Comment on "Flux Line Matching Effects in $YBa_2Cu_3O_{7-x}$ Thin Films"

Recently Hünnekes *et al.* [1] have shown intriguing maxima in the magnetic field dependence of the damping of an oscillating $YBa_2Cu_3O_{7-x}$ thin film when the field is applied in the a-b plane. They attribute these maxima to a matching effect of the in-plane flux line (FL) lattice with the sample thickness, similar to that proposed by Brongersma *et al.* [2]. The field at which the Nth maximum $H(N)$ occurs is given by

$$H(N) \simeq (\Phi_0/\mu_0\Gamma)[(N/t)^2], \tag{1}$$

where Φ_0 is the flux quantum, Γ the anisotropy parameter, and t the total thickness of the film. It should be realized that this expression is valid only for large N since in its derivation the flux in a vortex, instead of the fluxoid, is assumed to equal Φ_0. This is clearly not the case in thin samples containing only a few vortex chains because of the supercurrents contribution to the fluxoid. The actual flux through an in-plane vortex in a thin film [2] (derived in Ref. [3] with more detail) is

$$\Phi(x_0) = (\Phi_0 t^2/8\lambda^2)(1 - 4x_0^2/t^2), \tag{2}$$

where x_0 is the vortex coordinate along the c axis, limited by $-t/2 < x_0 < t/2$.

As the authors realize that Eq. (1) does not account for all the observed features, they propose that "Detailed calculations of the FL arrangement in thin films similar to those performed in Ref. [2] may help to get a better understanding of these effects." We have performed such calculations for their thinnest film ($t = 43$ nm), with $\xi_{ab} = 0.5$ nm and $\Gamma = 5$, using Eq. (5) in Ref. [2] for the free energy of a vortex lattice in a sample with a thickness smaller than the penetration depth. We find that the first peak occurs at $H_{c1\parallel}$, where the first chain of in-plane vortices enter the sample. The formation of the second and third chains results in two maxima at $H(2)/H_{c1\parallel} = 2.2$ and $H(3)/H_{c1\parallel} = 4.5$, respectively. Because the positions of the maxima depend only logarithmically on t/ξ_{ab}, they cannot be understood within this model.

Moreover, not only the ratios but also the absolute values disagree with the calculated data. In the theory of Ref. [2] all fields $H(N)$ are expressed in units of $H_{c1\parallel}$. The authors [1] state that $\mu_0 H_{c1\parallel} = 25$ mT and refer to Ref. [4]. This is, however, the value for a "bulk" single crystal with a thickness $t = 25\ \mu$m, much larger than $\lambda_{ab} = 170$ nm. For their thin film, with $t = 43$ nm, the thickness is significantly smaller than λ_{ab}, and $\mu_0 H_{c1\parallel}(\lambda_{ab} \gg t) \simeq (2\Phi_0/\pi t^2\Gamma)\ln(t/\xi_c)$ instead of the smaller bulk value $\mu_0 H_{c1\parallel}(\lambda_{ab} \ll t) = (\Phi_0/4\pi\lambda_{ab}\lambda_c)\ln(\lambda_{ab}/\xi_c)$ [5]. For $t = 43$ nm and $\xi_{ab} = 0.5$ nm, we find $\mu_0 H_{c1\parallel} = 0.56$ T [5] implying that the first maximum in Fig. 1 of Ref. [1] is observed well below the actual $H_{c1\parallel}$ for which an in-plane vortex lattice cannot exist.

We also calculated $H(N)$ for the film with $t = 270$ nm, and found $H(2)/H_{c1\parallel} = 2.0$ and $H(3)/H_{c1\parallel} = 3.6$ where $\mu_0 H_{c1\parallel} = 25$ mT. Since the theory in Ref. [2] is developed for the case $\lambda > t$, these results can be used for a rough approximation only. In terms of this model it is, however, evident that one expects a peak whenever a new chain of vortices is formed. We see no mechanism leading to so-called "additional selection rules" that would result in maxima at $H(N = 6, 8, 11)$ only. It would imply that the entering of the first few chains, which cause the largest rearrangements of the vortex lattice, has virtually no effect while the transition from six to seven rows would suddenly result in a peak in the damping.

Finally we would like to point out that the double-chain vortex lattice depicted in Fig. 3 of [1] does not correspond to the lowest energy configuration, which is a triangular lattice as shown in Fig. 3(c) in Ref. [2]. To justify the assumption of a square lattice, the authors refer to [6] which describes Bitter pattern observations of the vortex lattice with $B \perp c$ ($B < 10$ G) in $YBa_2Cu_3O_{7-x}$ bulk crystals. Clearly this is a different case from the one discussed here (high fields, small thickness), and already it is stated in [6] that "a vortex in a chain aligns with a gap in the next chain" and "When they are not aligned by defects, the chains appear to undulate. . . ."

The arguments given above show, within the anisotropic Ginzburg-Landau theory, that the maxima do not result from rearrangements of in-plane vortices. The correct explanation remains thus unclear but may be sought in the interaction of out-of-plane vortices, that are present even at low fields, with crystal defects. Internal friction experiments on samples where the rearrangements have been observed [2] would be very useful.

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[1] C. Hünnekes, H. G. Bohn, W. Schilling, and H. Schultz, Phys. Rev. Lett. **72**, 2271 (1994).
[2] S. H. Brongersma, E. Verweij, N. J. Koeman, D. G. de Groot, R. Griessen, and B. I. Ivlev, Phys. Rev. Lett. **71**, 2319 (1993).
[3] G. Stejic, A. Gurevich, E. Kadyrov, D. Christen, R. Joynt, and D. C. Larbalestier, Phys. Rev. B **49**, 1274 (1994).
[4] Y. Yeshurun, A. P. Malozemoff, F. Holtzberg, and T. R. Dinger, Phys. Rev. B **38**, 11 828 (1988).
[5] A. A. Abrikosov, *Fundamentals of the Theory of Metals* (Elsevier, New York, 1988), p. 444. The values are calculated using the exact equation (18.109).
[6] G. J. Dolan, F. Holtzberg, C. Field, and T. R. Dinger, Phys. Rev. Lett. **62**, 2184 (1989).

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