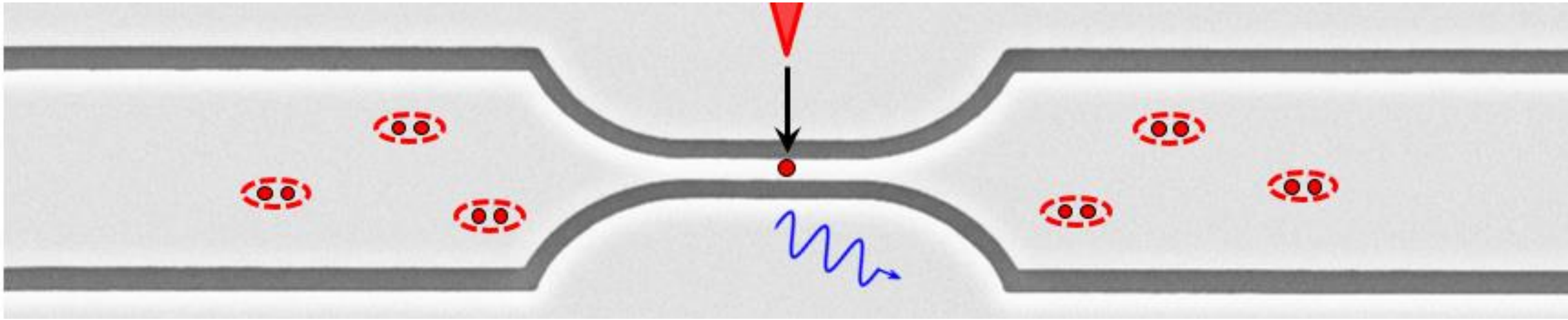
Scanning Critical Current Microscopy on an out-of-equilibrium superconducting nanowire



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Frédéric Gustavo
Jean-Luc Thomassin
Claude Chapelier

