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Spontaneous and Light-Induced Resistive Transitions in Superconducting Thin Film Bridges

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In order to study dynamically the resistive states which appear as jumps in the I–V curves of narrow bridges, we have submitted YBaCuO and Nb films to nanosecond current steps and laser pulses simultaneously. In constant current feed, the distinction between hot spots (HS) and phase-slip centers (PSCs) is unambiguous, since HS are compelled to grow or decay, at variance with the stable-in-time PSCs. Thanks to the transient method we show that, even if Joule dissipation associated to a current I is virtually sufficient to sustain the film above T_c, the zero resistance state remains metastable: a hot spot does not arise unless initiated by a PSC, which fact was not reported before. The domains of occurrence of HS and PSCs were then organized in a current–temperature plane. Finally, the theoretical problem of the HS velocity of growth is given an exact solution, in semiquantitative agreement with experiment.

KEY WORDS: nonequilibrium superconductivity; weak links; high-T_c films; high-speed techniques; conventional superconducting films.

1. INTRODUCTION

The traditional interpretation of the resistance in type-II superconductors [1], by vortices crossing the current lines, breaks down in geometries too narrow to accommodate a single vortex. Webb and Warburton [2], then Meyer *et al.* [3], measuring the resistive transition $R(T)$ of crystalline tin whiskers, may have been the first to observe tiny resistance steps, just below the critical temperature T_c, instead of a continuous increase. These steps, confirmed soon after in narrow thin films [4], were understood as arising from Josephson-like pulsations in Phase-Slip Centers (PSCs) which, in one-dimensional (1D) microbridges, are the substitutes to the vortex flow process. In the commonly used voltage-bias configuration, I–V (current–voltage) characteristics conceal some ambiguities, because simple hot spots (HS) also manifest themselves as voltage jumps [5,6]. By using current-bias electrical supply plus nanosecond pulse techniques, we characterize the two types of dissipative structures by their behavior in the time domain, and study their transformations into one another.

Although this paper reports essentially new data (HS-PSC phase-diagram; HS velocity of growth), we often refer to related experimental work [7–9].

2. DISSIPATION IN QUASI-1D SUPERCONDUCTORS

A superconducting bridge is one-dimensional if a current-carrying state may be considered homogeneous over the width of the bridge. In what may be called the standard PSC model [4], a PSC is a localized dissipation unit extending over twice the quasiparticle diffusion length Λ_{qp} (typically 1 μm), where the current periodically alternates between the superfluid and the normal forms at the Josephson frequency $\nu = 2$ eV/h. If the normal resistance of the $2\Lambda_{qp}$ zone is R_u, the voltage drop along the filament increases by a quantity ΔV of the order of $(1/2)R_u I_c$ for each new PSC created (Fig. 1). Above each critical current I_c, there is a linear increase of the voltage, with a differential resistance $dV/dI = R_u$. Let us mention

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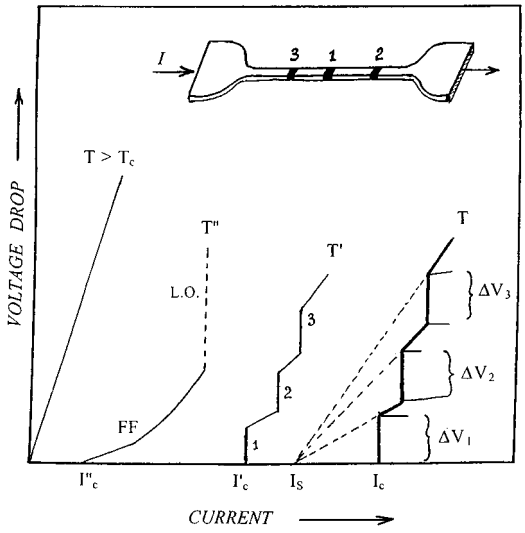

Fig. 1. Ideal voltage–current characteristic curve of a long bridge in the normal ($T > T_c$) linear and nonlinear flux-flow (FF), and phase-slip regimes, according to temperature. The critical currents bear the same index as the corresponding $T < T' < T''$. I_s is the time-averaged superfluid current flowing through PSCs 1, 2, and 3.

also the flux-flow regime sometimes observed in thin films (Fig. 1) at temperatures very close to T_c, although not in strictly 1D systems such as whiskers [2,3].

