Measurements of the Delay Time Between a Critical Current Pulse and the First Resistive Response in Superconducting Niobium Strips

K. Harrabi and J. P. Maneval

***Abstract*—We have measured in superconducting niobium filaments the delay time t_d that separates the initiation of a pulse of overcritical current $(I > I_c)$ from its first resistive response. The experiments were performed at various temperatures, typically 4, 5, and 6 K, well below the critical temperature T_c, for delays in the range 0.3 ns $< t_d <$ 80 ns, divided into two parts for technical reasons. The data $t_d(T/T_c, I/I_c)$ were analyzed through a time-dependent Ginzburg–Landau theory leaving the gap relaxation time τ_d as an unknown parameter. In a restricted range of current amplitudes ($I/I_c < 1.15$), a fit is obtained by choosing τ_d between 1.65 and 1.75 ns, which we interpret as a film cooling time of 23 ps per nm thickness, almost independently of the temperature.**

***Index Terms*—Nonequilibrium superconductivity, relaxation times and mean free paths, Ginzburg–Landau equations.**

I. Introduction

The resistive transitions induced by a critical current $(I > I_c)$ in a filamentary superconductor have very specific characteristic features. As the current is gradually increased, there appears in a V *vs* I plot a succession of voltage (V) steps of similar amplitudes, each followed by a linear increase of the voltage between two steps [1]. That behaviour was interpreted as revealing the creation of localised resistive units described as phase-slip centers (PSCs), different from normal spots [2], [3]. The model, originally designed for one-dimensional (1-D) superconducting bridges, such as whiskers, having their width w smaller than the coherence length ($w < \xi$), was found to apply to wider films ($w \gg \xi$). A second characteristic property of pulse-driven filaments, namely the delay time t_d between the initiation of a critical current pulse and the appearance of the first voltage step, was experimentally discovered in aluminium films, and explained on the basis of a simplified time-dependent Ginzburg-Landau (TDGL) treatment. A more developed approach [4] encompassing the temperature dependence of the delay times, was applied to a number of practical situations [5]–[8].

In whatever theory, the temporal evolution of the order parameter (or modulus of the superconducting wave function), relies on the value of the gap relaxation time τ_d which has generally been associated with the inelastic electron-phonon relaxation time [2]. However, the measurements performed over a wide temperature range, and over a variety of filament thicknesses seem to point to the cooling time of the filament on its substrate, sometimes called bolometric, or thermal relaxation time. (That is the point of view we adopt here). Actually, this cooling time has a direct influence on the count rate of single-photon superconducting detectors [9]. By using the known electron and phonon specific heats in the superconducting state, it can be converted into a phonon escape time τ_{esc}, more appropriate for comparison with independent results. In this work, we report an attempt to extend the investigations towards relatively large values of the ratio I/I_c, and associated short delay times. This objective implies using two slightly different mountings for measuring long and short times. From the displayed data, it seems that the two sets of data can be consistently linked.

II. Experimental Set-up

The Nb film, 80 nm thick, with $w = 10$ μm width, was deposited at room temperature on sapphire by DC magnetron sputtering in an argon-nitrogen plasma (STAR-Cryoelectronics, NM, USA). The final pattern, including two lateral probes, 1 mm apart from one another, plus four contact pads, was obtained by using standard photo-lithographic processes and ion milling. The measurements were performed at different temperatures 4, 5 and 6 K. The critical temperature T_c was 8.6 K. The normal resistivity at 10 K was found to be $\rho(10\ \mathrm{K}) = 7.68$ $\mu\Omega$.cm.

A pulse generator sending electrical pulses of variable duration and 10 kHz repetition rate, was used to excite the sample. 50 Ω coaxial cables and a delay line were used for the pulse measurement. The sample was designed to have a narrow width as mentioned $w = 10$ μm between the two lateral probes. The latter ones connected in series with with a 467 Ω, served to send the voltage response to a fast oscilloscope (Fig. 1-a). This configuration is used to measure long delay time starting from the maximum duration allowed by using a 240 ns delay line to 5 ns. To measure delay time shorter than 5 ns, the delay line was removed and replaced by a coaxial cable (Fig. 1).

