Influence of thermal, morphological and measuring variables on the thermal runaway of superconducting films under high current densities

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Abstract. We study the abrupt jump in voltage seen in the current-voltage characteristics of high-\( T_c \) films at current densities, \( J^* \), around 2-3 times the critical one, and for perturbations with characteristic times in the millisecond range. Customarily, even for these long characteristic times, the voltage jump has been ascribed to an electrodynamic vortex instability. Recent results based on finite-element analyses show quantitatively that smooth, i.e., jumpfree isothermal curves may show up themselves as the jumping, i.e., discontinuous curves experimentalists observe, once the nonlinearity, thermal feedback and measurement rate are properly accounted for. The thermal nature of the transition to a highly dissipative state in high-\( T_c \) superconductors at zero magnetic field makes the control of the instability transition easier in that there are more parameters available to experimentalists that may be tuned to tailor the phenomenon. This is specially relevant for devices working on their superconducting borderline as current-limiters or even magnets. Here we explore through finite-element analysis the role of film geometry, measurement rate and substrate thermal conductivity in the triggering of the thermal runaway.

1. Introduction
In the study of the Current-Voltage Curves (CVC) in high-\( T_c \) superconductors, there are two very important currents: the critical one, \( J_c \), at which dissipation first appears, and the supercritical current, \( J^* \) (the corresponding electric field will be denoted as \( E^* \)), where the system jumps abruptly to a highly dissipative state. This phenomenon is not well understood yet. The most widely accepted interpretation for this abrupt jump is an electrodynamic vortex instability [1, 2], even for characteristic perturbations times in the millisecond range, where the heating of the sample is very important. Using a Finite-Element Method (FEM) and by taking into account properly the nonlinearity of the CVCs, the thermal feedback and the measurement rate, we have simulated an abrupt jump from smooth, i.e., jumpfree, isothermal CVCs in good agreement with the experimental ones [3]. In this paper we complete these previous results by exploring the role of the film geometry, measurement rate and substrate thermal conductivity in the triggering of the thermal runaway.

2. Constant-temperature CVC
Figure 1 shows a typical set of experimental CVCs for a \( YBa_2Cu_3O_{7-\delta} \) microbridge of width 10 \( \mu \text{m} \) and thickness 120 nm, grown on a \( SrTiO_3 \) substrate by sputtering deposition and
measured using 1 ms pulse currents (for experimental details see Ref. [4]). No data points above the jump are shown because the factor of 50 discontinuity in voltage would downplay the most relevant lower data points.

(i) Our simulation procedure requires the knowledge of the constant-temperature current-voltage curves. Note that because of thermal effects, the experimental data have a steadily increasing temperature.

(ii) Figure 2 shows the low voltage range for the same experimental data as in Figure 1. This low range data is used to generate the constant-temperature curves we need in this paper. The functional form is:

\[ E(J, T) = E_0(T) \left[ \frac{J}{J_0(T)} - 1 \right]^n, \tag{1} \]

where

\[ E_0(T) = E_1 (1 - \frac{T}{T_c})^{n_0}, \tag{2} \]

\[ J_0(T) = J_1 (1 - \frac{T}{T_c})^{n_0}, \tag{3} \]

and where \( J_1, E_1, n \) and \( n_0 \) are taken as constant free parameters.

This functional form is very useful because: i) it fits quite well the data in the whole temperature range at low current (where we assume the overheating of the sample is negligible) and ii) it extrapolates smoothly to higher currents. These features are illustrated in Figure 2 where is shown the goodness of the fit in the low voltage region for any temperature. The isothermal curve of Figure 2 corresponds to the following parameters: \( T_c = 89.9K, E_1 = 3.24V/cm, J_1 = 33.2 \times 10^6 A/cm^2, n_0 = 1.38 \) and \( n = 3.95 \).

### 3. Simulation Results

The simulation procedure is too long-winded to be explained here, but the details of it can be seen in Ref.[3]. Only the neat results at zero applied magnetic field will be presented. Let us just mention that current is injected in the sample by current pulses with increasing high current intensity, the delay between pulses being long enough to guarantee that the bath temperature is the initial temperature of the sample. The simulated voltage at the end of each current plateau is the value reported in Figures 3 through 6. We will allude often to the time pulse as the “measurement time”.

