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Current-driven transformations of the intermediate-state patterns in type-I superconductors

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Dynamic structure of the intermediate state was studied in pinning-free thick Pb strips using real-time magneto-optical visualization. It is found that topological hysteresis can be lifted by applying sufficiently large transport current. Namely, laminar structure that appears in a static case when magnetic flux exits the sample is turned into a tubular pattern when sufficiently large transport current is applied. The tubes move under the influence of the Lorentz force and, at higher currents and fields, evolve into a dynamic pattern of equally spaced superconducting walls oriented perpendicular to the current (force-free configuration). Magnetic-field-current phase diagram of the intermediate state is discussed. Our results imply that tubular structure is more favorable than the laminar structure because it is topologically mobile, whereas tubular pattern is topologically constrained with the multitude of degenerate metastable state.

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I. INTRODUCTION

Over the years, much work has been done in studying the intermediate state in type-I superconductors, lead (Pb) in particular.[1–3] Most of the research was performed on thin films, but the degree of pinning was rarely checked or attempted to be minimized (note that chemical purity, which was taken seriously in early works, does not imply the absence of pinning). While these studies provided some important insights into the intermediate-state structure, the question of the *equilibrium* topology of the intermediate state remained open. It turns out that pinning is of utmost importance in defining the structure of the intermediate state.[4,5] While (what looks like) Landau laminar pattern has been observed in many experiments, on many occasions and in various materials, direct observations revealed tubular structure instead.[1,6] Most often, these were clean stress-free thick samples of mercury, tin, or lead.[1] Unlike Abrikosov vortices in type-II superconductors each bearing a single flux quanta, tubes in type-I superconductors may contain up to approximately 10^7 flux quanta. Goren and Tinkham[7] (GT) proposed a model in which flux tubes were considered as building blocks of the intermediate state. It has never been confirmed experimentally, citing various reasons. In our experiments with a thick (1.0 mm) Pb single crystal with very low pinning, an excellent, parameter-free agreement with the GT model was found. Figure 1 shows direct confirmation of the GT model from our measurements by analyzing the mean tube diameter as the function of a magnetic field. The GT equation for the tube diameter reads,

$$D = \left[\frac{2d\delta}{(1-h)(1-h^{1/2})} \right]^{1/2}, \qquad (1)$$

where d=1.0 mm is the sample thickness, $h = H/H_c$ is the normalized magnetic field, and δ is the wall energy parameter (effective thickness).[1] For the plot, δ was chosen in the range of reported experimental values of 55 nm and 80 nm for dashed and solid curves, respectively. If we try to use least-squares fit to Eq. (1) with δ as a free parameter, we obtain δ=79 nm, which is very close to the value of 80 nm shown by the solid line in Fig. 1.

In recent papers, we showed that the intermediate state in thick samples with a rectangular cross section exhibits distinct behavior tubes upon flux penetration and laminae upon flux exit.[4,5] We called this effect "topological hysteresis" to reflect the fact that hysteresis in the topology results in hysteresis in a macroscopically measurable parameters, such as magnetic moment. The tubular phase is robust and was shown to represent the equilibrium pattern by studying samples with and without geometric barrier[4] and statistically it behaves as a conventional two-dimensional (2D) froth.[8] The laminar pattern forms due to the absence of the geometric barrier on flux exit, so magnetic flux can continuously leave the sample (except for the narrow region at the edge where laminae break into tubes). The free-energy difference is not sufficient to turn this pattern into tubes in the bulk—it only leads to significant corrugation[9,10] of the initially straight lines. Perhaps conversion to the tubular pattern can happen in a dynamic state when domain walls are forced to move. In short, the laminar structure is topologically con-

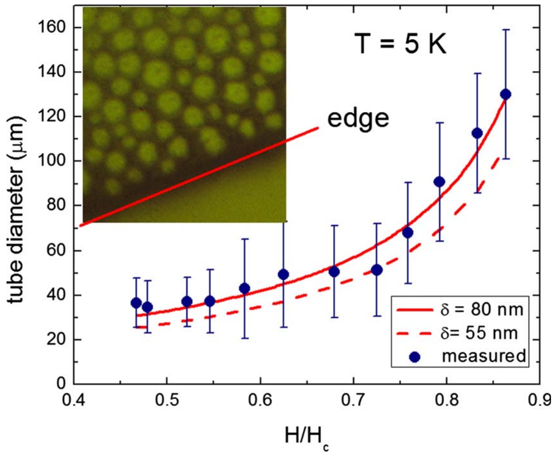

FIG. 1. (Color online) Mean tube diameter as a function of the applied field in Pb crystal measured at T=5 K. The solid and dashed lines are the plots to the Goren and Tinkham model (Ref. 7), Eq. (1), with parameters described in the text. Inset: example of flux tubes (bright) penetrating the sample from the edge marked by a line.

