The Interaction of Vortices with Twin Boundaries*

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INVITED: International Seminar on Superconductors in High Magnetic Fields, National Research Institute for Metals, Tsukuba, Japan, February 17-18, 1995

*Work supported by the U.S. Department of Energy, BES-Materials Sciences under contract #W-31-109-ENG-38 (GWC, WKK, UW) and the National Science Foundation-Office of Science and Technology Centers for Superconductivity under contract #DMR91-20000 (JF, CJvdB, DG, TG).

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CONF-950292--1

Invited paper at the International Seminar on Superconductors in High Magnetic Fields, National Research Institute for Metals, Tsukuba, Japan, February 17-18, 1995

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Introduction

Twin boundaries provide a convenient defect for investigating vortex dynamics in superconductors. They occur naturally in $YBa_2Cu_3O_7$, with well defined planar geometries. They are a strong pinning defect, and at the temperature of the melting transition they are the dominant pinning sites in clean crystals. Twin boundaries are easily seen in polarized light, making their location and number directly observable without special equipment. Finally, they present a highly anisotropic pinning potential to the vortices, creating the possibility of interesting new behavior.

In this paper, we describe experiments using twin boundaries to probe two effects in vortex dynamics: a new peak effect in the critical current occurring in the solid state just below the melting transition, and anisotropic pinning by planar defects.

Pre-melting Peak Effect

Figure 1 shows the resistivity of a single crystal of YBCO containing two twin boundaries oriented at 45° to the crystal edges and separated by 140 microns. The current direction is parallel to a sample edge in the ab plane, and the field is along the c-axis. The melting transition in this low field of 0.5 T is indicated by an arrow. At low current, the resistivity drops sharply in the liquid state as the temperature is lowered, going to zero at the freezing transition and remaining zero in the solid state. This behavior is typical of the freezing transition,[1] and is caused by the strong difference in the dynamic response of the liquid and solid phases. Because of the finite shear modulus in the solid state, a given configuration of pinning defects is much more effective in pinning the solid than in pinning the liquid. This change in pinning effectiveness causes the resistivity of the solid to go to zero abruptly at the freezing transition if the transport current is low.

However, even the solid state can be de-pinned by applying sufficient current, as occurs for the higher current values in Figure 1. In these cases, the vortex motion in the solid and liquid can be quite different, since elastic forces between vortices tend to make the solid move as single object throughout the crystal, while the liquid moves as individual vortices under the influence of viscosity and friction. The different dynamic mechanisms of the two phases are evident in Figure 1 in the non-Ohmic resistivity in the solid and in the different temperature dependences of the resistivity above and below the melting temperature.

