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Vortex Modeling in High-T_c Anisotropic Materials

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The calculation of the electron-optical phase shift experienced by high energy electrons in a transmission electron microscope, when they interact with vortices in high-T_c materials is here presented and discussed. The vortices are pinned to tilted columnar defects induced by ion irradiation in a thin anisotropic material. The obtained results, where the fluxon is described in terms of a pancake model [1] show that not only pinned vortices can be distinguished from unpinned ones, but also that the contrast feature of the images are sensitive to the anisotropy inherent to the model chosen for describing the fluxon [2].

However, apart from the relatively small number of layers, the major criticism that can be raised is that the layers are coupled only through the magnetic field, so Josephson coupling between the layers is neglected. As solving a layered structure with Josephson coupling (which is know as Lawrence-Doniach model [3]) turns out to be very difficult, especially taking into account the finite thickness of the specimen, we have extended our Fourier approach [1,4] to the anisotropic Ginzburg-Landau limit [3].

The corresponding anisotropic London equation for the vector potential has therefore been solved by Fourier methods and by taking into account the boundary conditions at the specimen surfaces with the surrounding vacuum. The obtained expressions, although very cumbersome, are nonetheless analytic in the Fourier representation and allow us to obtain also an analytic result for the Fourier transform of the phase shift, which can be inverted numerically and employed for the simulation of phase-contrast or holographic images.

This model, in addition to the transverse penetration depth λ_{ab} characterizing every superconducting material, introduces a dimensionless anisotropy parameter γ [3], whose value is 1 for the isotropic case, and 200 for the high-T_c materials investigated experimentally [5,6]. It is thus possible to explore how the out-of-focus images are affected by a change of the anisotropy parameter.

Figure 1 reports the results of a series of out-of-focus and holographic images calculated for a columnar defect angle of 60° and for increasing values of γ, from 1 (a), to 5 (b) to 200 (c). The last value is practically coincident with infinity and corresponds to the pancake model, reported in (d). The only visible difference between pancake and continuous anisotropic models is a slight deformation of the contrast contour lines. In the pancake simulation (d) the globule appear more enlarged, with respect to (c) which is a continuous anisotropic simulation calculated for the value γ=200. This discrepancy can be explained by the limited number of layers considered.

The practical coincidence between anisotropic and pancake models can be understood by noting that when γ is sufficiently high, the superconducting currents are flowing parallel to the specimen surfaces also in the bulk of the material, thus leading to a progressive vanishing of the corresponding component of the vector potential. The same component is identically zero in the pancake case, as no currents at all can flow bet ween the layers. These results also suggest that improving the model to take into account interlayer coupling is actually not necessary in relation to electron microscopy observations. In fact, the pancake and anisotropic models represent a lower and upp er bound with respect to the Lawrence-Doniach model and they give indistinguishable results for the phase -contrast and holographic images, at least for highly anisotropic materials.

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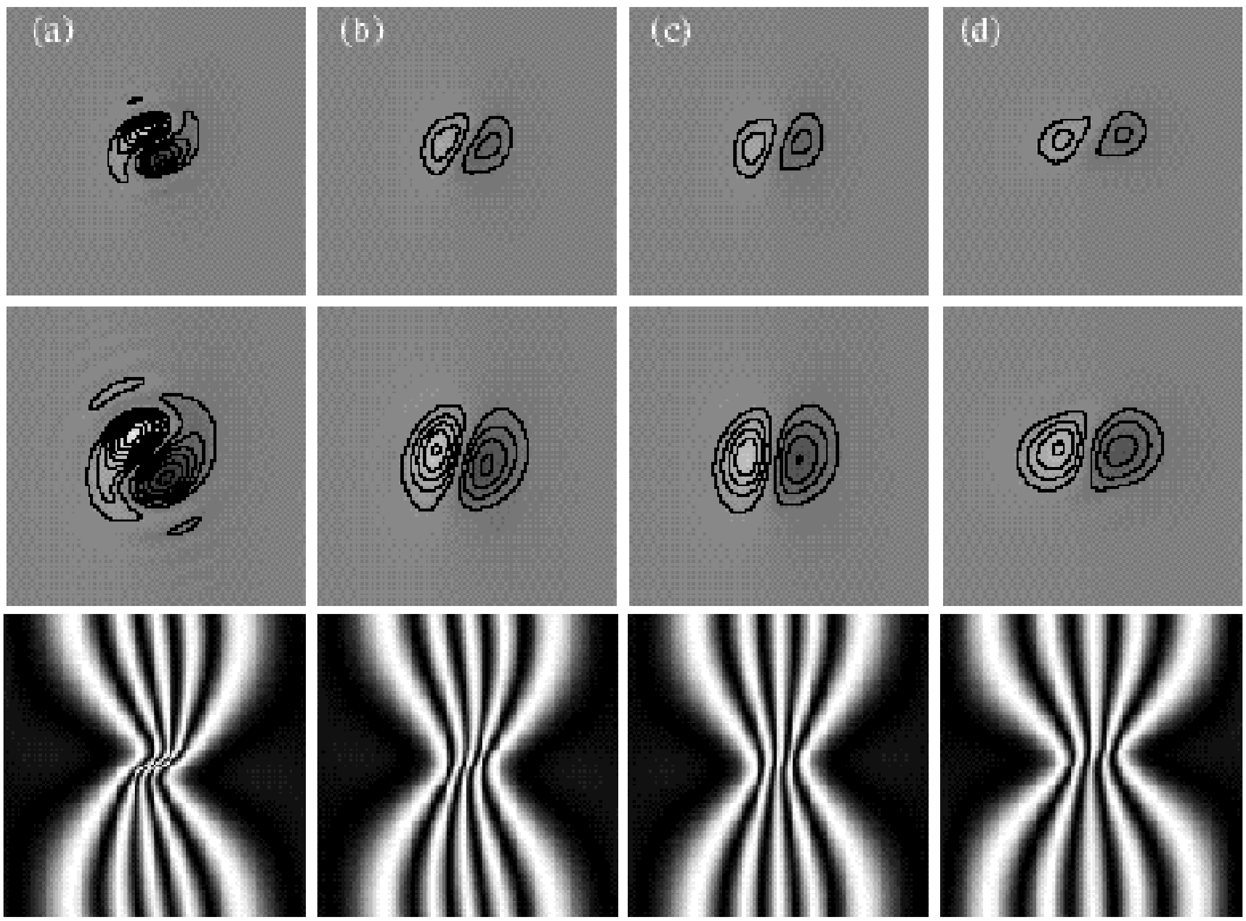

FIG. 1. Out of focus images (defocus distance 200 mm in first row and 500 mm in second row) calculated for γ=1 (a), 5 (b), 200 (c) and infinity (d) corresponding to the pancake model. Third row: holographic contour maps, 32x amplified. The square size is 4 μm, the transverse penetration depth was assumed to be equal to 200 nm and the specimen, tilted with respect to beam at 30°, has a thickness of 400 nm.

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