Josephson junction thermometry for dynamical investigations of thermal processes at nanoscale

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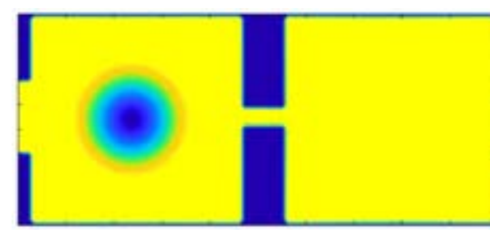
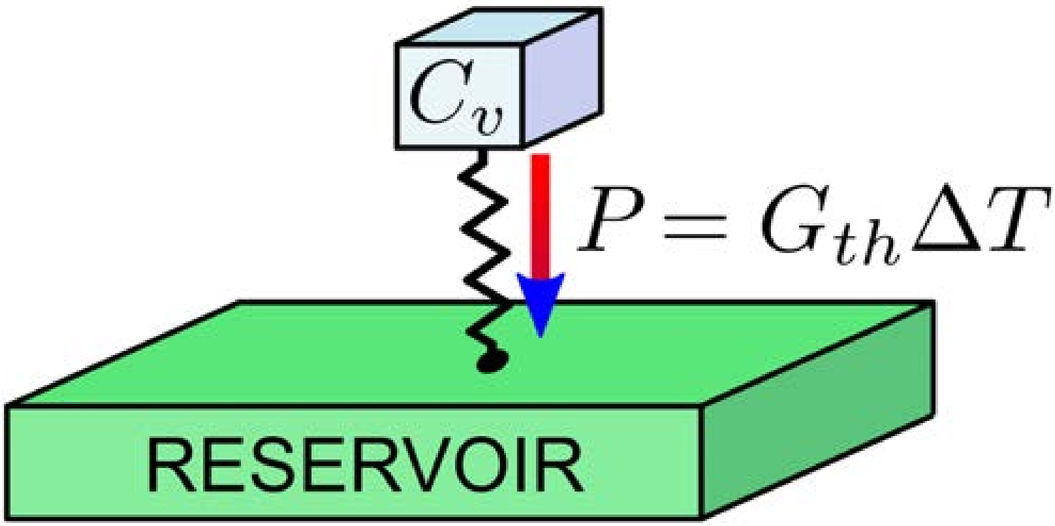
Summer School: Physics of Quantum Chips, University of Gdańsk, 04/07/2025

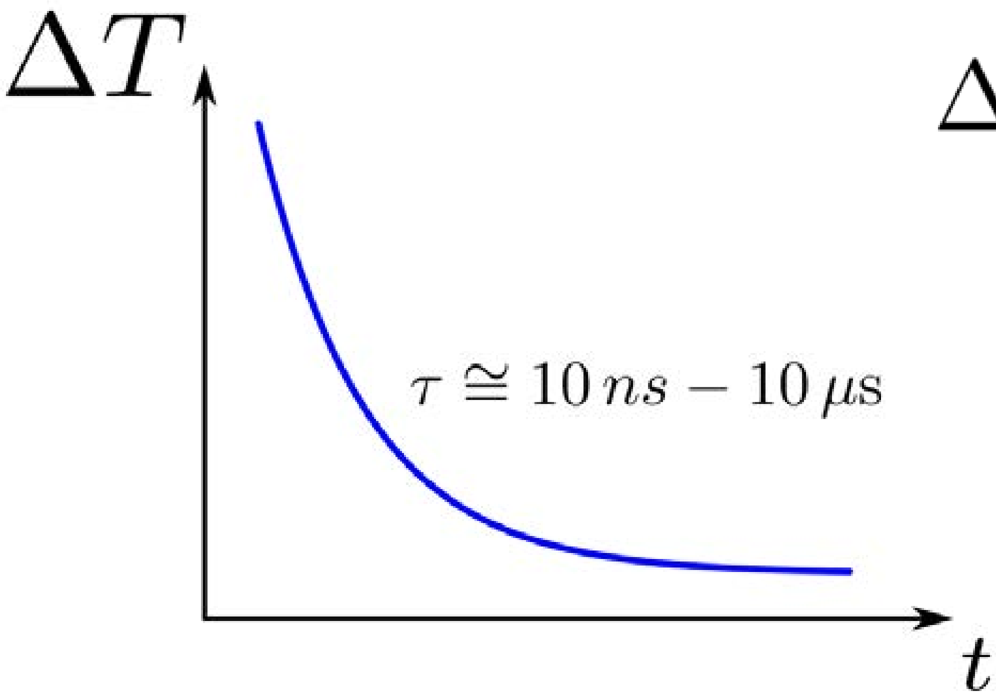


Problem



$$-C_v \frac{d(\Delta T)}{dt} = G_{th}\Delta T$$

Solution in a linear regime



$$\Delta T = \Delta T_0 exp\left(-\frac{t}{\tau}\right)$$

$$\tau = \frac{C_v}{G_{th}}$$

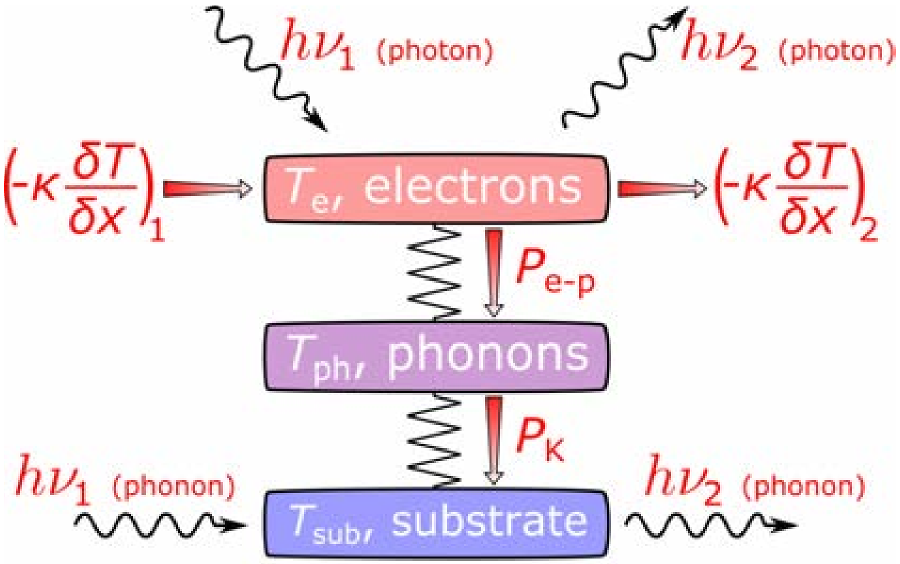
Thermodynamics at nanoscale

"Thermodynamic studies of mesoscopic devices have lagged far behind the corresponding electrical and magnetic investigations. This dearth can be attributed to a lack of fast, robust thermometers that can be easily integrated with nanoscale structures."

D.R. Schmidt, C.S. Yung, and A.N. Cleland

Nanoscale radio-frequency thermometry, Appl. Phys. Lett. 83, 1002 (2003)

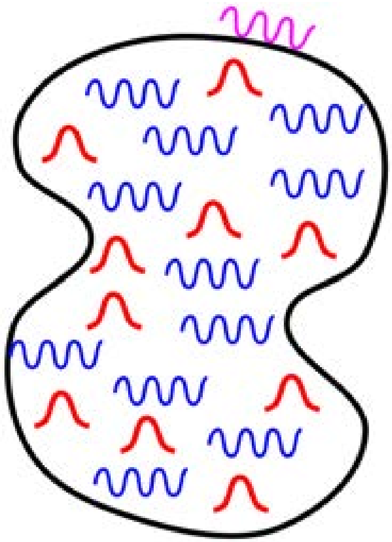
Heat flows at nanoscale

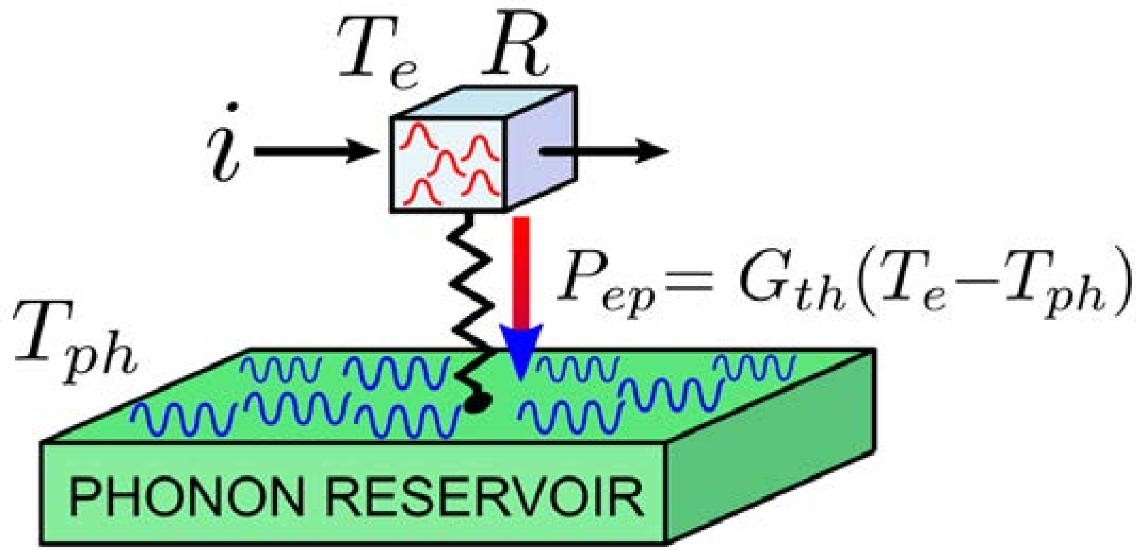


- Electron-phonon coupling
- Hot electron diffusion
- Photon radiation
- Phonon emission
- Kapitza resistance across metal-substrate interface

- Mainly investigations in steady states so far.
- Need to measure heat flows
  in the dynamic thermal transients in the nanosecond regime.

Example: Electron-phonon coupling



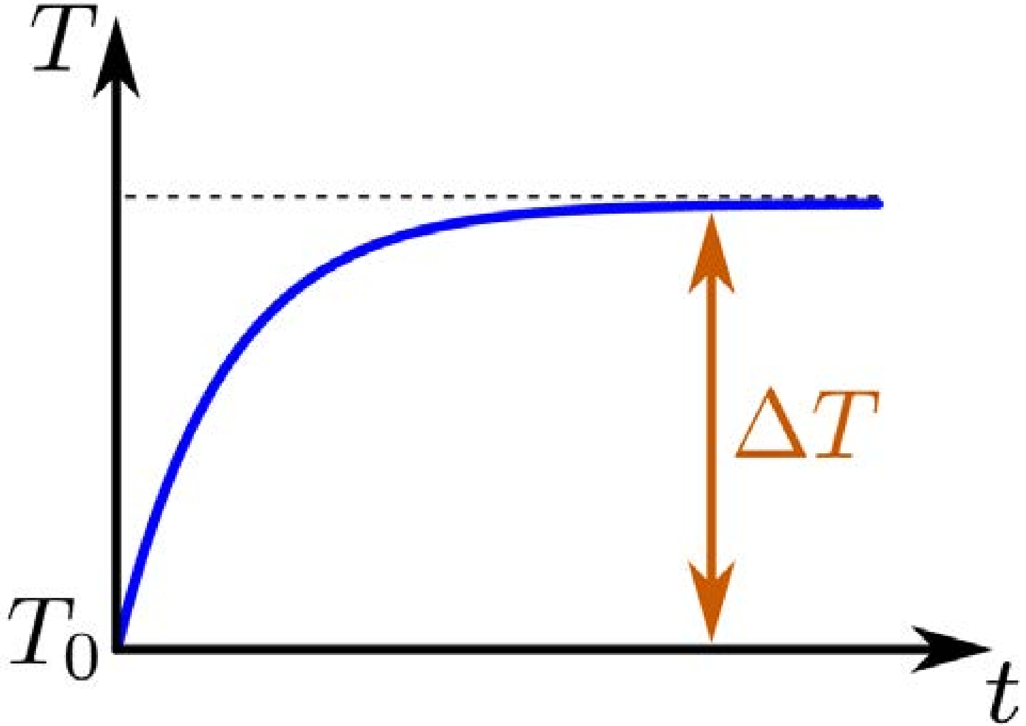


$$P_{ep} = \Sigma \left(T_e^5 - T_{ph}^5 \right)$$

$$P_{ep}^{linear} = \frac{\delta P_{ep}}{\delta T} \Delta T = 5 \Sigma T_0^4 \Delta T = G_{ep} \Delta T$$

$$G_{th} = G_{ep} = 5 \Sigma T_0^4$$

How to determine G_{th}?



$$G_{th}\Delta T = i^2 R$$

$$G_{th} = \frac{i^2 R}{\Delta T}$$

(Fast) nanothermometry

Calorimetry, Bolometry

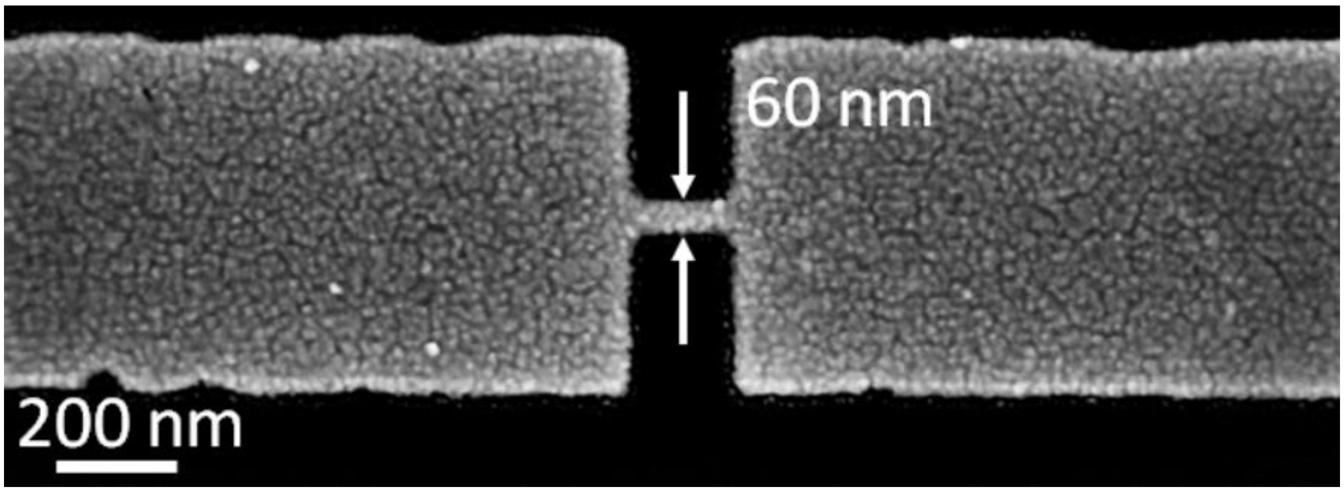
Quasiparticle population &propagation

Thermal budget of nanostructures

Quantum thermodynamics

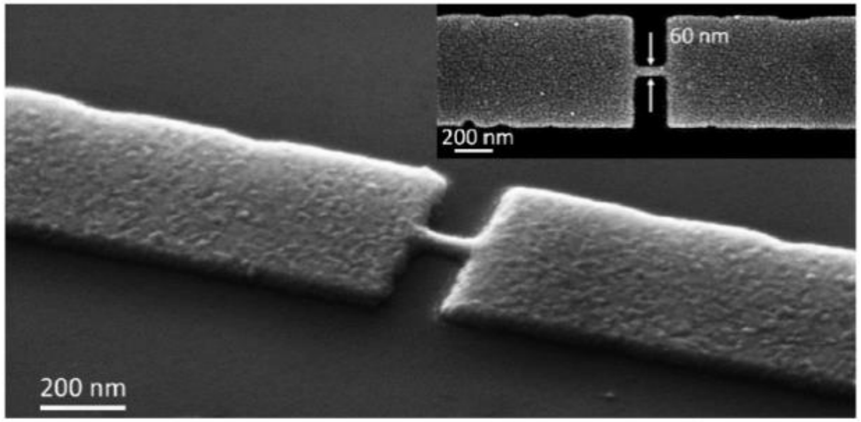
Dissipation (limits the coherence, breaks the topological protection)

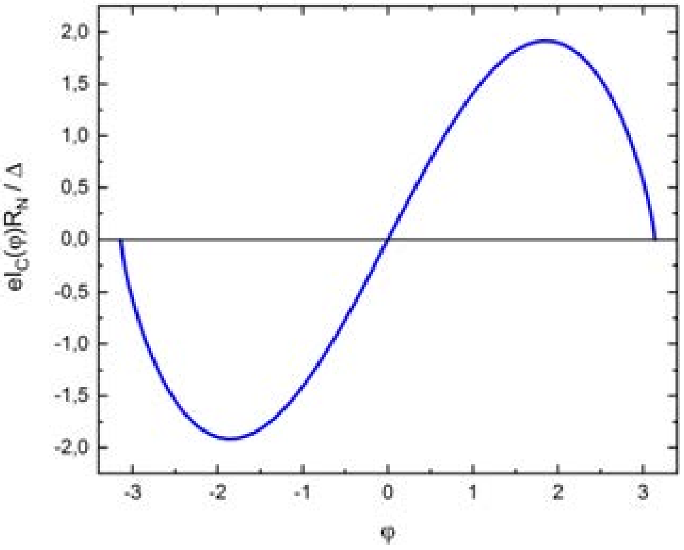
JJ: Dayem nanobridge

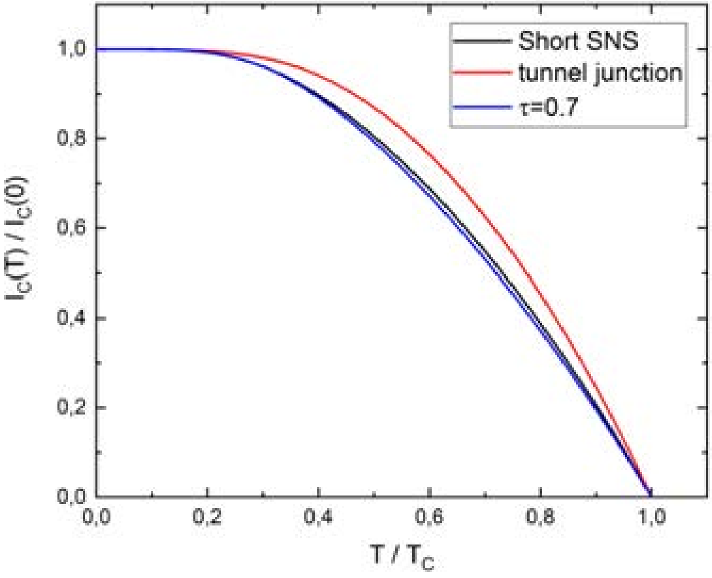


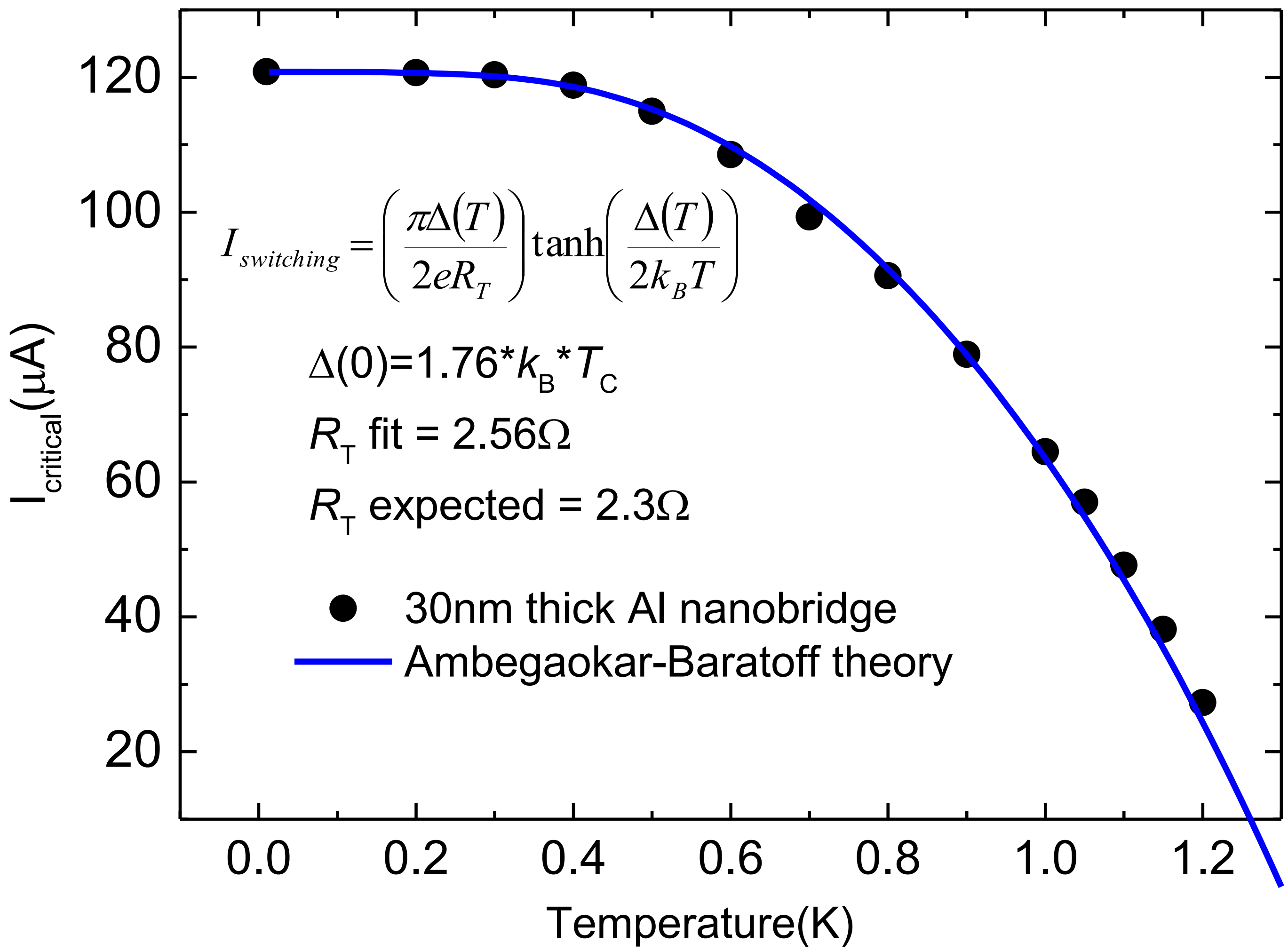
Diffusive JJ: average transmission tau~0.75

CPR for a diffusive link



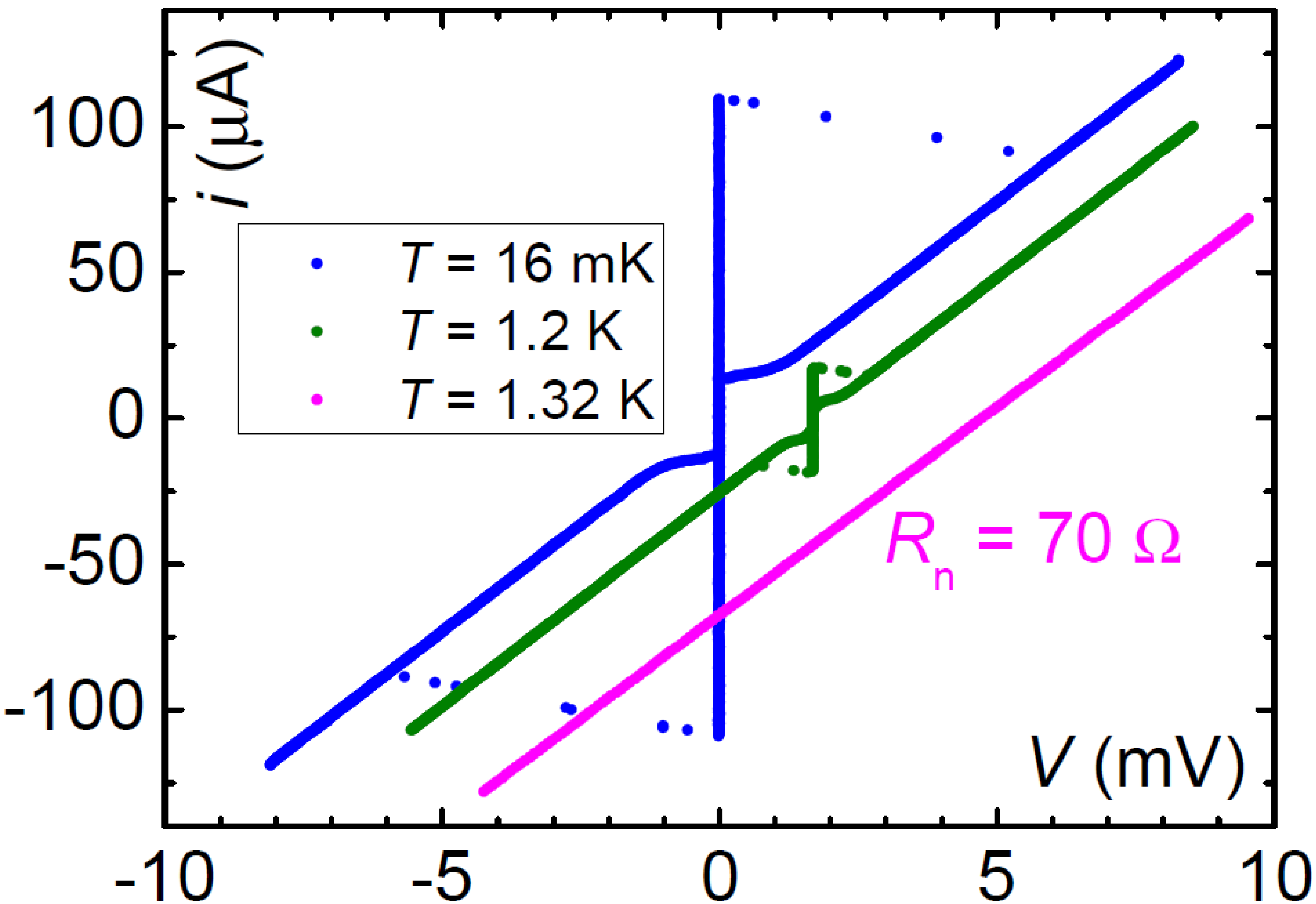




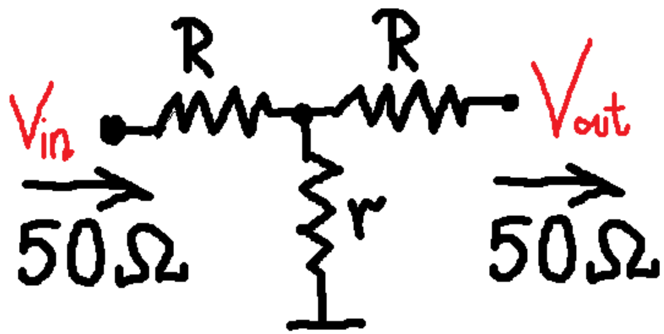


120
100
80
60
40
20
$I_{critical}(\mu A)$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Temperature(K)
$I_{switching} = \left(\frac{\pi\Delta(T)}{2eR_T}\right)\tanh\left(\frac{\Delta(T)}{2k_B T}\right)$
$\Delta(0)=1.76*k_B*T_C$
R_T fit = 2.56Ω
R_T expected = 2.3Ω
30nm thick Al nanobridge
Ambegaokar-Baratoff theory