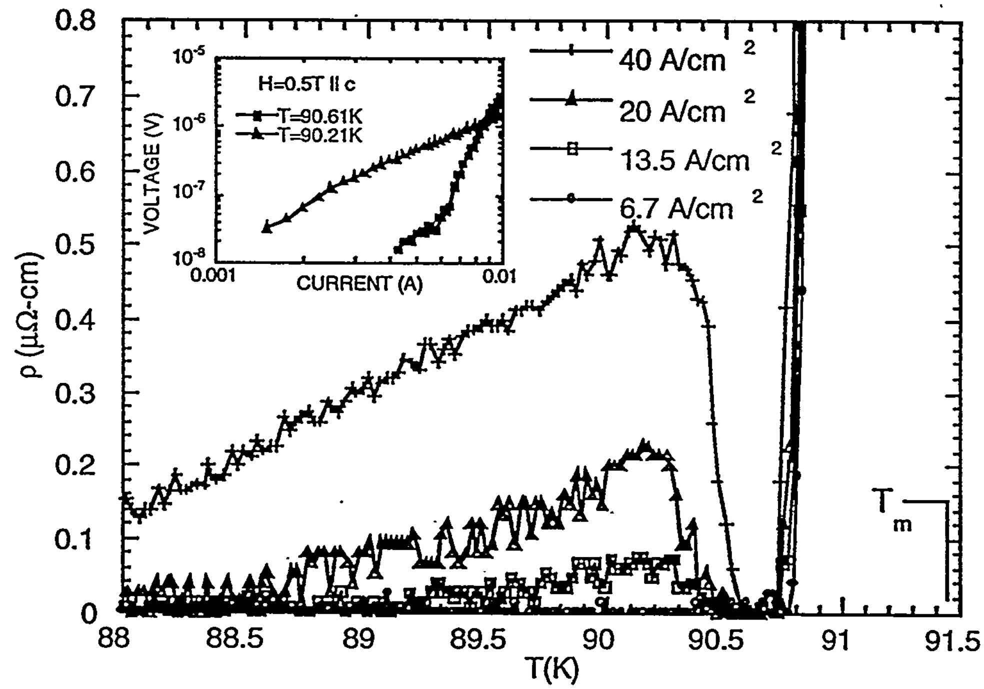

Figure 1: The resistivity of a crystal of $YBa_2Cu_3O_7$ containing two twin boundaries spaced 140 microns apart and oriented 45° to the crystal edge and to the current, for several applied currents. The measurements were taken with a four probe technique at a frequency of 17 Hz. Inset: typical I-V curves taken with a dc technique.

There is one remarkable feature of the current-dependent resistivity in Figure 1. At a temperature close to, but below, the melting point, all the curves approximately go through zero resistivity. This approximate zero indicates that pinning becomes dramatically stronger in the solid just before melting occurs. This trend is opposite to the intuitive expectation that pinning becomes weaker as the temperature is raised. The increase in pinning near melting can be quantified by measuring the critical current directly with dc I-V curves. Typical I-V curves are shown in the inset to Figure 1, and the critical transport current derived from such curves using a voltage criteria of 10^{-7} V is shown in Figure 2. A sharp peak in J_c, amounting to approximately a factor of 2, is seen just prior to melting. This pre-melting peak effect can also be seen[1] in crystals with twin boundaries oriented parallel to the vortex motion, and in untwinned crystals, though the magnitude of the effect is less pronounced in the latter case.

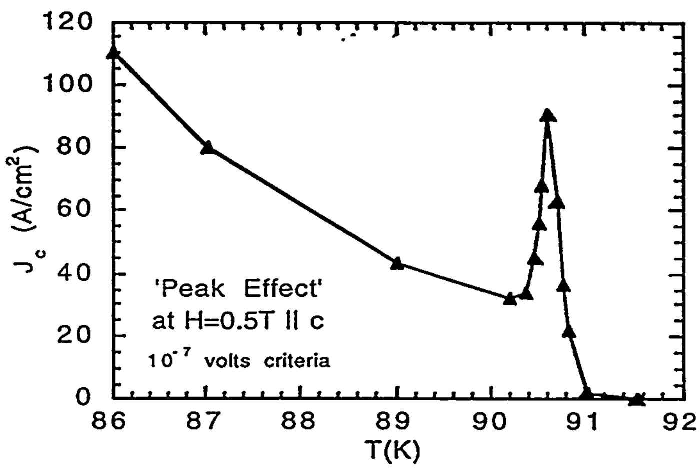

Figure 2: Critical transport current for the crystal shown in Figure 1. The values of J_c were determined from dc measurements of the I-V curve, assuming a voltage criterion of 10^{-7} volts.

The origin of the peak effect can be found in the weakening of the shear modulus prior to melting. Below the peak, where the shear modulus is strong, the moving vortices tend to take up the structure of the lattice to minimize their mutual interaction energy. This leads to elastic flow, where the vortex lattice moves through the crystal as a single elastic object. As the shear modulus weakens near melting, the lattice can accommodate more distortion without breaking its structure, and the vortices settle deeper into the pinning potential wells which oppose their motion. This accounts for the increase in J_c just prior to melting. At the peak of J_c, the shear modulus becomes so weak that the lattice is torn, leading to plastic flow. Once shear motion is allowed, the most weakly pinned vortices tear free of the lattice structure, leading to a lower critical current. In this picture, the peak in J_c marks the transition from elastic to plastic flow. It signals the weakening of the shear modulus, and is a precursor to the melting transition of the vortex solid.