Dissipation causes some temperature rise at the PSC location, proportionally to the Joule power ρI_c^2, where ρ is the normal state resistivity. This heating may be neglected close to T_c, owing to the specific temperature dependence of the critical current; however, a transition into the normal state is not excluded at lower substrate temperatures. (This point will be developed quantitatively in the rest of the paper.) So, although we challenge this idea, the PSC regime is usually considered [4,10] to be confined to a small temperature range, of the order of 1 K or even less, close to T_c.

The changes in currents and potentials occuring inside a PSC may be compared to those experienced by an observer placed in a vortex street. At each vortex crossing (frequency ν), the superconducting order parameter falls off to zero, then rebuilds, and the phenomenon repeats itself. Each cycle is accompanied by a phase slip between the two sides of the superconducting wave function, thereby allowing a voltage drop. If the phase slippage is quantized (by amounts of $\pm 2\pi$), there will be no overall loss of coherence of the wave function along the bridge. A picturesque mathematical description of this process, based on the Time-Dependent Ginzburg–Landau equation (TDGL):

$$\tau_0 \left(\frac{\partial}{\partial t} + 2\frac{i\mu}{\hbar} \right) \Psi = \left[\xi^2 \left(\vec{\nabla} - \frac{2ie}{\hbar} \vec{A} \right)^2 + (1 - |\Psi|^2) \right] \Psi \tag{1}$$

was given in 1972 by Rieger *et al.* [11]. In this equation, ξ is the coherence length, μ is the chemical potential of paired electrons, $\vec{A}$ is the vector potential, and $\tau_0 = \hbar/\Delta(T)$, with Δ(T) the temperature-dependent energy gap. So, τ_0 is the pair-breaking time, of the order of picoseconds or less.

This computation was designed for 1D superconductors (transverse dimensions smaller than ξ and the penetration depth λ). However, the work of Volotskaya *et al.* [12] on *wide* films (widths far in excess of the coherence length) brought about a very significant extension of the above picture. The essential features of PSCs are preserved, including the $2\Lambda_{qp}$ dissipative length, and the drop of the pair chemical potential over a coherence length. These observations triggered theoretical investigations of the problem in two dimensions [13], through the use of generalized TDGL equations:

$$\frac{\tau_0}{\sqrt{1 + \gamma^2 |\Psi|^2}} \left(\frac{\partial}{\partial t} + 2\frac{i\mu}{\hbar} + \frac{1}{2}\gamma^2 \frac{\partial}{\partial t} |\Psi|^2 \right) \Psi = \left[\xi^2 \left(\vec{\nabla} - \frac{2ie}{\hbar} \vec{A} \right)^2 + (1 - |\Psi|^2) \right] \Psi, \tag{2}$$

where $\gamma = \tau_E/\tau_0$ is the pair-breaking parameter. In order to go from Eq. (1) to Eq. (2), it had to be realized that macroscopic changes of the Cooper condensate (not single pair-breaking) imply energy exchanges with the surroundings, apparent in the inelastic collision time τ_E.

Profound consequences arise when τ_E, of the order of nanoseconds, is much longer than τ_0, which is most often the case. Numerical solutions were developed to investigate the stability of the PSC solution compared to the vortex street (VS) solution. For γ above the value 5.5, it turns out that the phase-slip line is favored over VS. The latter occurs at higher temperatures, because then the electronic relaxation becomes very efficient, while τ_0 is enchanced. We indeed observed this change of regime in YBCO films, in a manner similar to the graph of Fig. 1 at temperature T''.

