



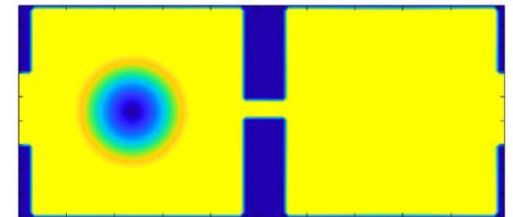
Thermodynamics of nanostructures at low temperatures.

How to measure temperature
by flipping a coin?

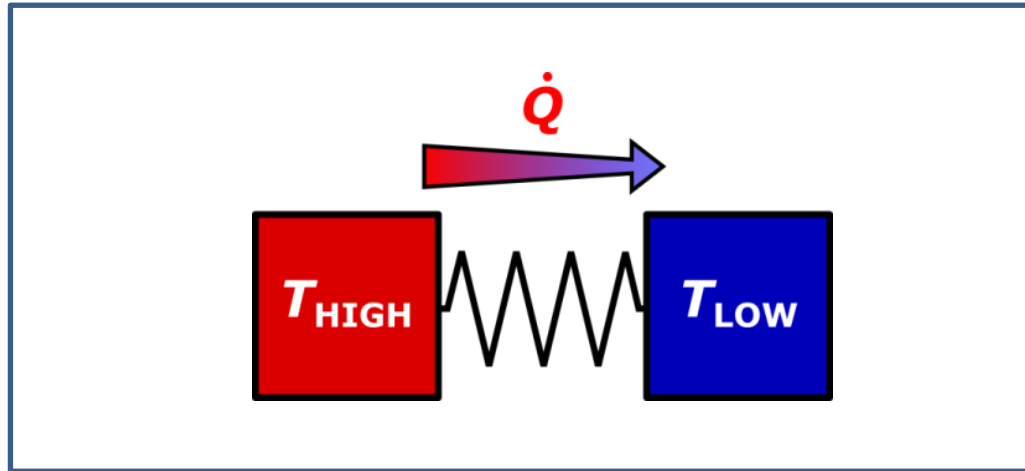
Maciej Zgirski

Institute of Physics of the Polish Academy of Sciences, **MagTop**, **CoolPhon Group**

Summer School: Ultrafast electronics meets quantum thermodynamics, ICTP Trieste, 22/09/2026

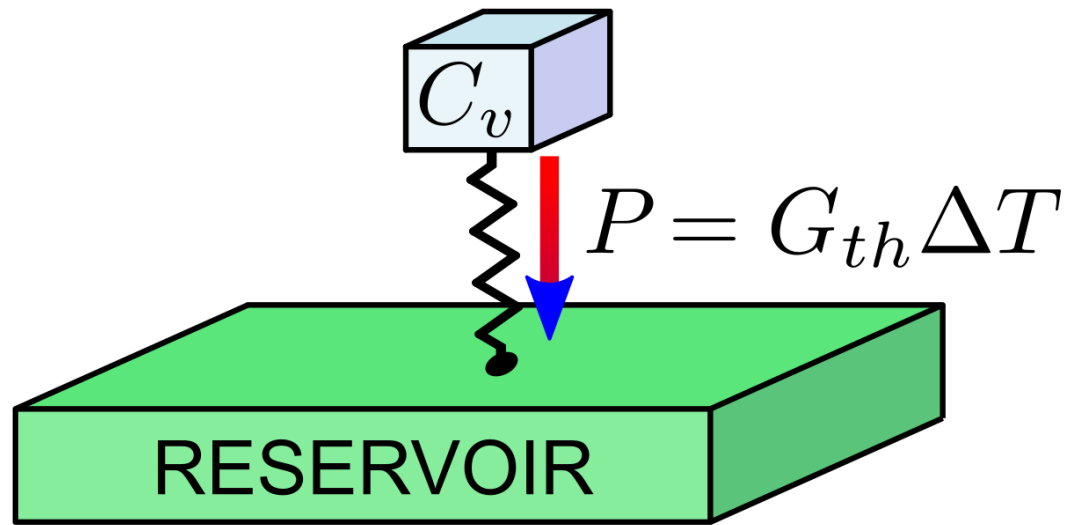


Thermodynamics



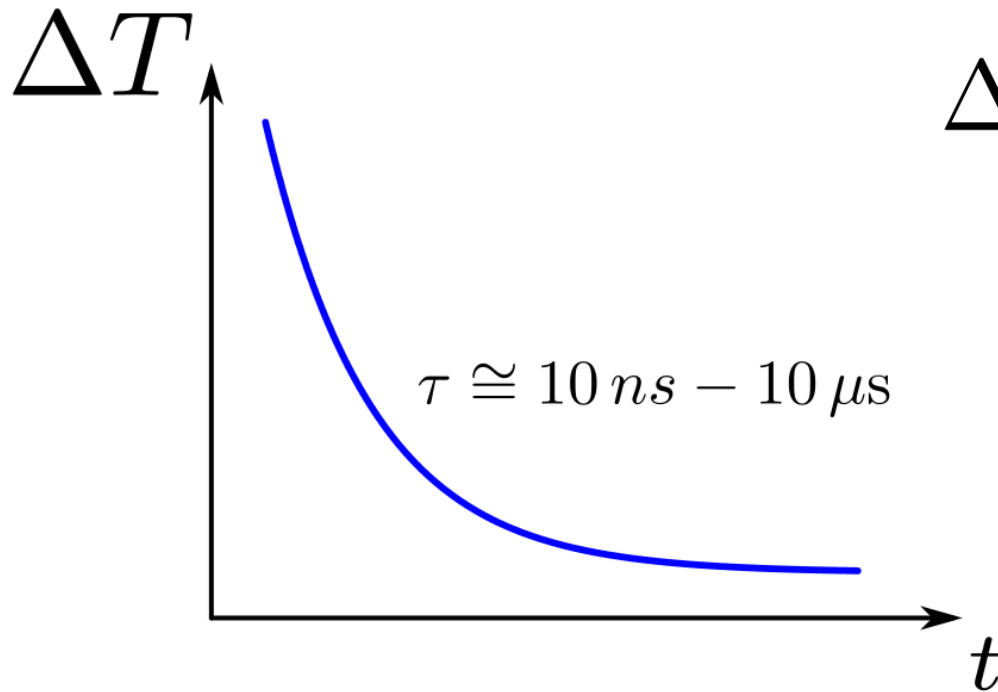
Thermodynamics is a discipline investigating heat flows between two bodies arising from the difference in temperature between them.

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

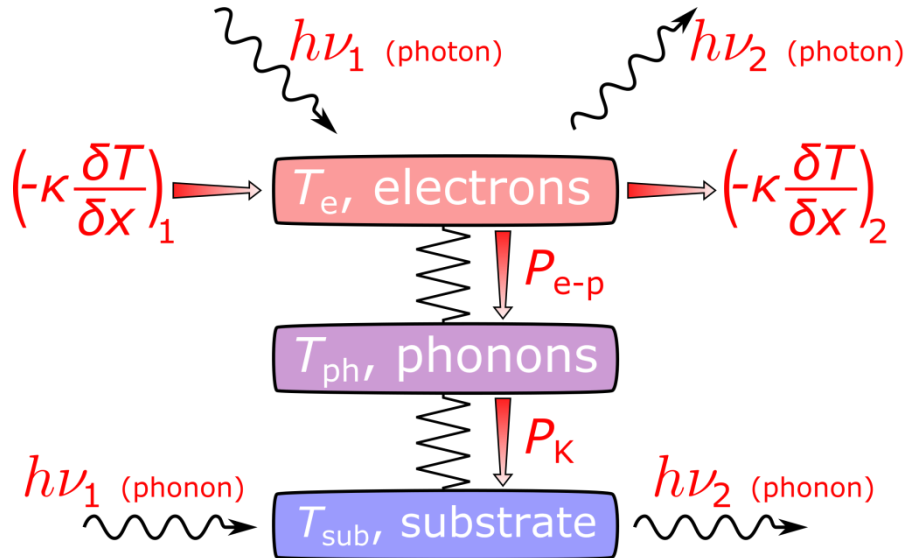
“Thermodynamic studies of mesoscopic devices have lagged far behind the corresponding electrical and magnetic investigations. This dearth can be attributed to a lack of fast, robust thermometers that can be easily integrated with nanoscale structures.”

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

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



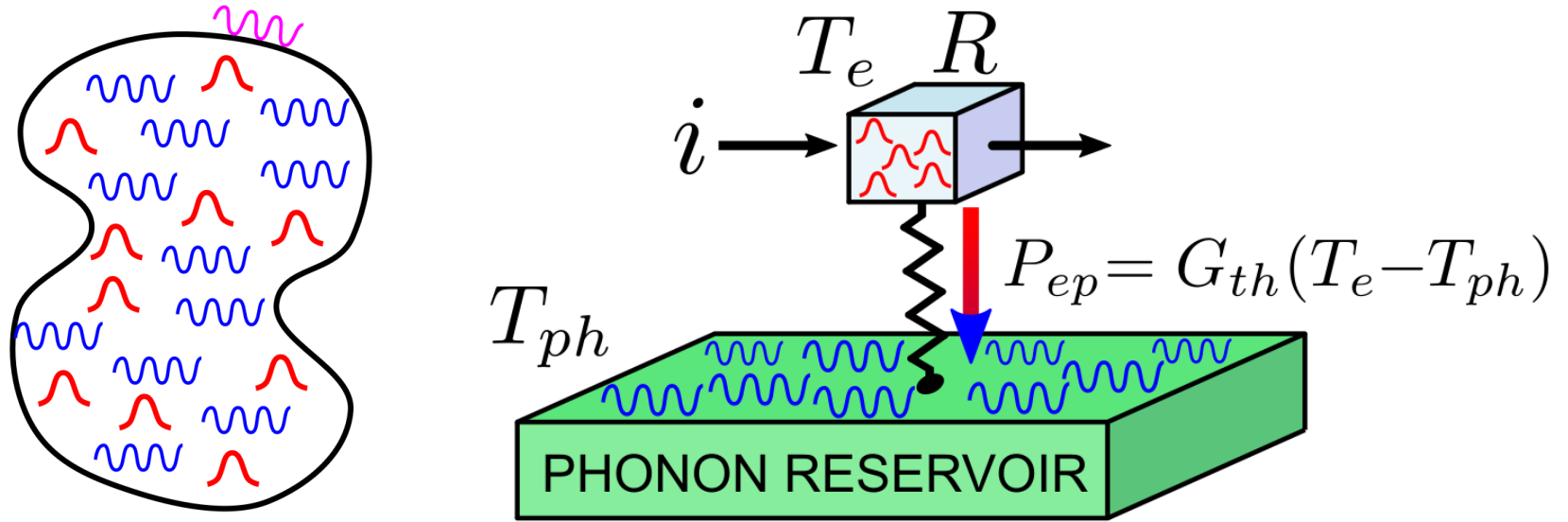
Heat flows at nanoscale



- 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

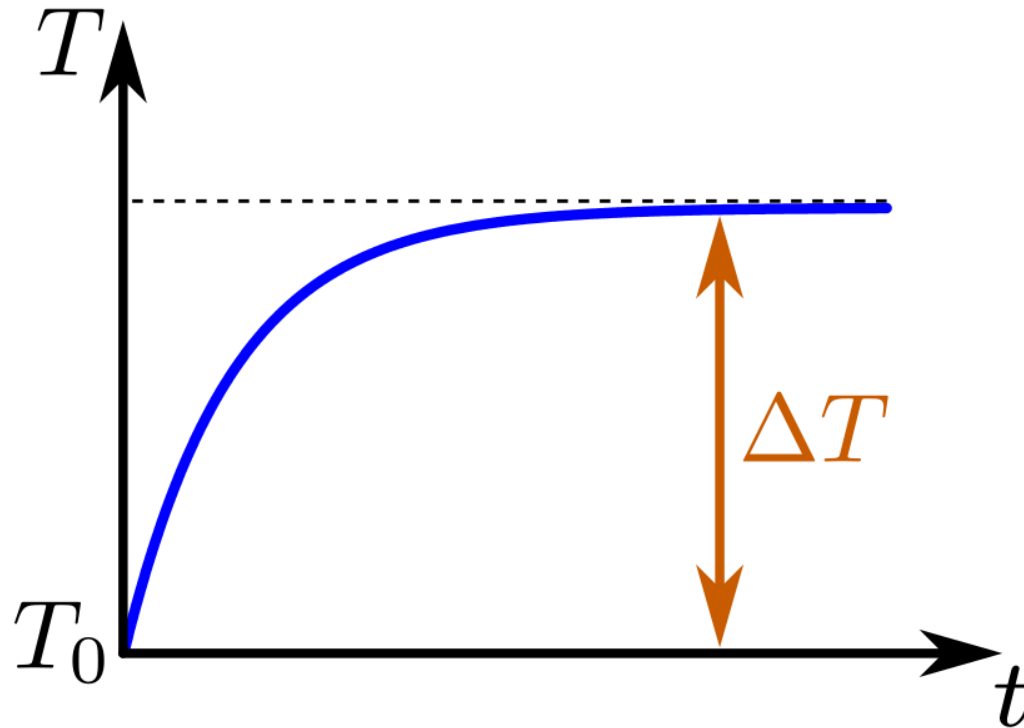


$$P_{ep} = \Sigma \left(T_e^5 - T_{ph}^5 \right)$$

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

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

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

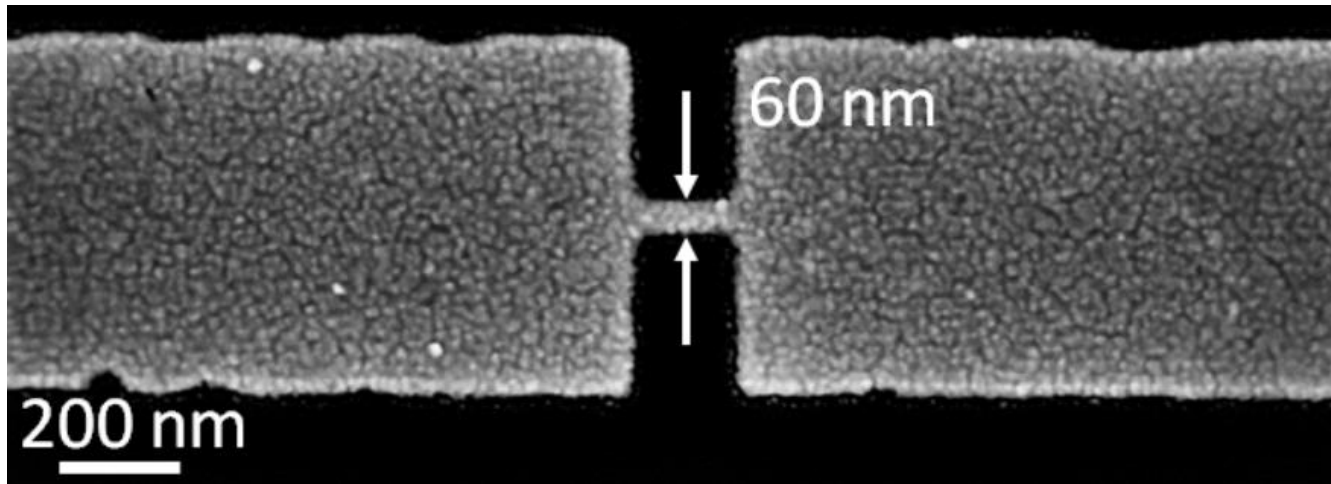


Thermal
budget of
nanostructures

Quantum
thermodynamics

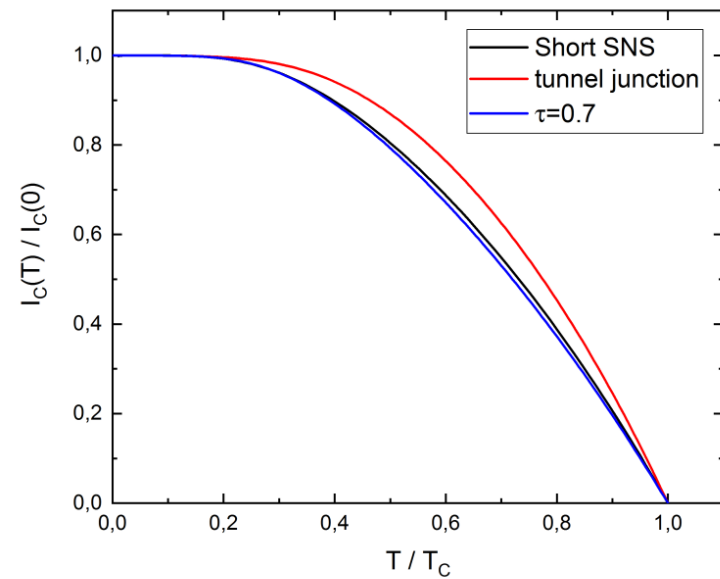
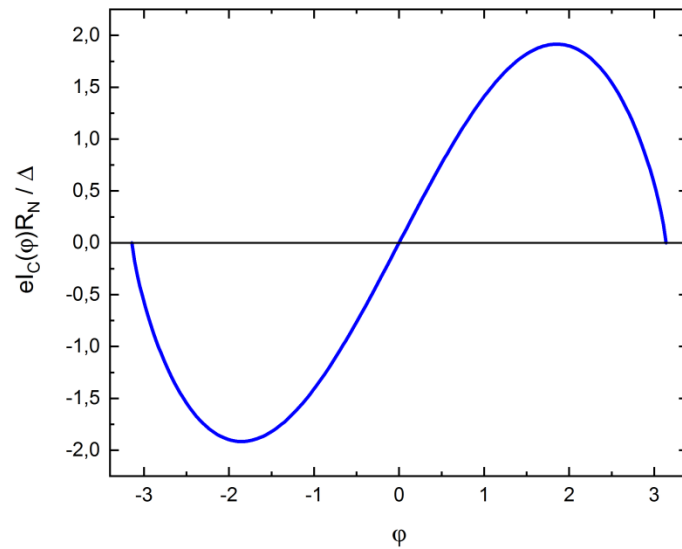
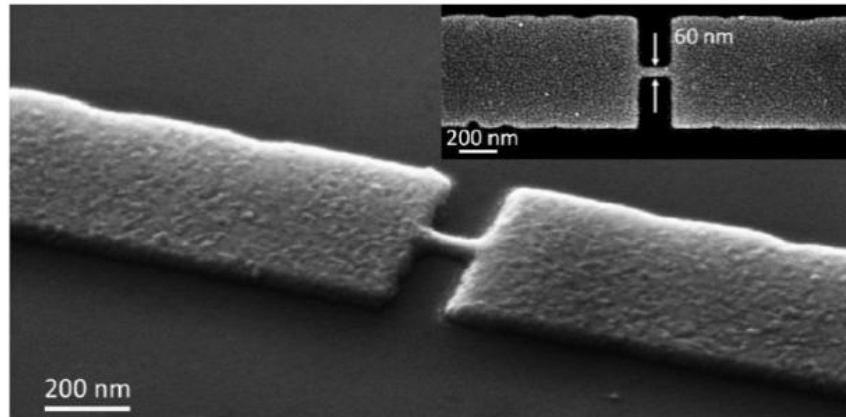
Dissipation
(limits the
coherence,
breaks the
topological
protection)

JJ: Dayem nanobridge

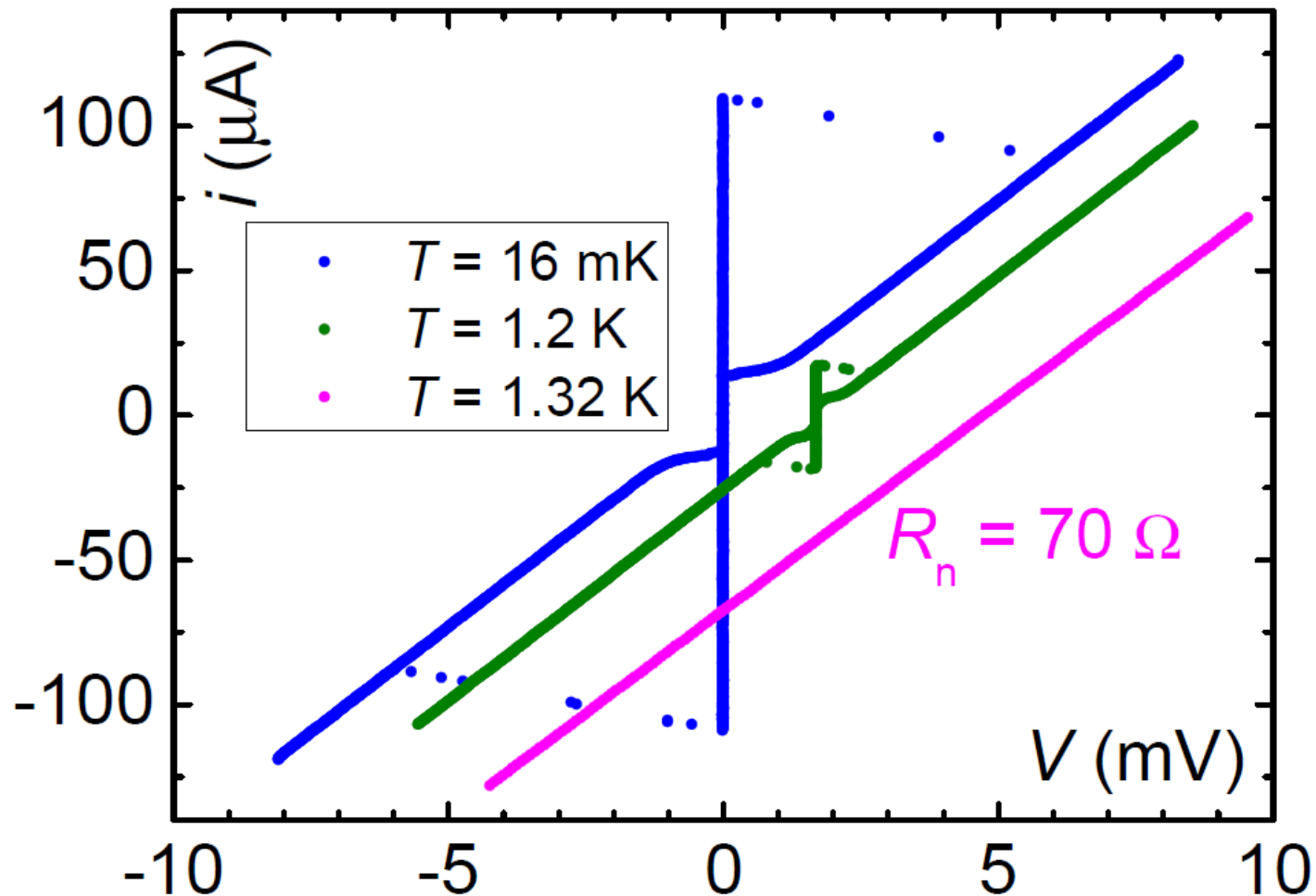


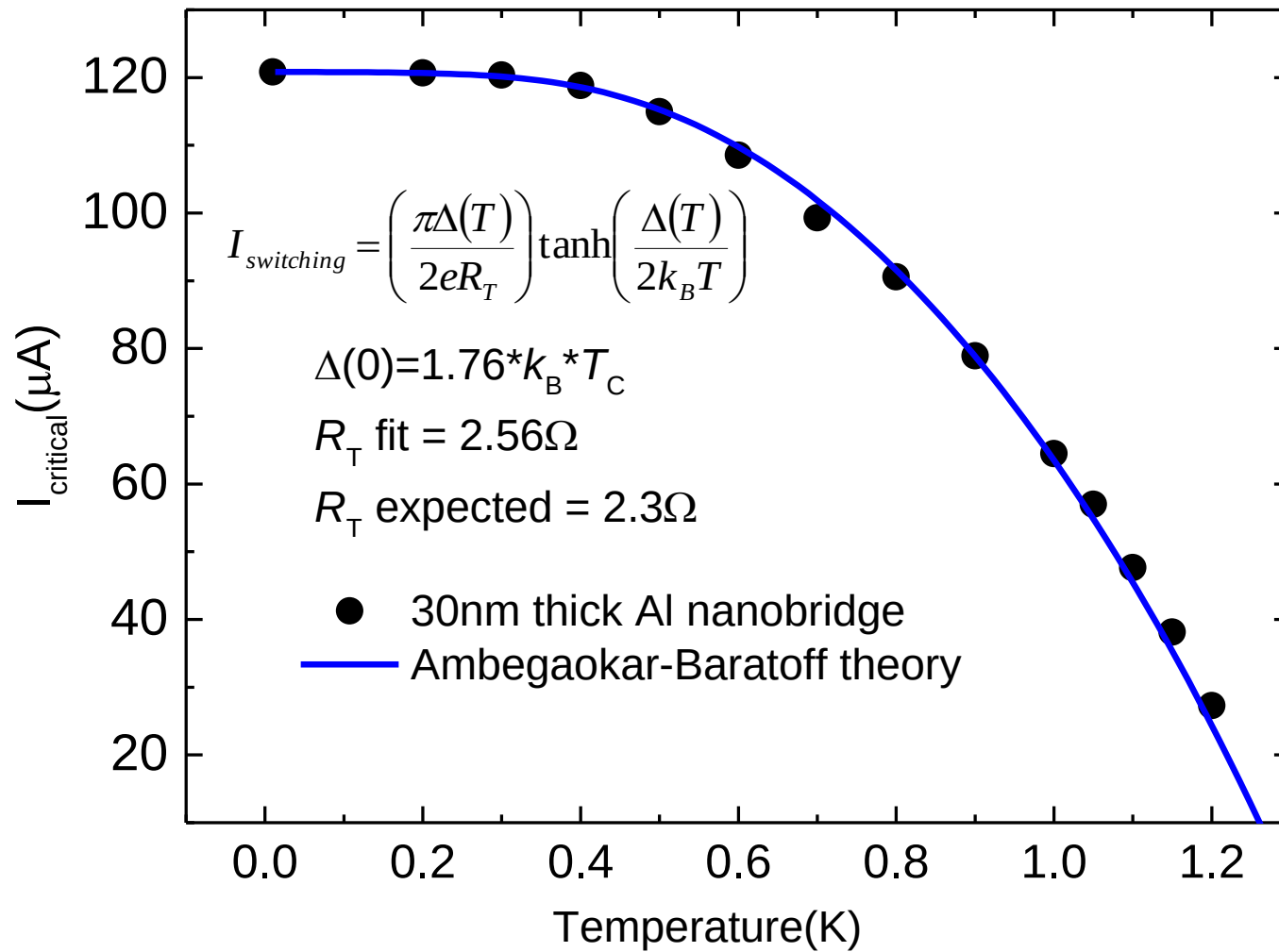
Diffusive JJ: average transmission $\tau \sim 0.75$

CPR for a diffusive link

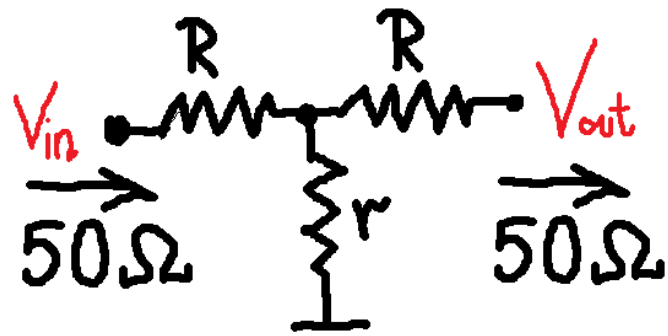


Superconducting bridge as a temperature sensor





Fridge wiring



$$R = \frac{1-\alpha}{1+\alpha} \cdot 50 \Omega$$

$$\alpha = \frac{V_{out}}{V_{in}}$$

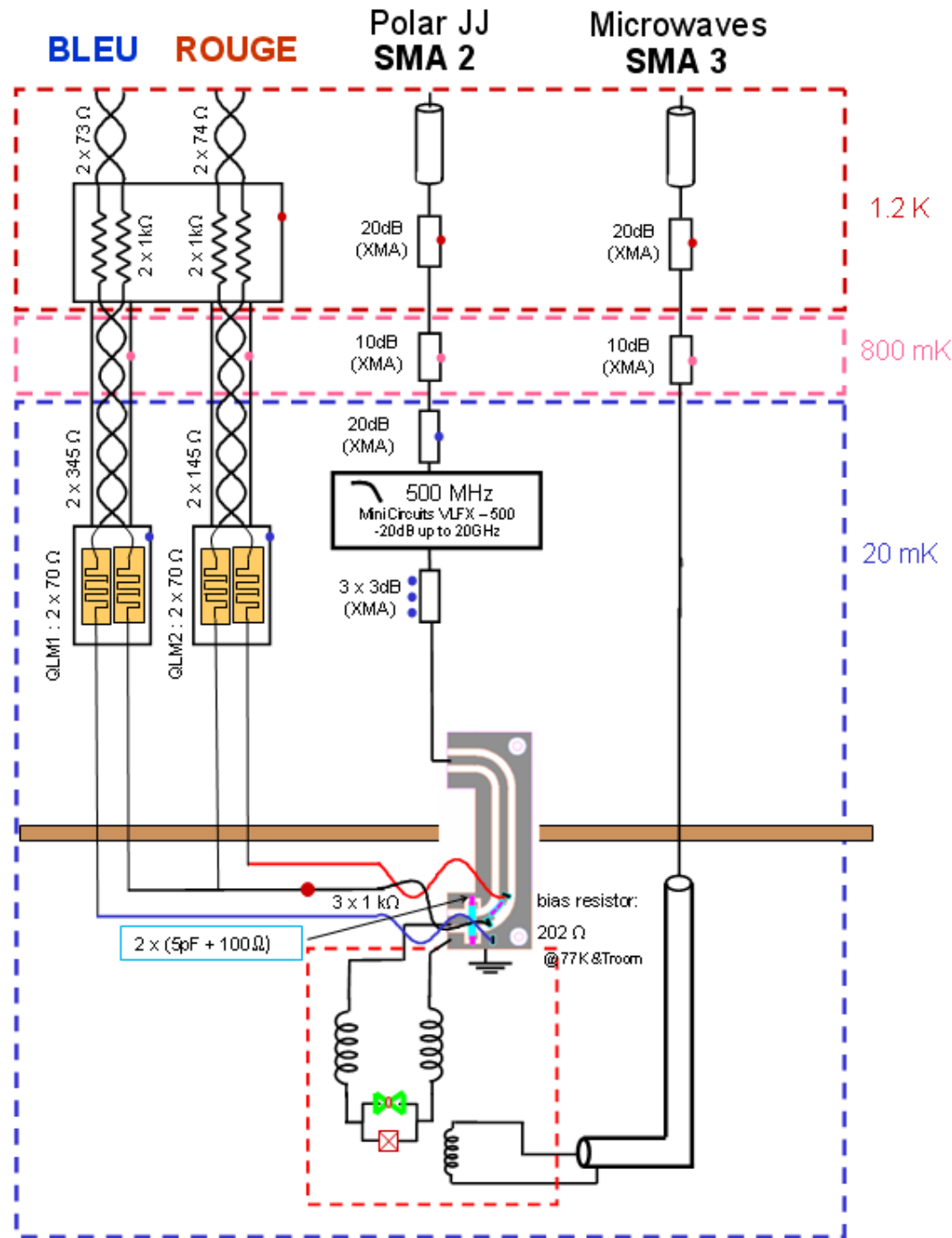
$$r = \frac{2\alpha}{1-\alpha^2} 50 \Omega$$

$$\alpha_{db} = 20 \log \alpha$$

α – attenuation

-10dB ($R=35 \Omega$, $r=26 \Omega$)

-20dB ($R=41 \Omega$, $r=10 \Omega$)

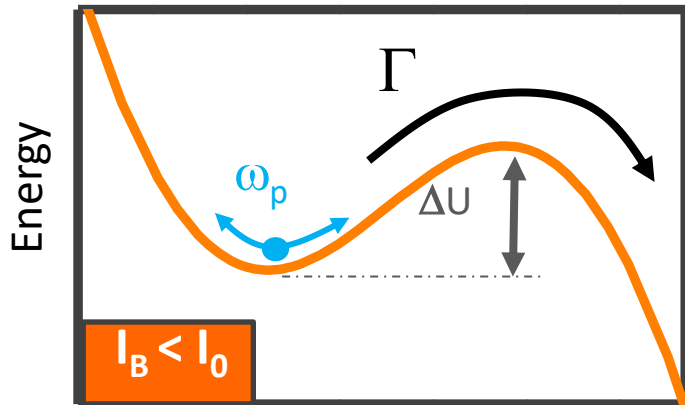


Dynamics of a fictitious particle in a tilted washboard potential

$$E_p = -E_J \left(\cos \gamma + \frac{I_b}{I_0} \gamma \right)$$



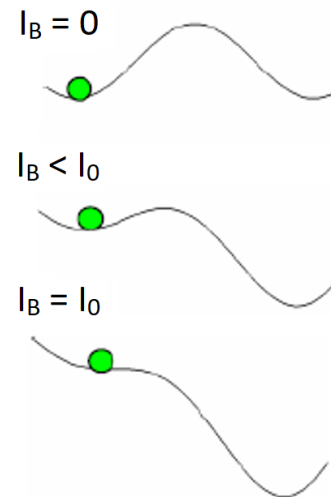
The potential is tilted with the bias current.



