Fizika Nizkikh Temperatur, 2011, v. 37, No. 2, p. 127–133

Thermoelectric instability induced by a single pulse and alternating current in superconducting tapes of second generation

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Received April 2, 2010, revised July 1, 2010

We have studied the instability of the current flow in a superconducting tape of the second generation and the transition of the tape into the resistive state. Contrary to usually studied quasisteady regimes of the instability development, we consider here the adiabatic case of fast sample heating. Two kinds of measurements of the current-voltage characteristics (CVC) have been performed, specifically, using the tape excitation by a single sine-shaped current pulse $I(t) = I_0 \sin(\omega t)$ with different amplitudes I_0 and by a continuous ac current flow. The main results were obtained for the current amplitudes I_0 exceeding the critical current value I_c. We have found that the dynamic CVC are practically reversible for low amplitudes, whereas they become irreversible and assume the N-shaped form for higher current amplitudes. The dynamic CVC are found to change radically if the dissipated energy attains some threshold value $\mathcal{W}_{\rm th}$ which is equal to about 5 mJ/cm for our tapes. Once achieving this energy, the tape transits to the resistive state due to a normal domain formation. The development of instability for a continuous ac current flow was studied for a relatively small amplitude when the energy dissipated per one half-cycle is much lower than $\mathcal{W}_{\rm th}$. Even in this case, the tape transition to the resistive state occurs owing to an effect of energy accumulation (heat pumping). Due to this pumping, the transition takes place after a definite number of ac current periods when the total accumulated energy reaches the same threshold value $\mathcal{W}_{\rm th}$. The specific features of dynamic CVC are qualitatively interpreted within an approach where the appearance of the resistive domain is taken into account. Estimations performed on the basis of the CVC agree well with our experimental data. The results obtained can be useful for the design of superconducting fault current limiters.

PACS: 74.25.Sv Critical currents;
74.25.–q Properties of superconductors;
74.78.–w Superconducting films and low-dimensional structures;
84.71.Mn Superconducting wires, fibers, and tapes.

Keywords: quench, normal domain, adiabatic regime, energy pumping.

1. Introduction

The problem of the transition of hard superconductors carrying transport current I to the normal state (quench) have called considerable attention of researchers for many years, see, e.g., papers [1–3] and references therein. To solve this problem, it is necessary to consider jointly a complex equation system involving the Maxwell and time-dependent heat transfer equations, material equations for superconducting materials. We have to take into account the temperature dependence of all ingressed parameters.

Usually, this problem is considered for quasisteady regimes of a current flow when the equality

$$P(I,T) = Q(T) \tag{1}$$

is satisfied. Here $P = UI$ is the Joule heating, U is the voltage drop along a sample, Q is a heat transferring from a sample to cryogenic liquid, T is the sample temperature.

Very interesting phenomena occur when the thermal balance Eq. (1) has three solutions, $T_1 < T_2 < T_3$. Two of them, $T = T_1$ and $T = T_3 > T_c$, correspond to stable states of a system, whereas $T = T_2$ is an unstable solution (T_c is the critical temperature). The development of instability can result in the resistive domain formation or in the propagation of a thermal wave.

The quench problem is important not only from the physical point of view, but for different applications also. One of the most promising applications are the fault current limiters (FCL) [4,5]. An operation of these devices, in their resistive version, is directly based on the transition to the dissipative state induced by current with density above the critical value J_c.

The resistance that is introduced into an electrical circuit by FCL is determined by the dynamic current-voltage characteristics (CVC) of the superconducting tapes. Specifically, these dynamic CVC determine the superconducting tape application in various electrical devices. The results of the dynamic CVC studies were published in a number of papers (see, for example, [2,6–8]). A physical nature of a superconductor response to a fast current increase within a millisecond range and the sample transition to the dissipative state was discussed in literature [9,10].

