The maximum transport current in multifilament composite superconductors has been studied. The experimentally obtained values of transport current exceed the normal phase minimum propagation current substantially. The current-voltage characteristics of the investigated samples have been studied. It is shown that the relatively high value of the maximum transport current is attributed, under the given experimental conditions, to the behaviour of the current-voltage characteristic in the region of low values of the electric field. The theory and experiment are in good agreement.

Superconducting current stability in composite superconductors

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Key words: superconductor; multifilament; transport current

The maximum value of transport current, I_m, which can flow in the conductor in a superconducting state, presents one of the principal characteristics of a composite superconducting material. Of substantial interest is the dependence of the value of I_m on external conditions (such as cooling, external magnetic field B_a, rates of variation of current $\dot{I}$ and magnetic field $\dot{B}_a$). In the case of thin well-cooled conductors, the value of I_m is defined by the density of critical current in superconducting filaments.

$$j_c = j_c(T, B): I_m = I_s = S \cdot x_s j_c$$

where T is the temperature, B is the magnetic field induction, S is the cross-sectional area of the sample and x_s is the concentration of superconductor in the composite. In the case of massive samples and/or under conditions of less intensive surface cooling, I_m may turn out to be substantially lower than I_s, due to the emergence of characteristic instabilities of the critical state, ie, magnetic flux jumps.[1-4]

In multifilament composite superconductors, the magnetic diffusion coefficient $D_m = c^2/4\pi\sigma$ is much less than the thermal diffusion ocefficient $D_t = \kappa/\nu$. This enables one to obtain, in the main approximation over $\tau = D_t/D_m \gg 1$, the limitation for I_m in the form (Hart's dynamic criterion)[1]:

$$I/I_s \leqslant I_m/I_s = \frac{W_0(T_c - T_0)\sigma P}{x_s^2 j_c^2 S} \qquad (1)$$

where σ is the longitudinal (along the filaments) electric conductivity of the composite, κ is the transverse heat conductivity, ν is the heat capacity, W_0 is the heat transfer coefficient, P is the cross-sectional perimeter and $T_c = T_c(B_a)$ is the critical temperature. While deriving (1), the values j_c, T_c and σ were assumed to be varying but slightly over the sample cross-section, $W = W_0 S/\kappa P \ll 1$ (which is usually true even in the case of liquid helium-cooled composites) and, finally, for $\partial j_c/\partial T$ it was used for the following approximation:

$$\partial j_c/\partial T = -j_c/(T_c - T_0)$$

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Under these conditions, the accuracy to which (1) defines the value of I_m/I_s is of the order of $(W\tau)^{-1/3}$.[5]

It follows from (1) that $I_m \propto \sigma$. The value of σ is usually assumed to be equal to the normal matrix conductivity along the filaments, ie, $\sigma = x_n \cdot \sigma_n$ where x_n is the concentration of normal metal of high conductivity (for example, copper) and σ_n is its electric conductivity.[1-6] Usually, it is assumed that $\sigma_n \gg \sigma_s$ where σ_s is the superconductor conductivity in the resistive mode. The latter condition is satisfied, for example, if the perturbations leading to the flux jump initiation are so strong that the superconductor undergoes the flux flow mode. It is known, however, that the current-voltage characteristic of hard superconductor in the region of low electric fields is substantially non-linear. The electric conductivity $\sigma(E) = dj/dE$ in the non-linear region may exceed considerably the value of the conductivity σ_f in the flux flow mode. This latter circumstance may affect the critical state stability in hard superconductors greatly.[7] As shown experimentally,[8-12] the current voltage characteristic of a composite superconductor is non-linear up to electric fields $E \sim 10^{-6} - 10^{-4}$ V cm^{-1}. In this region, the conductivity $\sigma(E) = dj/dE$ may be much greater than the value $\sigma_n x_n$. Accordingly, (1) with $\sigma = x_n\sigma_n$ will only define the value of I_m if there exists an external perturbation strong enough to give rise to the background electric field E_b at which $\sigma(E_b) \ll \sigma_n$.[3,4] From the literature,[12,13] in many cases of practical interest I_m is defined by the non-linear portion of the current-voltage characteristic and exceeds considerably (up to 2-3 orders of magnitude) the value obtained from (1) at $\sigma = x_n\sigma_n$.

This paper presents the experimental and theoretical study of the effect of the current-voltage characteristic of a superconductor upon the critical state stability. Results are presented of the measurements of I_m for a number of composite superconductors in a magnetic field of $0 < B_a < 6$T. The current-voltage characteristics, heat transfer from the samples to helium and the normal phase minimum propagation current were measured. The experimental techniques are described in detail, and the comparison of theory with experiment is presented.

Experiment

The main experimental studies have been devoted to the

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Table 1.

Samples	Diameter cm	Total number of wires with diameter 0.03 cm	Superconductor concentration X_s	Copper concentration X_n	Number of superconducting filaments
A1	0.03	1	0.32	0.68	6
A2	0.1	7	0.19	0.50	36
A3	0.25	49	0.19	0.52	252
A4	0.46	133	0.17	0.49	648
B1	0.03	1	0.44	0.56	18
B2	0.1	7	0.26	0.43	108
B3	0.46	133	0.23	0.42	1944

measurement of the dependence of the current I_m on the external field induction B_a and the current-voltage characteristics of the samples. Additional experiments were carried out to define the parameters essential for the qualitative and quantitative interpretation of the results and their comparison with theory.