The defects responsible for the increased pinning at the peak in J_c are the twin boundaries. This identification is made clear by the angular dependence of the resistivity and critical current shown in Figure 3. The valley in resistivity and the associated peak in J_c are largest when

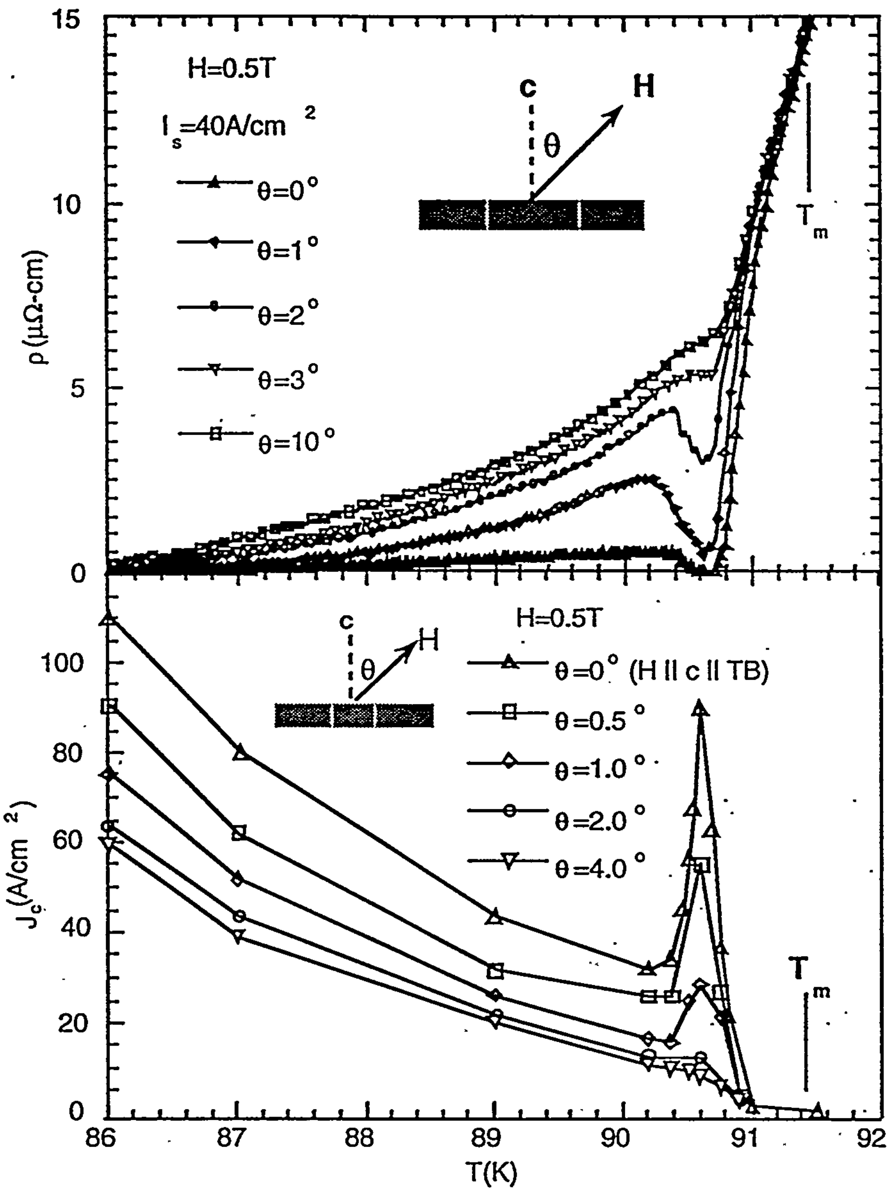

Figure 3: Temperature dependence of the resistivity and critical current as the field is rotated away from the twin boundary plane.

the field direction is aligned with the c-axis, parallel to the twin boundary plane. As the field direction is rotated away from the boundary plane, the valley in resistivity and the peak in J_c become less pronounced, disappearing at a misorientation of approximately 4°. This behavior is characteristic of twin boundary pinning, which is effective only over a narrow angular range of field directions nearly aligned with the boundary plane.

