Scaling of the angular dependence of the critical current density in high-T_c superconductors

G. Jakob, M. Schmitt, Th. Kluge, C. Tomé-Rosa, P. Wagner, Th. Hahn, and H. Adrian

Institut für Festkörperphysik, Technische Hochschule Darmstadt, 6100 Darmstadt, Federal Republic of Germany

(Received 2 December 1992)

We report a general scaling behavior of the dependence of the critical current density $j_c(B,T,\Theta)$ on the direction of the magnetic field at low temperatures in *c*-axis-oriented high-T_c superconductor thin films with different strengths of interlayer coupling. Measurements of $j_c(B,T,\Theta)$ for pure $YBa_2Cu_3O_7$, doped $YBa_2(Cu_{1-x}Zn_x)_3O_7$, $Bi_2Sr_2CaCu_2O_8$, and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattice films with different relative orientations of the current **j**, magnetic field **B**, and crystallographic direction **c** allow the identification of the dissipation caused by flux parallel to the superconducting layers moving in the *c* direction.

I. INTRODUCTION

In $YBa_2Cu_3O_7$ the layered structure results in a spatial modulation of the superconducting order parameter.[1] The absolute value of the order parameter is high in the superconducting CuO_2 planes and low in the CuO chains and BaO layers. This modulation causes a steplike flux-line structure and acts as an intrinsic pinning mechanism against motion of flux-line segments that are parallel to the *ab* plane. Considering twin boundaries as pinning centers which act in the *ab* plane, Tachiki and Takahashi were able to account for the angular dependence of the critical current density parallel to the *ab* plane $j_c^{ab}(B,T,\Theta)$ in magnetic fields **B** applied under an angle Θ to the *c* axis **c** at low temperatures.[2] $Bi_2Sr_2CaCu_2O_8$ shows a much stronger anisotropy than $YBa_2Cu_3O_7$ due to the nonmetallic BiO double layers. The coupling between the superconducting Cu-O planes is mediated by Josephson currents between them. Accordingly, it is described by a Lawrence-Doniach model.[3] Flux penetrating parallel to the layers forms Josephson vortices instead of Abrikosov vortices. For such an essentially two-dimensional (2D) system Kes *et al.* have proposed that the physical properties scale with the magnetic field component perpendicular to the layers.[4] Concerning $j_c^{ab}(B,T,\Theta)$ this scaling was shown by Schmitt *et al.* for $Bi_2Sr_2CaCu_2O_8$ films[5] and by Jakob *et al.* for $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattice films.[6]

In this paper we present measurements of $j_c^{ab}(B,T,\Theta)$ for pure $YBa_2Cu_3O_7$, doped $YBa_2(Cu_{1-x}Zn_x)_3O_7$, $Bi_2Sr_2CaCu_2O_8$, and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattice films. The Zn doping in $YBa_2Cu_3O_7$ introduces additional pointlike pinning centers in the CuO_2 planes but we do not expect a strong influence on the intrinsic pinning mechanism. The anisotropy is enhanced in case of $Bi_2Sr_2CaCu_2O_8$ films and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices.

At low temperatures we find the same scaling for the critical current density $j_c^{ab}(B,T,\Theta) = j_c^{ab}(B\cos\Theta,T,0°)$ for all these different classes of materials. This seems astonishing at first glance. However, we show that this scaling is compatible with the different existing models.

II. EXPERIMENTAL

All high-T_c films investigated in this paper were prepared by high-pressure dc sputtering in pure oxygen atmosphere from stoichiometric targets onto heated (100) $SrTiO_3$ substrates. With only slightly different parameters, this process is able to produce high-quality films of the different high-T_c superconductors. The film preparation, structural characterization, and superconducting properties have been studied in detail [$YBa_2Cu_3O_7$,[7] $YBa_2(Cu_{1-x}Zn_x)_3O_7$,[8,9] $Bi_2Sr_2CaCu_2O_8$,[10] $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices[6,11]]. This paper concentrates on the scaling behavior common to all of these different types of films at low temperature and the specific differences between them at higher temperatures.