The basic parameters of the experimental samples manufactured from Nb-40%Ti alloy in a copper matrix[14] are listed in Table 1. Samples A1 and B1 are twisted axially. Sample A1 comprises six superconducting filaments having a diameter of about 69 μm; sample B1 comprises 18 superconducting filaments having a diameter of about 47 μm. Structurally, sample A2 is made up of six conductors of the A1 type jointly twisted around a copper wire (0.03 cm in diameter). Samples A3 and A4 are made up of 7 and 18 conductors of the A2 type, respectively. In sample A4, all of the conductors are wound on a copper base consisting of seven copper wires 0.03 cm in diameter. Analogously, sample B2 is made up of six B1 conductors and one copper wire, and sample B3 – of 18 B2 conductors and seven copper wires.

All of the samples, with the exception of A1 and B1, are impregnated with a high-resistance indium-based alloy.

Samples A1 and B1 were insulated by low-temperature lacquer having a thickness of Δ_1 = 20 μm, while conductors A2, A3, A4 and B2, B3 were insulated by layers of teflon and lavsan having a thickness of Δ_2 = 100–200 μm.

When measuring the transport current, the samples were also coated with epoxy (Δ_3 = 300–400 μm). Listed in Table 2 are some thermo- and electrophysical properties of materials of the samples and insulating coatings.

The study of the maximum current-carrying capacity of high-current conductors was based on the contactless technique utilizing the principle of flux pumping.[15] The schematic of the apparatus is shown in Fig. 1. Sample 1 is placed in the centre of solenoid 2 serving as the source of external field and transport current in the sample. An induction coil 3 is located at a distance of 20–25 cm from the sample. The coil and sample are interconnected to form a closed circuit with a resistive (soldered) contact 4 whose resistance does not exceed 10^{-9} Ω. The intrinsic time of current decay in the circuit has a value of the order of 5 x 10^3 s. A pick-up coil, 5, of the Rogowsky type was used for measuring the current. A signal from the pick-up coil was supplied to an integrator, 6, the output voltage from which was recorded on an XY-recorder. The use of the heater 7 allows one to warm the sample up to $T > T_c$ and to find the value of I_m at any desired magnetic field B_a. The error of the measurements did not exceed 0.2%. The maximum transport current I_m corresponds to the value of the transport current I when a flux jump instability occurs in the sample.

The present paper contains data on the maximum transport current at low rates of current variation $\dot{I}$ and field variation $\dot{B}_a$, namely, $\dot{I} \simeq 10$ A s^{-1} and $\dot{B}_a \simeq 4 \times 10^{-3}$ T s^{-1}. The preliminary data for I_m obtained at higher values (up to a factor 10) of $\dot{I}$ and $\dot{B}$ are qualitatively analogous with the results presented here. The detailed study of I_m dependence on $\dot{I}$ and $\dot{B}$ will be presented elsewhere.

When measuring I_m, the samples were bifiliar-wound on a textolite frame and coated with a layer of epoxy. This technique was employed because of the following reasons.

1. When measuring I_m, a rather substantial ponderomotive force $F_p = IB$ acts upon the sample. This force may cause a shift of the sample and, consequently, may lead to the transition to normal state unrelated to magnetic flux jumps. Under conditions of our experiments, the epoxy coating helps to avoid the effect.

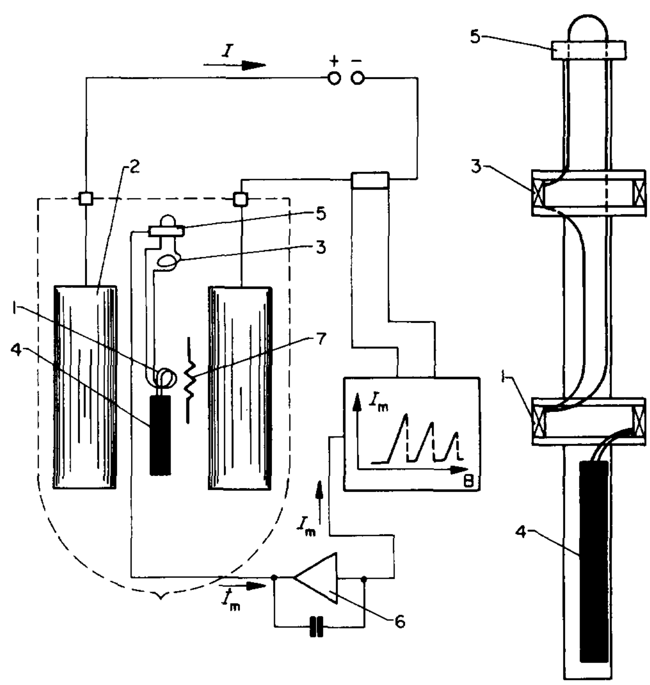

Fig. 1 Schematic of the apparatus for measuring the maximum transport current

2. The thermal conditions on the superconductor surface appear to simulate the conditions of the conductor operation in a magnet.
3. Under the given experimental conditions, the heat transfer to the cooler depends mainly upon the heat-insulating coating (including the epoxy). This helps avoid difficulties in the analysis of results, due to the change of the liquid helium boiling regime.