Superconducting bridge as a temperature sensor



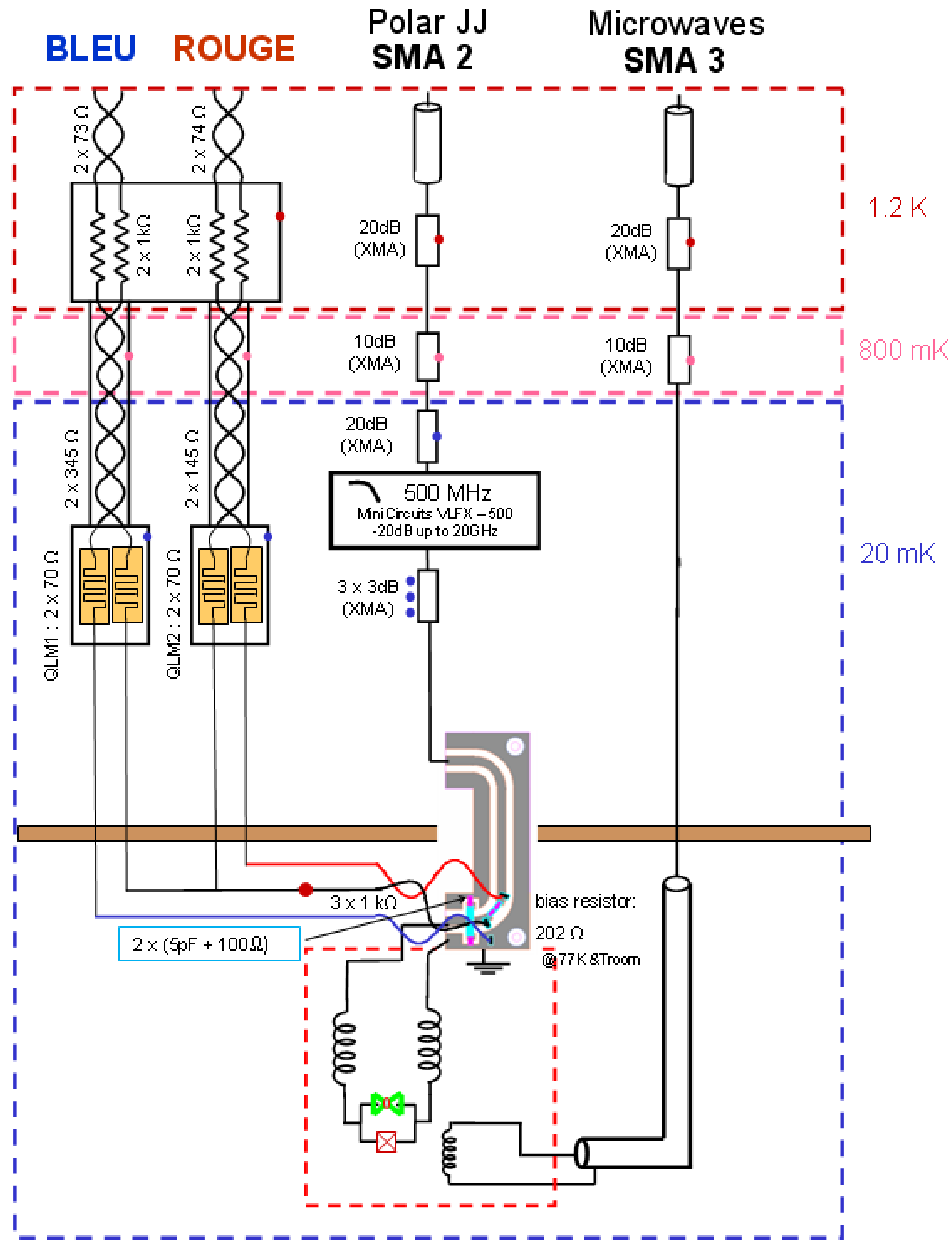
Fridge wiring



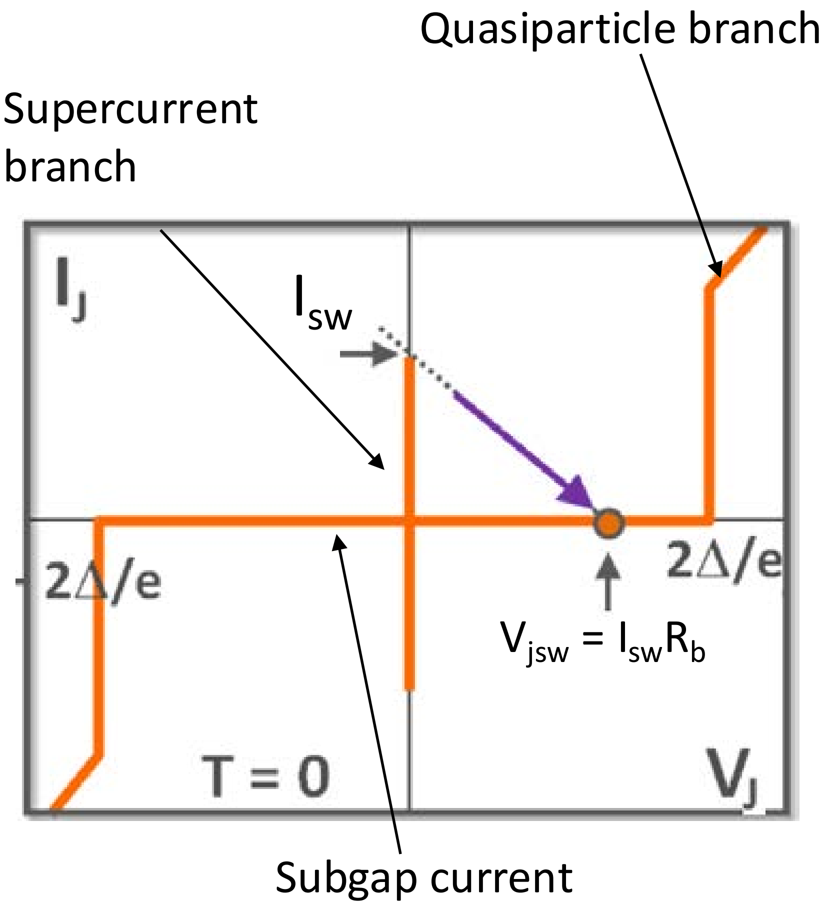
$$R = \frac{1-\alpha}{1+\alpha} \cdot 50\ \Omega \qquad \alpha = \frac{V_{out}}{V_{in}}$$

$$r = \frac{2\alpha}{1-\alpha^2} 50\ \Omega \qquad \alpha_{db} = 20 \log \alpha$$

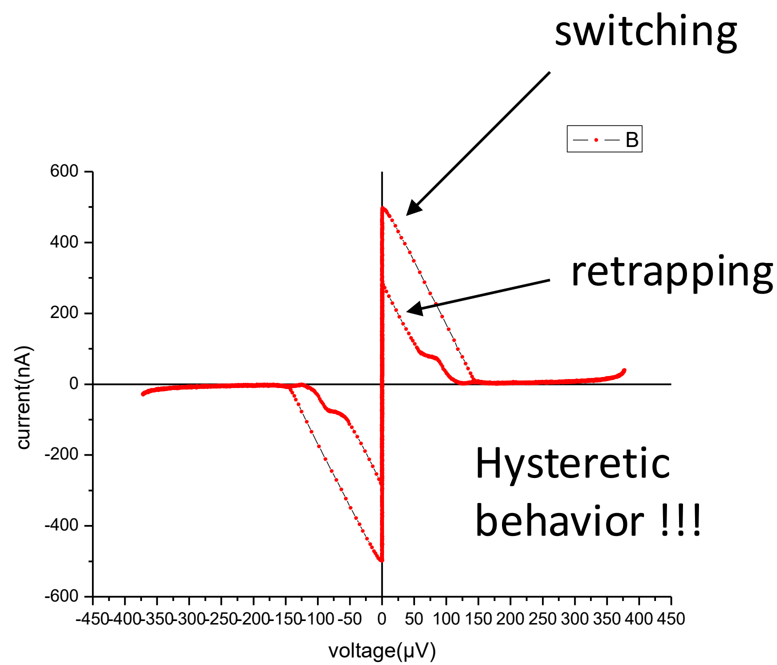
α– attenuation
-10dB(R=35 Ohm, r=26 Ohm)
-20dB (R=41 Ohm, r=10 Ohm)



IV curve



I-V characteristics of JJ biased through R_B bias resistor. JJ supports supercurrent only to certain level. On crossing the threshold value I_0 finite voltage develops across JJ.



$$I_j = I_j(V_j)$$

$$V_B = I_j \cdot R_b + V_j \Rightarrow I_j = -\frac{1}{R_b} \cdot V_j + \frac{1}{R_b} \cdot V_b \ (load \ \ line)$$

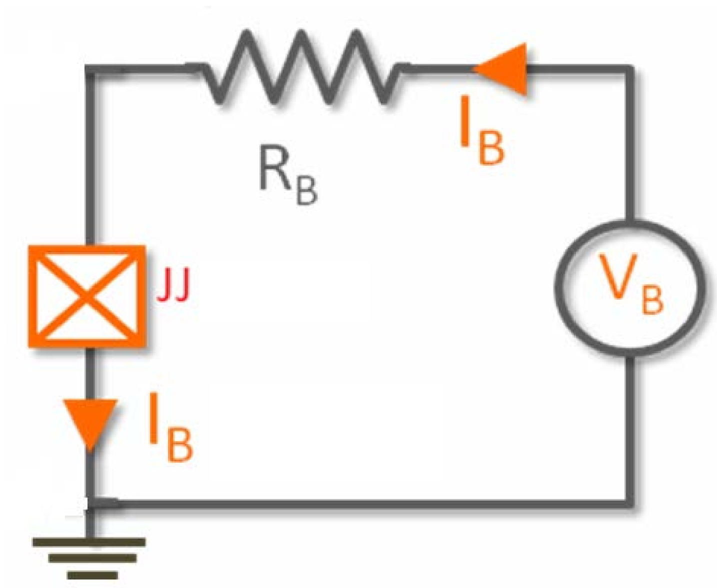
$$At \ switching \ V_j = 0, V_b = V_{bsw} \ and \ I_j = I_{sw} = \frac{V_{bsw}}{R_b}$$

$$I_j = -\frac{1}{R_b} \cdot V_j + I_{sw} \ (switching \ line)$$

RCSJ model

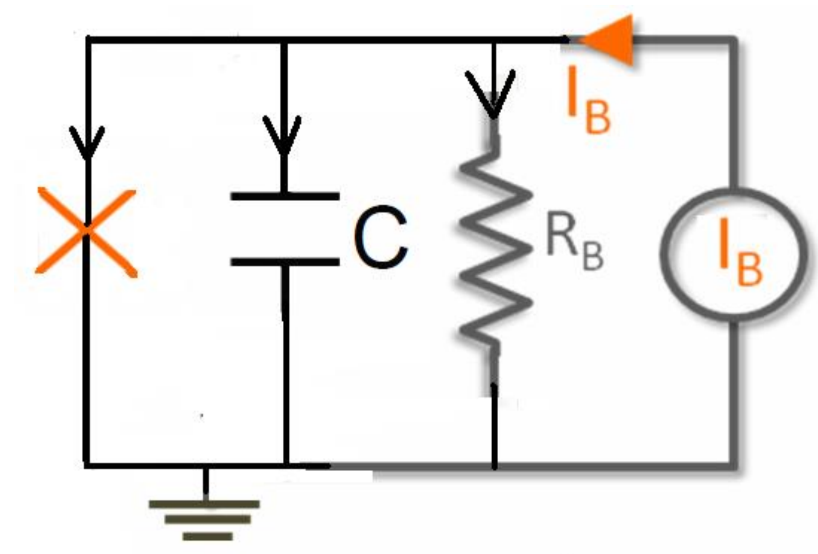
(Resistively and Capacitively Shunted Junction)

Thevenin equivalent

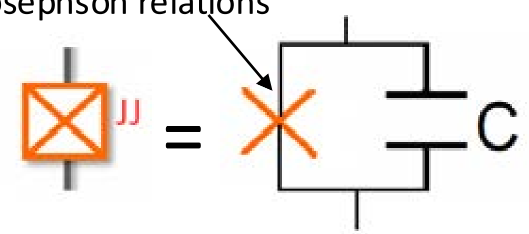


⇔

Norton equivalent



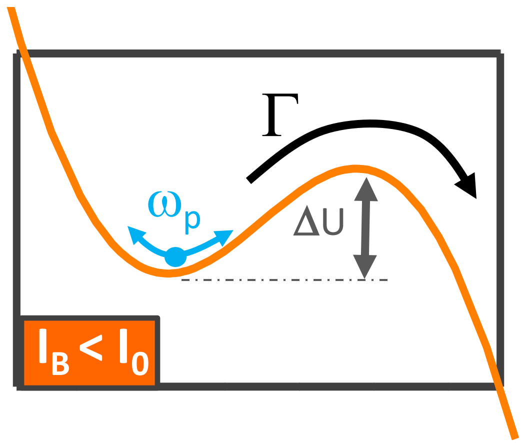
Pure Josephson element obeying Josephson relations



$$I_b = I_R + I_C + I_{JJ} = \frac{V}{R} + C\frac{dV}{dt} + I_0 \cdot \sin\gamma$$

Switching: Escape out of metastable state

Poisson process-> JJ switching, shot noise, Drude model of electrical conduction, rain, radioactive decay, switching of magnetic domains

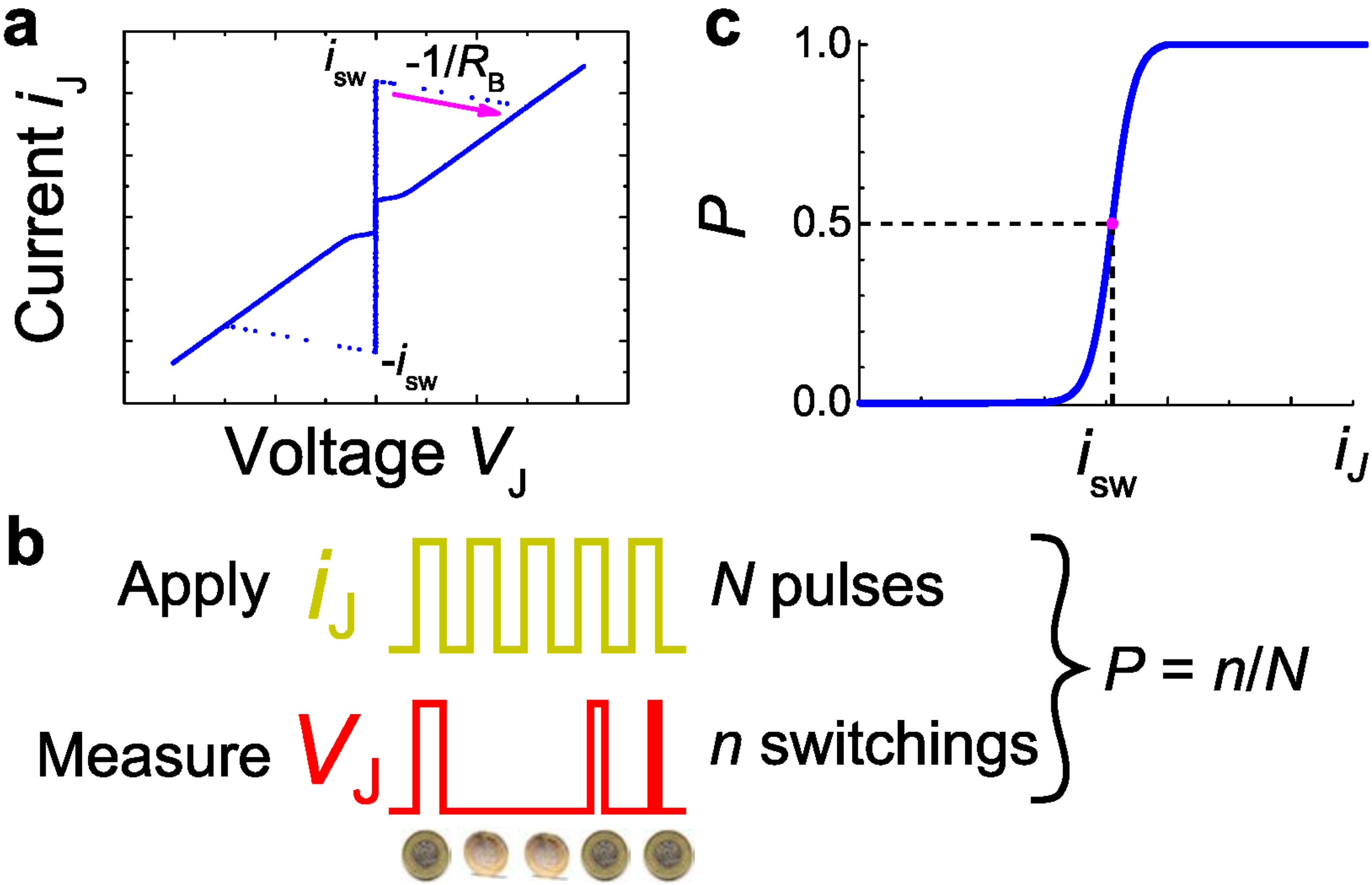


$$P = 1 - \exp(-\frac{T}{\tau}), \quad \frac{1}{\tau} = \Gamma$$

$$\Gamma = \frac{\omega_p}{2 \cdot \pi} \exp(-\frac{\Delta U}{k_B T}), \quad Arrhenius \;\; law$$

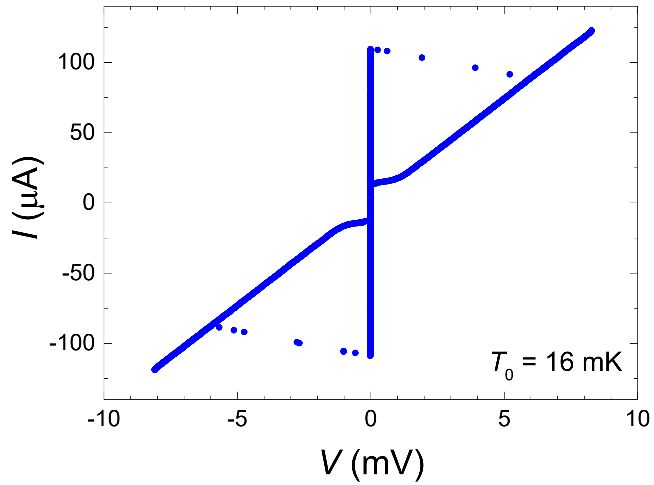
$$\Delta U(s) = \frac{4 \cdot \sqrt{2}}{3} \cdot E_J (1-s)^{3/2}, \; s = \frac{I_b}{I_0}, \; \omega_p = \omega_{p0} (1 - s^2)^{1/4}$$

Switching measurements

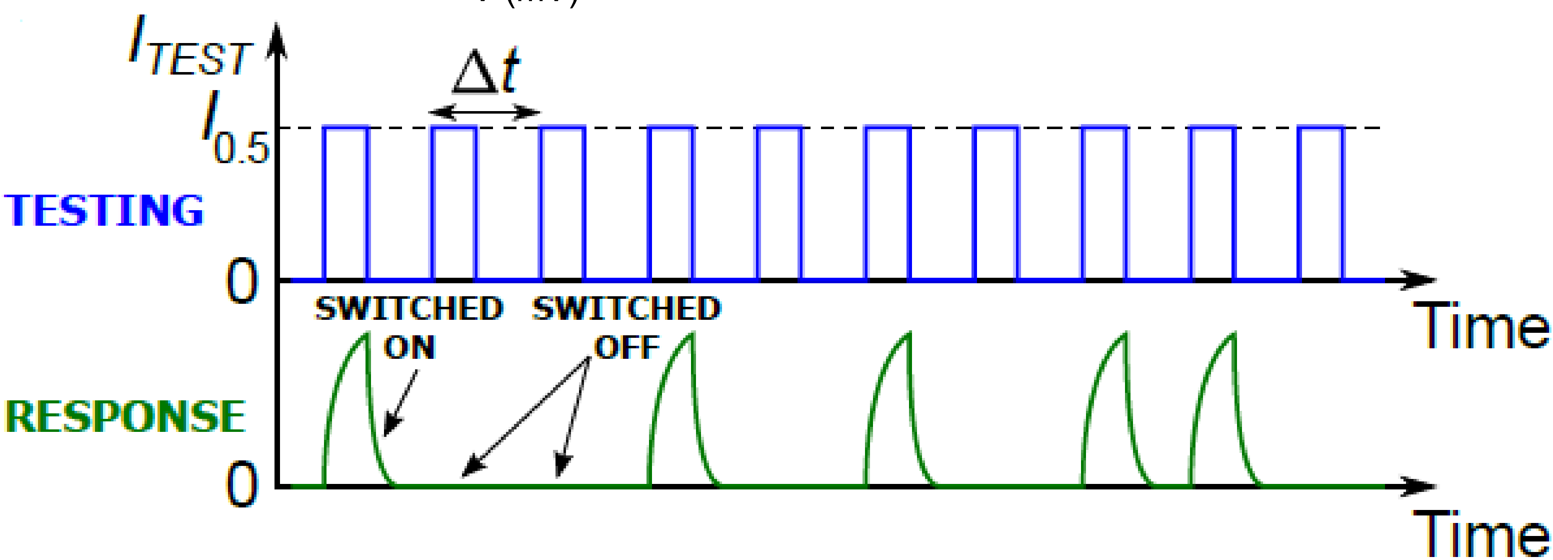


M. Foltyn and M. Zgirski**,** *Gambling with superconducting fluctuations,* **Phys. Rev. Appl. 4, 024002 (2015)**

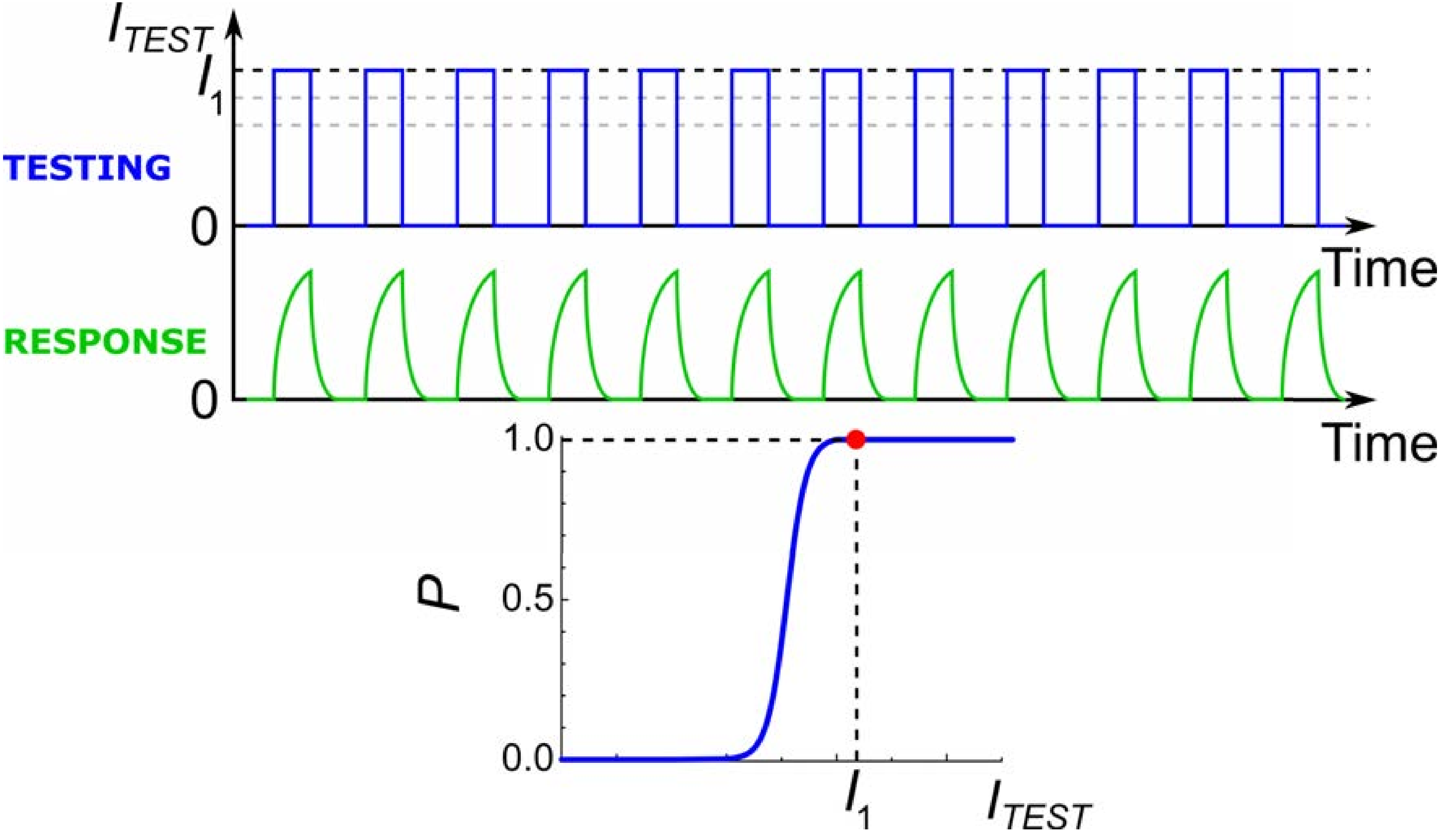
Switching measurements of the junction



$$P=n/N$$



Testing JJ with current pulses



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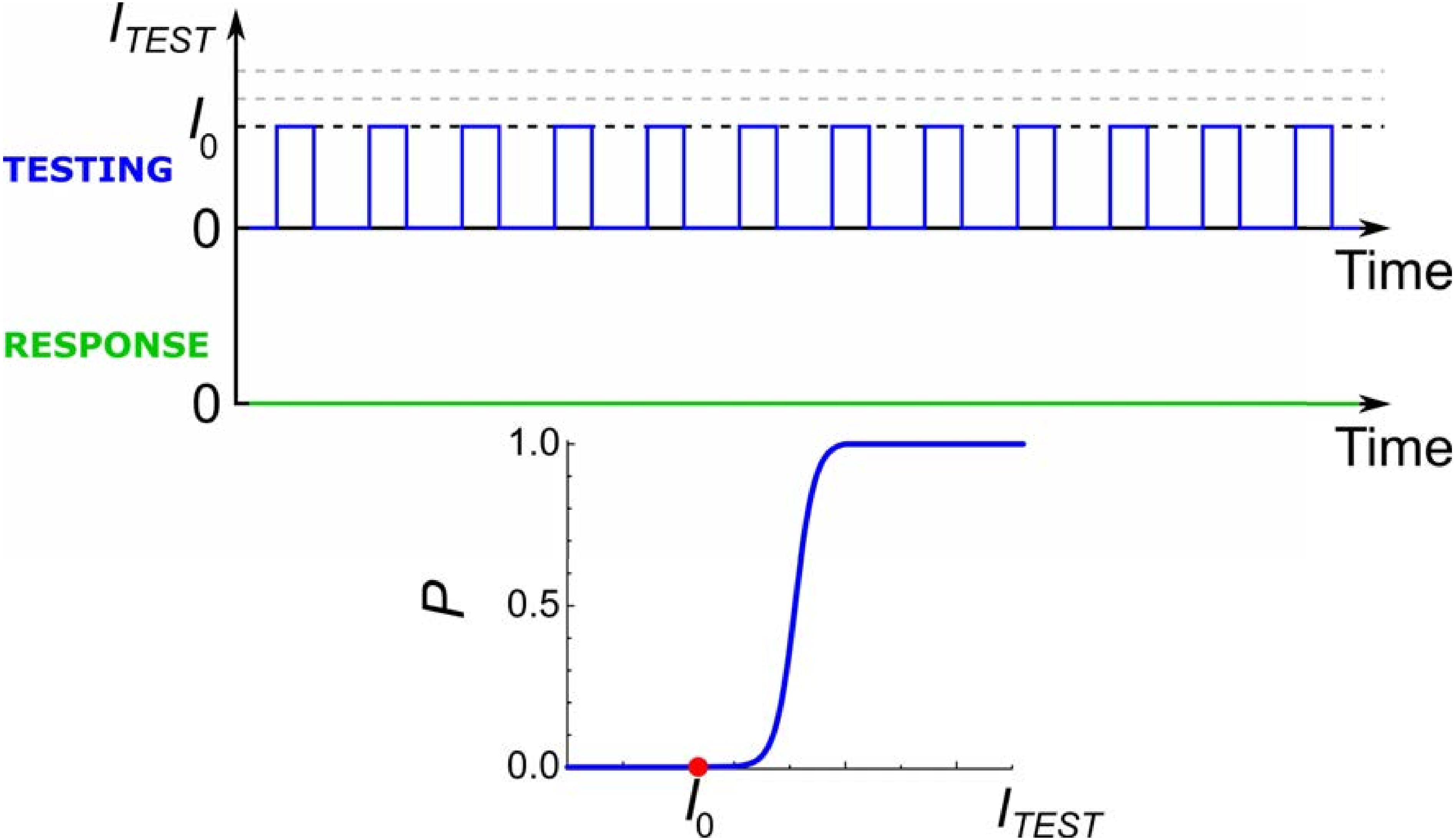