In this paper, we study the dynamic transport properties of the SuperPower tapes designed especially for the FCL application. These tapes do not have a thick metal cover and are characterized by a relatively high electrical resistance in the normal state. The specific feature of FCL operation is very fast heating, and their dynamics cannot be described well by the stationary thermal balance Eq. (1). Moreover, the adiabatic approximation is much more acceptable to describe the non-stationary processes in these composites. Indeed, the convective heat transfer process in liquid nitrogen is established several dozen milliseconds after a start of heating [11]. The more enhanced heat transfer process by nucleate boiling begins after the convection process is developed [12]. Thus, for short times the single mechanism which is responsible for the heat transfer from the tape to liquid nitrogen is the heat conduction. This process is characterized by a high thermal resistance. Therefore, the heating of a tape for times about 5 ms (specifically, the time duration will be interesting for us below) can be considered as adiabatic one. This statement was confirmed by the direct measurements in Ref. 13. We show that the dynamic CVC is irreversible and N-shaped for high current amplitudes exceeding I_c. The dynamic CVC become more cumbersome if the energy dissipated in a tape attains some threshold value $\mathcal{W}_{\text{th}}$ which is about 5 mJ/cm. For the case of a continuous ac current with amplitude I_0 above the critical value I_c, $I_0 \geq I_c$, we have observed an interesting feature of the tape transition to the resistive state. This transition occurs after a number of periods of the ac current. We prove that the tape resistance appears due to formation of a stationary domain of the normal phase. A number of current pulses necessary for the tape transition to the state with normal domain increases significantly when $I_0 \to I_c$. Thus, a phenomenon of the energy pumping during each half-period is observed for the case of a continuous ac current flow. All results are discussed on the basis of the current-voltage characteristics of our tapes.

2. Experiment

The dynamic current-voltage characteristics of tapes were measured using the scheme shown in Fig. 1. The short current pulse technique is widely used for studies of the critical current, nucleation and propagation of normal zones, etc. in various superconductors including coated conductors and devices based on them (see, for example, papers [1,2,6,7,14–19] and references therein). In our experiment, an alternating current $I(t)$ was excited due to a discharge of the capacitor C in the LC circuit with a resonance frequency close to 50 Hz. The coil $L = 270$ μH was wound of a copper bus and cooled by liquid nitrogen (LN_2) to increase its Q-quality. The current $I(t)$ in the circuit was triggered by the current feed to the gate cathode of the thyristor Th. The thyristor was turned off when the current changed its sign from positive to negative. Thus, the half-wave current was formed in the circuit. We have measured simultaneously an active part of the voltage drop on the potential probes of the sample and the voltage on the active standard resistor R_0 with the sampling period (1/40000) s. To suppress the reactive *emf* in the sample pickup circuit we used the auxiliary coil L_{aux} positioned near the «warm» current bus of the LC circuit. The coil L_{aux} was connected to the input of AD converter in series with the spring-loaded point potential contacts on the tape. Our results of the voltage measurements did not depend on whether contacts were placed at the tape edges or across the tape width. According to data of Ref. 7, the dynamic current-voltage characteristics can depend on the arrangement of the taps and can significantly differ from the dc characteristics. However, these results were mainly observed for the case of relatively low current amplitudes $I_0 \ll I_c$ whereas we made our measurements for $I > I_c$. We have tested the linearity and synchronism of the measuring circuits for the current amplitudes up to 1600 A

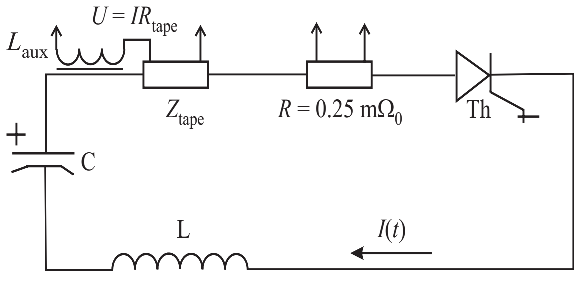

Fig. 1. Function circuit for measurement of a tape response to a single half-period current wave.

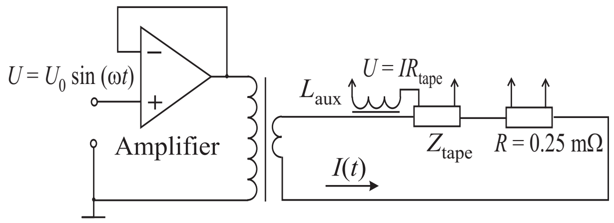

Fig. 2. Scheme of a soft ac current excitation of HTS tapes.

with a copper tape as a sample.