For measurements of the critical current density, all films were wet chemically patterned. A criterion of 1 μV was applied along a bar of 10-μm width and 0.1-mm length for the $YBa_2Cu_3O_7$ based films and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices, resulting in an electric field criterion of 100 μV/cm. For the $Bi_2Sr_2CaCu_2O_8$ films the values are 0.2 and 2.0 mm and the corresponding electric field was 5 μV/cm. However, the qualitative behavior of $j_c(\Theta)$ was in no case found to be dependent on this criterion. The films were mounted on a rotatable copper block which allows sample rotation at low temperatures.[9] In all experiments the current direction **j** was parallel to the *ab* plane. The magnetic field dependence of the critical current density was measured for fixed temperatures and magnetic field parallel to the *c* axis $j_c(B,T,0°)$. These measurements provide the data for the scaling curves. In addition, we measured the critical current density at fixed temperatures and at fixed magnetic field strengths as a function of the angle Θ

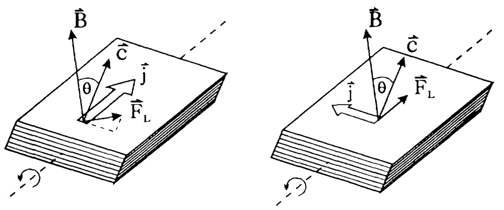

FIG. 1. Sketch of the different geometries used.

between the magnetic field $\mathbf{B}$ and the c axis $\mathbf{c}$. Here we used two different orientations of the current direction with respect to the axis of rotation. Figure 1 shows a sketch of the different geometries. In setup 1 (2) the current $\mathbf{j}$ is parallel (perpendicular) to the axis of rotation and therefore always perpendicular (parallel) to the plane spanned by $\mathbf{B}$ and $\mathbf{c}$. In setup 1 (2) the current direction does not (does) change with respect to the magnetic field direction.

III. RESULTS AND DISCUSSION

The critical current density j_c is reached if the macroscopic Lorentz-force density $\mathbf{f}_L = \mathbf{j} \times \mathbf{B}$ acting on flux lines equals the pinning force density $\mathbf{f}_p$. The Lorentz-force density is given by

$$\mathbf{f}_L^{(1)} = \mathbf{j} \times \mathbf{B} = jB(\sin\Theta \mathbf{e}_c + \cos\Theta \mathbf{e}_{ab}),$$
$$= \mathbf{f}_L^c + \mathbf{f}_L^{ab},$$
$$\mathbf{f}_L^{(2)} = \mathbf{j} \times \mathbf{B} = jB\cos\Theta \mathbf{e}_{ab} = \mathbf{f}_L^{ab},$$

in setup 1 and setup 2, respectively. $\mathbf{e}_c$ and $\mathbf{e}_{ab}$ are unit vectors along the c axis and the ab plane, respectively. For the least anisotropic case of $YBa_2Cu_3O_7$ and $YBa_2(Cu_{1-x}Zn_x)_3O_7$ there exists a steplike penetration of the flux lines through the film at low temperature. For the more anisotropic cases of $Bi_2Sr_2CaCu_2O_8$ and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices there will exist only pancake vortices in a wide temperature range.[12] This allows us to consider the flux motion parallel and perpendicular to the ab planes independently. Accordingly, a dissipation process starts if either the Lorentz-force component along the ab planes equals the in-plane pinning force density ($f_L^{ab}=f_p^{ab}$) or if $f_L^c=f_p^c$. Obviously the conditions are equal for flux motion in the ab plane, whereas flux motion in the c direction can only occur in case 1. Since the relative orientation of the magnetic field and the film is identical for both setups, the flux-line structure which penetrates the film will be identical. Therefore the difference between the measured j_c curves in setup 1 and setup 2 can be directly related to the flux motion in the c direction. Setup 2 will always yield equal or higher values for the critical current density since there is no Lorentz force in the c direction. This consideration predicts equal values for the critical current density measured in both setups if no flux motion in the c direction occurs and flux motion in the ab plane limits the critical current density. The value of $\mathbf{f}_L^{ab}$ is the same as that for a magnetic field of reduced strength $B_{\rm red} = B\cos\Theta$ which is applied parallel to the c axis and therefore a scaling behavior of the critical current density can be expected. Figure 2 shows this scaling behavior