Presented in Fig. 2 are the results of measurements of the current density $j_m = I_m/S$ as a function of the external magnetic field B_a for samples A1-A4 and, in Fig. 3, for samples B1-B3. An analysis of the data for $j_m(B_a)$ shows the transport current density to decrease with an increase of the number of filaments, this decrease being the greater the lower the external field. Shown in Fig. 4 is the ratio $i_m = I_m/I_s$ as a function of the conductor diameter (for samples A1, A2, A3, A4). As seen from the figure, a diameter increase leads to the deviation of i_m from unity of 10% in magnetic fields $B_a > 3$T and of the order of 40-50% at $B_a < 3$T.

The current-voltage characteristics were studied in a separate experiment for samples A1 and B1. These conductors are the basic superconducting structural elements of the other tested samples. The measurements were carried out in a standard manner by means of special experimental arrangements. The transport current from a stabilized external source was passed in a bifiliar-wound sample placed in an external transverse magnetic field. The current increased at a rate of no more than 0.1 A s^{-1}. The external magnetic field was generated by a superconducting solenoid. The measurements were taken at $T = 4.2$ K in the magnetic field range of $B_a = 0$-5 T. The conventional four-terminal arrangement is used to measure the current and voltage along the samples. The test facilities enables one to determine the electric field E within the limits of from 10^{-10} V cm^{-1} (with a sensitivity of at least 10^{-11} V cm^{-1}) to E_c when in the sample there emerges an instability accompanied by transition to normal state.

On studying I-V curves, the wire of the type A1 or B1 several meters long has been wounded on a textolite frame with axially and radially extended channels. Textolite spacers were placed between the wire layers, which helped attain a good thermal contact of each turn of the sample with liquid helium.

Presented in Fig. 5 are the current-voltage characteristics of sample A1 at different values of the external magnetic field. As seen from the figure, the value of the conductivity $\sigma(E) = dj/dE$ decreases with an increase of the magnetic field. The conductivity over the entire range of the electric field from 10^{-10} V cm^{-1} to E_c is two-five orders of magnitude higher than the normal matrix conductivity. Analyzing the $j(E)$ curves on the basis of the critical state model, it is natural to assume that the sample is completely filled with current having a density of $j \simeq j_c(B) \cdot \chi_s$, after which there occurs an increase of the electric field at an almost constant current $I \simeq I_s$. While the electric field varies from 10^{-8} V cm^{-1} to E_c, the value of j increases by no more than 10%. The j_c value is usually defined as the current density at which the field E in the sample is lower than some value E_0.[16] In the case under consideration, the choice of the E_0 value from 10^{-7} V cm^{-1} to E_c (and even as is usually done, to $E = 10^{-6}$ V $cm^{-1} > E_c$) affects but slightly the value of j_c. As in the case of I_m we shall suppose that $I = I_s$ at $E_0 = 10^{-6}$ V cm^{-1} or $E = E_c$ if $E_c < 10^{-6}$ V cm^{-1}.

