Dynamic Coupling-Decoupling Crossover in the Current-Driven Vortex State in $Tl_2Ba_2CaCu_2O_8$ Probed by the Josephson Plasma Resonance

V. K. Thorsmølle,[1,2] R. D. Averitt,[1] T. Shibauchi,[3] M. F. Hundley,[1] and A. J. Taylor[1]

[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*
[3]*Department of Physics, Kyoto University, Sakyo-Ku 606-8502, Japan*
(Received 22 December 2004; published 4 December 2006)

We have used terahertz spectroscopy to measure the Josephson plasma resonance in the superconductor $Tl_2Ba_2CaCu_2O_{8+\delta}$. This allows us to probe the longitudinal ordering of pancake vortices as a function of applied *ab*-plane current in a 2.5 kG *c*-axis magnetic field. With increasing current in the low temperature vortex solid phase, we observe a decrease in the interlayer phase coherence consistent with a progressive misalignment of the pancake vortices in neighboring layers. In the high temperature vortex liquid phase, an increase in the longitudinal ordering occurs above a certain threshold current. Our results show evidence of a current-driven coupling-decoupling crossover in the pinned liquid phase.

DOI: 10.1103/PhysRevLett.97.237001 PACS numbers: 74.25.Qt, 74.72.Jt

The properties of driven periodic structures subject to quenched disorder, including charge-density waves, Wigner crystals, and vortex lattices, have become one of the central issues in the phenomenology of nonequilibrium statistical mechanics [1–5]. In the context of the vortex lattice, Koshelev and Vinokur predicted the driven system to undergo a dynamic phase transition at some threshold current between the fluidlike and crystal-like moving states [2]. In other words, an applied current puts forth a scenario where a pinned vortex lattice flows plastically at first as some vortices are depinned, and then becomes more ordered at higher applied currents as more vortices are depinned, possibly forming a moving ordered vortex lattice. Thus, beyond some critical value, a dynamic phase transition may occur to a more ordered state, characterized by a change from incoherent to coherent vortex motion.

A dynamic phase transition has been suggested by observation of anomalies in *I*-*V* characteristics [6–10], by detection of changes in the correlation length which reflects the degree of ordering of the moving lattice [11–13], and most directly by neutron diffraction measurements, where the continuous development of the order of the vortex lattice was followed as long as the Bragg diffraction spots were detectable [11]. These previous investigations of the current-driven vortex lattice have mainly been concerned with the ordering of the vortex lattice in the plane perpendicular to the applied magnetic field in the vortex solid phase of either isotropic or moderately anisotropic superconductors. Much less attention has been given to the ordering along the vortex lines (longitudinal ordering).

In this Letter, we study the longitudinal ordering of the current-driven vortex lattice as a function of applied current in both the vortex solid phase and the vortex liquid phase of the highly anisotropic high-T_c superconductor, $Tl_2Ba_2CaCu_2O_{8+\delta}$ (Tl-2212) thin films at optimal doping. This is accomplished by directly measuring the Josephson plasma resonance (JPR) using terahertz (THz) spectroscopy. The JPR is a direct measure of the ordering along the *c*-axis (longitudinal ordering). This technique of probing the longitudinal ordering by measuring the JPR is only applicable to highly anisotropic high-T_c superconductors (i.e., Josephson-coupled layered superconductors). Fortuitously, it is exactly under these circumstances that, with application of an *ab*-plane current, a strong longitudinal reordering of the vortex phase is expected. We have, for the first time, measured this effect. Specifically, for an applied *c*-axis magnetic field of 2.5 kG, for temperatures above 80 K – in the pinned liquid phase, we observe a dynamic transition of the vortex lattice to a longitudinally more ordered state at a specific current threshold.