Anisotropic Twin Boundary Pinning

The pinning action of twin boundaries on vortices can be expected to be anisotropic, due to the planar nature of the boundary. In this respect twin boundaries differ from point defects, whose geometry is independent of angle, and columnar defects, where vortices aligned with the defect are effectively pinned against motion in either transverse direction. Twin boundaries present two different pinning strengths to vortices aligned with the boundary plane: relatively weaker pinning for motion within the plane, and relatively stronger pinning for motion transverse to the plane. Early transport measurements revealed this anisotropy.[2] The two different pinning potentials arise from two different aspects of the twin boundary structure. Transverse to the boundary, there is a strong interaction with vortices associated with the strain field of the boundary. TEM studies suggest that the strain field is 10-50 Å wide, enough to contain one vortex. As indicated by transport measurements and the flux images shown below, the pinning potential well transverse to the boundary effectively opposes the motion of flux across the boundary. If the boundary were a featureless plane, this transverse potential would not affect motion of the vortices parallel to the plane. In principle, vortices could move along the valley of the transverse potential, remaining trapped inside the twin boundary as they move. However, the twin boundary is not featureless along its length. Rather, there is likely to be considerable atomic disorder in the boundary, associated with the mismatch of the relatively perfect structures on the two sides. This atomic disorder creates point pinning defects in the boundary, which are responsible for impeding vortex motion parallel to and within the boundary.

The differing strength of the two pinning mechanisms can be seen clearly in the flux distributions near twin boundaries, observed by magneto-optical techniques. Such magneto-optical flux images can be obtained using the Faraday rotation of the polarization of light in an optically active indicator film placed on the sample.[3] Figure 4 shows the physical image of a single crystal of $YBa_2Cu_3O_7$ containing a series of parallel twin boundaries, and Figure 5 shows flux images of the same crystal at several applied fields. The single crystal is approximately 0.7 mm across from the left edge to the point on the right, and 20 microns thick. Twin boundaries extend vertically along the entire crystal, spaced at intervals of 50 to 300 microns.

The difference in pinning potential for motion parallel and perpendicular to the boundary is evident in the magnetic field patterns. Looking first at the bottom edge, where vortices enter the crystal in

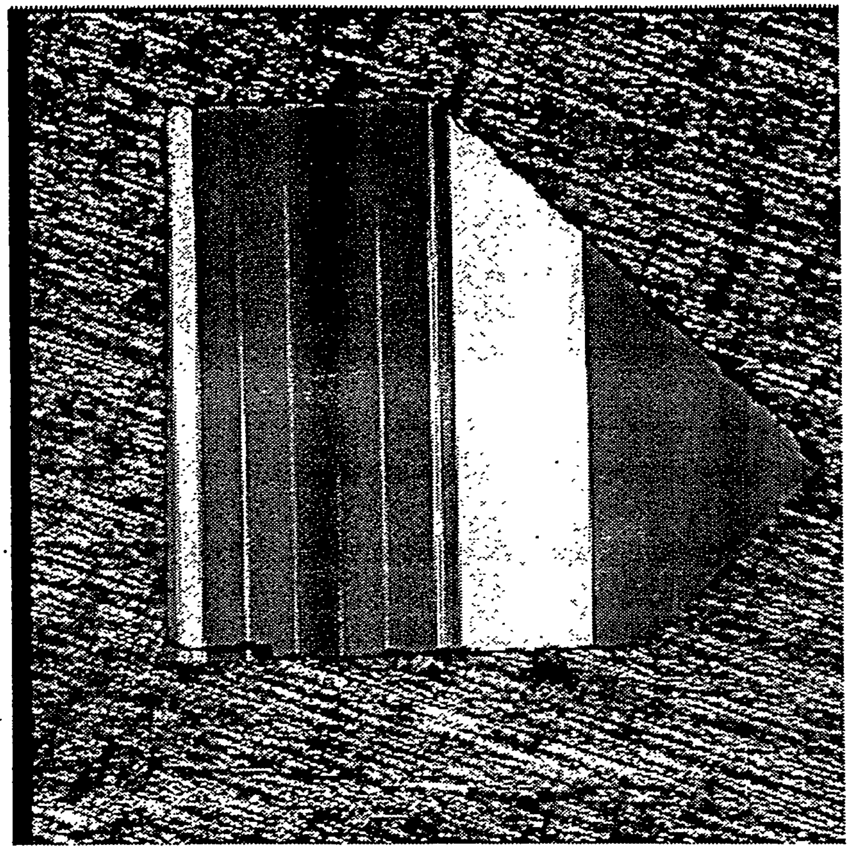

Figure 4: Physical image of a single crystal of $YBa_2Cu_3O_7$, showing parallel twin boundaries spaced at distances of 50 to 300 microns.