In a qualitative manner, the criterion established by Weber and Kramer [13] for the passage from the VS to the PSC mode of dissipation in a 2D geometry

may be pictured as follows. Let us consider the gap surface $z = |\Delta(x,\ y)|$ in the presence of vortices moving at the line velocity v_L. In the wake of the vortices, the order parameter is depressed efficiently over a distance $v_L \tau_E$, if we admit the gap relaxation time τ_Δ to be comparable to τ_E. Then, the phase-slip solution results when the passage of the vortices has digged a trench in the Δ-surface over the full width of the sample.

3. THE PSC NUCLEATION TIME

The next and then totally unpredicted step in the functional description of PSCs was the discovery by Pals and Wolter in 1979 [14] of a sizeable delay (nanoseconds) between the application of a supercritical current step and the first appearance of a voltage. In order to interpret a delay thousands of times longer than the pair-breaking time, the Philips Research scientists treated the prefactor of Eq. (1) as an adjustable parameter designed as the gap relaxation time τ_Δ, of the same order as τ_E, except in the immediate vicinity of T_c [10]. Further simplifications led them to

$$\tau_\Delta \frac{\partial f}{\partial t} = 1 - f^2 - \frac{4}{27} \cdot \frac{j^2}{f^4}, \tag{3}$$

where f is the normalized modulus of the order parameter. The presence of j (current normalized to I_c) is reminiscent of the gradient term in Eq. (1) or (2). We see that $\tau_\Delta \partial f/\partial t$ is analogous to the leading term of the first member of Eq. (2) in the limit of large γ's, and in this way, accounts for the slow decrease of f with destruction of superconductivity after a finite delay of the order of τ_Δ. In order to describe simultaneously the rapid rotation of the phase (Josephson oscillations) at the PSC core, one has recourse to the full Eq. (2) [15]. The behavior of $f(t)$ is displayed (top of Fig. 2) for the purpose of interpreting the effect of a transient perturbation.

While the superconducting bridge is passing an overcritical current, with a PSC voltage arriving with delay t_{d0}, a brief laser pulse is sent at time noted t_L. (The fact that the PSC turns into HS does not spoil the following argumentation.) If we admit that light has the irreversible effect of depressing the order parameter, this will result in a shortening of t_d, which readily appears on the oscilloscope traces of Fig. 2. For a moderate laser intensity, the depression is Δf_1 (see top curve), which saves a delay $(t_1 - t_L)$. Then, the voltage rises at time t_{d1} instead of t_{d0}. For stronger light intensity, the delay is merely suppressed, which signifies that the corresponding depression Δf_2 amount to about one half the unperturbed order parameter. Actually, in the present case, we see that the optical excitation has been enough to create a few micrometer long hot spot. Several versions of this simple experiment are currently under way. For the present time, we will note that a potentially very fast transient, such as the perturbation of the superconducting order by a sub-picosecond pulse, can be studied on a stretched scale, namely nanoseconds.

4. DISCRIMINATING BETWEEN PSCs AND HOT SPOTS BY INSPECTION

We summarize now the specific informations which the transient method provides to characterize the resistive state of current-carrying bridges, compared with steady-state observations.

Delay Time

Since, to our knowledge, no latency period has ever been reported at the onset of vortex flow or creep, the delay t_d appears as an unmistakable signature of the opening of a PSC. It is a sensitive function of the ratio $I/I_c(T)$ which, as a consequence of Eq. (3), follows a definite law [14]. Actually, the agreement with theory is impressive, within experimental uncertainty, provided one uses the improved model due to Tinkham [16].

Stable, or Linearly Changing, Voltage Signals

PSCs are in principle well-defined structures which, apart from heating effects, have a length $2\Lambda_{qp}$ not expected to change in time once they have been created, that is, after t_d. In contrast, a hot spot has a time-dependent size: a current able to sustain the normal state on a certain length is a fortiori able to sustain twice this length, and so on, propagation taking place by heat diffusion. Therefore, in constant-current bias, HS will manifest themselves as signals linearly rising with time. Let us remark that most investigations, with either pulse [14] or dc [3,4,17] bias, have been conducted in the constant-voltage configuration, with the main purpose of protecting the samples against excessive dissipation.