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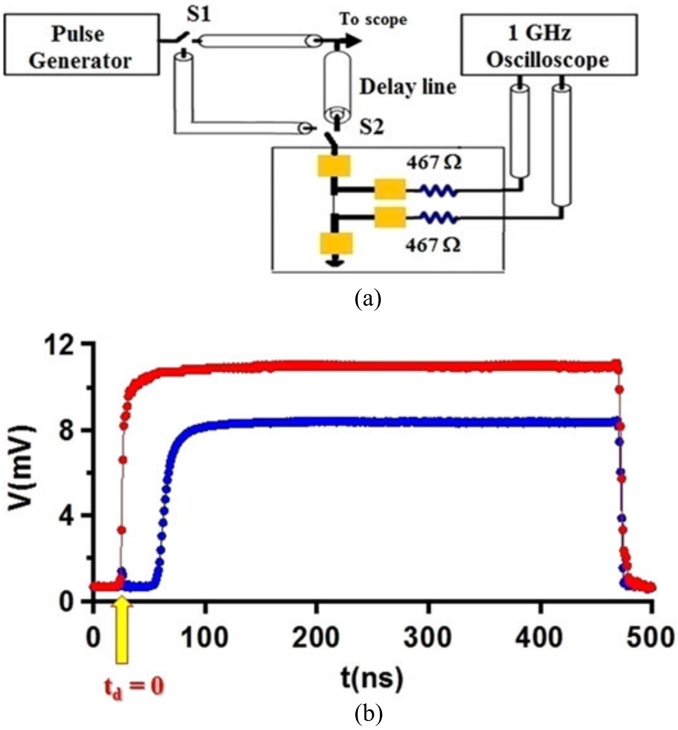

Fig. 1. (a) Experimental setup used to measure delay times t_d in the range of 15 ns and below 5 ns. The switches S1 and S2 allow commuting from the delay line to a single cable. (b) Oscilloscope traces of the voltage, with respect to ground, collected at the upper side electrode in the superconducting (blue color) and normal (red color) states. The origin of the times, defined by the onset of the current pulse coincides with the small inductive peak common to all traces (showed by the yellow arrow).

III. Theory of Nucleation of Phase Slip Center and Hotspot Formation

The response in the superconducting state of thin a filament to a critical current leads to several mechanisms of dissipation. It is first initiated by the motion of vortices, known as flux flow for low current amplitude. For larger currents, namely pair-breaking currents, a new type of dissipation occurs. Instead of extending over the whole sample length, it is limited to restricted zones (typically $\backsim 1\ \mu$m long) named phase-slip centers (PSCs). Strictly speaking, this behaviour is limited to one dimensional systems ($w < \xi$), where ξ is the coherence length. However, it was found to occur in wider films ($w \gg \xi$), with similar characteristics, under the name of phase slip line (PSL) [10], [11].

This behaviour is transcribed by the appearance of voltage steps and linear behaviour in the current voltage characteristic [7], [8]. The same features associated with PSCs in narrow bridges were reported in NbN [12]. The PSC is interpreted as a local spot in the filament, where the order parameter at its center oscillates between zero and one at the Josephson frequency [13]. Increasing further the current value, the well known dissipative mechanism steered by the HS appears. These two modes (PSC & HS) were explored in different materials (YBCO [5], Nb [6], NbTiN [8]). The discrimination was reported in the response to an overcritical current (YBCO [5], Nb [6]). The PSC showed the appearance of voltage after a delay time t_d, followed by non monotonic evolution in time [14]. However, the HS revealed