γ - superconducting phase

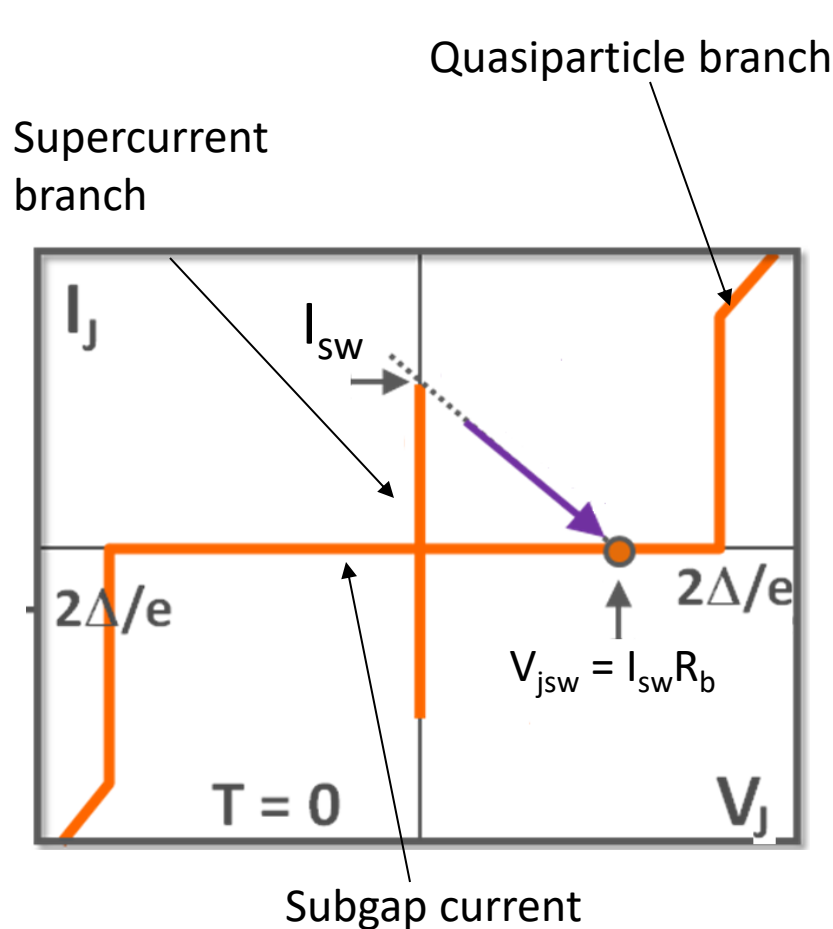
The oscillations of phase correspond to oscillating current across the junction.

$$I_J = I_0 \sin \gamma$$

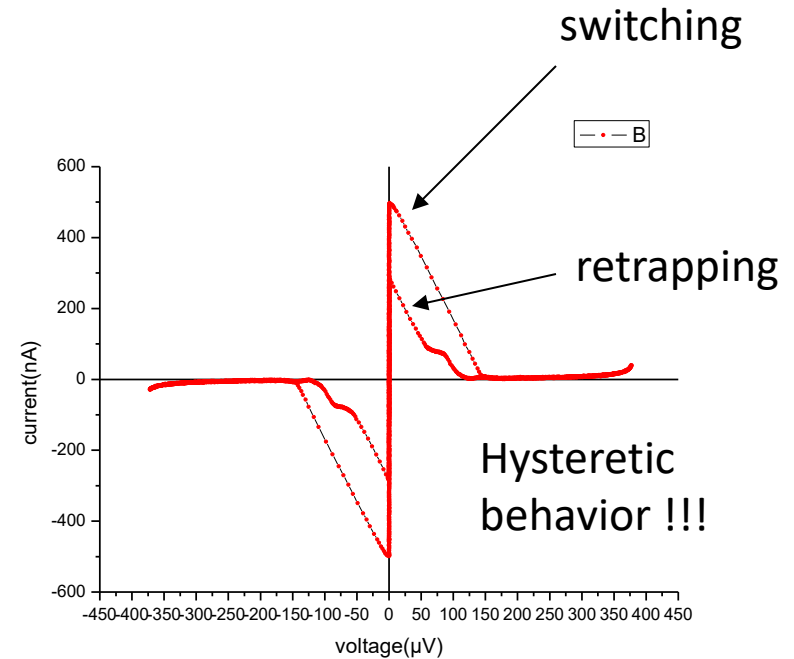


M. Foltyn, M. Zgirski,
Gambling with Superconducting Fluctuations,
Phys. Rev. Applied **4**, (2015)

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.



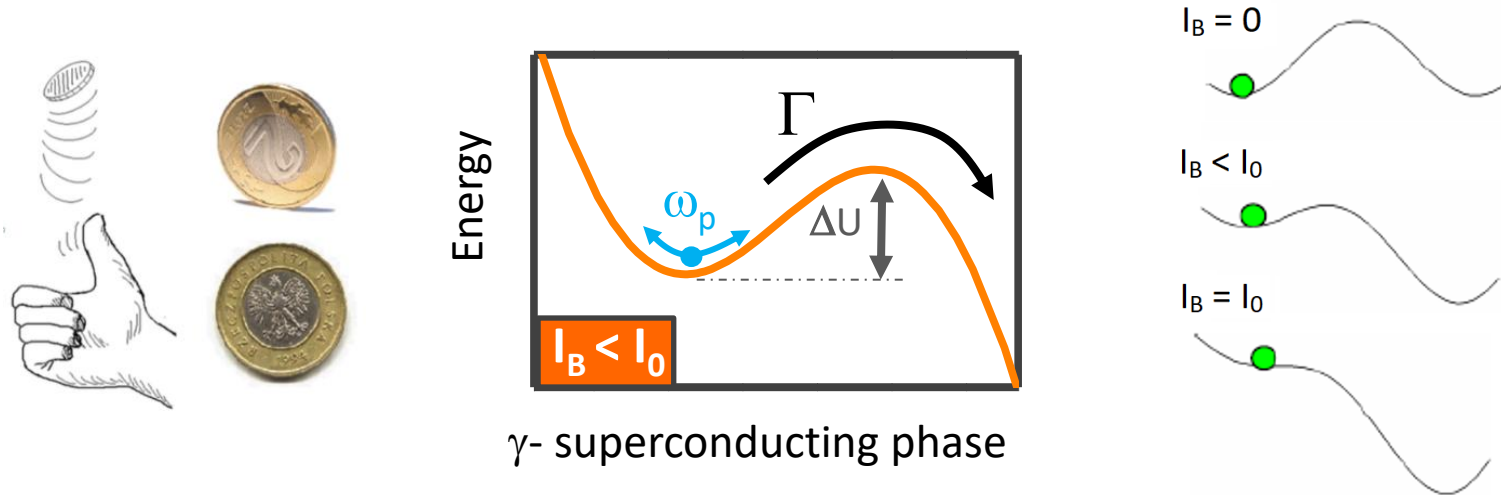
$$I_j = I_j(V_j)$$

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

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

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

Switching: Escape out of metastable state

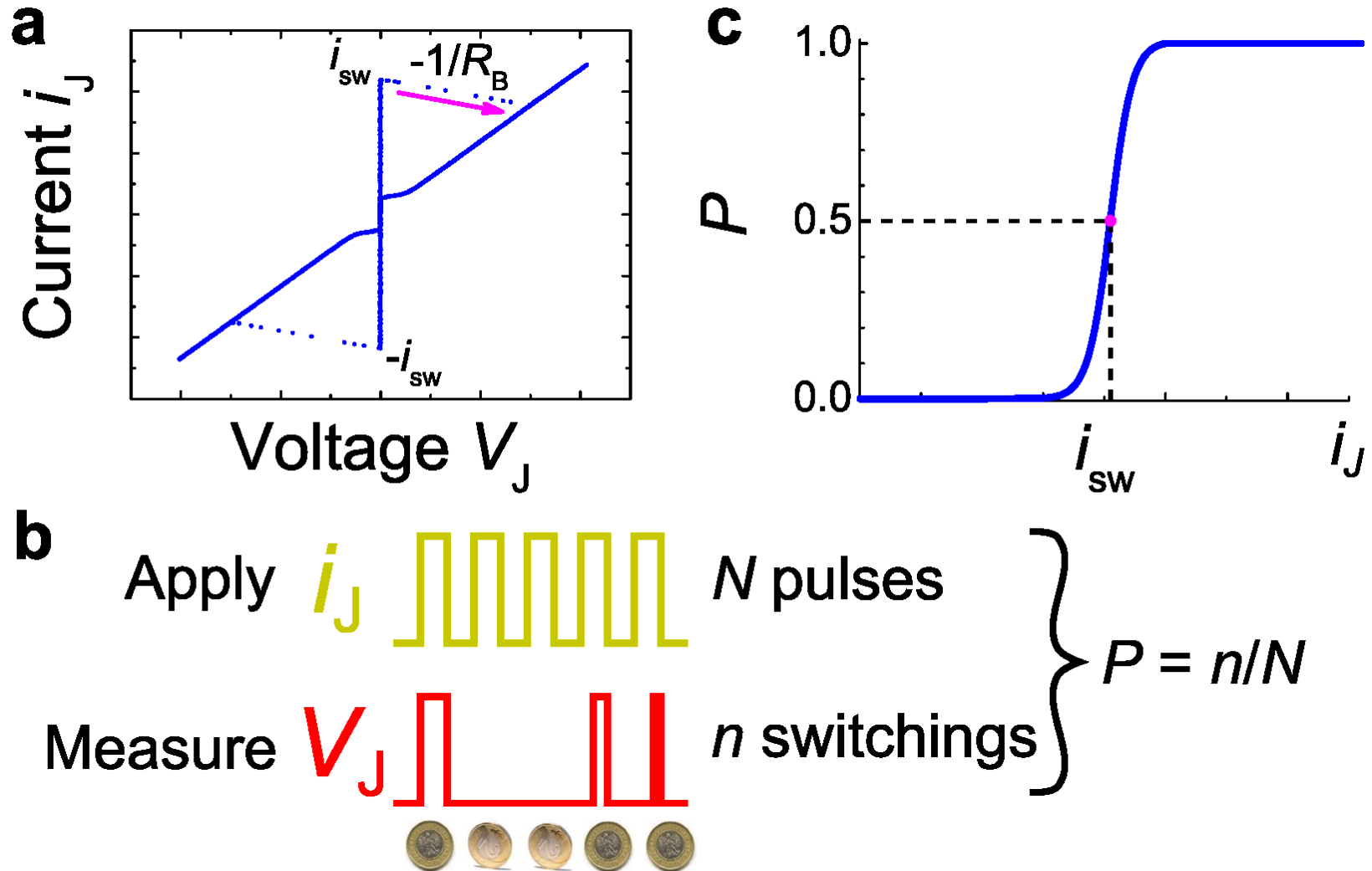


Escape rate Γ / lifetime in a metastable state τ :

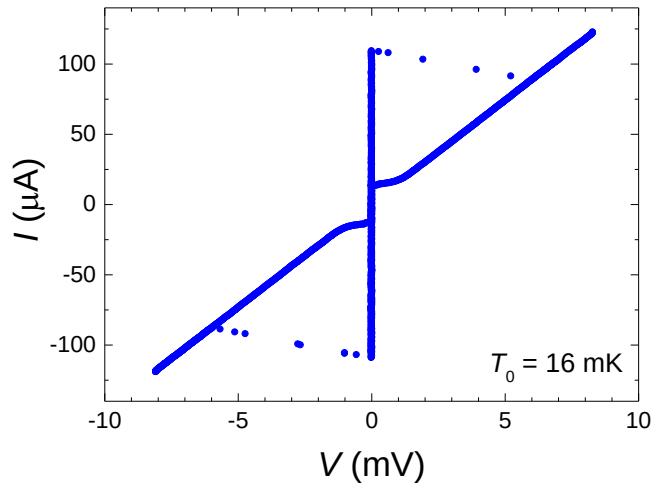
$$\Gamma = \frac{\omega_p}{2 \cdot \pi} \exp\left(-\frac{\Delta U}{k_B T}\right), \text{ Arrhenius law} \quad \frac{1}{\tau} = \Gamma$$

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

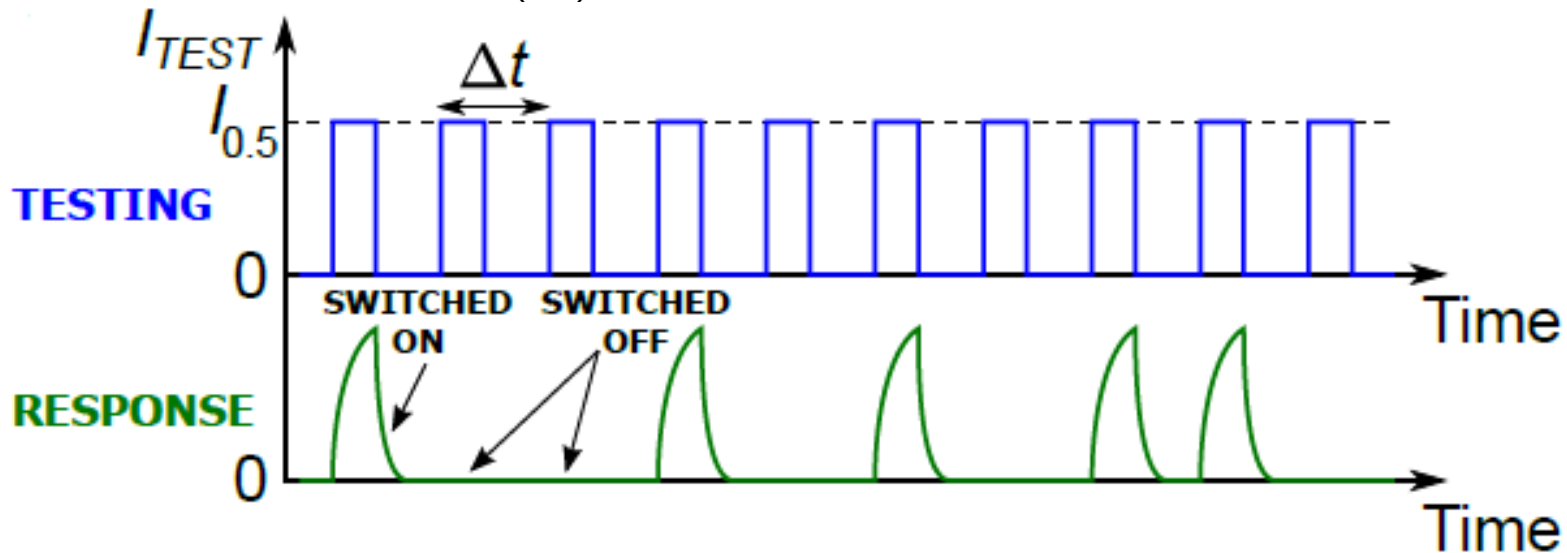
Switching measurements



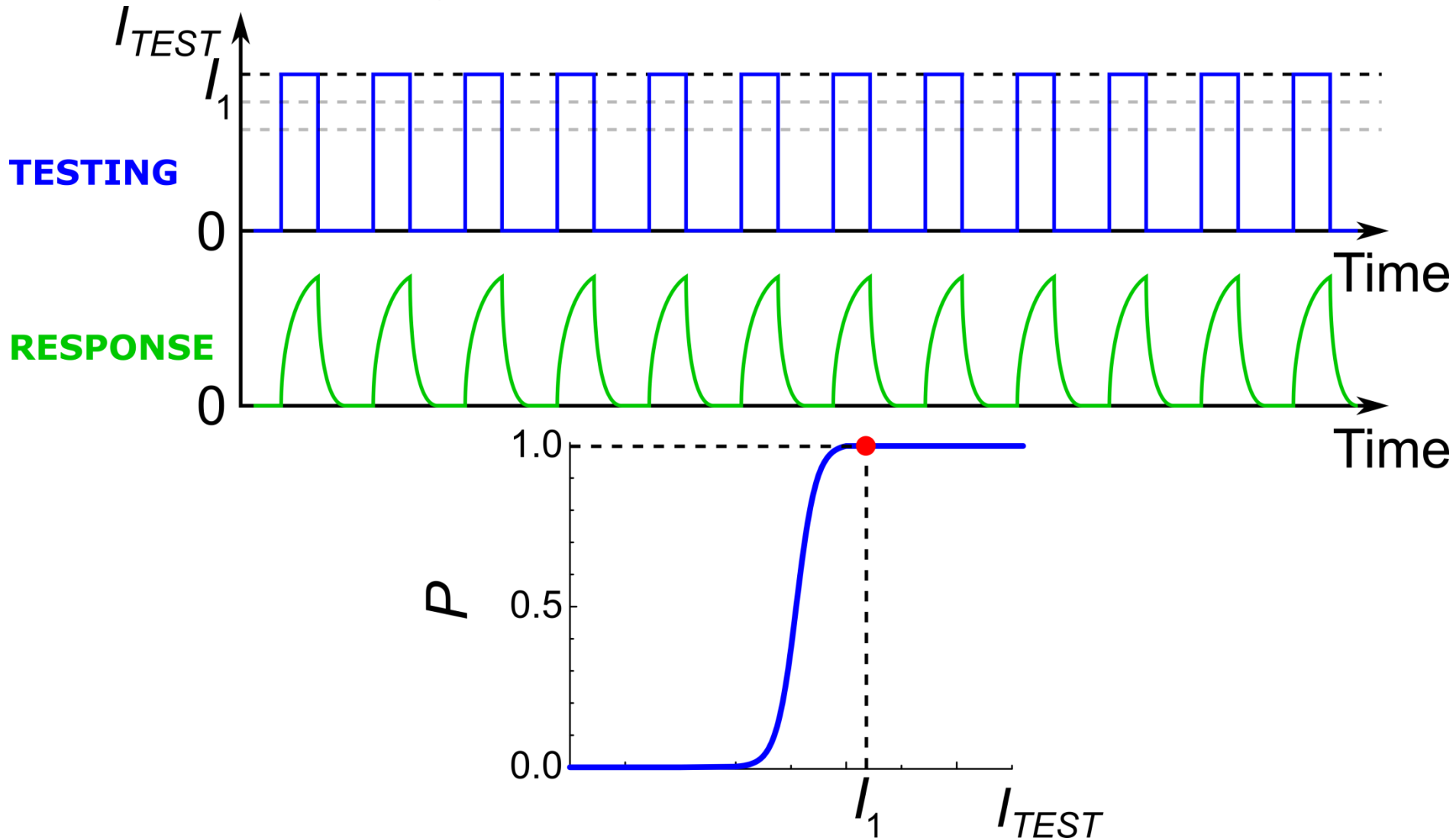
Switching measurements of the junction



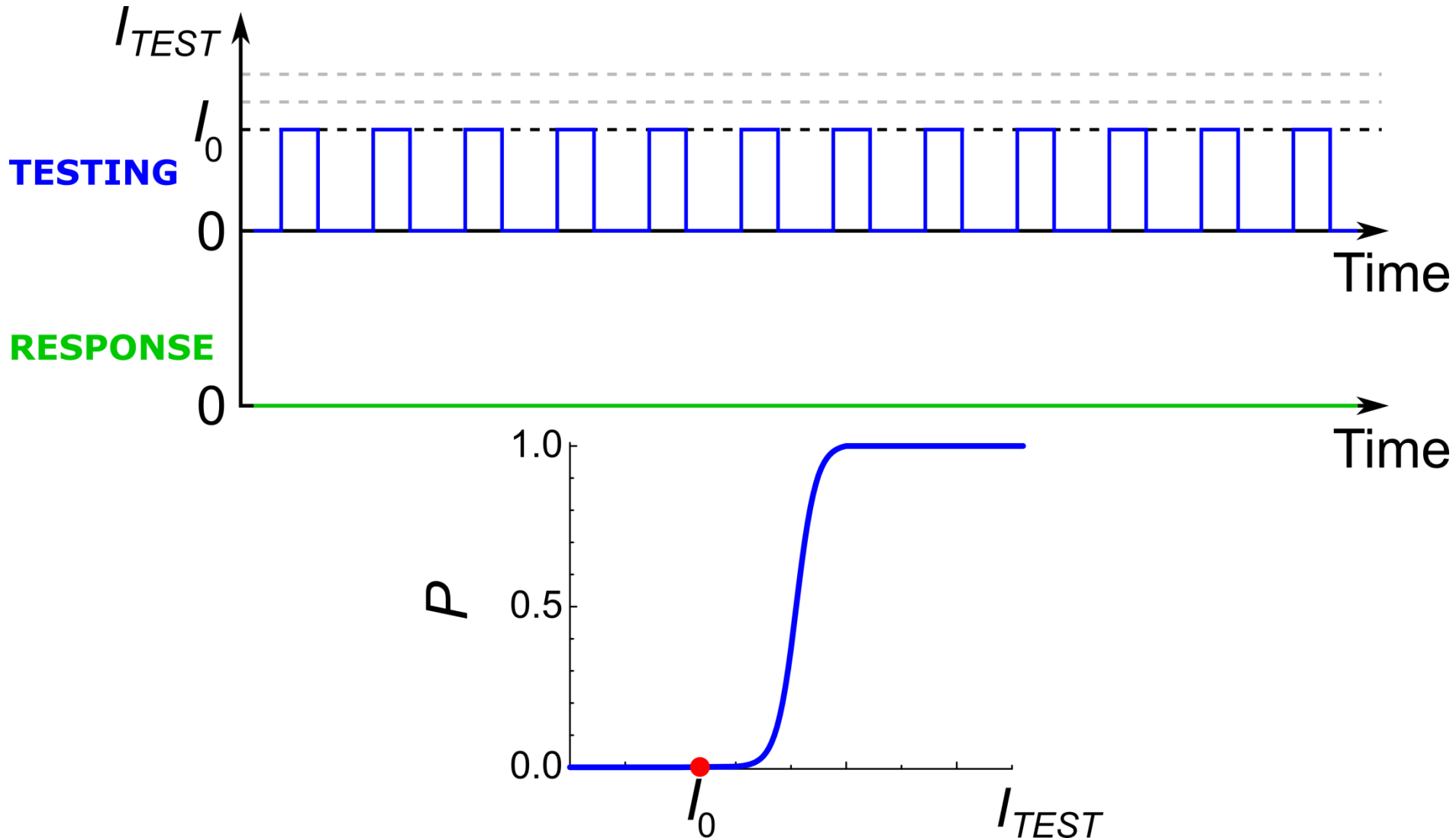
$$P = n/N$$



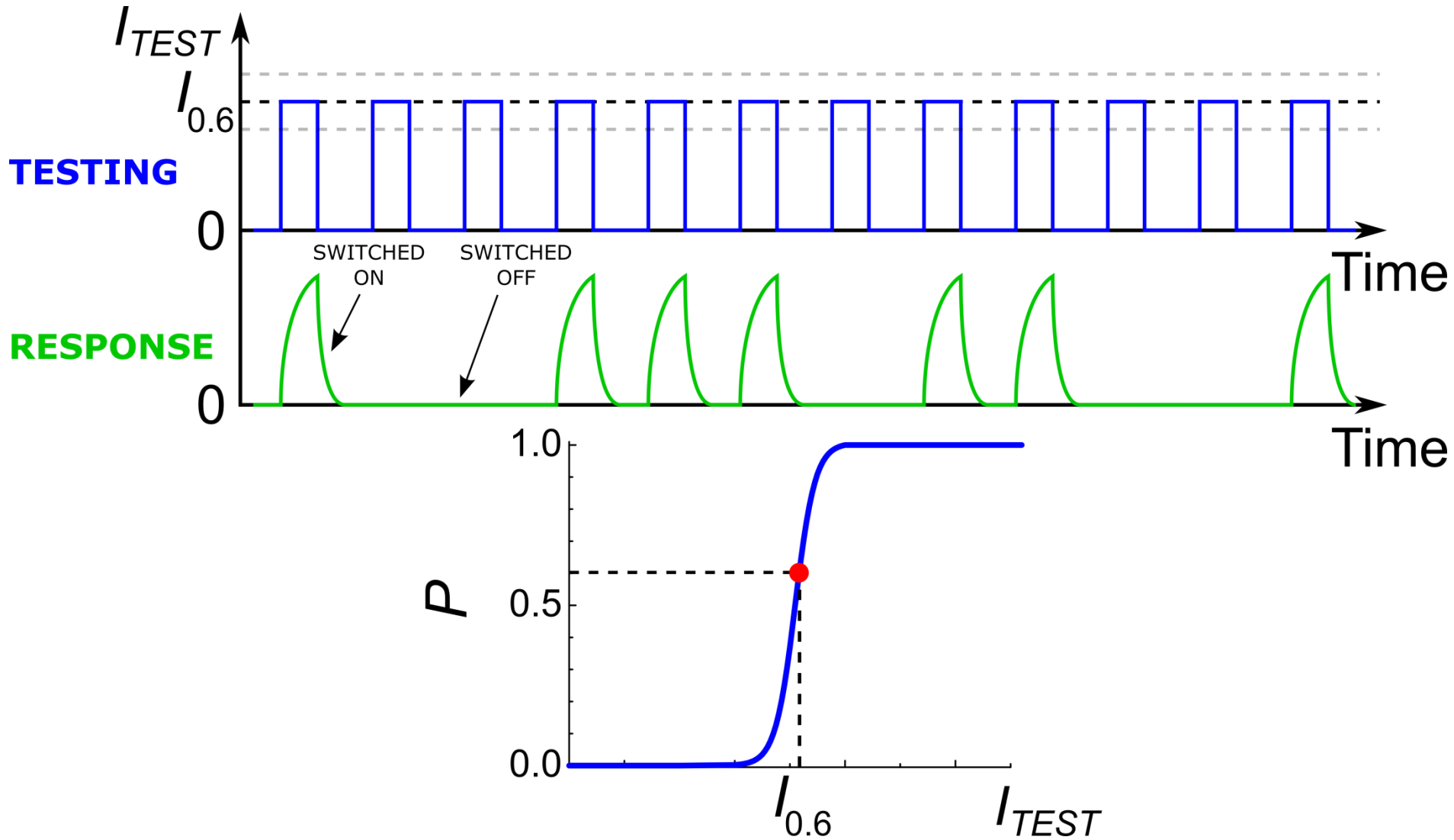
Testing JJ with current pulses



Testing JJ with current pulses

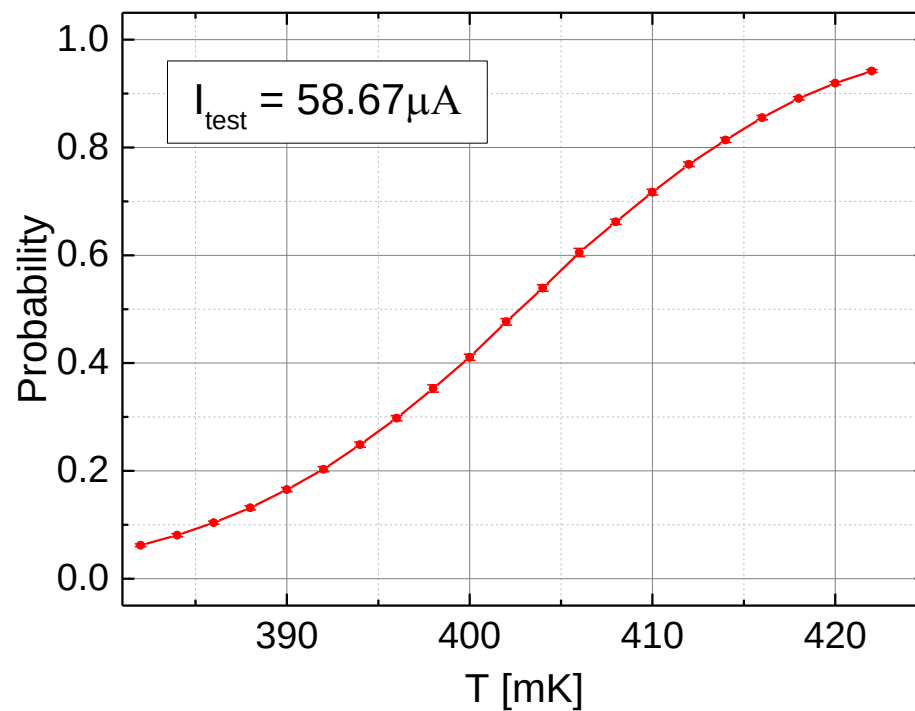
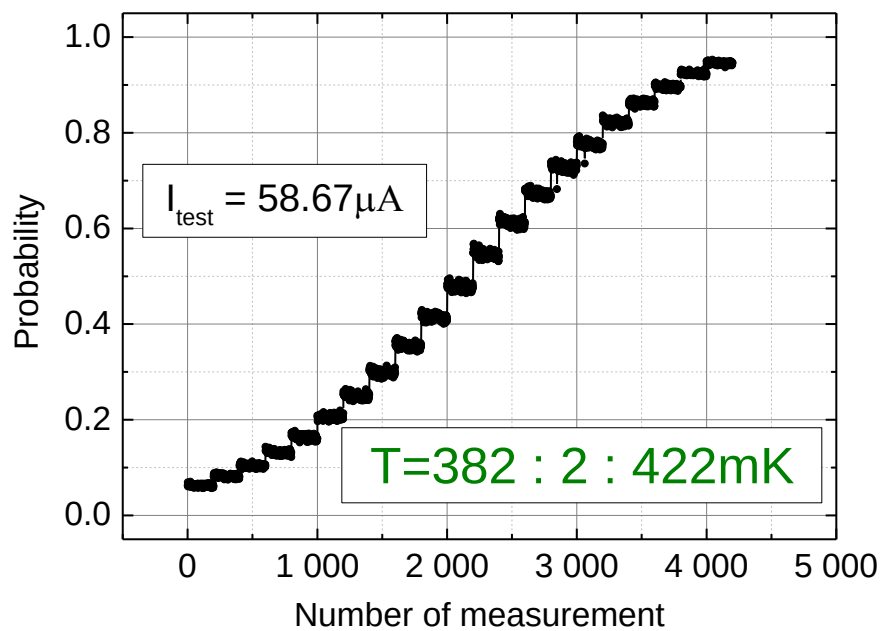


