Mapping the dynamic interactions between vortex species in highly anisotropic superconductors

M Tesei¹, G K Perkins¹, A D Caplin¹, L F Cohen¹ and T Tamegai²

¹ The Blackett Laboratory, Imperial College, London SW7 2BZ, UK
² Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

E-mail: m.tesei@imperial.ac.uk

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Abstract
Here we use highly sensitive magnetization measurements performed using a Hall probe sensor on single crystals of highly anisotropic high temperature superconductors Bi₂Sr₂CaCu₂O₈ to study the dynamic interactions between the two species of vortices that exist in such superconductors. We observe a remarkable and clearly delineated high temperature regime that mirrors the underlying vortex phase diagram. Our results map out the parameter space over which these dynamic interaction processes can be used to create vortex ratchets, pumps and other fluxonic devices.

1. Introduction

The controlled manipulation of flux quanta (known as vortices or fluxons) within superconductors has recently been proposed as the basis for an entirely new class of devices [1]. Collectively known as fluxonics, applications are far-reaching. Examples include rapid single flux quantum (RSFQ) logic devices for high speed computing and quantum computing, the control of many-body flux distributions in flux optics devices (flux lenses), as well as flux ratchets and pumps that could be used to disperse/concentrate flux in fluxonic nanodevices. There has been significant progress theoretically, particularly by molecular dynamics computer simulations [2, 3]. It has been hypothesized [1] that in certain anisotropic layered superconductors such as Bi₂Sr₂CaCu₂O₈ the dragging interactions between two separate families of fluxons, Josephson vortices (JVs) and stacks of pancake vortices (PVs), that are known to co-exist in such materials [4–6] could be used to manipulate the flux, thereby circumventing the need for complex nanofabrication in the devices. Experimental progress has been slow, although flux imaging experiments have shown that there is a significant static interaction between the two systems [5], and recently there has been encouraging evidence of flux ratcheting effects closely resembling predictions [7]. However, the nature of the dynamic interactions is poorly understood and little studied [8]. The present paper demonstrates that the interactions between PVs and JVs are complex and show several different regimes of behaviour due in part to the complexity of the underlying vortex phase diagram in this material. Our experimental results can be used to set out the anticipated parameter ranges (field, temperature, frequency) for optimum fluxonics device performance.

2. Experimental technique

Bi₂Sr₂CaCu₂O₈ single crystals (Tc ≈ 91 K determined by magnetization measurement with temperature, size ≈ 1 × 1 mm²) were grown by floating-zone technique, for more details see [9]. The crystals are exposed to a DC perpendicular (to the crystallographic ab-planes) magnetic field Hₐ that is aligned parallel to the ab-planes of the crystal. The perpendicular magnetization, associated with PVs, is monitored using an InSb Hall sensor (Te-doped 2 μm thick InSb on GaAs wafer) of active area 100 × 100 μm² and positioned above the centre of the sample.

2.1. Lensing

For DC dragging interaction experiments we use a DC magnetic field Hₐ that is aligned parallel to the ab-planes of the crystal. For these experiments the sensor is driven by an AC current of 20 mA (rms) at 2 kHz, with a noise threshold of 3 mG Hz⁻¹/². The background magnetic induction Bₐ is
2.2. Dynamic interactions

The second harmonic detection technique involves exciting the sample with a superimposed AC (sinusoidal) magnetic field \( H_{ab}^{AC} \) aligned with the sample plane, of maximum amplitude 2 Oe and frequency \( \omega/2\pi \), which drives JVs through the sample. The technique relies on the fact that the dragging interactions are symmetric with respect to the sign of the \( ab \) plane field as discussed above. It then follows directly that the dragging forces do not depend on \( JV \) vorticity and the time dependence of the driving force is given by the absolute value of the sinusoidal excitation, \( |H_{ab}^{AC}| \). Simply speaking this means that moving JVs into (or out of) the sample produces the same effect on the pancake vortices as moving anti-JVs in (or out). Such a driving force \( \sim|H_{ab}^{AC}| \) is similar to an excitation field \( H_{ab}^{AC} \) at twice the frequency \( 2\omega \) (or \( \pi/2 \) [8]). Thus the output from the Hall sensor (which is driven now by a DC current), is locked on the second harmonic (2\( \omega \)) response \( B'' \) at zero in-plane DC field (\( H_{ab} = 0 \)) and we use the quadrature component at \( 2\omega \), \( B'' \), to measure the JV–PV interactions. \( B'' \) is monitored while sweeping the temperature or the excitation frequency \( \omega/2\pi \). When measuring the response as a function of \( H_z \), the sample is zero-field cooled and then \( H_z \) is swept from zero (residual field) to positive and negative fields. Since we measure the second harmonic response, residual pick-up associated with the first harmonic is rejected and the noise threshold is two orders of magnitude smaller, of the order of 10 \( \mu G \) Hz\(^{-1/2} \).

