Critical Properties and Vortex Matter

(A comment to "Vortex dynamics at the Transition to the Normal State in $YBa_2Cu_3O_7$ Films" by P. Bernstein *et al.*)

R. Woerdenweber, IBN-2, Forschungszentrum Juelich, D-52425 Juelich, Germany
e-mail: r.woerdenweber@fz-juelich.de

***Abstract* – A general view on vortex matter and consequences for understanding the critical properties of superconductors is sketched. It is shown, that this field of research is extremely versatile and still of high interest for basic and application-related research. This contribution is intended to trigger a comprehensive discussion of vortex matter within the *News Forum*.**

(Manuscript received April 26, 2007, final revision May 7, 2007; Reference No. ST1-D1)

One of the roles of the online *News Forum* is to foster the discussion of issues of common interest to the superconductor community. Definitely, the analysis and understanding of vortex matter is such an issue. Vortex motion leads to voltage noise and, finally, the critical current density limit that usually confine the working regime in low- and high-power applications. Alternately, in vortex manipulating experiments or fluxonic devices controlling the vortex dynamics is explicitly desired.

Bernstein *et al*. discuss the vortex dynamic near the transition temperature in YBCO films not exposed to external magnetic fields. They restrict their analysis to one aspect, *i.e*, to the impact of twin boundaries on the vortex dynamics in epitaxial thin film of a high-T_c material. One could argue, whether or not twin boundaries provide the dominant contribution to vortex pinning and motion in these systems? However, in general flux pinning is much more complex in real systems. Therefore, I would like to use this opportunity to briefly sketch my view of flux pinning (restricted to Abrikosov vortices and excluding the impact of thermal activation) in a superconductor such as YBCO films, also in applied external fields, in the hope that this will stimulate a broader discussion of this subject so vital for most applications of superconductivity.

In general, the mechanism of flux pinning and, thus, flux motion in real type-II superconductors is determined by:

- the *interaction between individual vortices* (V-V interaction),
- the *interaction between individual pinning centres and vortices* (V-P interaction),
- the *driving force* provided by, *e.g*., a Lorentz force caused by an applied current, a field or temperature gradient or even elevated temperatures [1], and
- the *homogeneity* of the superconducting material in terms of amplitude and length scale of the variation of the superconducting properties.

This defines a number of problems that have to be solved in order to understand the diversity of effects caused by vortex motion in type-II superconductors:

(1) The dominant class or classes of defects, which are responsible for flux pinning, have to be determined and their elementary pin-vortex interaction, f_p, has to be computed. Generally the defects of interest have to modify the superconducting parameters on the length scale defined by the coherence length, which is extremely small in HTS materials. An exception is represented by surfaces and holes (*e.g*., antidots) that are interacting with vortices in spite of their large size. As discussed in the contribution of Bernstein at al., twin boundaries represent one class of defects tin

HTS material, but definitely not the only one and most probably not the dominant one. This is among others demonstrated in a number of visualization experiments.

(2) The ‘response’ of the vortex lattice to the V-P interactions has to be determined. With a driving force smaller than the volume pinning force F_p (static vortex lattice) this can lead to elastic deformations (described by the elastic matrix), plastic deformations or even instabilities in the vortex lattice. The different mechanisms are comparable to the reaction of solids upon internal stress. As long as the strain is small, the vortex lattice can reach its equilibrium position with respect to the pin distribution without plastic shear taking place in the lattice. In the case of larger strain, plastic shear will create a significant number of flux-line defects. The combination of (1) and (2) leads to the deformation of the vortex lattice described by the displacement field. The deformation can be two-dimensional (transversal displacement) or three-dimensional and is intensively discussed among others in numerous phase diagrams for the case of HTS material.

(3) The adequate summation of the effects of many pins usually at random positions leads to the prediction of the volume pinning force, F_p, taking into account the elementary vortex interaction, the distribution and density of pinning sites and the kind of deformation in the vortex lattice. This volume pinning force, F_p, is not automatically identical with the force $F_\mathrm{c}=J_\mathrm{c}B$, which is defined by the onset of vortex motion.