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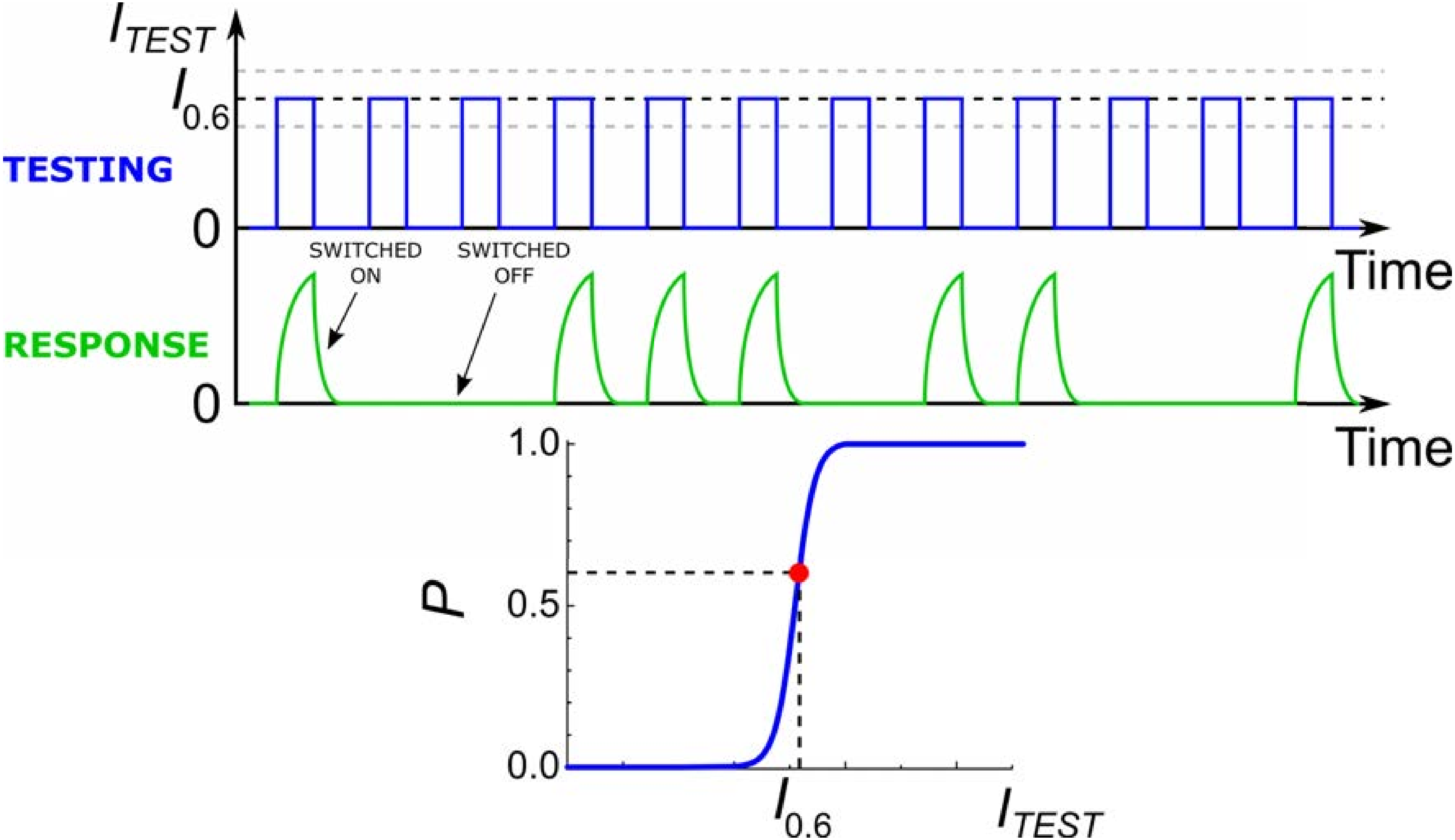
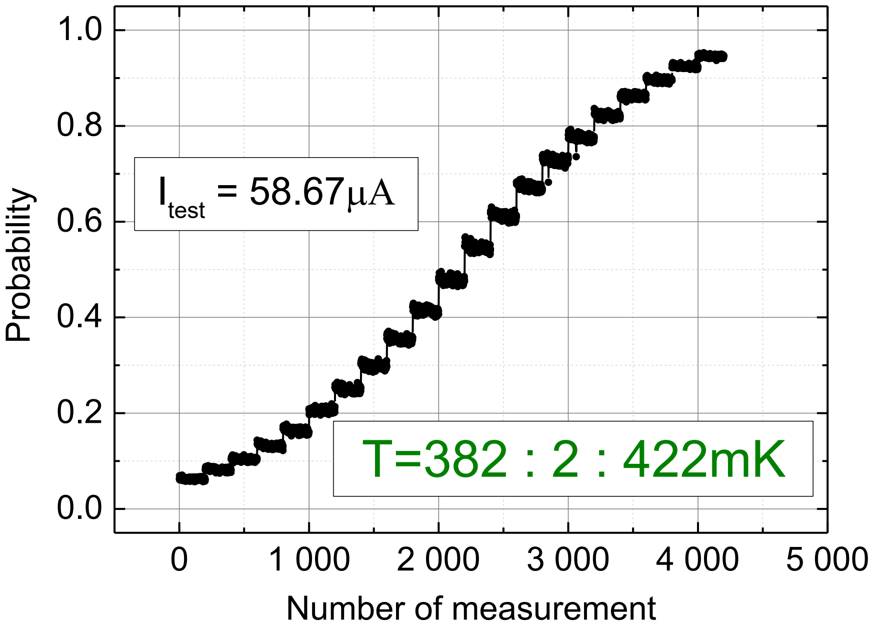
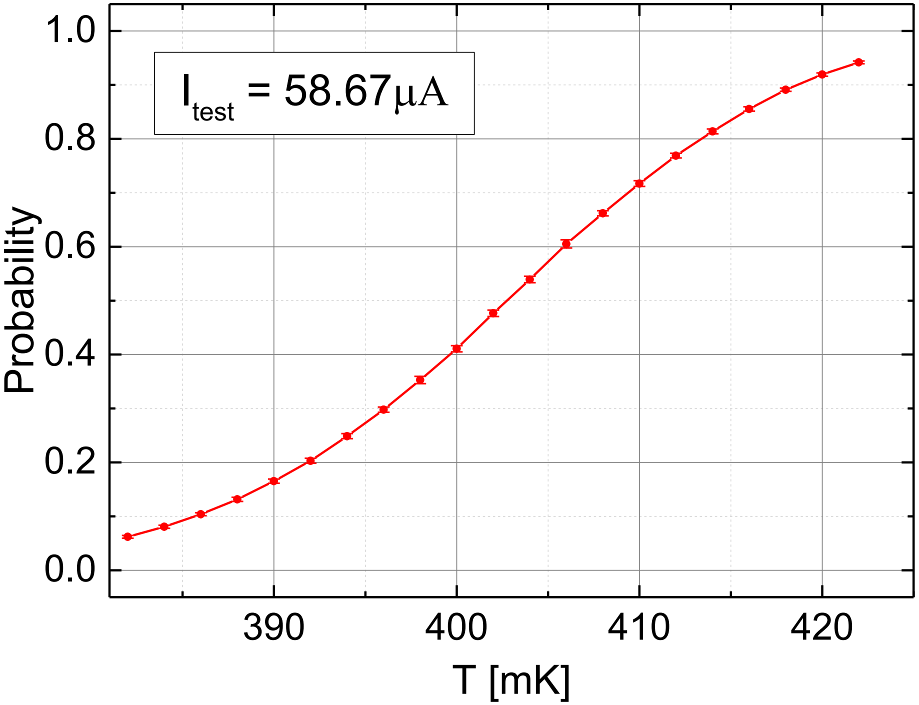


Switching thermometry

$P(T_e)$

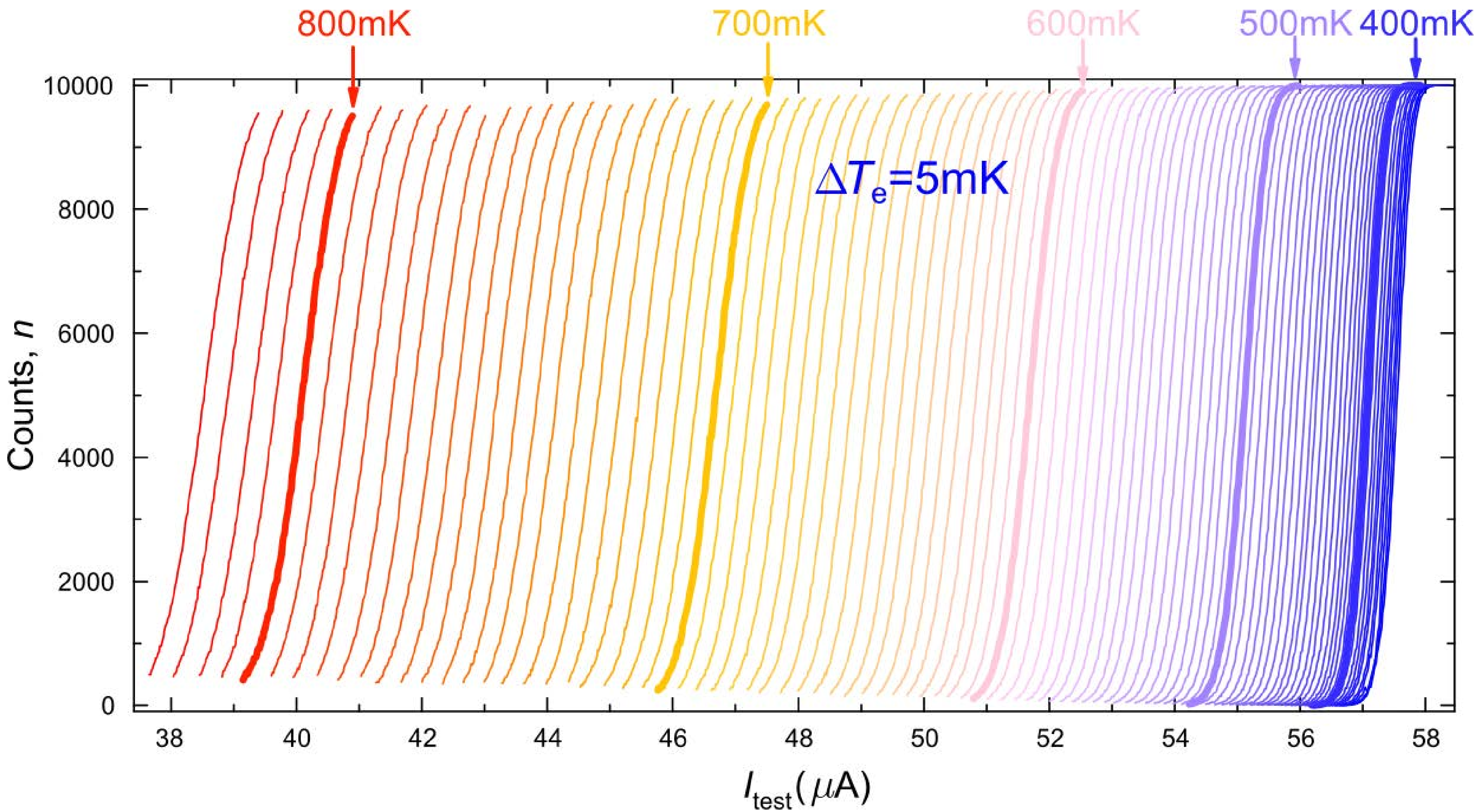


Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
1 000
2 000
3 000
4 000
5 000
Number of measurement
I_test = 58.67μA
T=382 : 2 : 422mK



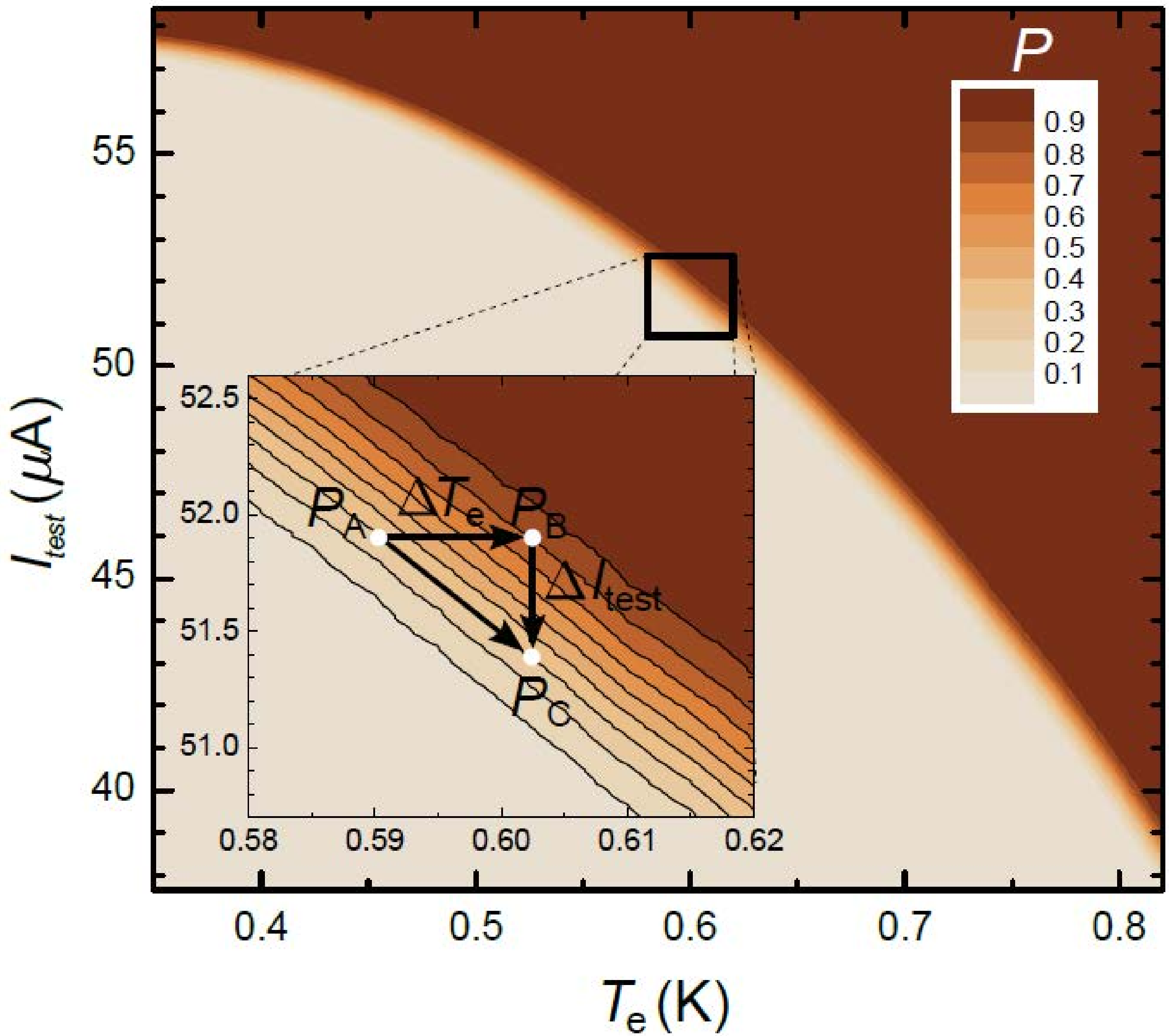
Probability
1.0
0.8
0.6
0.4
0.2
0.0
390
400
410
420
T [mK]
I_test = 58.67μA

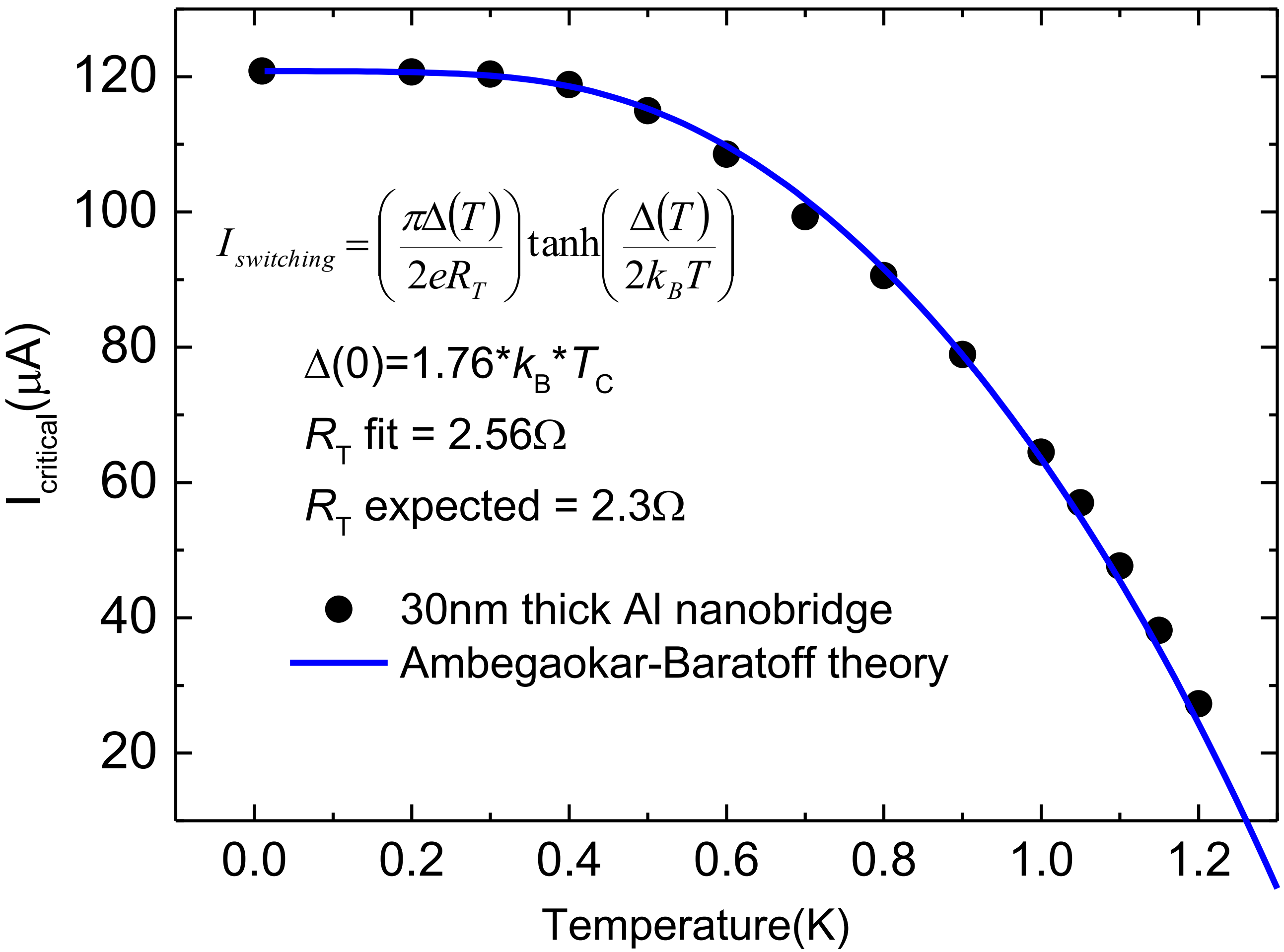
Temperature sensitivity



M. Zgirski, M. Foltyn, A. Naumov, A. Savin and K. Norowski
Heat hunting in freezer: Direct measurement of quasiparticle diffusion in superconducting nanowire,
Phys. Rev. Appl. 14, 044024 **(2020)**

Switching probability map $P(I_{test}, T_e)$





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$\Delta(0)=1.76*k_B*T_C$
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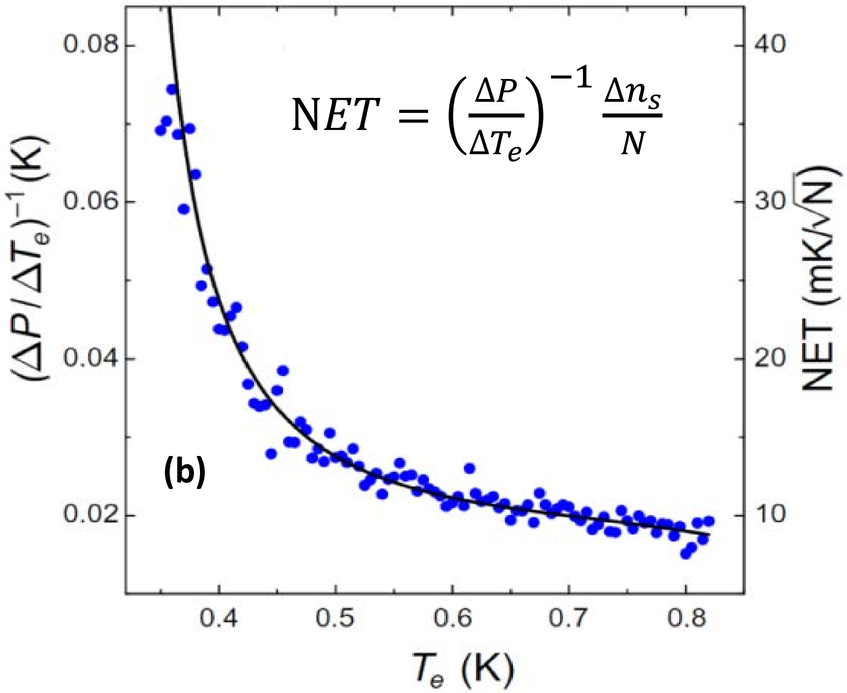
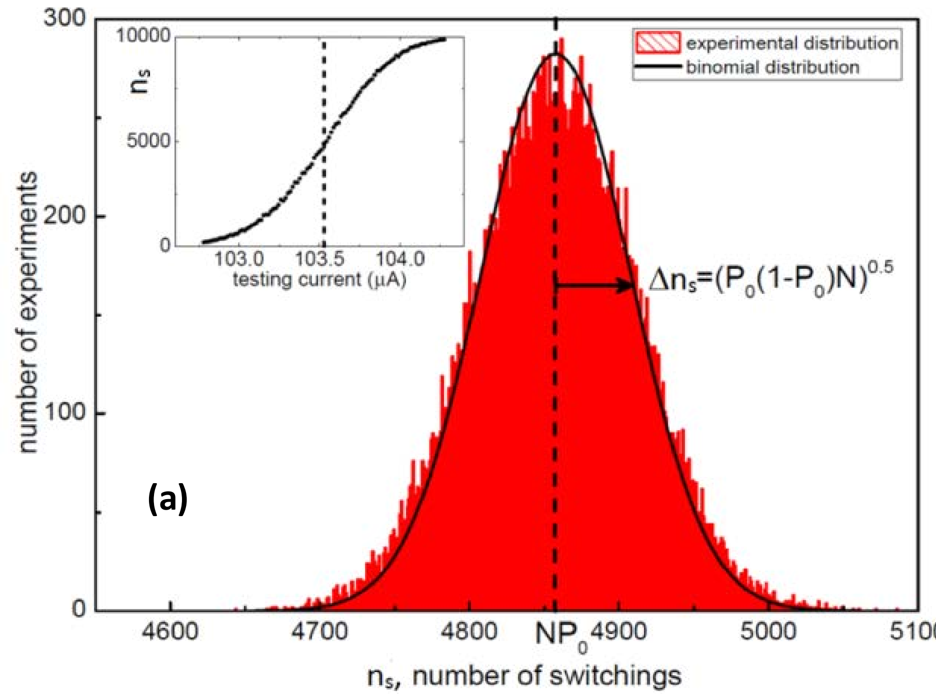




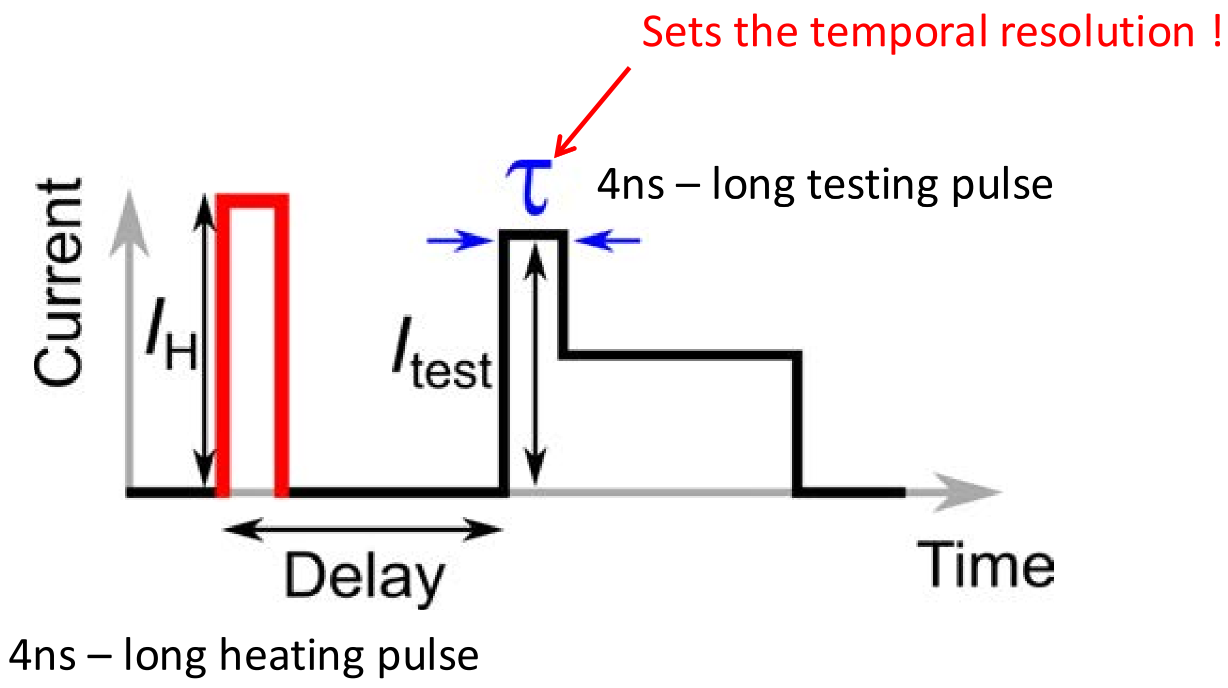
Example: NET=10mK/$N^{0.5}$
with N=10000 pulses
=> $\Delta T_{e,un}$=100μK

Toss a coin 10000 times.
Count number of heads.
Again toss it 10000 times.
Did you get the same number of heads?

„Statistical noise":

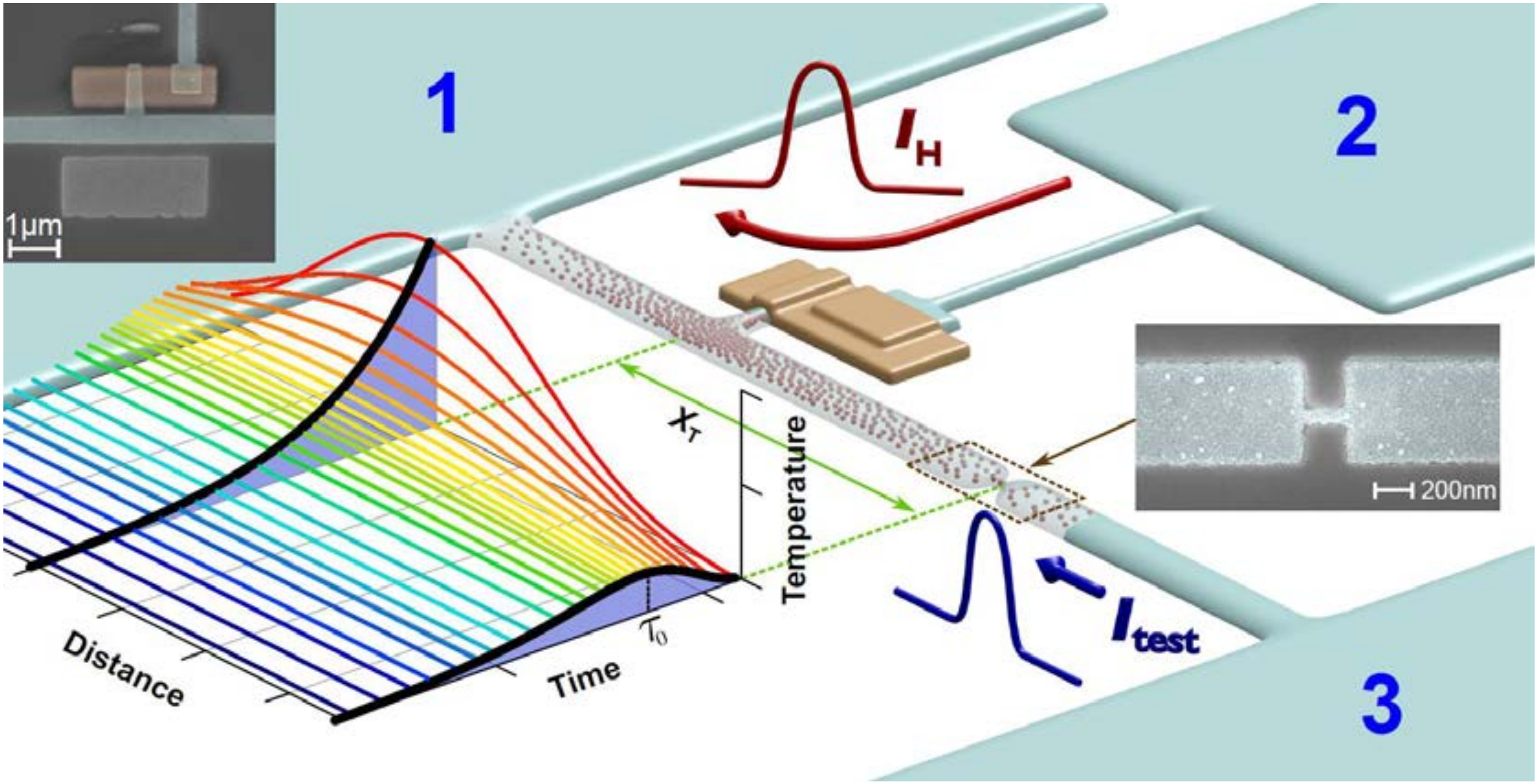
$$\Delta n_s = \sqrt{P_0(1 - P_0)N} = 50 \text{ for N=10000 and } P_0\text{=0.5 .}$$

„Pump and probe”



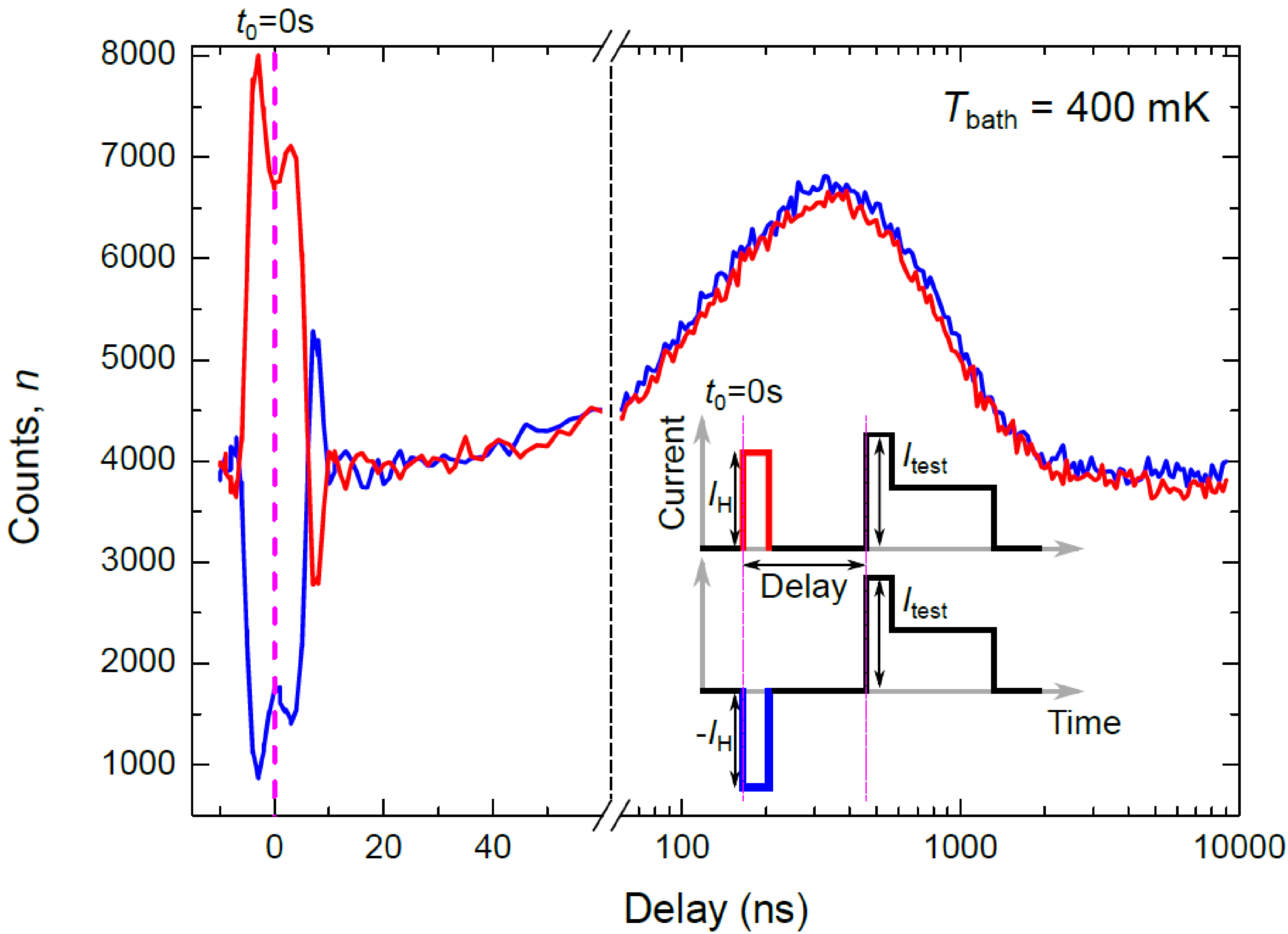
Addresses perfectly repeatable thermal processes
which can be initialized many times in the same initial conditions.

