

Local Studies of Vortex Instabilities and Memory Effects in NbSe₂

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Recent studies have shown a number of surprising vortex dynamics phenomena which include: low frequency noise, slow voltage oscillations, history dependent dynamic response, memory of the direction, amplitude, and frequency of the previously applied current, suppression of the *ac* response by a small *dc* bias, and a strong frequency dependence. These phenomena are incompatible with the current understanding of bulk vortex dynamics. We propose a generic mechanism in terms of the competition between the injection of a disordered vortex phase through the surface barriers, and the annealing of this metastable disorder by the transport current. The model is confirmed by investigating the current distribution across 2H-NbSe₂ crystals using arrays of Hall sensors.

In conventional superconductors like NbSe₂ the anomalous phenomena are found in the vicinity of the ‘peak effect’ (PE) in the critical current I_c as shown in Fig. 1. In HTS this situation is equivalent to the second magnetization peak where the ordered Bragg-glass phase is believed to transform into a disordered solid. Figure 1 shows that on the high temperature side of the PE I_c is frequency independent; in this region a disordered vortex phase is thermodynamically stable. In contrast, on the low temperature side, a significant frequency dependence is observed [1]. This is the region where all the unusual vortex response phenomena are found [1–4]. As described below, in the presence of an applied current a dynamic coexistence of the order phase (OP) and a metastable disordered phase (DP) is established in this region.

We propose [5] a dynamic model based on two main ingredients: The first is the observation that in NbSe₂ the DP can be readily supercooled to below the PE by field cooling, where it remains metastable, since thermal fluctuations are negligible. This supercooled DP is pinned more strongly and displays a significantly larger critical current J_c^{dis} as compared to J_c^{ord} of the stable OP. An externally applied current serves as an effective temperature and ‘anneals’ the metastable DP [1].

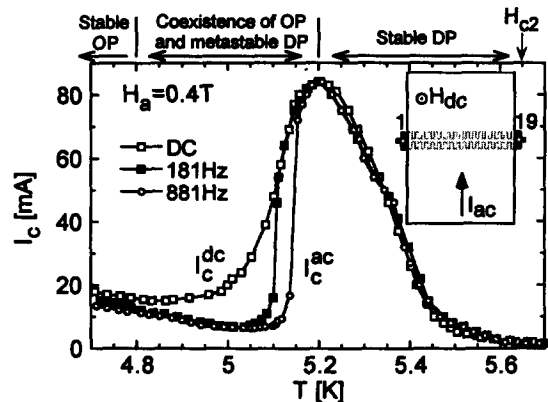


Fig. 1. The peak effect in I_c vs. T at various frequencies, as measured using a $1 \mu\text{V}$ voltage criterion. Inset: The experimental set up of NbSe₂ crystal on an array of 19 Hall sensors.

The second ingredient is the presence of substantial surface barriers (SB), as found [6] in NbSe₂. Consider a driven steady state flow of an OP. In the absence of SB, vortex penetration does not require any extra force, and the vortices penetrate close to their proper vortex lattice locations. In the presence of SB, however, a large force is required for vortex penetration and exit,

and hence much of the applied current flows at the edges [6,7]. Since the SB is very sensitive to surface imperfections, the penetrating vortices are injected predominantly at the weakest points of the SB, thus destroying the local order and forming a metastable DP near the edge, which drifts into the sample with the flow of the entire lattice. The applied current, therefore, has two effects: the edge current causes ‘contamination’ by injecting a DP, while bulk current acts as an annealing mechanism. The observed instabilities and memory phenomena arise from the fine balance between these two competing processes.

The annealing process is sensitive to the exact location on the $H - T$ phase diagram. Below the PE, the driven DP is highly unstable and therefore its relaxation time is short. As a result, it anneals rapidly over a short characteristic ‘healing’ length. On the other hand, near the PE the free energies of the DP and OP are comparable and therefore the ‘healing’ length is large. As a result, the DP penetrates deep into the bulk, resulting in a strong suppression of the dc response. In this situation the experimentally measured dc I_c does not reflect an equilibrium property, but rather a dynamic coexistence of two phases.

The ac response of the system is distinctly different since the contamination process occurs only near the edges, where the DP periodically penetrates and exits the sample, whereas most of the sample remains in OP. Thus, an ac current necessarily contaminates the sample less than a dc current of the same amplitude, and therefore $I_c^{ac} \leq I_c^{dc}$, as seen in Fig. 1. In addition, since the width of the DP near the edges decreases with frequency, I_c^{ac} should decrease with f explaining the frequency dependence of I_c^{ac} in Fig. 1. Furthermore, at sufficiently high frequency I_c^{ac} should approach the true I_c of the stable phase. The steep increase of the 881 Hz I_c^{ac} data in Fig. 1 therefore indicates that the OP transforms sharply into the DP at the PE.

We now provide a direct experimental manifestation of the model, which is the spatial variation of the disorder and $J_c(x)$, and of the transport current distribution that traces this $J_c(x)$. We use Hall sensors to measure the ac current self-induced field $B_{ac}(x)$, which is then directly in-

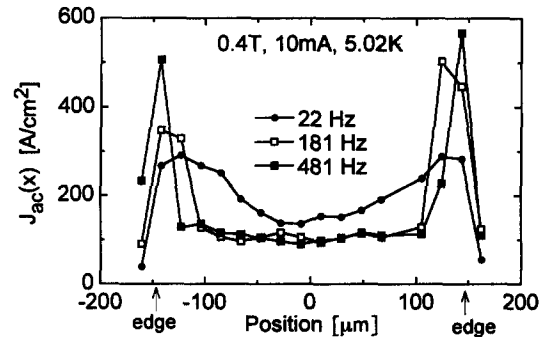


Fig. 2. Current density profiles $J_{ac}(x)$ at 22, 181 and 481 Hz, obtained by inversion of the self-induced field measured by the Hall sensors.

verted into the current density distribution $J_{ac}(x)$ using the Biot-Savart law [5,6] (inset to Fig. 1). Figure 2 shows the corresponding current profiles $J_{ac}(x)$ measured at different frequencies. At high f , the DP with the enhanced J_c is present only in narrow regions near the edges (481 Hz data). As the frequency is reduced, the enhanced $J_{ac}(x)$ flows in wider regions near the edges. The described phenomena should be absent in the Corbino disk geometry where vortices do not cross the sample edges, as confirmed by our studies of NbSe₂ in this geometry.

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