Testing JJ with current pulses

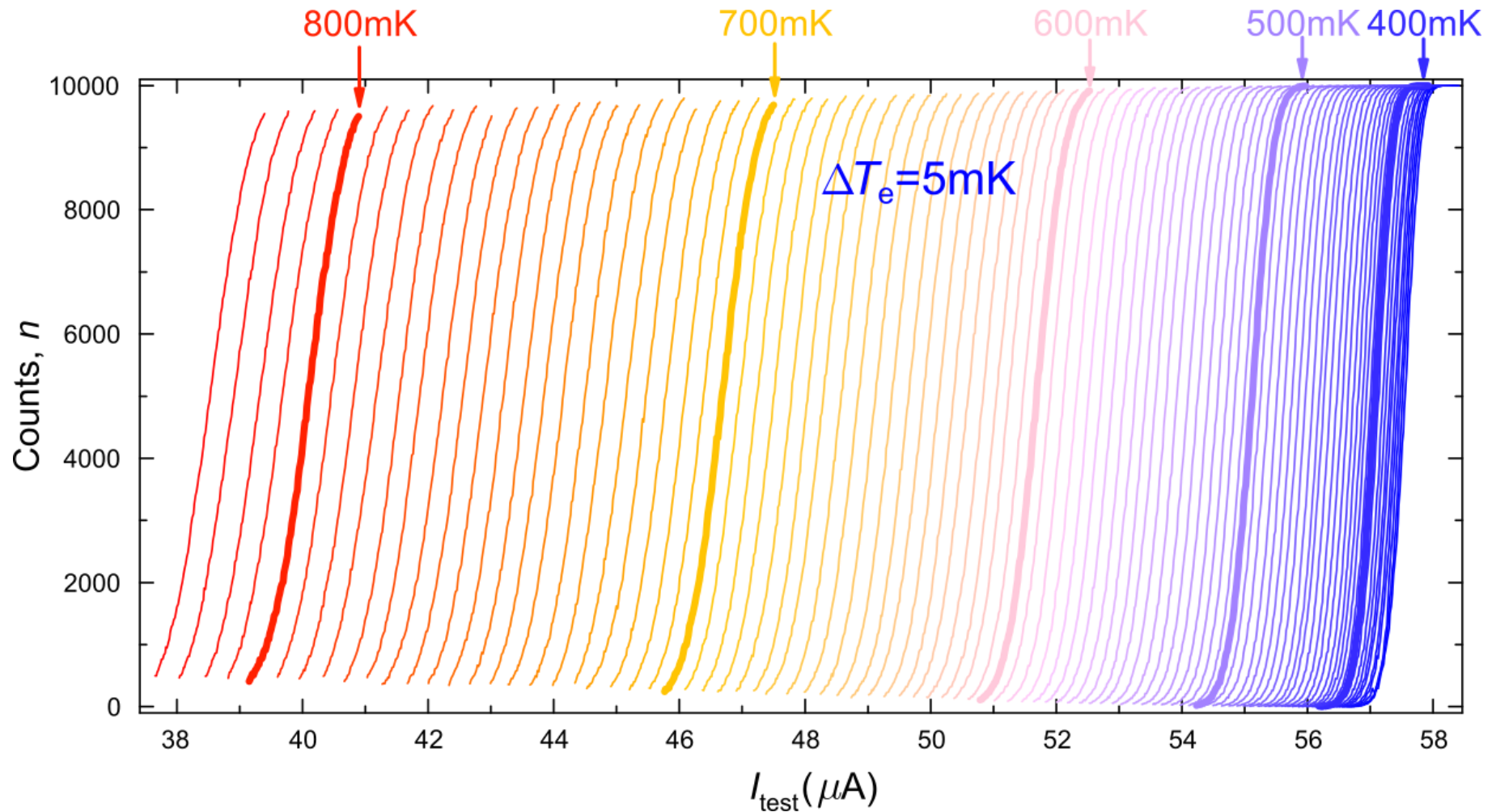


Switching thermometry

$$P(T_e)$$

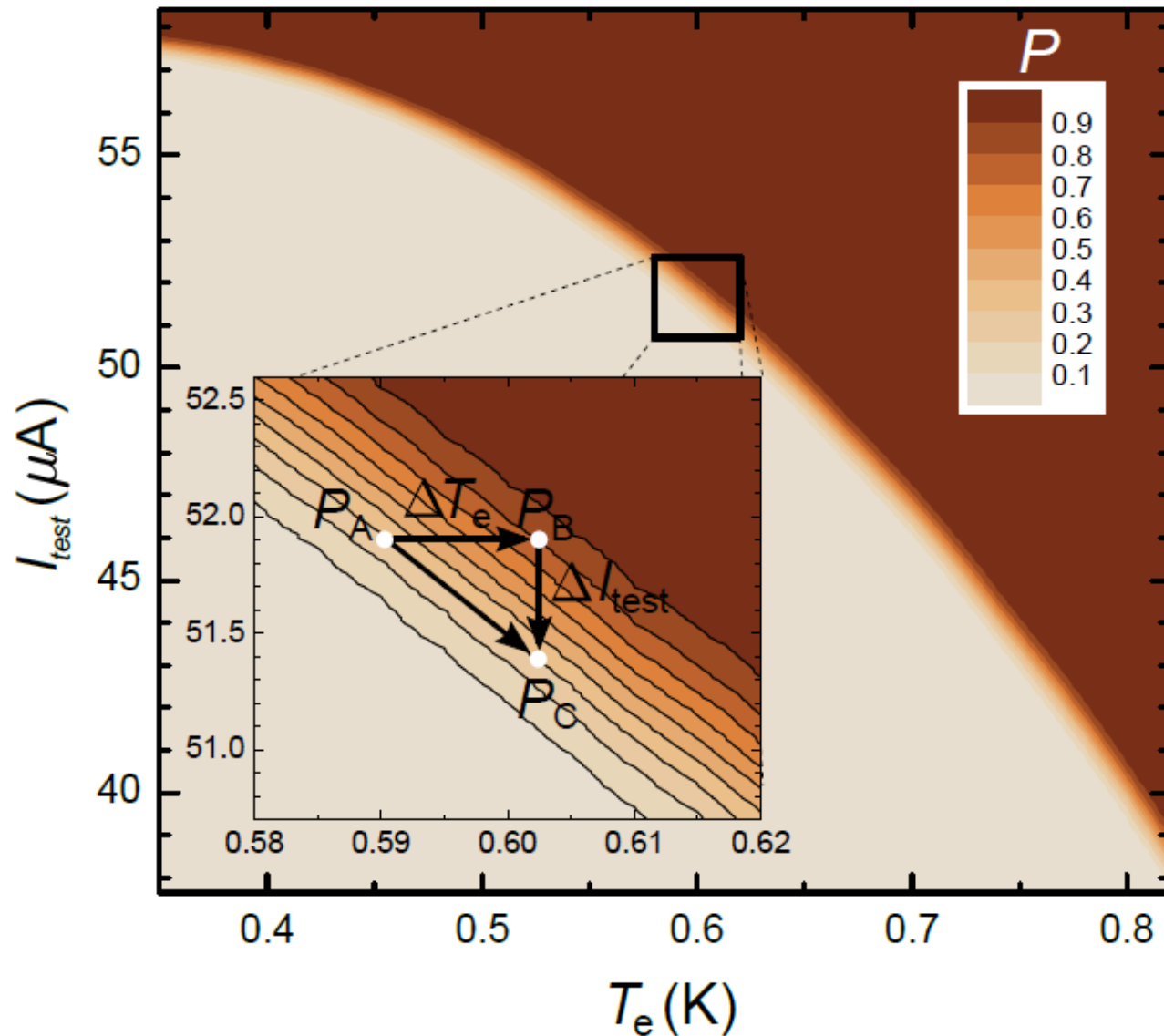


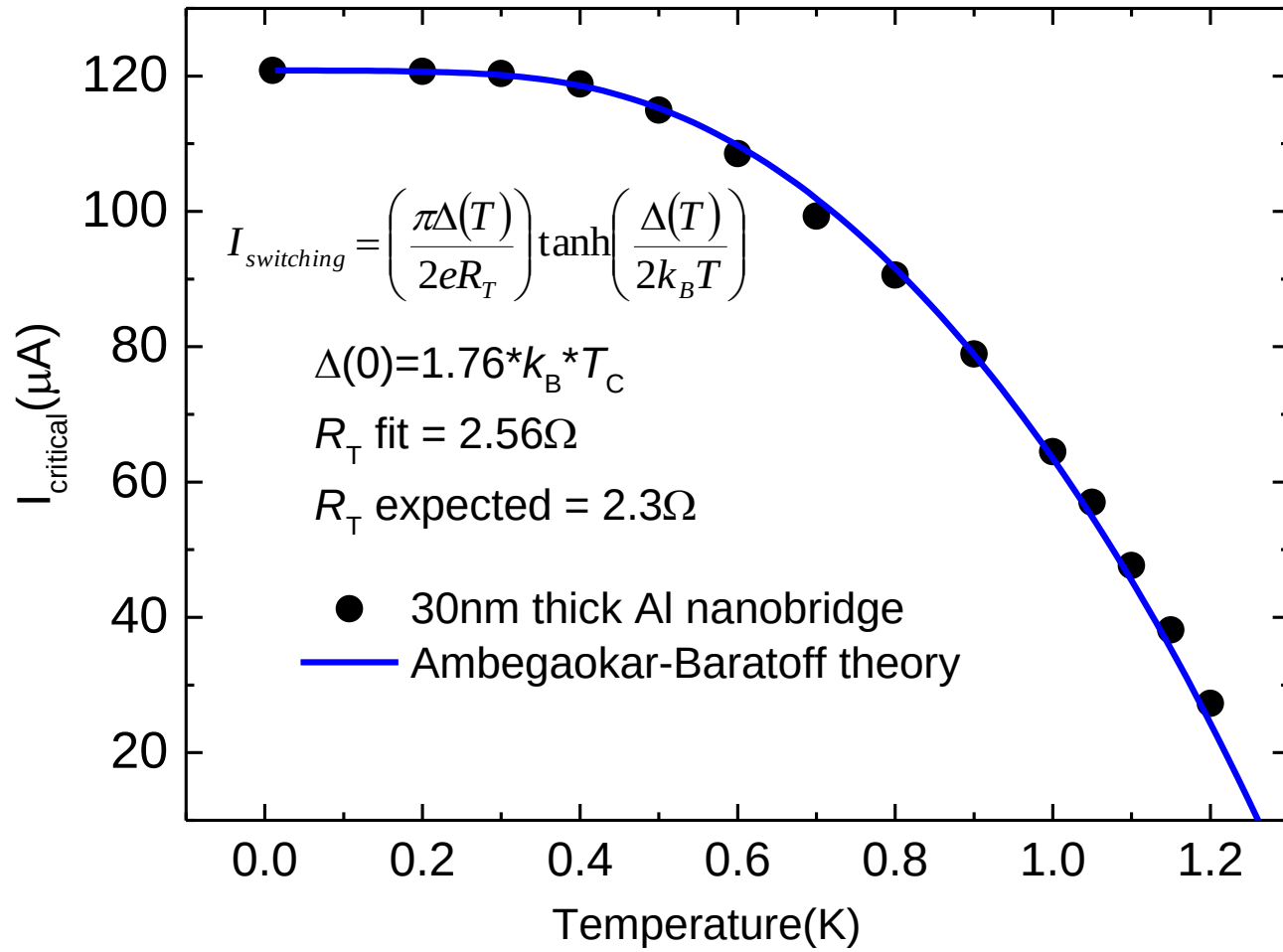
Temperature sensitivity



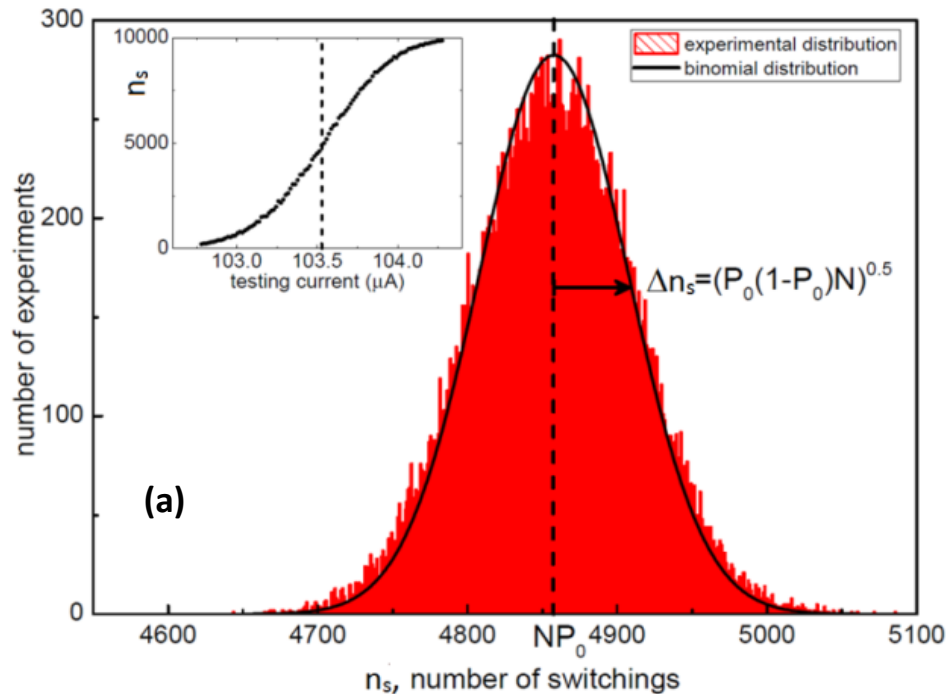
M. Zgirski, M. Foltyn, A. Naumov, A. Savin and K. Norowski
Heat hunting in freezer: Direct measurement of quasiparticle diffusion in superconducting nanowire,
Phys. Rev. Appl. 14, 044024 (2020)

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





Flipping coin experiment



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

„Statistical noise”:

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

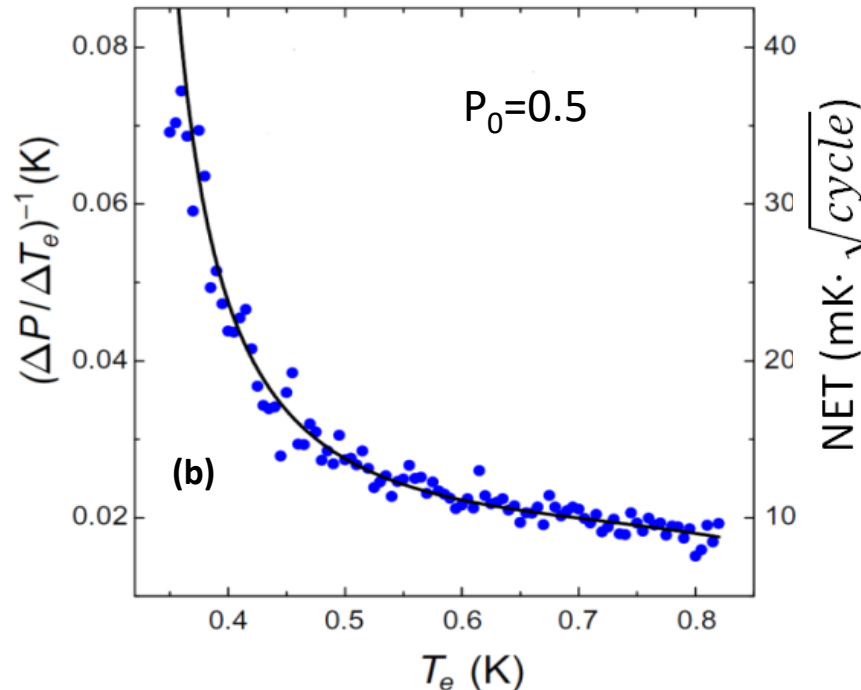
Temperature Responsivity and Noise-Equivalent Temperature (NET)

$$\Delta n_s = \sqrt{P_0(1 - P_0)N}$$

$$\Delta T_{e,un} = \left(\frac{\Delta P}{\Delta T_e} \right)^{-1} \frac{\Delta n_s}{N}$$

$$NET = \left(\frac{\Delta P}{\Delta T_e} \right)^{-1} \sqrt{P_0(1 - P_0)}$$

$$\Delta T_{e,un} = \frac{NET}{\sqrt{N}}$$

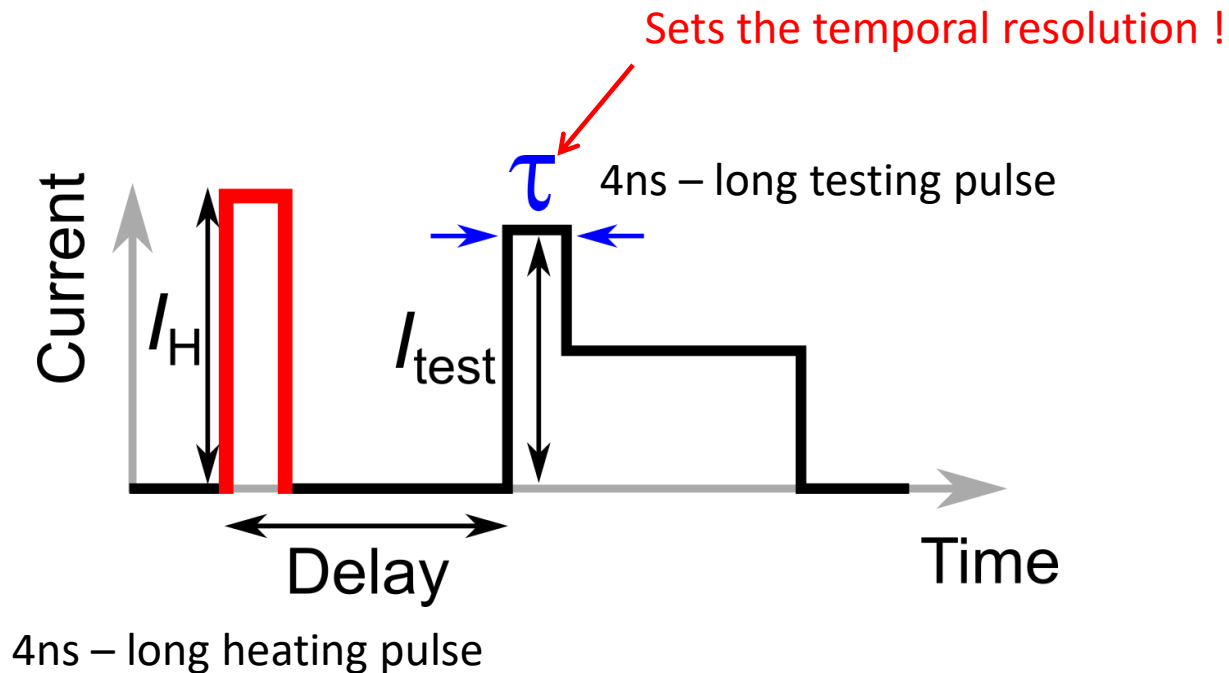


Example:

$$NET = 10 \text{ mK} \cdot \sqrt{\text{cycle}} \text{ with } N=10000 \text{ cycles}$$

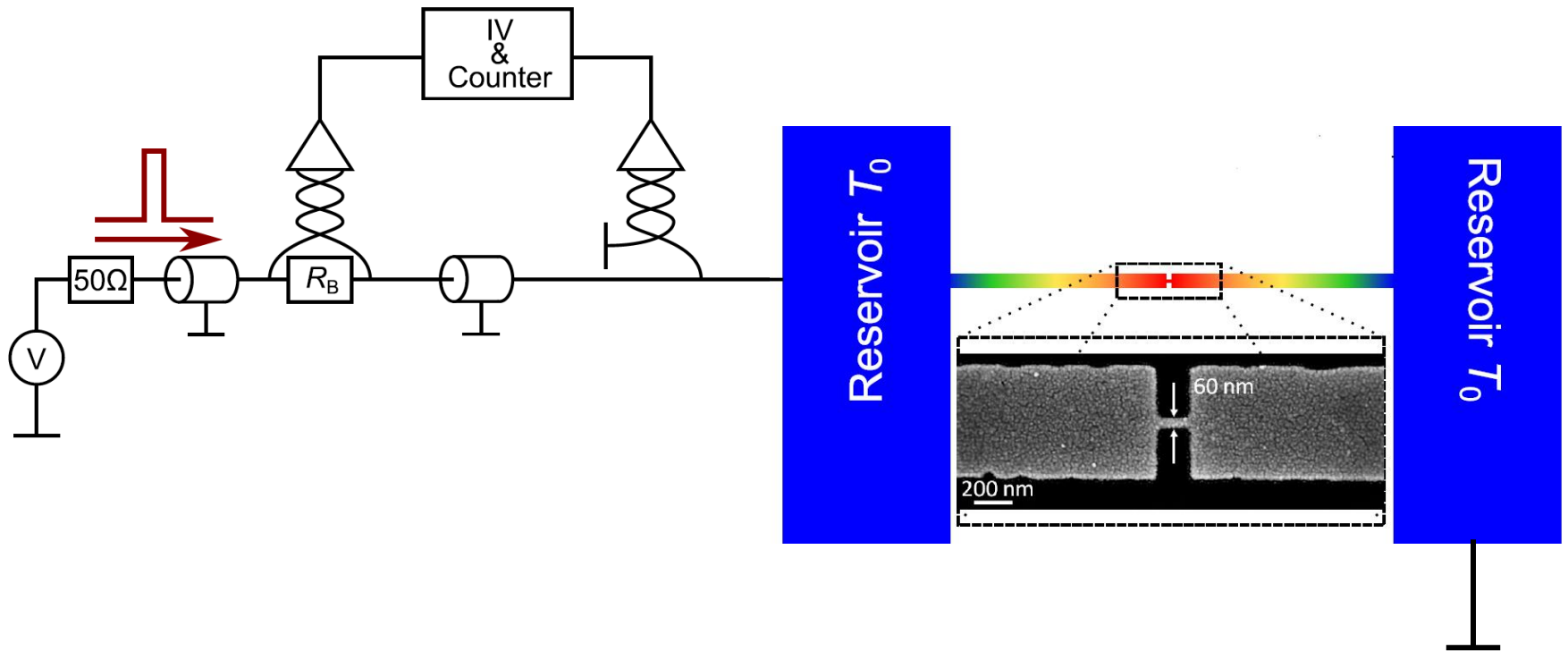
$$\Rightarrow \Delta T_{e,un} = 100 \mu\text{K}$$

„Pump and probe”



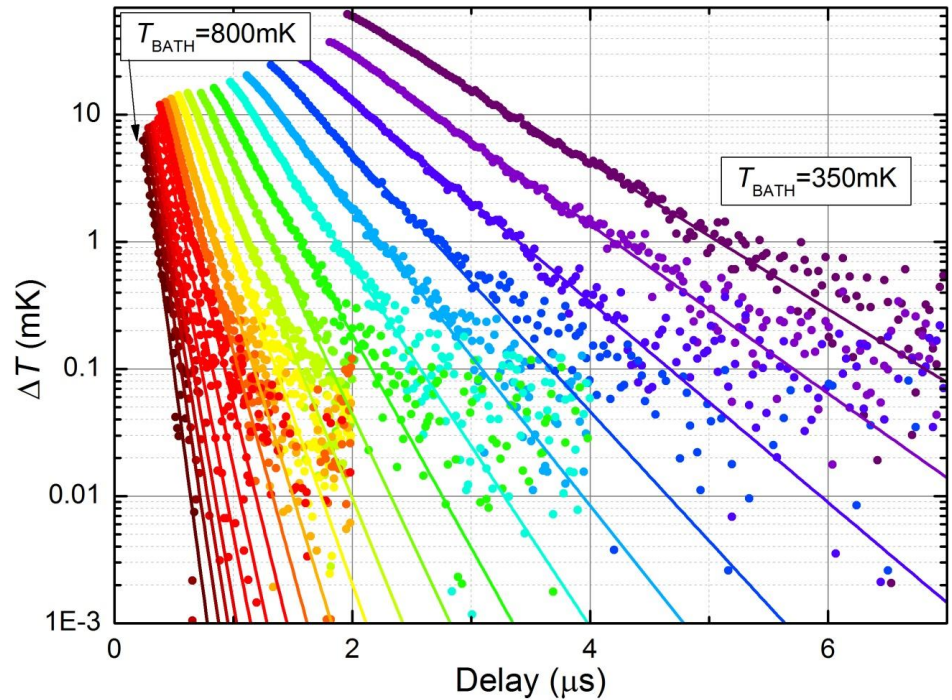
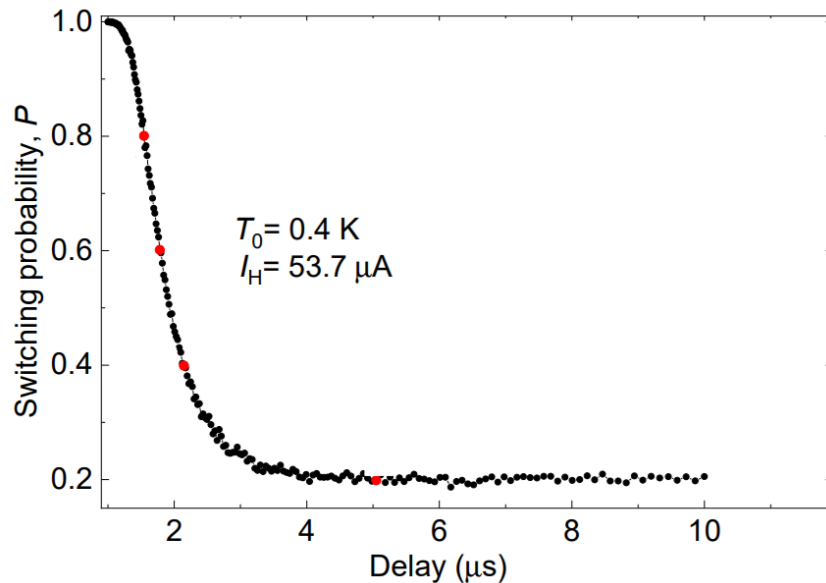
Addresses perfectly repeatable thermal processes
which can be initialized many times in the same initial conditions.

Sample

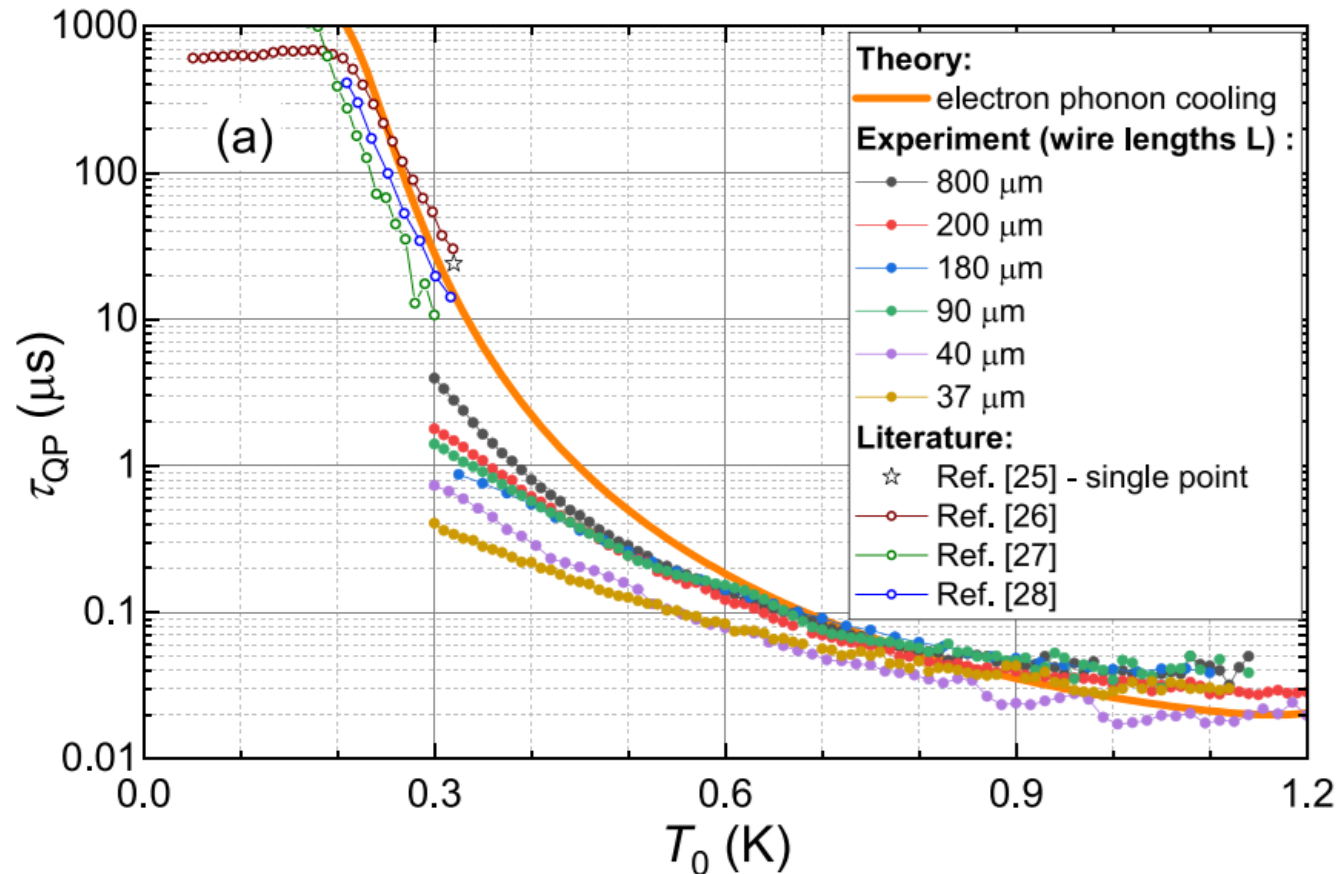


M. Zgirski, M. Foltyn, A. Savin, K. Norowski, M. Meschke, J. Pekola,
Nanosecond thermometry with Josephson junctions,
Phys. Rev. Appl. 10, 044068 (2018)

Monitoring relaxation of the switching probability



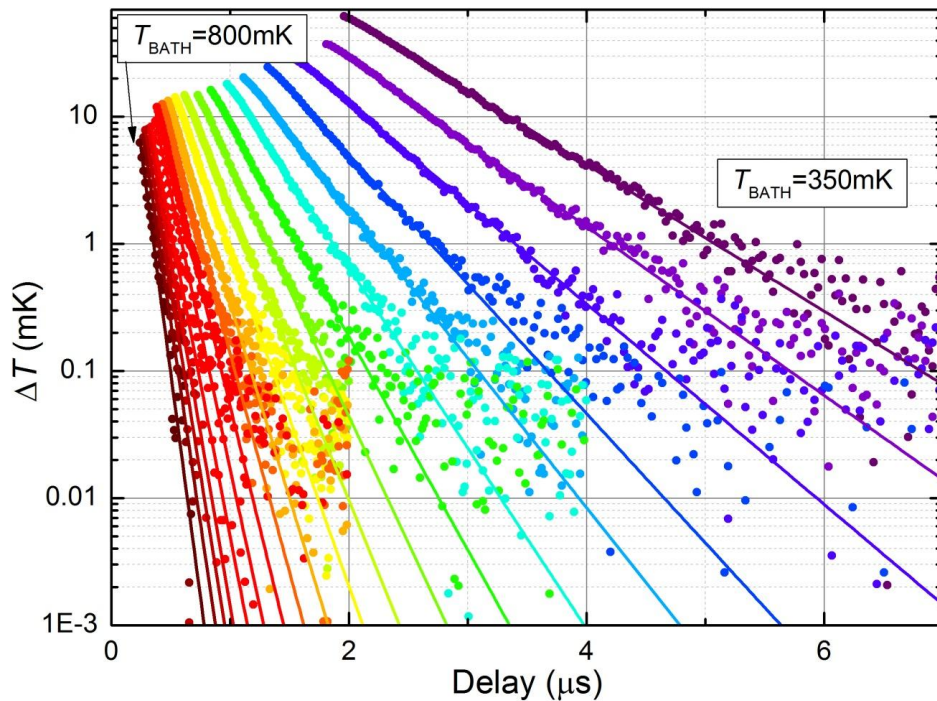
Quasiparticle lifetime in superconducting aluminum



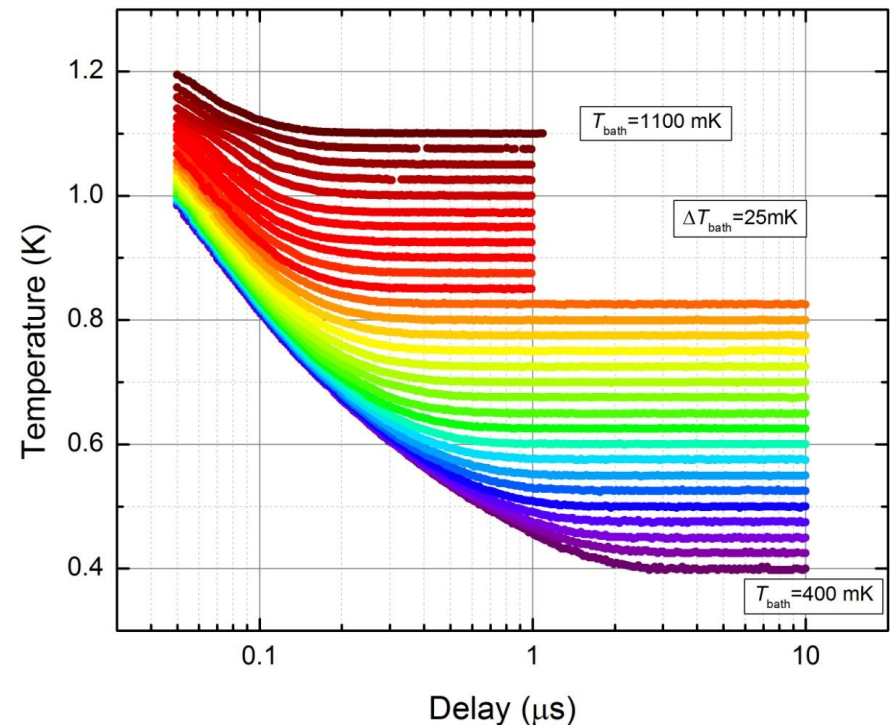
1. K. Norowski, M. Foltyn ,A. Savin, M. Zgirski, *Intrinsic Quasiparticle Lifetime in a Superconducting Aluminum*, **Phys. Rev. B** **113**, 214512 (2026)

Two methods of temperature measurement

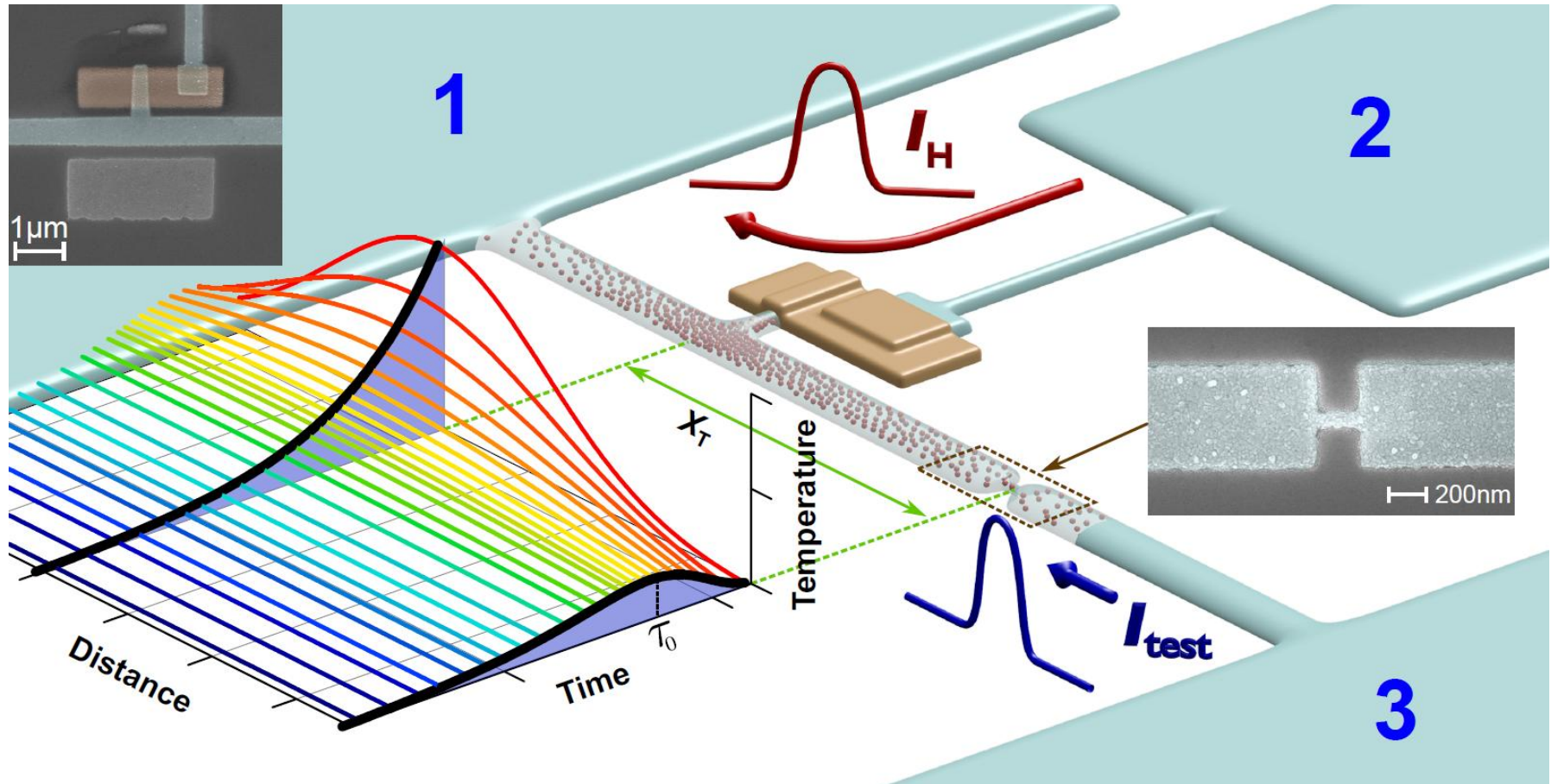
Temperature from Probability



Temperature from Switching Current



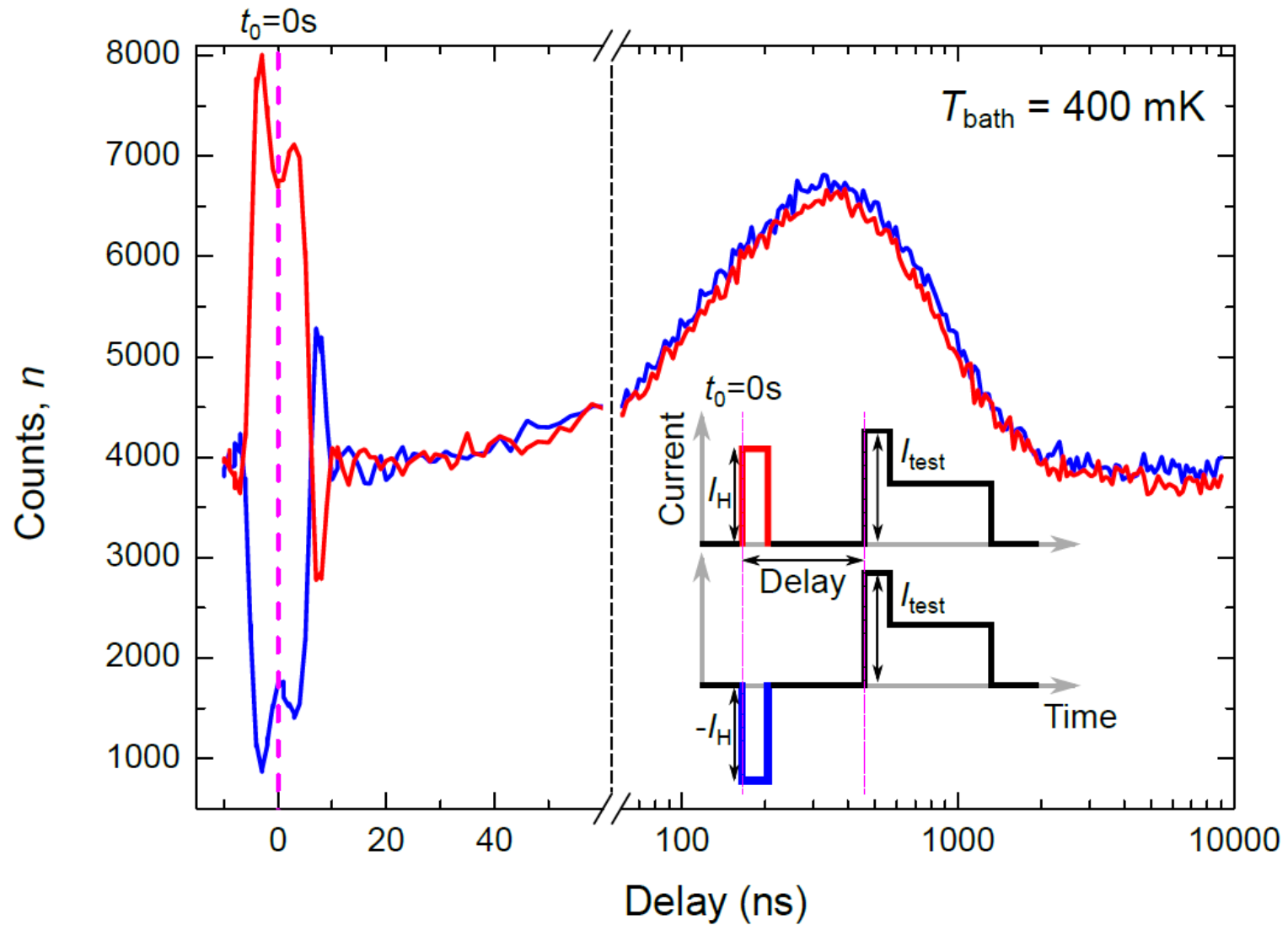
Diffusion of Quasiparticles (example 2)



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...