The electric field dependences of the specific resistance

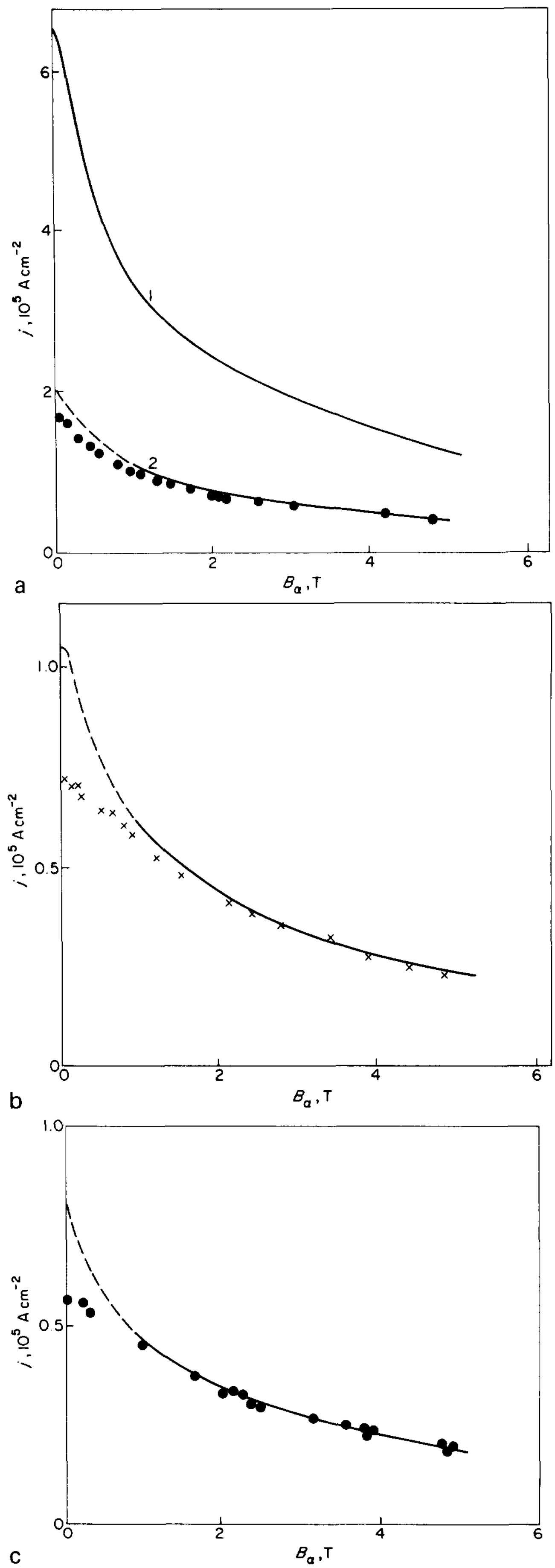

Fig. 2a — Curve 1 — Critical current density in Nb-Ti filaments (A1), $j_c(B_a)$ (experiment). Curve 2 — the theoretical dependence $j_m = j_m(B_a)$ for the sample A2, points — the experimental values of j_m for A2. 2 b — The function $j_m(B_a)$ for the sample A3: theory and experiment. 2 c — The function $j_m(B_a)$ for the sample A4: theory and experiment

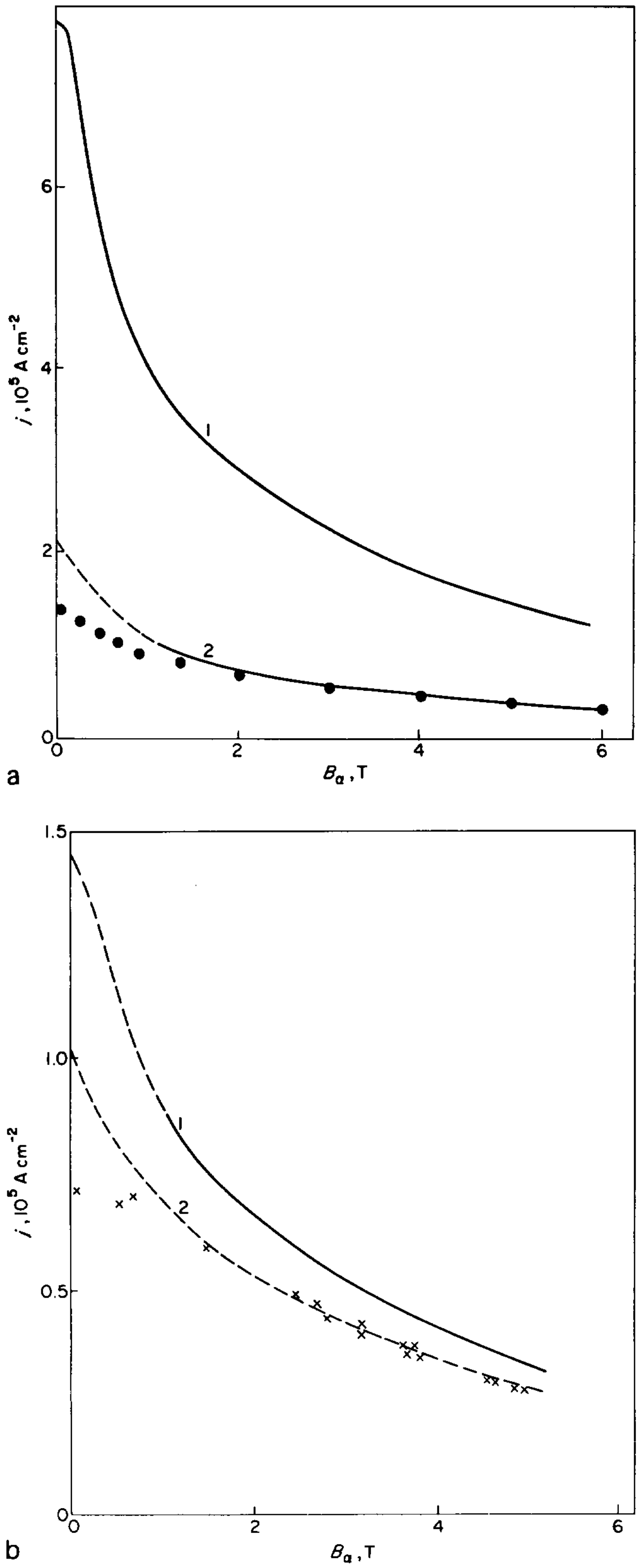

Fig. 3a – Curve 1 – measured value of $j_c(B_a)$ (B1), Curve 2 – theoretical dependence $j_m(B_a)$ for sample B2, points – the experimental values of j_m for B2. 3 b – Sample B3. Curve 1 – theoretical dependence $j_m(B_a)$ at A = 1. Curve 2 – $j_m(B_a)$ at A = 1/3. x – experiment

$\rho(E)$ of the samples in different magnetic fields were plotted using the obtained current-voltage characteristics (Fig. 6a – sample A1, and Fig. 6b – sample B1). Over a wide range of fields, $\rho(E) \propto E$, which agrees with experimental data.[8–11]