The method of the ac current excitation in HTS tapes is illustrated in Fig. 2.

To measure the dynamic CVC in a regime of the continuous ac current flow, we have used a soft excitation by means of an amplifier with a voltage feedback and a step-down transformer.

All our measurements were performed on the tapes SF12050 and SF12100 produced by the SuperPower Co. The tape sizes are $w = 12$ mm in width; superconducting and silver layers are $\delta_1 = 1$ μm and $\delta_2 = 2$ μm in thickness, respectively; hastelloy substrate 50 μm (for SF12050) and 100 μm (for SF12100) in thickness. They have no additional metal stabilizer layers. We used tapes of different lengths. The majority of results were obtained for long enough tapes SF12100 with distance $l = 23$ cm between the potential contacts. The tapes were immersed into liquid nitrogen at normal pressure.

3. Results and Discussions

The current-voltage characteristics for the tape SF12100 in a quasisteady regime are shown in Fig. 3 by open circles in a double logarithmic scale.

According to these data, the critical current for this tape (by criterion $E_c = 1\,\mu$V/cm) is about $I_c \simeq 420$ A at temperature $T = 77$ K. This current-voltage characteristics can be described by a power function,

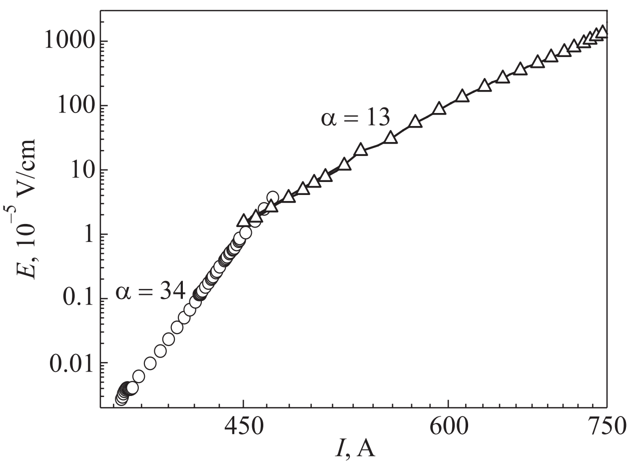

Fig. 3. Current-voltage characteristics in dc (open circles) and dynamic (triangles and solid line) regimes for SF12100 tape.

$$E = E_c \,|\, I / I_c \,|^{\alpha}, \qquad |\, I / I_c \,| \le 1.12 \tag{2}$$

with $\alpha = 34$. Unfortunately, the CVC measurements can be performed for currents $I \le 1.12 I_c \sim 470$ A only. Currents $I > 1.12 I_c$ deteriorate irreversibly the superconducting properties of the tape. However, the voltage drop across a tape for high currents can be determined by another way, specifically, making measurement in the dynamic regime. We made these measurements using the sine-shaped current pulse during its first quarter-period. The results of dynamic CVC measurement performed at different amplitudes I_0 are also displayed in Fig. 3. The dynamic CVC can be described by equation,

$$E = 10^{-5.09} \,|\, I(t) / I_c \,|^{13}, \quad |\, I(t) / I_c \,| > 1.12. \tag{3}$$

In spite of high currents and, correspondingly, high power dissipation, the temperature rise is limited due to a short time of the dissipation. The dynamic CVC can be also described by a power function (see Eq. (3)) but the exponent $\alpha = 13$ is less than in the case of the static CVC. The main reason of a significant change in the $E(I)$ behavior is related to noticeable shunting a superconducting layer by a silver one at currents $I > I_c$. We could not measure the dynamic CVC for currents less than 460 A because of lack of sensitivity.

Note that the experiments have been performed (see, e.g., Ref. 17) where the static and dynamic CVC have been measured for the same current region. These CVC were close to each other. Contrary to such experiments, we studied the non-stabilized tapes of the second generation that are deteriorated at high currents. Accordingly, our static and dynamic CVC meet each other in a narrow region near $I_0 \approx 464$ A.