the upward direction, the flux is seen to penetrate further into the twin boundaries than it does into the neighboring untwinned regions, creating a characteristic "flame" pattern at the boundary. The shielding current density flowing at the edge of the crystal can be estimated from the field penetration distance, using Maxwell's equation $\frac{4\pi}{c} J_c = \frac{\partial H}{\partial x}$. The greater penetration of the field in the twin boundary indicates that the critical current density in the boundary is lower than in the surrounding bulk. Thus the twin boundary is a weak link at these temperatures. The shielding current flowing parallel to the edge of the crystal must spread out at the twin boundary in order to lower its density to the critical value in the boundary. A quantitative model[3] of the current distribution near a twin boundary based on this V-shaped pattern is in good agreement with the local field values derived from images like those in Figure 5. The penetration of flux into the twin boundaries and the flame pattern are characteristic of pinning against vortex motion parallel to and within the twin boundary.

A very different pattern of field penetration occurs at the left hand edge of the crystal. Here the twin boundary planes are perpendicular

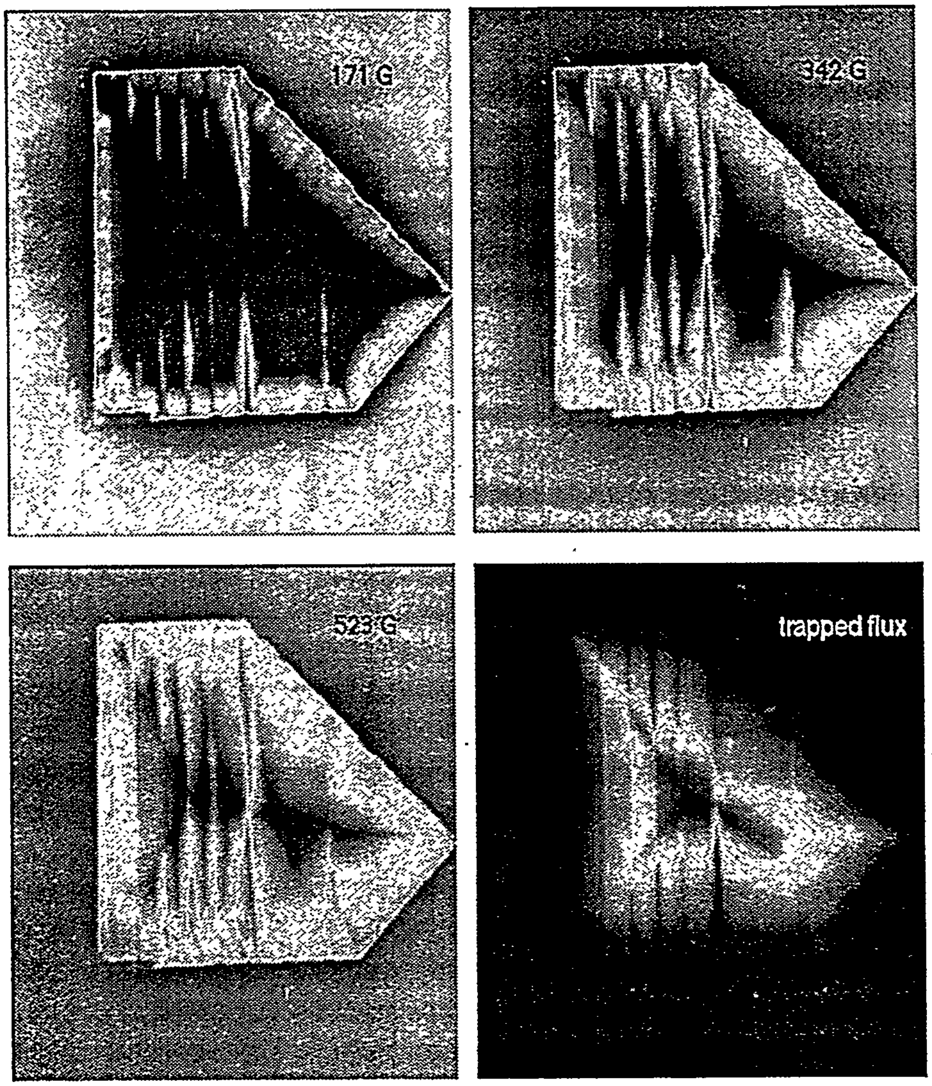

Figure 5: Flux images showing the effect of twin boundaries on the local field distribution. Images were taken in the applied fields indicated after zero field cooling to 40 K, and in zero field after applying a field of 855 gauss.