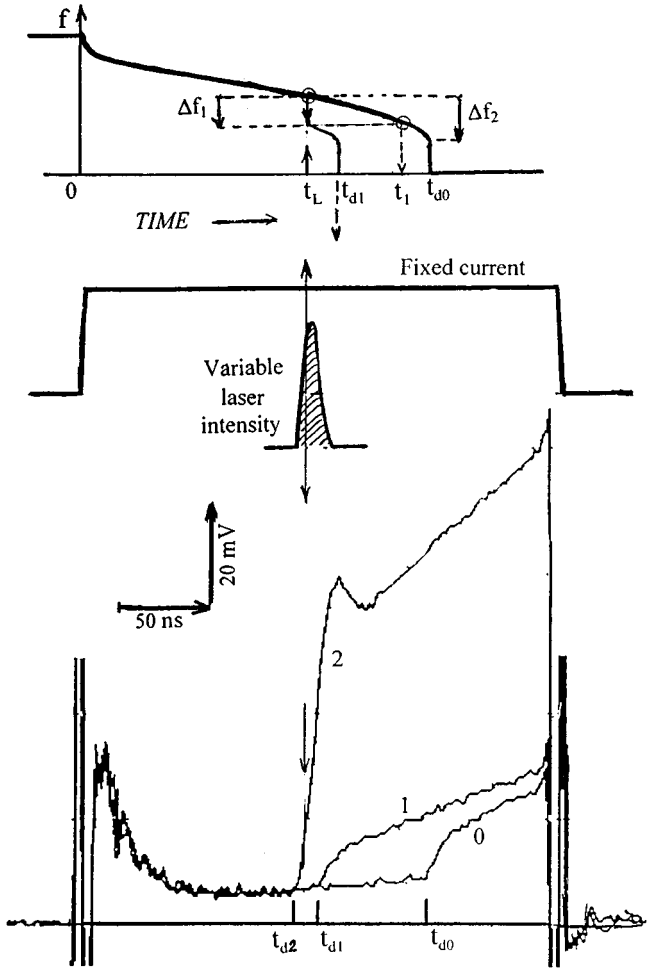

Fig. 2. Shrinking of the nucleation time t_d in Nb at 1.9 K due to a short-light pulse of increasing intensity from (0) to (2), arriving at time t_L. Trace (0) is the zero-light signal. At high intensity (2), time t_d coincides with t_L. Intermediate intensity (1): t_{d0} is shortened to t_{d1}. Upper graph: schematic evolution of the order parameter in cases (0), (1), and (2).

Differential Resistance

The I–V isotherm of a PSC structure (see Fig. 8 of [4]), taken on the top of the voltage response, extrapolates to zero voltage at a value I_s, which is the time-averaged superconducting component of the current. No such figure of course can be obtained with hot spots which are compelled to either growth or extinction.

5. EXPERIMENTAL PROCEDURE

Most of the YBCO samples reported on here were *c*-axis oriented films deposited by laser ablation on crystalline MgO. The niobium films, of similar thickness (typically 80 nm), were dc-sputtered on sapphire wafers. In both cases, the bridge pattern (5–100-μm wide) was obtained by dry-etching after a photolithographic process [8]. The contact pads were metallized by gold evaporation. The ability to pass large currents (sizeable fractions of an ampere) rely on the quality of contacts.

To observe the response on the nanosecond scale, we used a 50-Ω coaxial circuit including a delay-line (250 ns) to separate the input pulse from the reflected signal. The input excitation came from a pulse generator fitted with the times t_d to be measured. The main difficulty is to achieve the condition of constant-current bias: what is pretty obvious as long as the bridge has zero impedance, becomes problematic

when resistance sets in. With a source impedance at 50 Ω, we observed that the rising signal becomes sub-linear beyond a sample resistance of about 3 Ω, and even goes to saturation around 8 Ω. In some instances, it was necessary to insert an impedance matcher close to the thin film sample.