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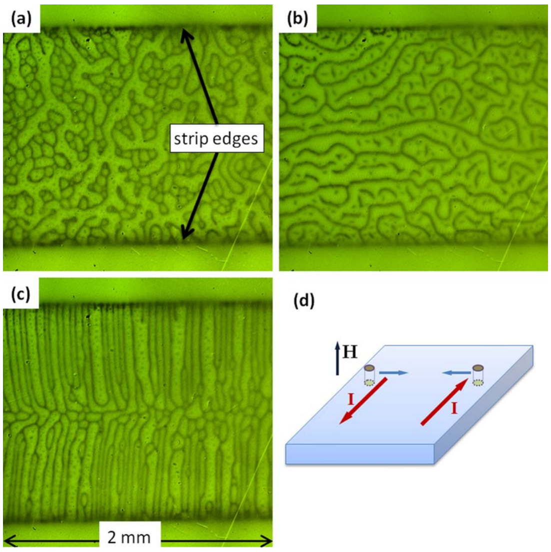

FIG. 2. (Color online) Magnetic-flux penetration and exit into a Pb strip at $T=5$ K and $H=300$ Oe. (a) Slow flux penetration; (b) flux exit; (c) flux penetration upon fast magnetic-field ramp; and (d) schematics of the experiment. Currents are induced by the magnetic field.

strained, while the tubular structure is topologically mobile. By "constrained" we mean that stripes' motion is very anisotropic, they can only move perpendicular to the superconductor/normal interface (therefore they corrugate); whereas, flux tubes can move equally well in all four directions. As a result, moving dynamic state will favor tubular phase over laminar.

This leads to a natural question of the dynamical characteristics of flux tubes. Dynamics of small tubes in thin films were analyzed in terms of the geometric barrier.[1,11,12] Experiments with fast ramping magnetic field (similar to applying transport current of different magnitude) were interpreted in terms of dynamical reorganization of laminar domains.[13] However, physics of such transformation was not clearly explained. Here we show that at first, the structure breaks into moving tubular pattern, then, due to the relatively long expose time (set by the video camera), the fast moving tubes appeared as streaks. At a higher driving force, the pattern finally evolves into equally spaced superconducting walls perpendicular to the current flow, which represents dynamically stable force-free configuration. Figure 2 also shows such behavior upon fast field ramp. Similar patterns of fast moving tubes driven by the Lorentz force were observed in 1970s by Solomon and Harris[14] and in 1990s by Dutoit and Rinderer[15] by imaging the flux structure driven by an applied current.

In this paper we discuss the influence of the transport current on the flux topology in the intermediate state of thick Pb strips. The prior works that involved transport current focused on the effects of geometric barrier[12] and estimation of flux velocity,[14,16] whereas, we are interested in topological transformations.

II. EXPERIMENT

In the experiment, magneto-optical imaging of the component of the magnetic induction perpendicular to the surface was conducted by utilizing the Faraday effect in bismuth-doped iron garnet indicators with in-plane magnetization.[17] A flow-type liquid ^{4}He cryostat with sample in vacuum was used. The sample was positioned on top of a copper cold finger and an indicator was placed on top of the sample. The cryostat was positioned under polarized light reflection microscope and the color images could be recorded on video and high-resolution charge-coupled device cameras. When linearly polarized light passes through the indicator and reflects off the mirror sputtered on its bottom, it picks up a double Faraday rotation proportional to the magnetic-field intensity at a given location on the sample surface. Observed through the (almost) crossed analyzer, we recover a 2D image.[18] Note that some images contain tooth-shaped overlay of darker and brighter areas. This is a side effect of a birefringence in the magneto-optical indicator that has in-plane magnetic domains and, at certain angles with respect to the polarization plane, these domains also show on the images. This, however, does not affect the underlying image in any way. High-purity (Puratronic, 99.999%) Pb foils of various thicknesses were obtained from AlfaAesar.

