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Nanomechanics of an individual vortex in a type-II superconductor

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ABSTRACT

The theory is presented for a recent experiment that uses a magnetic force microscope not only to image but also to move and deform an individual vortex line in an YBCO type-II superconductor. Anisotropic pinning and curving of the vortex line are accounted for.

Recently [1] magnetic force microscopy (MFM) was employed to image and manipulate individual vortices in a single crystal $YBa_2Cu_3O_{6.991}$, directly measuring the interaction of a moving vortex with the local pinning potential. When the magnetic tip of the MFM, kept at a height $Z = 0.08$ μm above the surface $z = 0$, was oscillated along x and moved slowly along y, individual vortices were dragged such that their ends at $(x_0,\ y_0,\ z = 0)$ performed a zigzag path that filled an approximately elliptical area stretched along y. Thus, the excursion of the vortex end perpendicular to the oscillation was much larger than the amplitude of the vortex oscillations. This strongly anisotropic response can be understood as follows; for details see [2].

Consider a single vortex of shape $x(z),\ y(z)$ inside a superconducting half space $z \leqslant 0$. The magnetic tip at position (X, Y, Z) may be modelled as a magnetic monopole that exerts an attractive force $\mathbf{F}(X - x_0, Y - y_0, Z) = (F_x, F_y, F_z)$ on the vortex end which may be approximated as a monopole of strength $2\Phi_0/\mu_0$ located at a depth λ [3]. The dragging force density on the vortex is modelled as $\mathbf{f}(x, y, z) = (F_x, F_y)\exp(z/\lambda)/\lambda$ where $\lambda \approx \lambda_{ab} = \sqrt{\lambda_a\lambda_b}$ is the in-plane London penetration depth. For YBCO we assume an anisotropy in the crystalline ab-plane $\zeta = \lambda_a/\lambda_b = 1.3$ and an $\epsilon = \lambda_{ab}/\lambda_c \ll 1$. Initially, at times $t \leqslant 0$ the vortex is straight and pinned at $x = y = 0$. The attractive monopole–monopole force of the tip acting near the vortex end depins and curves the upper section of the vortex such that each vortex segment is in equilibrium, i.e., the sum of the densities of the dragging force, of the pinning force, and of the elastic restoring force from the vortex line tension, is zero at all z.

At small tilt angles and in the limit $\lambda \to 0$ the resulting vortex shape is composed of parabolic sections depending on the previous history. Finite λ causes the vortex to end perpendicular at the surface $z = 0$. At larger tilt angles, detailed theory [4] shows that the critical force up to which the vortex remains in equilibrium depends on the angle of the vortex tilt and in general does not coincide with the pinning force even in uniaxial superconductors. This nonlinear effect together with the material anisotropy $\zeta > 1$ enhances the observed anisotropy of the vortex response during wiggling.

Two examples of this vortex wiggling are shown in Figs. 1 and 2 for $\lambda = 0.2$ μm, $\zeta = 1.3$. In Fig. 1 the tip starts its oscillating motion at $X = Y = 0$. The vortex end follows with some delay on a zigzag path to a maximum y, then recedes to smaller y and comes to a halt when the tip is too far away. The ratio of the maximum excursions of the vortex end, $r = \max(y_0)/\max(x_0) = 1.19/0.313 = 3.80$ is large since the x wiggling helps to depin the vortex line along y. This effect is similar to the "longitudinal vortex shaking" of [5]. It results in a large straight section in the depicted widest profile $y(z)$, which means that the y component of the pinning force has relaxed to zero. The profiles $x(z)$ do not exhibit such a straight section, and their depinned section $|x(z)| > 0$ penetrates less deep than the section $|y(z)| > 0$. At depths $z \leqslant z_0 = -1.1$ the vortex remains pinned at $x = y = 0$ at all times. For isotropic pinning with $\zeta = 1$ we obtain for the same input parameters the aspect ratio $r = 2.2$, and for large anisotropy $\zeta = 1.5$ we find $r = 5.5$. In Fig. 2 the oscillating tip approaches the vortex from large positive Y, goes

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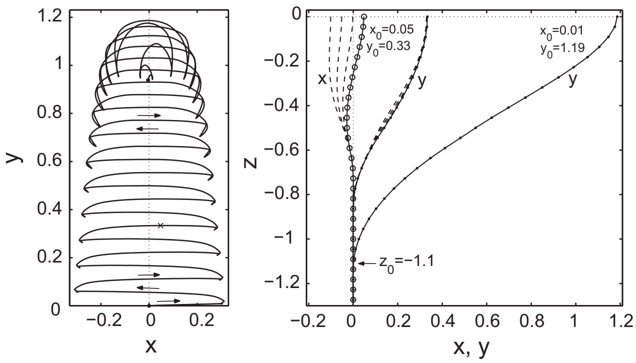