6. PHASE-DIAGRAM FOR PSCs AND HOT SPOTS

For a hot spot ($T > T_c$) to exist, the Joule dissipation, ρJ^2 per unit volume, must be sufficient to reach T_c. Let T_b be the bath, or substrate, temperature, τ the bolometric film cooling time, and C the specific heat per unit volume. Then, the thermal power transferred to the substrate per unit volume of the film at temperature T may be written as $\tau^{-1}C(T-T_b)$. Actually, additional lateral heat flow along the film may be shown to impose for a hot spot to exist the stronger condition $J > J_h$, with J_h given by

$$\rho \cdot J_h^2 = a\frac{C}{\tau}(T_c - T_b), \tag{4}$$

where a is a numerical factor of order 2 in the linear approximation. This formula defines a minimum current density J_h (or equivalently a current I_h), which, in a $I^2 \leftrightarrow T_b$ graph (Fig. 3), is represented by a straight line going to zero through T_c.

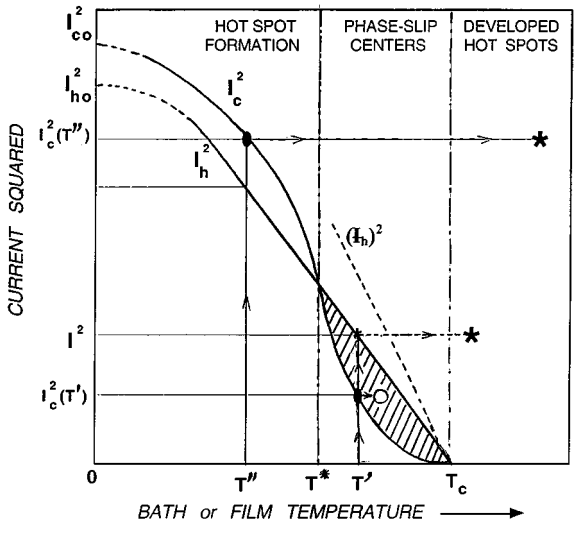

Fig. 3. Theoretical phase diagram in the $I^2 \leftrightarrow T$ plane for the appearance of PSCs and the disappearance of hot spot (see text). I_c is the superconducting critical current, and $I_h(T_b)$ is the minimum current sustaining a hot spot on a substrate at temperature T_b. PSCs are stable only in a limited region (hatched area) above T^*. Line $(I_h)^2$: see text.

On the other hand, the critical current I_c follows a $(1-T/T_c)^{3/2}$ -law in the vicinity of T_c, so that $I_h(T)$ and $I_c(T)$ usually have an intersection at a temperature called T^* in Fig. 3. Let us see how T^* determines two different domains of resistive states.

On increasing the amplitude of the current pulse at a temperature $T_b = T'$ such that $T^* < T' < T_c$, the critical value $I_c(T')$ is first encountered, with nucleation of a phase-slip center → stable voltage. Due to dissipation, the temperature inside the PSC is slightly raised (open circle). For a somewhat higher current, the representative point may reach the $I_h^2(T)$ line, where the PSC swings into a hot spot state with its characteristic linear rise in the voltage.

If, however, one starts from $T_b = T'' < T^*$, the value I_h is reached first, before I_c, and the question is whether a hot spot is formed. The experimental answer is that mere crossing of $I_h(T)$ brings in no voltage. So, $I_h(T)$ below T^* is a latent branch of the full $I_h(T_b)$ curve, which only shows on returning from a fully developed hot spot [9]. In the present case of a "zero-current cooled" superconducting film, a voltage appears only if the current amplitude I is raised up to $I_c(T_b)$. Then, since $I = I_c(T'') > I_h(T'')$, the conditions are met for the transformation of a PSC into a hot spot.