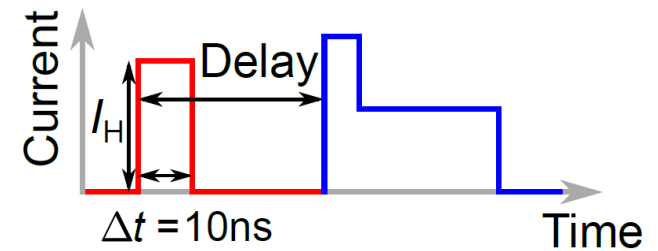
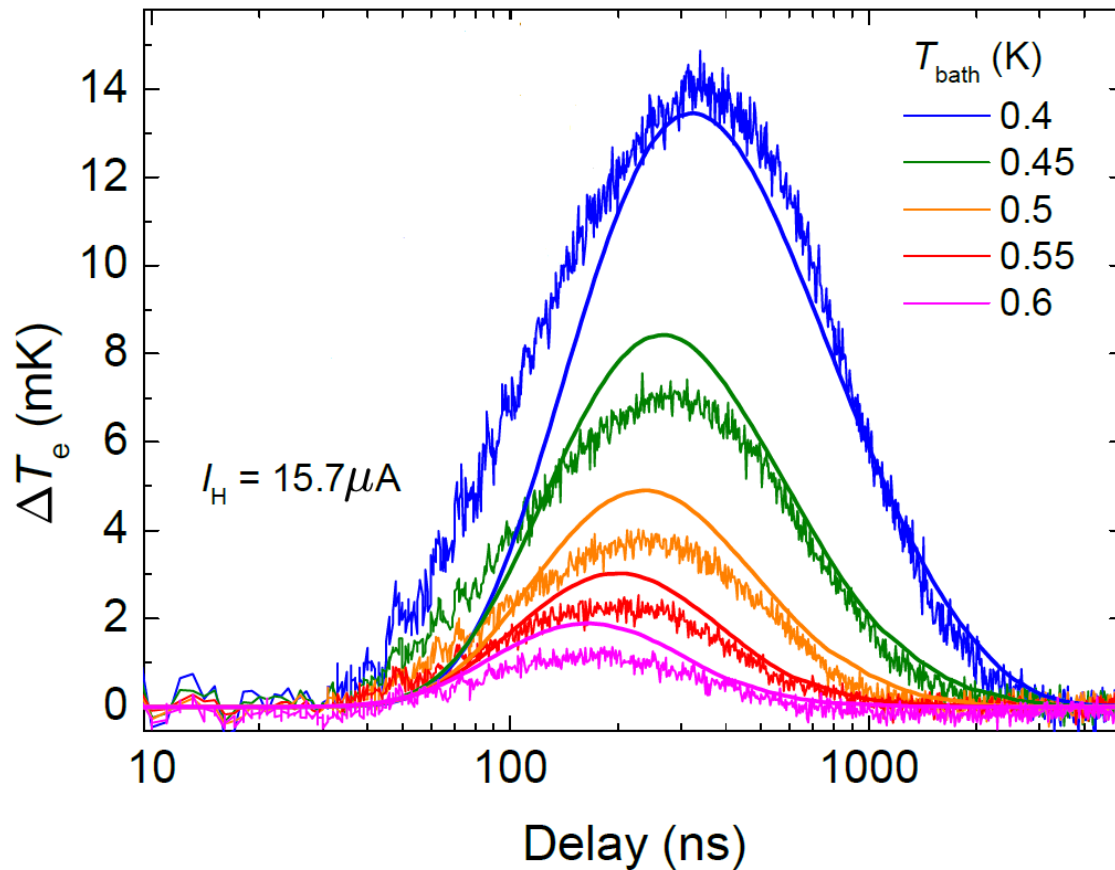


M. Zgirski, M. Foltyn, A. Naumov, A. Savin and K. Norowski

Heat hunting in freezer: Direct measurement of quasiparticle diffusion in superconducting nanowire,

Phys. Rev. Appl. 14, 044024 (2020)

...recalculated into excess electron temperature



Is it correct?

$$\langle X^2 \rangle = D \tau_{\text{MAX}} = (60 \mu\text{m})^2$$

$$\Rightarrow D = 100 \text{ cm}^2/\text{s}$$

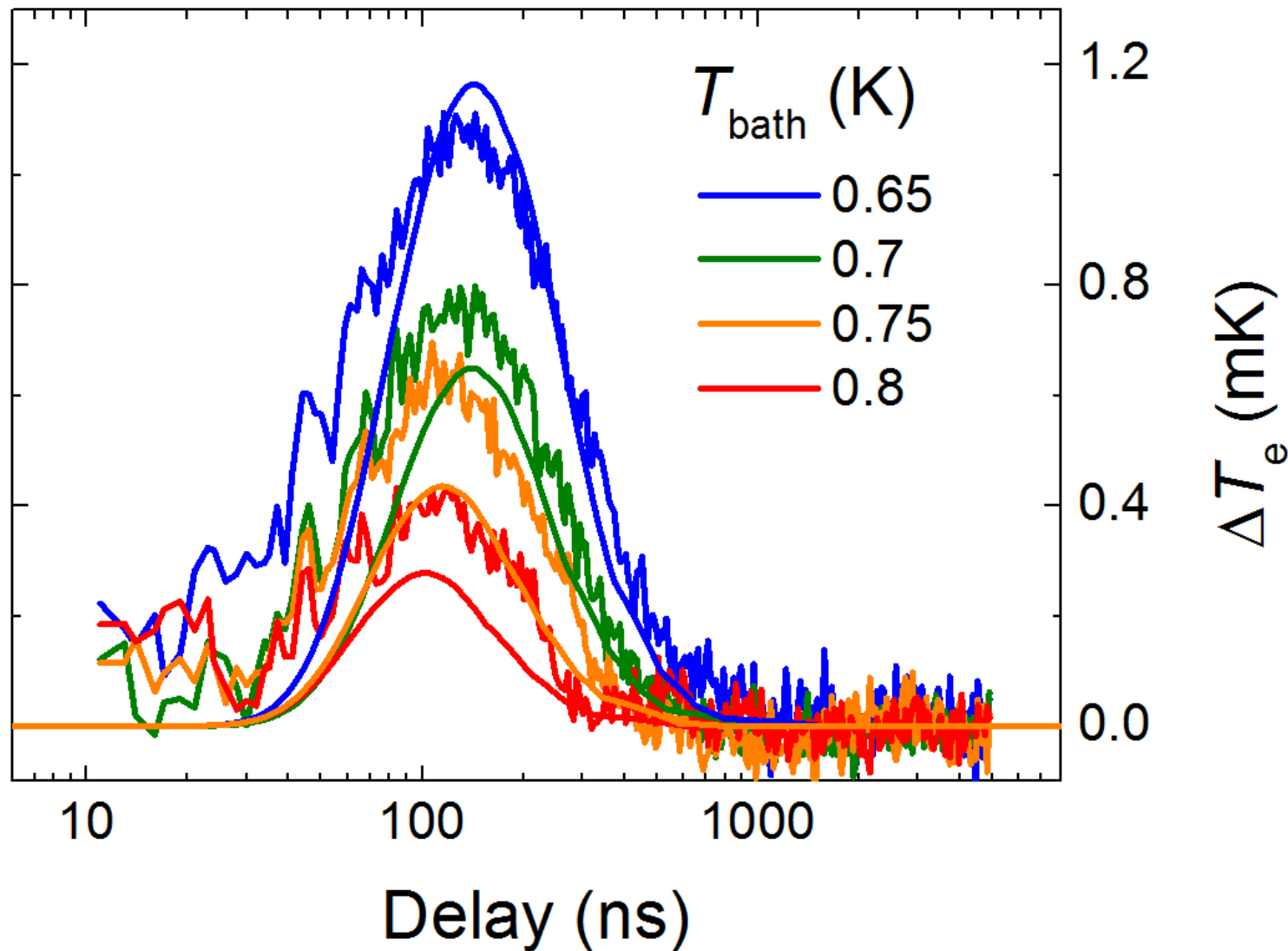
Expected: $D = 1/3 v_f l_{\text{mfp}}$

$$\Rightarrow l_{\text{mfp}} = 15 \text{ nm}$$

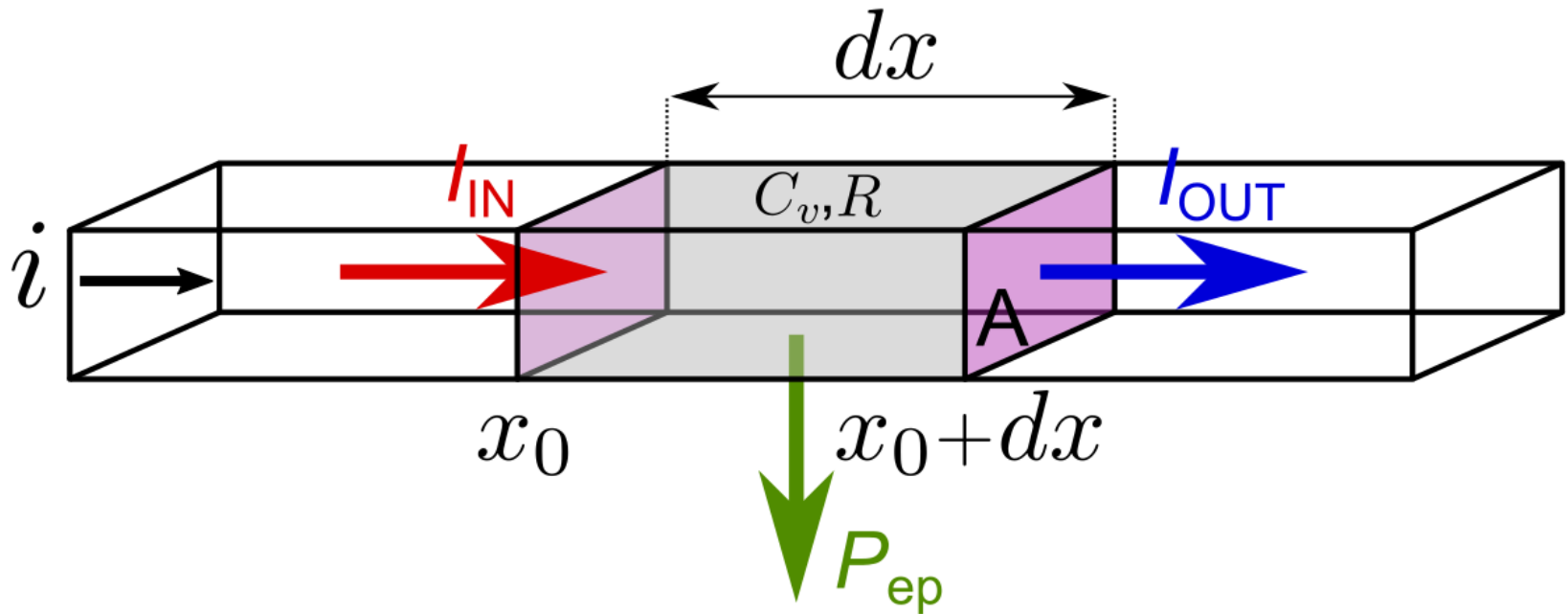
Note:

- temporal delay between generation and sensing $\sim 30 \text{ ns}$,
- position of the maximum at delay = 300 ns.

100 μ K resolution !!!



Heat balance equation



$$I_{IN} + Ri^2 = P_{ep} + I_{OUT} + C_v \frac{dT}{dt}$$

Heat flow into
volume $A dx$

Joule
heating

Heat conducted
away through
phonon channel

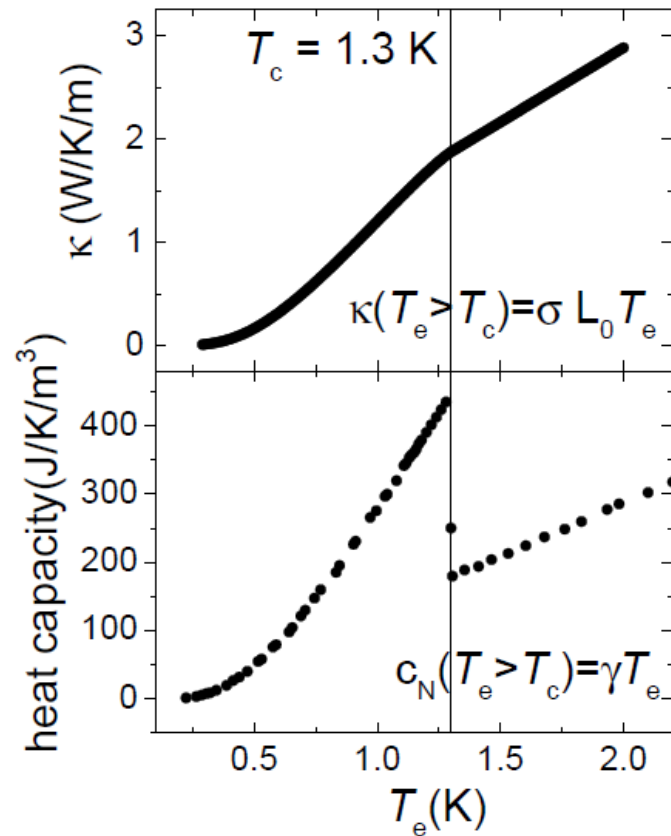
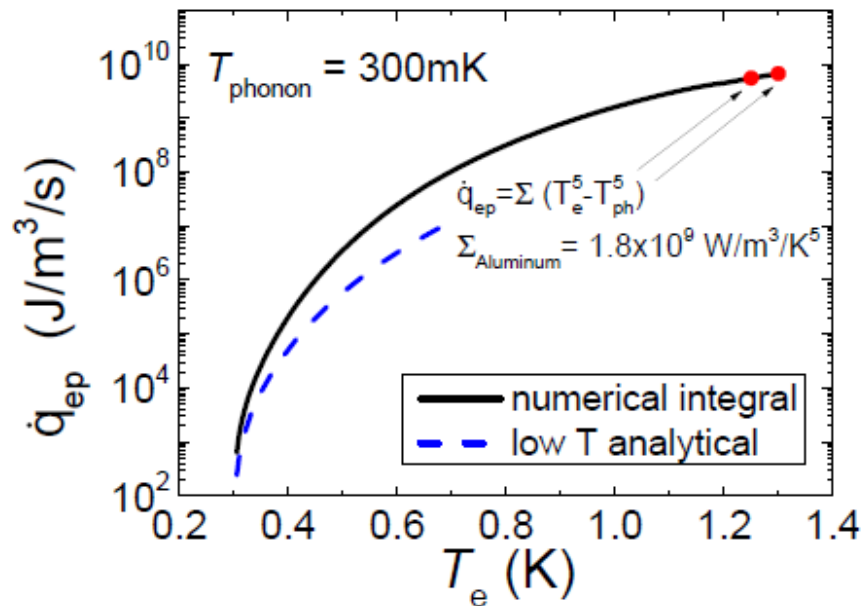
Heat flow out
from volume $A dx$

Increase of energy
of quasiparticles

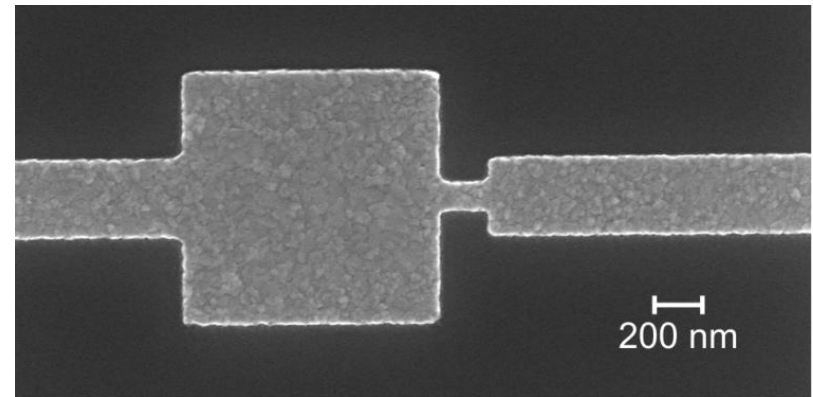
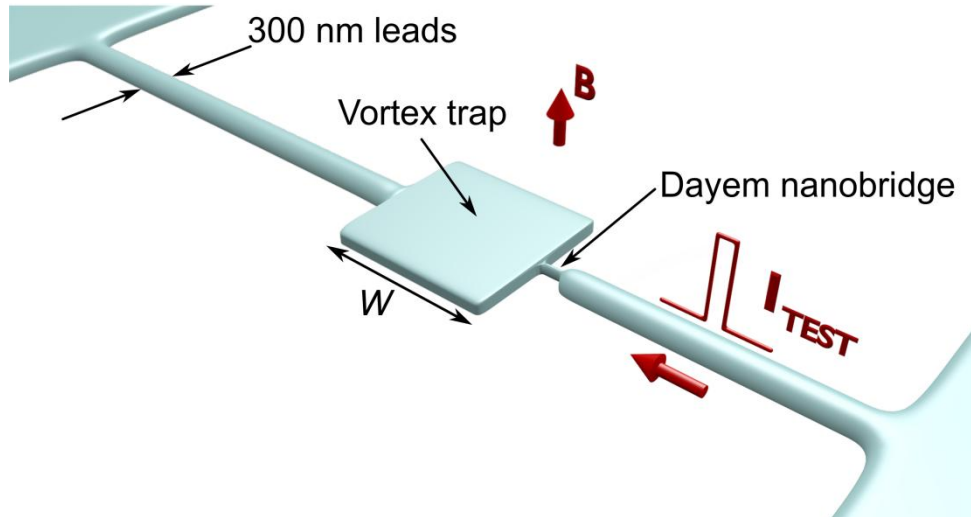
Heat balance equation

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

$$I_{th} = -\kappa \frac{\partial T_e}{\partial x}$$



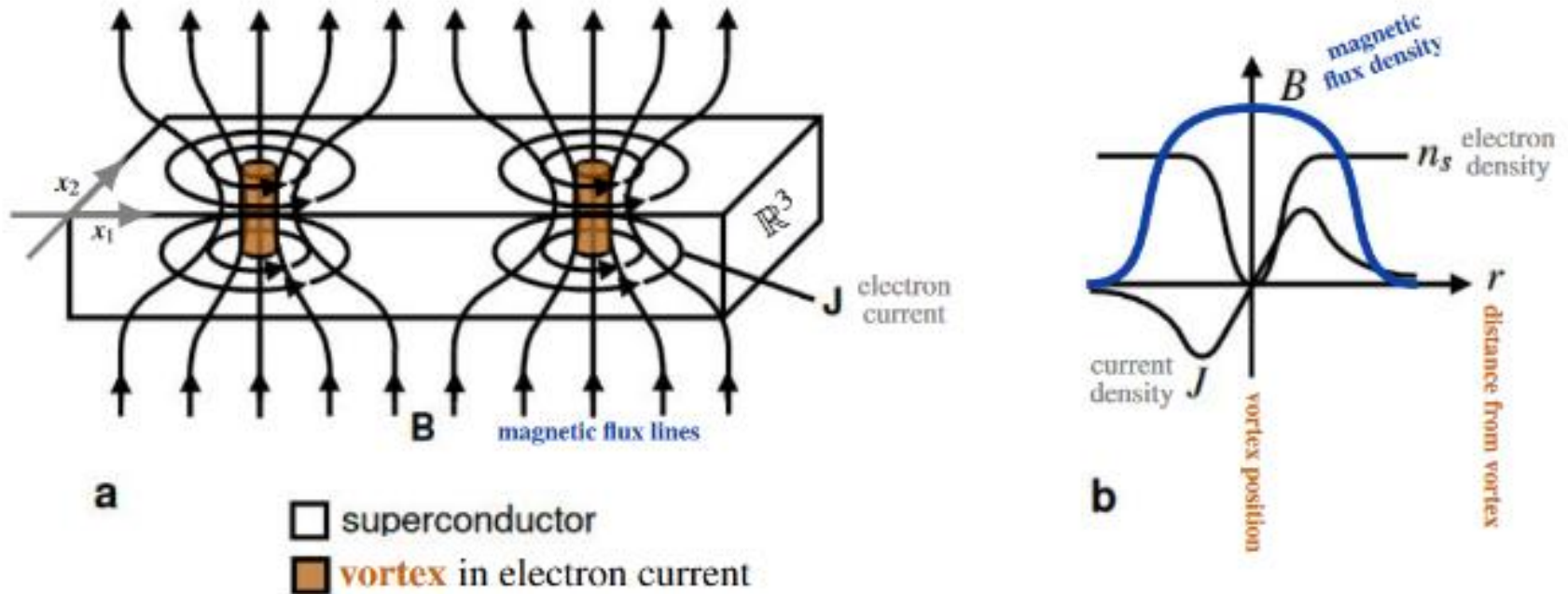
Teaser: Single Vortex Box (SVB)



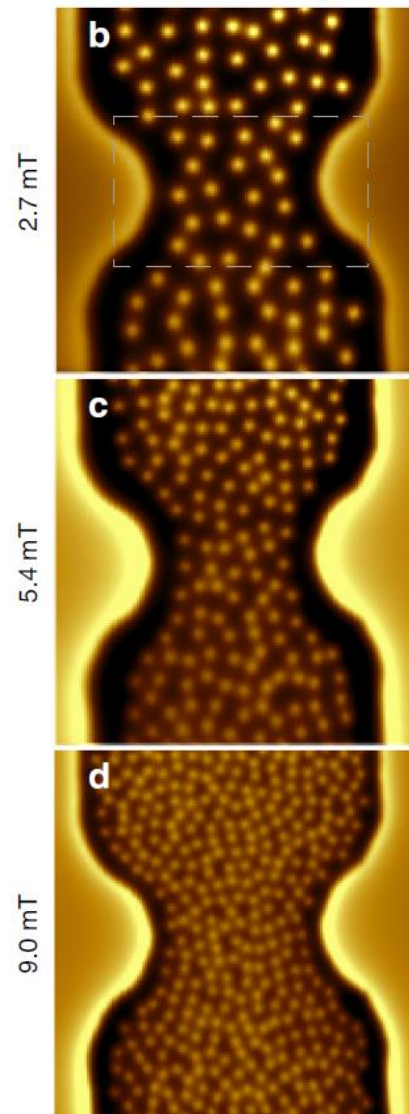
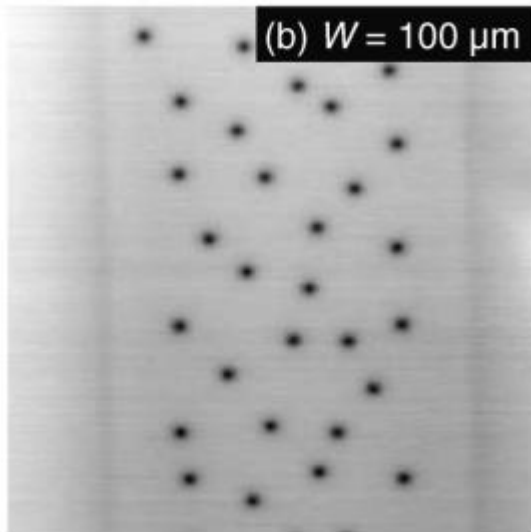
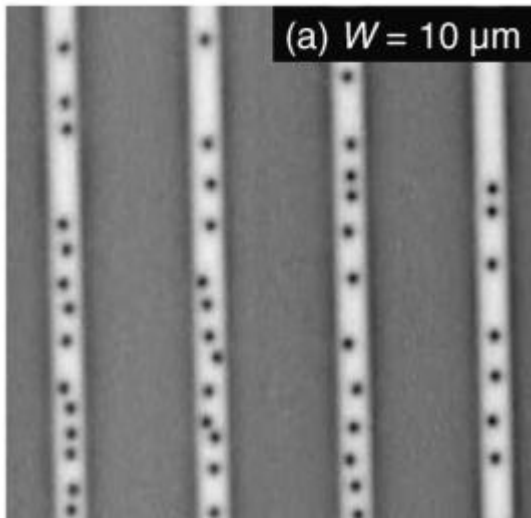
Vortex electronics:

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)

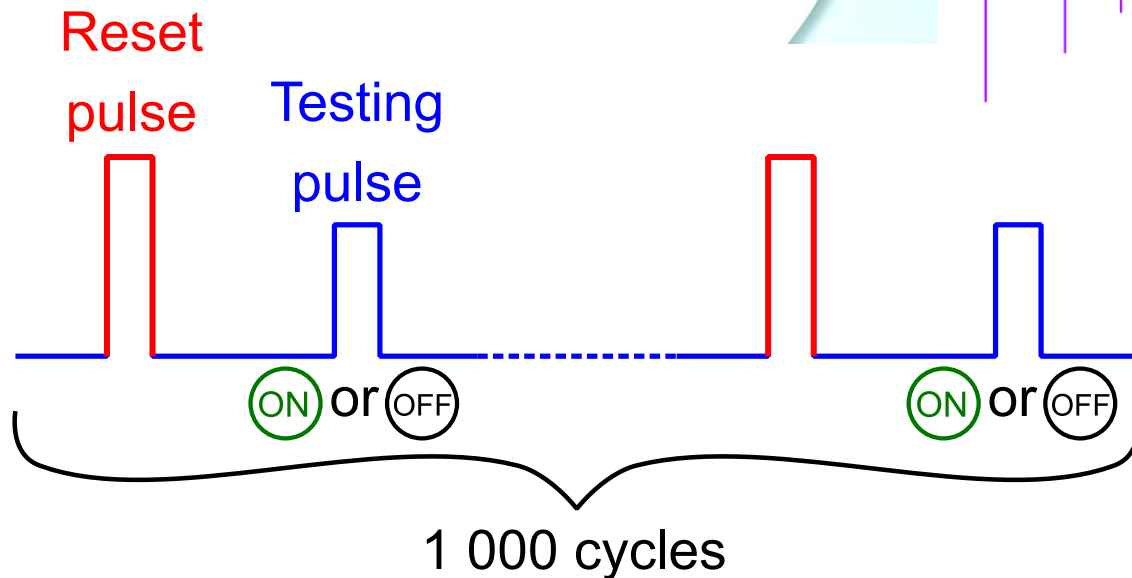
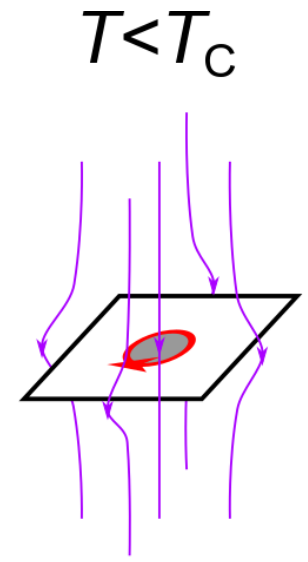
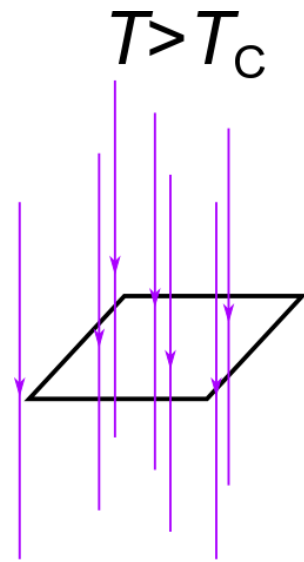
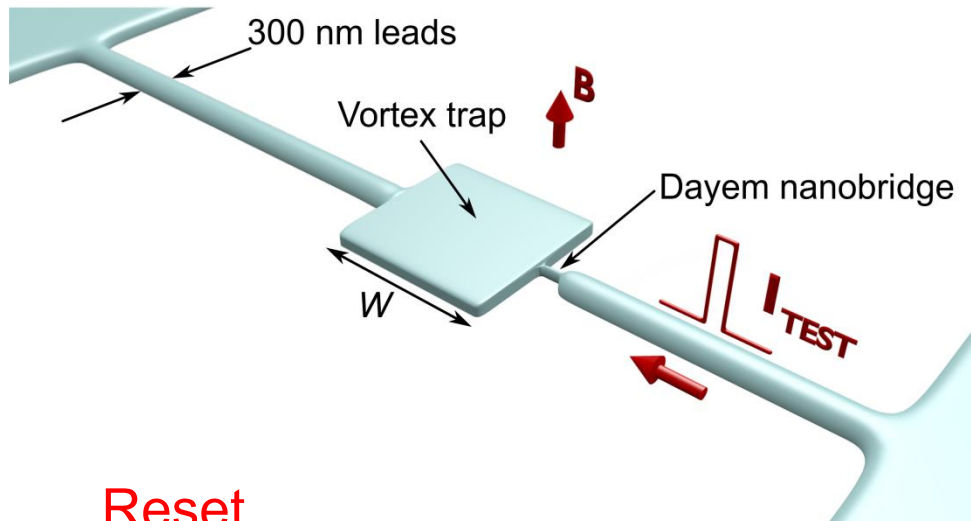
Can we harness it for an application?



single out and control

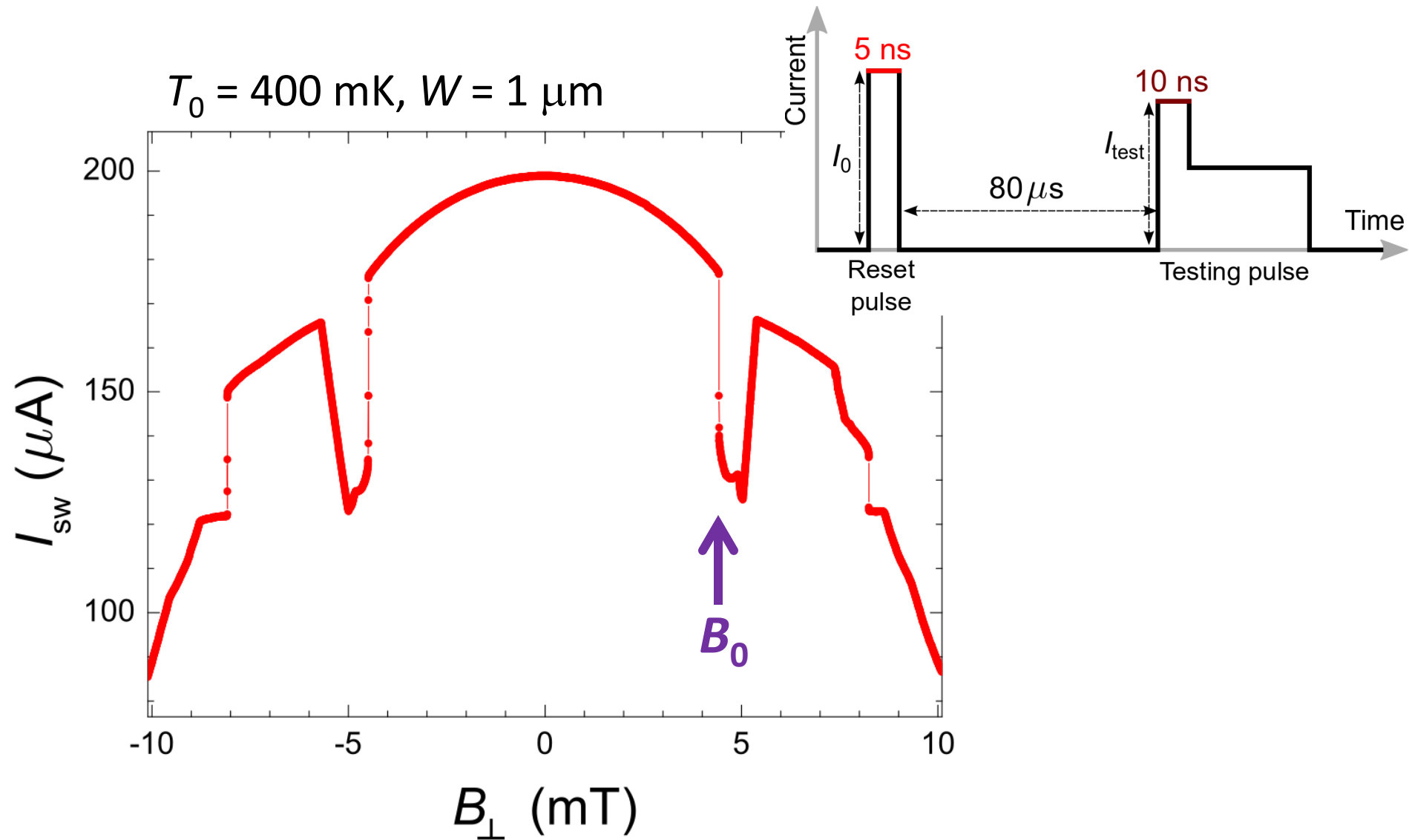


Trapping and detection of superconducting vortices

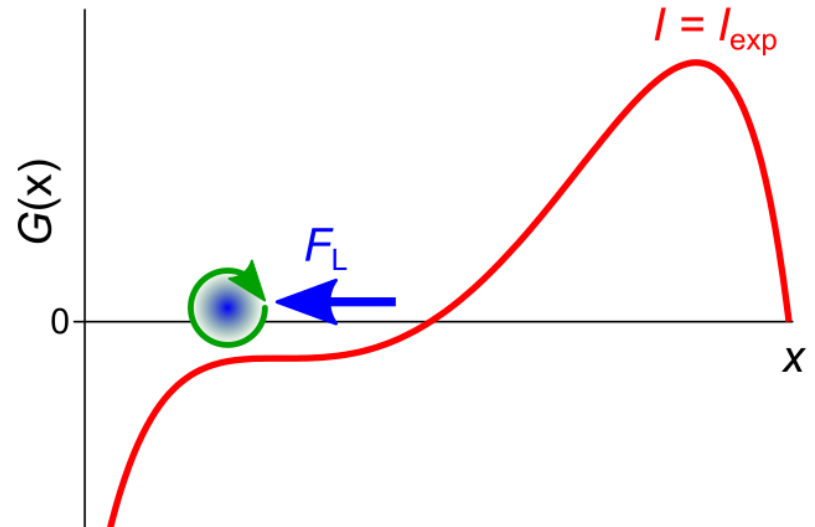
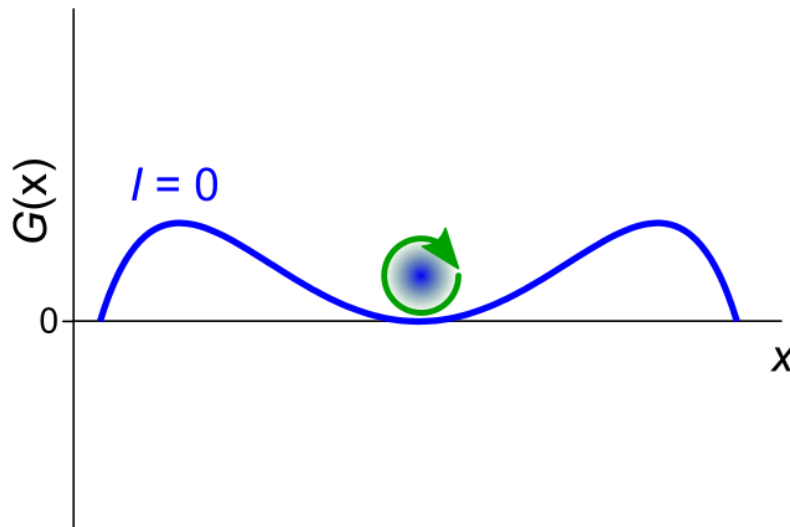
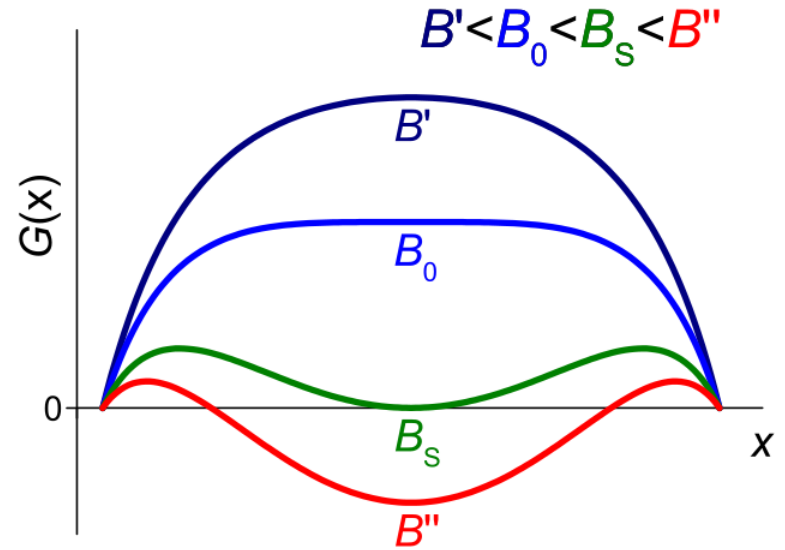
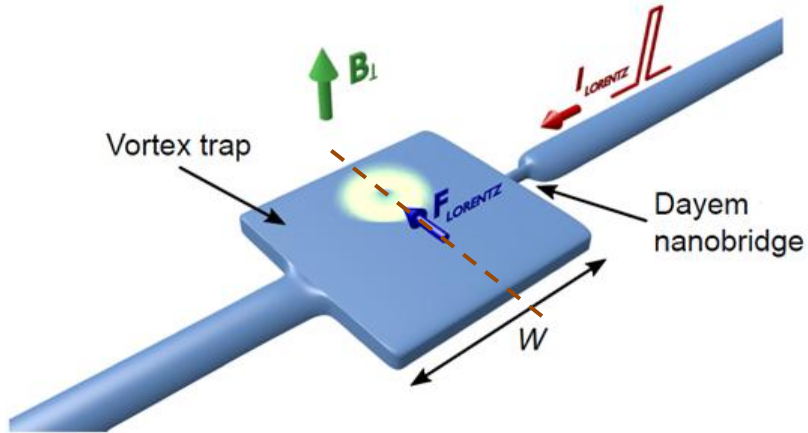


