Sensing superconducting vortices with Dayem nanobridge

M. Foltyn[1], K. Norowski[1], M.J.Wyszyński[2], M.V. Milošević[2], M. Zgirski[1]*

*e-mail: zgirski@ifpan.edu.pl

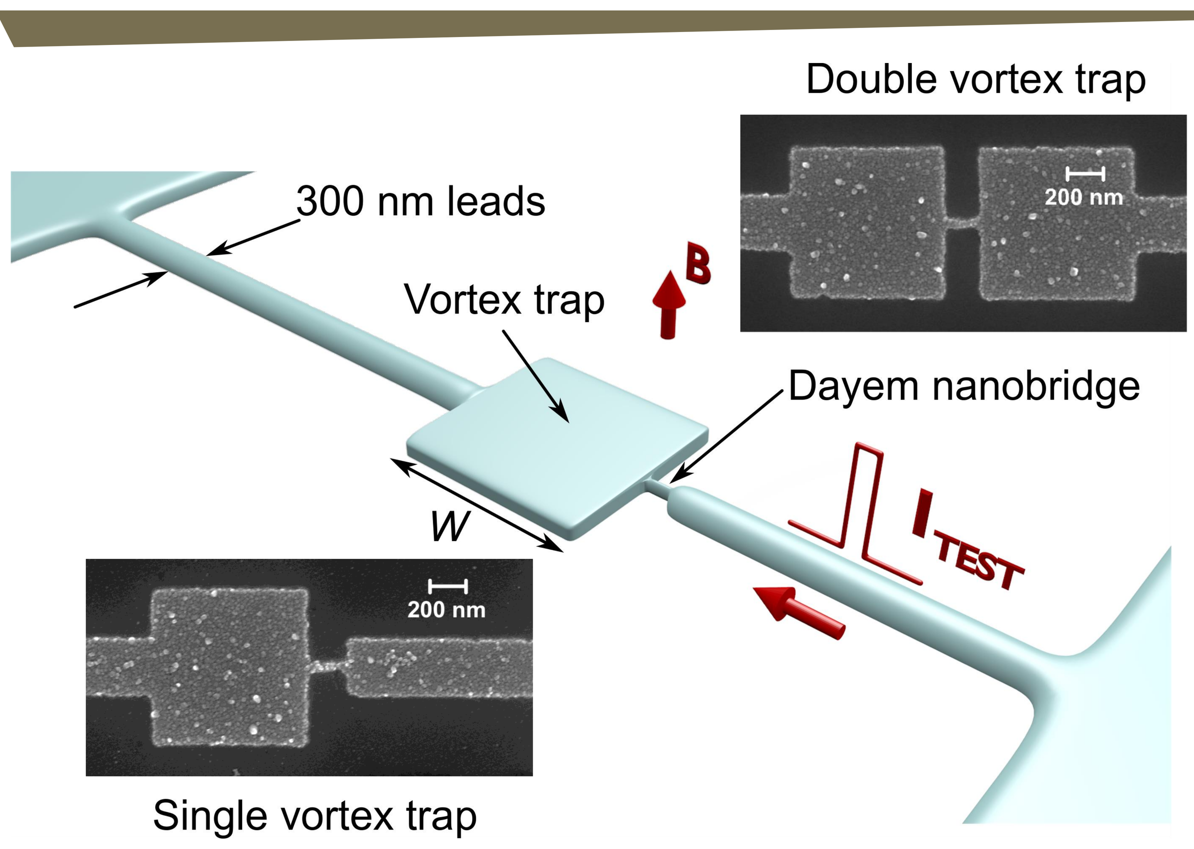
[1] Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL 02668 Warsaw, Poland

[2] Department of Physics & NANOlab Center of Excellence, University of Antwerp, Groenenborgerlaan 171, B-2020 Antwerp, Belgium