The team

Florence Levy-Bertrand

Eduard Driessen

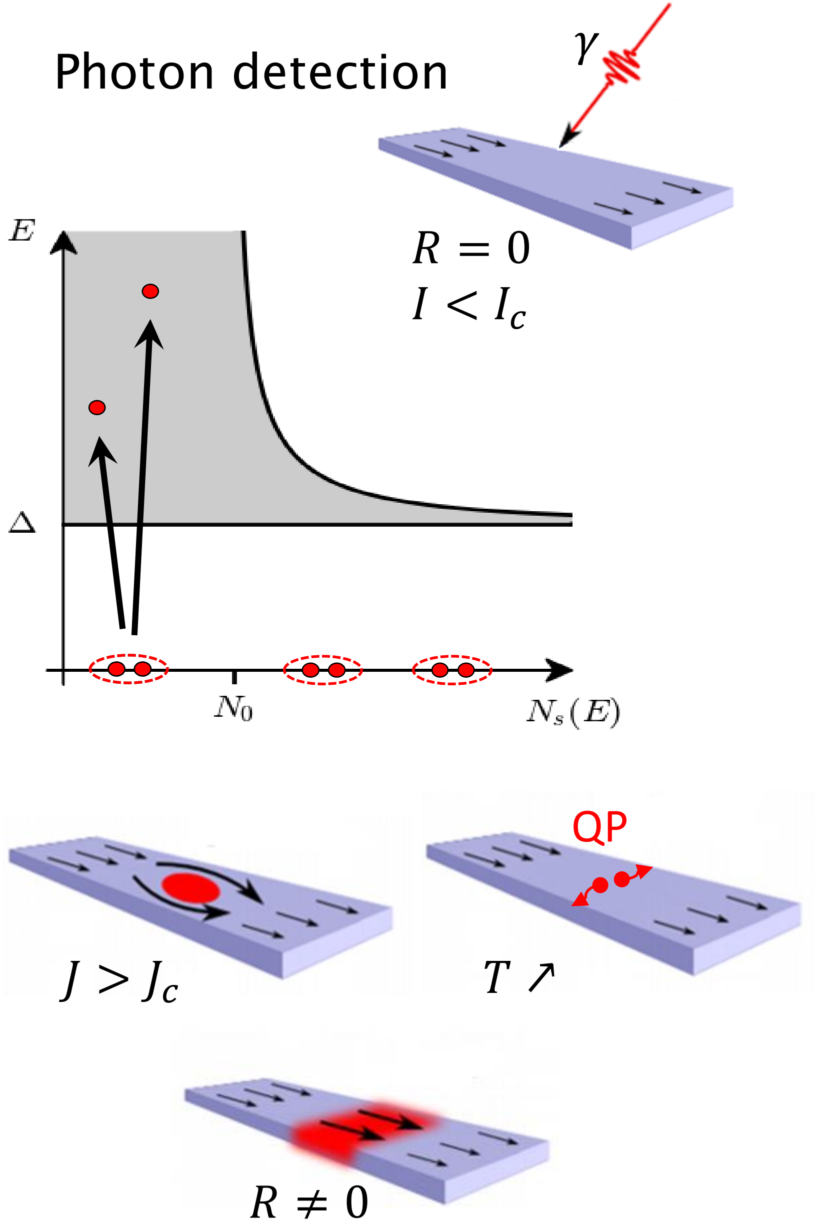
Thomas Jalabert

Frédéric Gustavo

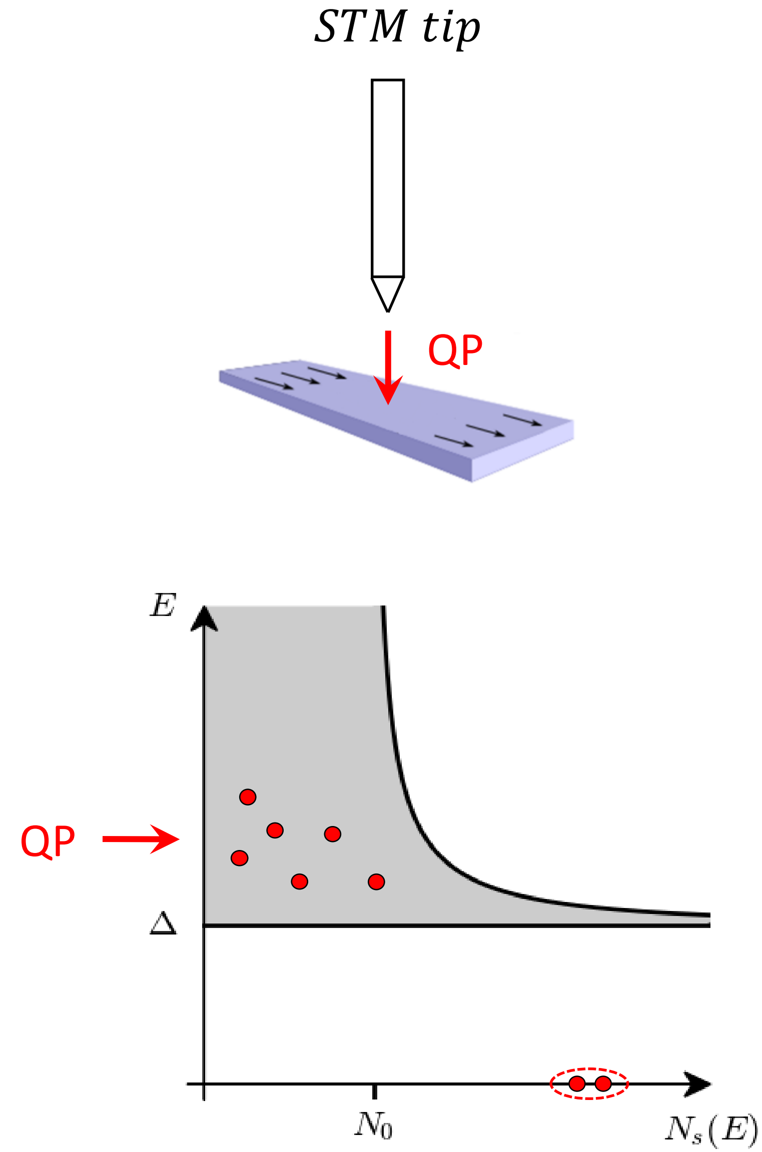
Jean-Luc Thomassin

Superconducting Nanowire Single Photon Detector

Photon detection



Direct injection of quasiparticles



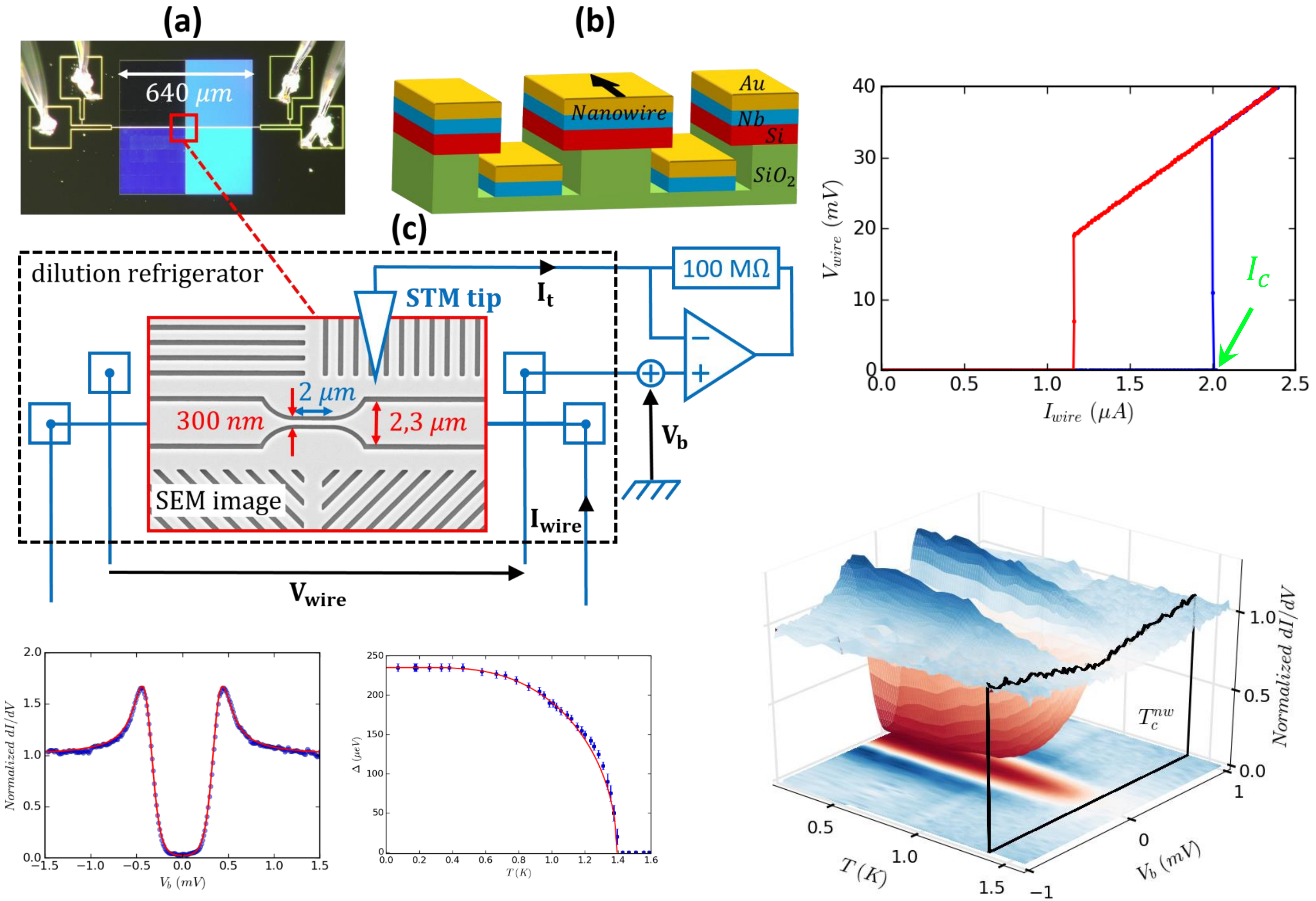
Renema, J. J. et al. *Phys. Rev. Lett.* (2014).