$$j_c^{(1)}(B,T,\Theta) = j_c^{(2)}(B,T,\Theta) = j_c(B\cos\Theta, T, 0°)$$

for a zinc-doped $YBa_2Cu_3O_7$ film measured at reduced temperature $t = T/T_c$=0.13 and $3T$. The curves are nearly identical. Note that we have made no assumptions about the nature of the pinning mechanisms neither in plane nor perpendicular. It is an experimental fact that there is no flux motion in the c direction. In case of $YBa_2Cu_3O_7$ films and $YBa_2(Cu_{1-x}Zn_x)_3O_7$ films, the intrinsic pinning mechanism proposed by Tachiki and Takahashi prevents flux motion in the c direction at low temperatures. The latter authors proposed a pinning mechanism by twin boundaries to be valid in the ab plane. This mechanism results in a typical proportionality $j_c \propto (\cos\Theta)^{-1/2}$ which gives also a good fit to the data. However, the detailed curve form depends on the actual pinning mechanism in the ab plane and the inclusion of pointlike pinning centers as Zn atoms, oxygen vacancies, or screw dislocations besides twin boundaries in the Tachiki model can strongly affect the curve form.[9] The density of these pinning centers, however, is strongly sample dependent and therefore deviations from $j_c \propto (\cos\Theta)^{-1/2}$ are easily understood. If the pinning in the ab plane results from collective pinning of the vortex kinks Pokrovsky *et al.* have shown that one should expect a scaling of the critical current density with the perpendicular field component.[13]

In Fig. 3 we show the scaling of the critical current density $j_c(B,T,\Theta) = j_c(B\cos\Theta, T, 0°)$ for a $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattice film with Y:Pr=10:1 (a) and a high quality $Bi_2Sr_2CaCu_2O_8$ film (b). Note that for the latter the absolute value of the critical current density is higher than 10^6 A/cm^2

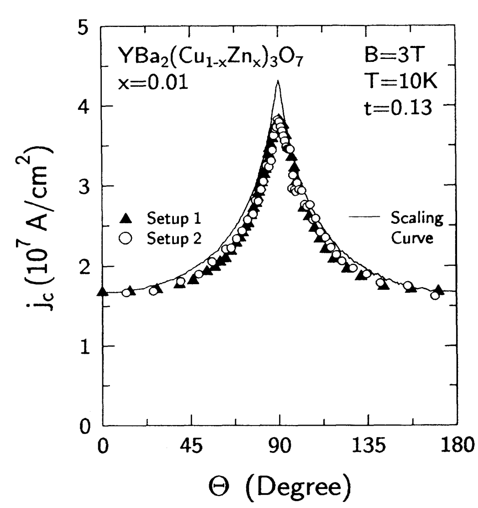

FIG. 2. $j_c^{ab}(3T, 10\,{\rm K}, \Theta)$ for setup 1 (triangles) and setup 2 (circles). For clarity only every third data point is shown. The solid line labeled scaling curve is the critical current density which was measured in a magnetic field parallel to the c axis but with reduced strength $B_{\rm red} = B\cos\Theta$.