The structure of different vortex phases and the nature of the phase transitions in the magnetic phase diagram of a high-T_c superconductor [14] depends strongly on the anisotropy parameter, $\gamma = \lambda_c/\lambda_{ab}$ [15]. Here λ_c and λ_{ab} are the London penetration depths along the *c*-axis and *ab*-plane, respectively. In $YBa_2Cu_3O_{7-\delta}$, which has a low degree of anisotropy, $\gamma \sim 8$, the vortex lattice melts by a first-order phase transition into a linelike liquid [16] up to rather high magnetic fields ~1–10 T [17]. For Bi- and Tl-based high-T_c superconductors, $\gamma \sim 500$ and ~150, respectively, a model of pancake vortices has been introduced; i.e., the vortices are stacks of two-dimensional "pancake" vortices in the CuO_2 layers weakly coupled by Josephson and magnetic interactions [18]. At low temperatures and low magnetic fields, the vortex lattice is composed of aligned stacks of pancakes (vortex lines). However, the interactions between pancakes in adjacent layers are very weak and vortex lines are easily destroyed by either thermal fluctuations at high temperatures, or by random pinning. In $Bi_2Sr_2CaCu_2O_{8+\delta}$, which is the most anisotropic superconductor known, the vortex lattice undergoes a first-order melting transition into a pancake liquid at magnetic fields $B \lesssim 500$ G [15]. In Tl-2212 films, the vortex lattice has been shown to undergo a glass transition, where vortex lines are preserved in the liquid state below 2.5 kG [19].

Interlayer correlations of pancakes in a driven vortex system in highly anisotropic layered superconductors were studied theoretically by Aranson *et al.* [1] by numerical simulations of the time-dependent Ginzburg-Landau-Lawrence-Doniach equations in a model of two coupled layers. The authors calculated the average of the cosine of the phase difference, $W_c = \langle \cos\varphi_{12} \rangle$, as a function of the electric field E along the layers produced by the intralayer current. When the pancake vortices form straight lines perpendicular to the layers, $\varphi_{12}(\mathbf{r}, B)$ vanishes and $W_c = 1$. However, when the pancake vortices are misaligned along the direction perpendicular to the layers, a nonzero phase difference is induced, which results in the reduction of W_c from unity. Hence, W_c characterizes the longitudinal ordering of vortices in Josephson-coupled layered superconductors. The authors found a decrease of W_c at low electric fields (currents) in the plastic flow regime accompanied by an increase of W_c at higher electric fields (currents) as smectic flow replaces plastic flow. The rate of increase becomes stronger as the anisotropy decreases because the vortex system approaches the limit of an isotropic superconductor where a dynamic transition should occur at some critical value of the current. Kolton *et al.* [20], by use of equations of motion for pancakes, also conclude that correlations of pancakes in different layers are nearly absent in the plastic flow regime but improve as the current increases and the pancake flow becomes smectic. In both theoretical studies, it was assumed that, in the absence of current, the vortex system is in the vortex solid phase at zero temperatures.

The JPR [21,22] provides direct information of W_c, and is thus one of the most powerful experimental probes of the longitudinal ordering of pancake vortices in highly anisotropic layered superconductors. The JPR is a Cooper pair charge oscillation mode perpendicular to the CuO_2 layers. In zero magnetic field the JPR is a direct probe of the Josephson coupling between the layers [23]. In this case the JPR frequency is given as $\omega_0(T) = c/[\lambda_c(T)\sqrt{\epsilon_\infty}] = c/[\gamma\lambda_{ab}(T)\sqrt{\epsilon_\infty}]$. Here, c is the speed of light, and ϵ_∞ is the high-frequency dielectric constant along the c-axis. In the presence of a c-axis magnetic field B, the JPR can be written as [24]

$$\omega_p^2(B, T) = \omega_0^2(T) W_c, \; W_c = \langle \cos[\varphi_{n,n+1}(\mathbf{r}, B)] \rangle. \quad (1)$$

$\langle \cos[\varphi_{n,n+1}(\mathbf{r}, B)] \rangle$ is the local thermal and disorder average of the cosine of the gauge-invariant phase difference between adjacent layers n and $n + 1$, and $\mathbf{r}$ is the in-plane coordinate. As discussed in the previous paragraph, W_c is a direct measure of the longitudinal vortex ordering. Equation (1) is thus extremely important as it shows that ω_p^2 (which we measure directly in our experiment) is proportional to the longitudinal vortex ordering. This equation also embodies the fact that ω_p^2 is proportional to the c-axis critical current density J_c, which is directly proportional to $\langle \cos[\varphi_{n,n+1}(\mathbf{r}, B)] \rangle$ (and inversely proportional to λ_c^2).

