HIGH-FREQUENCY EFFECTS IN SUPERCONDUCTORS FROM SHORT-DURATION DC PULSES

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The response of a superconductor to applied electric and magnetic fields is often studied in two regimes that represent extremes on the frequency scale: one is at zero frequency — the DC electrical transport regime; the other is the response to microwaves. A complex array of processes affect the dissipation and general response of a superconductor to an applied electromagnetic signal, ranging from different types of flux motion to pair-breaking and fluctuations. Some of the simplest and most basic regimes (e.g. free flux flow) can be accessed by either the application of very high frequency signals, such as the Gittleman-Rosenblum experiment using microwaves, or by large driving forces at low frequencies, such as the use of intense short duration DC pulses in our earlier work. Short DC pulses provide an effective means to study the continuous progression of behavior from the zero-frequency regime into the true high-frequency response regime. Using these methods we can now see "frequency effects" where the behavior departs qualitatively from the zero-frequency regime. These observations are discussed in the framework of highly driven flux flow and the Larkin-Ovchinnikov instability.

A superconductor is commonly thought of as having zero electrical resistance R below its transition temperature T_c. In general, however, the superconducting state can be resistive below the mean-field transition for several reasons, and this is especially true in the upper range of parameters like temperature T, magnetic field H, current density j, or signal frequency ω (e.g. microwave radiation). Dissipation within the superconducting state arises from several causes. Close to T_c, fluctuations give rise to finite resistance. Below this critical region, R drops sharply to zero with decreasing T for low values of the other parameters: J, ω, H, etc. At finite values of these parameters, however, the scenario is complicated by a rich variety of dissipative phenomena including the motion of flux vortices, partitioning of the sample into intermediate states, and the depairing effect of the current as it causes phase slippage and leads ultimately to the destruction of the superconducting state.

In our work we use short-duration electrical pulses to investigate the evolution of superconducting behavior along the current axis, well beyond the onset of dissipation and the depinning of flux vortices (j_c). In this regime the flow of vortices enters the unpinned free limit (assumed in elementary theories such as Bardeen-Stephen [1]) and at high velocities can show interesting effects such as the Larkin-Ovchinnikov (LO) instability caused by a non-equilibrium quasiparticle distribution in the vortex core.By controlling the pulse duration it is possible to tune the onset of the LO instability.

The transport measurements are conducted using a custom-built pulsed-current apparatus to alleviate sample heating while studying dissipative transport. Our present apparatus has submicrosecond rise times and can operate in both constant-I and constant-V modes (with compliance voltages as high as 400 V). Precise control over waveform shape permits non-destructive measurements at power-dissipation densities over $10^9 \mathrm{W/cm}^3$. The detection circuitry can measure small differential signals (e.g. a $\sim$ 1 mV Hall voltage) riding on a large common-mode level (longitudinal voltage $\sim$ 50 V) at μs pulse widths. Further details of the apparatus and measurement techniques are discussed in a review article [2]. The samples are c-axis oriented epitaxial films of $Y_1Ba_2Cu_3O_{7-\delta}$ on a (100) $LaAlO_3$ substrate. The films were deposited and post annealed by means of the BaF_2 process, described elsewhere [3]. The films were patterned into narrow bridges (3–100 μm wide) using electron-beam lithography and optical-projection lithography. The measurements are carried out in a vapour-flow variable-temperature insert inside a 16-Tesla superconducting magnet.

When a type-II superconductor is subjected to an applied magnetic field H greater than the lower critical field H_{c1}, it becomes permeated by quantized magnetic flux vortices each containing an elementary quantum of flux $\Phi_0 = hc/2e$, and is said to have entered the "mixed state" An applied current density j drives the vortices with a Lorentz force density of $\bar{F_L} = \bar{j} \times \bar{B}/c$, where B is the flux density. The resultant motion of vortices leads to an electric field $\bar{E} = \bar{B} \times \bar{v}/c$ (predominantly parallel to $\bar{j}$) with a power dissipation density $p = \bar{j}.\bar{E} = \rho j^2$ (where $\rho \equiv \rho_{xx}$). The operative resistivity ρ depends on the regime of flux motion and the state of the vortex matter. In a homogeneous isotropic superconductor, flux flows in the free limit leading to a resistivity given roughly by the Bardeen-Stephen (BS) formula [1]: $\rho \approx \rho_n B/H_{c2}$, where ρ_n is the normal-state resistivity. To a first approximation this result also applies to HTS. In practice, the free flux flow (FFF) regime is illusive because of several complications. Inhomogeneity in the underlying lattice ("quenched disorder") gives rise to a pinning force that hinders flux motion. Exactly how this pinning suppresses the flux motion depends on the state of the vortex matter, and calculations of the dynamic response and extended E–j characteristic are generally difficult (but see references [4]–[5]). Nevertheless, at sufficiently large driving forces ($j \gg j_c$) flux motion simplifies to free flow regardless of the particular vortex phase or regime of pinning.Most of the flux-dynamical fine structure discussed above disappears and the E–j characteristic approaches Ohmic behavior with roughly the BS value. Blatter et al. have written an excellent review on this subject with a very detailed discussion of the various regimes of flux phases and dynamics [5]. Figure 5 in that paper illustrates very nicely the evolution of $\rho(j)$ in the different regimes. Our previous work on YBCO films [6] was able to experimentally demonstrate the forcing of FFF behavior at high J and showed quantitative agreement with the BS prediction. FFF behavior has now also been observed in some intrinsically weaker pinning materials, such as 2H-$NbSe_2$ [7] and MoGe [8], where the high pulsed currents are not required for depinning the flux.