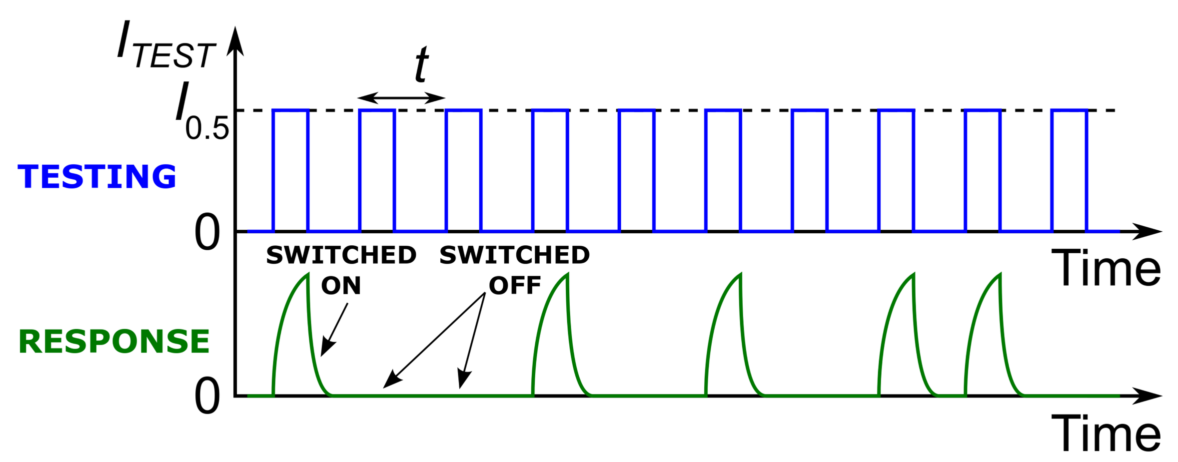
INTRODUCTION

We propose a simple-design nanodevice in which vortex trap in a form of the aluminum square is integrated with a Dayem nanobridge. We perform field-cooling of the boxes arriving to different vortex configuration, dependent on the applied magnetic field. We show that the switching current of the bridge is sensitive to the presence of vortices in the trap. Our measurements allow for easy observation of the first and successive vortex entries into squares of various sizes ranging from 580 nm to 1.9 µm. The experimental results are well accounted for by Ginzburg-Landau simulations. They reveal enhancement of the order parameter caused by reduction of the Meissner screening currents in the vicinity of the bridge when additional vortex enters into the trap. An ease of integration and simplicity make our design a convenient platform for studying dynamics of vortices in strongly confined geometries, involving a promise to manipulate vortex states with electric current.