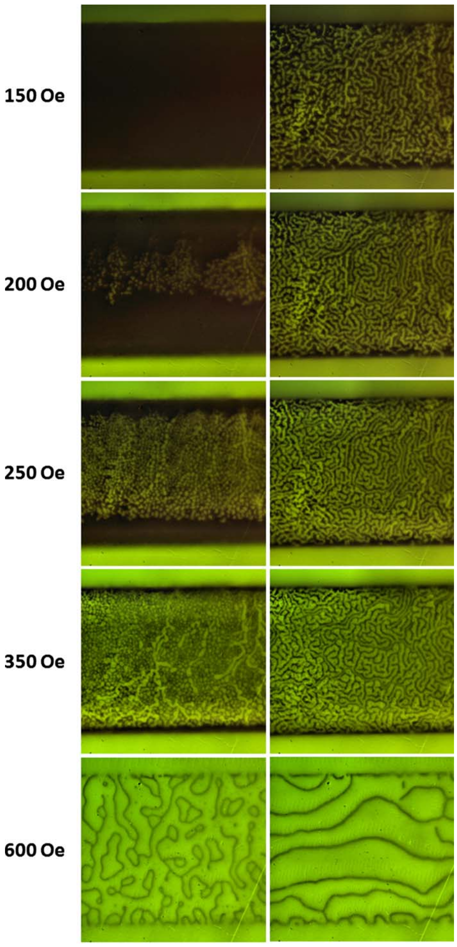

FIG. 3. (Color online) Pb strip of dimensions $9.30\times1.85\times0.48$ mm^3 at $T=5$ K. Left column shows penetration of the magnetic field (top to bottom) after cooling in zero field. Right column shows flux exit (bottom to top) upon decreasing of an external field from the normal state. External field was applied perpendicular to the page. Strip is oriented as in Fig. 2

(In our experiments, Goodfellow foils showed much larger magnetic hysteresis and pinning that resulted in disordered dendritic patterns of the intermediate state).

III. RESULTS AND DISCUSSION

Figure 2(a) shows the result of slow (1 Oe/s) magnetic-flux penetration and Fig. 2(b) shows the result of flux exit in the Pb strip without an applied current at 300 Oe and 5 K exhibiting typical topological hysteresis. Figure 2(c) shows fast magnetic-field penetration, clearly changing the resulting topology. Figure 2(d) shows schematics of the experiment and the relation between applied current and the Lorentz force acting upon tubes. The difference between slow and fast ramp is due to internal electric field that is proportional to dH/dt. Resistivity is determined by flux-flow viscosity and flux density, therefore, faster ramp rate corresponds to higher amplitude of the induced current. According to Fig. 2 topology of the resulting pattern is greatly affected by the ramp rate.

Before examining the effect of the transport current, we show flux penetration and exit upon slow field ramp. Figure 3 shows magnetic-flux penetration (left column) and exit (right column) at 5 K without applied current into a 5-mm-long, 1.85-mm-wide, and 0.48-mm-thick strip. As the applied magnetic field is increased, flux tubes "jet" into the center of the sample from the edges. These jets are caused by the Lorentz force exerted by the Meissner current on the tubes that just snapped off the fingerlike protrusions of flux at the sample edge.[19] The tubes passing the geometric barrier region accumulate at the strip center. The tubular structure then—builds upon itself—slowly pushes outward toward the edge of the sample as the applied field is increased. Once the tubes reach the edge of the sample, they grow and eventually merge, increasing the normal phase area until the entire sample reaches the normal state. From this point, the applied field is decreased (right column: ascending) and the magnetic flux exits the strip in such a manner as to leave the Landau laminar structure.