to the flow of flux entering the crystal. The images show a distinct drop in the vortex density at the twin boundary, indicating that the boundary acts as a barrier to flux motion. In contrast to the deeper penetration for motion within the boundary, motion transverse to the boundary is impeded. This stronger pinning for transverse motion is a feature of the boundary itself, rather than of the local atomic disorder within the boundary. The local field values adjacent to the twin boundary recovered from images like those in Figure 5 imply that the drop in vortex density across the boundary is approximately constant, independent of temperature. From this drop, the shielding current flowing at the boundary can be inferred, approximately 0.1 A.

The anisotropy in twin boundary pinning against motion within and across the boundary is illustrated dramatically by comparing the behavior of boundaries at the lower left corner and near the middle of the left edge. At the lower left, vortices enter the crystal from the bottom and these boundaries act as weak links, producing the characteristic flame pattern. Near the middle of the left edge, vortices enter from the left, and the same boundaries act as barriers to motion. Thus the anisotropy in pinning is a generic feature, independent of the structural details of individual boundaries.

Figure 5 reveals one other interesting feature which sheds light on the behavior of boundaries at orientations intermediate between parallel and perpendicular to the motion direction. The upper right edge of the crystal makes a 45° angle with the other crystal edges and with the twin boundaries. There is one twin boundary which extends vertically throughout the crystal, perpendicular to the edge of the crystal at the bottom, and oriented at 45° to the upper right edge. At the bottom this twin boundary exhibits the flame pattern characteristic of a weak link, as expected for vortex motion parallel to and within the boundary. However at the upper right, there is no flame pattern, in spite of the fact that the motion direction (perpendicular to the edge), has a component along the boundary plane. Close examination of the images in Figure 5 reveals that there is a slight barrier effect, with a shadow region behind the boundary where the vortex density is slightly lower than in front of the boundary. A reduced barrier effect can be expected for intermediate angles, since there is a path from the crystal edge to the shadow region that does not cross the twin boundary. Thus, unlike the case of boundaries perpendicular to the motion, it is possible for vortices to move into the shadow region by a curved trajectory which avoids the boundary altogether. Such a curved trajectory would be driven by the repulsive interaction between vortices, which tends to create a constant vortex density throughout the crystal.

Summary

Twin boundaries are a naturally occurring strong pinning defect which can be used to investigate and illustrate the basic features of vortex behavior in superconductors. This paper discusses twin boundary behavior in the context of two phenomena: the pre-melting peak effect, and anisotropic pinning. The pre-melting peak effect is a new feature of the vortex solid state, associated with the relaxation of vortices more deeply into their pinning potential wells as the shear modulus weakens prior to melting. Twin boundary pinning emphasizes the effect, since these defects are the dominant pinning sites in these crystals near the melting temperature. A pre-melting peak effect can also be seen in untwinned crystals, but with smaller magnitude than is shown here. The phenomenon of anisotropic pinning can be naturally investigated in twin boundaries, since their planar geometry contains two pinning mechanisms of different strength: strong pinning against motion transverse to the boundary, due to the strain field associated with the boundary itself, and weak pinning against motion parallel to and within the boundary, caused by atomic disorder occurring at the boundary. The weaker pinning for motion along the boundary allows greater penetration of the field into the boundary than into the neighboring untwinned regions, and produces a characteristic flame pattern in magneto-optical flux images. A quantitative model of the shielding current based on this pattern has been derived. For motion perpendicular to the twin boundary, the boundary acts as a barrier, producing a drop in vortex density across the boundary plane.

This work was supported by the U. S. Department of Energy, Basic Energy Sciences-Materials Science under contract #W-31-109-ENG-38 (GWC, WKK, UW) and by the U. S. National Science Foundation-Office of Science and Technology Centers under contract #DMR 91-20000 (VKV, JF, CJvdB, DG, and TG).

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