We investigate the current-driven vortex state in the high-T_c superconductor, Tl-2212, by directly probing the interlayer phase coherence with the JPR using terahertz time-domain spectroscopy (THz-TDS) in transmission. Details of the THz-TDS spectrometer are discussed in Ref. [25]. The Tl-2212 film (700 nm) was grown on a 1 mm thick 12×12 mm^2 MgO substrate, and exhibited a sharp superconducting transition (0.2–K width) at $T_c = 102.5$ K. The growth process is described in Ref. [22]. Current leads were attached along the ends of two opposite sides, thus providing a homogeneous current flow across the film. The sample was attached to a copper sampleholder with a 9 mm aperture in the following configuration; 700 nm Tl-2212 thin film, 1 mm MgO substrate, and a thin layer of thermal grease for good thermal contact to the copper sampleholder. An increase of the temperature caused by heating from the contacts ($\sim 1\ \Omega$ at 100 K) and the resistivity of the Tl-2212 film ($\sim 0.5\ \mu\Omega$–cm at 100 K, 2.5 kG) was found to be negligible for the applied currents used in the experiment. The sample was positioned inside an optical cryostat with optical access, between a pair of permanent magnets with the magnetic field oriented along the c-axis. Measurements were performed in field cooled mode. The configuration of the sample with respect to the THz beam is shown in Ref. [22], Fig. 1.

Figure 1(b) shows the electric field of the THz pulse transmitted through the sample (film plus substrate) in a 2.5 kG c-axis magnetic field at 10 K. Comparing to the reference (substrate only), shown in Fig. 1(a), one notices

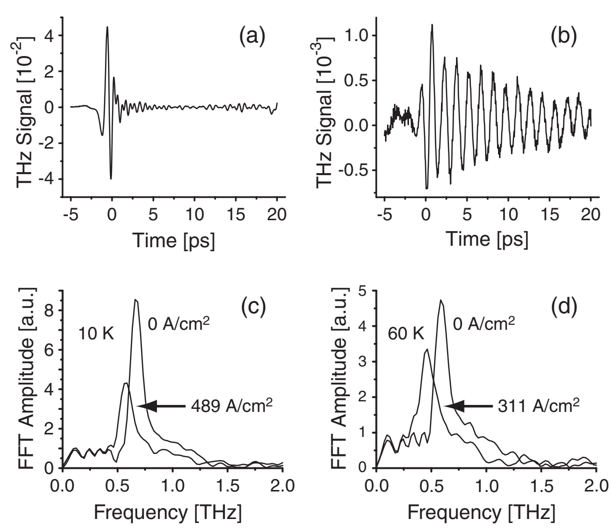

FIG. 1. Electric field $E(t)$ of THz pulse in the time-domain transmitted through MgO substrate as reference (a), and Tl-2212 thin film plus MgO substrate as sample (b) in 2.5 kG c-axis magnetic field at 10 K. (c) and (d) show the amplitude spectrum of $E(t)$ at 10 and 60 K, respectively, with and without an applied current in the ab-plane.