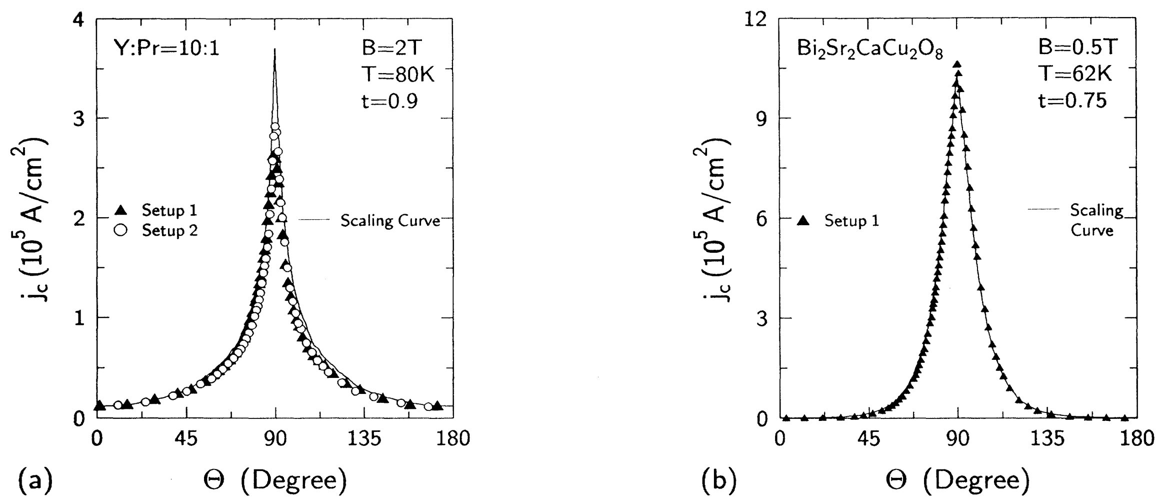

FIG. 3. Scaling of the critical current density for quasi-2D superconductor films. In (a) the data are from a $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattice with $YBa_2Cu_3O_7$ sheets of 10-unit-cell thickness each and decoupling $PrBa_2Cu_3O_7$ sheets of one-unit-cell thickness. The data from a $Bi_2Sr_2CaCu_2O_8$ film at t=0.75 are shown in part (b).

at 62 K. Again no flux motion in the c direction occurs in these cases and the scaling works. The perpendicular component results in pancake vortices or short vortex line segments whereas the parallel component causes Josephson vortices ($Bi_2Sr_2CaCu_2O_8$ or $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices with thin $PrBa_2Cu_3O_7$ sheets) or penetrates without the existence of vortices (decoupled $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattice with thick $PrBa_2Cu_3O_7$ sheets). In any case there are only weak, or no, shielding currents for this field component and therefore it does not influence the critical current density, i.e., these films are magnetically inert against the component of the field parallel to the planes. Near $\Theta = 90°$ there are always deviations from ideal scaling behavior. But they do not necessarily imply flux motion in the c direction. In the more anisotropic systems even small fields parallel to the c axis cause a large suppression of the critical current density. Due to the mosaic spread of the c-axis oriented grains (which is typically 0.3°) it is not possible to orient the whole film exactly parallel to the magnetic field. Therefore some grains will always experience a small perpendicular field component which results in a weak magnetic field dependence of j_c.[5] Furthermore, even if the field is exactly parallel to the layers a spontaneous creation of pairs of vortex kinks or vortex-antivortex pairs can occur. These kinks or vortex-antivortex pairs in the superconducting layers are driven apart by the transport current and cause dissipation.[14] In addition to the kinetic energy of the superconducting transport current, the kinetic energy of the shielding currents surrounding the centers of the flux lines in 3D systems must be taken into account. This is not the case in the quasi-2D systems. Since the total local kinetic energy density is limited by the value of the depairing current, higher fields will result in lower transport current densities. In agreement with this we find better scaling for $B = 3T$ than for $B = 6T$ for the film shown in Fig. 2.

So using the existence of the scaling behavior at low temperature and in moderate magnetic fields we still cannot decide whether the system is better described by a 3D anisotropic Ginzburg-Landau theory or 2D Lawrence-Doniach model. The choice of description depends on the ratio d of the superconducting coherence length in the c direction (ξ_c) to the periodicity of the layer structure D ($d = D/\xi_c$). Since the coherence length diverges at T_c a 3D description must hold near T_c. For low temperatures, however, a Lawrence-Doniach model is certainly appropriate in case of $Bi_2Sr_2CaCu_2O_8$ and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices. This contradiction is resolved by a new model for layered superconductors, that has recently been proposed by Koyama *et al.* which introduces spatially modulated Ginzburg-Landau coefficients.[15] This model can handle interlayer coupling of arbitrary strength and interpolates between the above limiting cases. In their paper the authors show that there is a strong modulation of the order parameter for large values of d which becomes weaker with smaller values of d and higher temperatures. Since only lowest-order Fourier coefficients of the Ginzburg-Landau parameters are used in their model, a quantitative determination of the variation of the intrinsic pinning strength is not possible. Therefore we treat the temperature dependence of the critical current scaling in the following only with qualitative phenomenological arguments. Figure 4 shows the scaling behavior for a pure $YBa_2Cu_3O_7$ film at temperatures of (a) $t = T/T_c$=0.5 and (b) t = 0.85. At low temperatures (t=0.1) we found for this film excellent scaling behavior for both setups. The Θ variation measured in setup 1, however, shows no scaling behavior at t=0.5, though there are still peaks in the critical current density for $\Theta = 90°$. This demonstrates that the intrinsic pinning mechanism still contributes considerably for hindering flux motion. At temperatures near T_c the angular variation of the critical current density with Θ is comparatively small and there is no significant enhancement