A peculiar effect that can arise in strongly driven vortices is an instability due to a drop in viscosity when quasiparticles in the vortex core become energized above their equilibrium distribution and diffuse out of the core. This was predicted by Larkin and Ovchinnikov (LO) [9] and first verified (in LTS) by Musienko et al. [10]. Since then it has been seen in other systems [11]–[14] including YBCO. The effect arises in the following way [11]: A finite energy-relaxation time τ_E (essentially the inelastic scattering time) causes the quasiparticles in the core to gain an energy above their equilibrium value by the amount

$$\delta\epsilon \approx \frac{jE}{n_{qp}} \times \tau_E, \qquad (1)$$

where E is the electric field in the core and n_{qp} is the quasiparticle density. This leads to a diffusion of quasiparticles out of the core and a reduction in viscosity, leading to a disproportionate increase in vortex velocity. The number of quasiparticles that escape the core is $\sim \delta\epsilon/\Delta$ where Δ is the energy gap, and the corrected viscosity is then given by

$$\eta(v_\phi) = \eta(0)(1 - \delta\epsilon/\Delta). \tag{2}$$

Making the usual connections[1] between vortex viscosity, velocity v_ϕ and the transport quantities E and j we get:

$$j = \rho_{FFF} \times \frac{E}{1 + (E/E^*)^2}, \tag{3}$$

with $E^* = \left(\frac{\phi_o B n_{qp} \Delta}{\eta(0)\tau_E}\right)^{\frac{1}{2}}$. Eq. 3 has some surprising properties. As a function of applied E (i.e., constant-voltage source), j varies non-monotonically; as a function of applied j (i.e., constant-current source), E is bivalued above E^* and therefore unstable, leading to an abrupt jump in the E versus j curve at this point. The value of E^* determined from the instability can then yield information on τ_E and Δ. An interesting twist to Eq. 1 is that if the current is pulsed with a duration $\delta t < \tau_E$, the energy rise is limited by δt rather than τ_E. Eq. 1 then becomes modified to

$$\delta\epsilon \approx \frac{jE}{n_{qp}} \times \delta t \tag{4}$$

leading to a suppression of the LO instability. We have observed exactly this effect in our pulsed measurement of the flux-flow resistivity. Fig. 1 shows the sample voltage versus time for three different current densities. At the two higher values of J, there is an onset of rapidly increasing V vs t beyond some point. This onset shifts to the left with increasing J as Eqs. 3 and 4 predict.

The onset of the instability contains information on the modulation of the gap. The presence of a well-defined and constant-energy gap everywhere on the Fermi surface leads to a sharper crossover where the quasiparticles suddenly start diffusing out of the vortex core, leading to a more abrupt instability. Whereas if the superconductor has nodes in its gap (e.g., d-wave), one might not expect an abrupt anomaly that can be suppressed temporally as observed, since quasiparticles will diffuse out of the core at arbitrarily low j or short times. The time-resolved measurement thus yields valuable details about this onset region that may not be apparent in the usual current-biased dc measurement. A more complete study of this effect is presently underway.

In conclusion, this paper discusses dissipation in superconductors due to strongly driven flux flow. The flux motion spans several regimes of behavior ranging from flux creep to free flux flow as a function of increasing current density. Under certain condition, the highly driven flux vortices can exhibit the Larkin-Ovchinnikov instability which can be suppressed by reducing the duration of the driving current pulse. We show preliminary data confirming such a temporal tuning of the LO phenomenon.

[1] $E = v_\phi B$, $j = \eta(v_\phi)v_\phi/\phi_o$, and $\eta(0) = \phi_o H_{c2}/\rho_n$, where ϕ_o is the flux quantum; the last relation follows from Bardeen and Stephen.

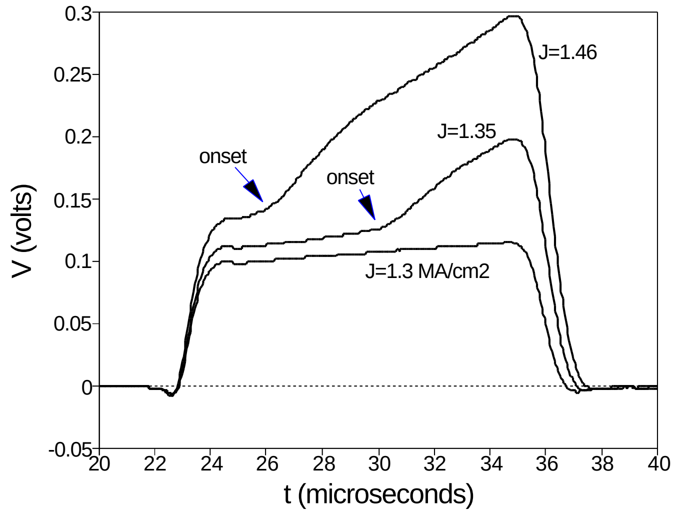

Figure 1: Pulse waveforms of sample voltage near the onset of the LO vortex instability. The quasiparticles in the vortex core gain an energy, $\delta\epsilon$, above equilibrium that is proportional to the duration of j and E. There is a sudden change in slope (marked as "onset") when $\delta\epsilon$ becomes comparable to the gap (Eqs. 3 and 4).

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