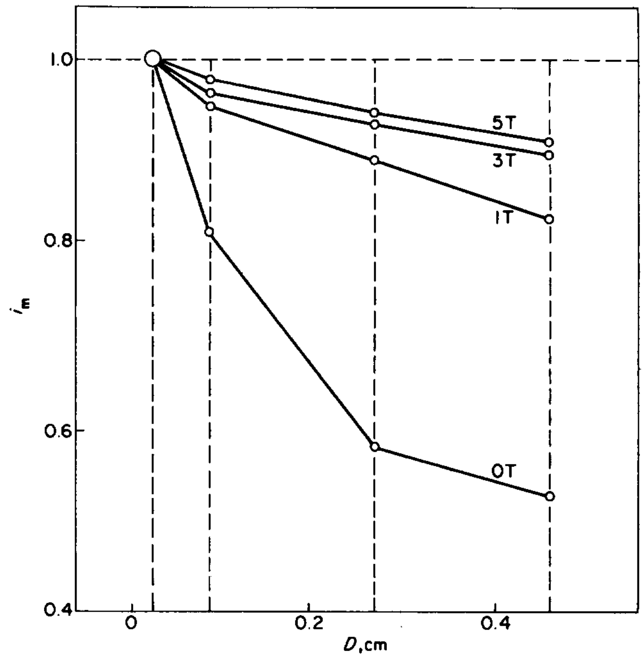

Fig. 4 The ratio $i_m = I_m/I_s$ as a function of the conductor diameter D in different magnetic fields (data for samples A1, A2, A3, A4)

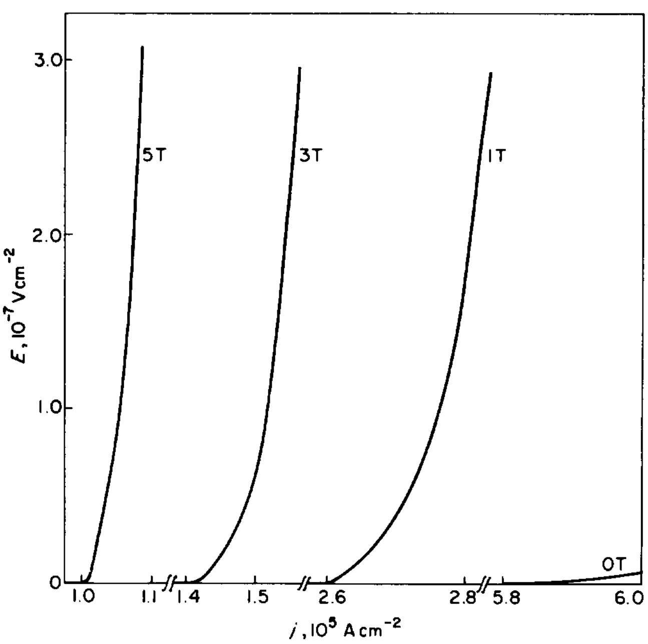

Fig. 5 Current-voltage characteristics of sample A1 in different magnetic fields

For sample B1, the linear dependence $\rho(E) \propto E$ is true up to the fields $E = E_c$. In the case of the sample A1 in magnetic field $B > 3$T at $E \gtrsim 10^{-7}$ V cm^{-1}, the $\rho(E)$ dependence deviates from the linear one. The extrapolation of the $\rho(E)$ according to the linear law shows that $\rho(E) \sim \rho_n \sim 10^{-8}$ Ohm cm at $E \sim 10^{-5}$ V cm$^{-1} \gg E_c$.

Therefore, in a wide range of parameters the conductivity $\sigma(E)$ and the current-voltage characteristics of superconductors may be presented in the form[8,9]:

$$\sigma(E) = \rho^{-1}(E) = j_1/E$$

$$j = j_0 + j_1 \ln(E/E_0)$$

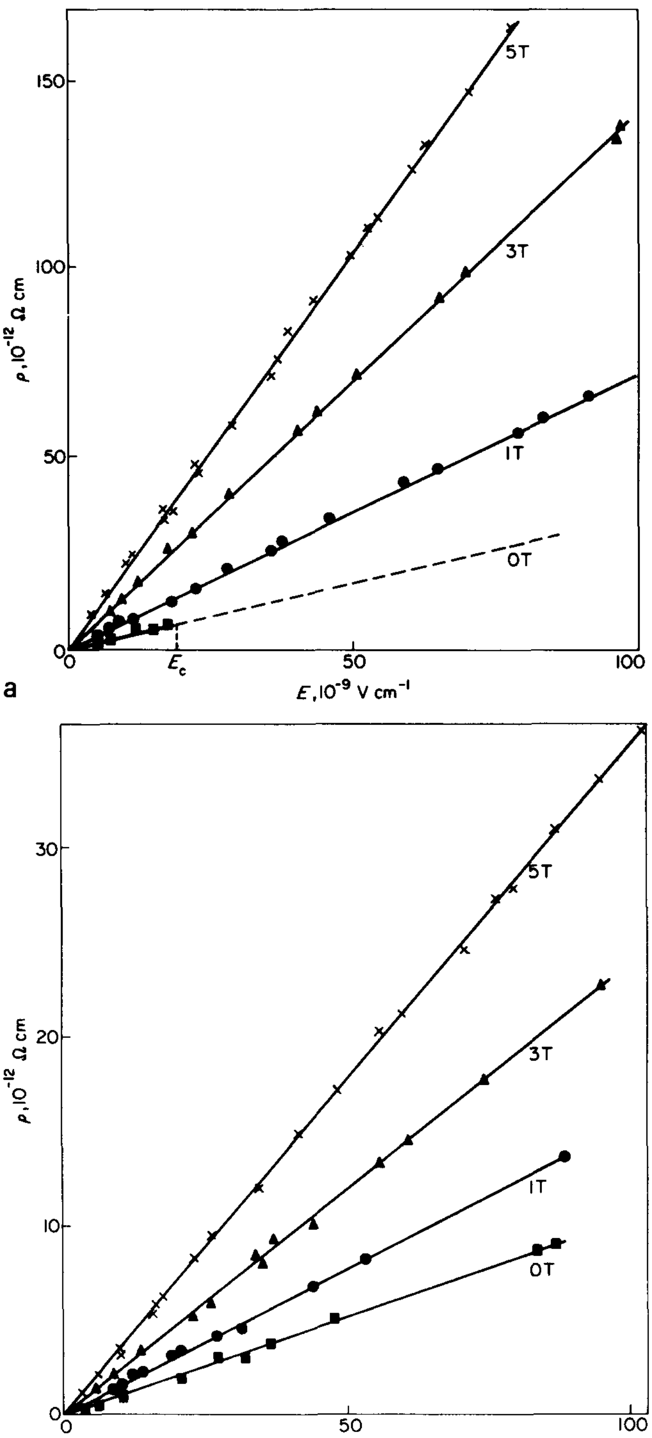

Fig. 6 The $\rho = \rho(E) = \sigma^{-1}(E)$ dependence in different magnetic fields in the $E < 10^{-7}$ V cm^{-1} range. a – sample A1. b – sample B1

The dependences of the values $j_1(B)$ for both samples A1 and B1 are shown in Fig. 7 (sample A1 – curve A, and sample B1 – curve B). As seen from the figure, $j_1 \propto B^{-1}$.

The specific electric resistance of the normal matrix has been determined as this value is rather difficult to calculate from the known literature data to a desired accuracy because its value depends considerably on the quality of the starting materials and manufacturing technology. In addition some other parameters necessary to calculate the value I_m theoretically, and to discuss the principal experimental results have been measured. These include the values of the normal phase minimum propagation current,

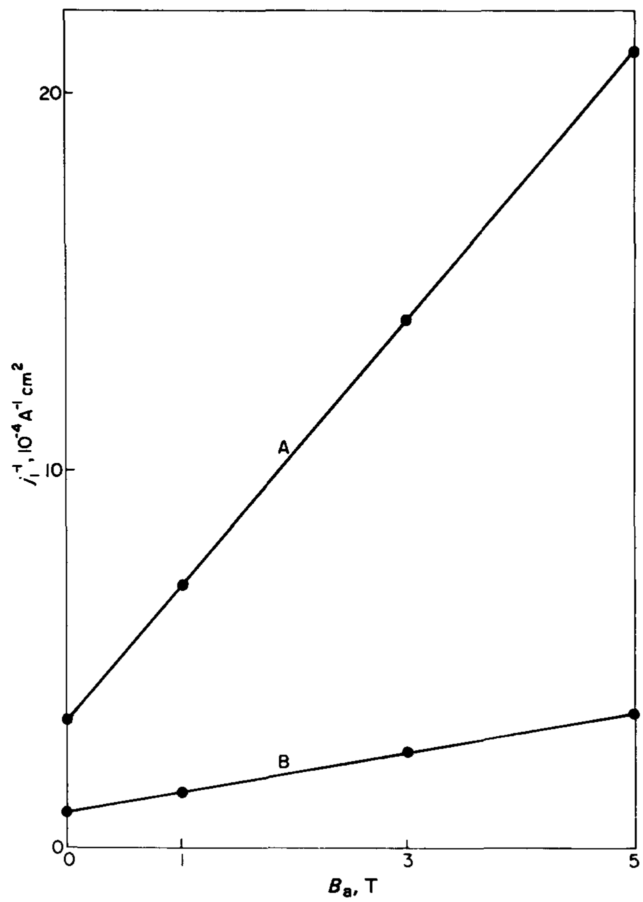

Fig. 7 The value $j_1^{-1} = \rho(E)/E$ as a function of the external field B_a. Curve A – sample A1. Curve B – sample B1

the effective thermal conductivity through a conductor insulation of complex structure, and the coefficient of heat transfer from the surface of the samples to the liquid helium.

The specific resistance ρ_n of the matrix at $T = 4.2$ K was found by extrapolating the temperature dependence of the conductor's specific resistance. The measured value of ρ_n is presented in Table 2.

The value of the normal phase minimum propagation current I_p was found by extrapolation of the dependence of the normal phase propagation velocity $v_p = v_p(I)$ to zero: $v_p(I_p) = 0$. As was assumed, the values of the normal phase minimum propagation current I_p are much less than those of the maximum transport currents of the samples I_m. For example, in the case of sample B3 I_p is about 400-450 A in the field of $B_a = 0.7$ T. The corresponding value of I_m exceeds 10 kA.