This sequence of events is what experiment confirms as the bath temperature is swept across T^* in a niobium film (Fig. 4). Beyond the first inductive peak, and above the ohmic voltage of the leads noted $R_0 I$, trace (1) taken at 6 K shows a constant voltage, identified as arising from a PSC. In contrast, trace (4) taken at 4.6 K clearly designates a growing hot spot, which, we note, is also preceded by a delay time t_d. Actually, the study of this t_d as a function of I/I_c confirms its interpretation as a PSC nucleation time. Trace (2) can be understood as a PSC voltage slightly growing in time due to the dissipation term $\rho J(J - J_s)$. Trace (3) was taken at such a temperature (5.2 K) that a hot spot is just being formed from the original PSC.

It has been indicated above that, below T^*, the value of I_h cannot be determined directly from the current that leads to a hot spot. A procedure is to use a superposition of two pulses, to create first a hot spot by applying $I > I_c(T_b)$, then to reduce I toward the limit of extinction of the just created HS. $I_h(T_b)$ is then defined as the border between the amplitudes that maintain a growing HS, and the amplitudes that sustain only temporarily the hot spot [9]. We will see in the following an alternative method using an auxiliary laser pulse.

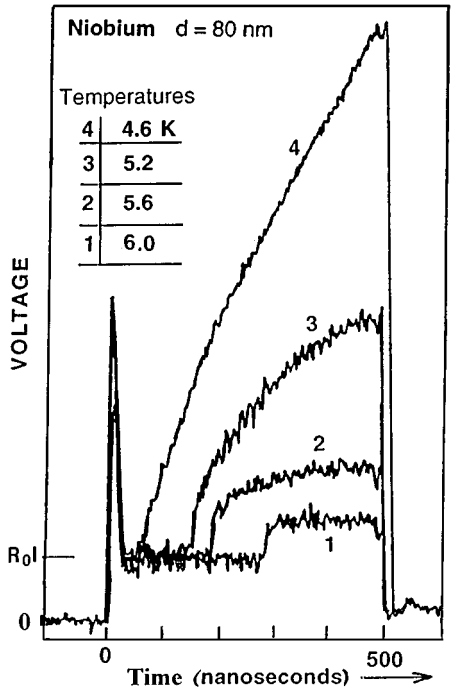

Fig. 4. Resistive response of a niobium bridge to a pulse of critical current at several temperatures, decreasing from (1) to (4). Note the different shapes, from stable PSC voltage (1) at 6 K to growing hot spot signal (4) at lower substrate temperature.

An entirely different situation is left possible, namely that $I_h(T)$ does not cross $I_c(T)$, as it is for the dashed line (I_h^2) of Fig. 3, which would correspond to films having either a reduced critical current density, or small resistivity and small thickness. In such a case, the PSC domain extends over the whole temperature range, contrary to the general assertion. This has indeed been definitely verified in several YBaCuO films of small thickness (30 nm) [7,9], where the PSC behavior was obtained from 1 K to 77 K.

7. VELOCITY OF GROWTH OF DEVELOPED OF HOT SPOTS

Let us consider (Fig. 5, top) a thin film of normal resistivity ρ holding a current density J, in the situation where a hot spot has formed. The Joule power generated, ρJ^2 per unit volume, is shared between the heat flux to the substrate, $C\tau^{-1}(T-T_b)$ per unit area, and a longitudinal component which can be equated to $-\kappa(\partial^2 T/\partial x^2)$ per unit cross section of the film. Here, $T(x,t)$ is the position and time-dependent temperature of the film and κ is the bulk coefficient of thermal conductivity of the superconductor, related to D, the diffusivity of heat, by $\kappa = C \cdot D$. For simplicity, we assume all parameters to be temperature independent, and identical (except ρ) in the normal and