Diffusion of Quasiparticles (example 2)



M. Zgirski, M. Foltyn, A. Naumov, A. Savin and K. Norowski
Heat hunting in freezer: Direct measurement of quasiparticle diffusion in superconducting nanowire,
Phys. Rev. Appl. 14, 044024 **(2020)**

Trace of diffusing QPs recorded at the nanobridge…



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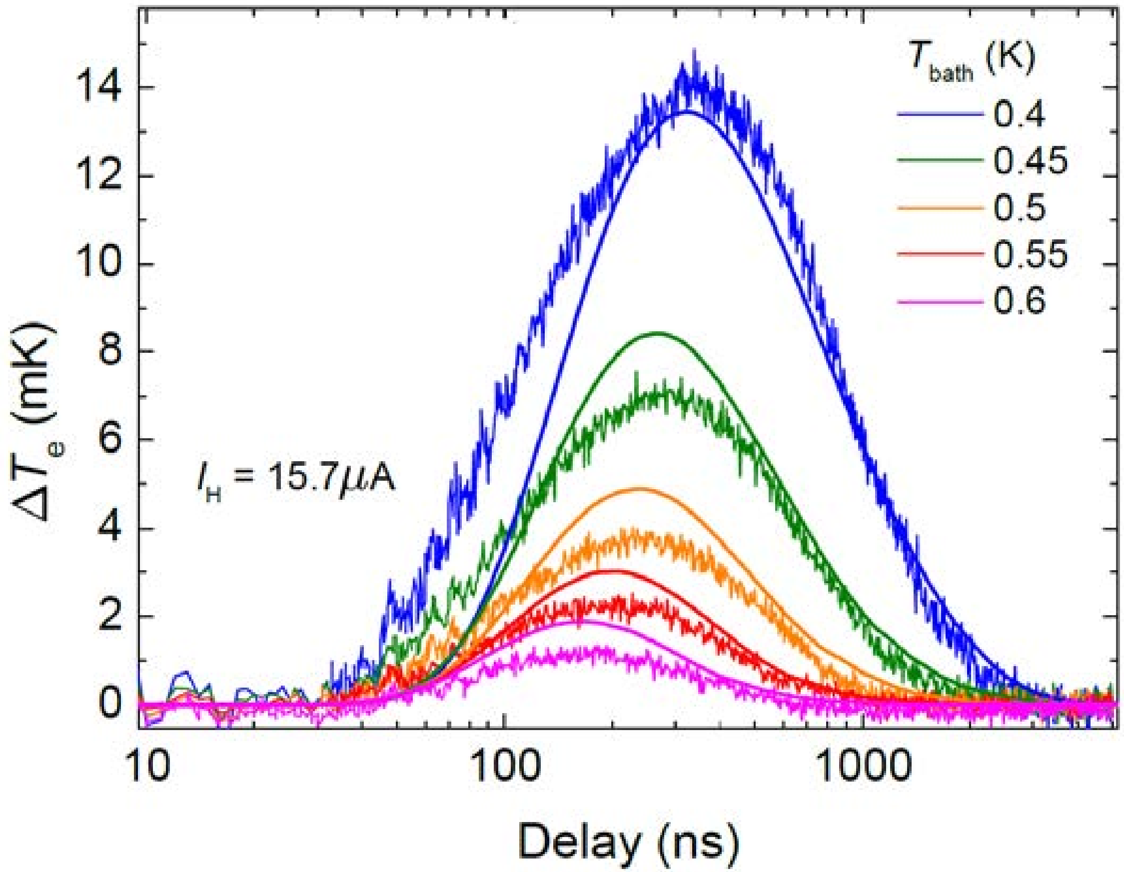
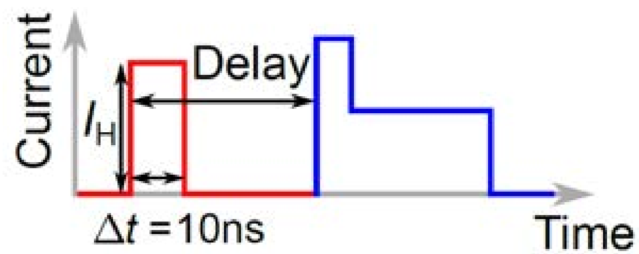
…recalculated into excess electron temperature





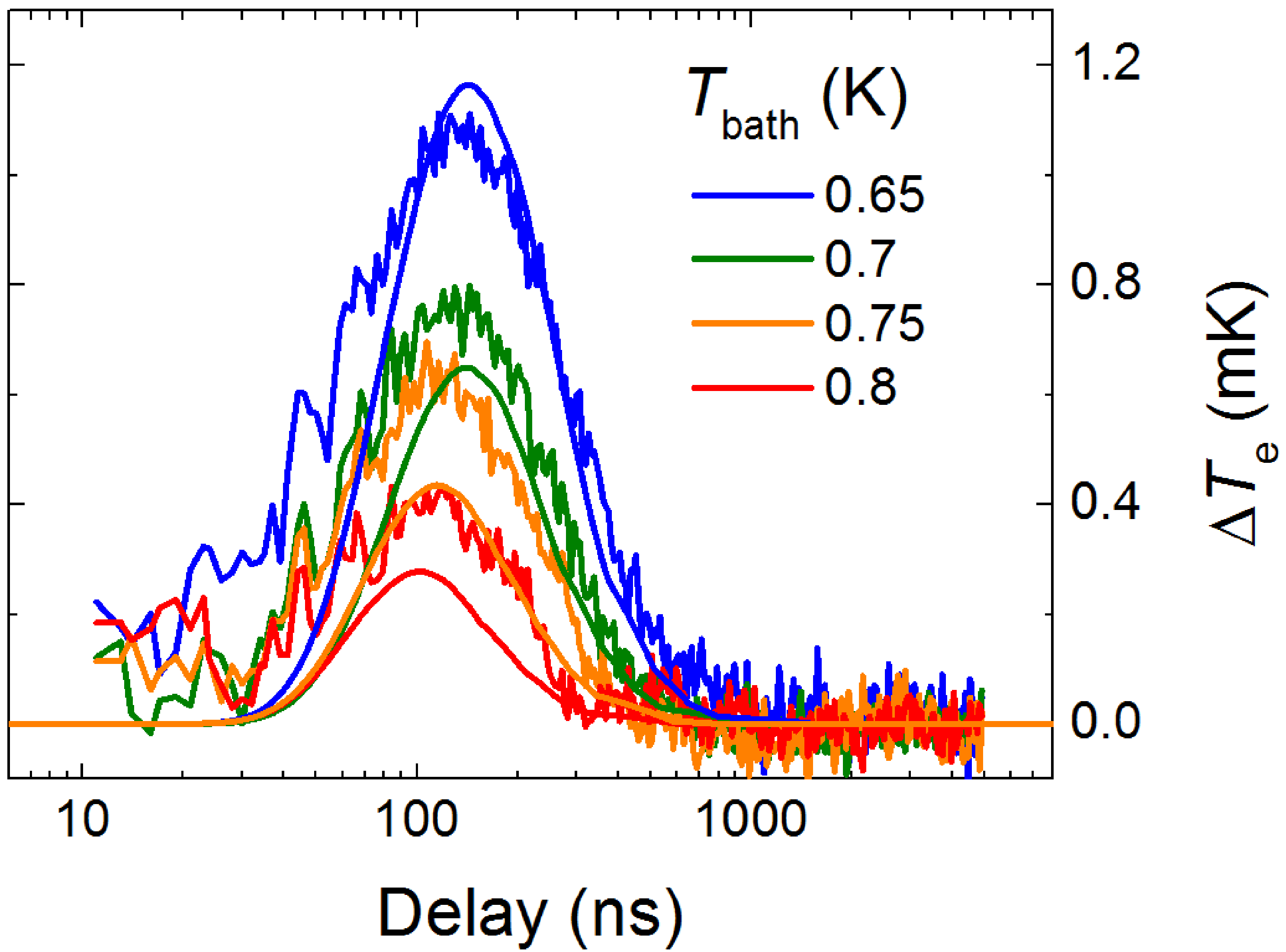
Note:
- temporal delay between generation and sensing ~30ns,
- position of the maximum at delay = 300ns.

Is it correct?

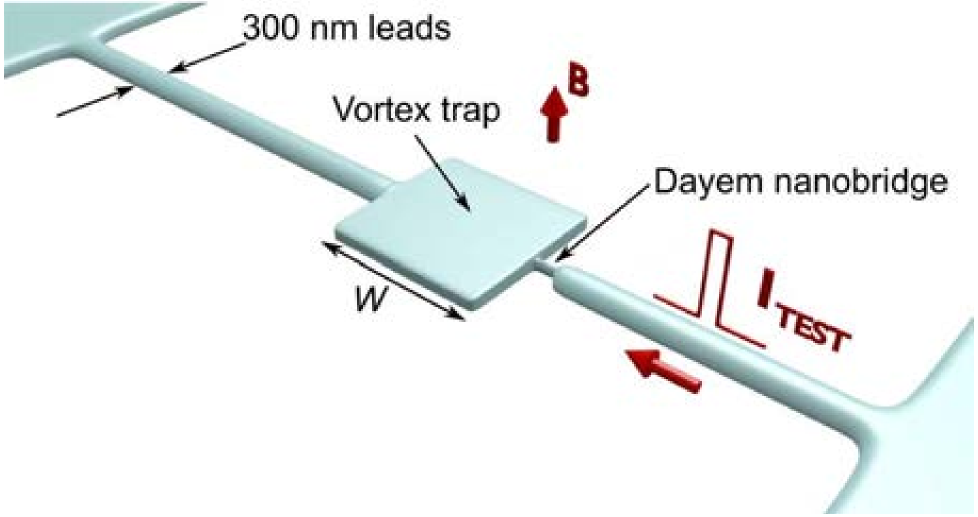
$\langle X^2\rangle = D\,\tau_{MAX} = (60\mu m)^2$
=> $D = 100\ cm^2/s$

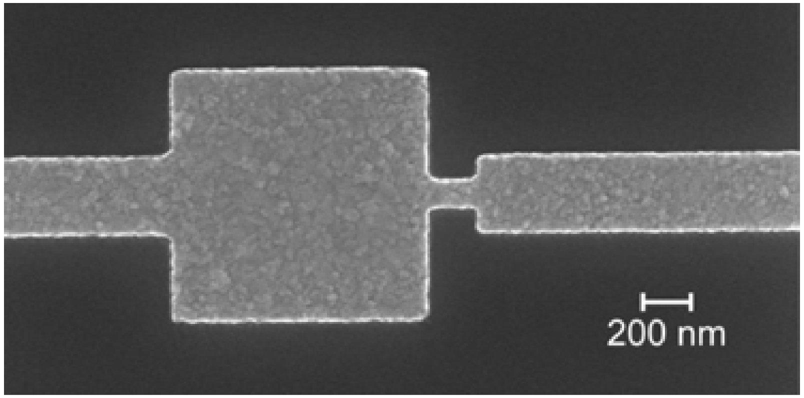
Expected: $D = 1/3\ v_f\, l_{mfp}$
=> $l_{mfp} = 15nm$

100μK resolution !!!



Teaser: **S**ingle **V**ortex **B**ox (**SVB**)

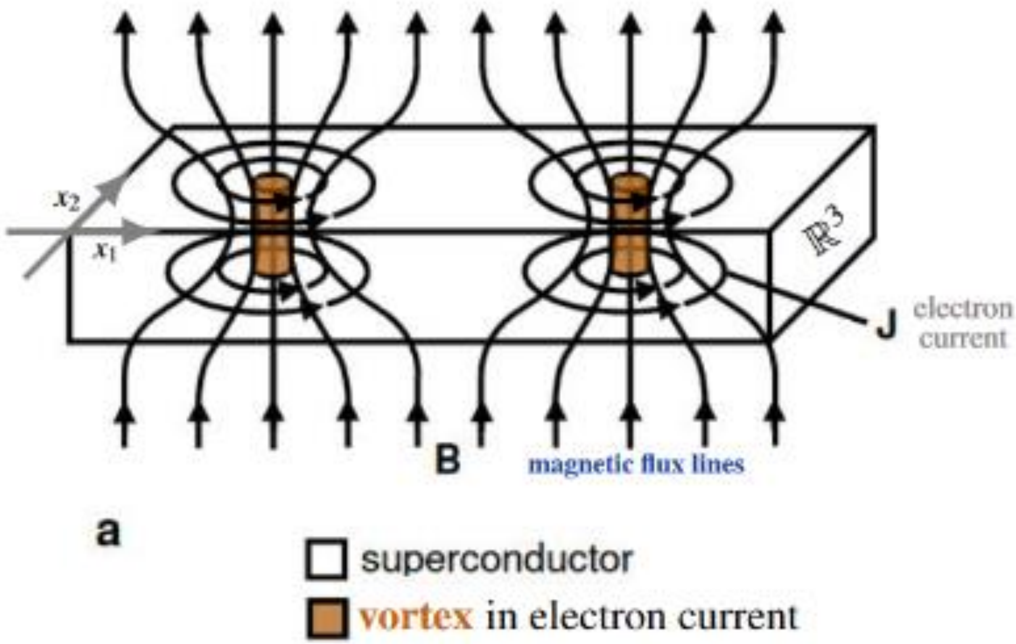


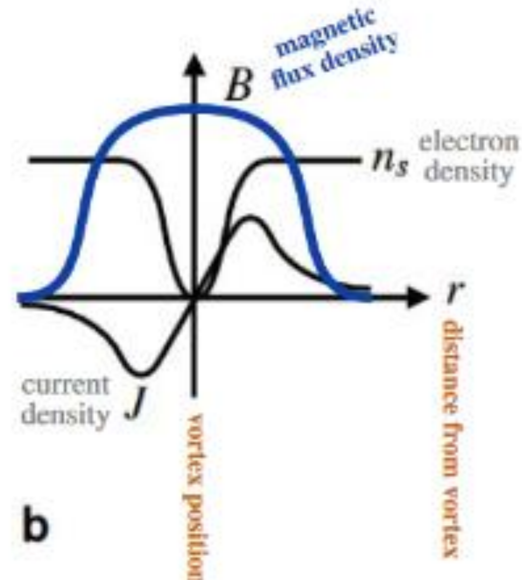


<u>Vortex electronics:</u>

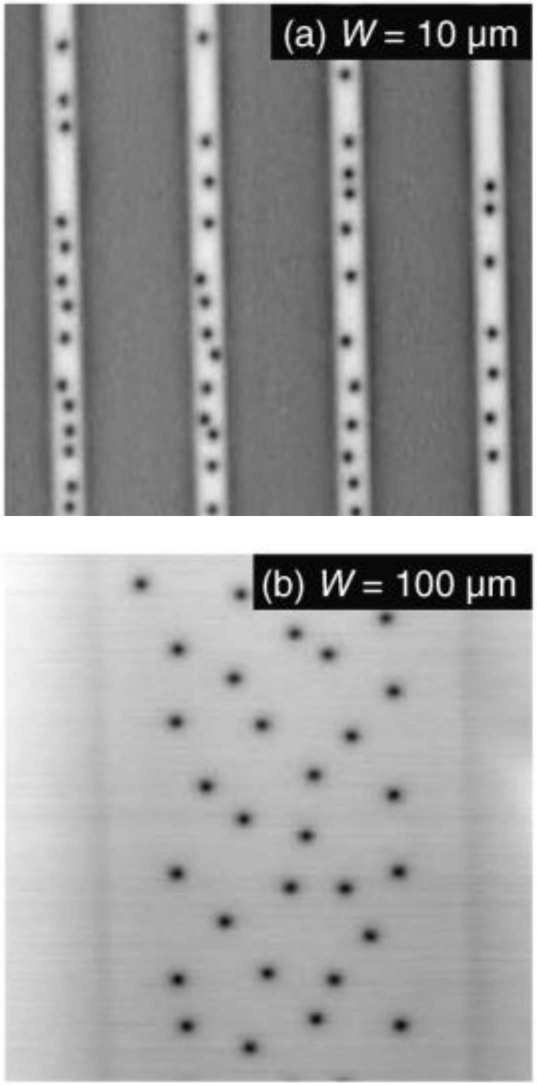
Monitoring and manipulation of vortices with electric current and magnetic field.

Vortex is a topological object

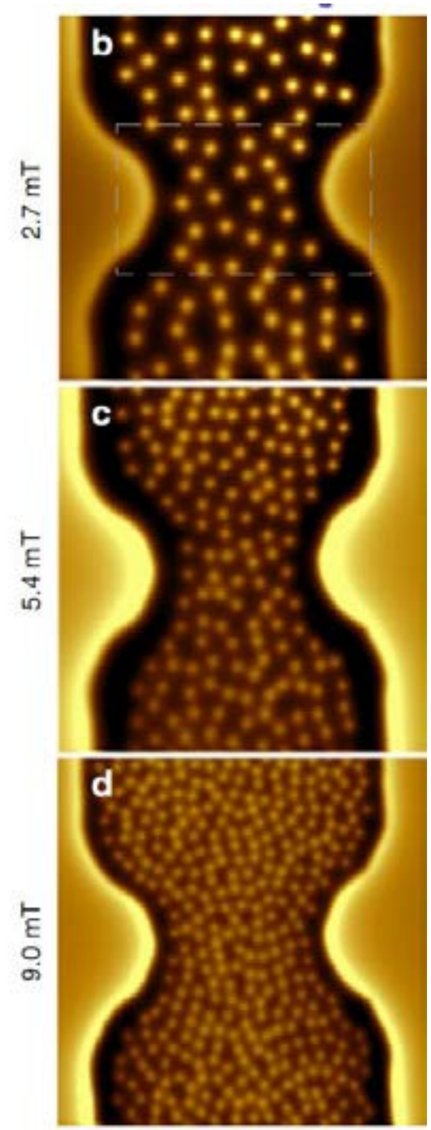




Figs taken from: https://ncatlab.org/nlab/show/superconductivity#Chapman00



G. Stan, S. B. Field, J. M. Martinis, Phys. Rev. Lett. 92, 097003 (2004)



Nat.Comm. 8, 85 (2017)

Can we harness it for an application?

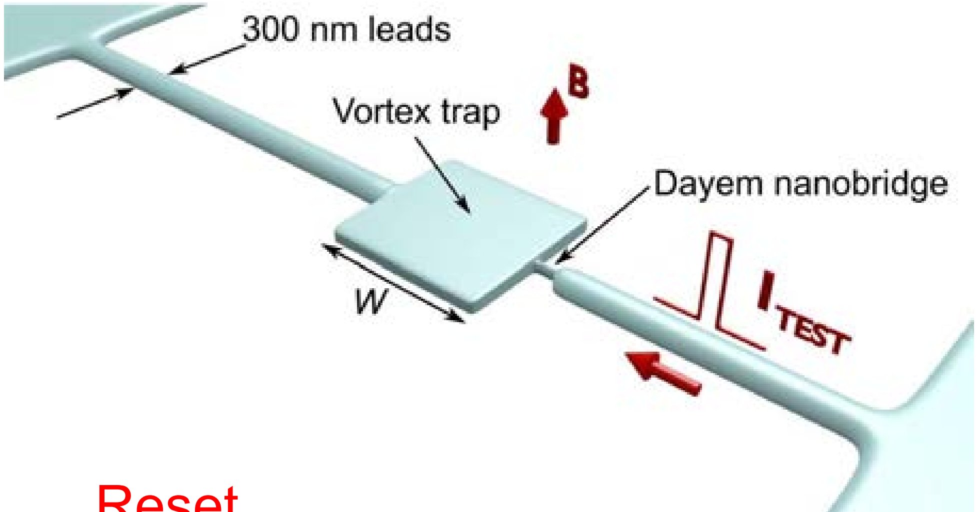
single out →

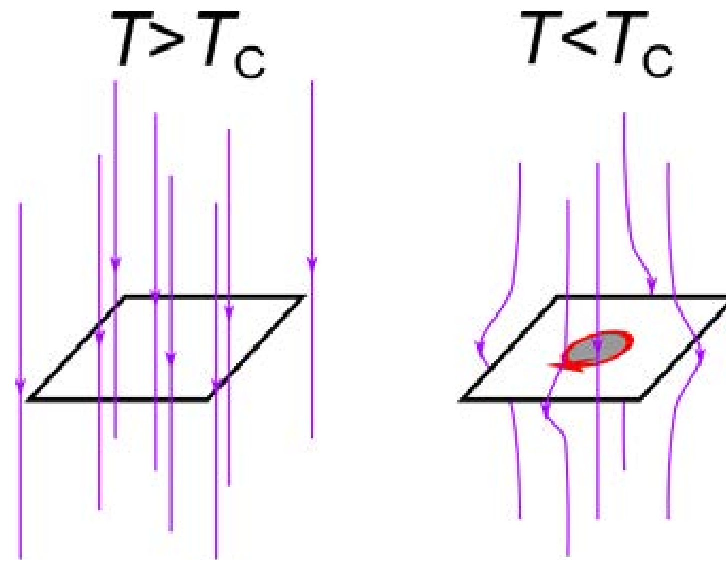
define criteria for observation & sense

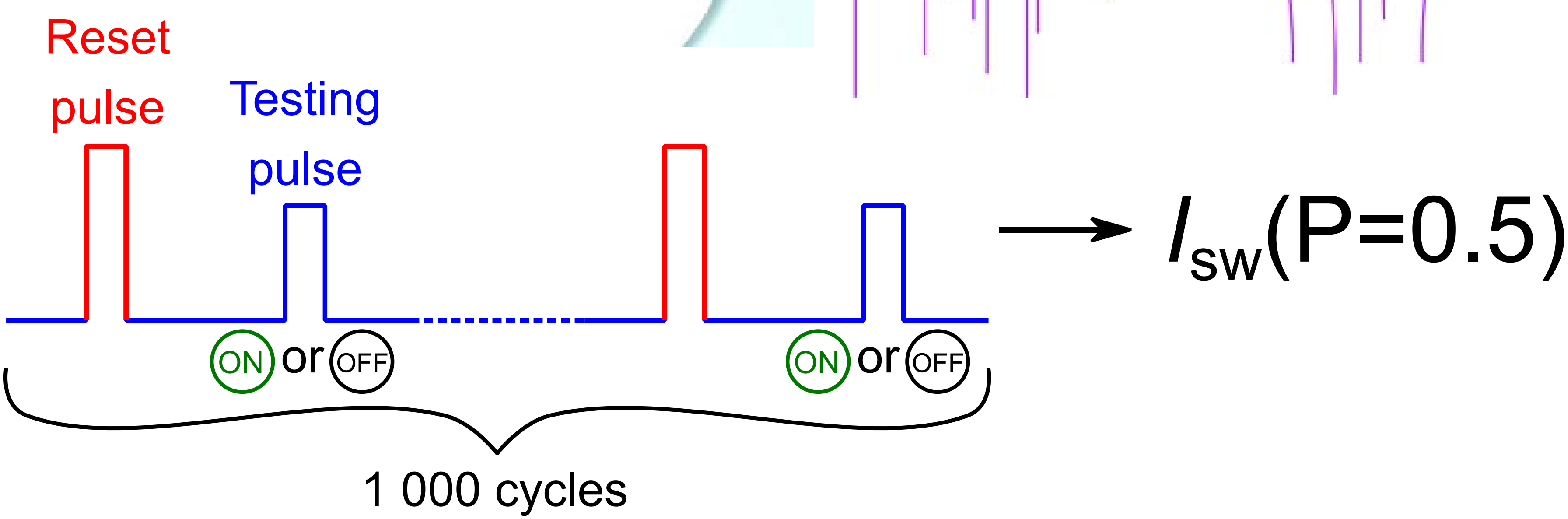
catch and tame ↓

← control

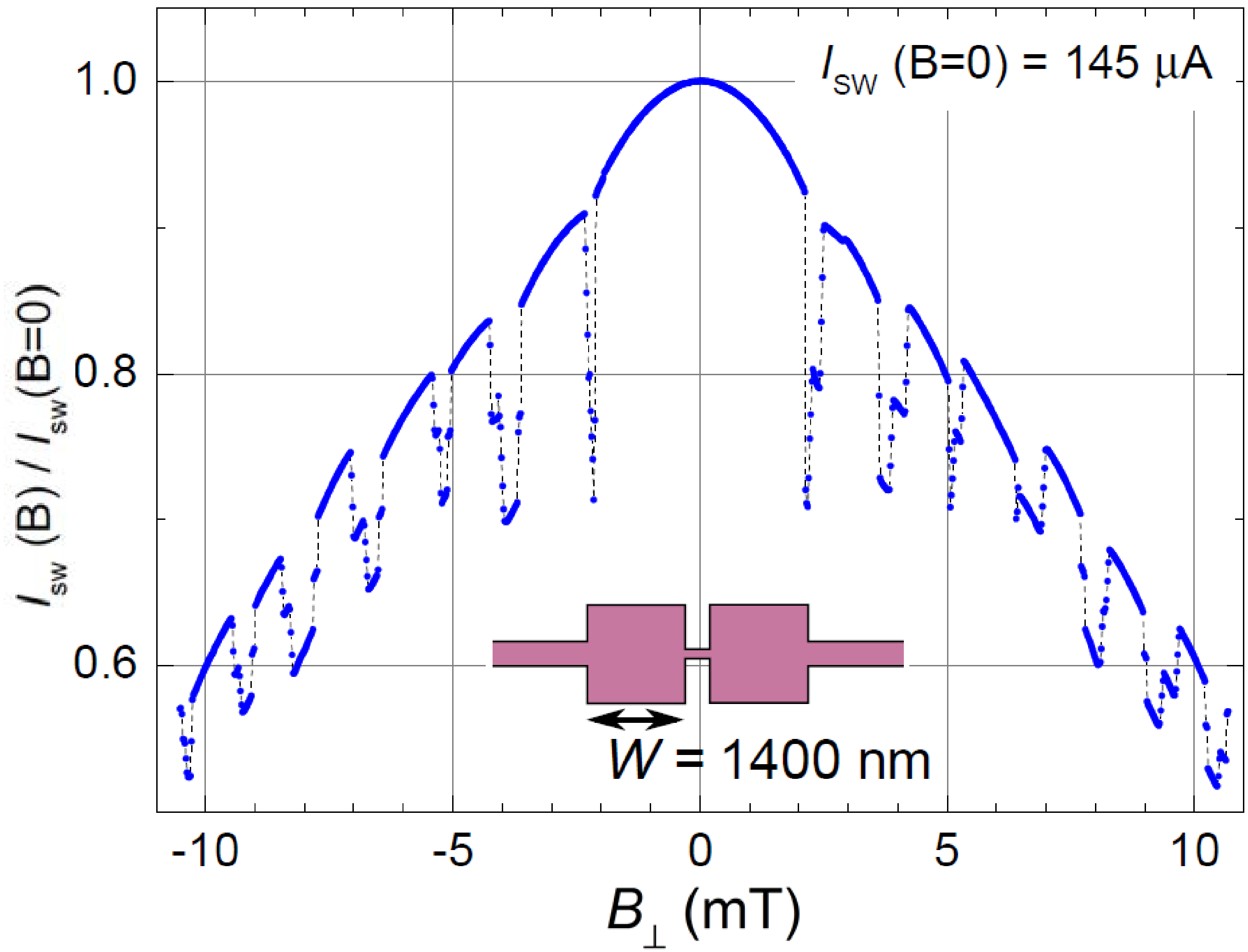
Trapping and detection of superconducting vortices