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**Figure 1.** Experimental data up to the jump for a 10 \( \mu \)m width of \( YBa_2Cu_3O_{7-\delta} \) microbridge with \( T_c = 89.9K \).

**Figure 2.** Low-\( E \) data range of Figure 1. Solid lines are the isothermal CVCs obtained from fitting Equation 1 to this low-\( E \) range.
3.1. Measurement time
In Figure 3 we show our FEM simulations for five different measurement times: 10 ms, 1 ms, 100 µs, 10 µs and 1 µs. The change from solid to dashed lines shows where the abrupt jump is located. The microbridge simulated is $YBa_2Cu_3O_{7-\delta}$, over a $SrTiO_3$ substrate. The width of the microbridge is 10 µm and the thickness is 120 nm. When the measurement time is lower, the supercritical current $J^*$ is bigger. This is because the longer the measurement time the higher the sample heating, and the more difficult is to maintain the thermal balance (the balance between the dissipated power due to the Joule heating and the evacuated power through the substrate), and thus the easier takes place the thermal runaway originating the jump. Note that the simulated curves tend to the isothermal CVC (labeled $t=0s$) as the measurement time is shortened.

![Figure 3. Results of our simulations corresponding to different measurement timerates.](image)

3.2. Microbridge’s width
In Figure 4 we show our FEM simulations for four different widths: 10 µm, 20 µm, 40 µm and 60 µm. The change from solid to dashed lines shows where the abrupt jump takes place. In this case we simulate a $YBa_2Cu_3O_{7-\delta}$ microbridge over a $SrTiO_3$ substrate, measurement pulses of 1 ms, and film thickness of 120 nm. The effect of the width is a very relevant one. The bigger the microbridge width, the lower the values of $J^*$ and $E^*$. This is because wider films are less edgy than narrow films, the two edgy regions having more cold substrate volume at their disposal. This makes more difficult for wider microbridges to keep the thermal balance and they jump sooner in current than narrower microbridges (see Ref. [5] for experimental details about the behavior of the abrupt jump with the microbridge’s widths).

![Figure 4. Results of our simulations corresponding to different microbridge’s widths.](image)

3.3. Microbridge’s thickness
In Figure 5 we show our FEM simulations corresponding to 3 different microbridge’s thicknesses: 60 nm, 120 nm and 240 nm. The abrupt jumps are signaled by the change from solid to dashed lines. The simulated microbridge is a $YBa_2Cu_3O_{7-\delta}$ one over $SrTiO_3$ substrate, with 10 µm width and measurement pulses of 1 ms. When the thickness is bigger, $J^*$ and $E^*$ are lower. This is because when thickness is bigger more heat generates, more difficult is to keep the thermal balance with the same heat interchange area with the substrate, and more easily the thermal runaway appears.

![Figure 5. Results of our simulations corresponding to different microbridge’s thicknesses.](image)
3.4. Substrate type
Figure 6 shows our FEM simulations for three different kinds of substrates: SrTiO$_3$, MgO and sapphire (Al$_2$O$_3$). The change from solid to dashed lines indicates the abrupt jump. The microbridge is of 10 µm width and of 120 nm thickness of $YBa_2Cu_3O_{7-\delta}$, and the measurement time is 1 ms. Note that the $J^*$ and $E^*$ values obtained for Al$_2$O$_3$ and MgO are higher than those for SrTiO$_3$. This is because Al$_2$O$_3$ and MgO have a thermal conductivity (10 and 2 W cm$^{-1}$ K$^{-1}$ respectively) bigger than the SrTiO$_3$ (0.18 W cm$^{-1}$ K$^{-1}$). The bigger the thermal conductivity of the substrate, the better the evacuation of the dissipated power through the substrate and, thus, the easier to maintain the thermal balance avoiding the thermal runaway.

4. Conclusions
We have explored the influence of various relevant variables on the voltage jump that takes place at high current densities in $YBa_2Cu_3O_{7-\delta}$ films. Because of the thermal nature of the voltage jump, the current injection rate (Figure 3) is worth emphasizing. All together these results should enter into the design of superconducting devices working at the limits of their superconductivity.

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Figure 5. Results of our simulations corresponding to different microbridge’s thickness.

Figure 6. Results of our simulations corresponding to different substrates.