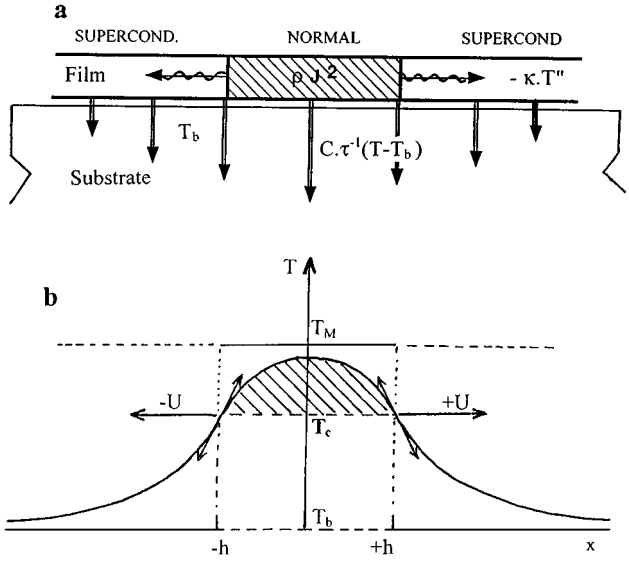

Fig. 5. (a) Thermal transfers into and out of a hot spot: dissipation ρJ^2 above T_c, heat conduction along the film $-\kappa T''$, and escape to the substrate (double arrows), proportional to $(T - T_b)$. (b) Hot spot temperature profile at instant t. T_b: bath temperature; T_M: asymptotic temperature. U is the HS wall velocity.

superconducting parts of the system. We then have in the normal state the following heat rate equation:

$$C\,\frac{\partial T}{\partial t} = \kappa T'' - \frac{C}{\tau}(T - T_b) + \rho J^2, \qquad (5)$$

and a similar equation—excluding the term ρJ^2—in the superconducting regions. At the superconducting/normal interface, the two temperatures equal T_c, and the first space derivatives $(\partial T/\partial x)$ must be equal. A progressive solution of this coupled set can be found, with an interface velocity U given by

$$U = \frac{y^2 - 2}{\sqrt{y^2 - 1}}\sqrt{\frac{D}{\tau}}. \qquad (6)$$

Here y is the ratio I/I_1, with I_1, given by Eq. (4) with $a = 1$. Equation (6) predicts not only the positive values of U but also an interval $I_1 < I < I_h$, where U is defined and negative. Then, the situation is that of a receding hot spot with a central temperature $T > T_c$.

A plausible temperature profile at a fixed instant is drawn in Fig. 5. It is constrained between the limits T_b and T_M such that

$$\rho J^2 = C \cdot \tau^{-1}\,(T_M - T_b). \qquad (7)$$

The normal zone expands or shrinks with velocity $2U$ (U on each side). An illustration of the current dependence of the velocity is given in Fig. 6. It is interesting to compare HS velocities in two materials such as YBCO and Nb. (For the measurement procedure, see [9].). The factor $(D/\tau)^{1/2}$ is equivalent to $(vl/3\tau)^{1/2}$, where v is the velocity of the heat carriers and l their mean free path. Let us assume that heat is transported by the electrons in Nb and by the phonons in YBCO, with approximately the same l of the order of 2–3 nm. Cooling times in our films are also of the same order of magnitude, around 10 ns. So, the main difference between the two materials is in the velocity of the heat carriers, $\approx 2 \times 10^6$ m/s for electrons in niobium and $\approx$3 km/s for phonons in YBCO. This difference accounts for a factor of about 20 in the observed HS experimental velocities between the two materials.

8. FIXED CURRENT: RESPONSE TO A TEMPERATURE PULSE

A niobium bridge biased with a *subcritical* curent I was exposed to a laser pulse, and its subsequent behavior studied as a function of I. For the sake of interpretation, we will assume that the sole effect of the light is to raise locally the temperature of the film of a few kelvins, sufficiently to launch a short section of the film into the normal state. The bath temperature is below T^* in the phase diagram (Fig. 3).