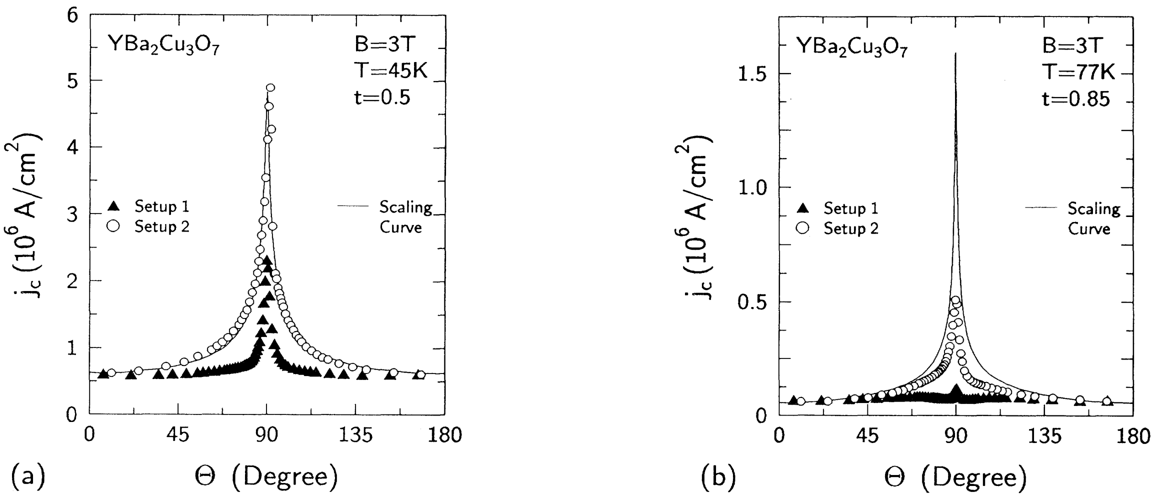

FIG. 4. Scaling behavior for a pure $YBa_2Cu_3O_7$ film at different reduced temperatures (a) $t=T/T_c=0.5$ and (b) $t=0.85$.

for $\Theta = 90°$ compared to the scaling curve. Therefore, we conclude that the intrinsic pinning mechanism is already considerably weakened at t=0.85 for $YBa_2Cu_3O_7$. Since the distance between the CuO planes and CuO chains is 4.1 Å which is of the same order of magnitude as the Ginzburg-Landau coherence length at zero temperature [$\xi_c(0)$=3 Å] even a small increase of $\xi_c(T)$ due to a higher temperature can considerably smear out the modulation of the order parameter along c direction. If we take the approximation $\xi_c(t) = \xi_c(0)/\sqrt{1-t}$ at t=0.85, the coherence length is approximately 8 Å which is larger than the distance between the strong and weak superconducting layers. In agreement with our measurements, one therefore expects no significant intrinsic pinning. In $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices the intrinsic modulation of the superconducting order parameter is much weaker than the extrinsic modulation due to the synthetic structure with superconducting and semiconducting sheets. Here we find an excellent scaling behavior even at t=0.9 (see Fig. 3). Since the $YBa_2Cu_3O_7$ layers are rather thick we find a high value of T_c (89 K). Accordingly the coherence length should not differ too much from the value of pure $YBa_2Cu_3O_7$. But now the distance between the decoupled superconducting CuO planes, that are on top of the nth and on bottom of the (n+1)th $YBa_2Cu_3O_7$ sheet, is (11.7+2·4.1)Å. Even at this high temperature this value is larger than the coherence length and enables strong intrinsic pinning. However, the absolute values of the critical current density are lower than in pure $YBa_2Cu_3O_7$ films. This results from the shorter correlated length of the flux lines which are interrupted by the $PrBa_2Cu_3O_7$ sheets. It is remarkable that even $PrBa_2Cu_3O_7$ sheets of one-unit-cell thickness can effectively decouple the flux motion in adjacent $YBa_2Cu_3O_7$ sheets at t=0.9. At higher temperatures near T_c we measured the activation energy U of this sample for thermally activated flux creep in a magnetic field applied perpendicular to the ab plane. The values of U are higher than expected from the linear thickness dependence of U found by Fischer *et al.* for completely decoupled superlattices with thick $PrBa_2Cu_3O_7$ layers.[16] Also the lines in the Arrhenius plot are not straight as is found for $Bi_2Sr_2CaCu_2O_8$ and decoupled $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices where one deals with pancake vortices but show the same curvature as typical $YBa_2Cu_3O_7$ films. We think that in the activation energy measurements the flux line shows a temperature dependent correlation length which is larger than the thickness of the $YBa_2Cu_3O_7$ sheets. Therefore the flux lines are not decoupled in this temperature range and show a 3D behavior in contrast to the 2D behavior found for the critical current measurements performed at lower temperatures.