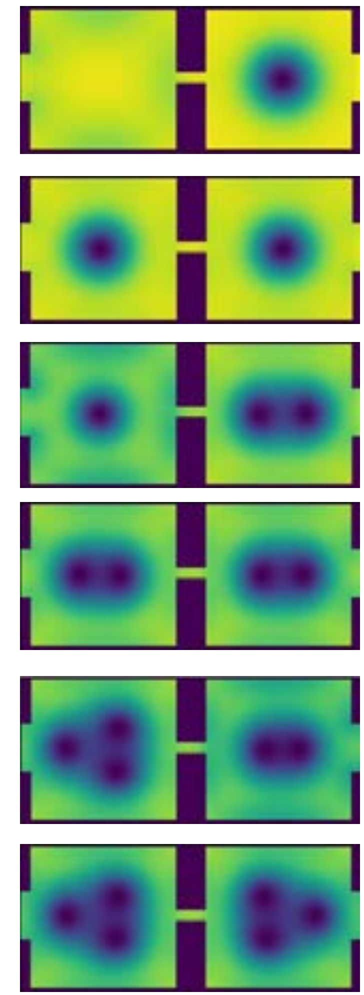






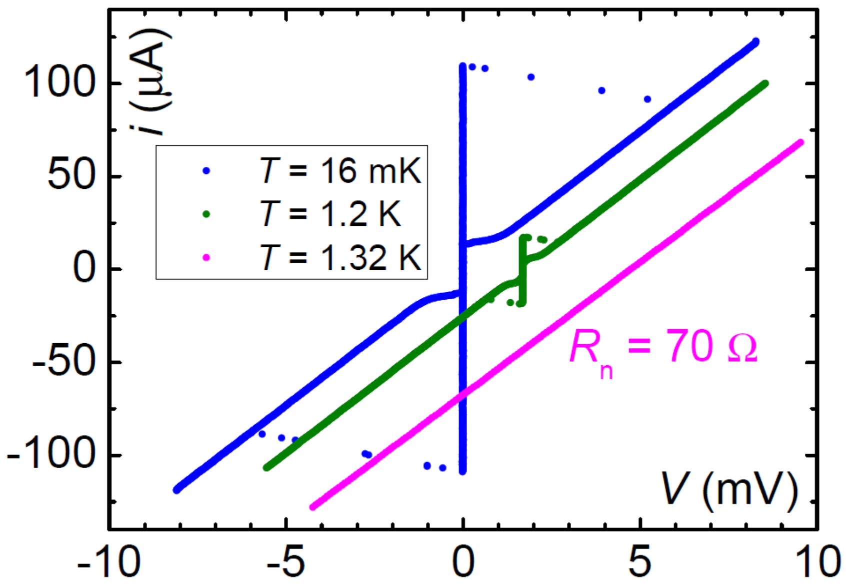
A single vortex detection

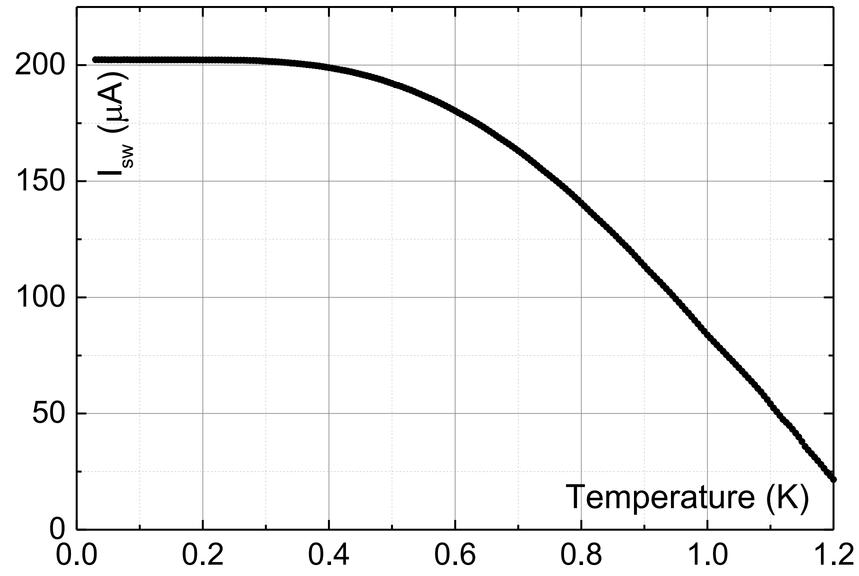




GL simulations by the theory group of prof. M. Milošević from Univ. Of Antwerp

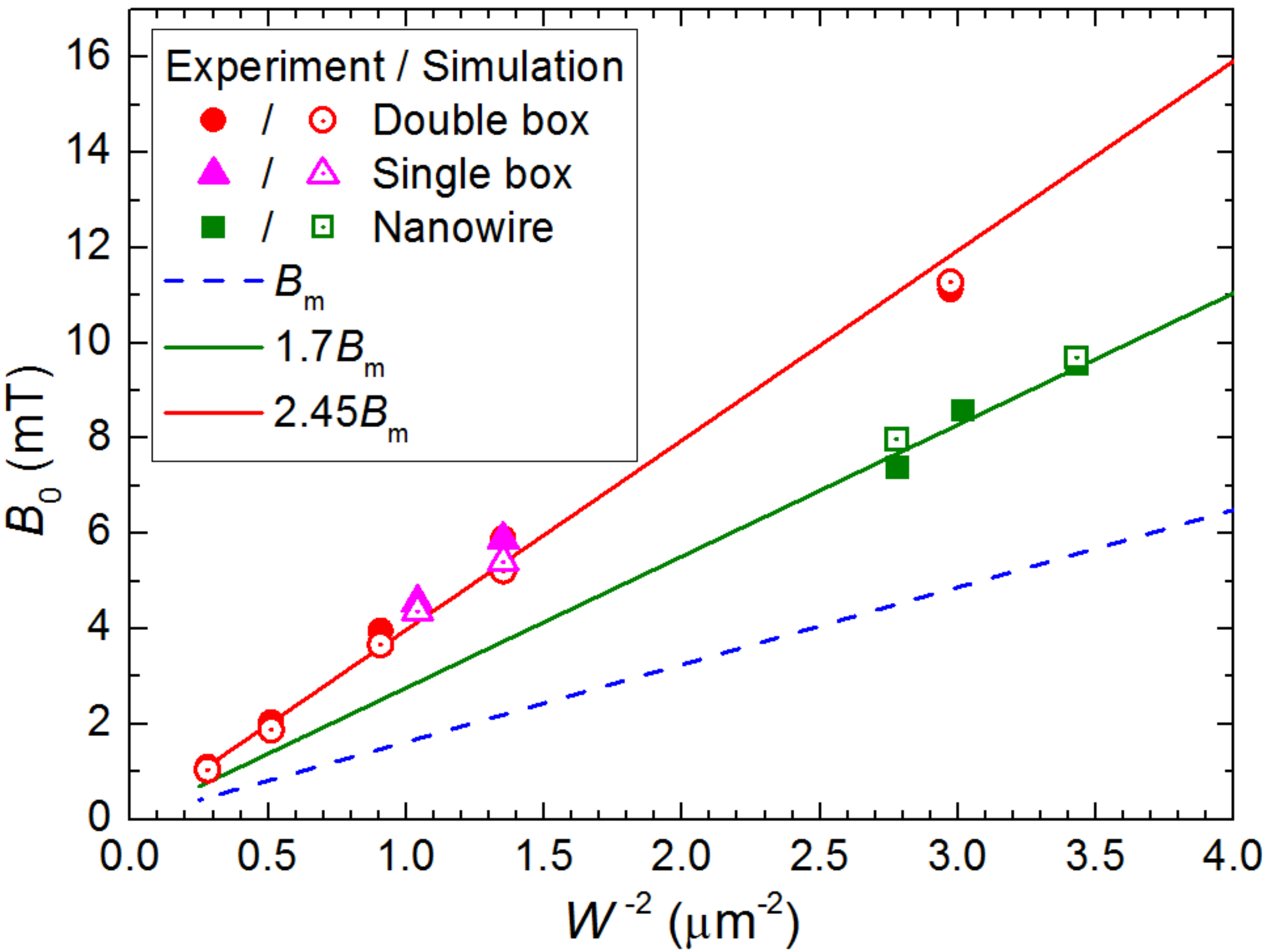
Sensing due to dissipation





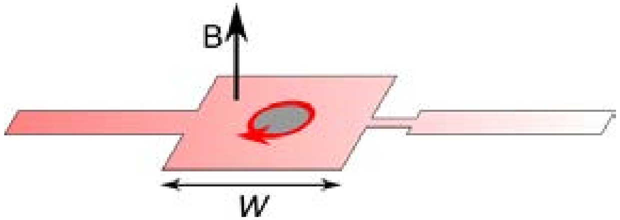
Suppression of I_c is a sign of dissipation !

Threshold field for a vortex entry



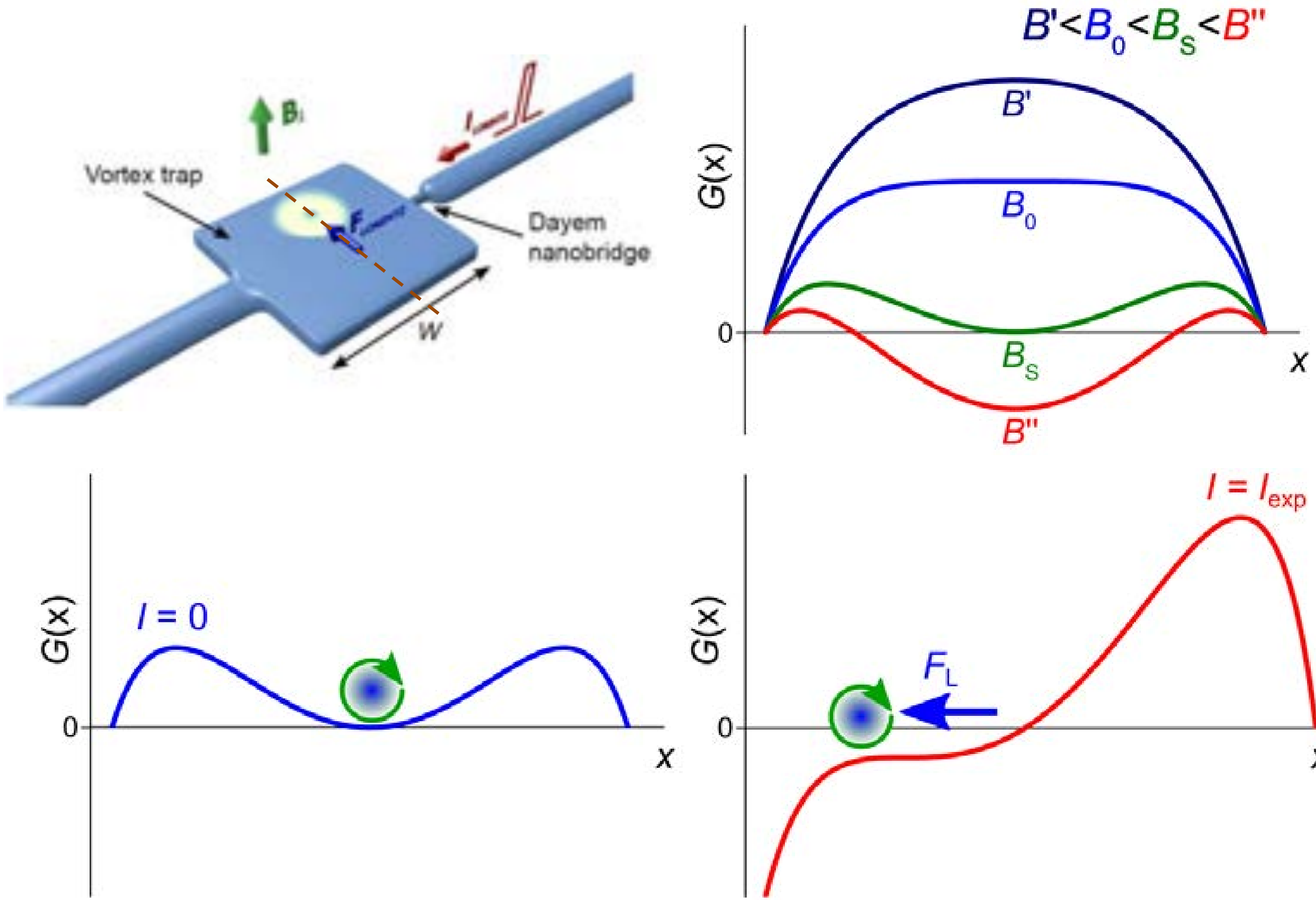
$$B_m = \frac{\pi \Phi_0}{4W^2}$$

G. Stan, S. B. Field, J. M. Martinis, Phys. Rev. Lett. 92, 097003 (2004)



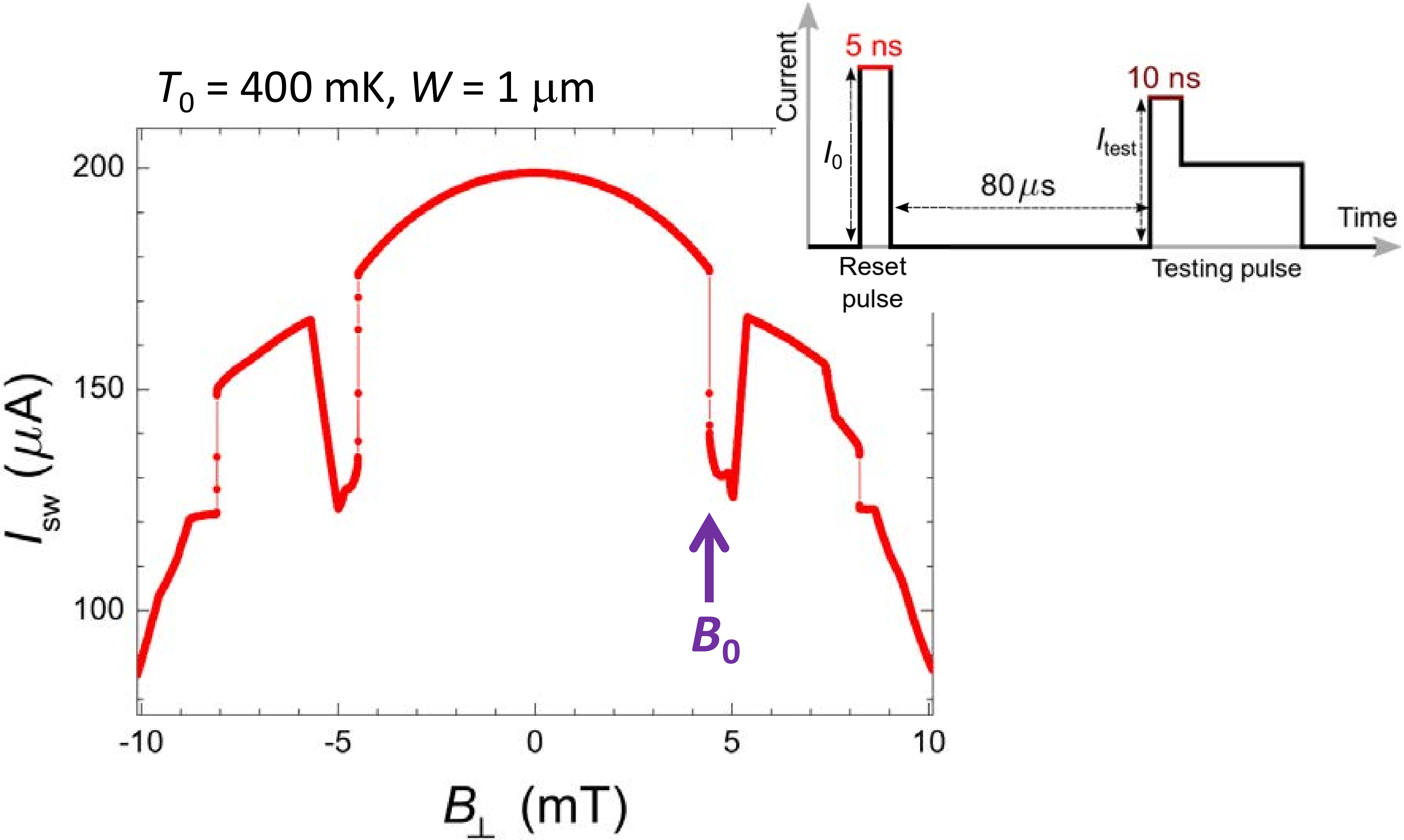
M. Foltyn, K. Norowski, M. Wyszyński, A. de Arruda, M. Milosević, M.Zgirski
Probing confined vortices with a superconducting nanobridge,
Phys. Rev. Applied 19, 044073 (2023)