Outline

1 – High energy quasiparticles injection

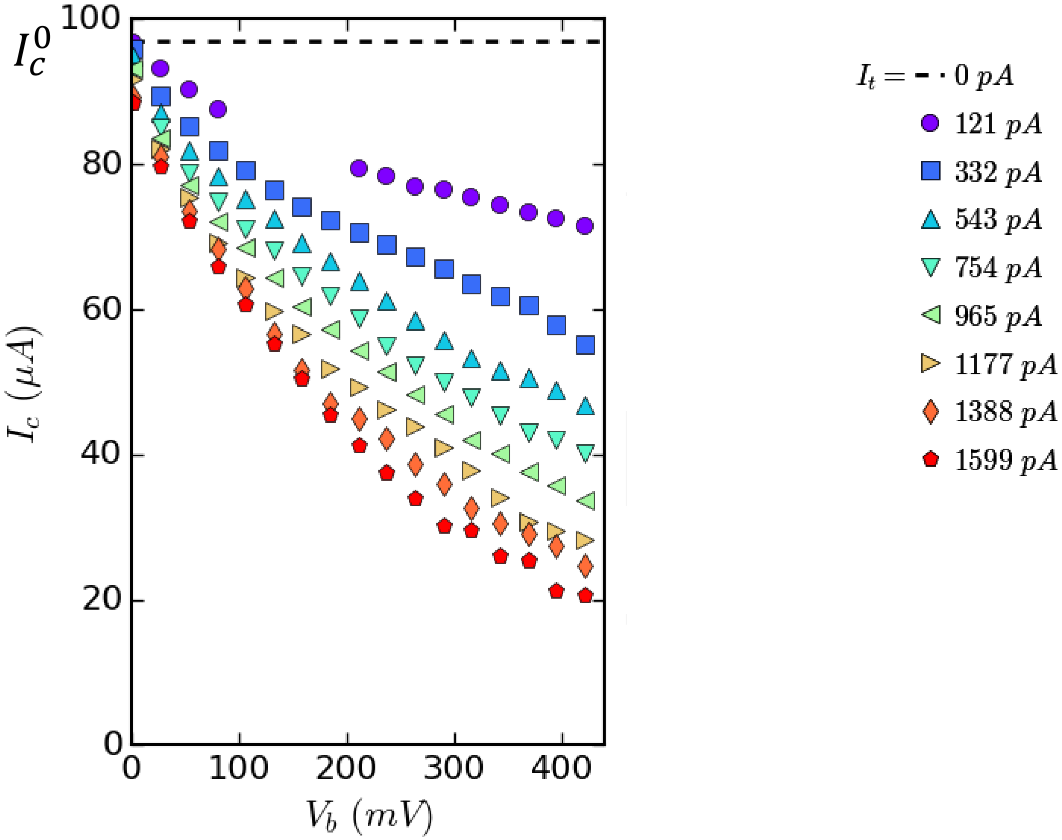
T. Jalabert, et al., Nat. Phys. (2023)