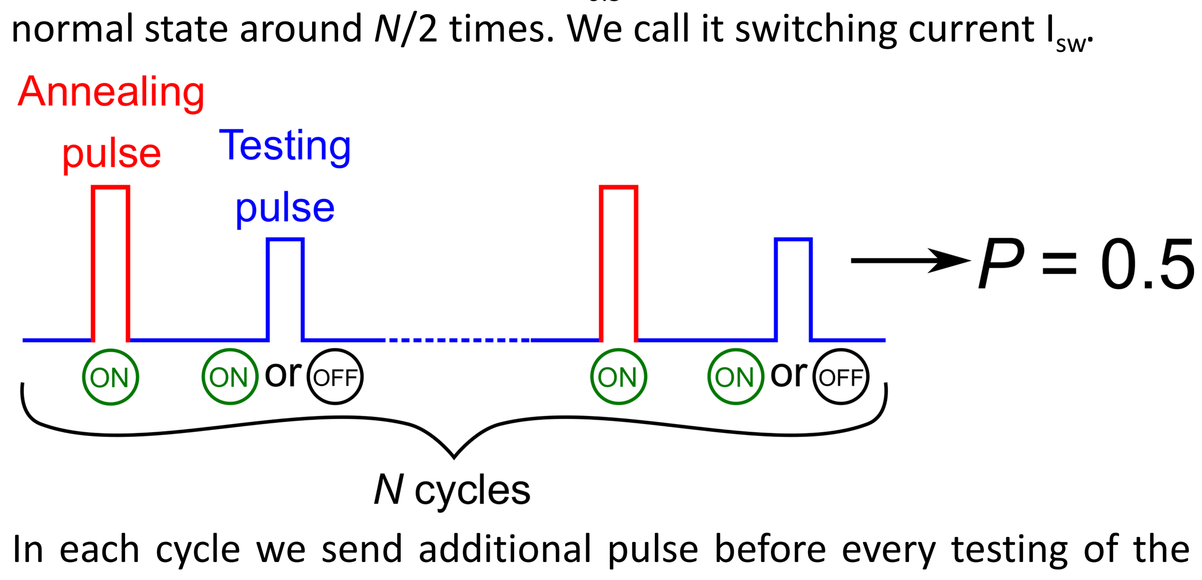
SAMPLE & MEASUREMENT



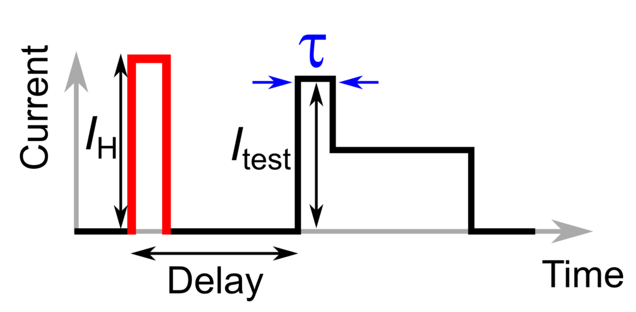
The sample consists of the square vortex trap(s) in immediate contact with a short Dayem nanobridge. The traps are connected to the contact pads via a ~100 µm-long and 300-nm wide leads. Electric pulse is applied to one contact pad, while the second pad is grounded. Insets show SEM photos of the typical aluminum structures of the single and double vortex traps.



We use the same measurement protocol like in our previous works [1-4]. We send a train of N pulses to the nanobridge in order to determine its switching probability P. For a certain current amplitude of the testing pulses ($I_{0.5}$) the nanobridge switches to the normal state around $N/2$ times. We call it switching current I_{sw}.



In each cycle we send additional pulse before every testing of the nanobridge, which acts as a "reset". The annealing pulse always switches the nanobridge to the normal state and overheats the vortex trap above T_c.