Manipulation with electric pulses



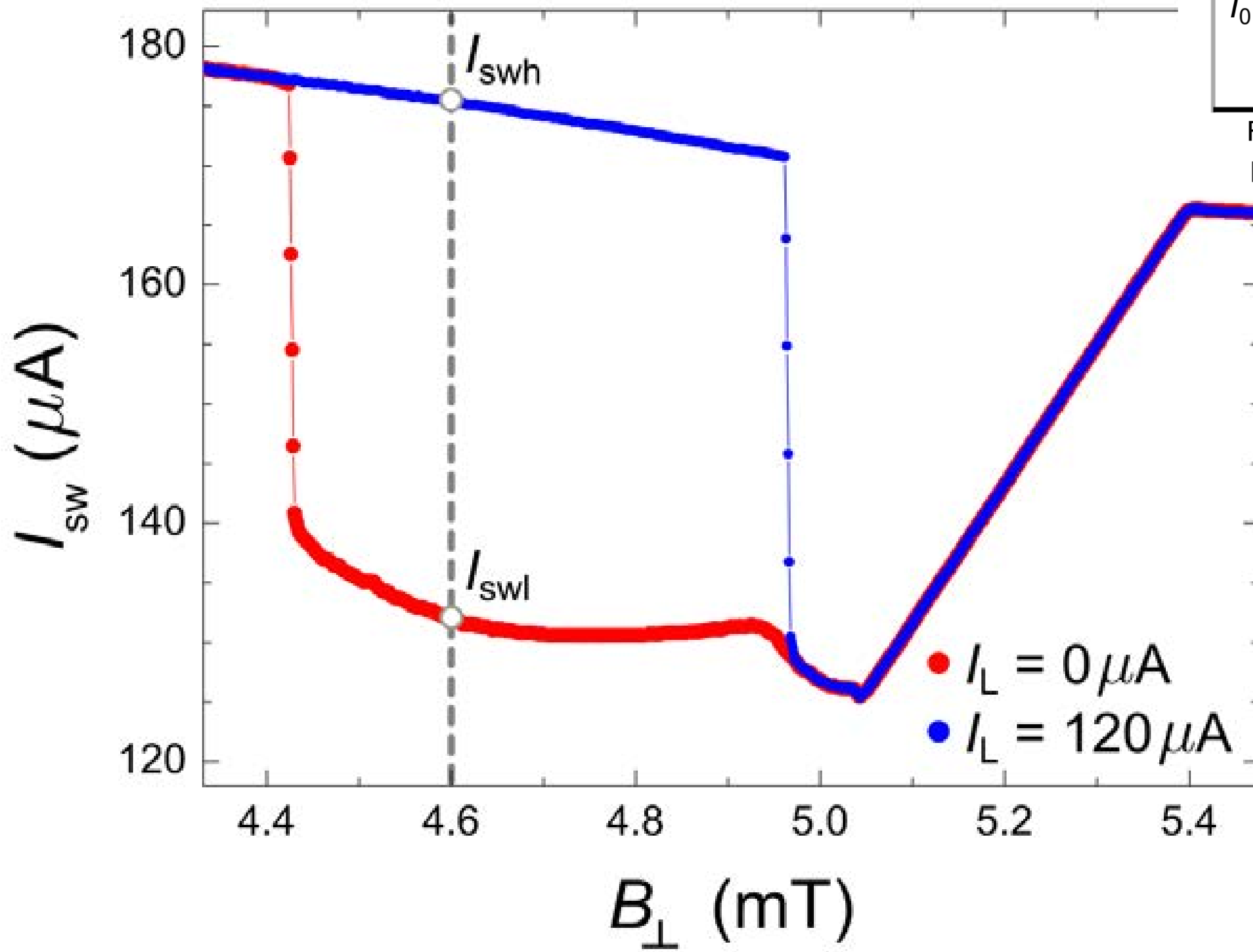
The presence of a vortex lowers I_{sw}

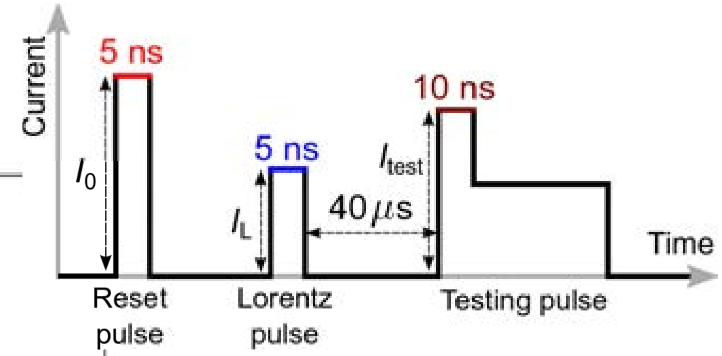
T_0 = 400 mK, W = 1 μm

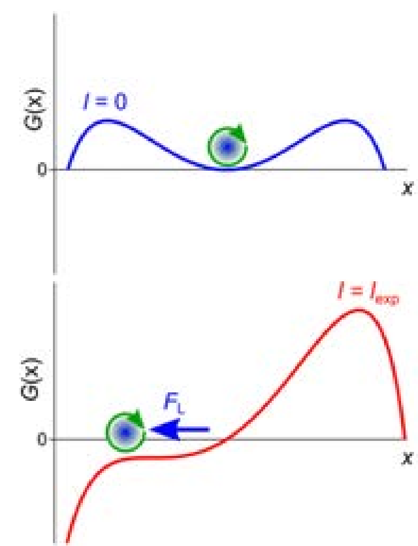


Let’s try to get rid of the vortex…

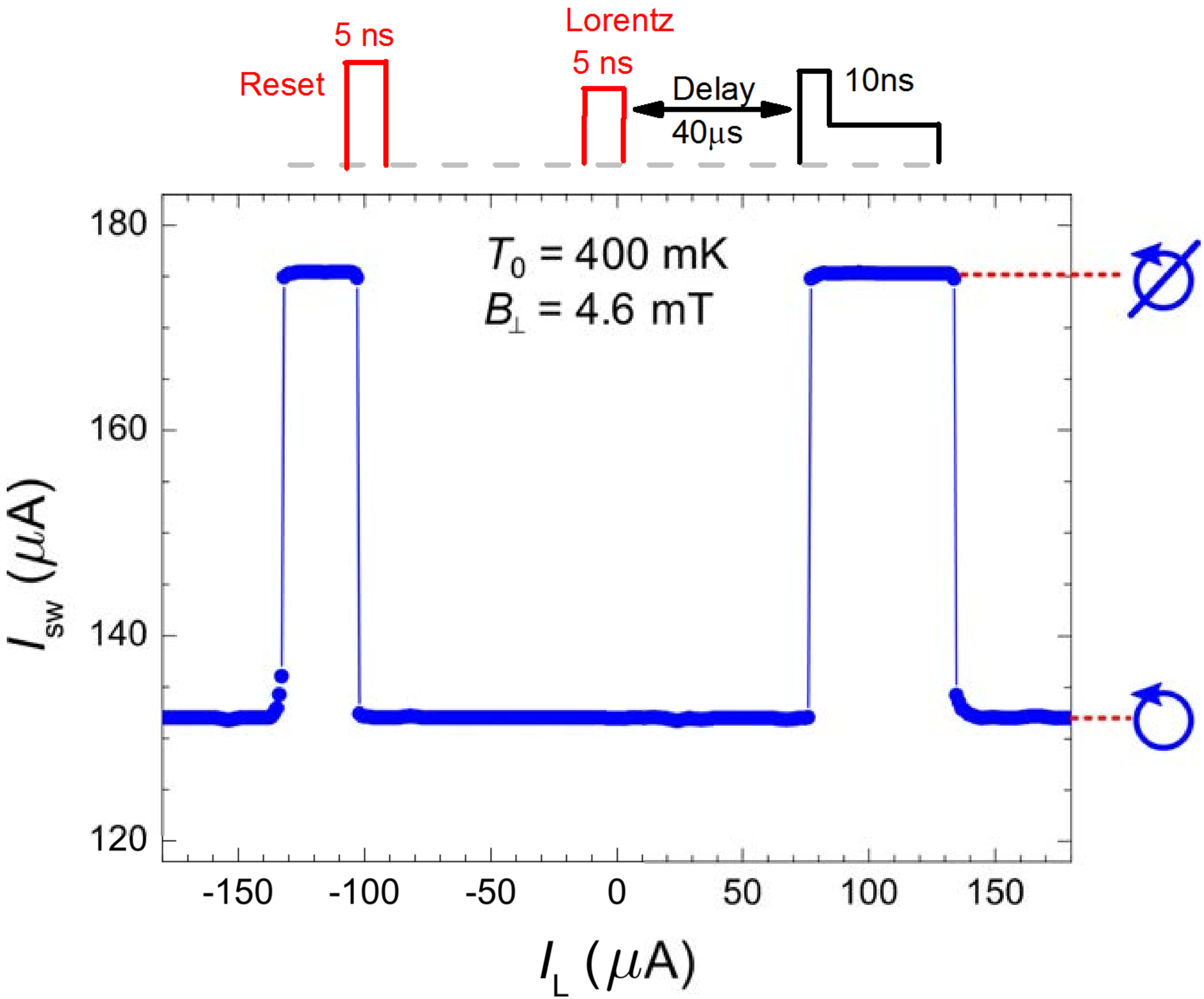
T_0 = 400 mK, W = 1 μm

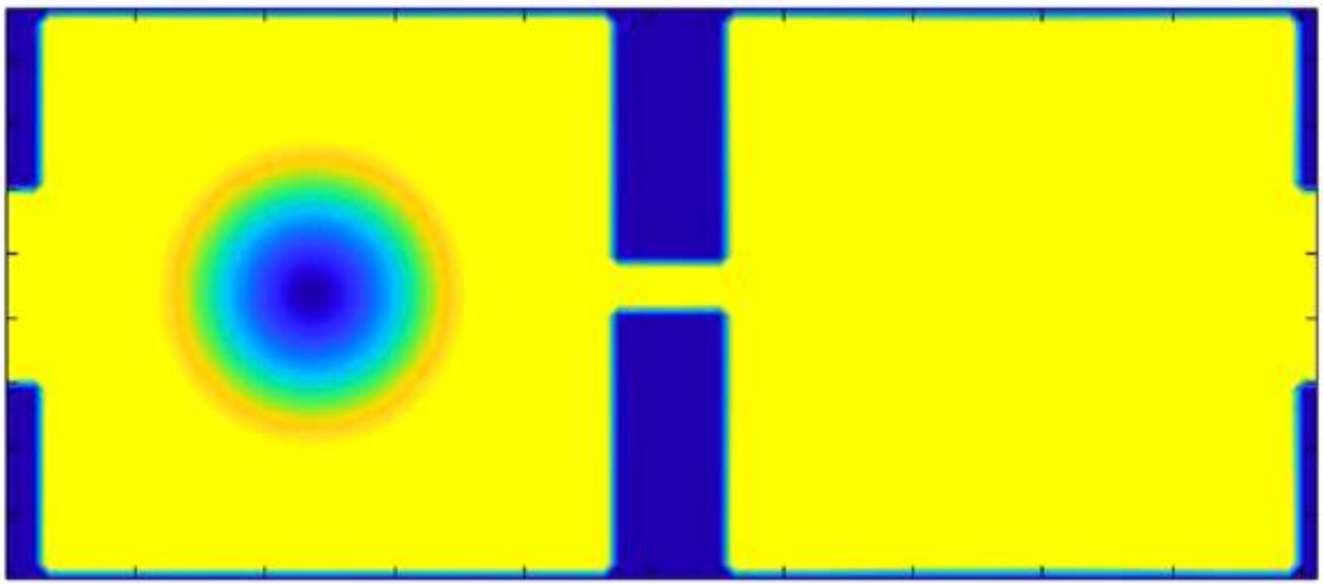






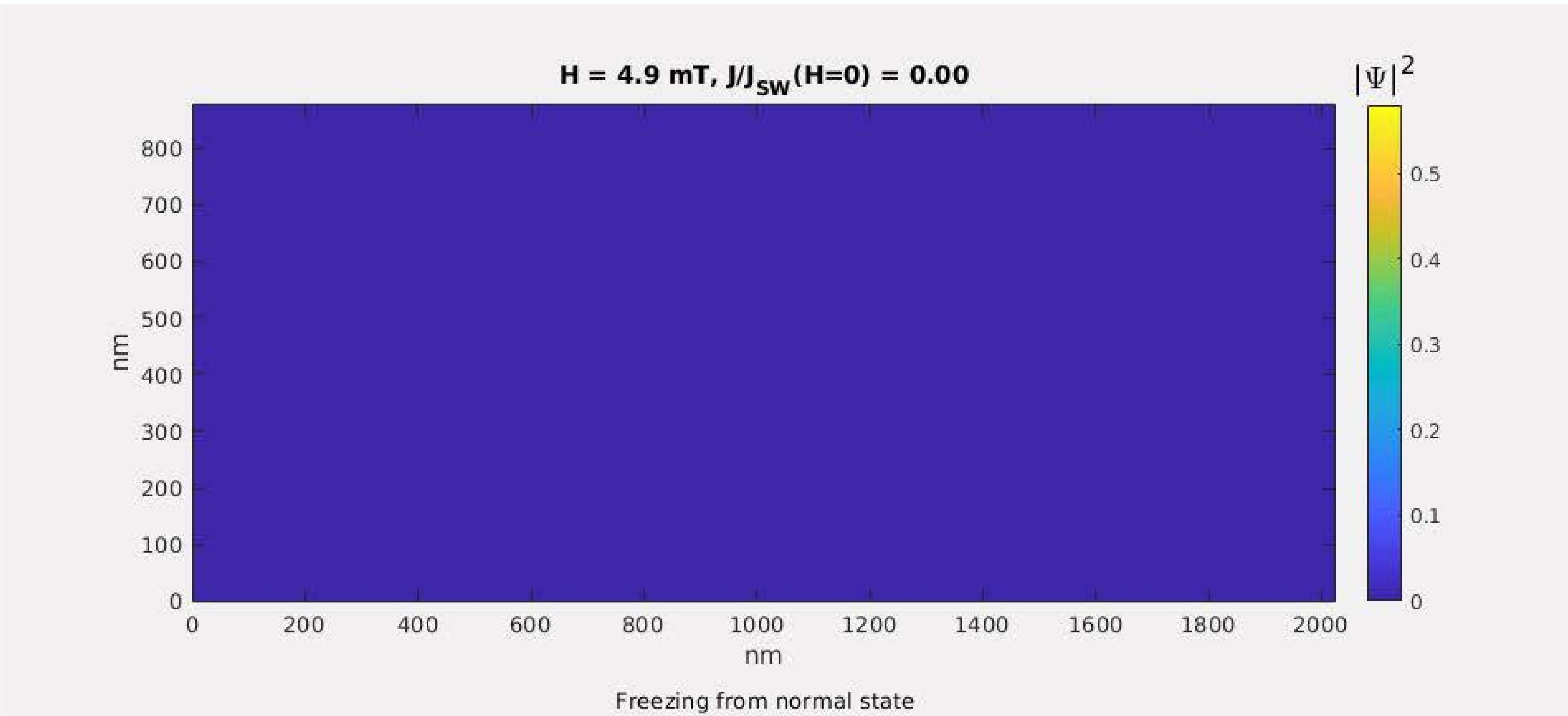
Get rid of the vortex…





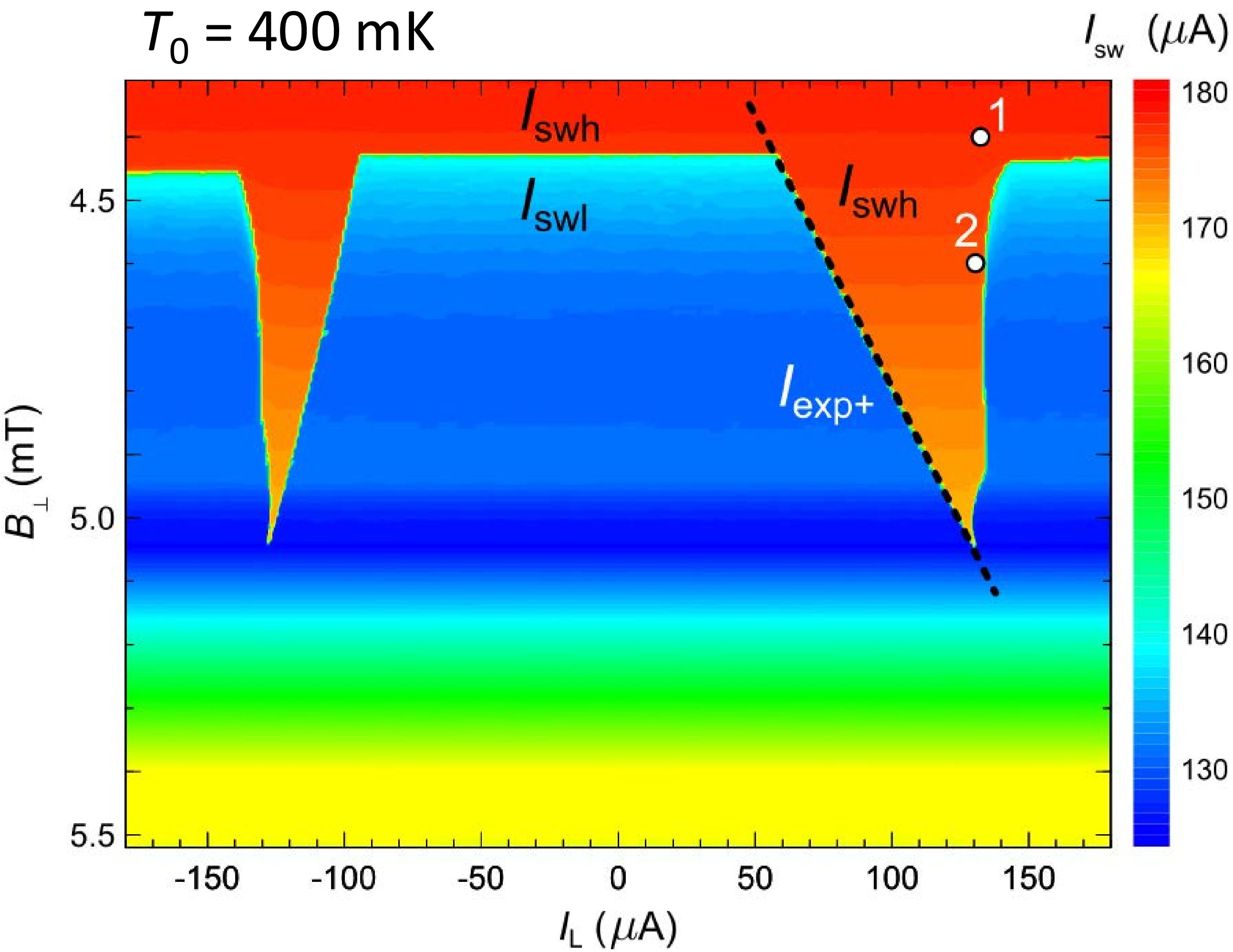
Device_3_1v.avi

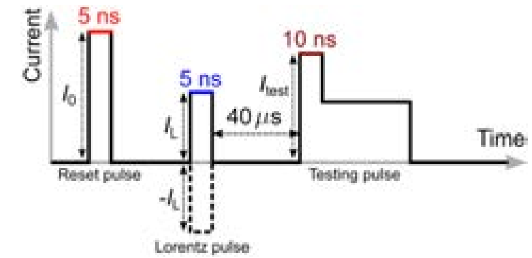
GL simulation of the Single Vortex Box

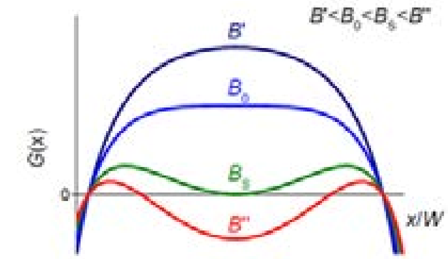


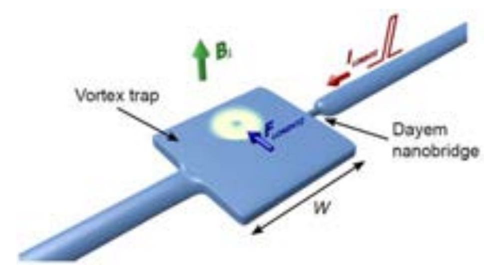
M. Foltyn, K. Norowski, M. Wyszyński, A. de Arruda, M. Milosević, M.Zgirski
Probing confined vortices with a superconducting nanobridge,
Phys. Rev. Applied 19, 044073 (2023)

Vortex stability diagram



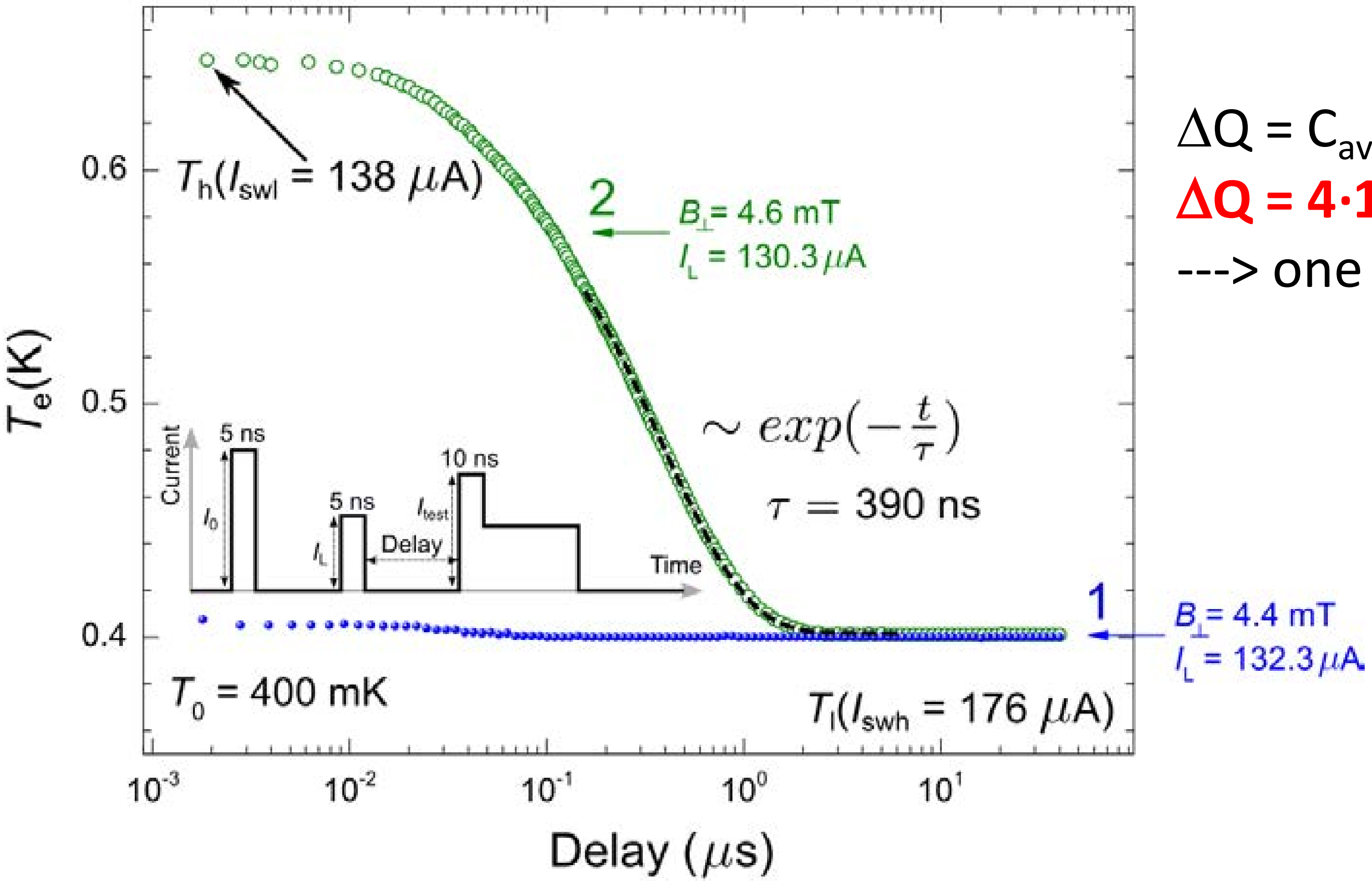






M. Foltyn, K. Norowski, A. Savin, M. Zgirski, *Quantum thermodynamics with a single superconducting vortex*, Science Advances **10**, eado4032 (2024)

Calorimetric detection of a single expelled vortex



$\Delta Q = C_{av}\,\Delta T$

$\Delta Q = 4 \cdot 10^{-19}$ J

---> one visible photon

M. Foltyn, K. Norowski, A. Savin, M. Zgirski, *Quantum thermodynamics with a single superconducting vortex*, Science Advances **10**, eado4032 (2024)

How much energy does the vortex expulsion dissipate?

Experiment:

$\Delta T = 250mK$, $\Delta Q = C_{av}\,\Delta T$

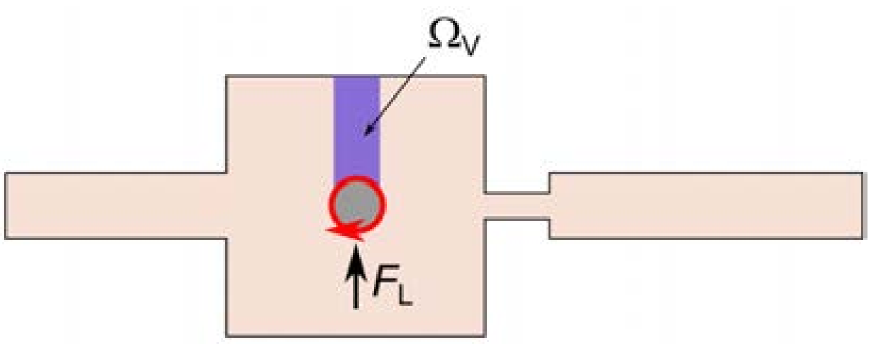
$\Delta Q = 4 \cdot 10^{-19}$ J ---> one visible light photon

Theory: Viscous flow of the vortex

- vortex anihilates Cooper pairs as it moves across the Single Vortex Box,
- Lorentz force makes a work against the viscous force and the heat is released,

$\boldsymbol{N_{qp} = g(E_F)\Omega_V\Delta}$

$\boldsymbol{\Delta = 1.76 k_B T_C}$ (superconducting gap)

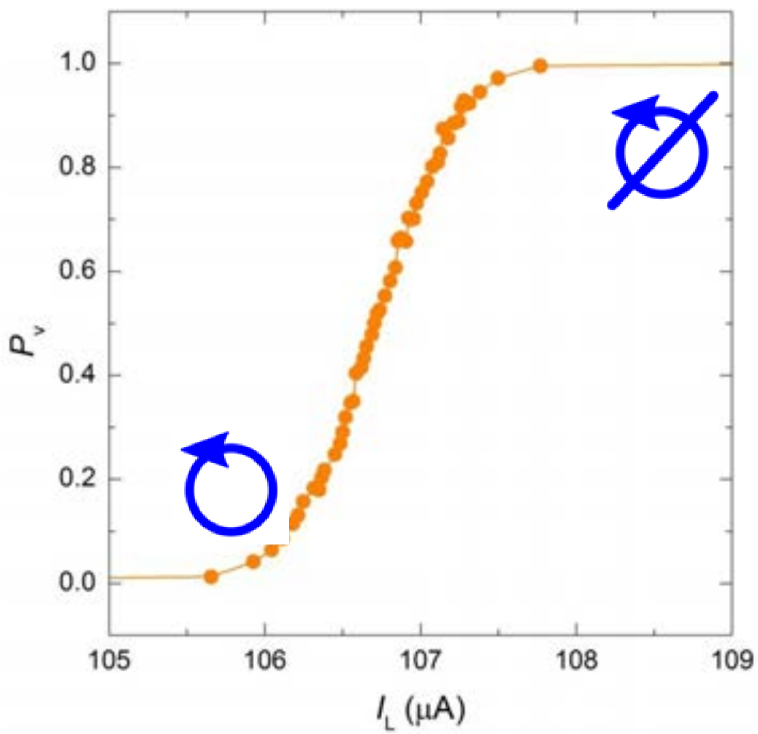


$\Delta Q = N_{qp}\,\Delta = 3 \cdot 10^{-19}$ J

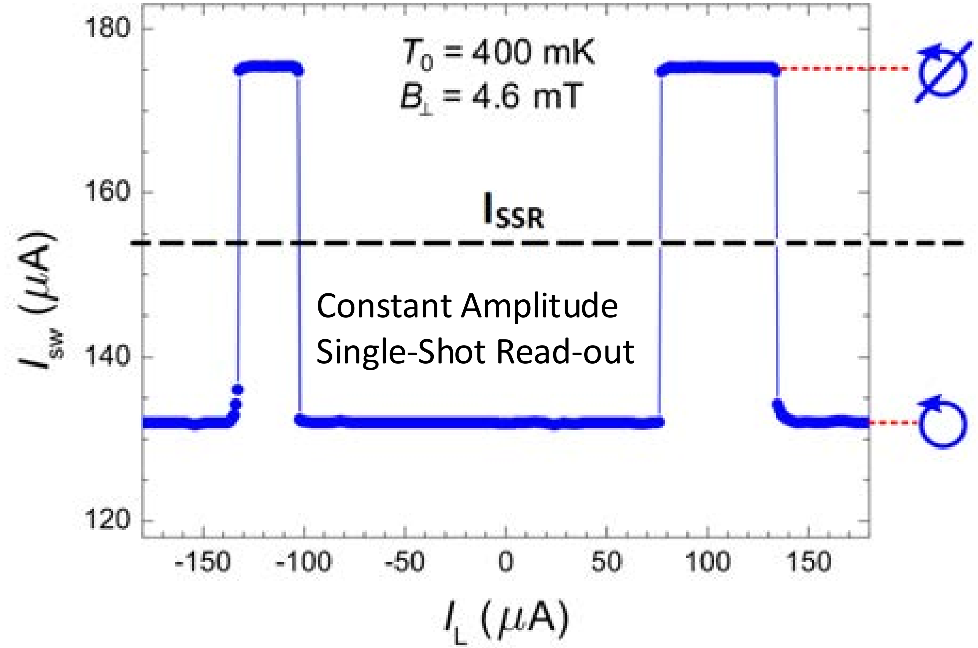
M. Foltyn, K. Norowski, A. Savin, M. Zgirski, *Quantum thermodynamics with a single superconducting vortex*, Science Advances (2024)

Vortex expulsion probability P_v: memory cell

WRITE: The Lorentz pulse changes logical state of the box: „0" or „1".



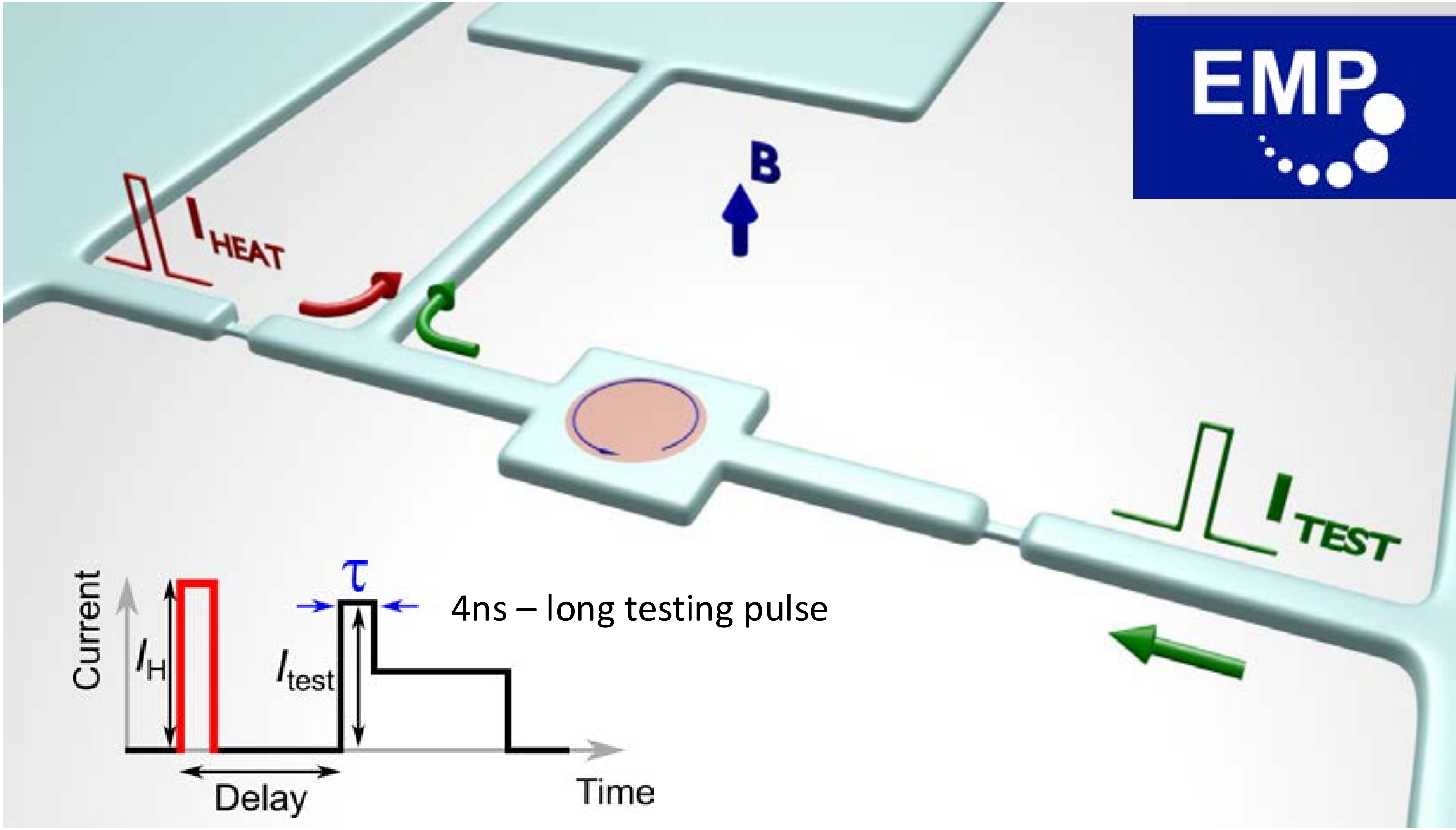
READ-OUT checks the state.



1. Bridge FOR SURE switches
if the vortex is present in the box,

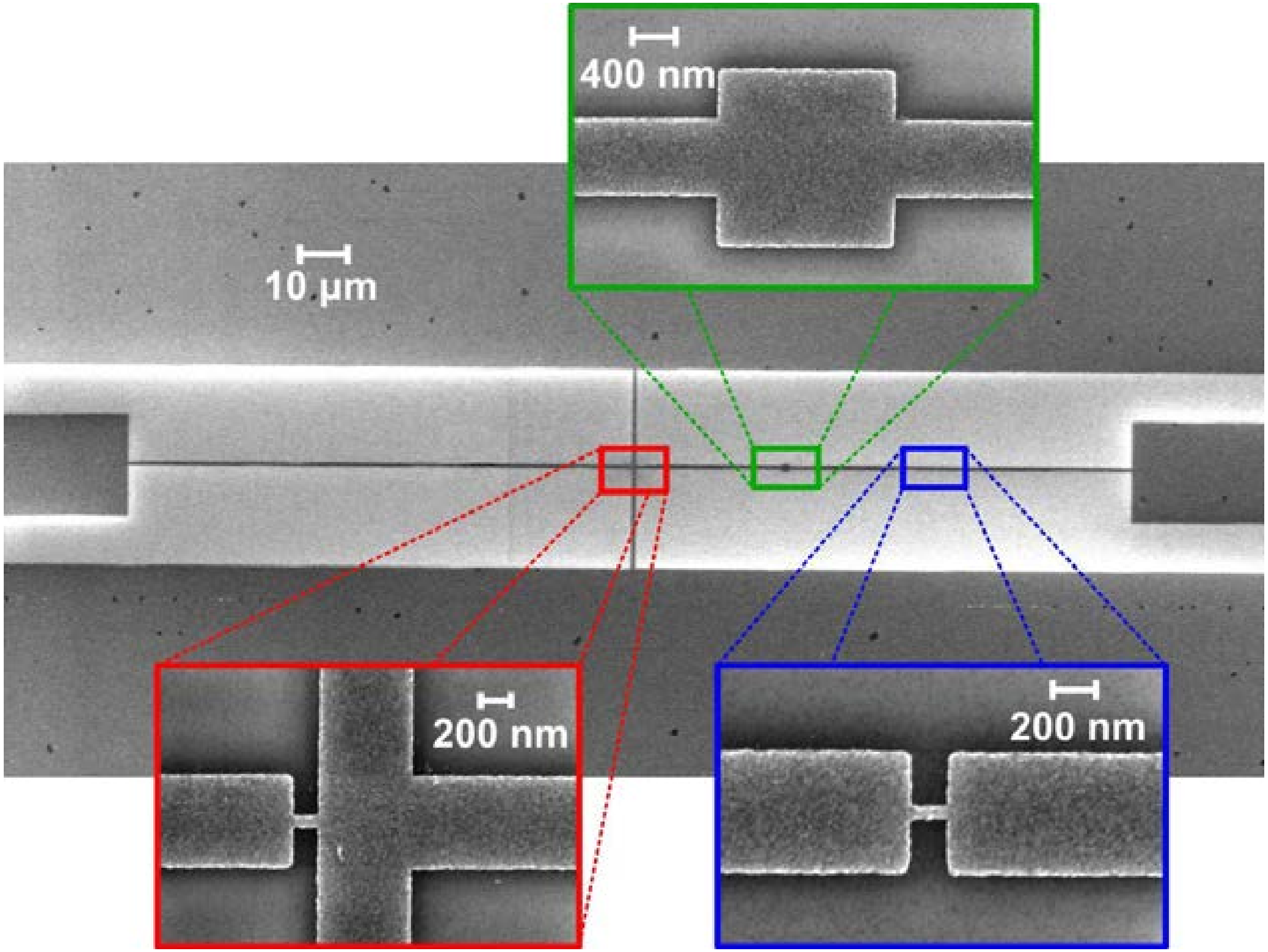
2. Bridge FOR SURE does not switch
if the box is „empty"

Single Vortex Box as QPs trap



4ns – long heating pulse

Sample

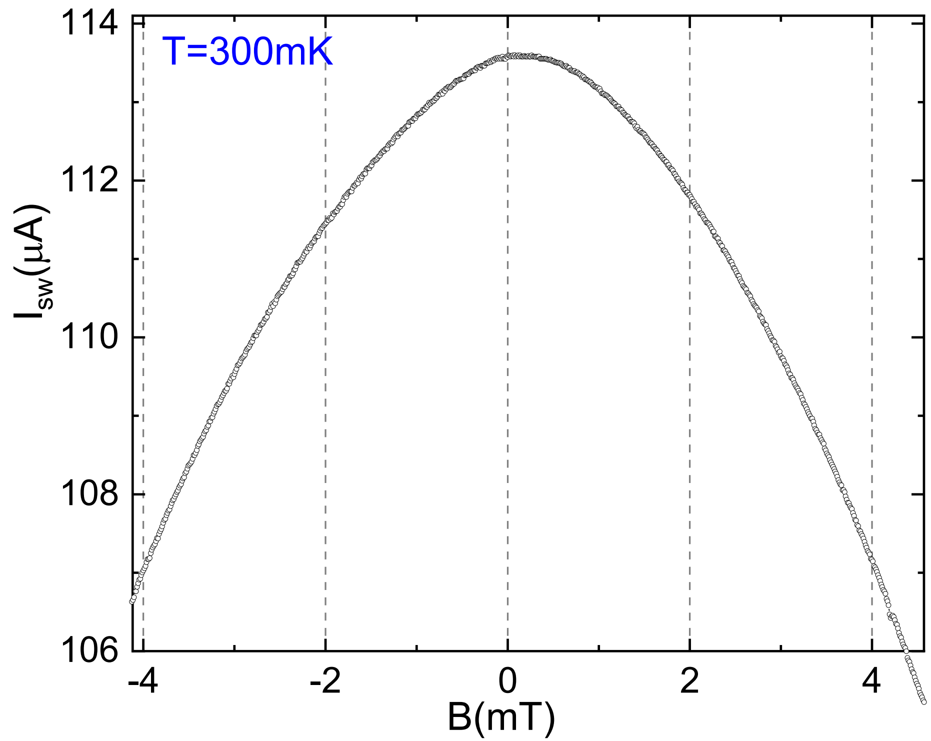


Sample design: M.Zgirski; Sample fabrication: J.Peltonen, Aalto Univ., Finland

Reference response of the QPs detector (No heating)

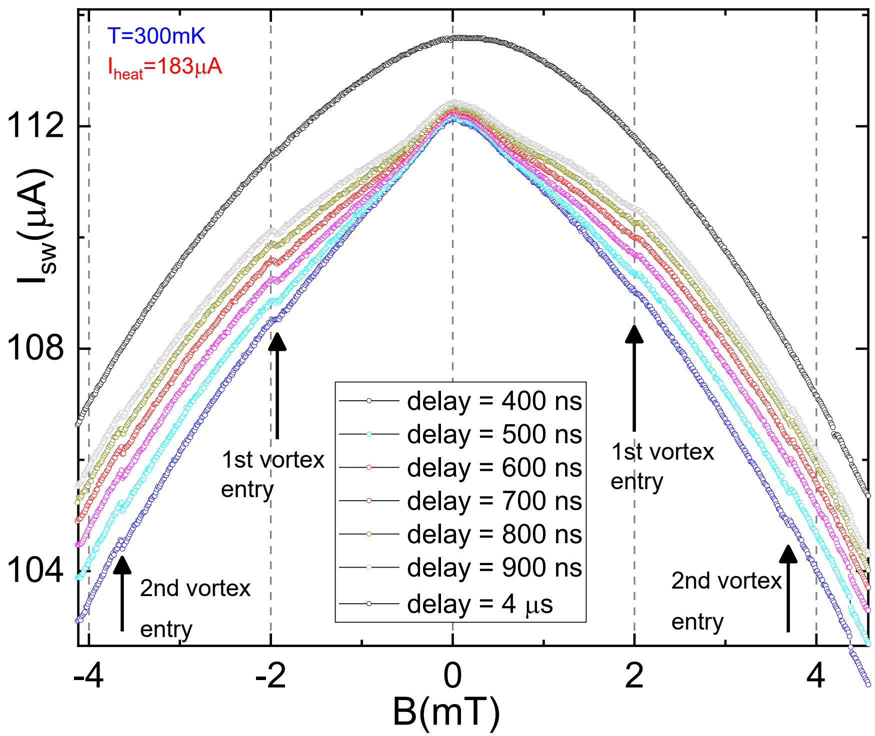
Suppression of I_c in magnetic field.