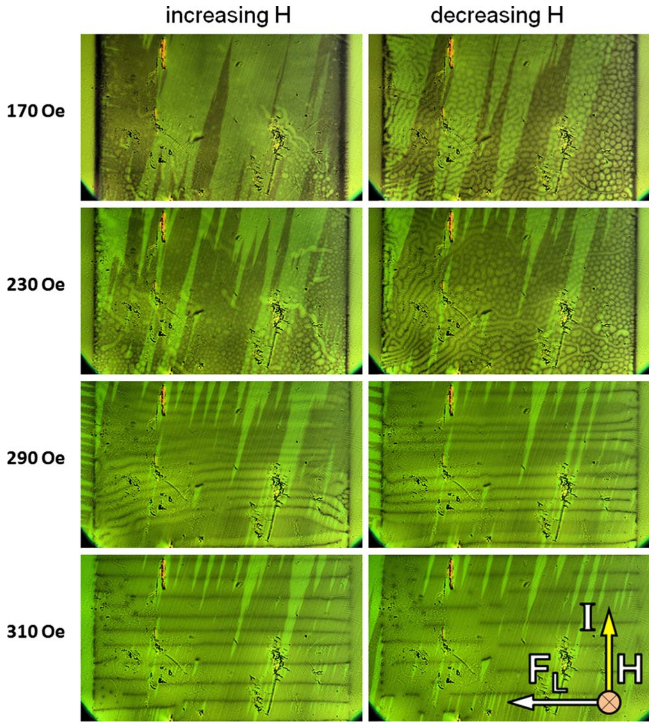

FIG. 4. (Color online) Pb strip of dimensions 9.10×2.15 ×0.25 mm^3 zero field cooled with an applied constant current of 0.5 A. The left column shows increasing field (top to bottom). The right column shows decreasing field (bottom to top). At fields 230, 290, and 310 Oe there is constant motion of flux from the right to the left side. (See comment on the tooth-shaped overlay images). Inset shows direction of the applied magnetic field (into the page), transport current, and the Lorentz force. The same configuration is applied to Figs. 5 and 6.

With the applied field decreasing, the laminar structure stays uniform throughout the sample while merely "thinning" to allow flux exit and allow an increase in the area of the Meissner state. At small fields the laminar structure breaks at the sample edge and exits the sample as flux tubes.[20] An applied current in a Pb sample in the intermediate state will move the magnetic flux according to the Lorentz force. The inset in Fig. 4 shows the direction of the magnetic field (into the page), transport current, and the Lorentz force. The same arrangement is kept in Figs. 5 and 6. Figure 4 shows flux penetration and exit in a sample that was initially cooled in zero magnetic field to 5 K with a constant current of 0.5 A. Upon penetration, the nucleated flux tubes move slowly at first, but quickly gain speed with the increase of an applied magnetic field: the highest velocity of which

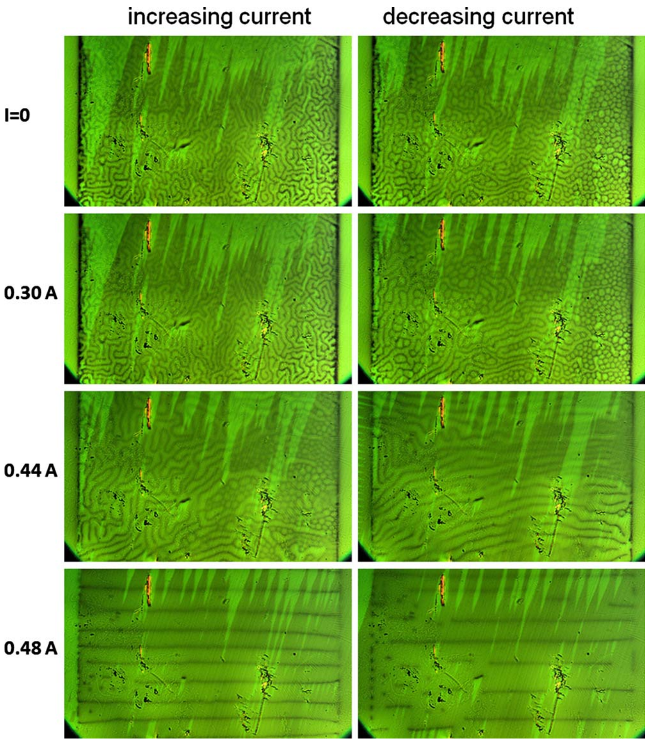

FIG. 5. (Color online) Pb strip of dimensions 9.10×2.15 ×0.25 mm^3 field cooled in a 350 Oe applied magnetic field. The left column shows an increasing (top to bottom) applied current. The right column shows a decreasing (bottom to top) applied current after the sample was driven to the normal state using current.

