Dynamical fluctuations in mode locking experiments on vortices moving through mesoscopic channels

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We have studied the flow properties of vortices driven through easy flow mesoscopic channels by means of the mode locking (ML) technique. We observe a ML jump with large voltage broadening in the real part of the rf-impedance. Upon approaching the pure dc flow by reducing the rf amplitude, the ML jump is smeared out via a divergence of the voltage width. This indicates a large spread in internal frequencies and lack of temporal coherence in the dc-driven state.

I. INTRODUCTION

One of the powerful techniques for probing the dynamic state of driven vortex matter in type II superconductors is the mode locking (ML) experiment. ML is a dynamic resonance between a superimposed rf drive and the dynamic lattice mode (as expected to appear when vortices flow coherently in a (random) pinning environment) excited collectively at the internal (washboard) frequency \( f_{int} = qv/a \) with \( q \) integer, \( v \) the average dc velocity and \( a \) the lattice spacing of the array along the flow direction. When \( f_{int} \) and the rf drive frequency \( f \) are harmonically related, i.e., \( f_{int} = pf \) with \( p \) integer, the resonance appears as steps in the dc current-voltage \((I-V)\) characteristics and also emerges more sensitively as jumps (dips) in a real (imaginary) part of rf impedance at low rf drives \( I_{rf} < I_{dc} \) [1] [2] [3].

So far, some features of the ML phenomenon have been well studied in sliding charge density waves in quasi one dimensional conductors [4]. It turns out that complete ML features characterized by ”perfect” steps in dc \( V-I \) curve appear when the flow is coherent enough, whereas incomplete features like rounded and broadened steps in the \( V-I \) curve appear if the flow becomes more incoherent. Thus, the ML feature provides information on the amount of coherency in the flow. In this study, we have employed the ML technique to study flow of vortices driven through disordered mesoscopic channels [3].

II. EXPERIMENTAL

The channel device consists of a strong pinning NbN film (thickness \( d=50\text{nm} \)) on top of a weakly pinning amorphous Nb\(_{1-x}\)Ge\(_x\) film (\( d=550\text{nm} \) and \( x \approx 0.3 \)). By reactive ion etching and proper masking, straight channels were etched leaving a 300nm thick NbGe layer. The width and length of each channel is 230nm and 300\(\mu\)m, respectively. The pinning potential for vortices inside the channel is dominated by the interaction with strongly pinned edge vortices which form a disordered configuration (see the inset to Fig.1). The transport current is applied perpendicular to the channel and drives the vortices along the channel. For ML experiments, we sweep the dc current with a constant superimposed rf current and record both the in- and out-of-phase part of the rf-voltage as well as the dc voltage. The sample was immersed in superfluid \(^4\)He at a temperature of 1.9K.

III. RESULTS AND DISCUSSION

Because of the confinement of the vortex array in the channels, an integer number \( n \) of rows is expected to form inside each channel. In a previous study, we demonstrated that the flow configuration can be related to the voltage \( V_{1,1} \) at which the fundamental ML \((p=q=1)\) occurs [3]. Namely,

\[
V_{1,1} = f \phi_0 n N_{ch}
\]

with \( \phi_0 \) the flux quantum and \( N_{ch} \approx 200 \) the number of channels.

\[\text{FIG. 1. The dc voltage dependence of the real part of the rf impedance } Z_{real} \text{ measured by applying 6MHz rf currents of various amplitudes at 1.9K and 170mT. The upper two curves are shifted upwards by 3 and 6 mΩ. The inset shows a schematic configuration of vortex array around a channel.}\]

In Fig.1 we plot the real part of the rf-impedance \( Z_{real} \) versus the dc voltage \( V \) taken at several magnitudes of rf currents \( I_{rf} \) of 6MHz. We choose a field of 170mT where moving configurations of \( n=4 \) rows form in each channel. Around \( V_{1,1} \approx 9\mu\text{V} \) we observe rounded jumps, while below and above \( V_{1,1} \) \( Z_{real} \) increases monotonically with \( V \).
It is clear that the height and the voltage broadening of the rounded jump are enhanced when $I_{rf}$ is reduced. For definition of the jump height $\Delta Z$, we take the derivative of $Z_{\text{real}}$ versus $V$ and integrate over the corresponding peak in a differential plot of $dZ_{\text{real}}/dV$ versus $V$. The inset to Fig.2 shows a plot of $\Delta Z$ as a function of $I_{rf}$. By decreasing $I_{rf}$, $\Delta Z_{\text{real}}$ first increases and then levels off at low $I_{rf}$. Thus, $\Delta Z_{\text{real}}$ is "ohmic" at low $I_{rf}$, consistent with the Fiory experiment [1] and theory [2].

Next we turn to the voltage broadening $\delta V$ of the rounded jump. Figure 2 shows the rf current dependence of $\delta V$. We determine $\delta V$ by taking the full width at half maximum of the peak in the differential plot. It is clear that, with reducing $I_{rf}$, $\delta V$ increases monotonically and seems to diverge at $I_{rf} \approx 0$. Since $\Delta Z_{\text{real}}$ is constant, this indicates that the jump is smeared out toward $I_{rf} \rightarrow 0$.

Such divergence of $\delta V$ implies a pronounced spread in the internal frequency, i.e., a wide distribution of local velocities and/or lattice spacings. In fact, we find that no narrow band noise at $f_{\text{int}}$ is detectable in the dc vortex flow. With increasing $I_{rf}$, however, the spread in $f_{\text{int}}$ gradually decreases. This can be explained by the frequency pulling effect where the distribution of $f_{\text{int}}$ narrows and becomes locked into $f$ [5]. Thus, with increasing rf drive, the ML gradually enhances the order of the moving vortex lattice.

At high rf drives, the ML jumps in the $Z_{\text{real}}(V)$ curves disappear. Therefore, we determined $\delta V$ from the measured current steps in the dc $I-V$ curves. The open symbols in Fig.2 show that this $\delta V$ first decreases monotonically and then levels off at large $I_{rf}$. This indicates that complete (characterized by $\delta V=0$) ML does not occur, even at high rf drives. Since $\delta V$ is more than one decade larger than what is expected for purely elastic deformations [1,2], we conclude that slip between moving rows and possibly remaining plastic regions in the channel partially influence the ML characteristics. This plasticity is caused by the disordered vortex configurations in the channel edges.

FIG. 2. Plot of voltage widths for fundamental jump in real part of rf impedance (solid symbols) and fundamental dc current step (open symbols) as a function of rf current. The height of the impedance jump is plotted against rf current in the inset.

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