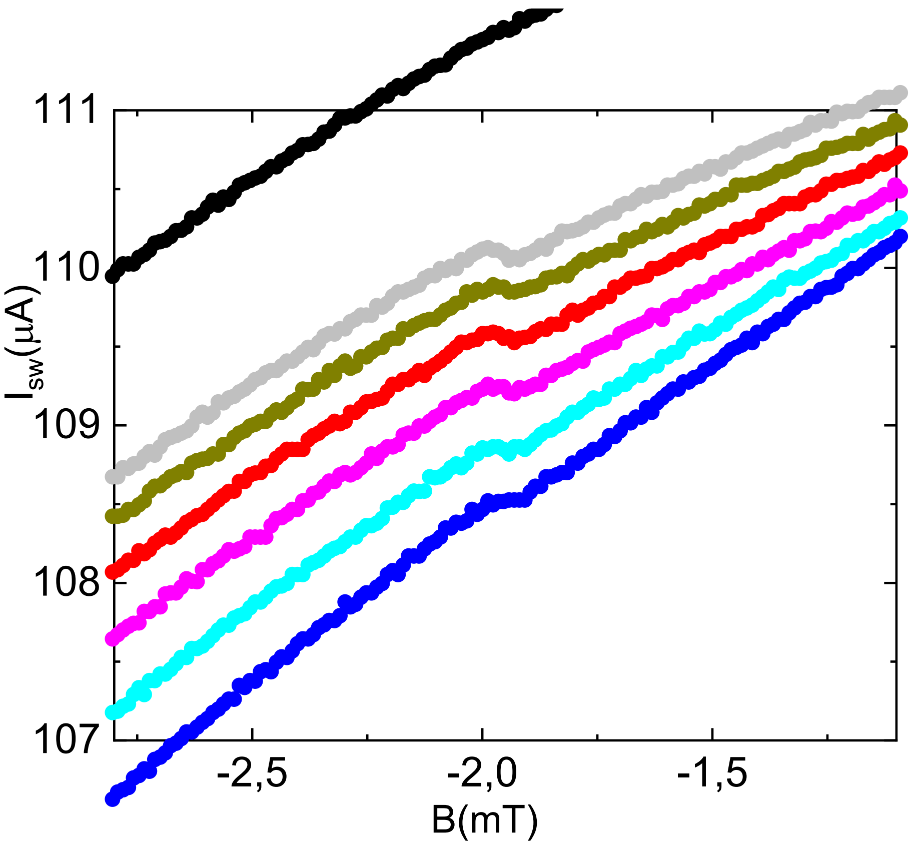
$$I_{CR}(B) = I_{C0}\left(1 - \left(\frac{B}{B_0}\right)^2\right)$$



M. Foltyn, K. Norowski, J. Peltonen, A. Savin, M.Zgirski,
Caloritronics with a single superconducting vortex, in preparation

Single vortex absorbs QPs



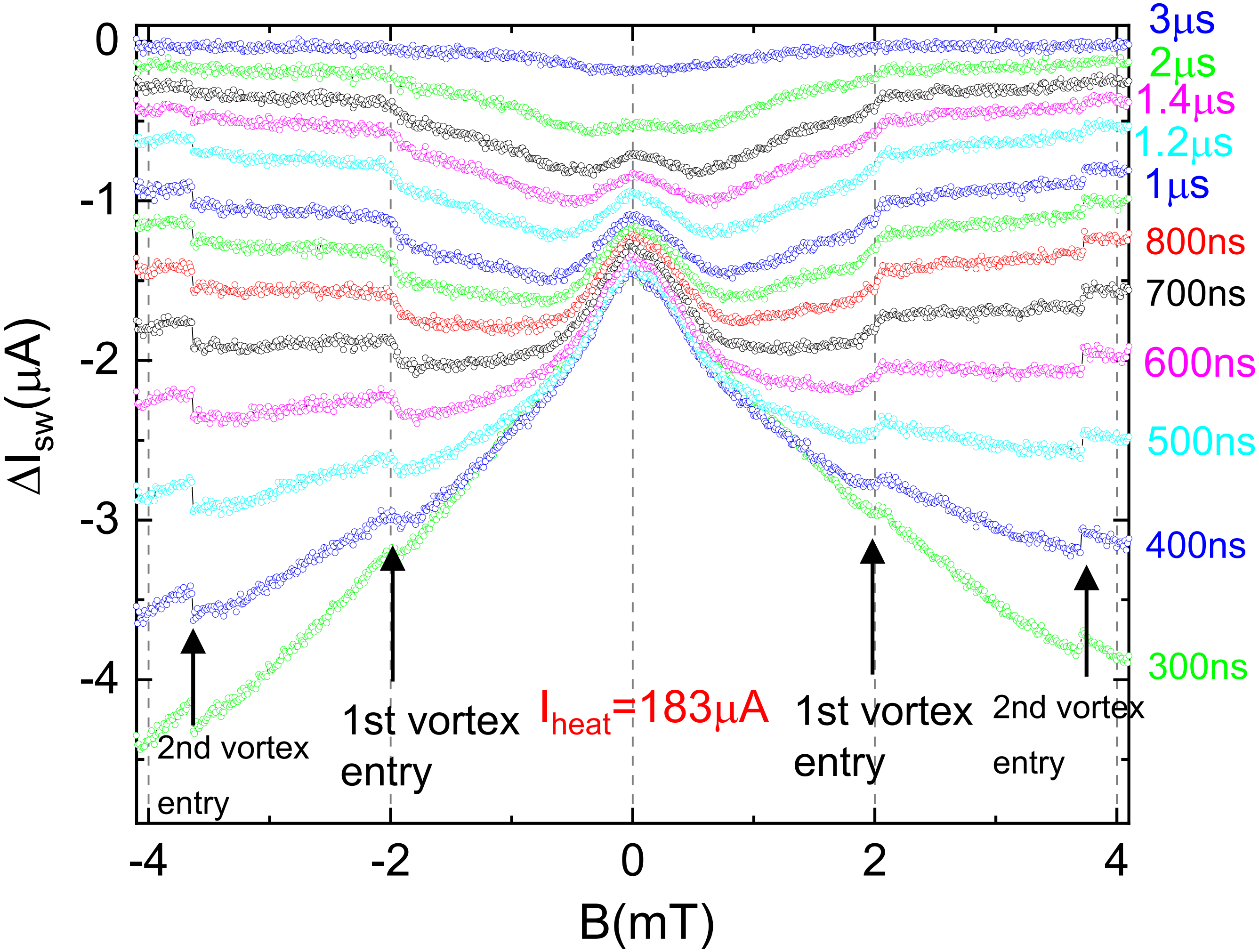


M. Foltyn, K. Norowski, J. Peltonen, A. Savin, M.Zgirski,
Caloritronics with a single superconducting vortex, in preparation

Single vortex absorbs QPs

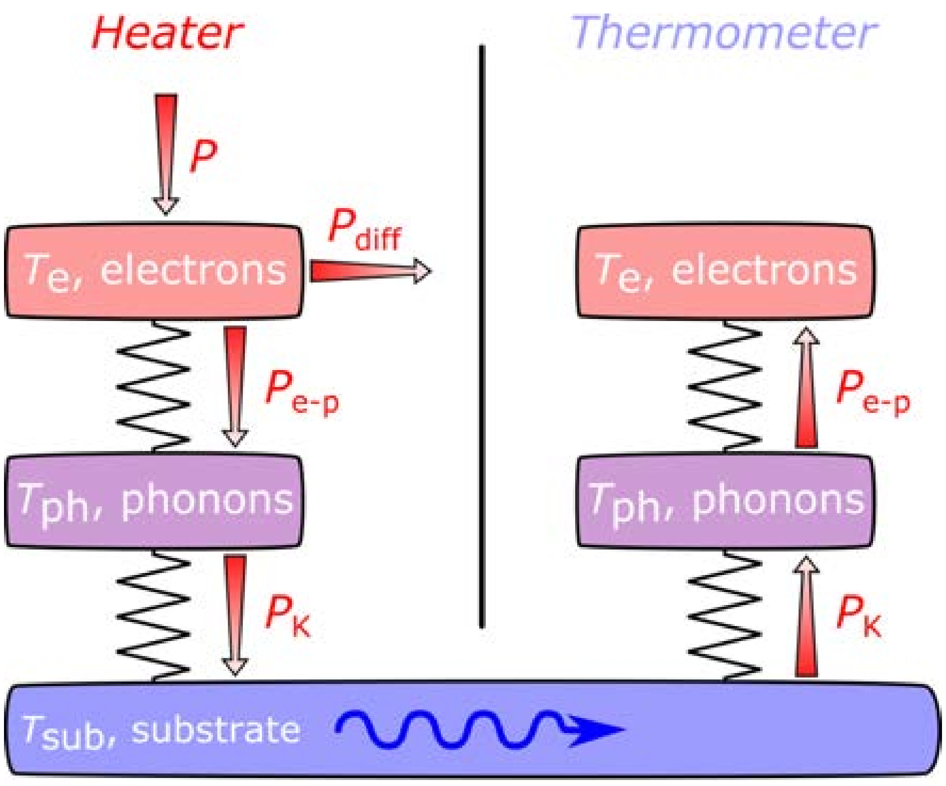
Suppression of I_c due to hot QPs arriving from the heater.

$\Delta n(B) \sim -\Delta I_{sw}(B)$

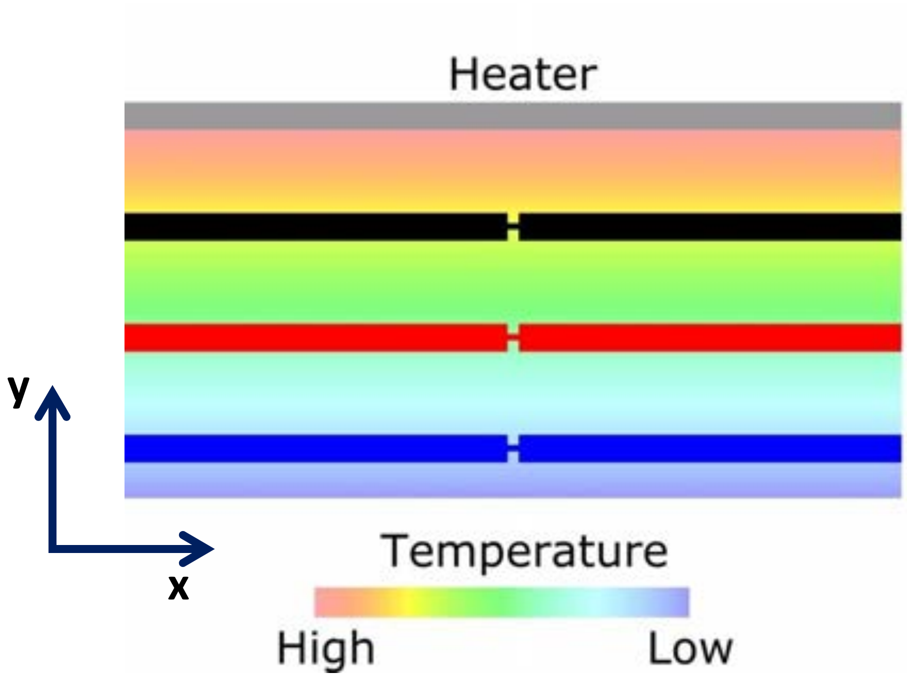


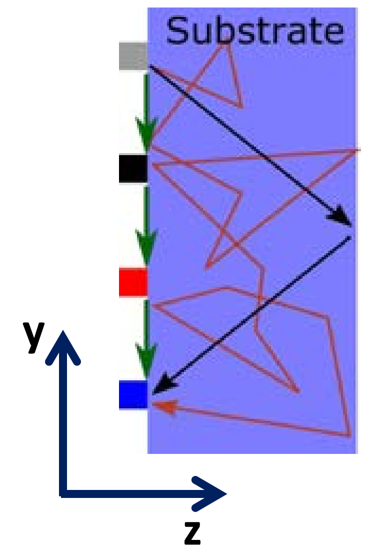
The kinks are fingerprints of the SINGLE VORTEX acting as a QP trap.
The vortex reduces flux of diffusing QPs,
which is visible as a smaller suppresion of the switching current at the kink.

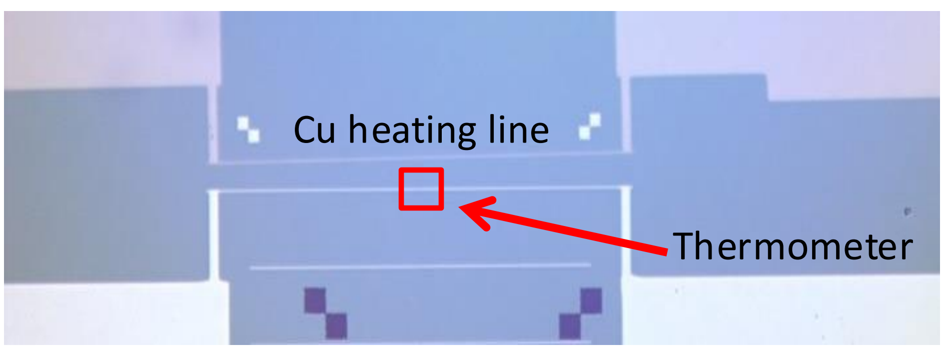
Phonon emission channel in an insulating substrate



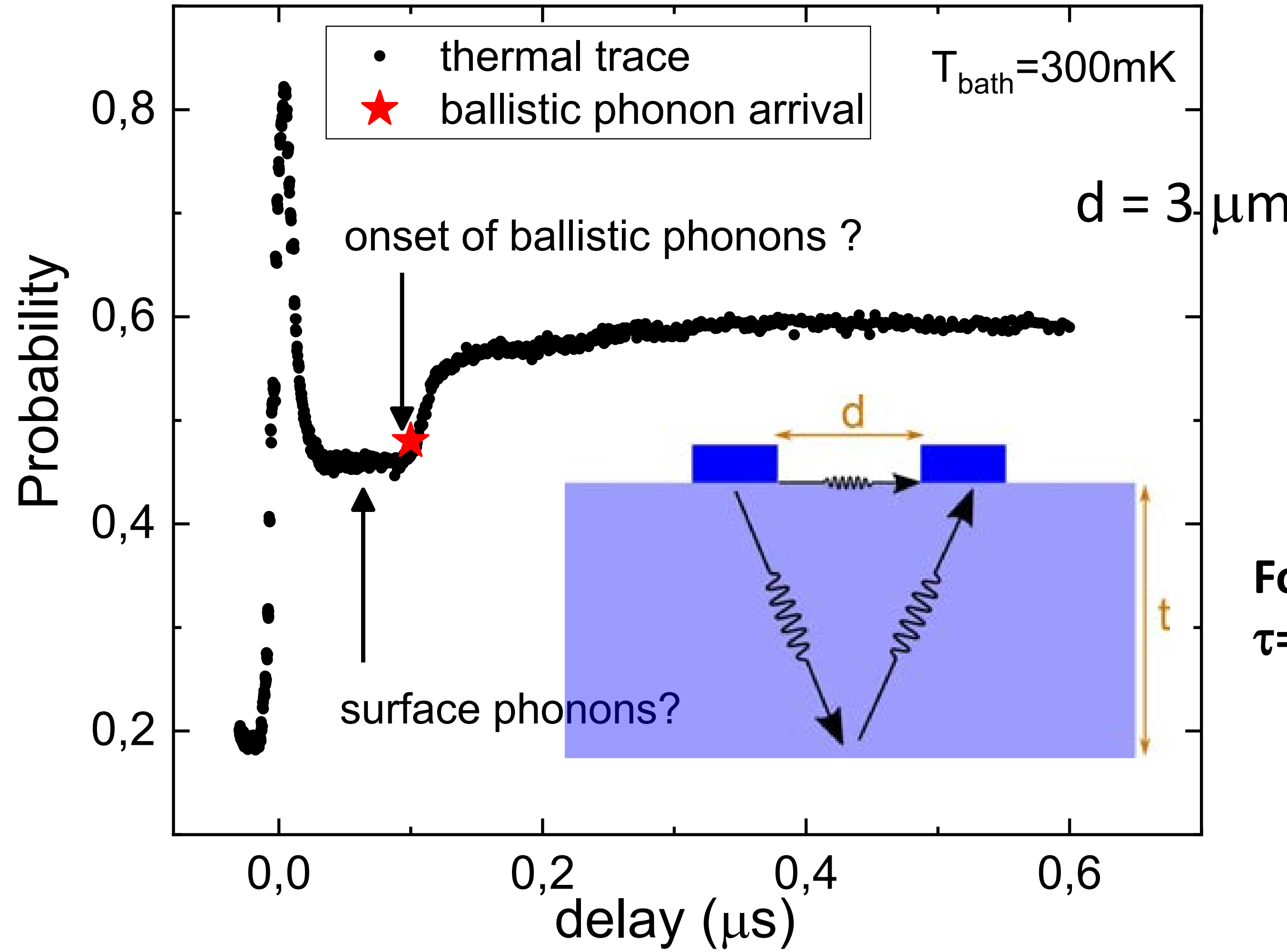
Are phonons ballistic or diffusive?







Phonons:
-ballistic,
-diffusive,
-bulk,
-surface.



For d<<t,
$\tau=2t/V_s$

V_s=5850m/s (speed of sound in Si, transversal wave), t=300μm, d=3μm

=> $\tau = \frac{2*t}{V_s}$ = 100ns

Unpublished

Coolphon Group:

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Konrad Norowski, IF PAN

Mujeeb Ahmed, IF PAN

Alissa Aouba, IFPAN/Grenoble

Collaboration:

Alexander Savin,
LTL, Aalto Univ.

Watch us at:
http://coolphongroup.ifpan.edu.pl

Relevant publications

1. M. Foltyn, K. Norowski, A. Savin, M. Zgirski, *Quantum thermodynamics with a single superconducting vortex*, **Science Advances 10, eado4032** (2024)

2. K. Norowski, M. Foltyn ,A. Savin, M. Zgirski, *Intrinsic Quasiparticle Lifetime in a Superconducting Aluminum*, **arxiv.org**/abs/2411.16614 (2024)

3. M. Foltyn, K. Norowski, M. Wyszyński, A. de Arruda, M. Milosević, M.Zgirski
Probing confined vortices with a superconducting nanobridge, **Phys. Rev. Applied** 19, 044073 (2023)

4. M. Zgirski, M. Foltyn, A. Savin, K. Norowski,
Stochastic thermal feedback in switching measurements of superconducting nanobridge caused by overheated electrons and phonons, **Phys. Rev. B 104**, 014506 (2021)

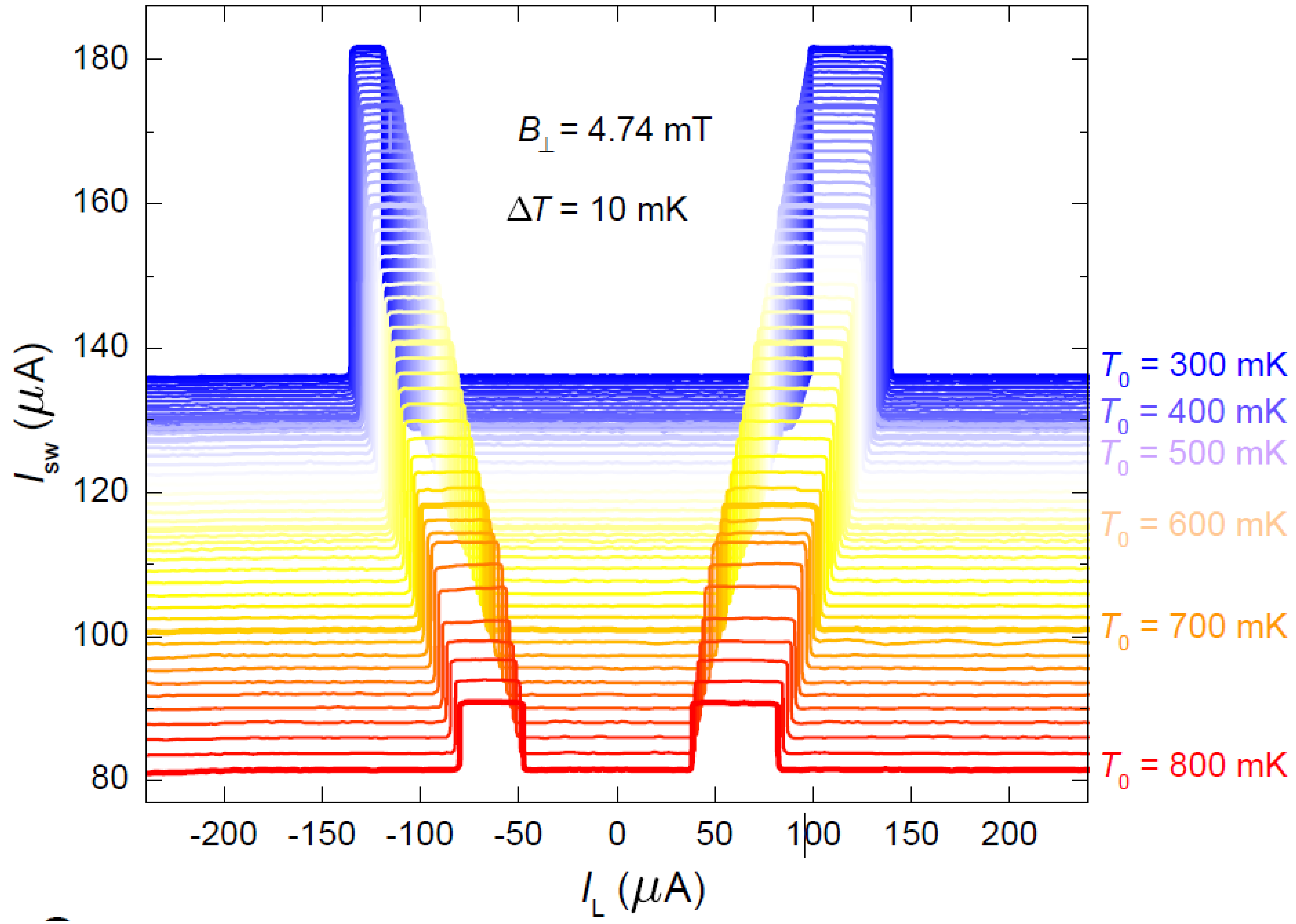
5. M. Zgirski, M. Foltyn, A. Savin, A. Naumov, K. Norowski,
Heat Hunting in a Freezer: Direct Measurement of Quasiparticle Diffusion in Superconducting Nanowire,
Phys. Rev. Applied 14, 044024 (2020)

6. M. Zgirski, M. Foltyn, A. Savin, K. Norowski,
Flipping-Coin Experiment to Study Switching in Josephson Junctions and Superconducting Wires,
Phys. Rev. Applied 11, 054070 (2019)

7. M. Zgirski, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J. Pekola,
Nanosecond Thermometry with Josephson Junctions, **Phys. Rev. Applied 10**, 044068 (2018)

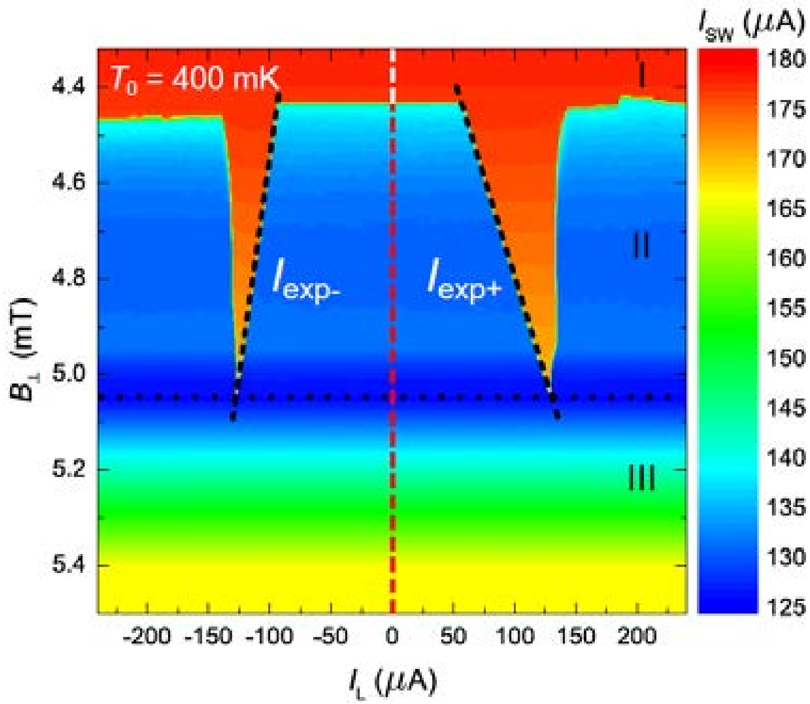
8. M. Foltyn, M. Zgirski,
Gambling with Superconducting Fluctuations, **Phys. Rev. Applied 4**, 024002 (2015)

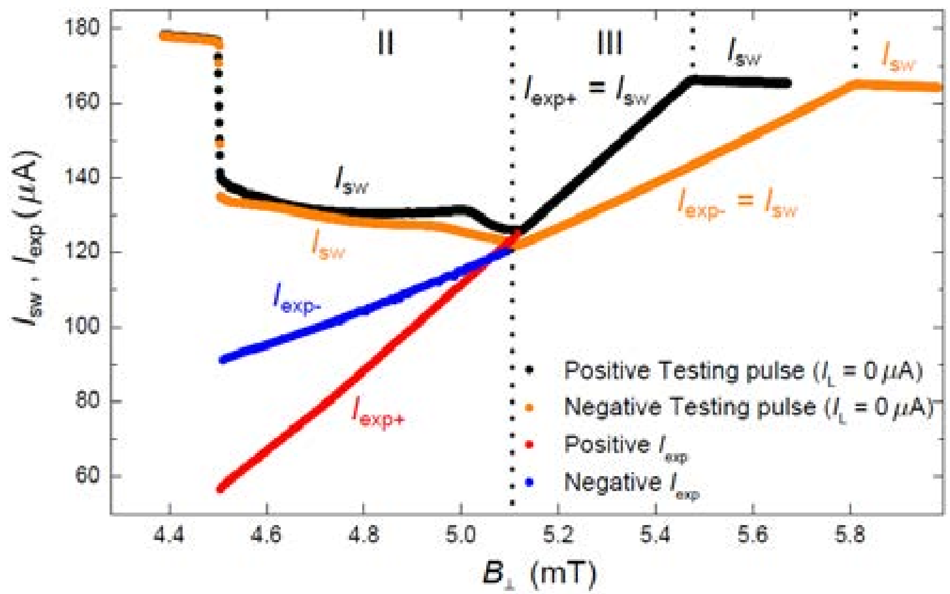
Temperature dependence of the vortex expulsion threshold