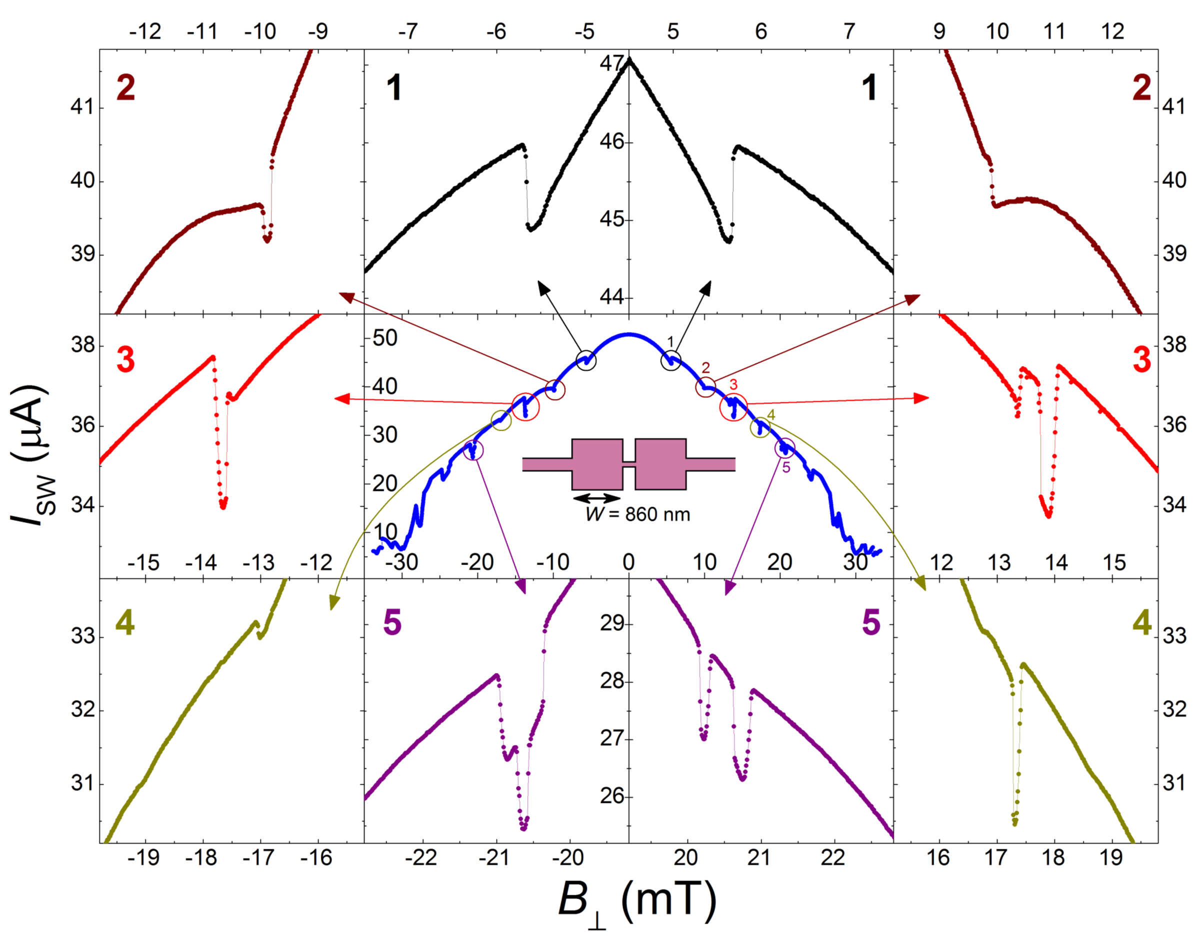


Pump and probe protocol [1-4] is convenient to investigate thermal transients of the nanostructure. We use it to study quasiparticle diffusion in vortex state.

References

[1] M. Zgirski, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J. Pekola, ***Phys. Rev. Applied*** 10, 044068 (2018)
[2] M. Zgirski, M. Foltyn, A. Savin, A. Naumov, K. Norowski, ***Phys. Rev. Applied*** 14, 044024 (2020)
[3] M. Zgirski, M. Foltyn, A. Savin, K. Norowski, ***Phys. Rev. Applied*** 11, 054070 (2019)
[4] M. Zgirski, M. Foltyn, A. Savin, K. Norowski, ***Phys. Rev. B*** 104, 014506 (2021)
[5] M. V. Milosevic, R. Geurts, **Phys. C: Superconductivity** 470, 791 (2010)

