influence on the recovery part of the $I-V$ characteristics.

This method together with SEM allows quite complete information on non-uniformities in superconductors to be obtained.

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