Diode effect

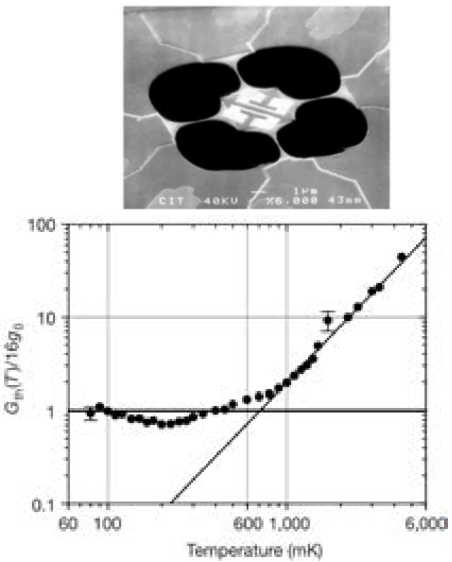
$$I_{exp+} \neq I_{exp-}$$





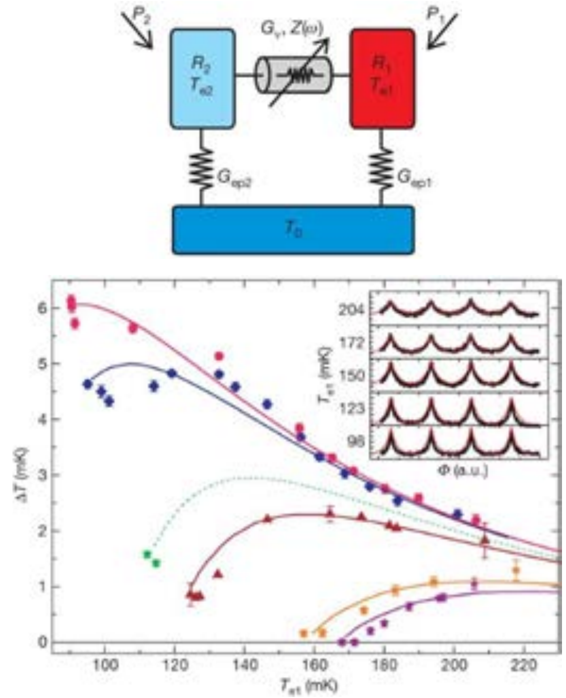
Quantum thermodynamics

Single phonon heat transfer



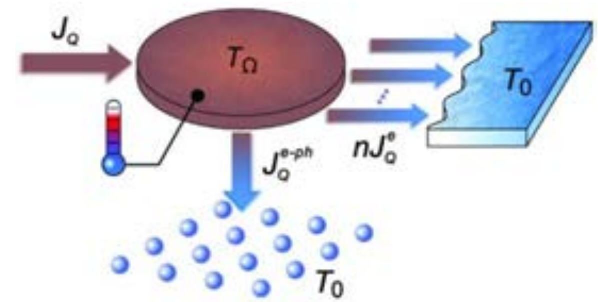
K. Schwab, E. A. Henriksen,
J. M. Worlock, M. L. Roukes,
Nature **404**, 974–977 (2000)

Black body radiation on chip



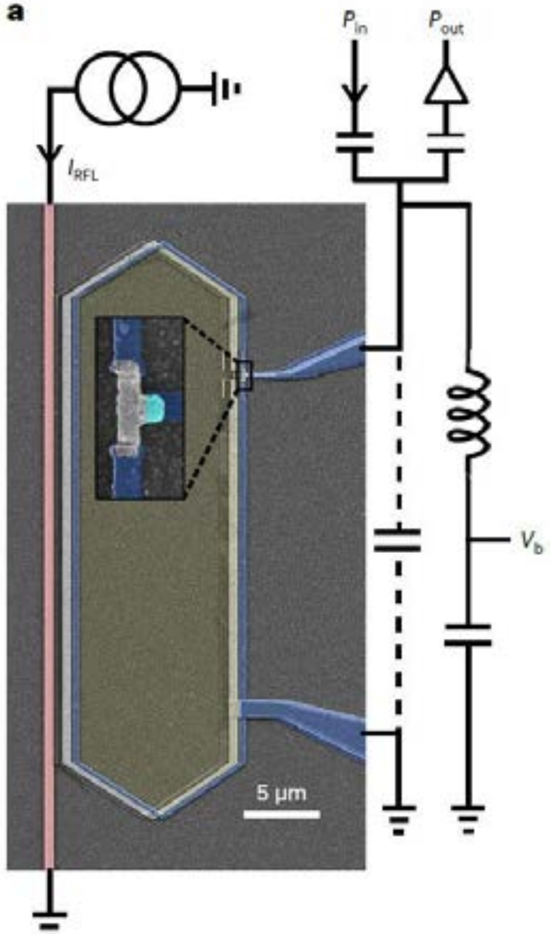
M. Meschke, W. Guichard, J.P. Pekola,
Nature **444**, 187–190 (2006)

Single electronic channel heat transfer

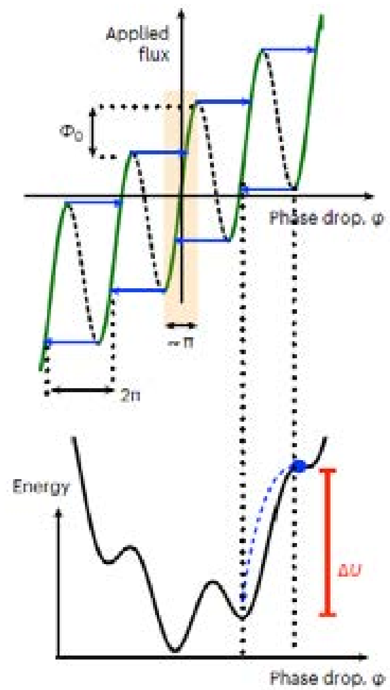


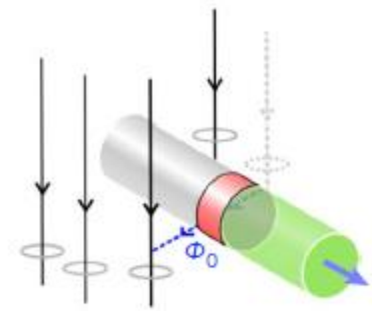
S. Jezouin, F. D. Parmentier,
A. Anthore, U. Gennser,
A. Cavanna, Y. Jin, F. Pierre,
Science **342**, 601-604 (2013)

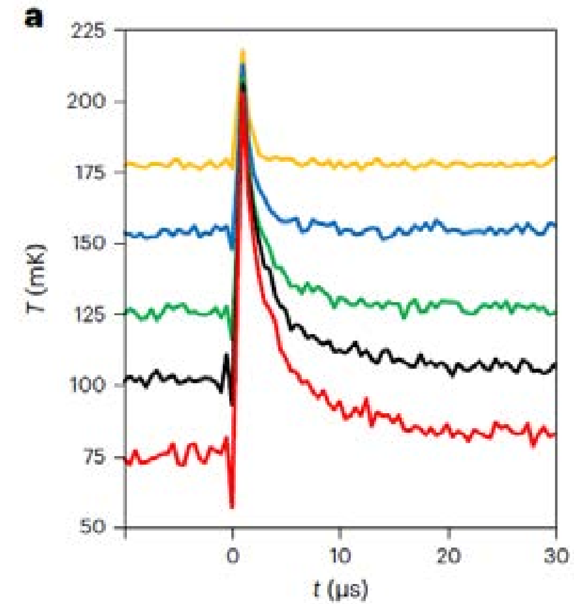
Heating due to a phase slip (example 2)



$$2\pi(\Phi_X/\Phi_0) = \varphi + \beta \sin(\varphi)$$

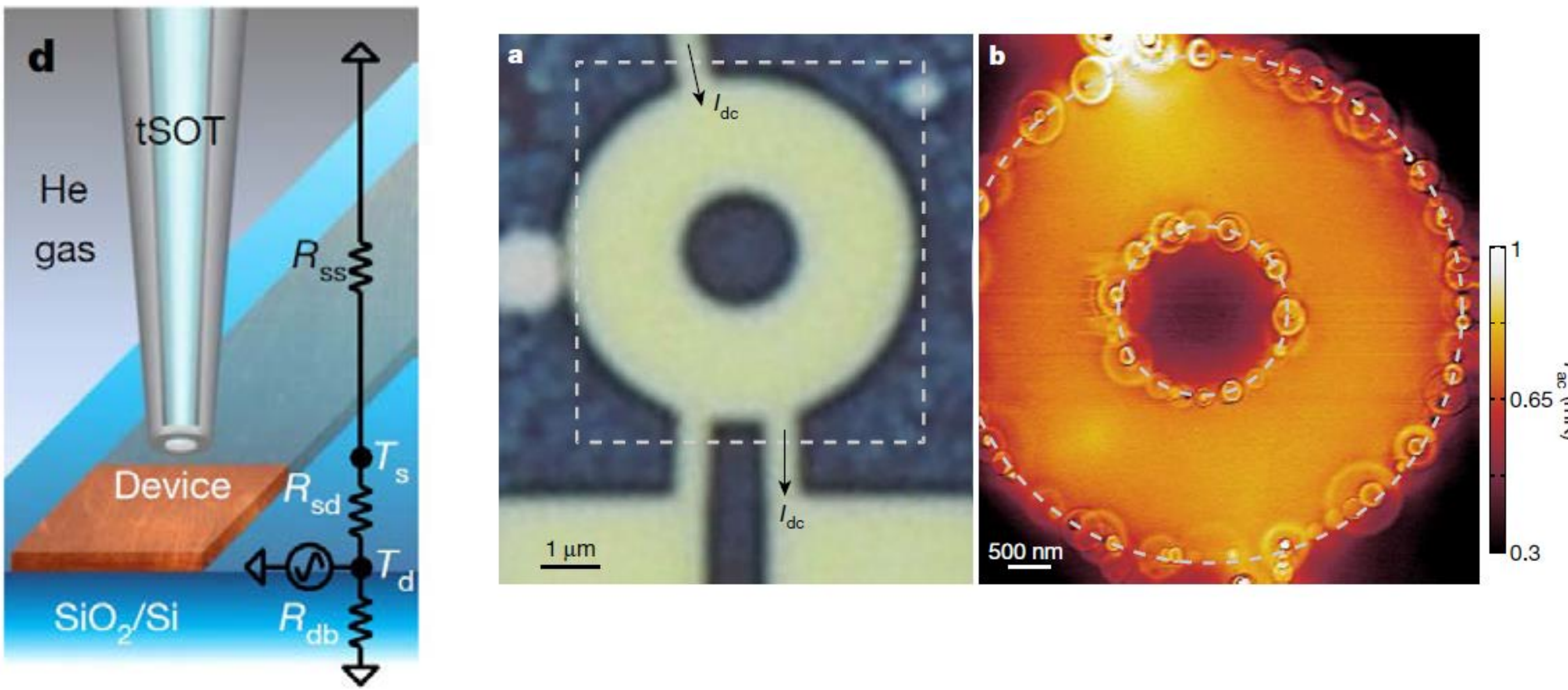






E. Gumus, et al., *Calorimetry of a phase slip in a Josephson junction*, Nature Physics 19, 196 (2023)

Thermal imaging of edge states in graphene (example 1)



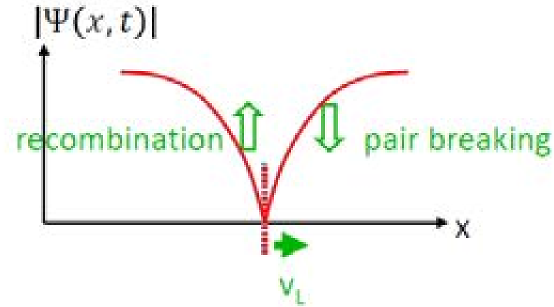
D. Halbertal, et al., *Nanoscale thermal imaging of dissipation in quantum systems*, Nature 539, 407 (2016)

Viscous interpretation of pair breaking

6.2.2 Depinning Critical Current Density

power dissipation during vortex motion:

a. pair breaking and recombination:



- in front of flux-line: $|\Psi|$ decreases

  $\Rightarrow$ pairs have to break up

- pair breaking due to absorption of phonons:

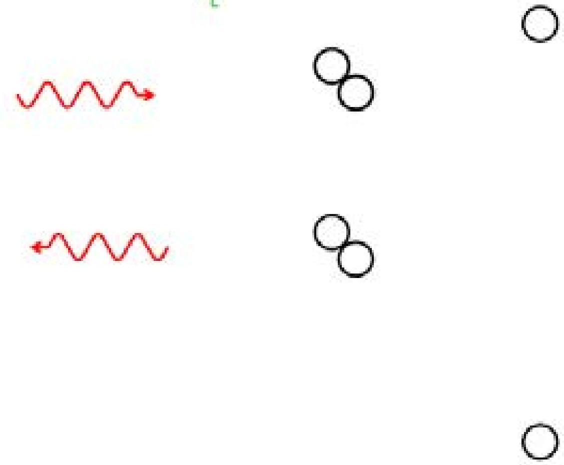
- behind the flux-line: $|\Psi|$ increases

  $\Rightarrow$ recombination of pairs by phonon emission:

- finite phonon lifetime delays thermal equilibrium:

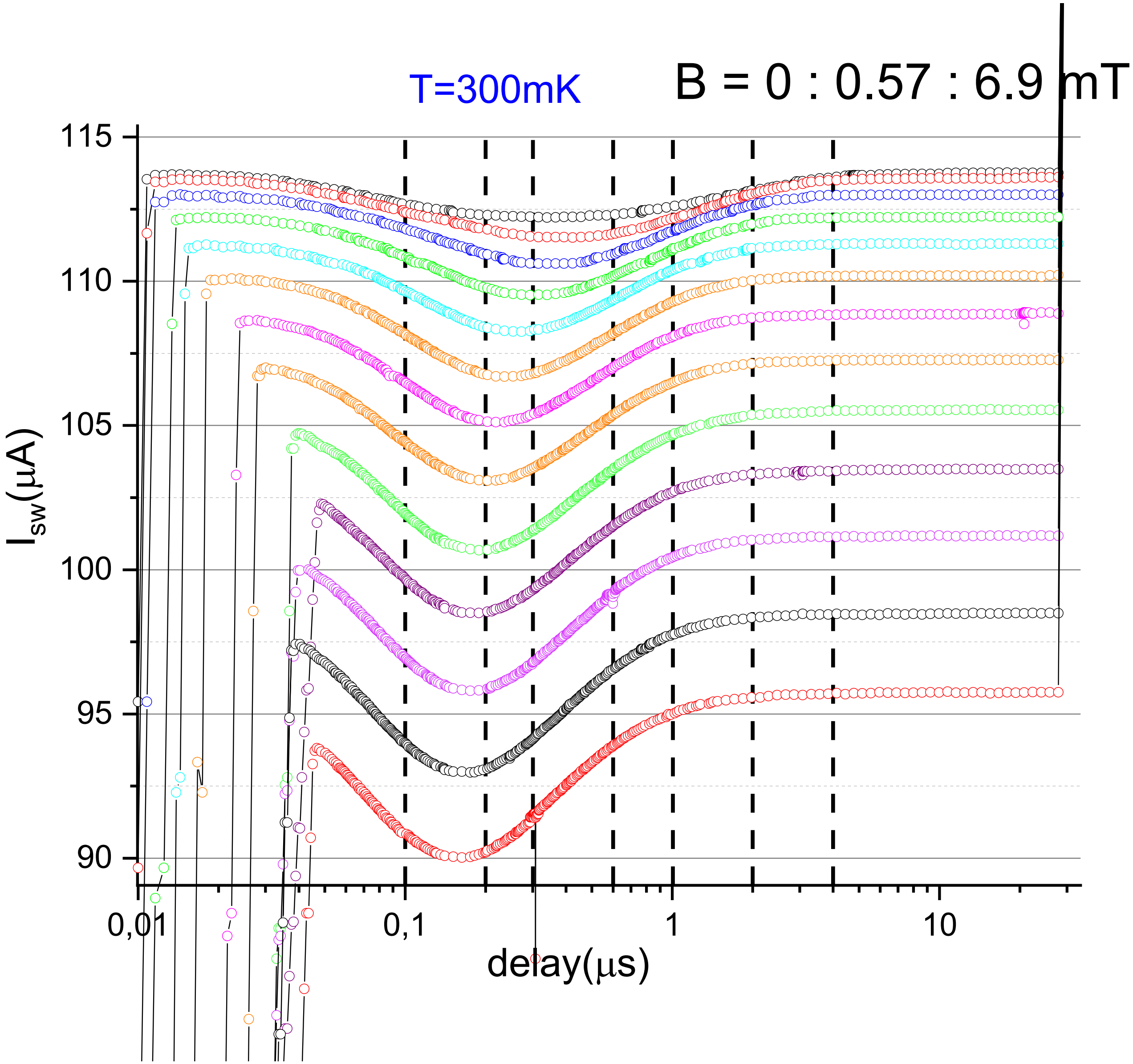
  irreversible process → friction, viscous flow

- electric energy is transferred to heat



Source: Lecture Notes, Winter Semester 2021/2022, R. Gross, © Walther-Meißner-Institut

QPs diffusion in magnetic field



Suppression of I_c:
- in magnetic field,
- due to hot QPs arriving from the heater.

Thermal vs. „quasiparticle" approach

Thermodynamical approach => QPs are described with an equilibrium distribution (Fermi-Dirac function), The quantity under study is TEMPERATURE

$$\frac{\partial}{\partial x}\left(\kappa \frac{\partial T_e}{\partial x}\right) = C_v \frac{\partial T_e}{\partial t} + P_{ep} - \frac{r\,i^2}{A}$$

<u>Parameters:</u>

κ – electron thermal conductivity,
C_v – electron heat capacity,
P_{ep}-electron-phonon power flow

Microscopic approach => QPs are not populated according to Fermi-Dirac;
The quantity under study should be $n_{qp}(E)$,
but often it is just n_{qp}

$$D\nabla^2 n_{qp} - \Gamma_R n_{qp}^2 + \gamma_i - \Gamma_v n_{qp} e^{-\left(x-x_v^i\right)^2/l_v^2} = 0$$

Phys. Rev. Lett. **113**, 117002 (2014)

$$D\nabla^2 n - \Gamma n^2 + (I/e)g(x) = 0$$

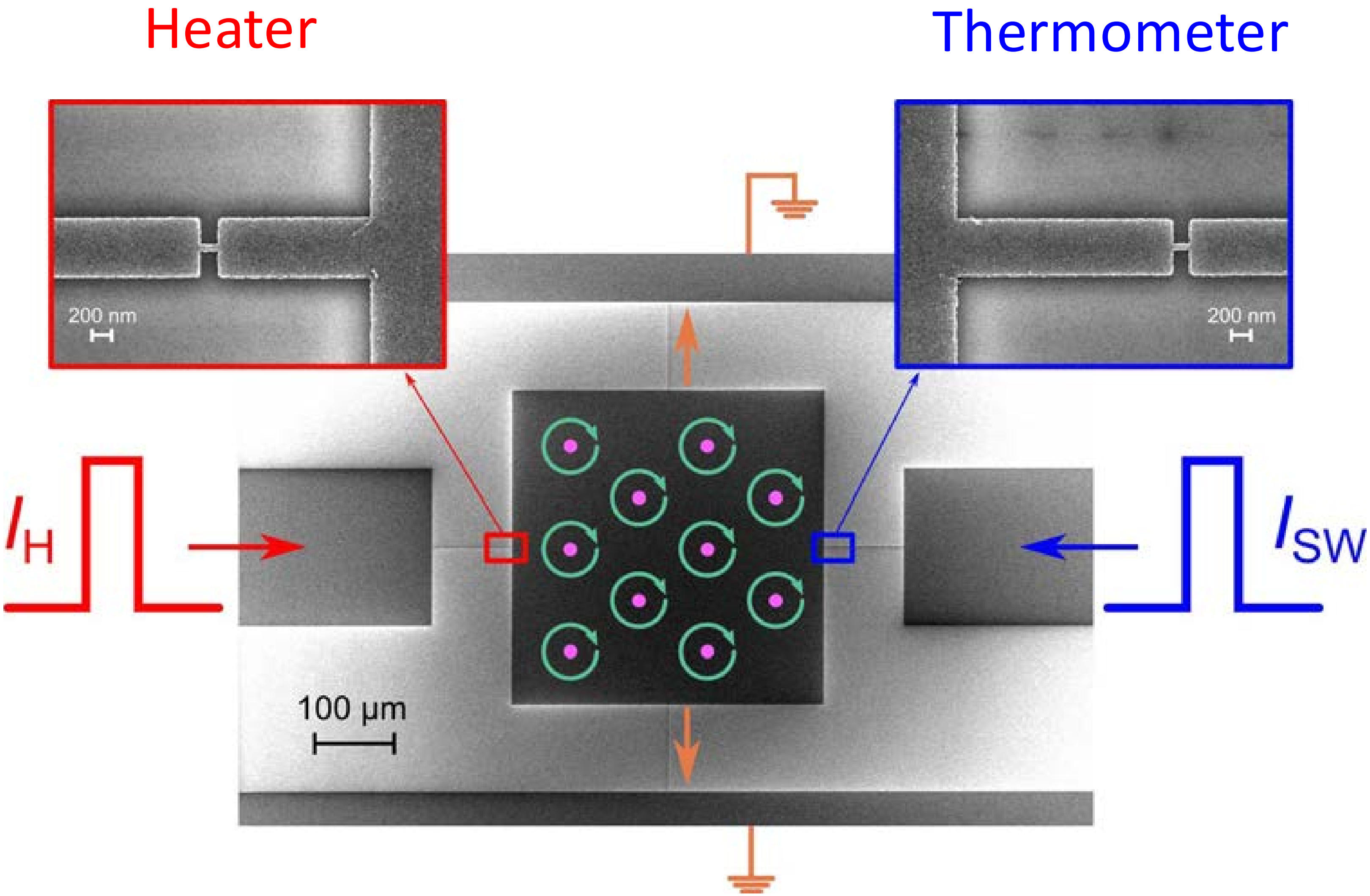
Phys. Rev. B 58, 8225 (1998)

<u>Parameters:</u>

recombination rates Γ,
diffusion constant D

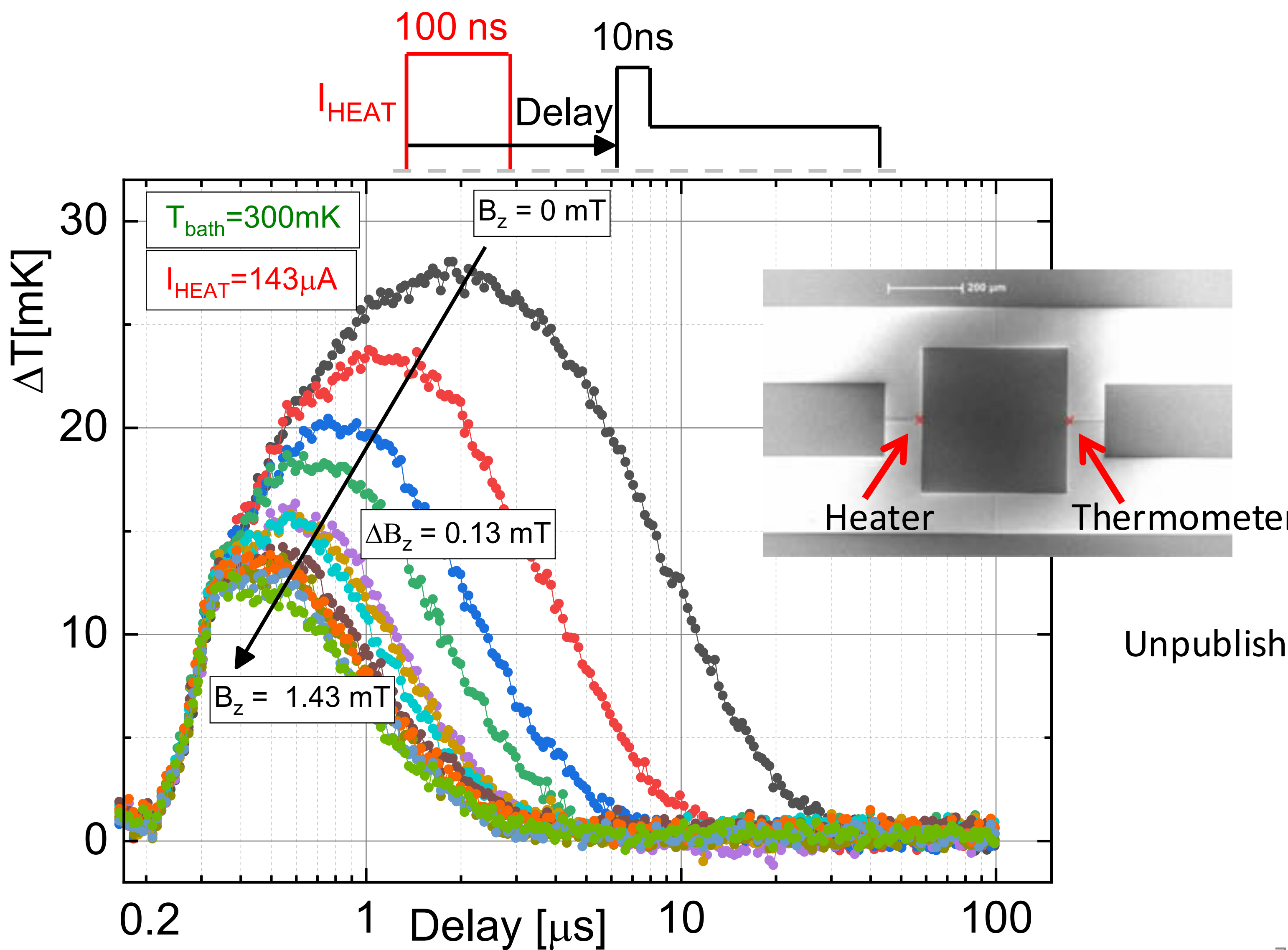
should be in principle E-dependent,
If not, we get a simplified phenomenological equation

Quasiparticle annihilation



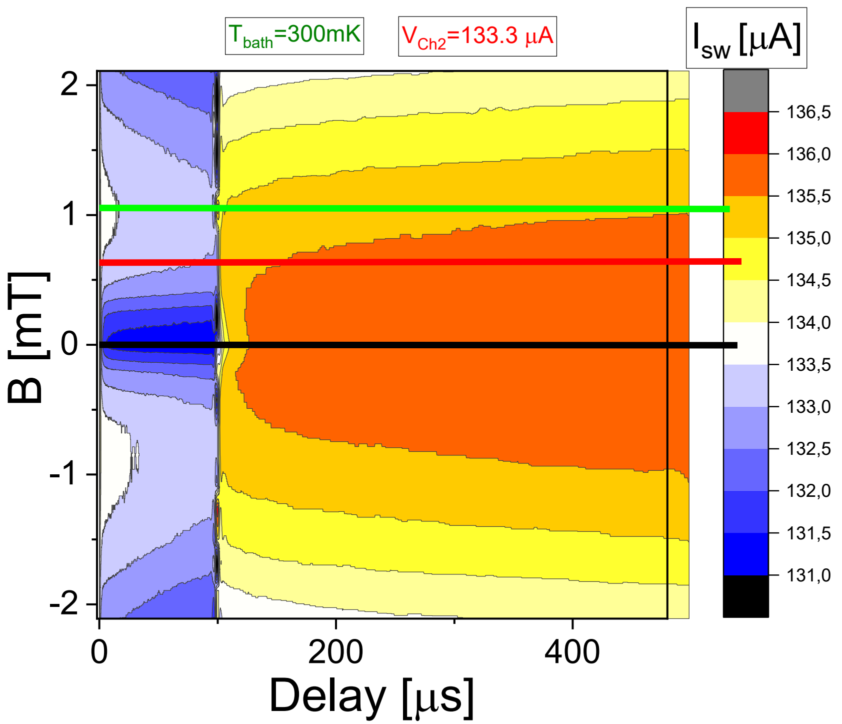
Sample design: M.Zgirski; Sample fabrication: J.Peltonen, Aalto Univ., Finland

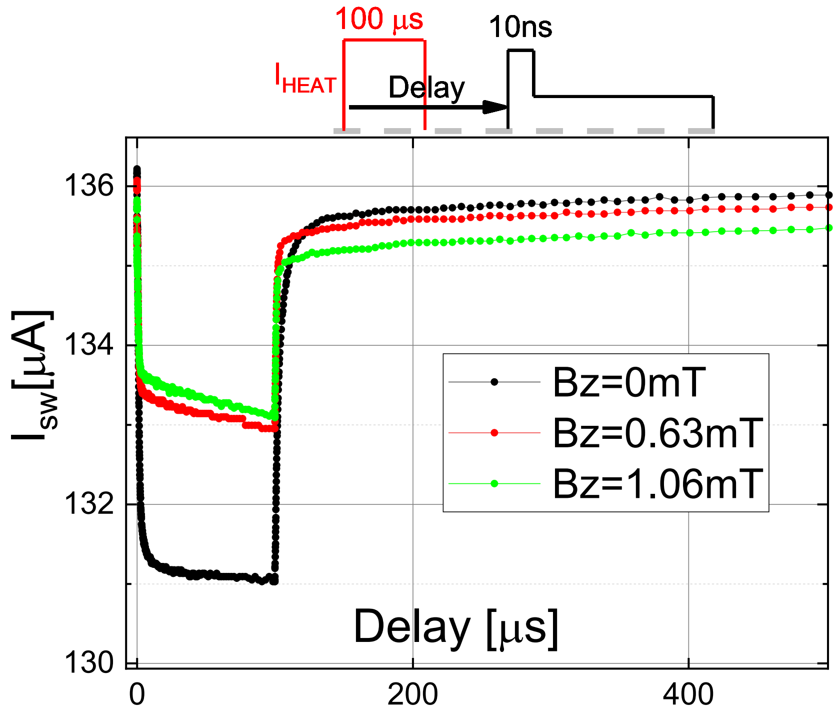
Quasiparticle annihilation



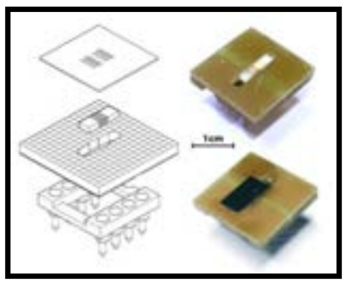
Unpublished.

Steady state suppression





Unpublished.



Lab