NANOBRIDGE AS A VORTEX DETECTOR

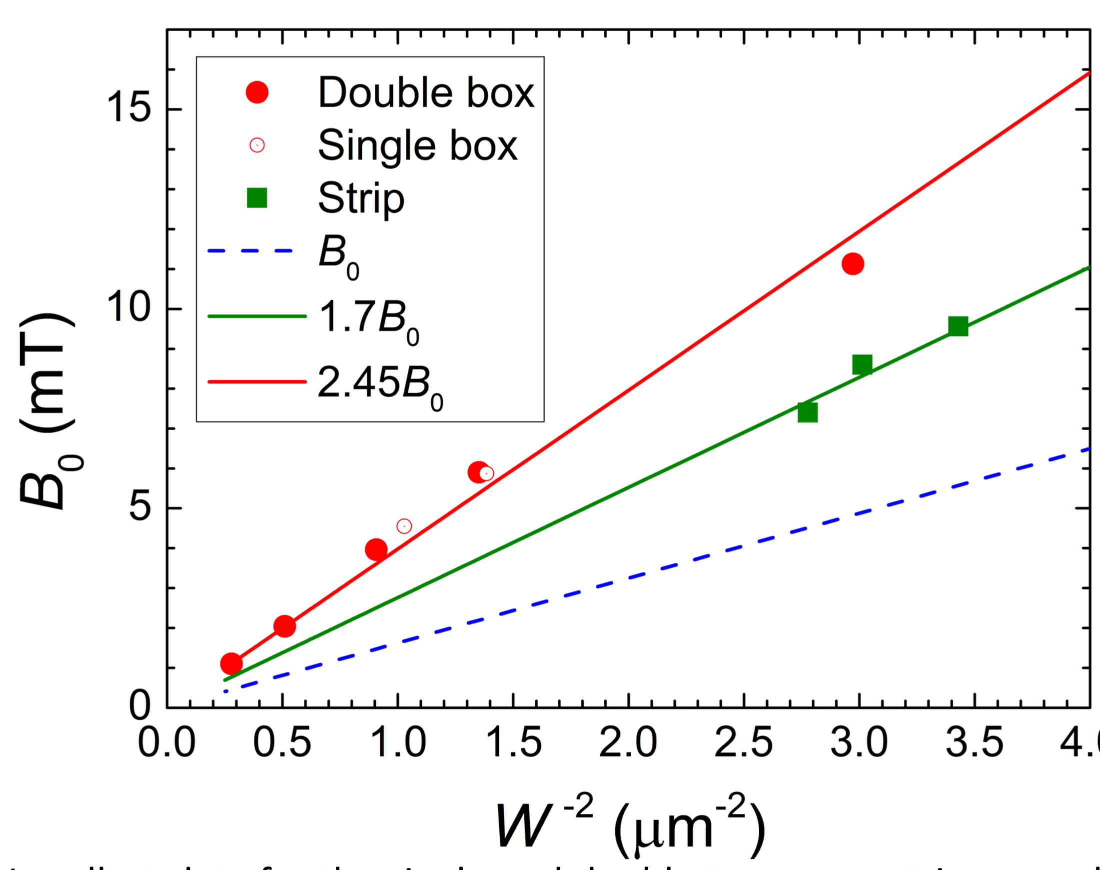


We measure switching current I_{SW} as a function of perpendicular magnetic field $B_\perp$ for various samples (one of the results is shown above) at bath temperature T_0=400mK. Independently of the sample geometry, for low applied perpendicular magnetic fields we see monotonous lowering of the I_{SW}, which we associate with influence of the Meissner screening currents on the superconducting order parameter. As we increase the magnetic field we see a step-like change of the bridge I_{SW}. The further steps are visible at larger magnetic fields. We associate the appearance of the steps with the entries of magnetic field vortices.

For long type-II superconducting strips it is predicted that upon exceeding B_0 Gibbs free energy start to develop a metastable minimum for the existence of vortices. It is localized in the middle of the strip and separated with barriers placed at the edges of the strip. The critical magnetic field for vortex penetration is:

$$B_0 = \beta \frac{\pi \Phi_0}{4W^2}$$

where W is the nanowire width, Φ_0 is the magnetic quantum flux ($h/2e$) and β is the phenomenological scaling parameter, which in the original prediction is equal 1.