The summation problem can be solved in some ideal or model systems. In the easiest case, every pinning centre is able to exert its maximum pinning force, f_p, on the vortex lattice, and the net volume pinning force, F_p, would be given by the direct summation: $\mathrm{F_c} = F_p = \sum\left(\mathrm{f_p}/V\right)$. This case is usually not observed in natural (*i.e.*, non-artificial) systems at moderate or large applied magnetic induction. The direct summation is appropriate only for very small magnetic fields (V-V interaction is negligible), as in the case of Bernstein *et al.* At higher fields a completely flexible vortex lattice or a distribution of pin sites which is matched to the vortex lattice (e.g., artificial pinning array) would be necessary in order to allow the use of the direct summation.

Realistic scenarios for the summation of the elementary V-P interactions for real type-II superconducting material in moderate or large magnetic fields are quite different. Larkin and Ovchinnikov were the first to shed light on this problem. Most summation theories are still based on their collective pinning theory[2].

(4) Finally, depending on the strength, density and distribution of pinning centres, on the elastic or plastic response of the vortex lattice, and the homogeneity of the superconducting material, at least two different types of mechanisms of flux motion should be distinguished: *pin breaking* and *flux-line shear mechanisms*. In homogeneous systems the complete vortex lattice will collectively unpin if the driving force exceeds the pinning force. This situation is referred to as *pin breaking*.

In contrast, when the local pinning force strongly varies over length scales comparable to or larger than the vortex-vortex distance, vortices or bunches of vortices will start to move independently as soon as the driving force exceeds the flow stress of the vortex lattice. In the so called *flux-line shear mechanisms,* F_c is determined by the V-V interaction (not by the pinning). As a result, the volume pinning force is determined by the plastic shear properties of the vortex lattice. Areas, that are weakly pinned, shear away from strongly pinned regions. The resulting volume pinning force shows a characteristic temperature and magnetic field dependence (Kramer’s scaling law[3]) of the shear module of the vortex lattice: $F_c \propto \left(B_{c2}^2/w\right)b(1-b)^2$ with $b=B/B_{c2}$ and w representing the effective width of the area, in which the flux-lines move (channel). The field dependence is characterized by a peak at $B \approx B_{c2}/3$ and a quadratic decrease at high fields; the temperature dependence is identical to the temperature dependence shown in the contribution of Bernstein et al.. The flux-line shear mechanisms are usually encountered in strong pinning systems, whereas only weak pinning superconductors show types of pin breaking behaviour. Although, weak pinning channels could be caused by twin boundaries, vortex visualization experiments indicate, that flux line shear takes place in percolative paths that are defined by more severe inhomogeneities in HTS thin films.

In conclusion, the mechanisms of flux pinning and vortex motions are extremely versatile due to the complex interplay of the different interactions (V-V and V-P), the inhomogeneity of the real superconductor at different length scales, and the impact of additional forces or energies like driving forces or thermal energy. Consequently, there doesn't exist a single model for the explanation of vortex matter, which could be applicable to all systems. Only if the system under consideration is clearly defined it is possible to model flux pinning and vortex motion. For instance, flux-line shear mechanisms are likely to dominate the type of vortex motion in strong pinning superconducting systems. Temperature and field scaling can help to identify this mechanism, visualisation of the vortex motion can identify the channels for vortex motion. This should also be the approach to prove or disprove the model of Bernstein *et al.*, (twin boundaries are responsible for pinning and flux transport in HTS films at temperatures close to the transition temperature).

Vortex matter is an extremely interesting and intensely analysed field of research that still delivers new insights. This is among others triggered by technical innovation, new concepts, and (potential) applications such as:

- novel and improved preparation technologies of complex superconductors (*e.g.*, coated conductors) whose critical properties need to be understood and optimized,
- improvement of vortex visualization technologies (e.g., visualization of single vortices and antivortices including their dynamics) leading to new insight and phenomena in the field,
- improved numerical simulation tools ranging from Monte-Carlo, molecular dynamics to more-dimensional time-dependent Ginzburg-Landau approaches, and
- vortex matter in mesoscopic and nanoscopic systems, that leads to vortex manipulation and the possible development of novel fluxonic concepts.

A comprehensive discussion of these aspects of vortex matter within this *News Forum* is highly encouraged.

References and Notes

[1] Elevated temperature will lead to thermal assistance or thermal activation of flux motion. Due to the complexity of these mechanisms, the impact of thermal energy on flux motion will be neglected in this discussion.
[2] A.I. Larkin and Yu.N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979)
[3] E.J. Kramer, J. Nucl. Mater. **72**, 5 (1978)