$$\longrightarrow I_{sw}(P=0.5)$$

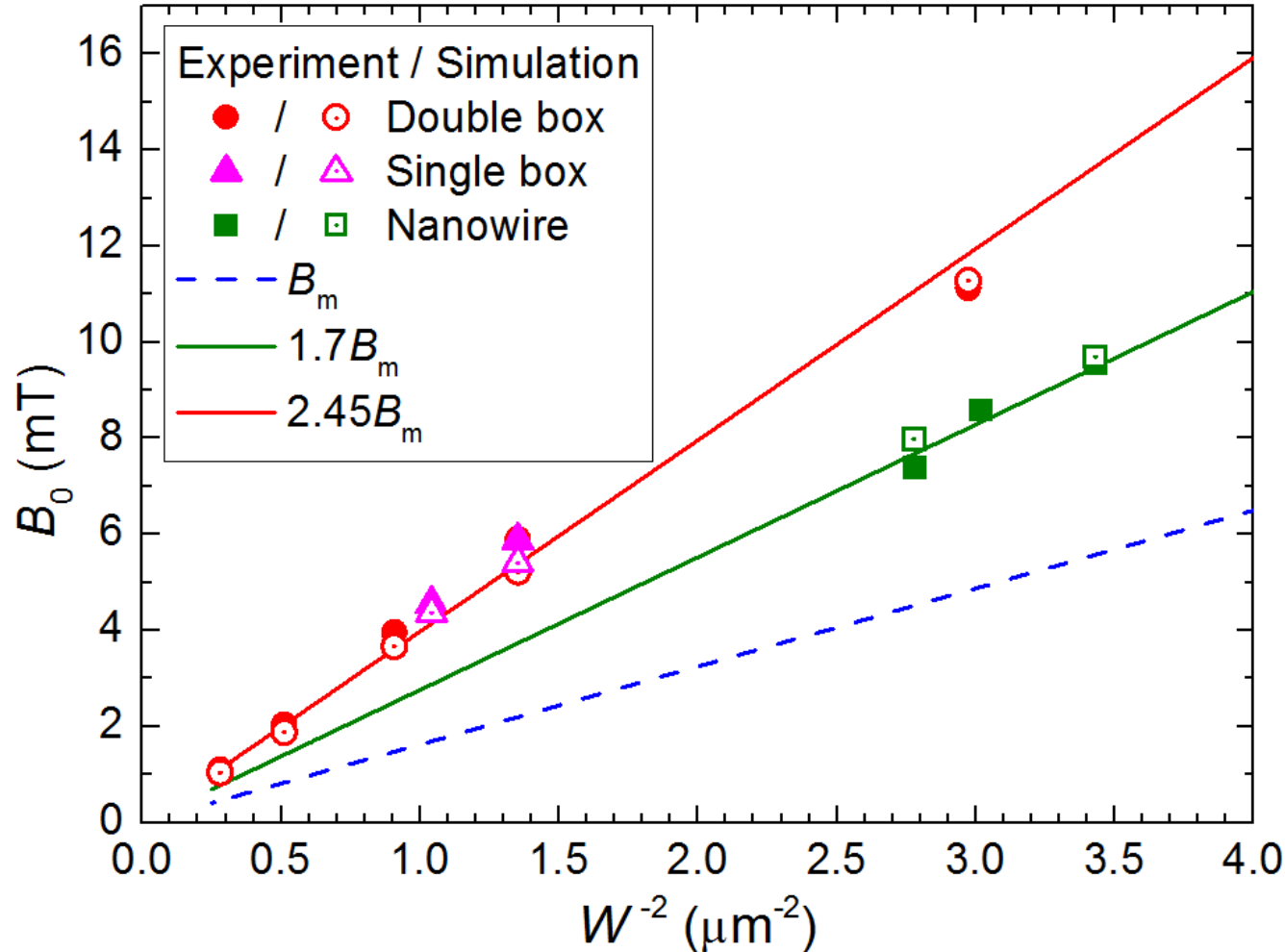
The presence of a vortex lowers I_{sw}



Single Vortex Box



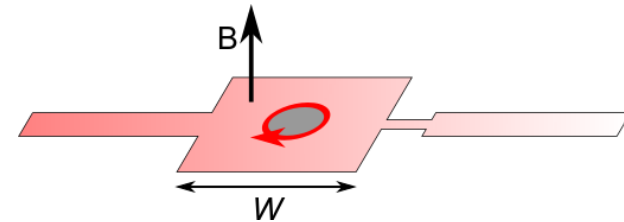
Threshold field for a vortex entry



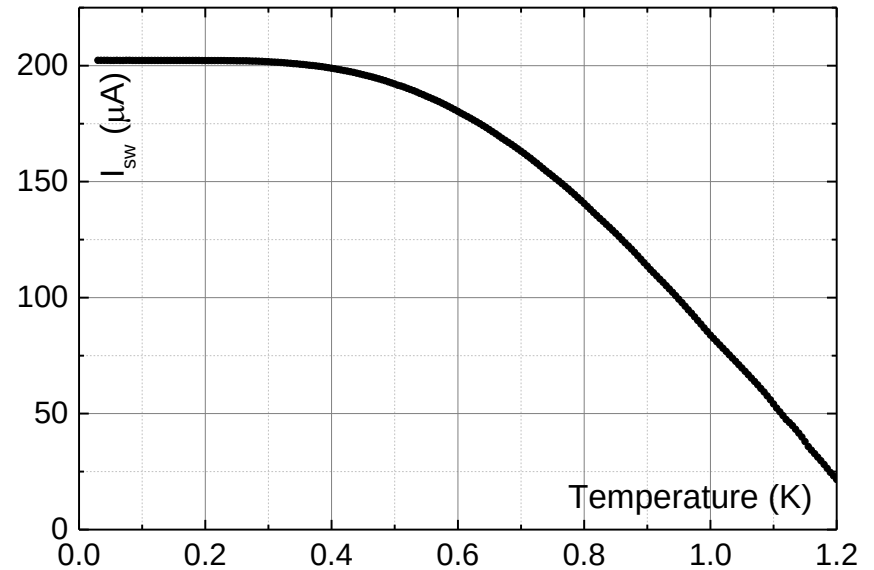
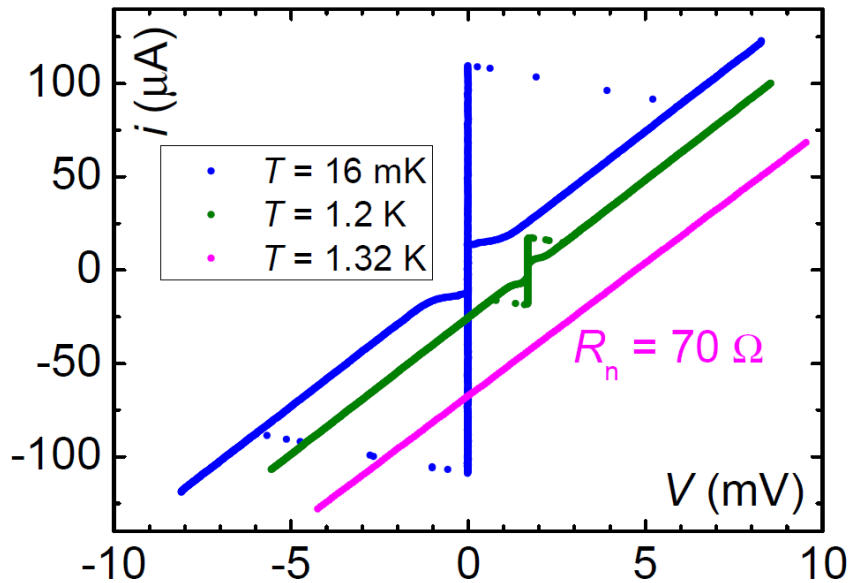
$$B_m = \frac{\pi \Phi_0}{4W^2}$$

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

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

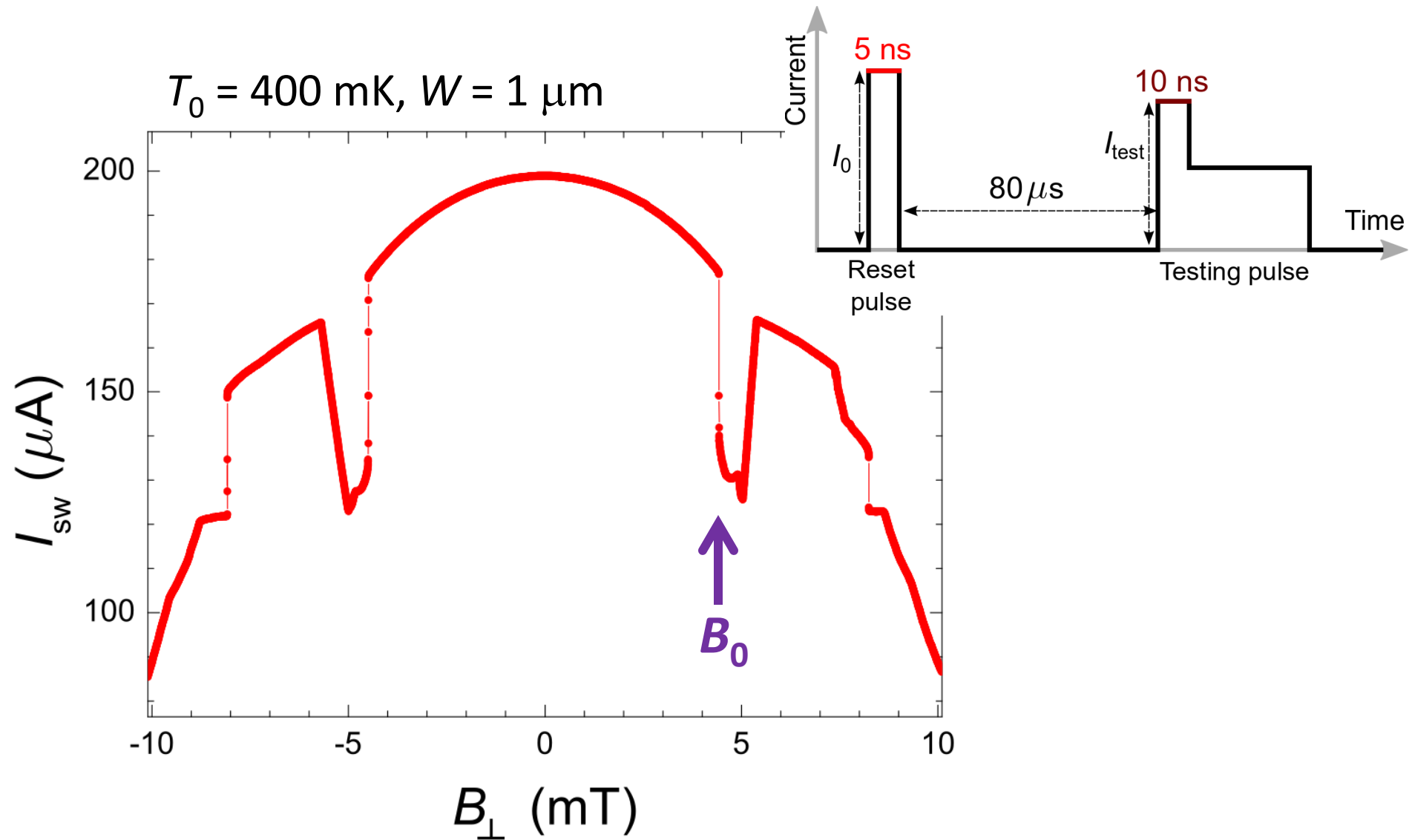


JJ is sensitive to temperature



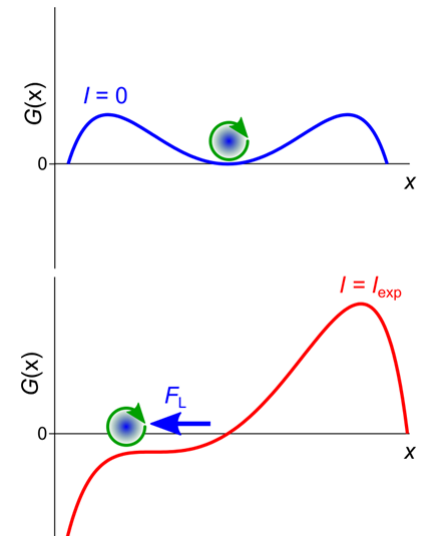
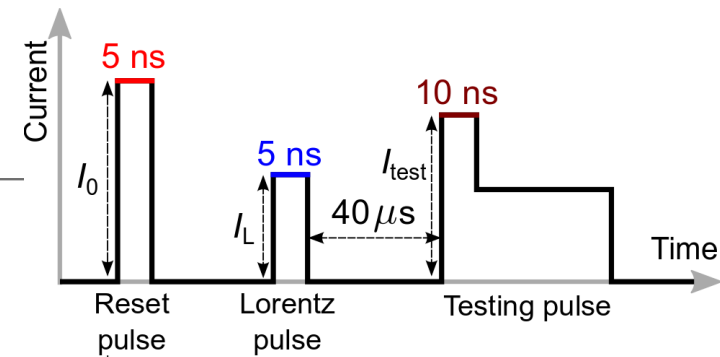
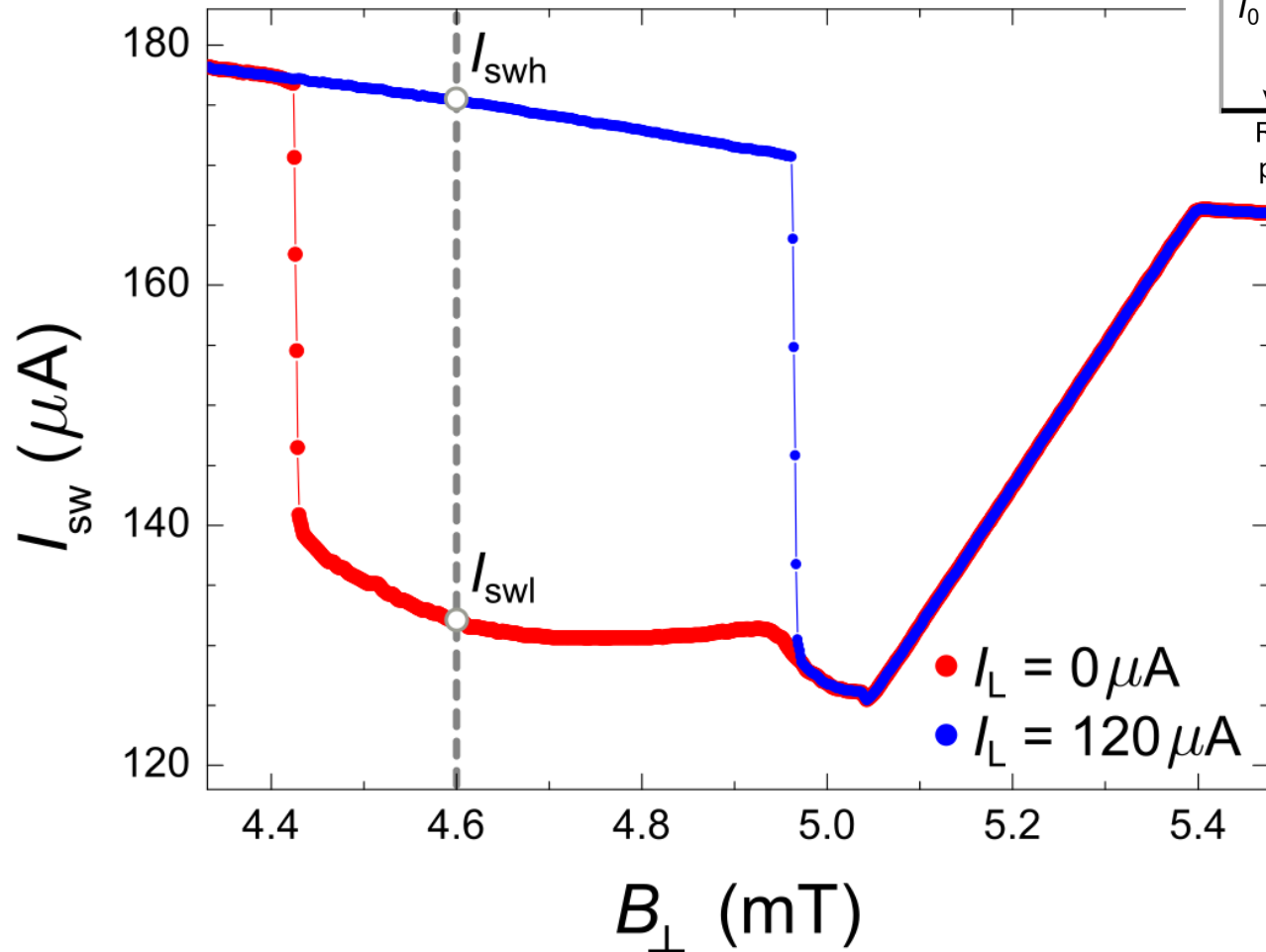
Suppression of I_c is a sign of dissipation !

The presence of a vortex lowers I_{sw}

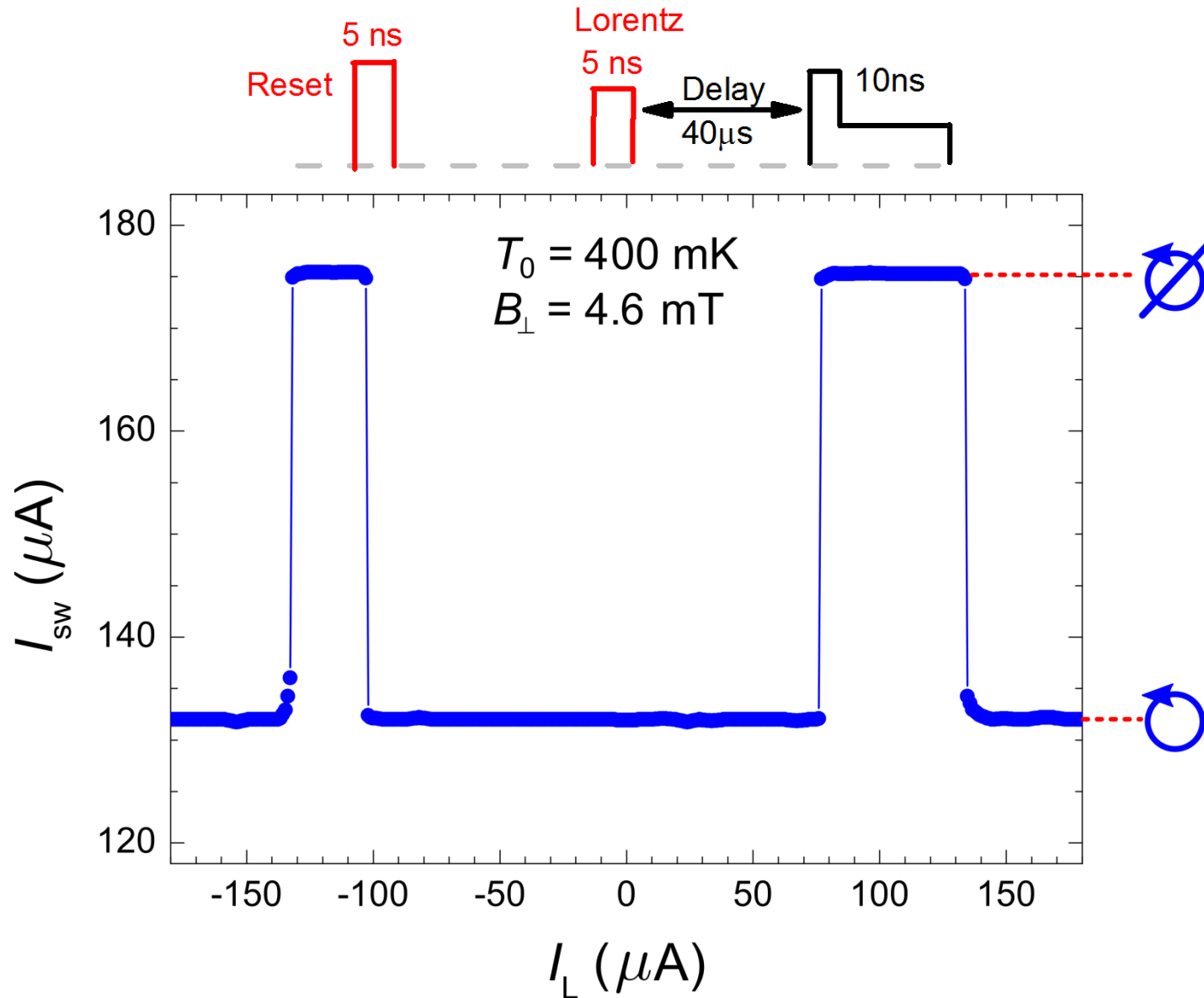


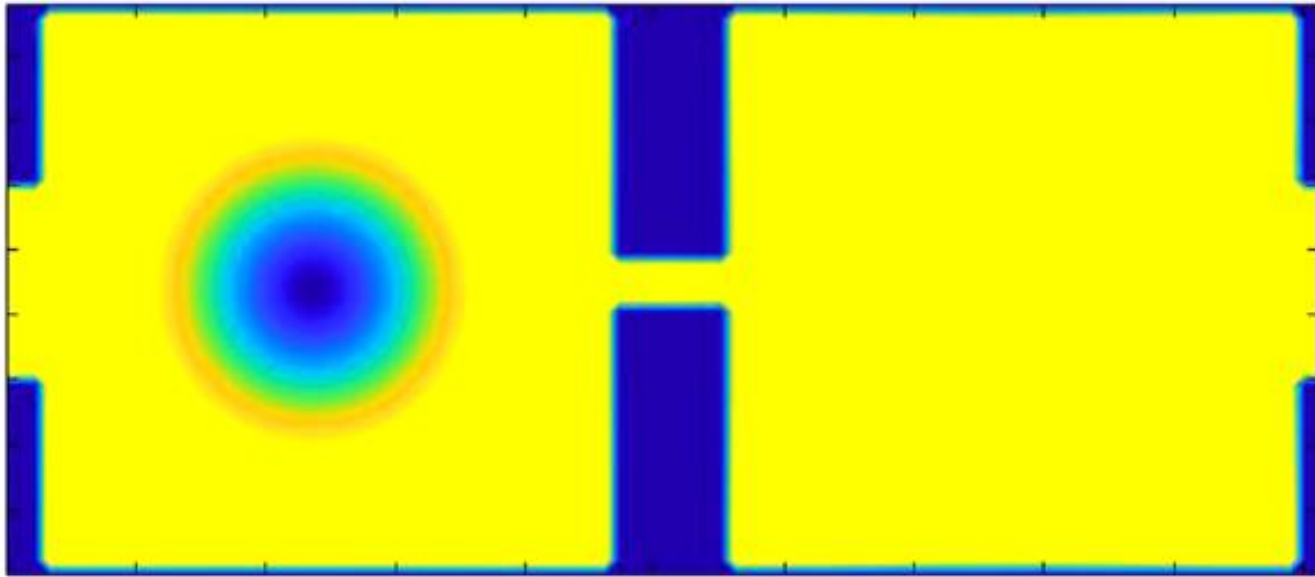
Let's try to get rid of the vortex...

$T_0 = 400 \text{ mK}$, $W = 1 \mu\text{m}$



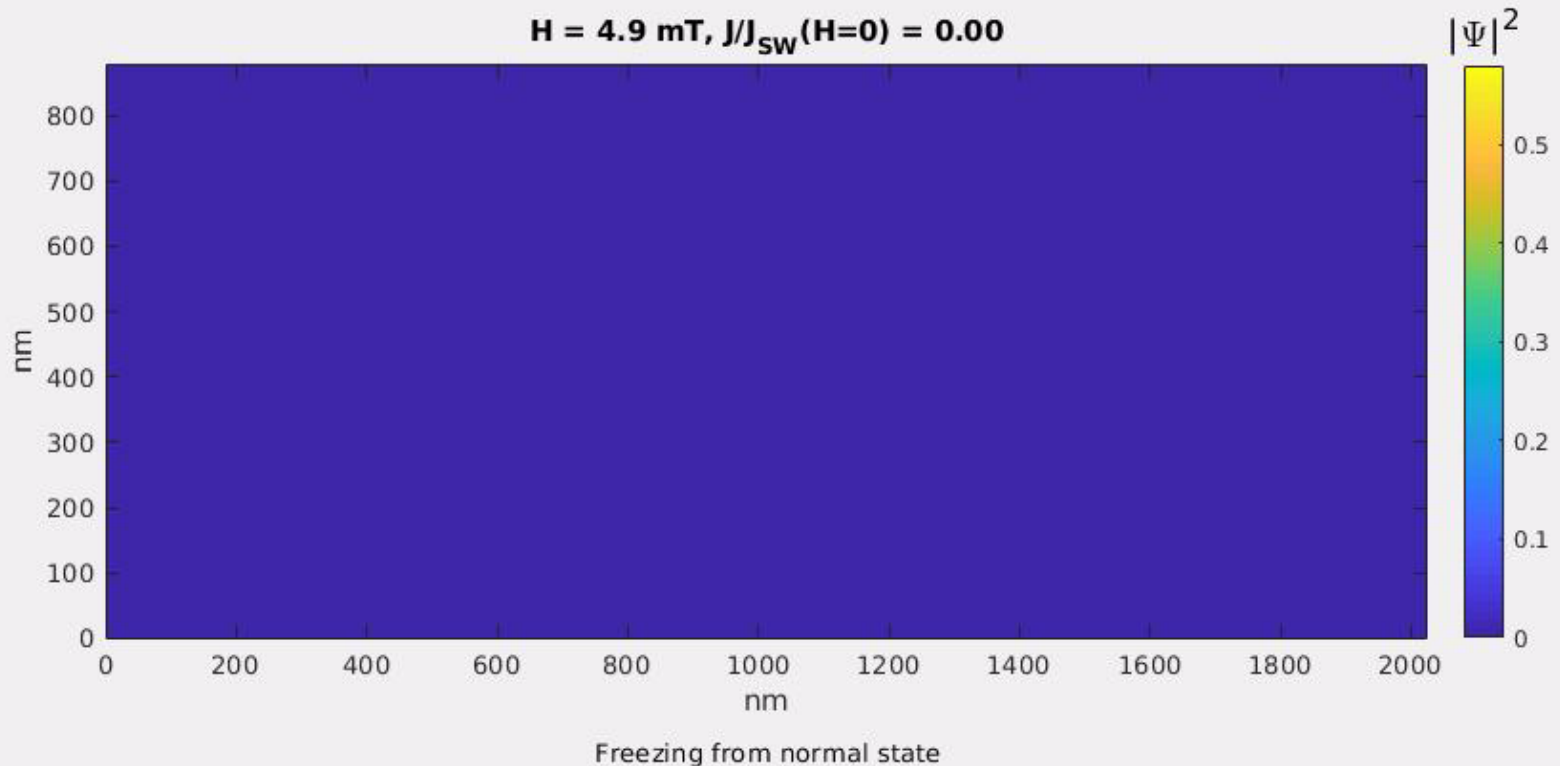
Get rid of the vortex...