Fig. 1. Left: The zigzag path $x_0(t),\ y_0(t)$ of the vortex end at the surface $z = 0$ when the magnetic tip is oscillated at a height Z above the surface between $X = -a$ and $X = +a$ and slowly moves from $Y = 0$ to higher Y. Here $Z + \lambda = 0.44,\ a = 1.6,\ \max(x_0) = 0.313$, all lengths in µm. Right: The vortex shape expressed as $x(z)$ (solid line with circles) and $y(z)$ (solid line with dots) at the two moments when in the left plot $x_0 = 0.05,\ y_0 = 0.33$ (marked by a cross) and when the maximum $y_0 = 1.19$ is reached near $x_0 = 0$. The dashed lines show $x(z)$ and $y(z)$ at three previous times. At $z \leqslant z_0 = -1.1$ one has $x = y = 0$.

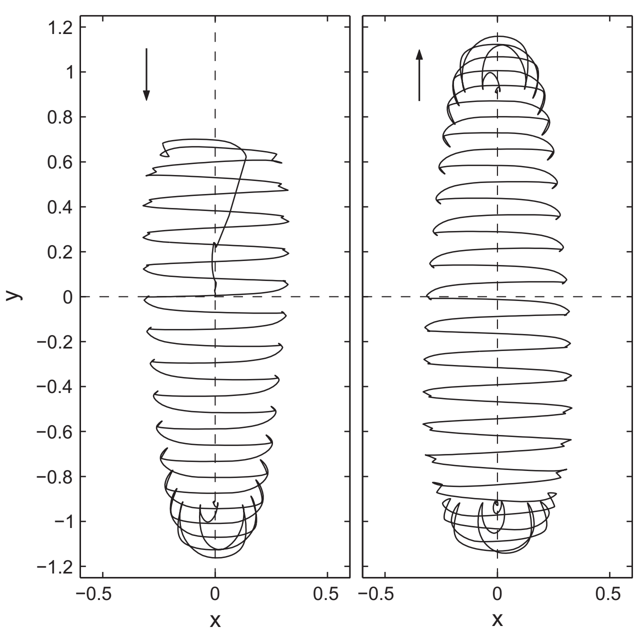

Fig. 2. Path of the vortex end when the tip oscillates along x with large amplitude and moves down from large positive $Y \geqslant 2$ (in µm) to large negative $Y \leqslant -2$ (left plot) and then moves up again to large positive $Y \geqslant 2$ (right plot). A pinned straight vortex waits at $x = y = 0$. When the tip approaches from above, the vortex end suddenly jumps towards the tip and starts to oscillate with large amplitude, following the tip downwards until it comes to a halt as in Fig. 1. When the oscillating tip approaches again from below, the vortex end starts to oscillate again along a path that looks similar to the path on which the vortex end came to a halt.

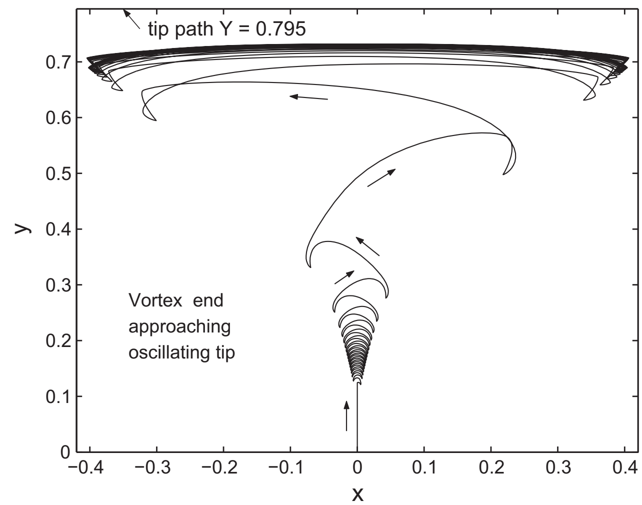

Fig. 3. Attraction of the vortex end $(x_0,\ y_0)$ to a tip that oscillates with large amplitude along the straight line $Y = 0.795$ (in µm, see also Fig. 12 of [2] in which $Y = 0.80$, else same parameters) starting from $X = 0$ at time $t = 0$. When the tip approaches the starting point from large positive Y, the vortex end jumps to $y_0 \approx 0.11$, attracted by the tip. At $t > 0$ the vortex end oscillates along x with small increasing amplitude, slowly moving to higher y values. When $y_0 \approx 0.3$ is reached the vortex end jumps in a few big leaps to its maximum $y_0 \approx 0.73$. After that it oscillates on a stationary curve.

to large negative Y, and returns. The resulting path of the vortex end looks similar as in the experiments [1].

Fig. 3 shows how the vortex end approaches a magnetic tip that oscillates along a straight line. This path again looks similar as in the experiments [2]. For previous MFM manipulation of vortices see [6].

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