3.1. Instability induced by a single current pulse

It is of interest to consider the dynamic CVC during the first half-period since the irreversibility of CVC can be observed in this regime. The dynamic CVC for different pulse amplitudes I_0 are shown in Fig. 4. These characteristics are almost reversible for amplitudes $I_0 \le 660$ A

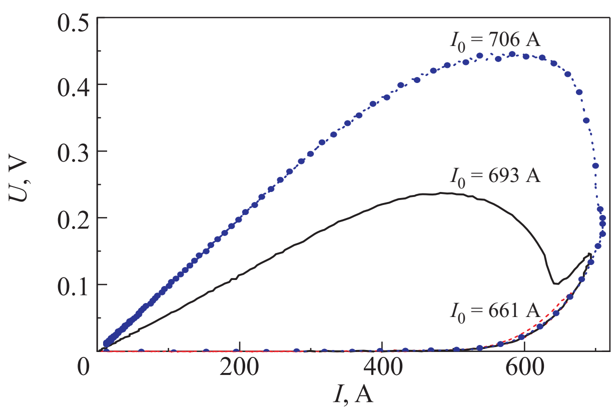

Fig. 4. Dynamic current-voltage characteristics of a sample 23 cm in length for different amplitudes I_0 of current pulse.

(see the red dashed line in this figure). Actually, a very weak irreversibility related to a small temperature rise due to the Joule heating is observed for such small currents. The curves $U(I)$ undergo a qualitative change for current amplitudes $I_0 > 680$ A.

They become irreversible and assume the N-shaped form with two peaks (see the solid curve in Fig. 4). For higher amplitudes, the dynamic CVC assume the strongly irreversible form with a single maximum whereas the first peak is transformed into the inflection point (see the blue dashed curve with symbols in Fig. 4). The analogous results have been obtained for other tapes.

The effective electrical resistance R can be calculated from dynamic CVC shown in Fig. 4. Using the temporal dependences $U(t)$ and $I(t)$ we plotted the resistance $U(t)/(I(t)l)$ per unit length versus time in Fig. 5. The resistance starts to increase at a time moment when the current I exceeds the critical value I_c and is saturated for $t > 6$ ms. Notice a remarkable feature of the curves in Fig. 5. Namely, the effective electrical resistance increases even after the current $I(t)$ has passed a maximum.

The saturation values of the total resistance of the tape are $R \simeq 0.5$ mΩ for current amplitude $I_0 = 693$ A and $R \simeq 0.8$ mΩ for $I_0 = 706$ A. These results indicate that our tape is in the resistive state. However, the resistance values are much less than the total tape resistance in the normal state. Indeed, the normal resistance of the tape is about 1.4 mΩ/cm$\times$23 cm $= 32.2$ mΩ at 92 K that is much greater than 0.8 mΩ. There exist two ways to interpret this result.

— First, following to commonly used consideration, we can suppose that a domain of the normal phase is formed in the tape [1]. A simple estimation gives a surprisingly short length of this domain (about 5 mm). Recall that the tape width is 12 mm.

— Second, it is not necessary for the resistive domain to be in the normal state. It can be longer than 5 mm but in the superconducting resistive state.

Anyway, a sharp change of the dynamic CVC near the minimum $U(I)$ (solid curve in Fig. 4) justifies the formation of the resistive domain which structure and geometry are not important for further study. Below all results and estimations in the text and figures are presented for one of our samples of the tape SPC12100.

To determine the conditions for the tape transition to the resistive state, we have estimated the accumulated energy in the tape before this transition. The temporal dependence of the dissipated power $P(t)$ is presented in Fig. 6 for the same current amplitudes as in Figs. 4 and 5. The solid curve in Fig. 6 corresponds to the case of almost reversible dynamic CVC while two other curves shown by symbols describe the irreversible transition to the resistive state.

Integrating the function $P(t)$ over t we obtain the accumulated energy $\mathcal{W}(t)$ in the tape (upper curves in Fig. 6). The threshold value $\mathcal{W}_{th}$ of the accumulated energy that initializes the transition to the resistive state is revealed to be near 5 mJ/cm for all our samples.