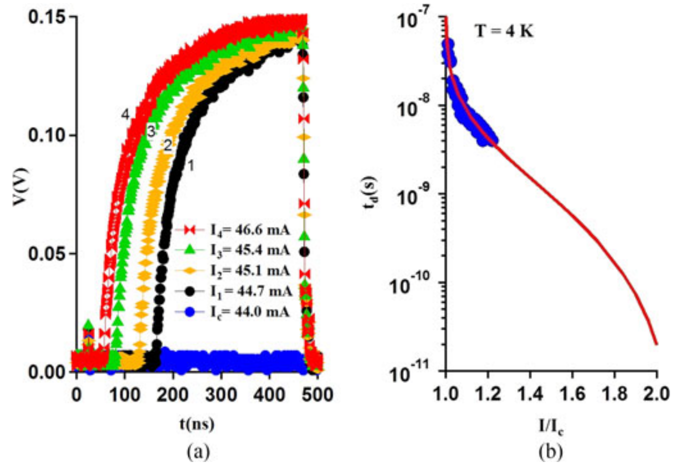

Fig. 2. (a) Hotspot voltage responses as function of time and their corresponding current amplitudes through the filament for sample using the delay line. (b) Delay time t_d (log scale) as a function of the reduced current I/I_c fitted with the Tinkham‘s TDGL theory (continuous traces) and the prefactor $\tau_d = 1.8$ ns was deduced.

a voltage after a delay time t_d, accompanied by a monotonic behaviour [15].

The response of superconducting filament to a step electrical current pulse leads to the appearance of a resistive state after a certain delay time t_d. The latter is interpreted as the time needed to suppress locally the order parameter. It was produced experimentally in Al bridge [16], and theoretically expressed by the TDGL and given by:

$$t_d(I/I_c) = \tau_d \int_0^1 \frac{2f^4 df}{\frac{4}{27}(\frac{I}{I_c})^2 - f^4 + f^6} \quad (1)$$

The temperature dependence was developed by Tinkham‘s theory [2]. The pre-factor τ_d, was first interpreted as the gap relaxation time, related to electron-phonon inelastic time. Different studies reported on different type of materials [5], [6], showed its dependence of the film thickness. Therefore, it is identified as the film cooling time.

First, we used a delay line in the circuit, where two switches were used S1 and S2 (Fig. 1-a). The delay time $t_d = 0$ used as the origin defined by the arrival of the electrical current pulse to the filament. Therefore, it is determined by the onset of the current pulse, we compared the response of the filament in the superconducting state ($T = 6.8$ K $< T_c$) to the one in the normal state ($T = 10$ K $> T_c$) (Fig. 1-b).

Fig. 2-a illustrates the appearance of the resistive state in response to a step current pulse excessing the critical value I_c. In this case a 240 ns delay line was used to separate the incident and the reflected pulses. The delay times t_d were plotted as a function of the ratio I/I_c at 4 K and fitted by Tinkham theory, the fitting parameter was deduced $\tau_d = 1.8$ ns (Fig. 2-b).

IV. Measurement of Short Delay Time

We investigated the initiation of the first resistive response to an overcritical pulse appearing after a delay time t_d. The measurement of the delay time below 5 ns becomes difficult to determine, therefore we performed the same measurement

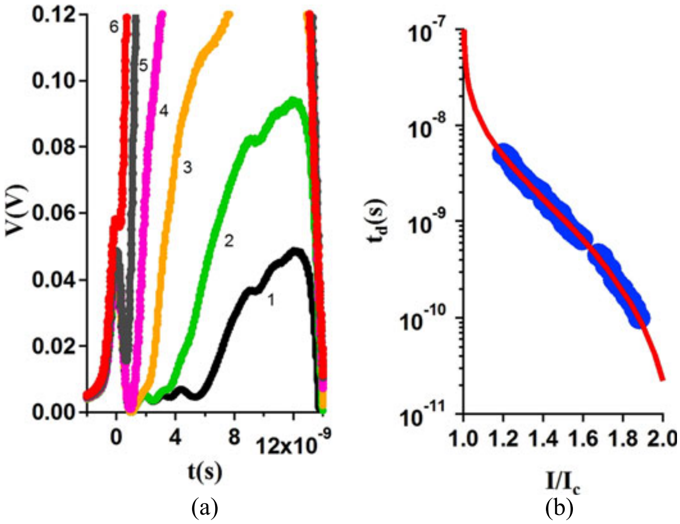

Fig. 3. (a) Hotspot voltage responses as function of time and their corresponding current amplitudes through the filament and when the delay line was bypassed ($I_1 = 57.2$ mA, $I_2 = 61.6$ mA, $I_3 = 70.4$ mA, $I_4 = 74.8$ mA, and $I_5 = 81.4$ mA). (b) Delay time t_d (log scale) as a function of the reduced current I/I_c fitted with the Tinkham's TDGL theory (continuous traces), and the prefactor $\tau_d = 1.65$ ns was obtained at T = 4 K.