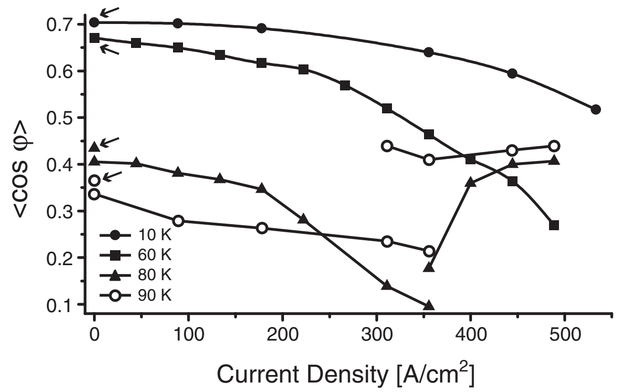

FIG. 2. Interlayer phase coherence factor $W_c = \langle \cos\phi_{n,n+1} \rangle$ versus applied *ab*-plane current density in Tl-2212 in 2.5 kG *c*-axis magnetic field at 10, 60, 80, and 90 K. The solid lines are guides for the eye and show W_c for increasing applied currents. The arrows at 0 mA indicate the value of W_c for each temperature after the current has been switched off.

that the oscillations characteristic of the JPR in the Tl-2212 film is absent in the reference scan. Figs. 1(c) and 1(d) show the behavior of the JPR in the frequency-domain at 10 and 60 K, respectively, when applying a current in the *ab*-plane. This clearly illustrates a downward shift in the JPR frequency when current is applied.

In Fig. 2, we show the interlayer phase coherence factor, $W_c = \omega_p^2(B = 2.5\ \text{kG}, T, J)/\omega_0^2(0, 10\ \text{K}, 0)$, as a function of applied current density (J) in the *ab*-plane at 10, 60, 80, and 90 K in a 2.5 kG *c*-axis applied magnetic field. Three different types of behavior for $W_c(J)$ are observed: (a) at low current W_c decreases with J, i.e., plastic flow regime, (b) a rapid increase of W_c with J as smectic flow establishes above the threshold current, and (c) a slower increase of W_c with increasing J. At low temperatures, in the vortex solid phase, the pinning is strong, and the effect of the applied current is small on the longitudinal ordering. This is more true for 10 K than for 60 K where the pinning is weaker and we see a more pronounced drop off of W_c at higher currents. While we cannot clearly rule out the effect of heating, we note that the decrease at 10 K is consistent with the suppression of W_c in the zero field cooling condition as observed in $Bi_2Sr_2CaCu_2O_{8+\delta}$ below the irreversibility line [26]. For the 60 K data, a weak knee structure at $\sim$220 A/cm^2 is observed where the slope of W_c increases. The Lorentz force exerts a force on the vortices which diminishes the effect of pinning with increasing current. At 80 K, now in the vortex liquid phase (Ref. [19]), the first slope is approximately the same as for 60 K up to the knee structure which occurs at $\sim$180 A/cm^2 for 80 K. The second slope is slightly steeper than for 60 K. Then W_c at 80 K displays a very pronounced increase at $\sim$350 A/cm^2, which is not observed at 60 K in the vortex solid phase. In the vortex liquid phase, the critical current density is zero and the pinning is much weaker. The vortex lattice is thus driven into a supposed flux-flow state at higher currents where now vortex-vortex interactions become important, and the vortex lattice rearranges itself into a longitudinally more ordered state. This is the effect which was predicted by Koshelev and Vinokur [2] to occur in the vortex solid phase described earlier, where the vortex lattice is proposed to undergo a dynamic phase transition at some threshold current between the fluidlike and crystal-like moving states. The same phenomenon is observed at 90 K at $\sim$320 A/cm^2, although no knee structure is observed. Both at 80 and 90 K, two JPR's are observed for the same current. This observation will be discussed below Fig. 4.

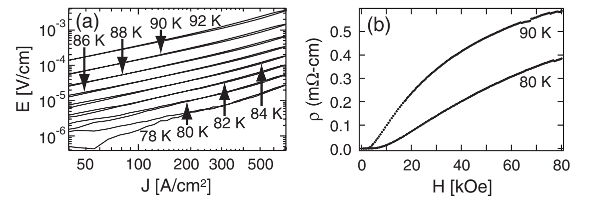

FIG. 3. (a) *I*-*V* characteristics at various temperatures (see arrows) in 2.5 kG *c*-axis magnetic field. (b) Resistivity versus *c*-axis magnetic field in the low current regime ($J = 7$ A/cm^2).