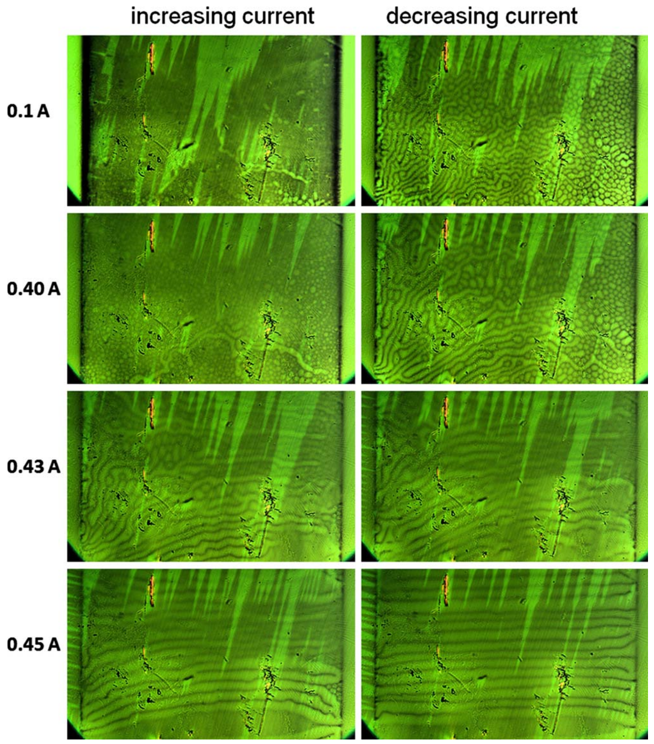

FIG. 6. (Color online) Similar to Fig. 5 but after cooling in zero field.

was measured at 3 mm/s. The magnetic flux has been found to move faster[1] but these higher speeds are not resolvable with our imaging equipment; so at a high enough flux density, this dynamic picture switches over to a striped pattern that only *appears* static. In our interpretation, this pattern is initially due to fast moving flux tubes that later evolves into a force-free configuration of superconducting walls that are perpendicular to the applied current. This stripe pattern can be seen to begin at 290 Oe and is fully developed at 310 Oe. Upon further increase of the magnetic field, the number of stripes decreases with individual stripes snapping off and (sometimes) creating what looks like dislocations.[20] It would be interesting to measure voltage—current characteristics in this state—they should show steps approaching normal-state linear $V(I)$. Perhaps these steps could be used to determine energy of the S/N boundary. After bringing the sample to the normal state and subsequently lowering the applied field, this striped structure reappears. In stark contrast to a static case, the Landau laminar structure does not develop. Instead, we see a tubular pattern very similar to that observed on flux entry (but with larger tubes).

In order to take a closer look at the response of the intermediate-state structure to a transport current, two other basic experiments were performed. Figures 5 and 6 show the situation when the applied field is fixed while the current was gradually changed. Figure 5 shows results obtained in a sample that has been cooled in a constant applied field of 350 Oe. Figure 6 shows the experiment performed after cooling in zero field, after which the same 350 Oe field was applied. While the initial states in two cases are different, laminar in the case of Fig. 5 and tubular in the case of Fig. 6, the end result is very similar-tubular structure (that at higher densities looks like a froth). It should be noted that the tube size after ramping the current is larger than that obtained after cooling in zero field.

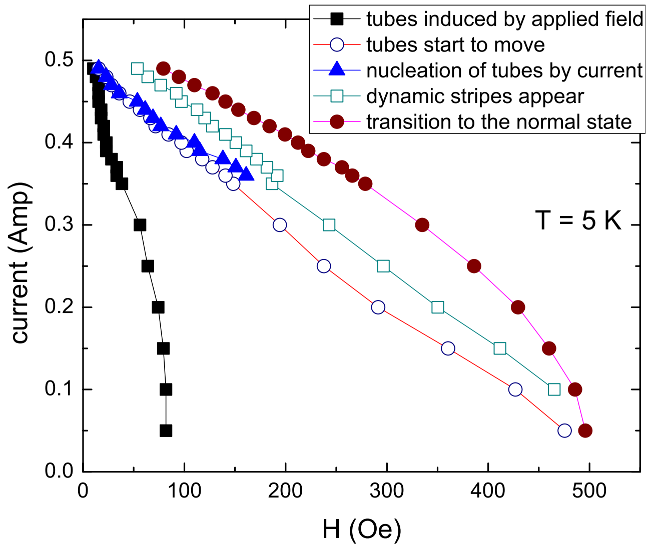

FIG. 7. (Color online) *H-I* phase diagram at $T=5$ K. Different lines are explained in the text.