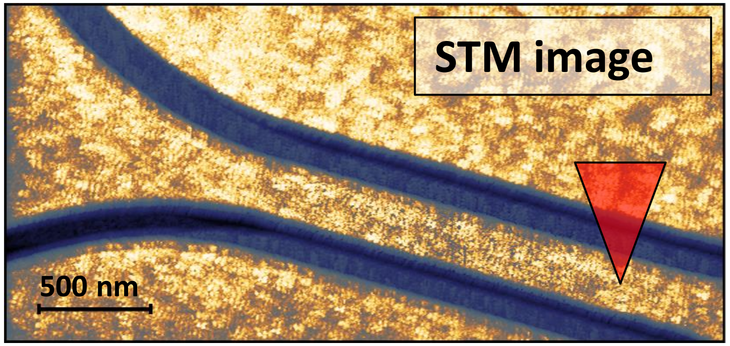
2 – Low energy quasiparticles injection

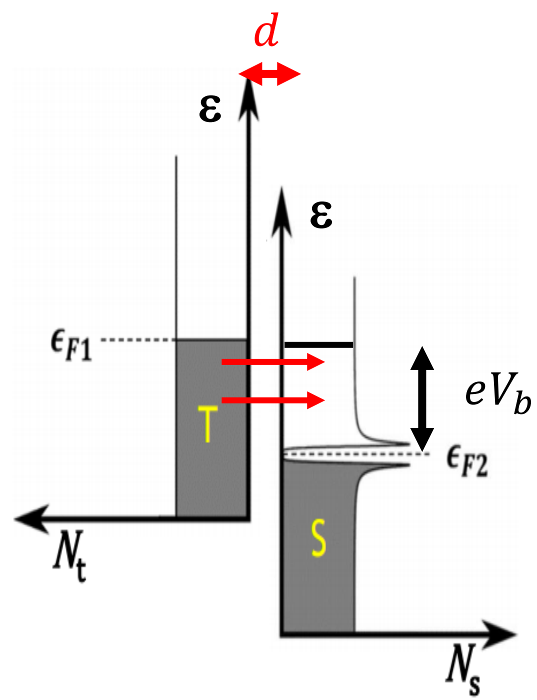


(a)
640 μm
(b)
Au
Nanowire
Nb
Si
SiO2
(c)
dilution refrigerator
STM tip
It
100 MΩ
2 μm
300 nm
2,3 μm
SEM image
Vb
Iwire
Vwire
Ic
Vwire (mV)
Iwire (μA)
Normalized dI/dV
Vb (mV)
Δ (μeV)
T (K)
Tc^nw

