attoMICROSCOPY
Sophisticated Tools for Science

Dynamic Visualization of Nanoscale Vortex Motion using attoSTM in an attoLiquid3000

M. Timmermans, T. Samuely, B. Raes,
J. Van de Vondel, V. V. Moshchalkov
INPAC Institute for Nanoscale Physics and Chemistry, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

B. Sipos
attocube systems AG, Munich, Germany

Scanning Probe Microscopy (SPM) and especially Scanning Tunneling Microscopy (STM) is well known for its outstanding spatial resolution. Therefore it is a particularly powerful technique to study superconductors. As such, STM has been used to image the Abrikosov vortex lattice in $NbSe_2$ and explore details of the superconducting gap in various High-T_c superconductors. Until now, all these studies lack temporal resolution, disregarding any dynamic nature of superconductivity and the vortex lattice.

Matias Timmermans and co-workers invented an innovative technique removing this limitation [1]. They used an attoSTM in an attoLiquid3000 ^{3}He cryostat to measure and study vortex motion in 2H-$NbSe_2$ on a much shorter time scale. They induced a periodic movement of the vortices by applying a small AC magnetic field. The external perturbation results in a distinct smearing of the vortex (Fig 1b) as compared to the image where no excitation was used (Fig 1a). Instead of collecting several consecutive images, the tunneling current is recorded at each point over three cycles of the excitation. The exceptional thermal and spatial stability of the attoSTM in the attoLiquid3000 allows further analysis of the time dependence of this signal at each point. Using an additional lock-in technique more details and understanding of the vortex motion is revealed. By mapping the first and a second harmonic of the tunneling signal, they were able to visualize changes of the vortex lattice when the vortex density is increased by increasing the DC magnetic field.

At low vortex densities (i.e. low DC magnetic fields) the vortex motion is relatively unordered, and mainly determined by local impurities overruling the vortex-lattice interaction. By increasing the vortex-vortex interaction the motion evolves from individual to collective. At higher DC magnetic field values higher harmonics are observed in the recorded signal, as shown in Figure 2a-d. This is a clear indication of mode-locking in this dynamic system.

In a next step, they used the AC excitation as a time reference to track the motion of individual vortices in time. This results

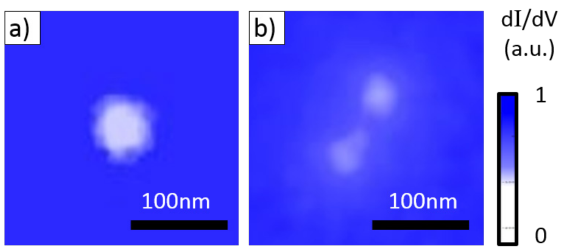

Figure 1: *The tunneling current map of a superconducting vortex without AC magnetic field (a). The application of the AC excitation smears the vortex along the line of its movement (b).*

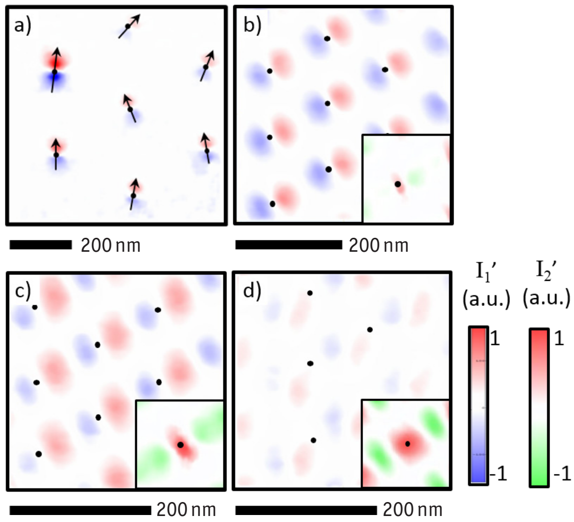

Figure 2: *The intensity of the first harmonic of the tunneling current at different DC magnetic field levels. In the inset the second harmonic is plotted. One can see how first the motion becomes collective (b) and then the first harmonic disappears (d) when the mode-locking happens.*

in time resolved snapshots of the vortex motion, which allows them to construct a movie frame by frame. This visualization procedure is unprecedented and promises a much better understanding of the dynamical behavior of the superconducting condensate. The trajectories of two vortices are shown on Figure 3. Contrary to the expectation the vortex does not move in a line but follows a circular motion, due to a potential created by atoms and/or vortices.

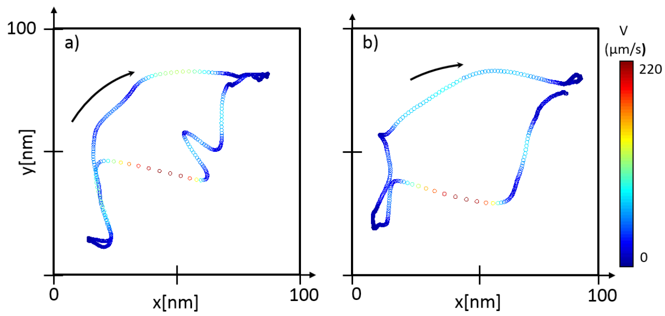

Figure 3: *The trajectory of two vortex orbits. The color code shows the velocity at each point.*

This note shows the application of a novel technique capturing the dynamics of superconducting vortex motion. Measuring the local time dependence of the tunneling current with an attoSTM, Matias Timmermans and co-workers recorded the vortex trajectory revealing a nano-scale orbit. This unique technique can be transferred to any system with periodic motion or where periodic motion can be imposed on.

References

[1] M. Timmermans, T. Samuely, B. Raes, J. Van de Vondel, V. V. Moshchalkov, ACS Nano **8**, 2782 (2014).

attocube
WITTENSTEIN Group