Finally, by observing real-time imaging and recording characteristic events, a magnetic field vs current phase diagram (at constant temperature $T=5$ K) can be constructed. Figure 7 summarizes various transitions in the flux topology at 5 K. Filled squares show the first appearance of tubes due to applied field at a constant current. Open circles show the start of tube motion under the applied current (at a given value of the applied magnetic field). The same line is obtained when a magnetic field was increased at a fixed value of the transport current. Filled triangles indicate the start of tube nucleation at the sample's edges due to self-field of the current. These tubes are being immediately driven across the strip. Open squares mark the formation of the dynamic striped flux structure. In our interpretation, initially, these are fast moving tubes irresolvable by the video camera. Yet at higher currents and/or fields, they evolve into superconducting walls that will orient themselves perpendicular to the transport current, which is a force-free configuration. Finally, filled circles show the transition to a normal state.

IV. CONCLUSIONS

In conclusion, presented experiments on a driven intermediate state demonstrate convincingly that tubular pattern represents topologically equilibrium state. Even if the two topologies have very close or equal free energies, the laminar pattern is topologically constrained with many different anisotropic (with respect to the current flow) geometric configurations, resulting in a multitude of the metastable states. The tubular structure on the other hand is isotropic and is highly mobile. As a result, in a clean pinning-free sample, this gives an advantage to the tubular structure over the laminar pattern.

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[1] R. P. Huebener, *Magnetic Flux Structures in Superconductors* (Springer-Verlag, Berlin, 2001).

[2] M. Tinkham, *Introduction to Superconductivity* (Dover, New York, 2004).

[3] J. D. Livingston and W. DeSorbo, in *Superconductivity*, edited by R. D. Parks (Dekker, New York, 1969), Vol. 2, Chap. 21.

[4] R. Prozorov, Phys. Rev. Lett. **98**, 257001 (2007).

[5] R. Prozorov, R. W. Giannetta, A. A. Polyanskii, and G. K. Perkins, Phys. Rev. B **72**, 212508 (2005).

[6] A. Meshkovsky and I. A. Shalnikov, Zh. Eksp. Teor. Fiz. **11**, 1 (1947).

[7] R. N. Goren and M. Tinkham, J. Low Temp. Phys. **5**, 465 (1971).

[8] R. Prozorov, A. F. Fidler, J. R. Hoberg, and P. C. Canfield, Nat. Phys. **4**, 327 (2008).

[9] C. R. Reisin and S. G. Lipson, Phys. Rev. B **61**, 4251 (2000).

[10] A. T. Dorsey and R. E. Goldstein, Phys. Rev. B **57**, 3058 (1998).

[11] H. Castro, L. Rinderer, and B. Dutoit, Physica C **282**, 2343 (1997).

[12] H. Castro, B. Dutoit, A. Jacquier, M. Baharami, and L. Rinderer, Phys. Rev. B **59**, 596 (1999).

[13] V. Jeudy, C. Gourdon, and T. Okada, in *Low Temperature Physics: 24th International Conference on Low Temperature Physics-LT24*, AIP Conf. Proc. No. 850 (AIP, New York, 2006), pp. 985–986.

[14] P. R. Solomon and R. E. Harris, Phys. Rev. B **3**, 2969 (1971).

[15] B. Dutoit and L. Rinderer, Helv. Phys. Acta **62**, 886 (1989).

[16] R. P. Huebener and D. E. Gallus, Phys. Rev. B **7**, 4089 (1973).

[17] L. A. Dorosinskii, M. V. Indenbom, V. I. Nikitenko, Yu. A. Ossip'yan, A. A. Polyanskii, and V. K. Vlasko-Vlasov, Physica C **203**, 149 (1992).

[18] Ch. Jooss, J. Albrecht, H. Kuhn, S. Leonhardt, and H. Kronmuller, Rep. Prog. Phys. **65**, 651 (2002).

[19] T. E. Faber, Proc. R. Soc. London **A248**, 460 (1958).

[20] See EPAPS Document No. E-PRBMDO-78-038834 for Supplemental online video: Evolution of the intermediate state structure with increasing and decreasing transport current applied after cooling in 300 Oe to $T=5$ K. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.