Tuning the critical current

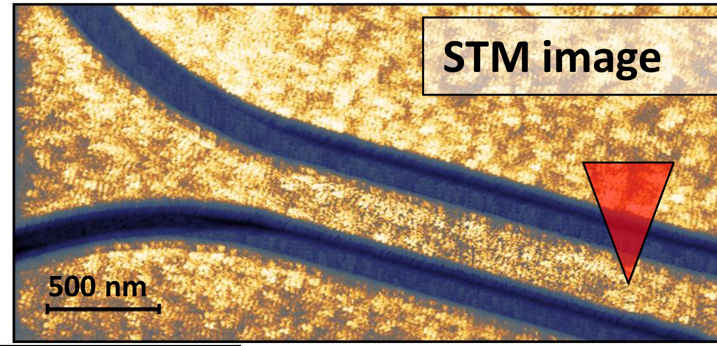


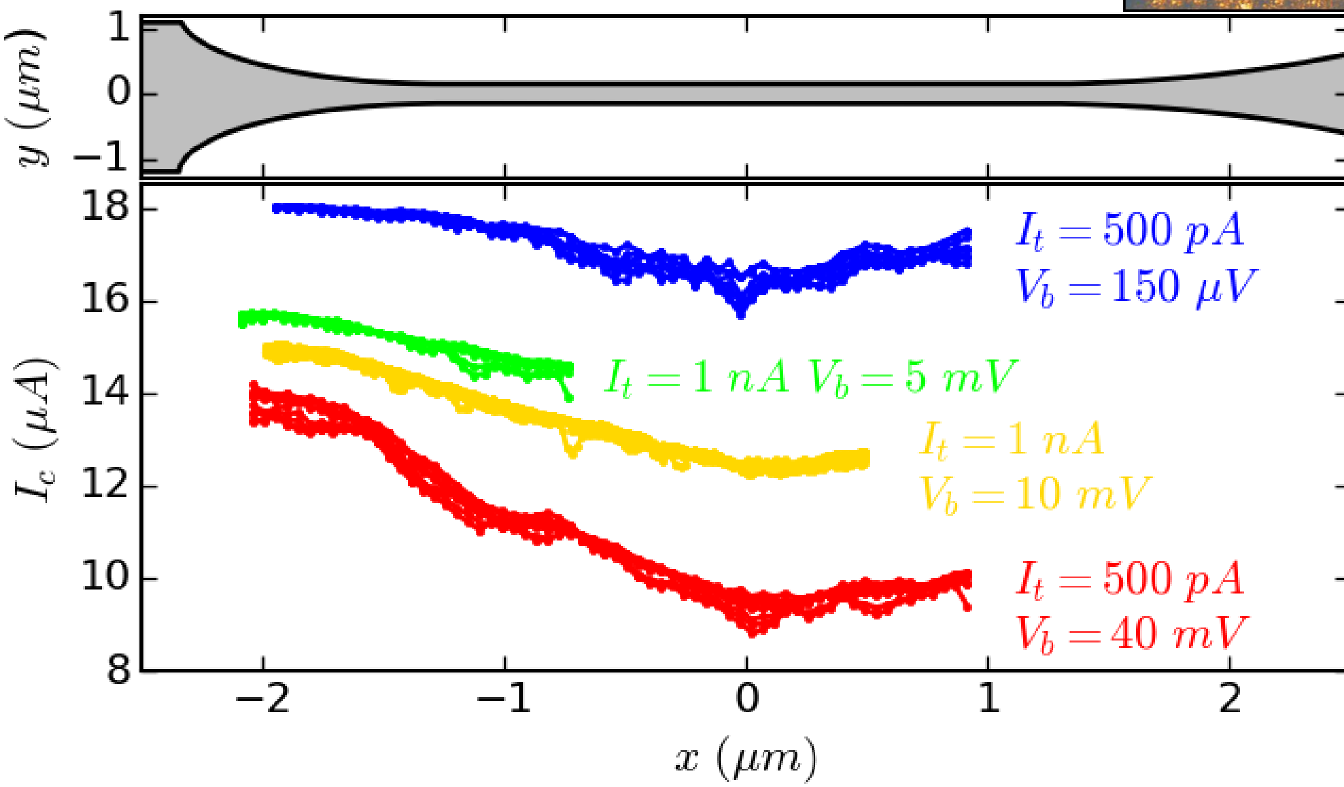


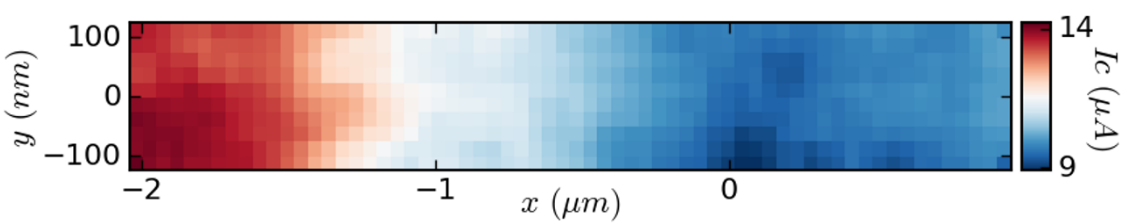


- $\frac{I_c}{I_t} \sim 10^6$

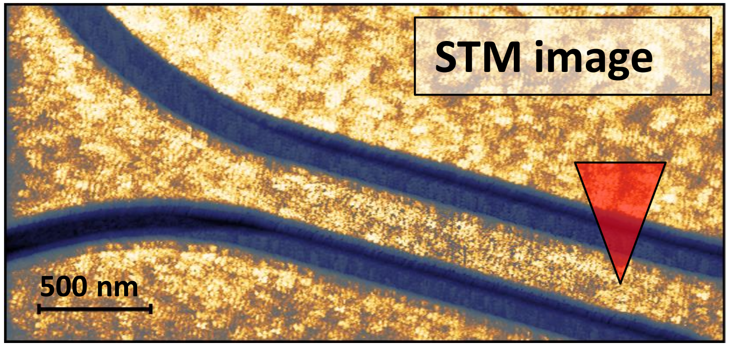
Mapping the local critical current

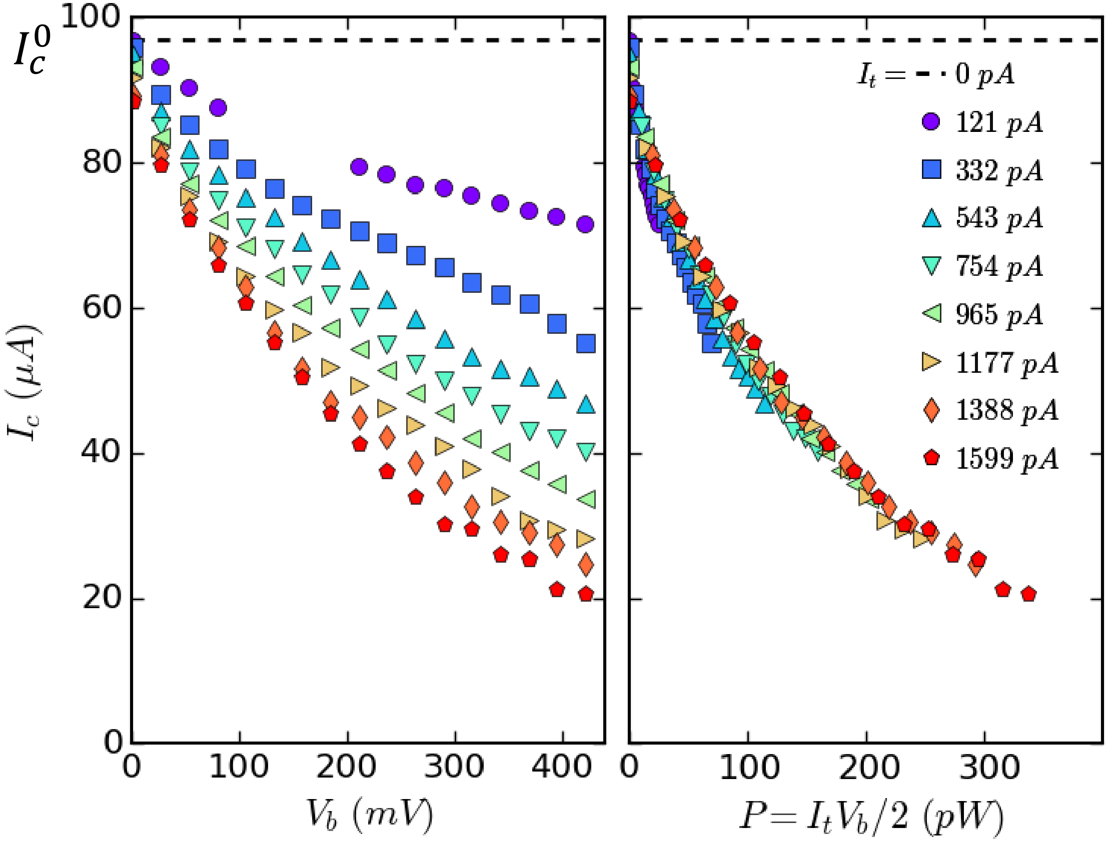






Power dependence