It is possible to estimate the temperature rise ΔT of the YBCO layer by a simple relation (4) if we assume that this threshold energy is accumulated in the YBCO and silver layers only:

$$\Delta T = \frac{\mathcal{W}_{th}}{\delta_2 wa\gamma C_p}. \qquad (4)$$

Here the parameter C_p is the specific heat of silver, γ is the silver density, a is the tape length. We can neglect the specific heat of the YBCO layer in comparison with the specific heat of silver. Substituting the numerical values of

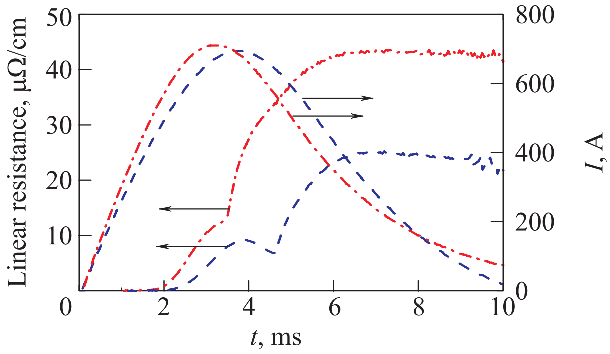

Fig. 5. Effective electrical resistance per 1 cm of the tape length (left axis) and electrical current (right axis) vs time t.

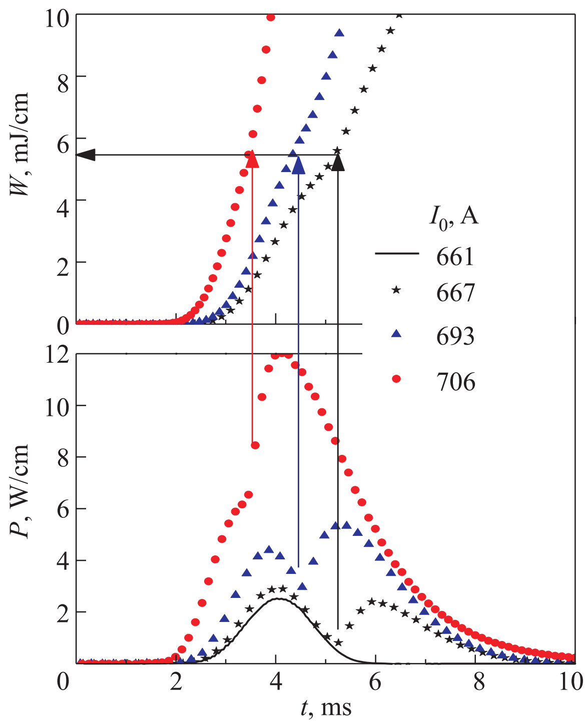

Fig. 6. Temporal dependence of the dissipated power (lower curves) and accumulated energy (upper curves) in the tape per 1 cm of its length.

these quantities ($\mathcal{W}_{th} = 5$ mJ/cm, $\delta_2 = 2$ μm, $w = 1.2$ cm, $\gamma = 1.049$ g/cm^3, $C_p = 0.15$ J/(g·K), $a = 1$ cm) into Eq. (4), we obtain that the temperature increase of YBCO and silver layers is about 10 K approximately.

It is important to note that all described experiments were performed so quickly (duration Δt was less than 10 ms) that heat has not time to be not transferred to the environment. This fact was confirmed by additional direct measurements of the temperature rise $T(t)$ of the tape which was heated by the single current pulses with different amplitudes and corresponding theoretical estimations within the adiabatic approximation.

Thus, we consider that the instability develops as follows. When increasing the current $I(t)$, the dissipated energy is accumulated in the tape. At some moment $t = t_{inst}$, $\mathcal{W}(t)$ achieves the threshold value $\mathcal{W}_{th}$. Accordingly, the resistive domain is nucleated in the sample at $t = t_{inst}$ that is indicated by the kink in the temporal dependence of the tape resistance (see Fig. 4). Then the domain develops during about two milliseconds, and the resistance increases despite the decrease of the transport current $I(t)$.