Device_3_1v.avi

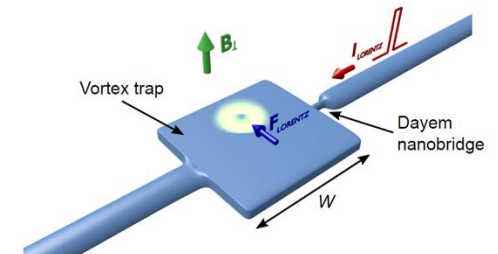
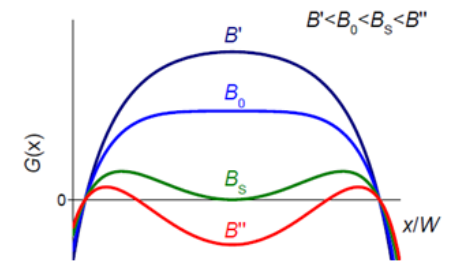
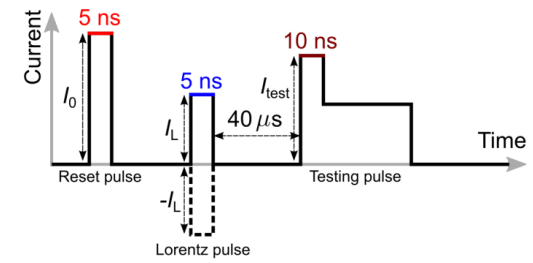
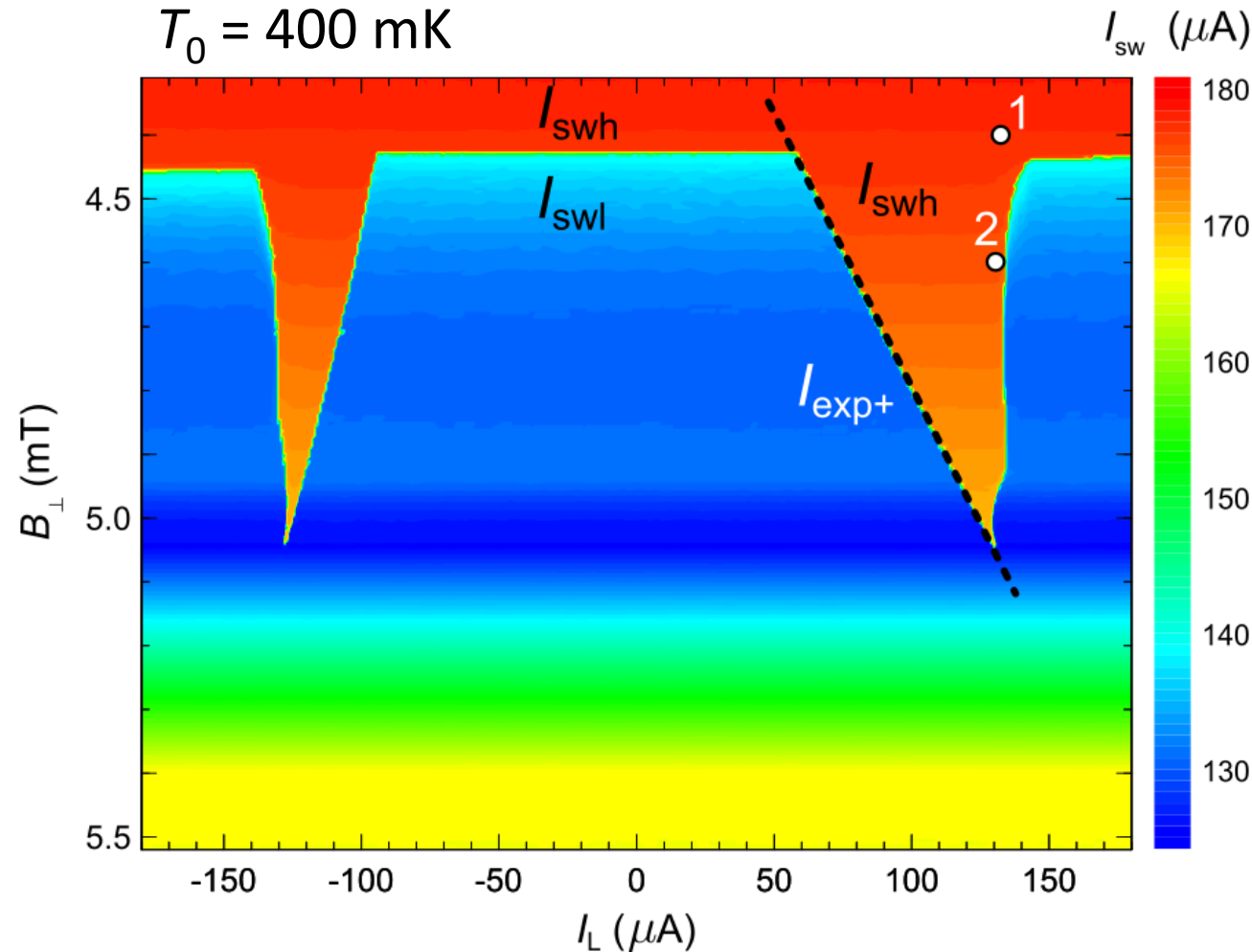
GLsimulation of the Single Vortex Box



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

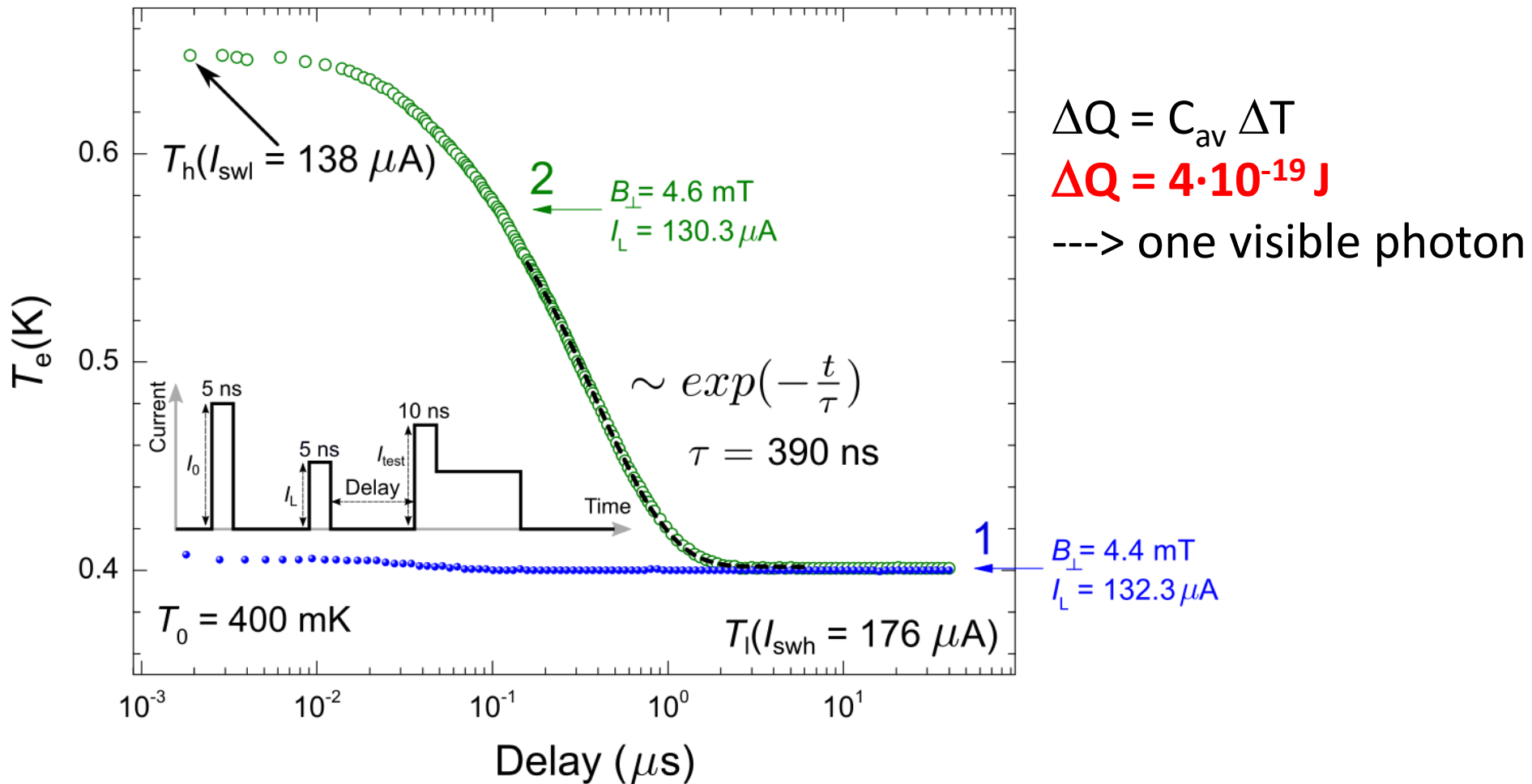
Vortex stability diagram

$T_0 = 400 \text{ mK}$



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



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:

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

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

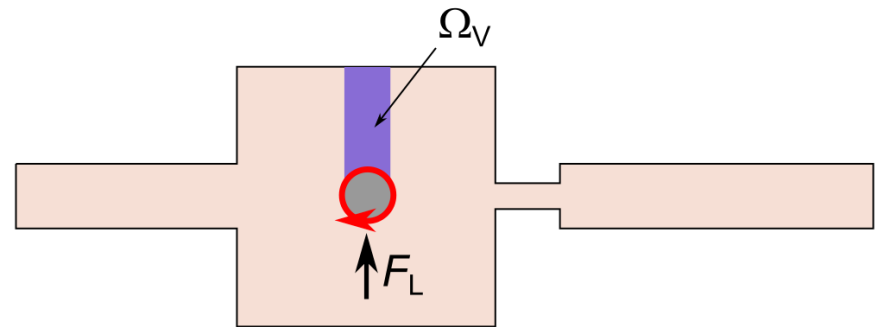
Theory: Viscous flow of the vortex

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

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

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

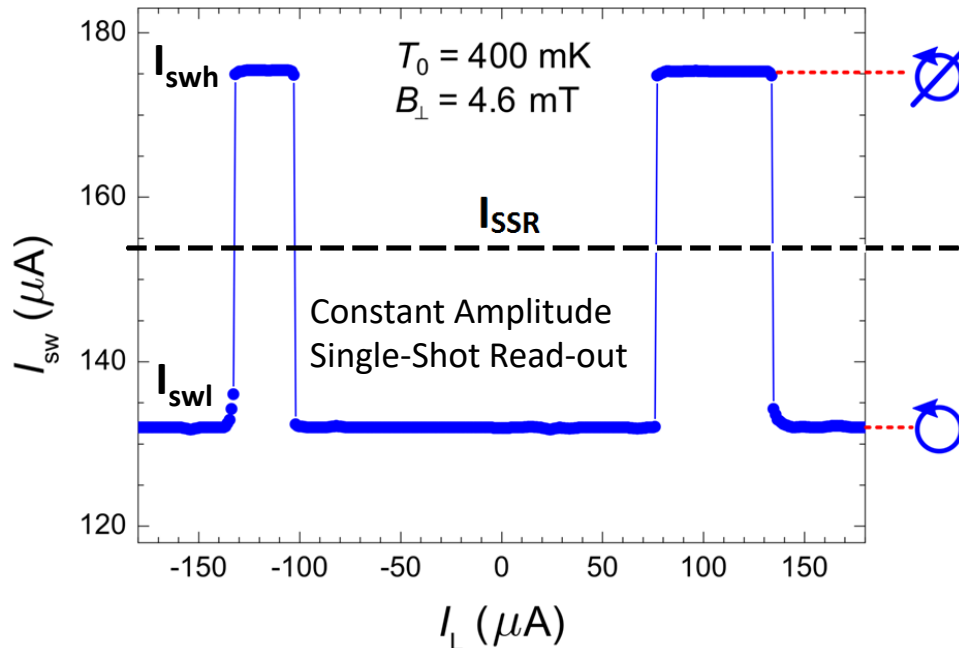
$$\Delta Q = N_{qp} \Delta = 3 \cdot 10^{-19} \text{ J}$$



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

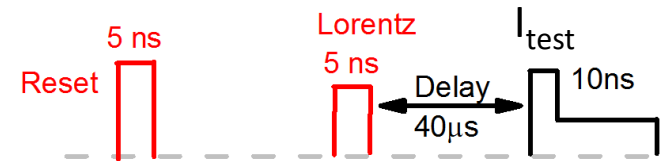
Single Vortex Box (SVB) as a memory cell

READ-OUT: I_{test} checks the state.

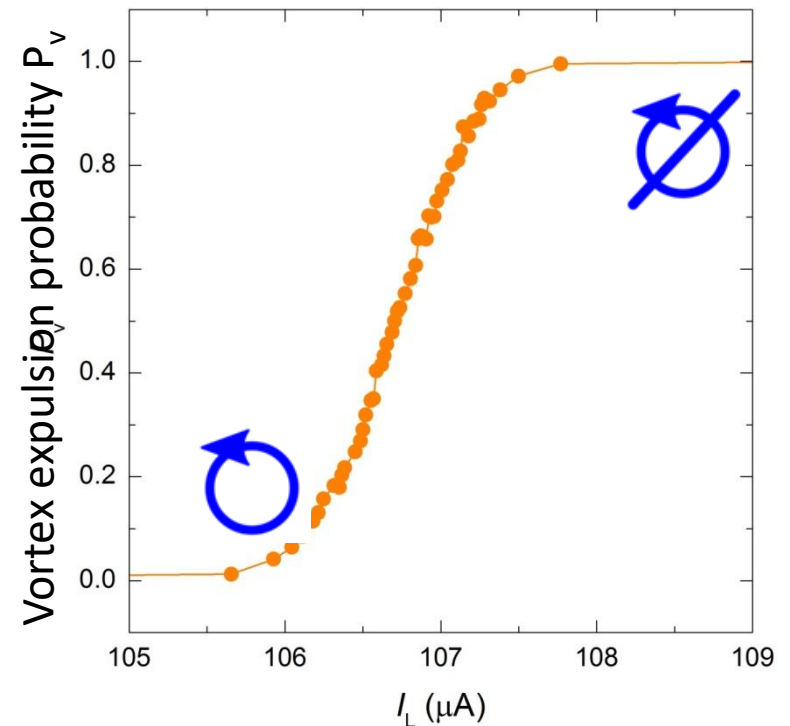


For $I_{\text{test}} = I_{\text{SSR}}$

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“

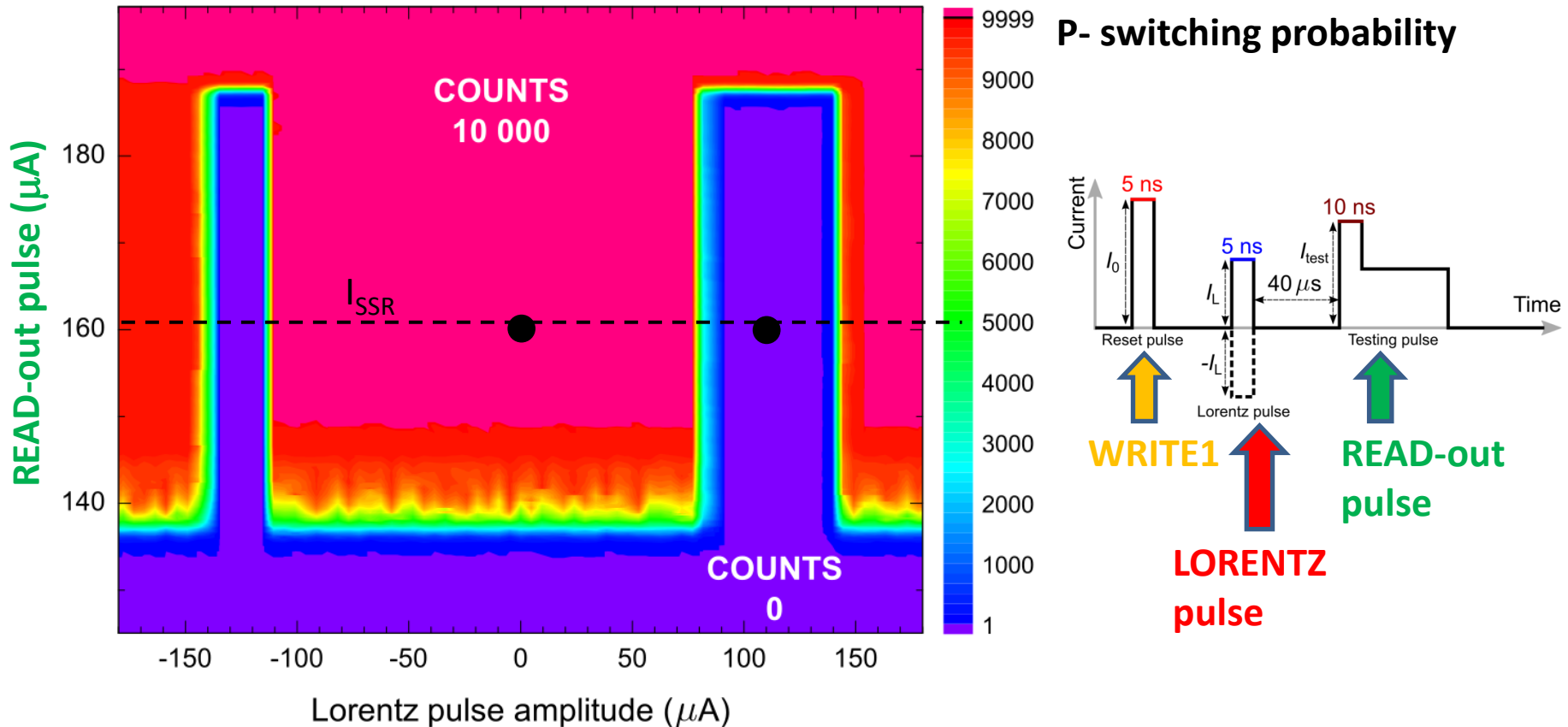


WRITE: The Lorentz pulse changes logical state of the box: „0“ or „1“.



WRITE-READ fidelity map

Let's send $N = 10000$ sequences and measure the switching probability P

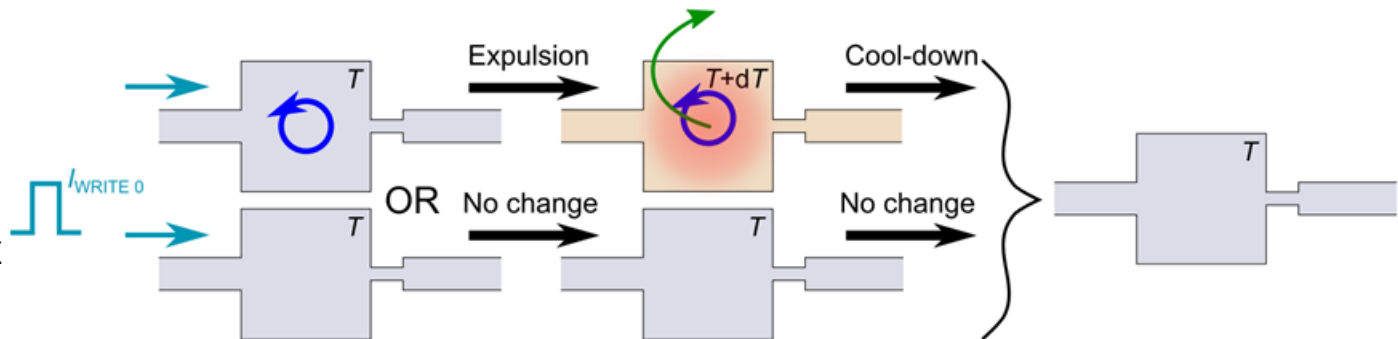


We can distinguish the state of the box in a single-shot measurement!

WRITE operation of the SVB

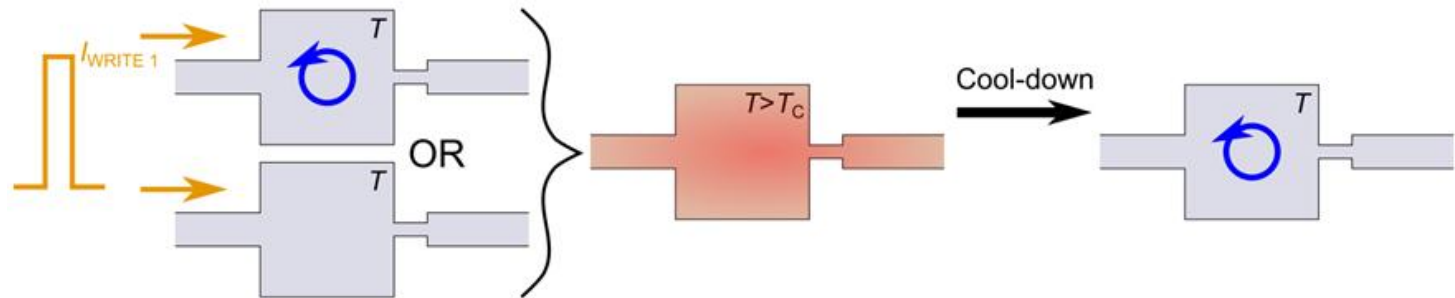
STATE „0”:

Use LORENTZ pulse
to get rid of the vortex

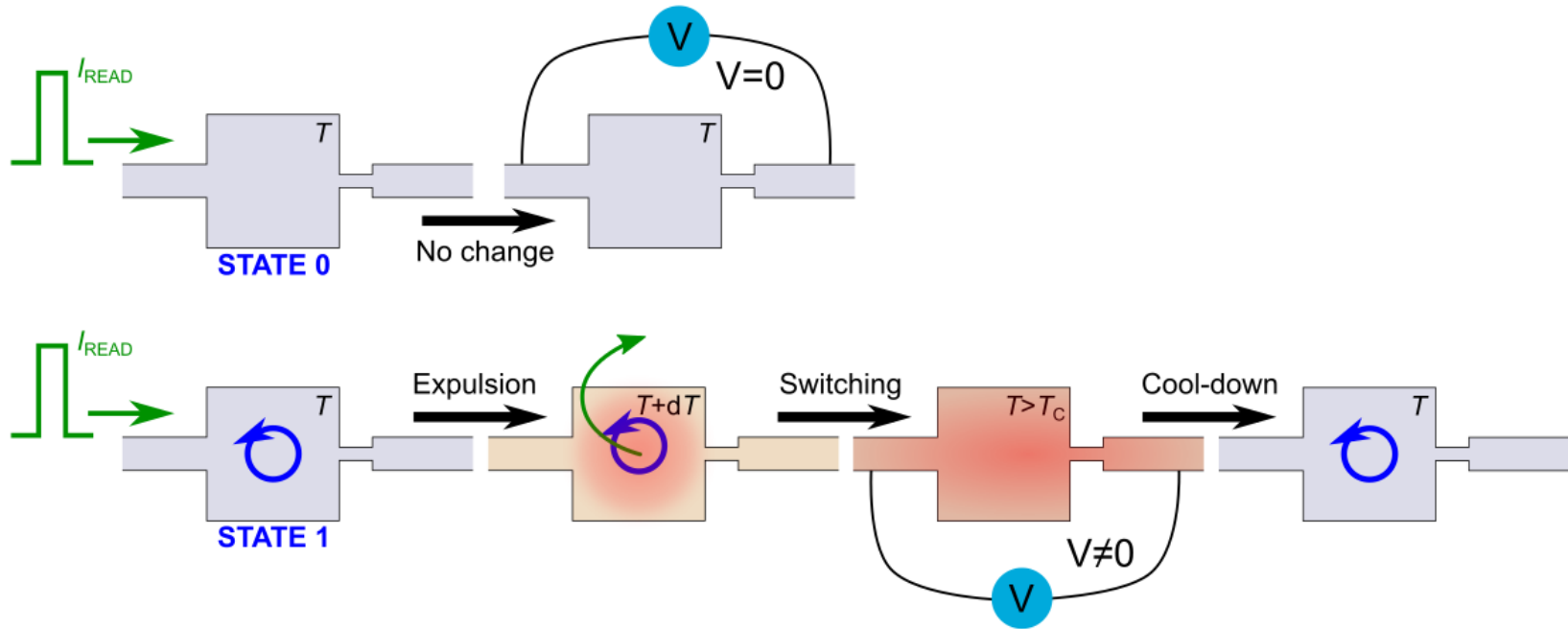


STATE „1”:

Use RESET pulse
to anneal the box
and trap the vortex

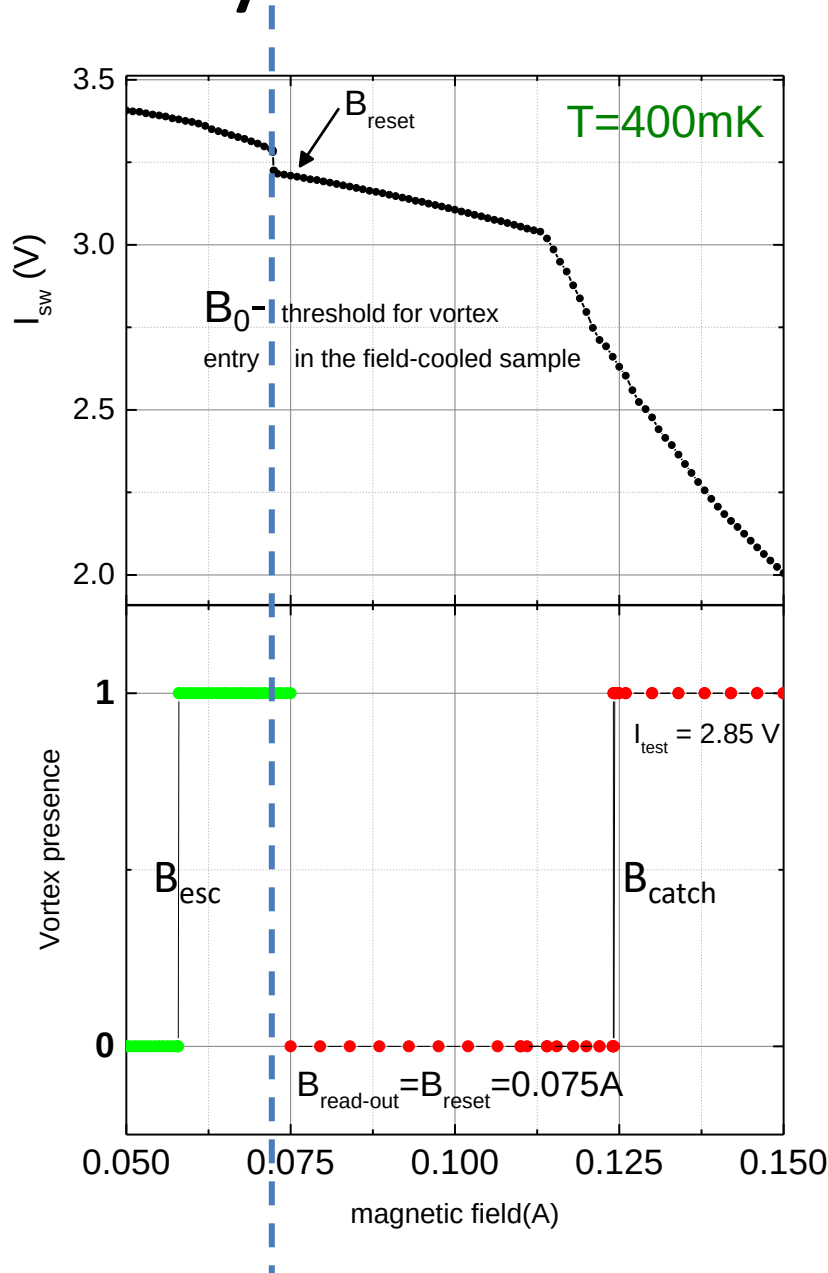


READ operation of the SVB



Bridge switches only if vortex is in the box !!!
(vortex-driven switching)

Stability of the vortex in magnetic field

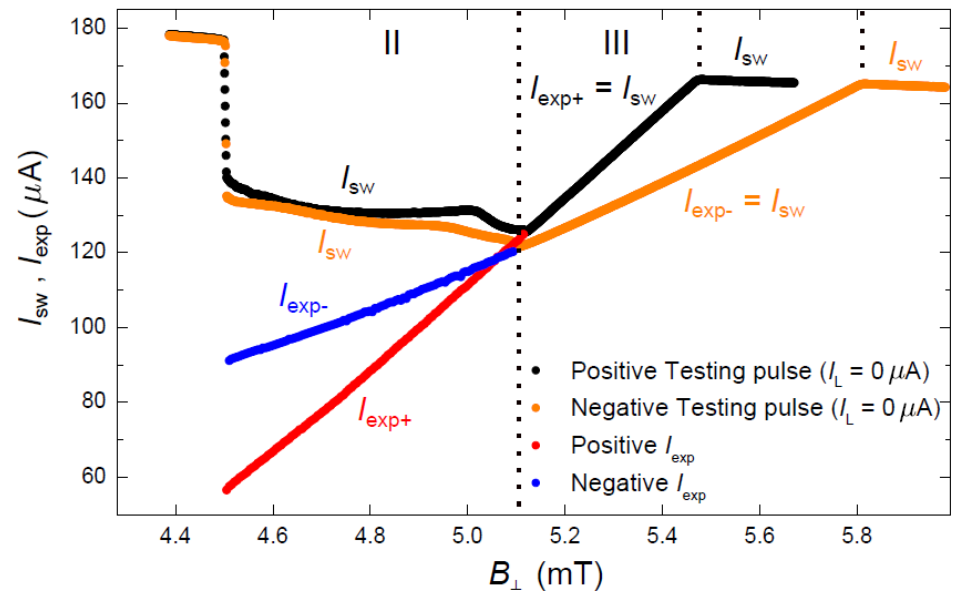
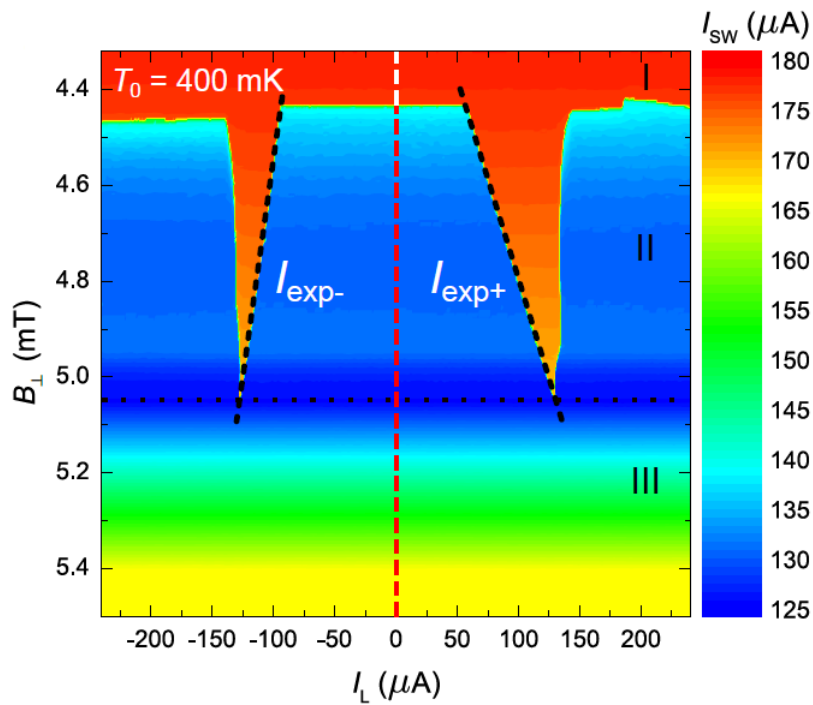


Protocol for testing the escape field B_{esc} :

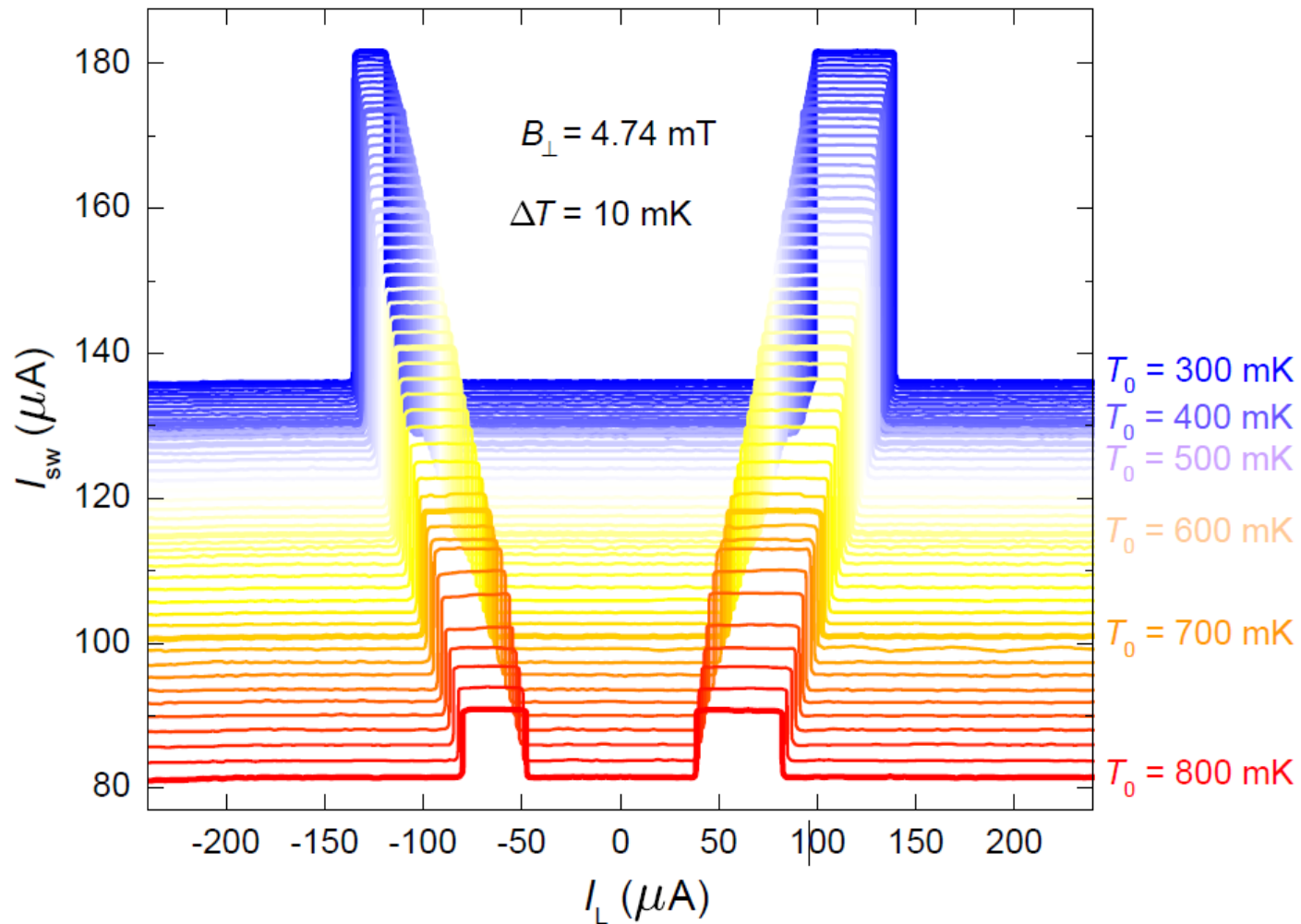
1. Anneal the box at $B_{reset} > B_0$
=> vortex trapped in the box
2. Lower field below B_0
=> vortex may escape
3. Come back to the initial field
 $B_{read-out} = B_{reset}$
4. Perform the single-shot read-out to verify the presence of the vortex in the box

Diode effect

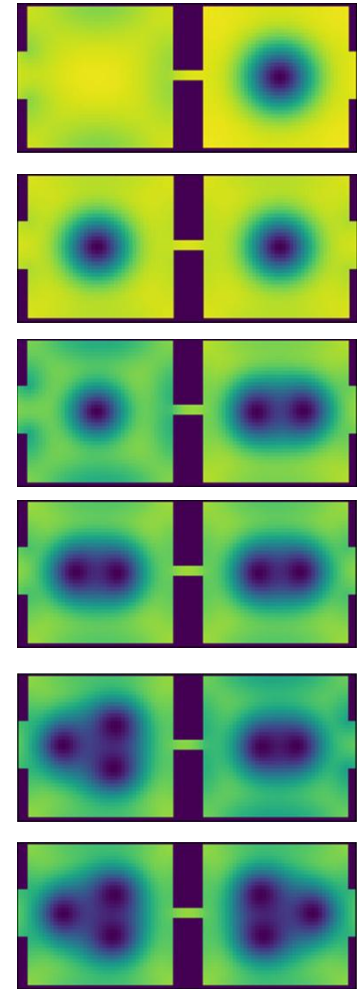
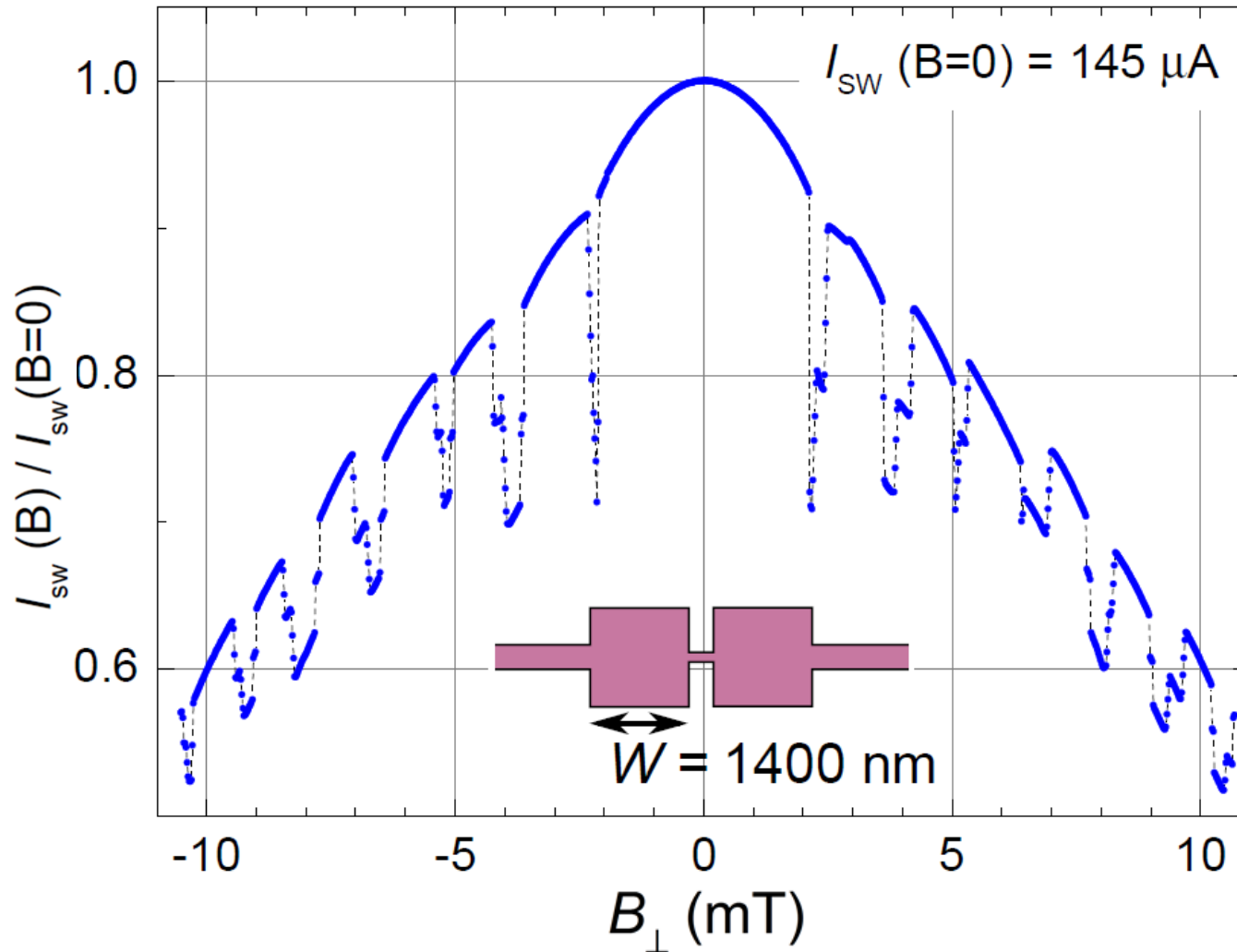
$$I_{exp+} \neq I_{exp-}$$