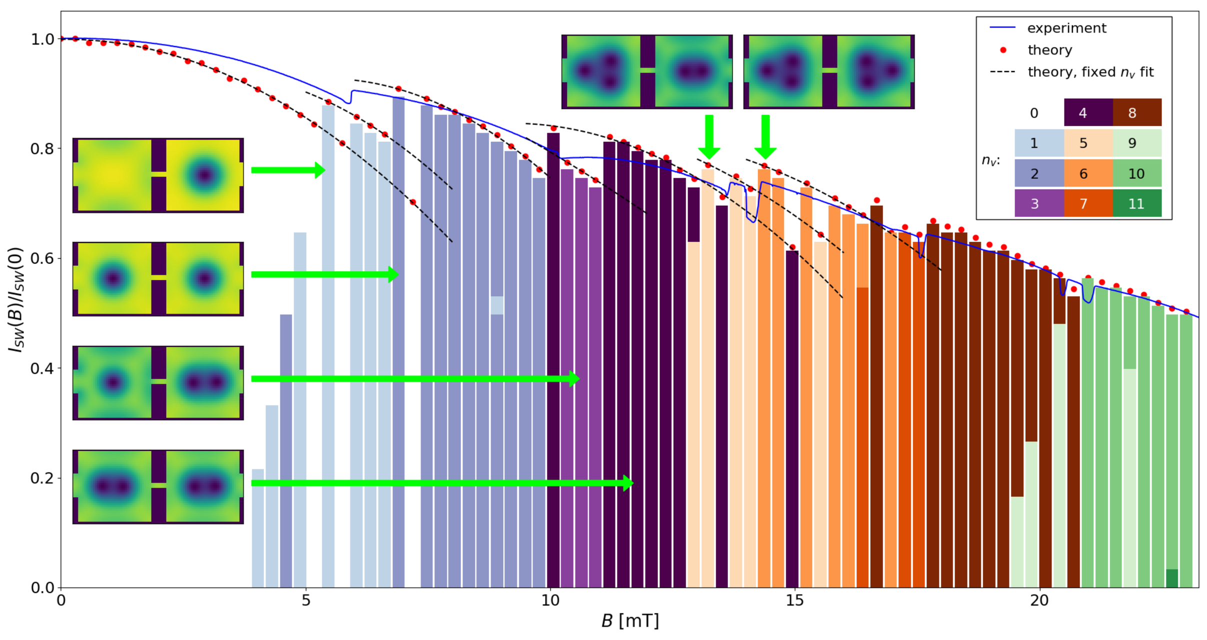
We collect data for the single and double trap geometries as well as for the reference nanowires, and verify B_0(W) relation by plotting the first-vortex-entry field B_0 vs. W^{-2}. The functional dependence of the above equation properly describes our data, if to assume the additional phenomenological scaling parameter β. The measured values of B_0 for the single and double traps are 2.45 times larger than it is predicted for superconducting strips. The data for nanowires also point to the increased value of the critical field compared to the primary prediction with β=1.7.

GINZBURG-LANDAU SIMULATIONS

In order to gain insights into vortex states in the traps, we have performed time-dependent Ginzburg-Landau (tdGL) simulations. The behavior of the superconducting condensate is described by a complex-valued order parameter which is allowed to vary in time and space. We have used the tdGL equations for dirty superconductors [5], where the equation for order parameter reads:

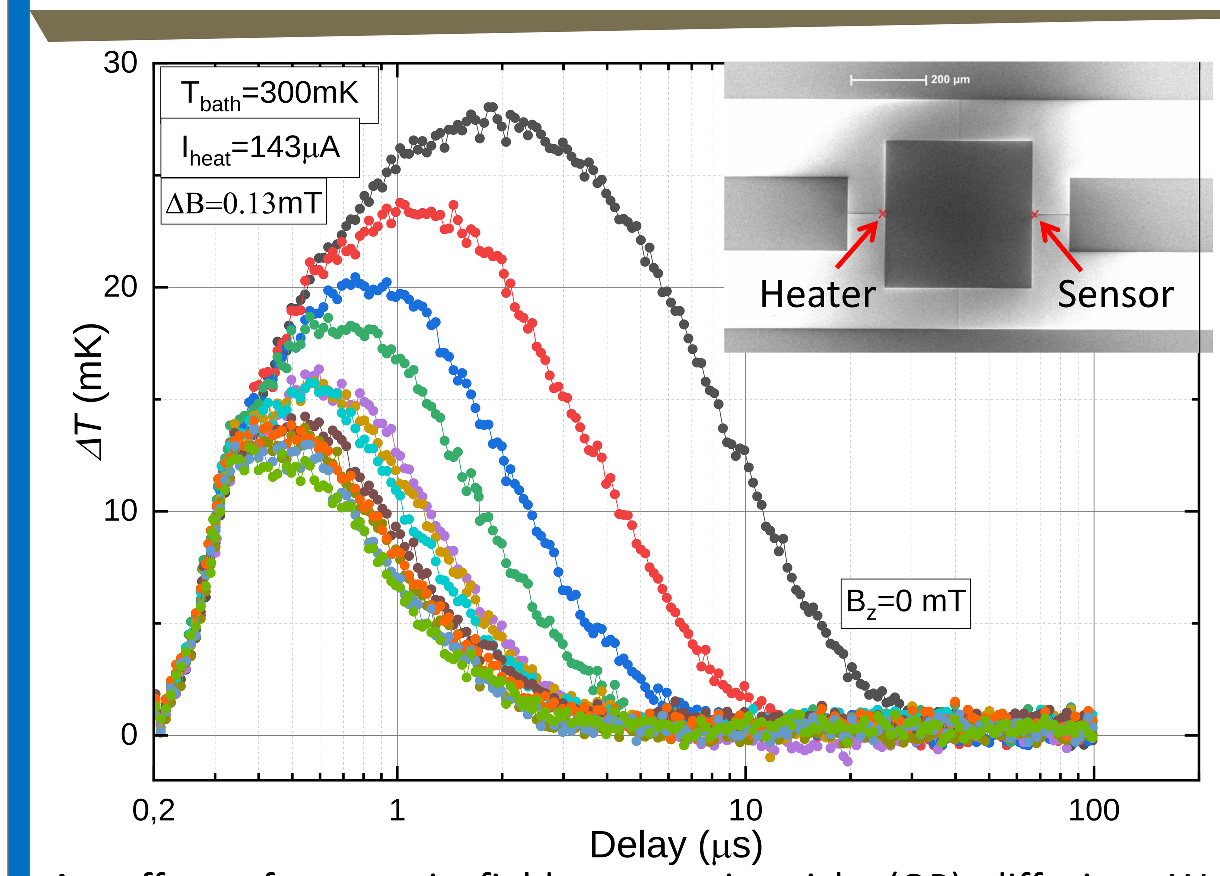
$$\frac{u}{\sqrt{1+\gamma^2|\Psi|^2}}\left(\frac{\partial}{\partial t}+i\varphi+\frac{\gamma^2}{2}\frac{\partial|\Psi|^2}{\partial t}\right)\Psi=(\nabla-i\mathbf{A})^2\Psi+\left(1-|\Psi|^2\right)\Psi$$

where u≈5.79 is the ratio of the relaxation time for the amplitude and phase of the order parameter, **A** is the external magnetic vector potential, φ is the electrostatic potential and γ is a measure of the dirtiness of the sample, which characterizes the influence of the inelastic phonon-electron scattering on the condensate.