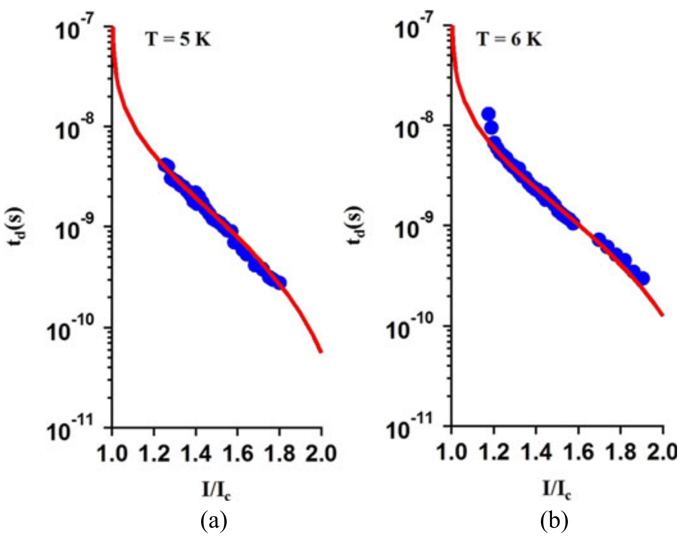

Fig. 4. Delay time t_d (log scale) as a function of the reduced current I/I_c fitted with the Tinkham's TDGL theory (continuous traces) for two different temperatures 5 and 6 K. The prefactors were deduced respectively at 5 and 6 K to be 1.6 and 1.75 ns.

with short electrical current pulse of about 14 ns. The delay line was removed and the pulse was sent directly to the sample (using switches S1 and S2). The voltage responses are shown in Fig. 3-a. The critical current value used in the plots of Fig. 3-b, Fig. 4 a & b was the same as that deduced from the measurement using the delay line in the circuitry. It corresponds to $t_d \to \infty$.

We performed the same measurement at different temperatures 4, 5 and 6 K for short delay times ($t_d \leq 5$ ns). The maximum current that could be applied for a measurable delay time $t_d \simeq 0.3$ ns was about 1.9 I_c. This value is limited by the anomaly of the experimental set-up, due to the inductance associated with the wire connecting the coaxial cable to the sample. The experimental measurement is well fitted with Tinkham theory as shown in Fig. 3-b, Fig. 4-a & b. If we compare this new data to the one using the delay line (T = 4 K), despite the lower limit of $t_d \simeq 5$ ns, we obtained almost the same cooling time τ_d.

The measurement at different temperatures of the pre-factor τ_d shows its independence upon the temperature. We consider the prefactor τ_d as the time needed by the film to regain its initial state by cooling on its substrate. By taking the mean value of τ_d over Fig. 3 and 4, that is 1.7 ns for a common thickness of b = 80 nm, one arrives at the result τ_d/b = 21 ps/nm. Considering that the total specific heat C of superconducting niobium is about three times that of its phonon component $C\phi$ [6], the phonon escape time $\tau_{\rm esc} = C/C_\phi\ \tau_d$, verifies the relation $\tau_{\rm esc}$/b = 7 ps/nm, a very short escape time indeed [17]. An elevated temperature brings into play a larger proportion of high-frequency phonons, with several consequences which all cooperate to reduce the efficiency of heat transmission at interfaces. The bending of the dispersion relations leads (a) to smaller energy velocities. (b) phonons more sensitive to scattering by defects (c) more numerous channels for phonon-phonon decay [18]. The quasi-invariability of the phonon escape time in niobium proves inversely that the phonons are still in the Debye regime up to the maximum temperature T_c [17].

V. Conclusion

We investigated the appearance of the first resistive voltage due to an overcritical current after a short delay time t_d less than 1 ns by sending the electrical pulse directly to the sample. The experimental measurement of the delay time t_d was interpreted using the TDGL equation. The heat escape times were subsequently deduced. We compared the heat escape time measured for short delay time t_d to the one obtained using a delay line, and we found a small discrepancy due the delay line (less than 0.5 ns). Both results are well fitted with TDGL. Assuming proportionality to the thickness, we then deduce a phonon escape time $\tau_{\rm esc}$/b = 7 ps/nm.

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