Figure 3(a) shows *I*-*V* characteristics in a 2.5 kG *c*-axis field up to 700 A/cm^2. In contrast to anomalies detected in previous experiments in the vortex solid phase suggesting a dynamic phase transition [6–10], no anomaly is observed here. The main difference is that in our measurements, the crossover point occurs in the pinned liquid phase. This observation furthermore emphasizes the point that the JPR is a much more sensitive probe of longitudinal ordering in comparison to *I*-*V* measurements. Measurements of the resistivity as a function of *c*-axis magnetic field, shown

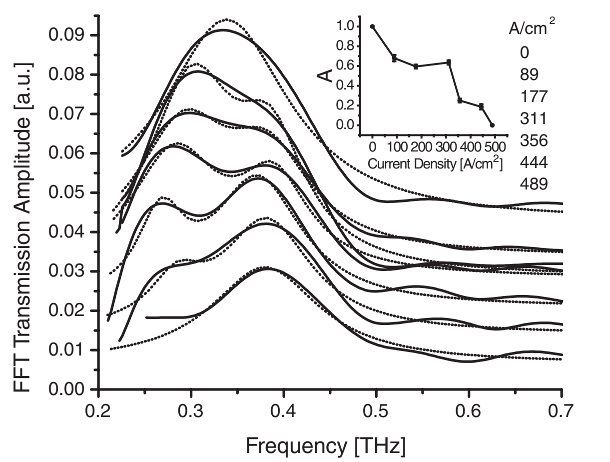

FIG. 4. FFT transmission amplitude at 90 K at increasing applied *ab*-plane current density in Tl-2212 in 2.5 kG *c*-axis magnetic field. The dotted lines are fits using two Lorentzian functions for the two JPR's (One Lorentzian Function at 0, 489 A/cm^2 for one JPR). The plots are displaced vertically for clarity with decreasing current densities. The inset shows the dominance of the lower to the higher JPR (see text).

in Fig. 3(b), reveal that the true flux-flow state where all vortices are depinned and free to move (linear regime where $\rho \propto H$) is first reached at much higher fields than 2.5 kG. The true flux-flow state is thus not a prerequisite for the phenomena of improved longitudinal ordering in the pinned liquid phase with increasing current.

Our experimental results for W_c shown in Fig. 2 agree qualitatively with theoretical simulations of $W_c(J)$ for a two coupled layered system as described in Ref. [1]. However, a quantitative comparison is not possible because our dynamic c-axis ordering occurs in the liquid phase, which has not yet been studied theoretically.

Figure 4 shows the JPR at 90 K at various current densities applied to the ab-plane. The JPR is seen first to drop in frequency with increasing current where after a second JPR develops at a higher frequency. At higher currents the first JPR then disappears and the higher lying JPR increases slightly, which is consistent with a longitudinally more ordered state where vortex-vortex interactions dominate. The two observed JPR's are seen to fit well to two Lorentzian functions as shown in Fig. 4. The normalized amplitudes for the two Lorentzian fitting functions, A, $1 - A$, corresponding to the lower, higher lying JPR's, respectively, are shown in the inset to Fig. 4. The observation of two JPR's at different frequencies indicates the existence of two different phases of different ordering at the crossover point. This same behavior is also observed at 80 K (still in the vortex liquid phase), but not at 10 and 60 K (in the vortex solid phase). The observed behavior at 80 and 90 K might be due to inhomogeneities of the film where some regions have stronger pinning than other regions. In the regions with stronger pinning, the vortex lattice would be moving slower, thus giving rise to a JPR with a lower frequency. However, two JPR's are not observed at any current at 10 and 60 K, suggesting that this is an intrinsic effect related to the longitudinal reordering.