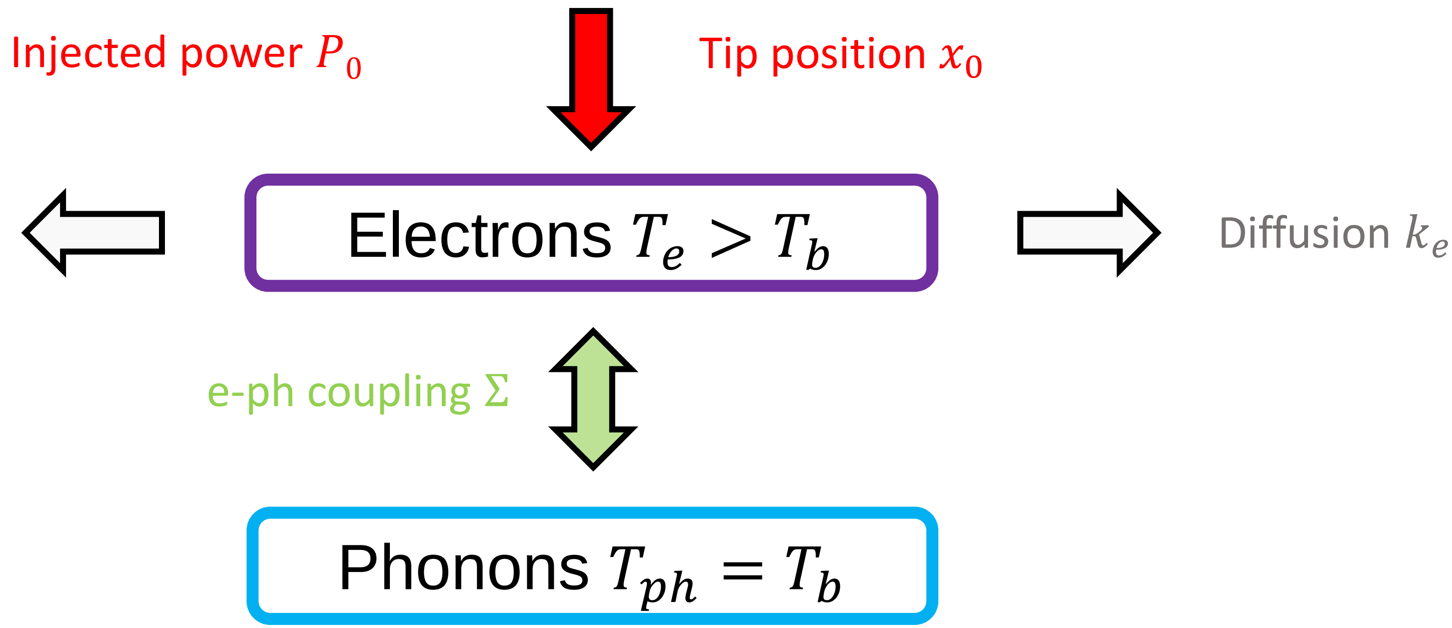




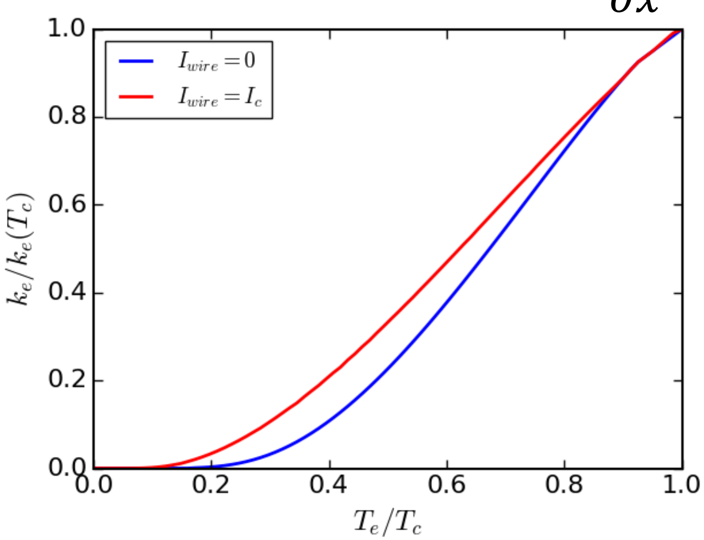
- I_c controlled by P

- $\frac{I_c}{I_t} \sim 10^6$

Heat diffusion model



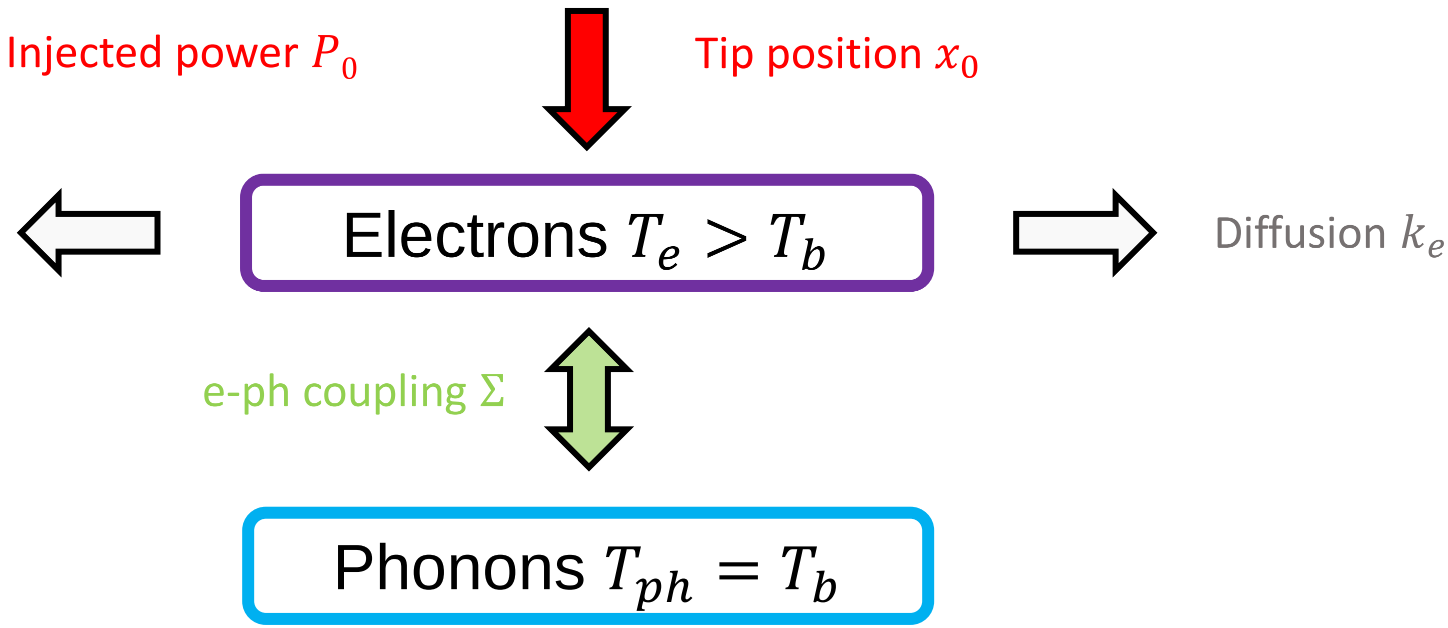
$$\nabla\left(twk_e \frac{\partial T_e(x)}{\partial x}\right) = \Sigma wt\left(T_e^p(x) - T_{ph}^p\right) - P_0\delta(x - x_0)$$