Corresponding waveshapes are displayed as a function of time in Fig. 7. The laser pulse (20 ns halfwidth) of fixed intensity arrives at time marked t_L. Trace 3 has the characteristic shape of a growing hot

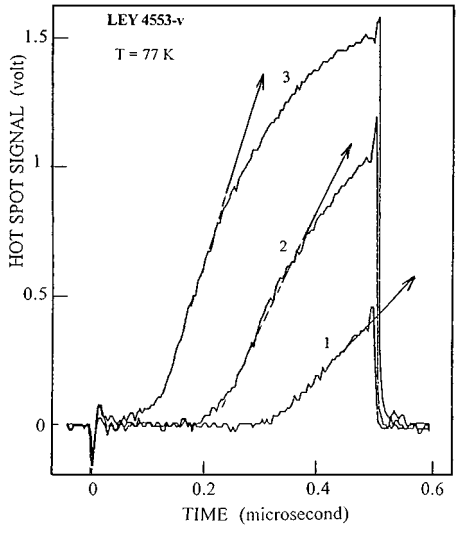

Fig. 6. Change of the HS velocity of growth along with amplitude of the current. YBCO sample LEY 4553-v ($d = 120$ nm). HS velocities are, from 1 to 3: 14 m/s; 30 m/s; 38 m/s. Corresponding current densities in MA/cm^2: 3.04; 3.10; 3.23; I_c (77 K) = 3.02.

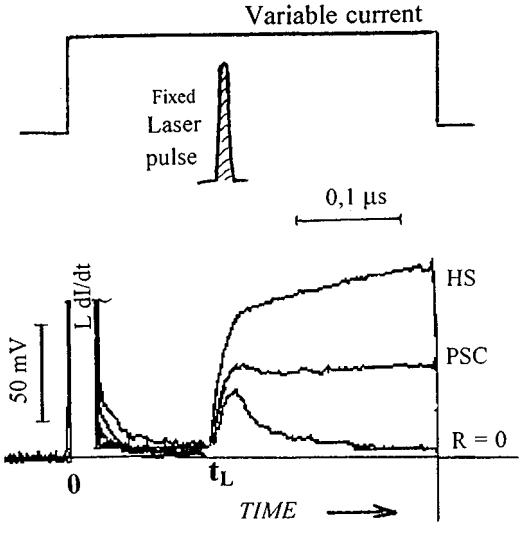

Fig. 7. Voltage response at $T_b = 1.9$ K of a Nb film ($d = 80$ nm), carrying a subcritical current I, to a short (fixed) light pulse at time t_L. According to I, the film is left either in the zero-resistance state, or in a PSC state, or in a hot spot state. The truncated initial voltage (LdI/dt) is of inductive origin.

spot; therefore, the associated bias current (64 mA) is above $I_h(T_b)$, because it sustains a growing hot spot, and it is below $I_c(T_b)$, since it does not induce a voltage by itself. Trace 1 is a receding hotspot: we conclude that then the current (50 mA) is intermediate between $I_1(T_b)$ and $I_h(T_b)$. More intriguing is trace 2 (bias current 60 mA), which, according to our criterion (stable voltage), cannot be anything else than a phase-slip center. This might be the first evidence of a process considered in the theoretical paper of Weber and Kramer [13], namely a PSC born from a hot spot. We can add that a similar result (not shown here) obtains if the hot spot has been formed by using an additional δ-pulse of current instead of a laser excitation.

9. CONCLUSION

By monitoring the transient voltage following electrical and light excitations, we have determined the respective domains of occurrence of the dissipative modes in superconducting films, namely phase-slip centers, hot spots, and, to a certain extent, vortex flow. According to this classification, conventional and high-T_c films display similar features. It appears that PSCs occur more frequently than it is generally admitted: under certain conditions on the films, they exist very far from T_c. As for hot spots, they are not generated directly from a current pulse, but only through a short-lived PSC state.

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