3.2. Instability induced by a continuous ac current

It is of interest to realize the described scenario of the instability development for a continuous ac current. Obviously, the instability can develop at lower ac current amplitudes I_0 than in the case of a single pulse (but still for $I_0 > I_c$). The threshold energy can be accumulated after several periods in this case. One can evaluate a necessary number of periods that depends on the current amplitude. The dissipated power P and accumulated energy $\mathcal{W}$ per one cycle and 1 cm of the tape length can be written as,

$$P(t) = |E(t) I_0 \sin(\omega t)|, \qquad (5)$$

$$\mathcal{W} = 4 \int_0^{\pi/2\omega} P(t)\, dt \qquad (6)$$

where ω is the current cyclic frequency; the value E in Eq. (5) is determined by Eq. (2) for $|(I_0 \sin(\omega t)/I_c)| \le 1.12$ and by Eq. (3) for $|(I_0 \sin(\omega t)/I_c)| > 1.12$.

A number n of cycles and time τ necessary for the domain nucleation are,

$$n = \mathcal{W}_{th} / \mathcal{W}, \quad \tau = (2\pi/\omega)n. \qquad (7)$$

This number can be large enough if the current amplitude I_0 is close to I_c. For example, our tapes should transit to the resistive state after $n = 100$ periods of the current 480 A in amplitude.

To check this prediction we have measured the temporal dependence of the voltage drop and current along the tape 43 cm in length. The ac current through the sample was supplied using the ac power amplifier with the voltage feedback and output step-down transformer (see Fig. 2).

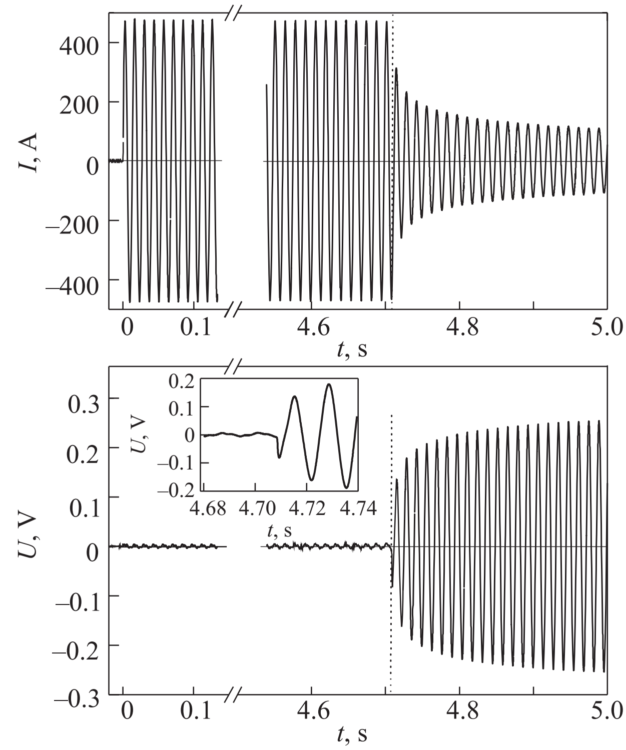

Fig. 7. Initial and final fragments of the computer records of $I(t)$ and $U(t)$ for $I_0 = 475$ A, $f = 73$ Hz. Insert shows a voltage drop across the tape in the vicinity of sharp transition to the resistive state. The vertical dashed line shows the time delaye τ.

The superconducting tape was connected to the transformer secondary winding. The computer records of the initial and final fragments of the $I(t)$ and $U(t)$ dependences are shown in Fig. 7 for the amplitude $I_0 = 475$ A and frequency $f = 73$ Hz. The curves in this figure demonstrate a nontrivial behavior of $I(t)$ and $U(t)$. After switching on the ac current $I(t)$ at $t = 0$, it changes quasi-harmonically during 4.71 s and then decreases abruptly owing to the transition of the tape into the resistive state. The fragment of CVC shown in the insert demonstrates details of this transition. During the transition, the current is lowered dramatically by a factor about four. Such a behavior resembles a current limitation after the action of a fault current limiter. Simultaneously with a current change, the voltage drop increases considerably. A direct observation of the tape immersed into the liquid nitrogen shows an appearance of intensive boiling along a short part of the tape that corresponds to the occurrence of the resistive domain. The length of this domain is about of 1 cm. The resistance R_d of the domain can be evaluated using measured I and U. We obtain $R_d \simeq 0.2/100 = 2$ mΩ that is higher than the tape resistivity 1.4 mΩ per 1 cm at 92 K. This means that the domain is *definitely in the normal state*.