3. Results and discussion

To demonstrate the sensitivity of the second harmonic technique we first show that it is able to capture the onset of the formation of the crossing lattice, i.e. the formation of separate JVs and PVs states. This onset field has only been measured previously by Hall probe microscopy [5], and it is consistent with our measurements. Figure 1 shows the variation of \( B'' \) with \( H_{ab}^{AC} \) for several temperatures. As can be seen in the figure, there is a temperature-independent (within the measurement noise) minimum amplitude \( H_{ab}^{AC} \leq 0.7 \) Oe to drive the PVs (for \( H_z = 8 \) Oe) with the amplitude of the Josephson oscillations. This is the threshold where the separate lattice states are formed. In our second harmonic technique we do not want to overly disturb the system and consequently we use a relatively small \( H_{ab}^{AC} \) field of 2 Oe amplitude for most of the experiments described here to act as a minor perturbation only. Having set up the parameters for the experiment we are able to characterize the vortex interactions as a function of temperature, pancake density and AC frequency.

Figure 2 shows the evolution of \( B'' \) whilst field cooling the sample from above \( T_c \). We use two values of the perpendicular magnetic field, \( H_z = 6 \) Oe and the residual ambient field \( H_{ZRES} = -0.4 \) Oe. We observe two quite distinct regimes of behaviour. A quite remarkable sharp peak close to \( T_c \) and a broad bump that extends approximately between \( T = 65 \) and 85 K. The bump grows from zero field to reach a maximum close to \( H_z = 6 \) Oe, for a temperature close to \( T = 80 \) K. The sharp peak has a maximum at a temperature \( T_p \) which is weakly field-dependent (see upper inset to figure 2), and the full-width at half-maximum FWHM broadens (linearly) with field (see lower inset to figure 2).

Figure 3 establishes the sharp dependence of the response on PV density, as the field dependence of the two features
is explored by sweeping $H_z$ at particular temperatures, in the bump region and close to the peak maximum. The dependence is similar for both features, showing an optimum pancake density for which the response is maximal. For a specific temperature and perpendicular field, we also find that the PV–JV interaction drops for frequencies above $\approx 1$ kHz, as shown in the inset of figure 3. It is important to stress that here PVs are vibrating close to their equilibrium lattice sites (whereas in a ratchet experiment when pancake vortices are dragged macroscopic distances, high frequency interactions could be impeded still further [7]).

There are likely to be several mechanisms at play in these experiments including the temperature and field dependence of the pancake lattice stiffness and the role of pinning. The bump feature is likely to be a direct measure of the strength of the interaction between JVs and PVs, the interaction vanishing at zero field (no PVs), and being limited when the PV repulsion dominates over the dragging interaction at higher fields. The coupling between the two vortex species increases as the temperature is lowered and becomes arrested, at low temperature, when vortex pinning is so strong as to prevent PV motion. Clues about the enhanced response just below $T_c$ comes from the field dependence of the peak whose temperature $T_p$ drops at higher pancake densities. The $T_p$ versus $H_z$ curve mimics the vortex melting line observed in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals [12] and clearly the interaction between the two species of vortices is affected by the process of melting. We can tentatively associate $T_p$ with the softening of the pancake lattice just before the lattice melts. Above the melting line the pancake vortices behave in a liquid state and are free to move independently in response to the JV driving force. Below the melting line the interaction strength between the two sublattices may be too weak for us to observe any signature of interaction until the crystal is cooled further down in temperature. Interestingly two distinct peaks were previously observed in the temperature behaviour of the microwave absorption in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ crystals and attributed to two exotic collective modes of the Josephson plasma resonance associated with interaction with pancake vortices [13]. However, as we do not observe any shift of the peak feature with temperature when changing the frequency of the AC oscillation by two orders of magnitude, this strongly suggests that our observations are unlikely related to a coherent collective plasma like resonance in the system.