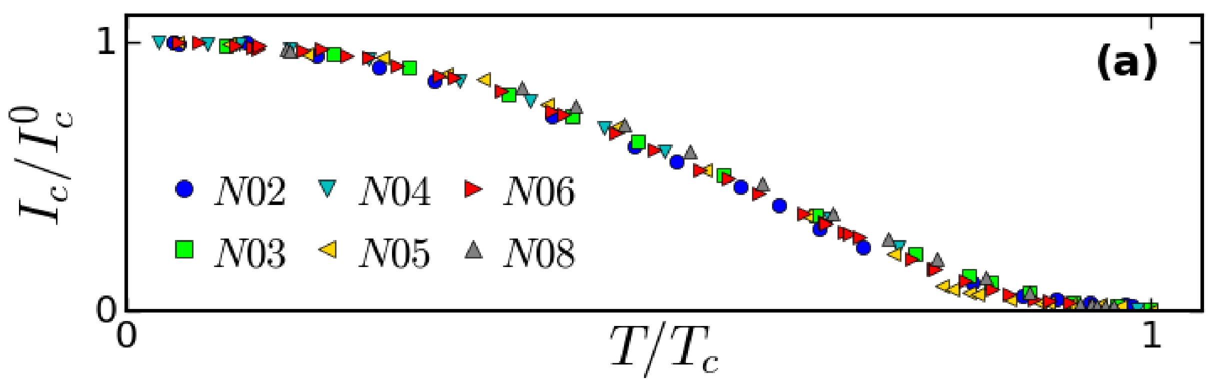
$$k_e = \frac{\sigma_N}{2e^2}\int_{-\infty}^{\infty} d\varepsilon \, \frac{\varepsilon^2}{2k_BT^2}\left(1 - \tanh^2\left(\frac{\epsilon}{2k_BT}\right)\right) \cos^2(\mathcal{R}e[\theta])$$

$$\frac{k_e(T_c)}{\sigma_N T_c} = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$$