The effective thermal conductivity coefficient of insulation and the coefficient of heat transfer from the surface to helium were found for the samples of A1-based group from the measurements of the temperature distribution in the samples and ambient medium at different heat fluxes generated by the heater placed in the centre of the sample. The value of effective thermal conductivity is presented in Table 2. The experimental value of the effective heat transfer coefficient from the superconductor to helium $W_0(0.7\text{-}0.8 \times 10^{-2}$ W cm^{-2} K$^{-1})$ is in satisfactory agreement with the values calculated both by the experimental data for I_p and the effective thermal conductivities of the insulations. Note, that the thermal resistance of the liquid-helium-

Table 2.

Material	Specific resistance Ω cm	Heat conductivity W cm^{-1} K^{-1}	Heat capacity J cm^{-3} K^{-1}
Cu	1.5×10^{-8a}	2.4^{b}	8.5×10^{-4b}
Nb-Ti	5.3×10^{-5b}	1×10^{-3b}	3×10^{-3b}
Lacquer insulation of samples A1, B1	–	3×10^{-4c}	4.6×10^{-3c}
Insulation of samples A2, A3, A4, B2, B3 (teflon, lavsan, epoxy)	–	$\simeq 3 \times 10^{-4a}$	$\simeq 4 \times 10^{-3c}$

a – our experiments, b – Data from Reference 19, c – Data from Reference 20.

surface contact is, as assumed, less than the thermal resistance of insulation by over an order of magnitude. Therefore, the variation of heat transfer conditions on the surface has practically no effect on the temperature distribution in the samples and on the experimental results of their current-carrying capacity.

Discussion

As seen from the experimental results, the value of the maximum transport current I_m is, by an order of magnitude close to I_s for all samples. Moreover, in a magnetic field $B_a > 3$T, the current density j_m practically coincides with $j_c \cdot \chi_s$ even for a conductor having a diameter $D = 0.5$ cm and insulated from liquid helium by the organic coating having a thickness of about 500 μm. Equation (1) leads, under the given experimental conditions, to a j_m value of no more than 10^2-10^3 A cm^{-2} $\ll j_c\chi_s$ if $\sigma = x_n \cdot \sigma_n$.

Further, the measured value of the normal phase minimum propagation current I_p turns out to be much less than the measured value of I_m. Note that the comparison of the value I_m derived from (1) with the expression for I_p[18]

$$I_p = I_s \frac{(1+8\alpha)^{1/2} - 1}{2\alpha}$$

$$\alpha = \frac{S}{P} \frac{j_c^2 \chi_s^2}{W_0 \sigma \cdot (T_c - T_0)} \tag{2}$$

leads to the inequality $I_m \leqslant I_p$ if the values of σ in the (1) and (2) coincide.

Both facts listed above can be readily understood in view of the non-linear behaviour of the current-voltage characteristic of the sample in the fields $E < 10^{-7}$ V cm^{-1}. Indeed, the simplest estimate of $\sigma = j_1/E$ where $j_1 \sim 10^3$ A cm^{-2} and $E \sim 10^{-7}$ V cm^{-1} yields the value of $\sigma \sim 10^{10}$ 1 Ω cm. Accordingly, it follows from (1) that $j_m \sim 10^5$-10^6 A cm^{-2}.

In order to calculate the value of I_m more correctly, one should investigate the stability of the Maxwell and heat equations relative to small perturbations taking into account the electric field dependence of conductivity $\sigma(E) = \mathrm{d}j/\mathrm{d}E$. Such a problem was considered from simple qualitative considerations and, more rigorously later.[13] In this series of experiments the dependence j_c on the local value of B was not determined, but it was measured averaged over the cross-section value $j_c = j_c(B_a)$. Then the theory and the experiment can only be compared to an adequate degree of accuracy in the region of high magnetic fields where $j_c(B) \simeq \text{const} = j_c(B_a)$. As can be readily understood, it is necessary that $B > B_I = \mu_0/\pi D \cdot I$ where B_I is the current self field. Under the given experimental conditions, $B_I \simeq 0.3$-0.5 T. Then, following the results obtained in,[13] we shall write down the stability criterion as

$$j < j_m = \frac{4W_0(T_c - T_0)j_1}{D \cdot \chi_s^2 j_c^2 <E>} \tag{3}$$

where D is the conductor diameter, $<E> = S^{-1} . \int E\mathrm{d}S$ is the electric field averaged over the sample cross-section, W_0 is the effective heat transfer coefficient from superconductor to liquid helium (taking in account the thermal resistance of the heat insulation). The measurements and calculations gives one the approximately coinciding values of $W_0 \simeq 0.7 \times 10^{-2}$ W cm^{-1} K^{-1} (for samples of the A series).

When deriving (3), it is assumed that $W\tau \gg 1$, $W \ll 1$, $\partial j_c/\partial T = -j_c/(T_c - T_0)$ which, as can be readily shown, is true in our experimental conditions.

The estimates show that the heating of the sample up to the emergence of instability is negligibly low (not higher than 0.1-0.2 K). Therefore, the value of current j_c in (3) may be taken at $T = T_0$.