Figure 2. Temperature dependence of second harmonic quadrature component $B''_2$ measured at (a) $H_z = 6$ Oe and at (b) residual negative field $H_{\text{RES}}^z = -0.4$ Oe with excitation amplitude $H_{\text{AC}}^z = 2$ Oe and frequency $\omega/2\pi = 120$ Hz. Upper inset: effect of $H_z$ on peak temperature ($T_p$). Lower inset: evolution of the full-width at half-maximum (FWHM), illustrated with horizontal arrows, as a function of $H_z$.

Figure 3. Quadrature component of the second harmonic signal $B''_2$ measured with an excitation amplitude $H_{\text{AC}}^z = 2$ Oe, and (a) frequency $\omega/2\pi = 1$ kHz at $T = 83$ K and (b) $\omega/2\pi = 120$ Hz at $T = 88$ K as a function of $H_z$ swept from positive to negative values starting at residual field. Arrows indicate field direction. Inset: frequency dependence of $B''_2$ at $T = 83$ K and for $H_z = 8$ Oe. The line is a guide for the eye.
4. Conclusions

In this paper we confirm the existence of DC lensing by monitoring the change in PV density induced by manipulation of JVs. These observations stimulated us to use the highly sensitive second harmonic method to chart the strength of the PV–JV interactions as a function of temperature and field. We have observed an unexpected and striking regime, very close to the critical temperature, where these interactions are enhanced. These results aid our understanding of how the JVs might be used for lensing and also, by extension, for the manipulation of PVs in ratcheting experiments. These very sensitive measurements of the dynamic interactions yield the optimum temperature and magnetic field conditions as well as frequency range for the strongest coupling.

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References

[1] Savel’ev S and Nori F 2002 Experimentally realizable devices for controlling the motion of magnetic flux quanta in anisotropic superconductors Nat. Mater. 1 179–84
[2] Olson C J, Reichhardt C, Janko B and Nori F 2001 Collective interaction-driven ratchet for transporting flux quanta Phys. Rev. Lett. 87 177002
[3] Wambaugh J F, Reichhardt C, Olson C J, Marchesoni F and Nori F 1999 Superconducting fluxon pumps and lenses Phys. Rev. Lett. 83 5106–9
[4] Bending S J and Hodgson M J W 2005 Vortex chains in anisotropic superconductors J. Phys.: Condens. Matter 17 R855–93
[5] Grigorenko A, Bending S J, Tamegai T, Ooi S and Henini M A 2001 A one-dimensional chain state of vortex matter Nature 414 728–31
[6] Koshelev A E 1999 Crossing lattices, vortex chains, and angular dependence of melting line in layered superconductors Phys. Rev. Lett. 83 187–90
[7] Cole D, Bending S J, Savel’ev S, Grigorenko A, Tamegai T and Nori F 2006 Ratchet without spatial asymmetry for controlling the motion of magnetic flux quanta using time-asymmetric drives Nat. Mater. 5 305–11
[8] Perkins G K, Caplin A D and Cohen L F 2005 Dynamic interactions between pancake vortex stacks and Josephson vortices in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ single crystals: relaxation and ratchets Supercond. Sci. Technol. 18 1290–3
[9] Ooi S, Shibauchi T and Tamegai T 1998 Evolution of vortex phase diagram with oxygen-doping in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ single crystals Physica C 302 339–45
[10] Cole D, Bending S J, Savel’ev S, Tamegai T and Nori F 2006 Manipulation of magnetic-flux landscapes in superconducting Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ crystals Europhys. Lett. 76 1151–7
[11] Tamegai T, Chiku H, Aoki H and Tokunaga M 2006 Visualization and control of vortex chains in highly anisotropic superconductors Physica C 437 314–8
[12] Khaykovich B, Zeldov E, Majer D, Li T W, Kes P H and Konczykowski M 1996 Vortex-lattice phase transitions in Bi$_2$Sr$_2$CaCu$_2$O$_y$ crystals with different oxygen stoichiometry Phys. Rev. Lett. 76 2555–8
[13] Kakeya I, Wada T, Nakamura R and Kadokawa K 2005 Two phase collective modes in a Josephson vortex lattice in the intrinsic Josephson junction Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ Phys. Rev. B 72 014540