All considerations performed above correspond to the adiabatic case. If this approach is correct, the tape transition to the resistive state should be observed for any current amplitude $I_0 > I_c$, owing to the heat pumping phenomenon. However, according to our experimental data, this transition takes place only for currents higher than some threshold value $I_{th} = 468$ A. As is found, the ac current with amplitude $I_0 < I_{th}$ can flow continuously through the tape without its transition to the non-uniform state. This means that the tape is in the thermal equilibrium for $I_0 < I_{th}$, i.e., the dissipated energy is transferred to LN_2. It is possible to evaluate this amount of energy by means of Eqs. (2)–(6). We obtain $Q = 0.03$ mJ/cm per a cycle. Accordingly, to take into account a heat transfer, Eq. (7) should be corrected by subtraction of Q from the denominator,

$$n = \mathcal{W}_{th} / (\mathcal{W} - Q). \quad (8)$$

We have studied the time delay $\tau = n / f$ for the tape transition to the resistive state for different currents $I_0 > I_{th}$. The results of measurement are presented by points in Fig. 8.

The solid curve in this figure corresponds to the calculation data obtained by means of Eq. (8) and Eqs. (3)–(6). The experimental and calculated results are in a good agreement. It should be noted, however, that such a correlation can be considered as a qualitative result only. The matter of fact is that the parameter Q in Eq. (8) is not measured but evaluated only. We can also evaluate the domain temperature. For the dissipated power $P \simeq 0.5 I_0 U_0 = 12$ W (see Fig. 7) we have the heat flux about $P / w = 10$ W/cm^2. According to the steady-state boiling curve of LN_2, the temperature excess within the domain in this case is about 13 K.

4. Conclusion

In this paper, we have studied experimentally the transition of non-stabilized HTC tapes of the second generation to the resistive states under the action of single current pulses, or ac continuous current, with amplitudes higher than the critical one. It turned out that the quench in such a kind of tapes cannot be interpreted within the commonly accepted theory that is valid only for the stationary regimes of the current and heat flows. Moreover, due to the low heat capacity of examined tapes, the adiabatic regime is characteristic for our experiment. In addition, the existing theory (see reviews [1,2]) is constructed for spatially uniform superconductors whereas the non-stabilized tapes of the second generation can be essentially non-uniform. The nucleation of the normal domain in the same point on the tape in our multiple experiments is a manifestation of the sample inhomogeneity. A key point for the physics of tape quenching in the adiabatic regime is the revealed fact of the existence of the threshold accumulated energy necessary for the appearance of the instability. On the basis of this approach, we have qualitatively interpreted our observations of the domain nucleation induced by both a single current pulse and the continuous ac current flow. For quantitative calculations, a new theory should be developed.

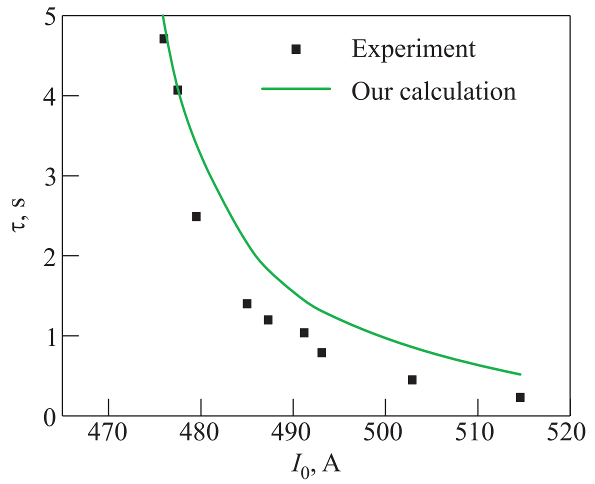

Fig. 8. Time delay for the tape transition to the resistive state.

This work is supported by RFBR grant 08-08-00453.

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