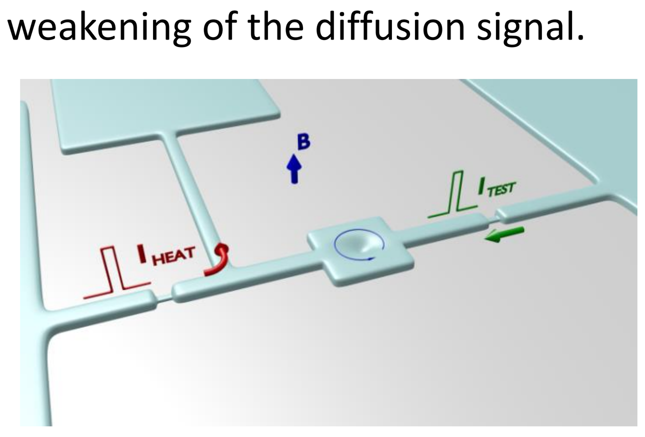


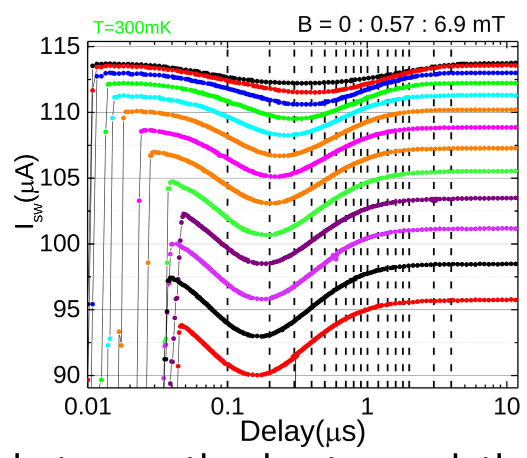
Red points are switching current values I_{sw} predicted by simulation, while the solid line is experimental. Each simulated point is calculated independently for the fixed value of the applied magnetic field. It is obtained as a result of successive equilibrations at step-like increasing values of the applied current. The switching current is defined as the one corresponding to the onset of the phase-slip process in the nanobridge. The colorful bars denote the number of vortices trapped at the given applied magnetic field n_v(B). This number is stochastic: it is possible to obtain different number of trapped vortices when repeating the simulation with the same initial conditions. The trapping stochasticity is at the root of not sharp transitions between vortex configurations i.e. reentrant behavior is observed whenever we see a decrease in v(B) although B was increased. The stochasticity may explain rounding of the experimental curves since they result from measurement performed over N=10 000 realizations. Noteworthy, the simulated points belong to different families, each family with its own vortex number. They are marked with broken lines in the plot to provide a convenient guide for an eye. For some magnetic field values, simulation predicts expulsion of the vortex during testing pulse before the switching current is reached: it is visible for the two-color bars with the transition in color indicating the current for which vortex was expelled.

VORTEX AS A QUASIPARTICLE TRAP

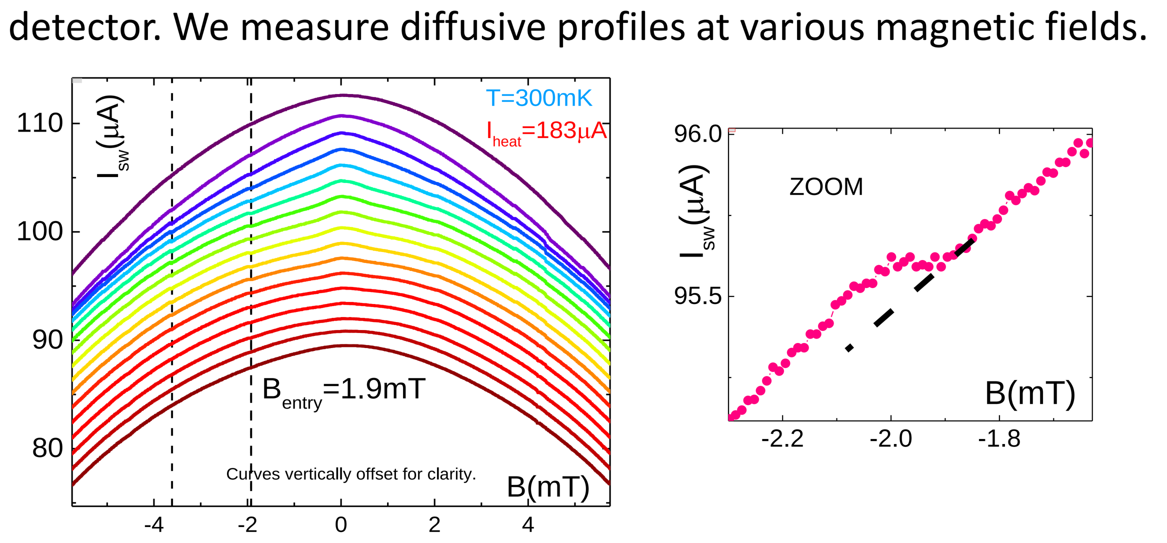


An effect of magnetic field on quasiparticle (QP) diffusion. We excite the heater with a short current pulse (~5 ns), initiating the diffusion of quasiparticles. The testing signal sent on the detector is delayed with respect to the heating pulse. The vortices, that are present in a big central pad, trap quasiparticles. It leads to the weakening of the diffusion signal.





We place a small box on the way between the heater and the detector. We measure diffusive profiles at various magnetic fields.



Absorption of QPs by a single vortex is visible as a small enhancement of the switching current observed on the I_{sw}(B) curves measured at various delays after application of the heating pulse. The kink corresponds exactly to the field where a single vortex entry into the box is expected.