In summary, we have measured the JPR in Tl-2212 thin films using THz-TDS in transmission. We used the JPR frequency measurements to study the interlayer phase coherence in a 2.5 kG c-axis magnetic field as a function of temperature and applied current in the ab-plane. Our results indicate that, when driving the vortex lattice with increasing current at lower temperatures (10 and 60 K), the interlayer coupling decreases in the vortex solid phase. However, at higher temperatures, in the vortex liquid phase (80 and 90 K), the decoupling-coupling crossover takes place as the current increases in qualitative agreement with theoretical results [1]. We find that it is not a prerequisite to reach the true flux-flow state in order to observe improved longitudinal ordering in the pinned liquid phase. Furthermore, at both 80 and 90 K, two JPR's are observed for the same applied currents, indicative of two coexisting phases of different ordering at the point where the current-driven vortex lattice enters a longitudinally more ordered state with increasing current.

We thank Superconductivity Technologies Inc. for providing the Tl-2212 thin films. This research was supported by the UC Campus-Laboratory Collaborations and by the Los Alamos LDRD Program by the US DOE.

[1] I. Aranson, A. Koshelev, and V. Vinokur, Phys. Rev. B **56**, 5136 (1997).
[2] A. E. Koshelev and V. M. Vinokur, Phys. Rev. Lett. **73**, 3580 (1994).
[3] L. Balents and M. P. A. Fisher, Phys. Rev. Lett. **75**, 4270 (1995).
[4] T. Giamarchi and P. Le Doussal, Phys. Rev. Lett. **76**, 3408 (1996).
[5] K. Moon, R. T. Scalettar, and G. T. Zimányi, Phys. Rev. Lett. **77**, 2778 (1996).
[6] M. C. Hellerqvist *et al.*, Phys. Rev. Lett. **76**, 4022 (1996).
[7] S. Ryu *et al.*, Phys. Rev. Lett. **77**, 5114 (1996).
[8] S. Bhattacharya and M. J. Higgins, Phys. Rev. Lett. **70**, 2617 (1993).
[9] J. A. Fendrich *et al.*, Phys. Rev. Lett. **77**, 2073 (1996).
[10] R. Besseling *et al.*, Phys. Rev. Lett. **91**, 177002 (2003).
[11] U. Yaron *et al.*, Phys. Rev. Lett. **73**, 2748 (1994).
[12] M. Marchevsky *et al.*, Phys. Rev. Lett. **75**, 2400 (1995).
[13] E. Rodríguez *et al.*, Phys. Rev. Lett. **71**, 3375 (1993).
[14] G. Blatter *et al.*, Rev. Mod. Phys. **66**, 1125 (1994).
[15] B. Khaykovich *et al.*, Phys. Rev. Lett. **76**, 2555 (1996).
[16] H. Safar *et al.*, Phys. Rev. Lett. **72**, 1272 (1994); Yu. Eltsev and Ö. Rapp, *ibid.* **75**, 2446 (1995); A. Pautrat *et al.*, Phys. Rev. B **59**, 199 (1999).
[17] A. Schilling *et al.*, Nature (London) **382**, 791 (1996).
[18] J. R. Clem, Phys. Rev. B **43**, 7837 (1991); K. B. Efetov, Sov. Phys. JETP **49**, 905 (1979); S. N. Artemenko and A. N. Kruglov, Phys. Lett. A **143**, 485 (1990).
[19] V. K. Thorsmølle *et al.*, Phys. Rev. B **66**, 012519 (2002).
[20] A. B. Kolton, D. Domínguez, and N. Grønbech-Jensen, Physica C (Amsterdam) **341–348**, 1007 (2000).
[21] M. B. Gaifullin *et al.*, Phys. Rev. Lett. **84**, 2945 (2000).
[22] V. K. Thorsmølle *et al.*, Opt. Lett. **26**, 1292 (2001).
[23] M. B. Gaifullin *et al.*, Phys. Rev. Lett. **83**, 3928 (1999).
[24] A. E. Koshelev *et al.*, Phys. Rev. B **62**, 14 403 (2000).
[25] R. D. Averitt *et al.*, J. Opt. Soc. Am. B **17**, 327 (2000).
[26] Y. Matsuda *et al.*, Phys. Rev. Lett. **78**, 1972 (1997).