The value of $j_1 = j_{1k}$ for each k-th conductor is calculated from the experimental data for the samples A1 and B1. Each one of the conductors comprises several basic elements of the A1 or B1 type connected in parallel, therefore we obtain for j_{1k}:

$$j_{1k} = j_1 \frac{n_k S_1}{S_k}$$

where n_k is the number of basic elements in the k-th sample, S_1 is the cross-sectional area of a basic element, S_k is the cross-sectional area of k-th the sample.

Therefore, all of the values included in the right-hand term of (3) are known to us, with the exception of $<E>$ and $T_c(B_a)$. The B_a dependence of T_c for Nb-Ti alloys has been well studied. In our calculations we have used the function $T_c = T_c(B_a)$.[17]

And now to calculate j_m one should find the averaged field $<E>$ in the cylindrical sample with growing transport current placed in the varying transverse magnetic field. However, it proves impossible to find an analytical solution to this problem, and to avoid the complicated numerical calculations we use the following simplest approximation given in the literature.[12] Let us assume the electric field in the sample to be generated by the varying transport current $I(t)$ alone. To take into consideration the effect of the variable external field $B_a(t)$ we shall use the effective value of $\dot{I}_{ef} = \dot{I} + \pi D/\mu_0 \dot{B}_a$ instead of I. Then, solving the appropriate Maxwell equations: one can readily find:

$$<E> = \frac{\mu_0}{4\pi} \dot{I}_{ef} \left[-1 - \frac{1}{i} \ln(1-i) \right]$$

where $i = I/I_s$. Therefore, we derive from (3) for $i_m = I_m/I_s$:

$$i_m + \ln(1-i_m) + A \frac{16\pi}{\mu_0 \dot{I}_{ef}} \frac{W_0 \cdot (T_c - T_0) j_1}{D \cdot \chi_s^2 j_c^2} = 0 \qquad (4)$$

The adjusting parameter $A \sim 1$ allows one to correct the approximations made while calculating $<E>$, as well as some indeterminancy of the value W_0 for each specific case.

The electric field $<E>$ depends on $\dot{I}$ and $\dot{B}_a$, therefore the value I_m is the function of the variation rate of external parameters (under conditions of the absence of strong uncontrolled perturbations giving rise to the emergence of the electric field in the sample).[3,4]

Note that, at $i_m > 0.5$, the dependence of I_m upon W_0 and D is considerably weaker than that predicted for I_m by the dynamic criterion (1) with $\sigma = x_n \cdot \sigma_n$.

Shown in Figs 2 and 3 are the $j_m(B_a)$ curves calculated with the aid of (4) at the value of adjusting parameter $A = 1$ and $B_a > 1$T where the approximation $j_c(B) \simeq j_c(B_a)$ can be assumed adequate. The curves are extended to the $B_a < 1$T region by a broken line. As seen from Fig. 2, the theory and experiment are in a good qualitative agreement for the Al-based samples at $B_a > 1$T. At $B_a < 1$T, although the qualitative agreement remains correct, the quantitative deviation increases up to 30-40%. For the sample B3, a good agreement between the theory and experiment is observed at $A = 1/3$ (cf., Fig. 3b). As may be shown by an analysis of the experiment, the cooling conditions of sample B3 were indeed less favourable than those of sample A4.

Calculations show that, under the experimental conditions of determining the value I_m, the electric field $<E>$ is confined within the 10^{-8}-10^{-7} V cm^{-1} range.

Note further that if $I_p \ll I_m$ some decrease of I_m may be associated with the presence in the sample of weak spots wherein the superconducting state stability is less than the average stability of the entire sample.[21] Such non-uniformities may be due, for example, to the inhomogeneity of the conductor material, inhomogeneity of the heat-insulating coating etc. A resistive zone arises near such a weak spot and as $I_m \gg I_p$ the normal phase propagates rapidly throughout the samples.

As distinct from (4), the dynamic stabilization criterion (1) with $\sigma = x_n \cdot \sigma_n$ gives for j_m a value that is two-three orders of magnitude less than the experimentally observed one. In addition, it can be readily shown that in this approximation, the current density j_m increases motonically with B_a through the entire range of magnetic fields $0 < B_a < 6$T which is also inconsistent with the experiment.

Conclusions

This paper contains a study of the magnetic field dependence of the maximum transport current I_m for superconducting composites. It has been shown that, over a wide range of parameters, I_m is close to the critical current I_s. The value of I_m turns out to be much greater than the normal phase minimum propagation current I_p.

The current-voltage characteristics of the samples have been measured in the range of electric fields 10^{-10} V cm^{-1} $< E \lesssim 10^{-7}$-10^{-6} V cm^{-1}. The specific resistance of the sample $\rho(E)$ proves to be much lower than the resistance of the normal matrix. Over a wide range, $\rho(E) \propto E$, which is in agreement with the experimental results.[8-11]

Based on theory[12,13] and taking into account the actual current-voltage characteristic of superconductor, the maximum transport current has been calculated. The obtained results are in good agreement with the experiment.

Thus it is shown that the high values of transport current in composites are associated with the high value of conductivity of composite superconductors in the region of low electric fields.

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