Vortex thermometry

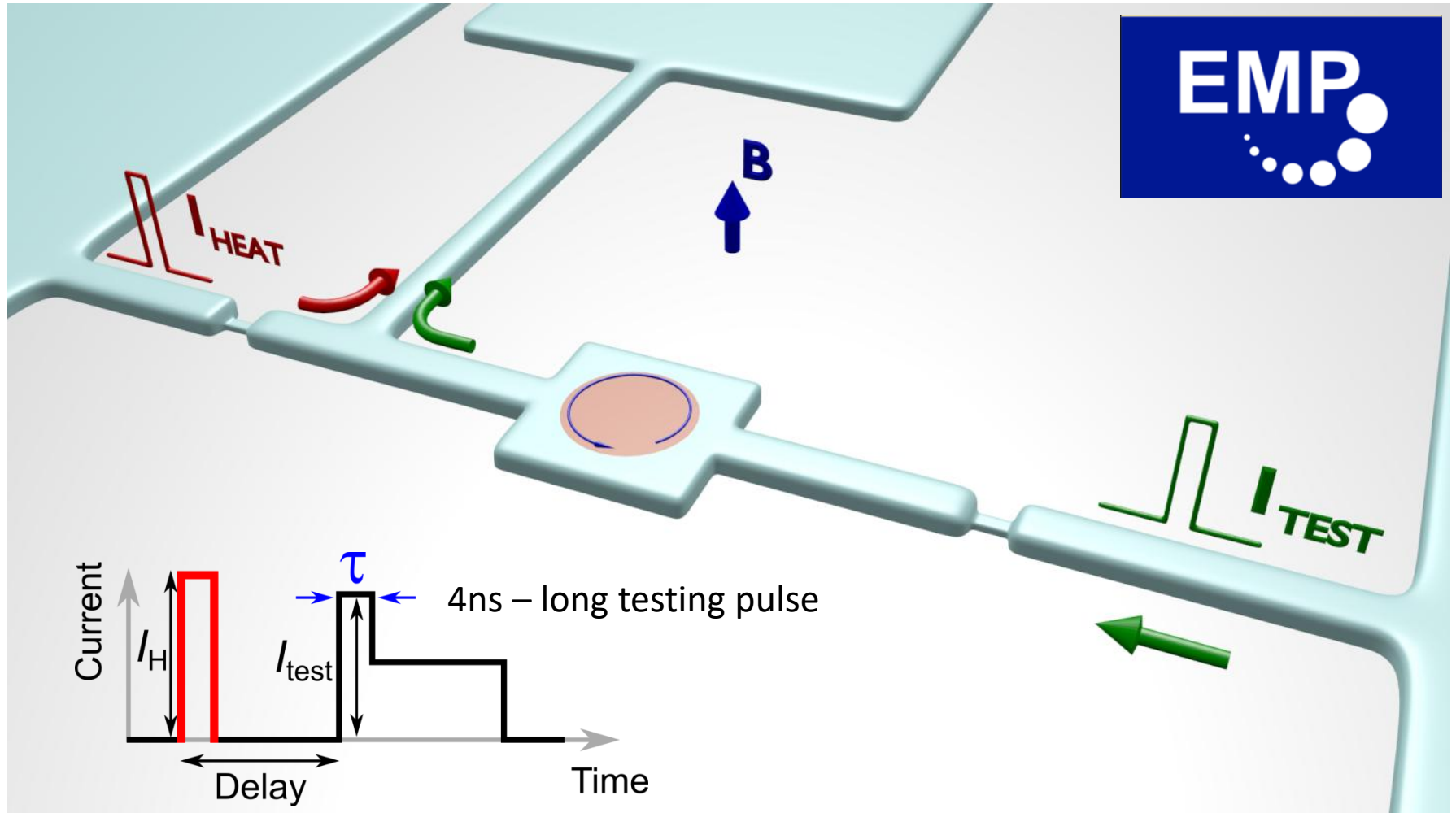


A single vortex detection

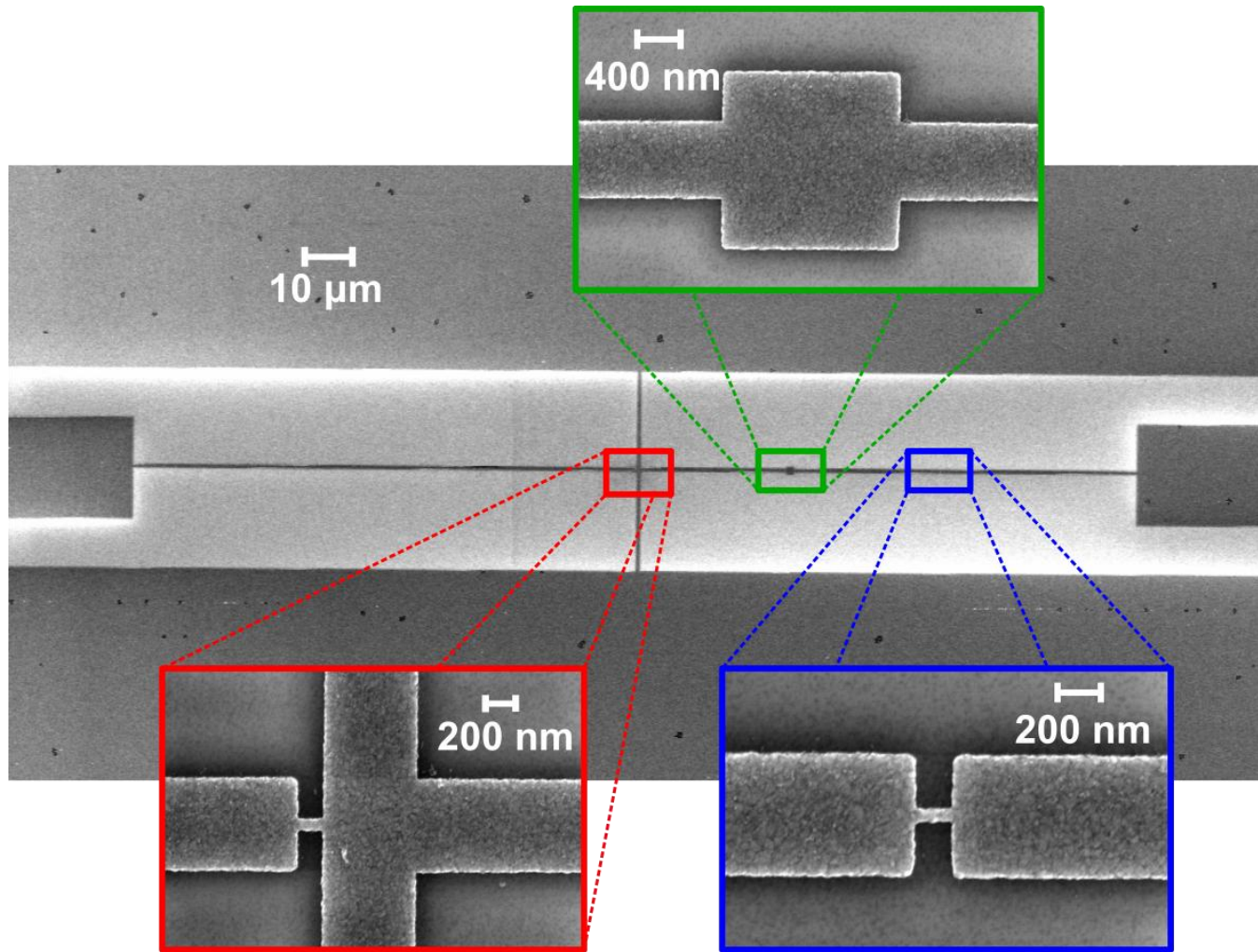


GL simulations by the theory group
of prof. M. Milošević
from Univ. Of Antwerp

Single Vortex Box as QPs trap



Sample

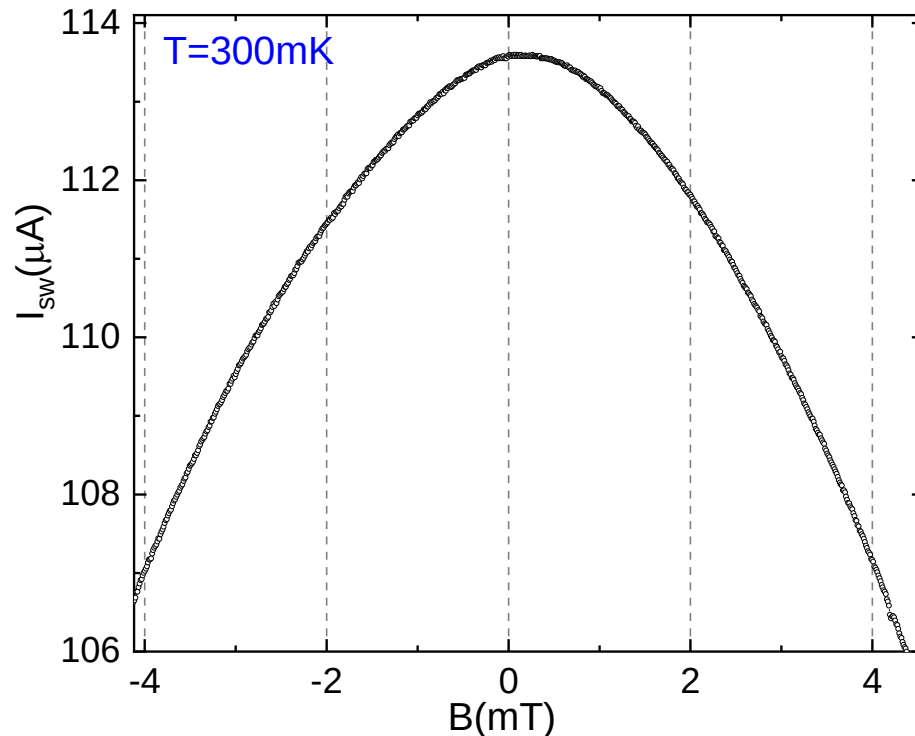


Sample design: M.Zgirski; Sample fabrication: J.Peltonen, Aalto Univ., Finland

Reference response of the QPs detector (No heating)

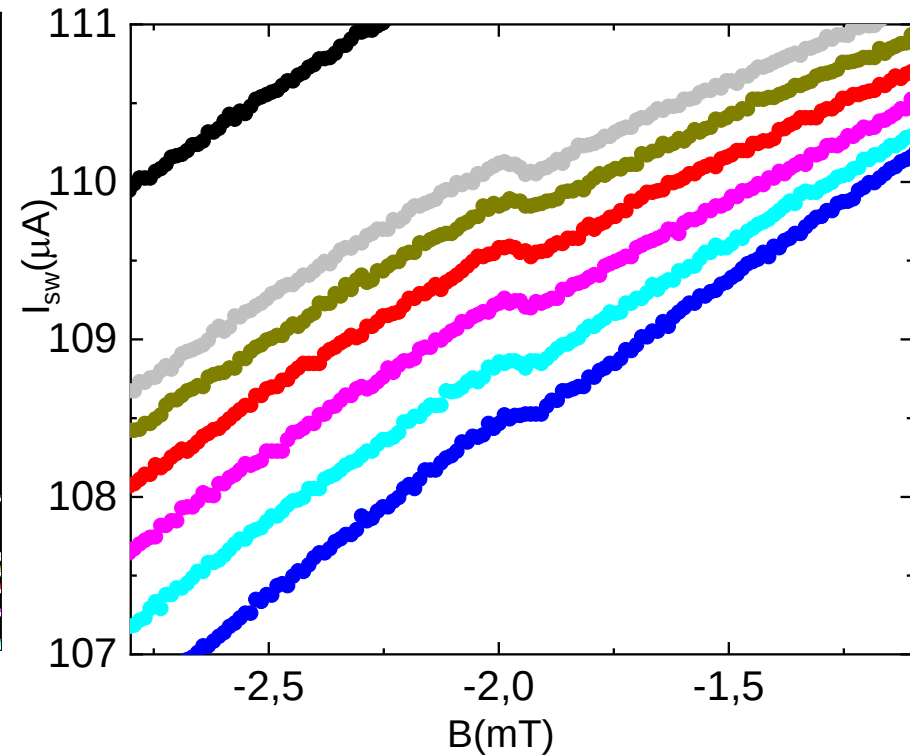
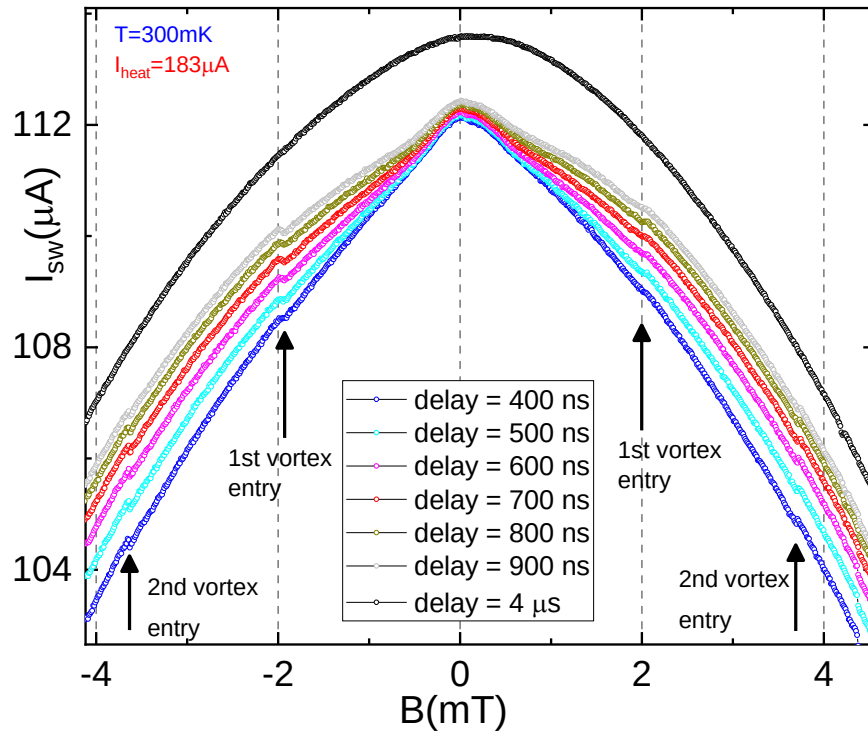
Suppression of I_c
in magnetic field.

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



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

Single vortex absorbs QPs

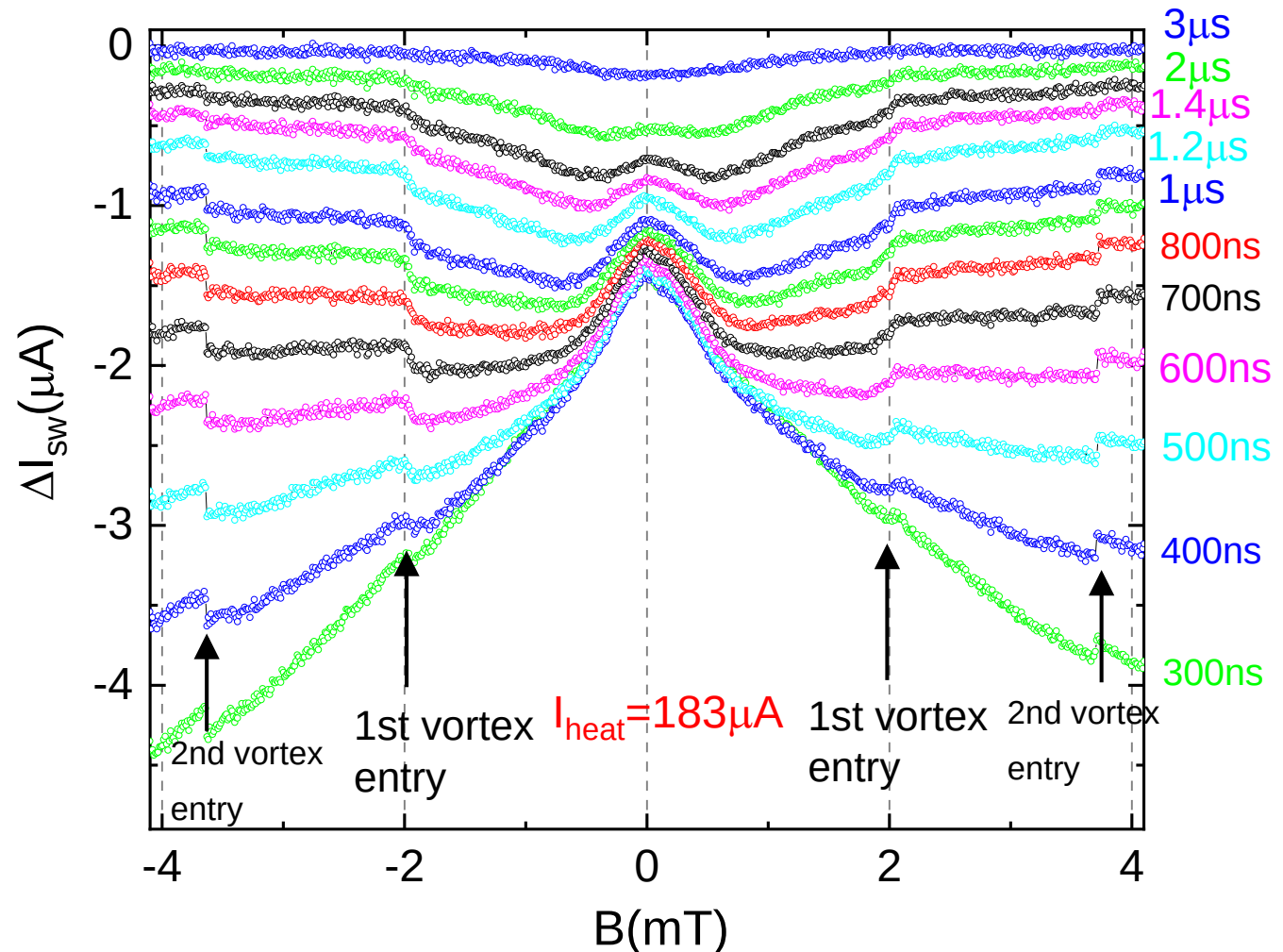


M. Foltyn, K. Norowski, J. Peltonen, A. Savin, M. Zgirski,
Caloritronics with a single superconducting vortex, in preparation

Single vortex absorbs QPs

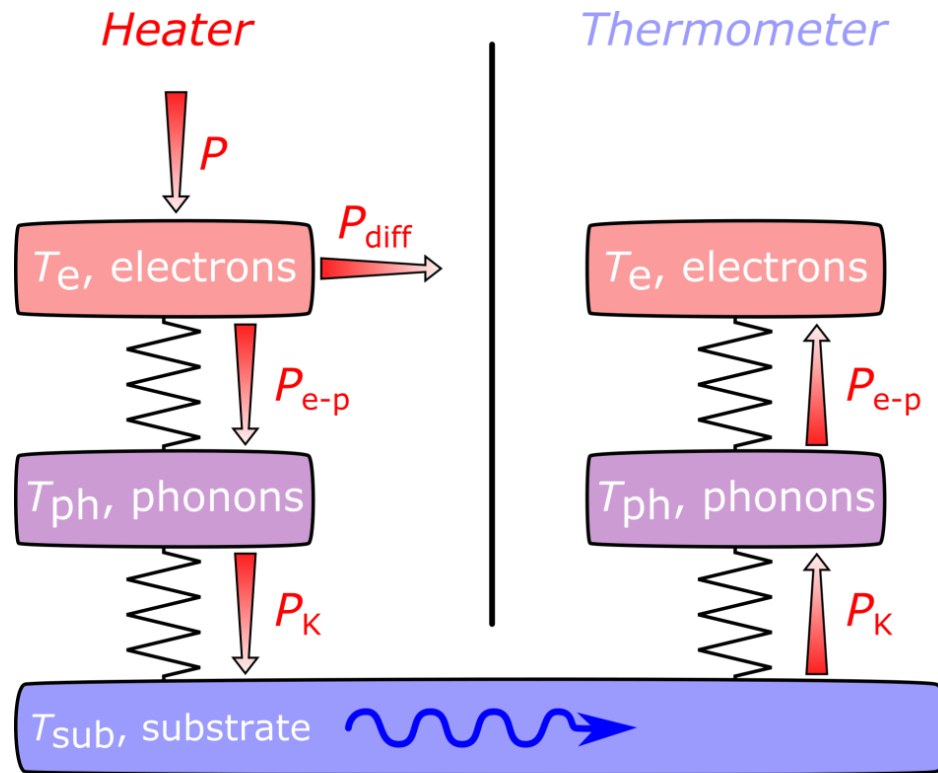
Suppression of I_c
due to hot QPs
arriving
from the heater.

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

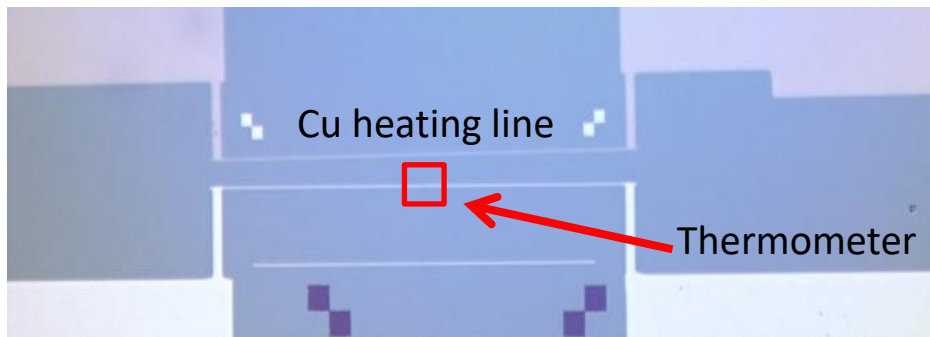
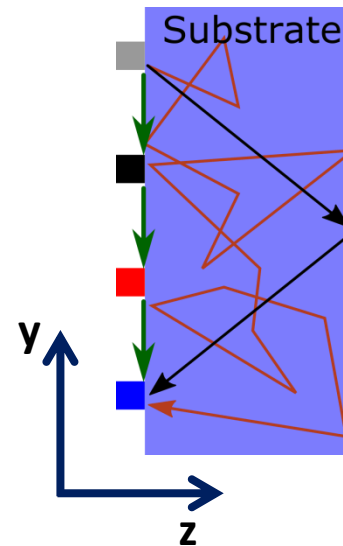
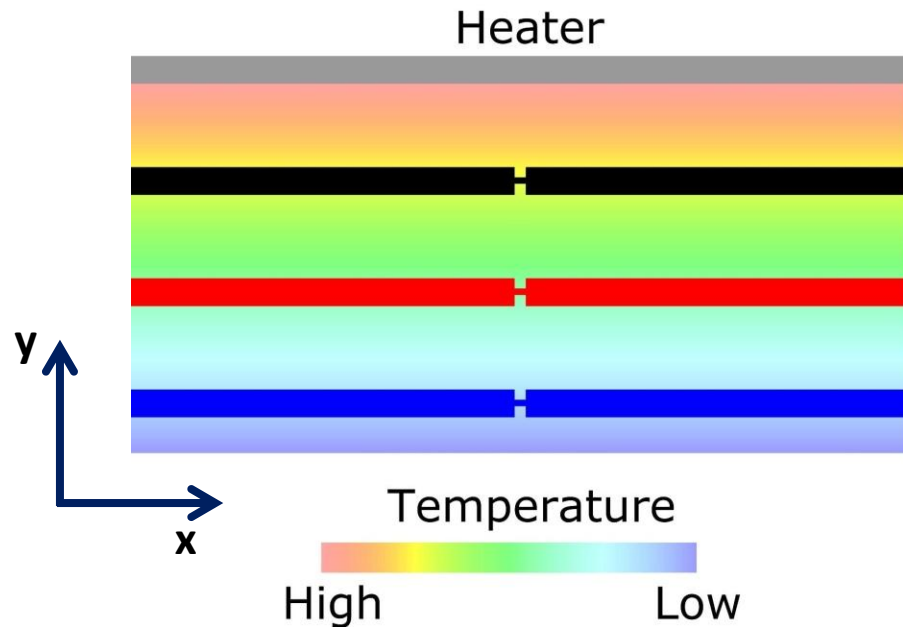


The kinks are fingerprints of the SINGLE VORTEX acting as a QP trap.
The vortex reduces flux of diffusing QPs,
which is visible as a smaller suppression of the switching current at the kink.

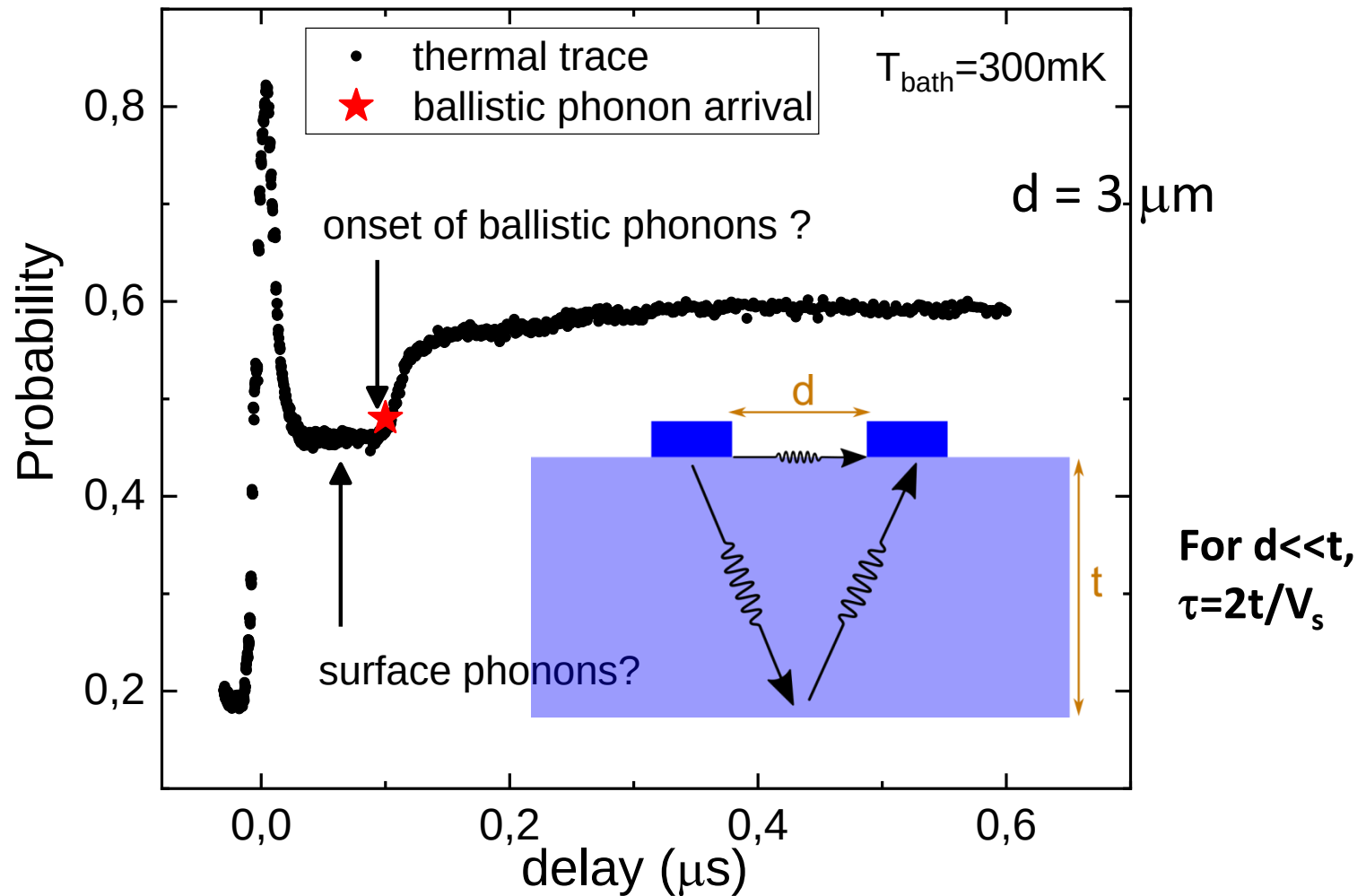
Phonon emission channel in an insulating substrate



Are phonons ballistic or diffusive?



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



$V_s = 5850\text{m/s}$ (speed of sound in Si, transversal wave), $t = 300\text{ }\mu\text{m}$, $d = 3\text{ }\mu\text{m}$

$$\Rightarrow \tau = \frac{2 \cdot t}{V_s} = 100\text{ns}$$

Unpublished

Coolphon Group:



Marek Foltyn, IF PAN



Mujeeb Ahmed, IF PAN



Konrad Norowski, IF PAN

Collaboration:



Alexander Savin,
LTL, Aalto Univ.

Watch us at:

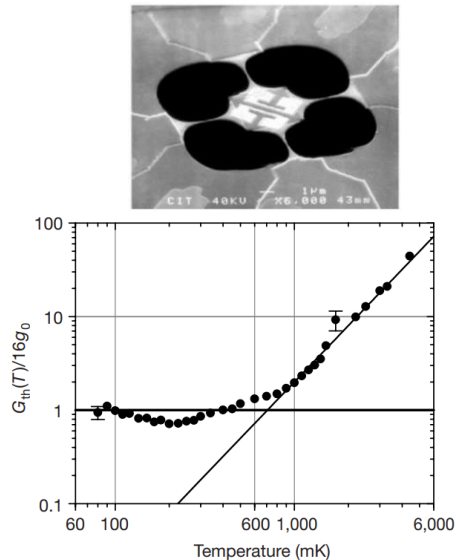
<http://coolphongroup.ifpan.edu.pl>

Relevant publications

1. K. Norowski, M. Foltyn ,A. Savin, M. Zgirski, *Intrinsic Quasiparticle Lifetime in a Superconducting Aluminum*, **Phys. Rev. B** **113**, 214512 (2026)
2. M. Foltyn, K. Norowski, A. Savin, M. Zgirski, *Quantum thermodynamics with a single superconducting vortex*, **Science Advances** **10**, eado4032 (2024)
3. M. Foltyn, K. Norowski, M. Wyszynski, 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)

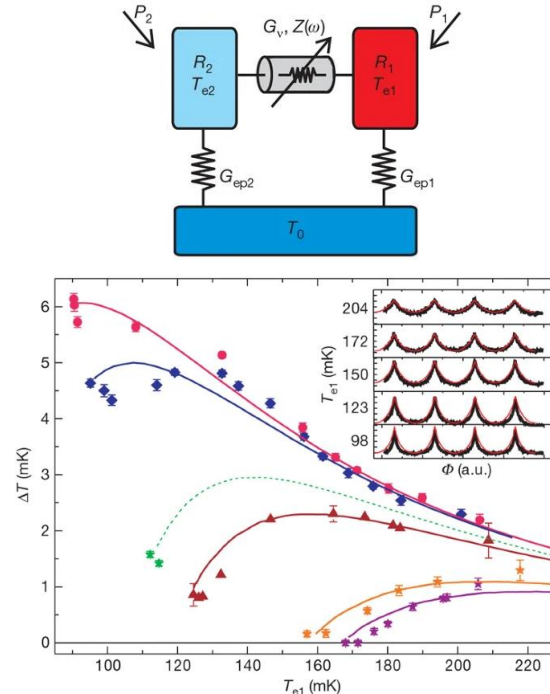
Quantum thermodynamics

Single phonon heat transfer



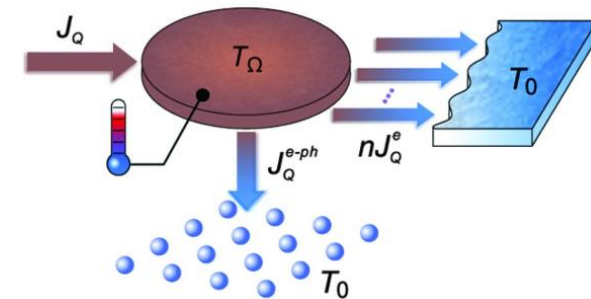
K. Schwab, E. A. Henriksen,
J. M. Worlock, M. L. Roukes,
Nature **404**, 974–977 (2000)

Black body radiation on chip



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

Single electronic channel heat transfer

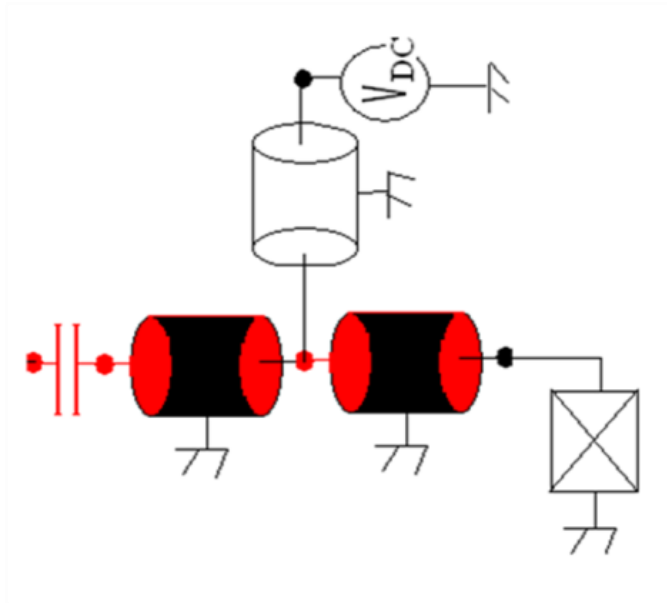
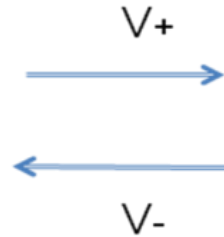


