BNL-72268-2004-CP

Comparison between Discrete and Semi-continuous Layered Models of Superconducting Vortices in High T_c Materials for TEM Observations

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In order to interpret Transmission Electron Microscopy observations of superconducting vortices in anisotropic or layered materials we have found the analytical solution for the Fourier transform of the electron optical phase shift for the case of a straight vortex piercing the specimen at arbitrary angle [1]. The layered case suffered from the shortcoming that only a limited number of pancakes; up to 7, is allowed by the discrete approach followed. Seven layers, however, are scarcely representative of the real stack of pancake vortices, especially when the core pierces the specimen at large angles with respect to the specimen normal. In fact, in these conditions, the pancake discrete structure may no longer be buried in the diffraction fringes of the Fresnel image. Moreover, a small number of layers is a limiting factor when more exotic vortex structures with no straight cores are investigated.

This drawback has been overcome by a semi-continuous approach, where each pancake layer is considered singularly, and the discrete structure of the other pancakes is substituted by a superconducting continuous medium that carries supercurrent only parallel to the layers [2], as proposed by Clem [3] and further developed by Coffey and Phipps [4]. The solution for the vector potential has been found by Fourier methods, connecting the general solutions in the vacuum with those in the superconducting regions. The presence of a vortex in the layer is taken into account by considering the layer as an additional superconducting region of negligible thickness. Once the vector potential is found, the electron optical phase shift can be calculated by integrating the vector potential along a straight trajectory suitably chosen in order to take correctly into account the overall geometry of the experimental set-up, including a tilt of the specimen with respect to the electron beam [1].

By this approach the pancake number can be increased by a factor of 2 or 3, resulting in the disappearance of the artifacts linked to the insufficient number of layers. This is shown in the following figures, where case of a vortex piercing the specimen, of thickness 400 nm, at an angle of 85° and lying in the (x,z) plane is considered. Figure 1 displays the trend of the projected magnetic field seen from the y direction for the case of the previous algebraic approach of 7 layers (a), the new semi-continuous one of 15 layers (b) and the anisotropic-continuous model (c). The 32× amplified contour maps of the electron optical phase shift, when the specimen is tilted at 45° with respect to the electron beam, are reported in Figure 2 (a-c) respectively, whereas the out-of-focus images calculated for a defocus of 50 cm, in a high-voltage (1 MV) electron holography microscope are shown in (d-f).

It can be seen that the artifacts due to the insufficient number of layers both in the holographic and out-of-focus images are clearly visible in Figure 2 (a,d). On the contrary the results obtained by the semi-continuous, (b,e), and anisotropic (c,f), approaches are almost indistinguishable, confirming that the second can be considered the limiting case of the first for a very large number of layers. From a practical standpoint, 15 layers are sufficient to reach this limit in the case of a piercing angle of 85°. For larger angles, the number of layers should be increased further.

[1] M. Beleggia et.al.; Phys. Rev. B 66, 174518 (2002).
[2] M. Beleggia, G. Pozzi and A. Tonomura, J. Magn. Magn. Mater. (2004) in press.
[3] J.R. Clem, Phys. Rev. B 43, 7837 (1991); Physica C 235, 2607 (1994).
[4] M.W. Coffey and E. T. Phipps, Phys. Rev. B 53, 389 (1996).

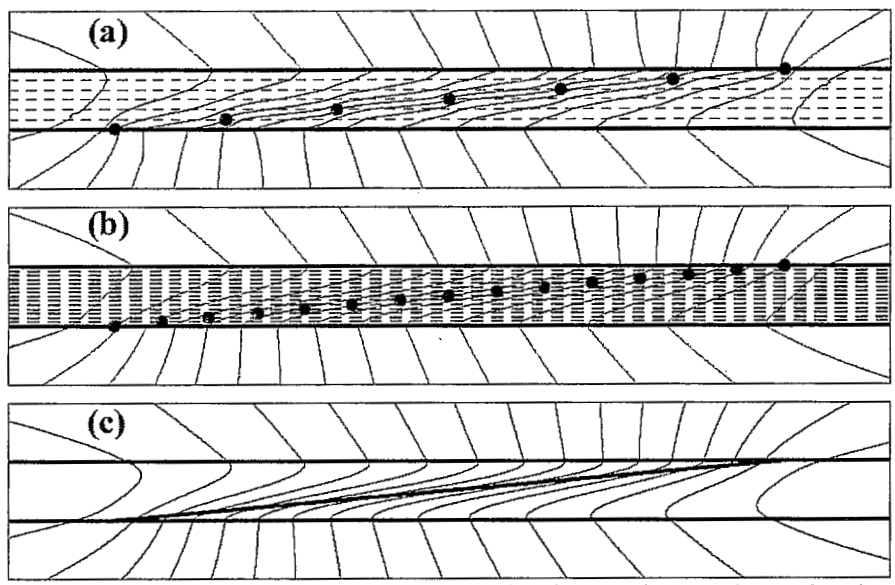

FIG. 1. Projected magnetic induction maps for of a stack of pancake vortices piercing the specimen of thickness 400 nm at 85°. From top to bottom: pancake model with 7 layers, semi-continuous model with 15 layers, continuous-anisotropic model. Each contour line represents a phase variation of $\pi/16$ rad. The image size is 6×1.2 μm and the penetration depth is 200 nm.

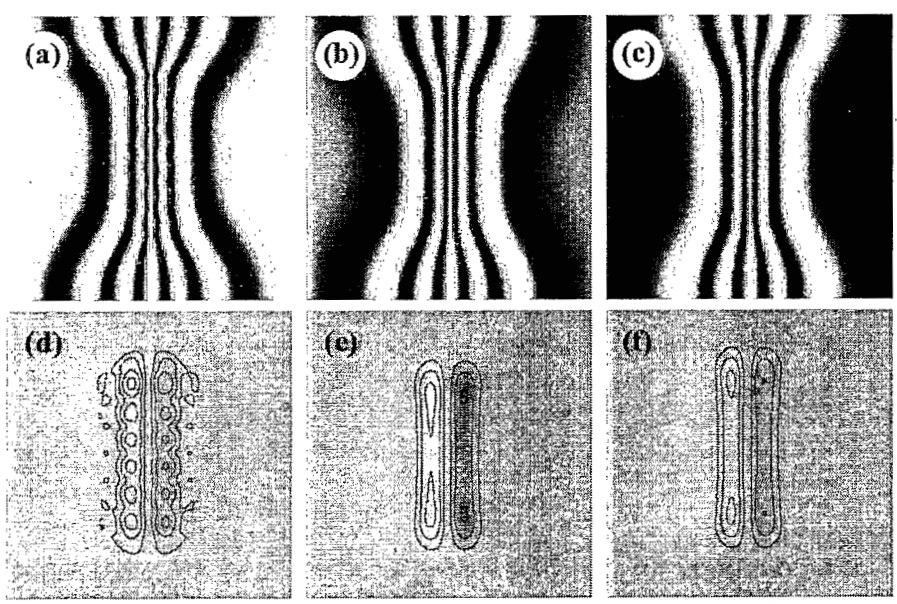

FIG. 2. Holographic cosine maps (a-c, 32× amplified) and Fresnel images (d-e, 50 cm defocus) for the three models developed: pancake (a,d), semi-continuous (b,e) and continuous-anisotropic (c,f). The image size is 6 μm, and each contour line in the out of focus images represents a 3% contrast variation.

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