IV. CONCLUSIONS

Concluding, we found a general scaling behavior of the critical current density for layered superconductors at low temperatures. The dependence of the critical current density on the angle between magnetic field and c axis is governed by the magnetic field component parallel to the c axis. In $YBa_2Cu_3O_7$ and $YBa_2(Cu_{1-x}Zn_x)_3O_7$ films the scaling behavior breaks down for reduced temperatures $t \geq 0.4$ due to weakening of the intrinsic pinning mechanism. In $Bi_2Sr_2CaCu_2O_8$ and $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattice films weak, or no, shielding currents flow in the c direction, which causes a magnetic inertness for the field component parallel to the layers. The scaling works whenever there is no dissipation due to flux motion in the c direction regardless of the mechanism preventing dissipation. Therefore one cannot conclude from the existence of scaling at low temperatures alone whether the system is quasi-two or three dimensional.

ACKNOWLEDGMENTS

The authors acknowledge financial support by the Bundesminister für Forschung und Technologie der Bundesrepublik Deutschland and the Deutsche Forschungsgemeinschaft through SFB 252.

[1]M. Tachiki and S. Takahshi, Solid State Commun. **70**, 291 (1989).
[2]M. Tachiki and S. Takahashi, Solid State Commun. **72**, 1083 (1989).
[3]W. E. Lawrence and S. Doniach, in *Proceedings of the 12th International Conference on Low Temperature Physics*, edited by E. Kanada (Academic, Kyoto, Japan, 1971), p. 361.
[4]P. H. Kes, J. Aarts, V. M. Vinokur, and C. J. van der Beek, Phys. Rev. Lett. **64**, 1063 (1990).
[5]P. Schmitt, P. Kummeth, L. Schultz, and G. Saeman Ischenko, Phys. Rev. Lett. **67**, 267 (1991).
[6]G. Jakob, P. Przysłupski, C. Stölzel, C. Tomé-Rosa, A. Walkenhorst, M. Schmitt, and H. Adrian, Appl. Phys. Lett. **59**, 1626 (1991).
[7]C. Tomé-Rosa, G. Jakob, A. Walkenhorst, M. Maul, M. Schmitt, M. Paulson, and H. Adrian, Z. Phys. B **83**, 221 (1991).
[8]C. Tomé-Rosa, G. Jakob, M. Maul, A. Walkenhorst, M. Schmitt, P. Wagner, P. Przysłupski, and H. Adrian, Physica C **171**, 231 (1990).
[9]A. Walkenhorst, C. Tomé-Rosa, P. Wagner, T. Kluge, C. Stölzel, G. Adrian, G. Jakob, and H. Adrian, Europhys. Lett. **18**, 641 (1992).
[10]P. Wagner, H. Adrian, and C. Tomé-Rosa, Physica C **195**, 258 (1992).
[11]G. Jakob, T. Hahn, C. Stölzel, C. Tomé-Rosa, and H. Adrian, Europhys. Lett. **19**, 135 (1992).
[12]J. R. Clem, Phys. Rev. B **43**, 7837 (1991).
[13]V. L. Pokrovsky, I. Lyuksyutov, and T. Nattermann, Phys. Rev. B **46**, 3071 (1992).
[14]Y. Iye, A. Fukushima, T. Tamegai, T. Terashima, and Y. Bando, Physica C **185-189**, 297 (1991).
[15]T. Koyama, N. Takezawa, Y. Naruse, and M. Tachiki, Physica C **194**, 20 (1992).
[16]O. Brunner, L. Antognazza, J.-M. Triscone, L. Miéville, and Ø. Fischer, Phys. Rev. Lett. **67**, 1354 (1991).