S. Jezouin, F. D. Parmentier,
A. Anthore, U. Gennser,
A. Cavanna, Y. Jin, F. Pierre,
Science **342**, 601-604 (2013)

RF on-chip thermometry

Reflectometry

$$\Gamma_R = \frac{Z_R - Z_0}{Z_R + Z_0}$$



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

Temporal measurement of hot-electron relaxation in a phonon-cooled metal island,

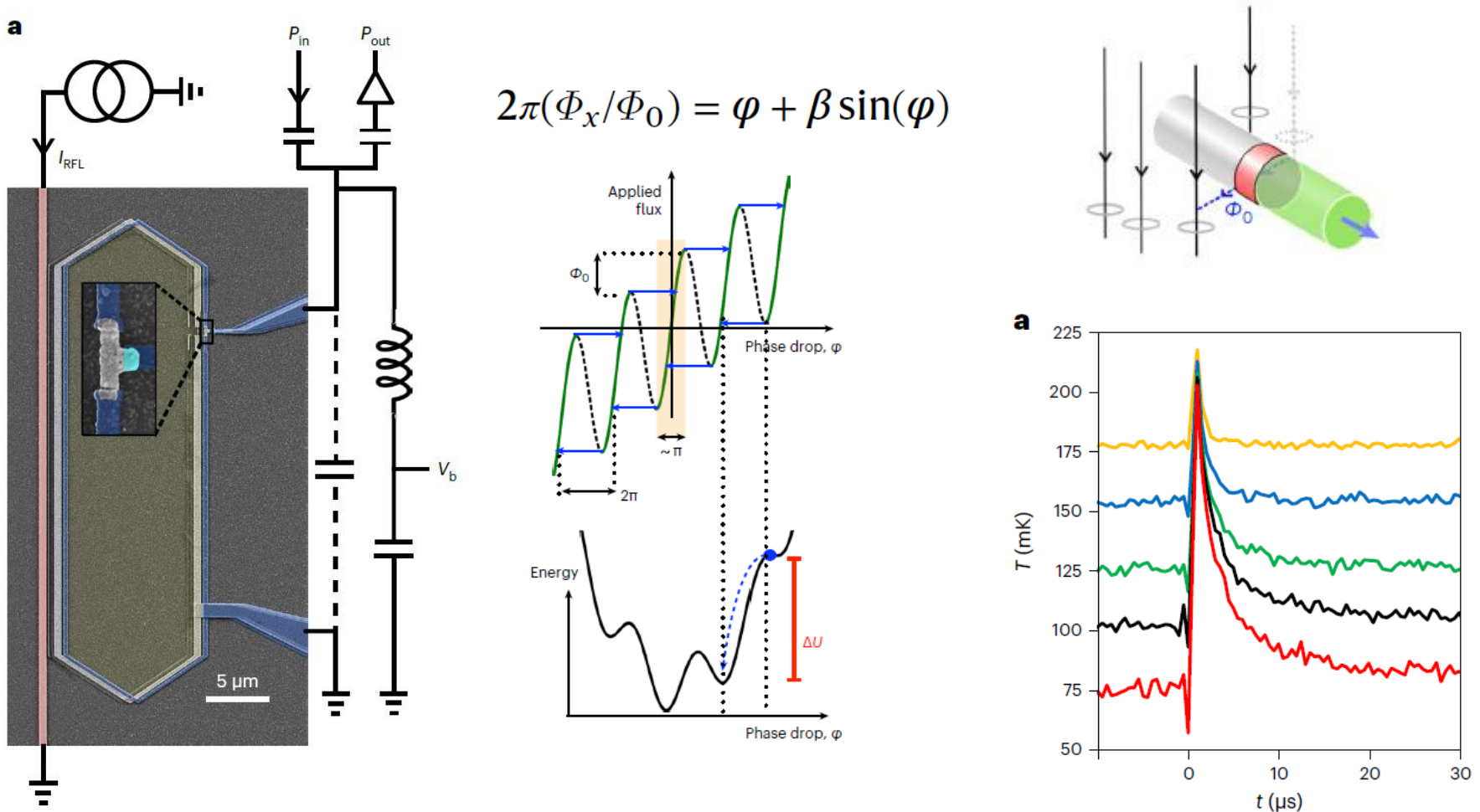
Phys. Rev. B 69, 140301 (2004)

O.-P. Saira, **M. Zgirski**, K.L. Viisanen, D.S. Golubev, and J.P. Pekola

Dispersive thermometry with a Josephson junction coupled to a resonator

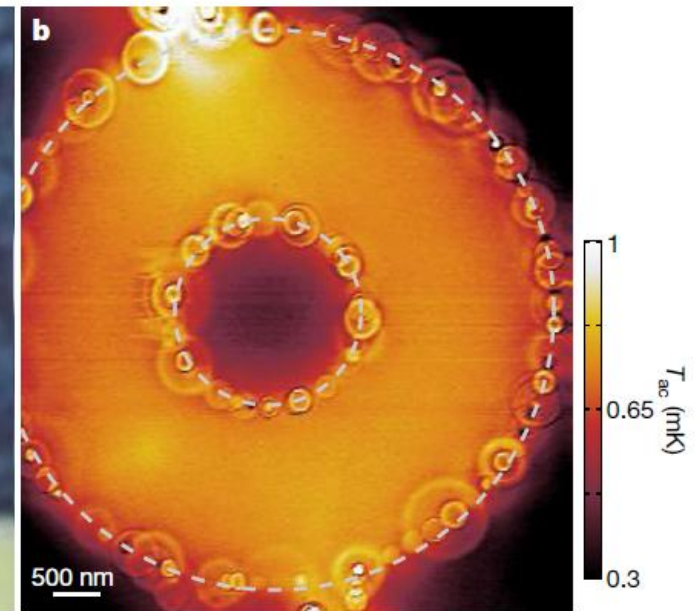
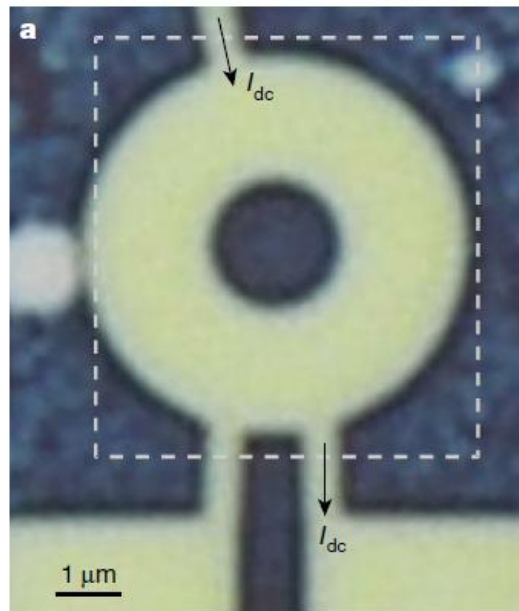
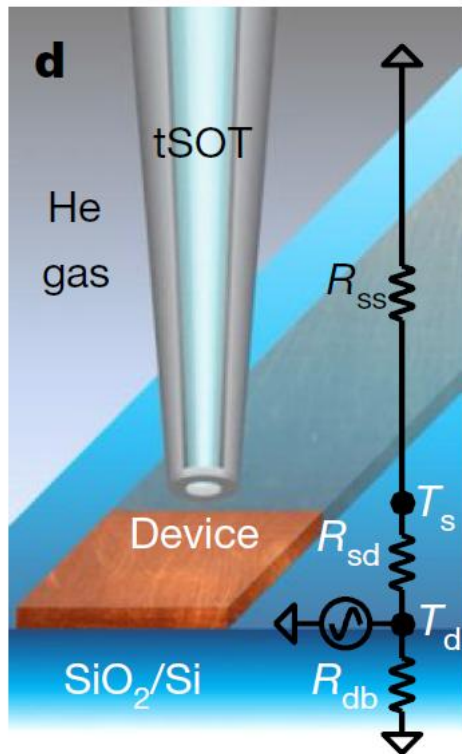
Phys. Rev. Appl. 6, 024005 (2016)

Heating due to a phase slip (example 2)



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

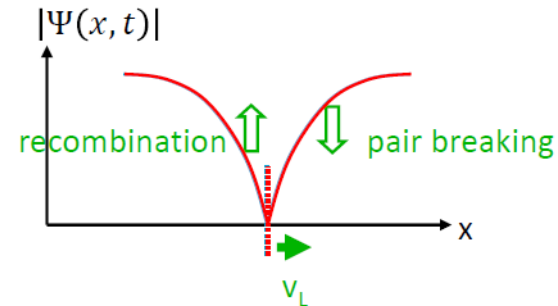


6.2.2 Depinning Critical Current Density

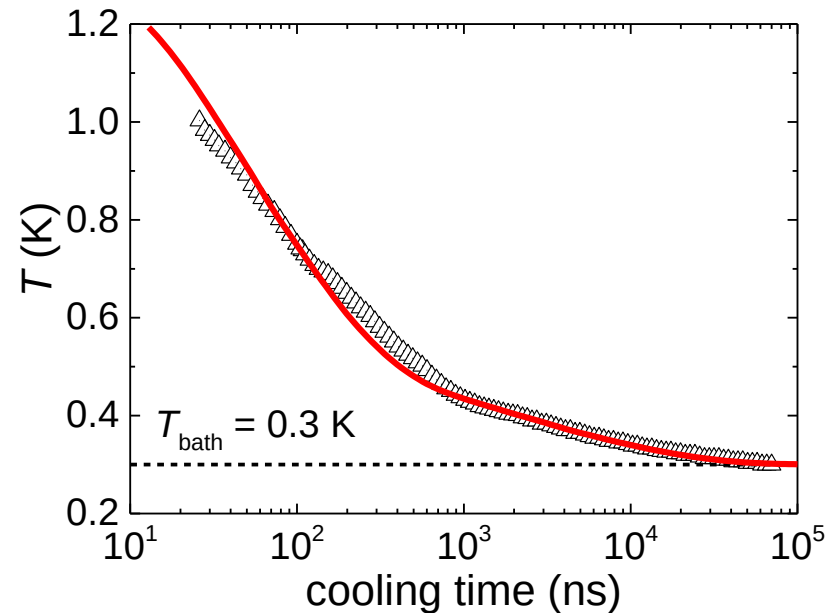
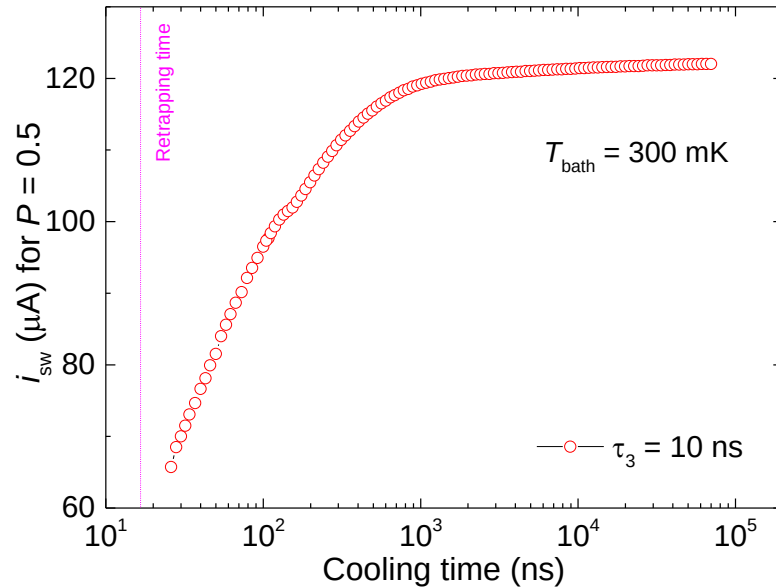
power dissipation during vortex motion:

a. pair breaking and recombination:

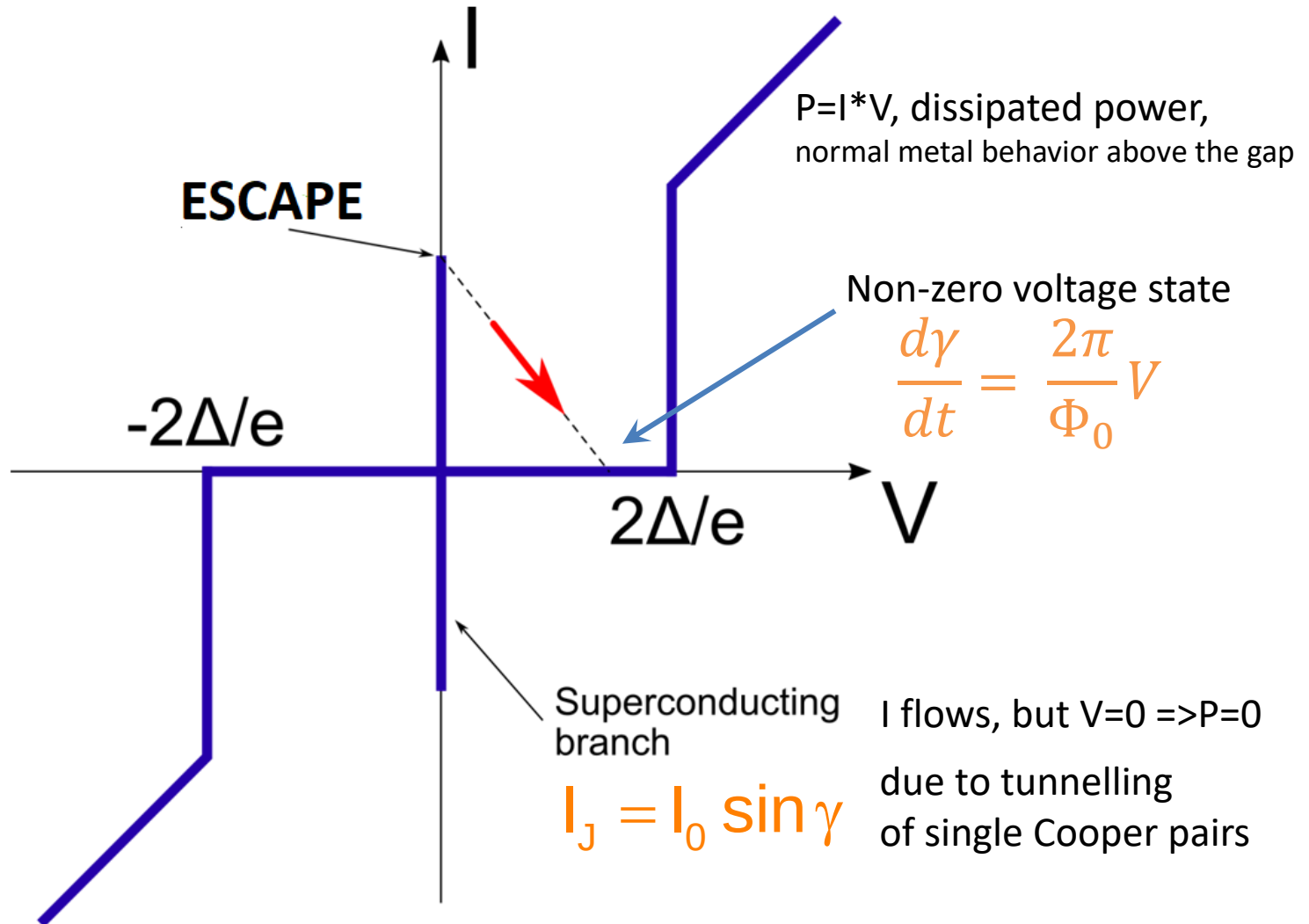
- in front of flux-line: $|\Psi|$ decreases
 $\Rightarrow$ pairs have to break up
- pair breaking due to absorption of phonons:
- behind the flux-line: $|\Psi|$ increases
 $\Rightarrow$ recombination of pairs by phonon emission:
- finite phonon lifetime delays thermal equilibrium:
- irreversible process $\rightarrow$ friction, viscous flow***
- electric energy is transferred to heat



Thermal relaxation of superconducting wire

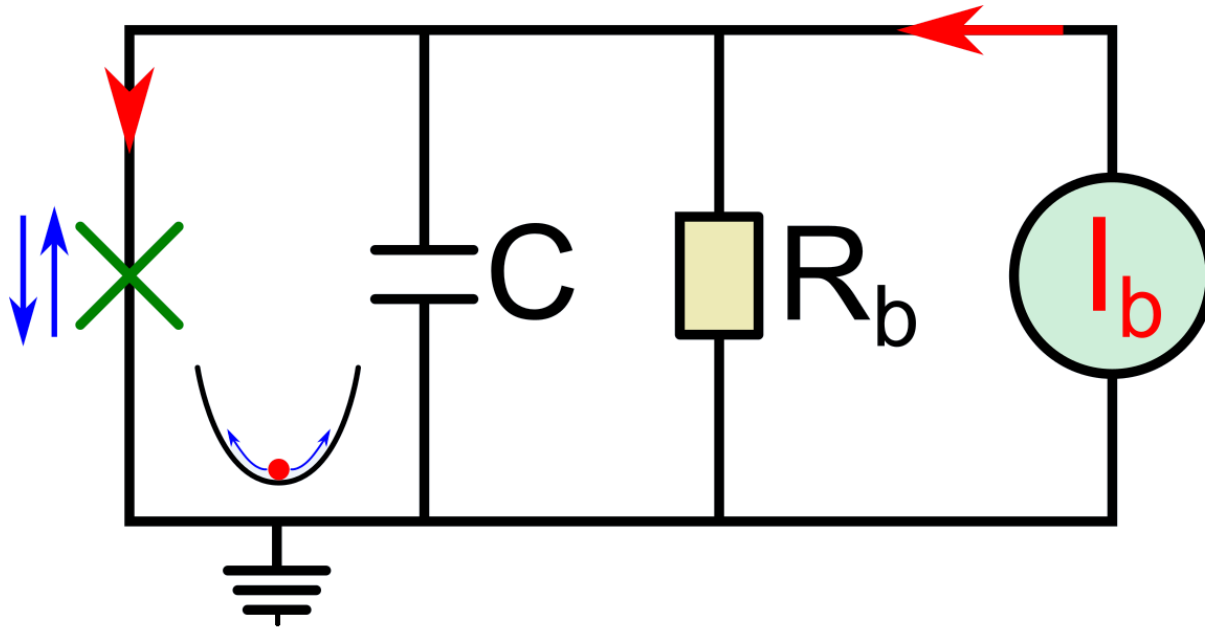


Metastable state of the junction



RCSJ model

(Resistively and Capacitively Shunted Junction)



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

RCSJ model

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

2nd Josephson formula $\dot{\gamma} = \frac{1}{\varphi_0} \cdot V$

$$I_b = \frac{\varphi_0}{R} \dot{\gamma} + C \varphi_0 \ddot{\gamma} + I_0 \sin \gamma$$

$$m = C \varphi_0^2, \quad \omega_0 = \left(\frac{I_0}{C \cdot \varphi_0} \right)^{1/2}, \quad b = \frac{\varphi_0^2}{R}, \quad Q_0 = \frac{\omega_0}{b/m} = RC \omega_0, \quad k = \varphi_0 I_0 = E_J$$

$$\ddot{\gamma} + \frac{\omega_0}{Q_0} \dot{\gamma} + \omega_0^2 \left(\sin \gamma - \frac{I_b}{I_0} \right) = 0$$

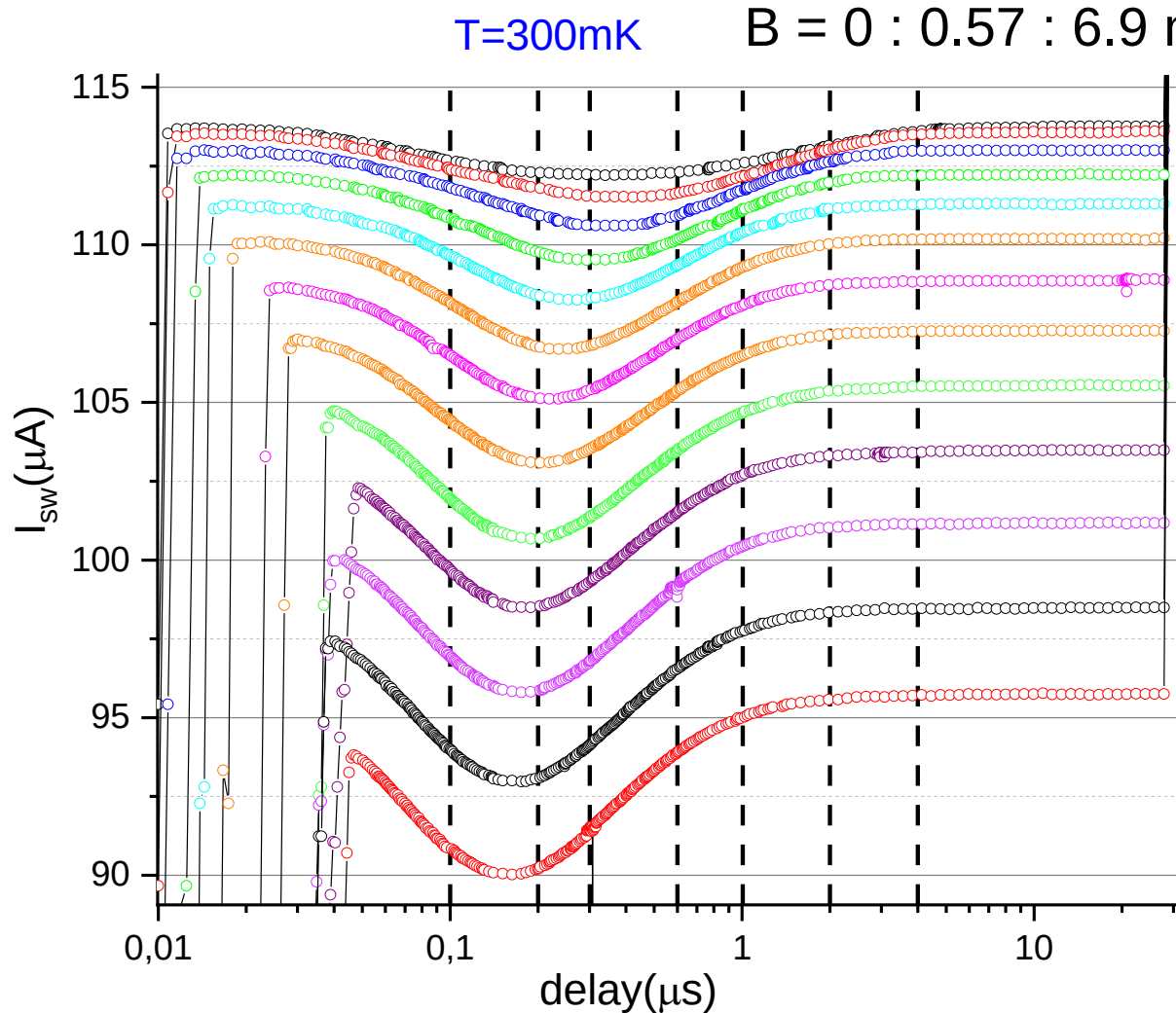
It looks like harmonic oscillator,

but now restoring force is not $-k\gamma$ (as in the Hook's law), but:

$$F = -k \left(\sin \gamma - \frac{I_b}{I_0} \right) = -\nabla E_p$$

$$E_p = +k \int \left(\sin \gamma - \frac{I_b}{I_0} \right) d\gamma = -E_J \left(\cos \gamma + \frac{I_b}{I_0} \gamma \right) \quad \text{tilted washboard potential}$$

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

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

Parameters:

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}

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

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

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

Phys. Rev. B **58**, 8225 (1998)

Parameters:

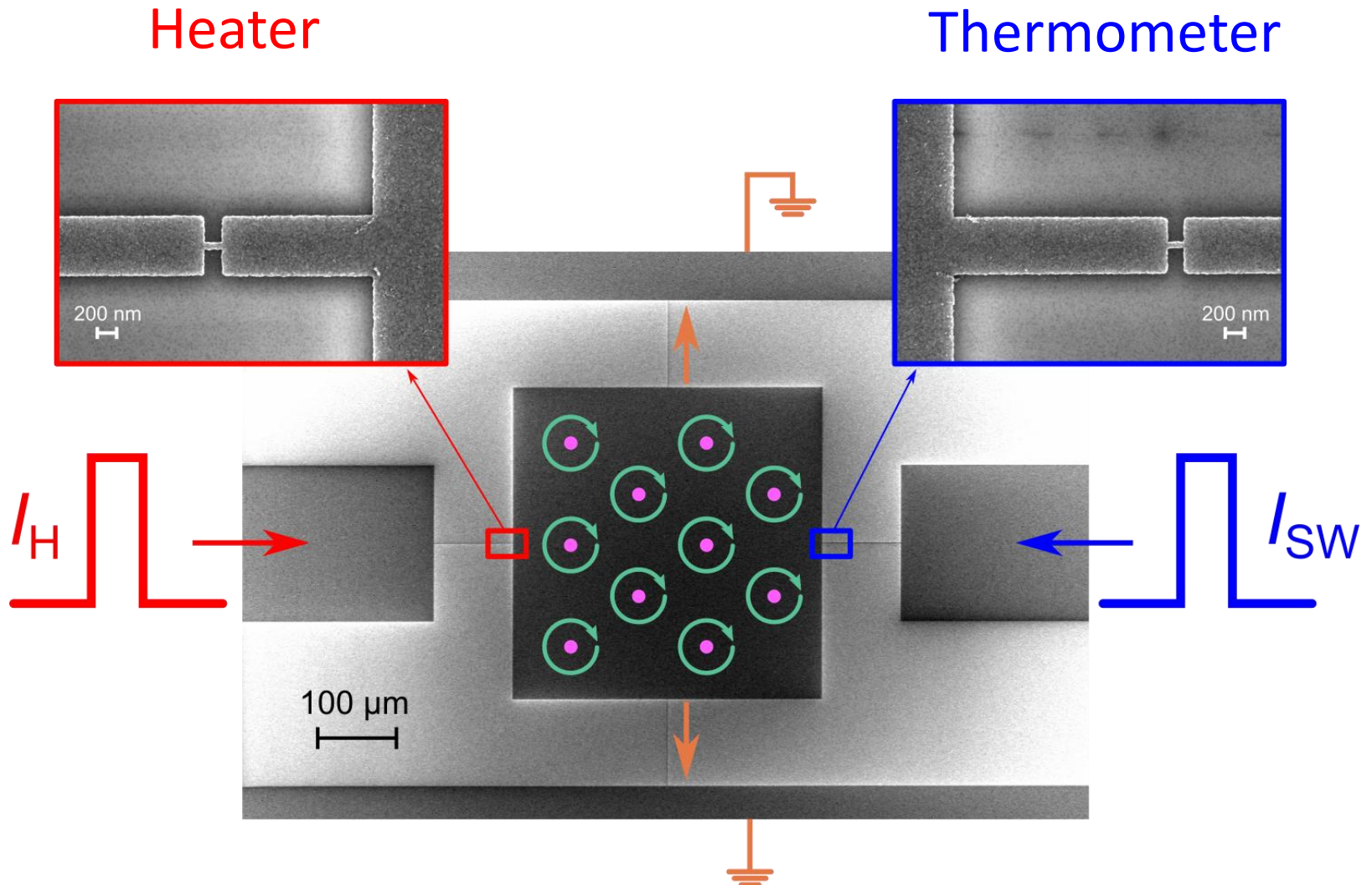
recombination rates Γ ,

diffusion constant D

should be in principle E-dependent,

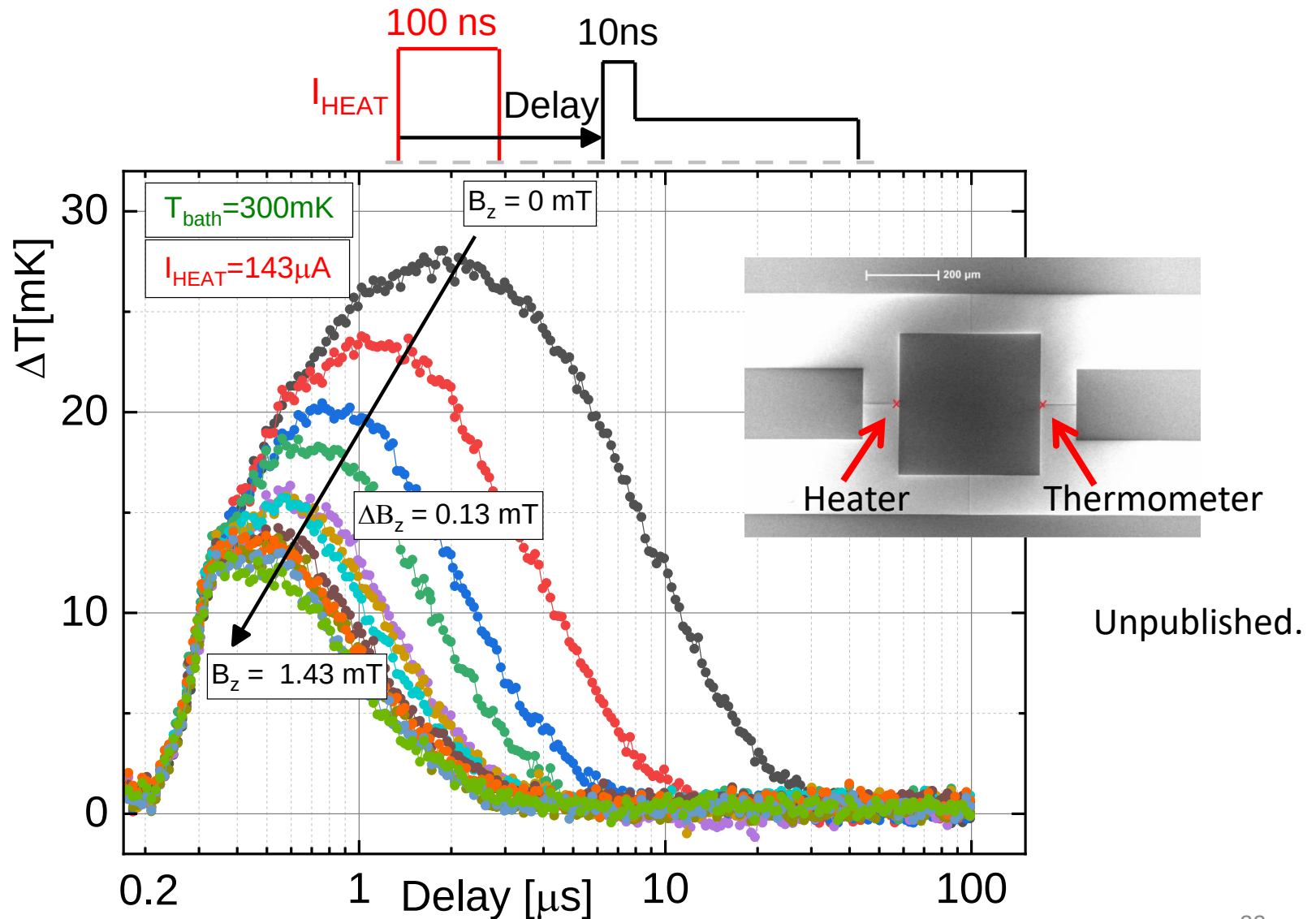
If not, we get a simplified
phenomenological equation

Quasiparticle annihilation

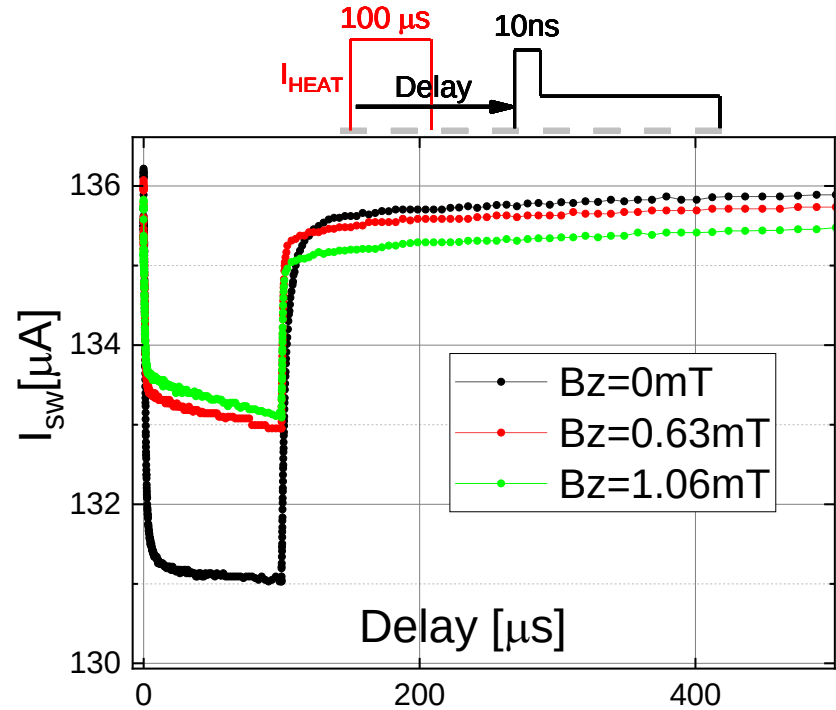
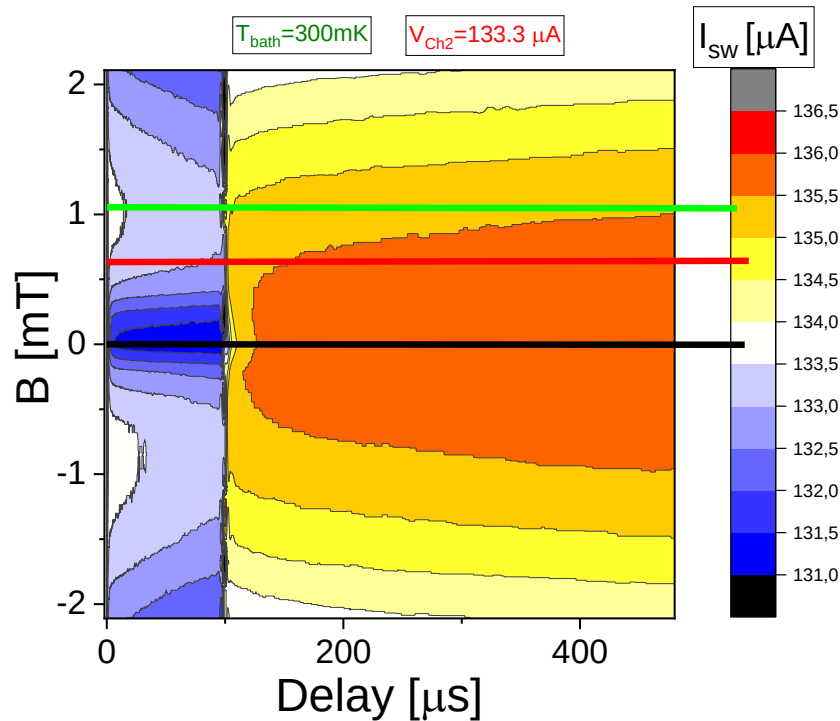


Sample design: M.Zgirski; Sample fabrication: J.Peltonen, Aalto Univ., Finland

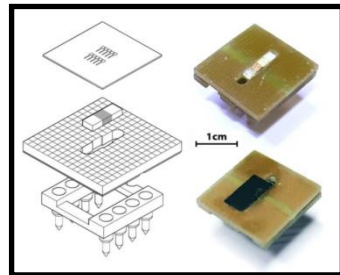
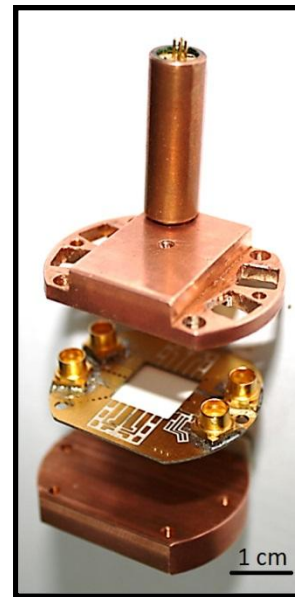
Quasiparticle annihilation



Steady state suppression



Unpublished.



Lab