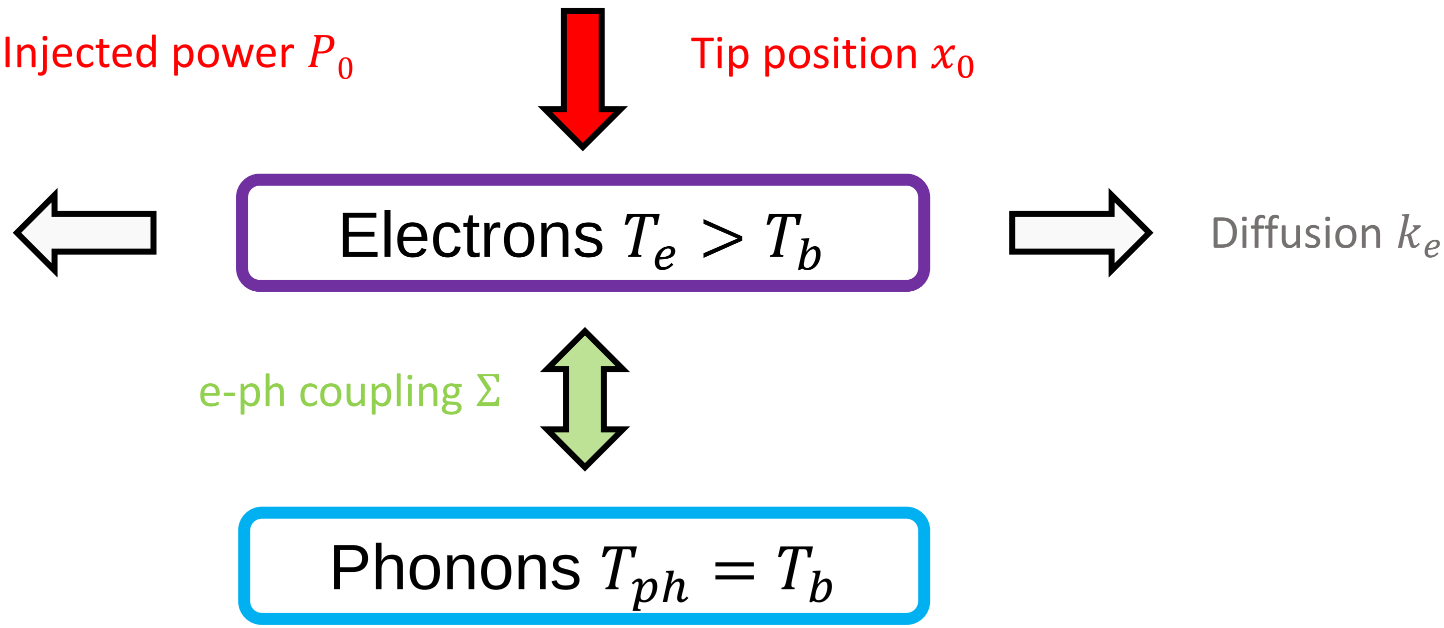
Heat diffusion model



$$\nabla\left(twk_e \frac{\partial T_e(x)}{\partial x}\right) = \Sigma wt \left(T_e^p(x) - T_{ph}^p\right) - P_0 \delta(x - x_0)$$



Heat diffusion model



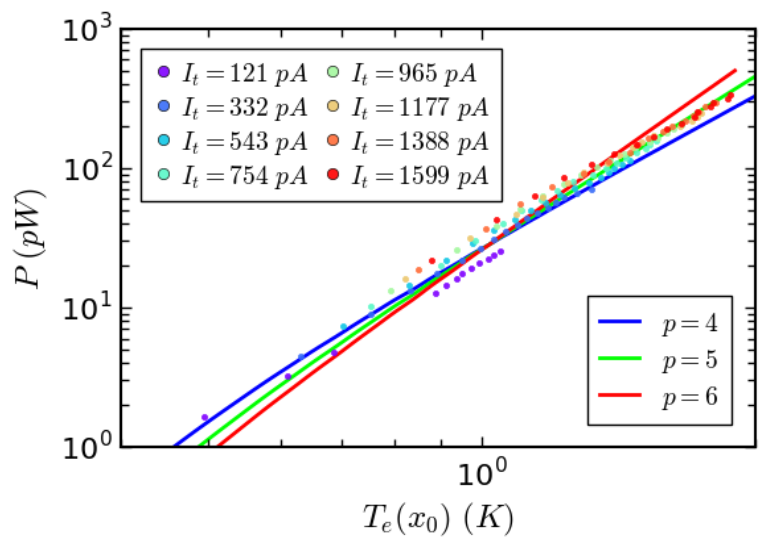
$$\nabla\left(twk_e\frac{\partial T_e(x)}{\partial x}\right) = \Sigma wt\left(T_e^p(x) - T_{ph}^p\right) - P_0\delta(x - x_0)$$

$p = 4$ $\quad l < \lambda_{ph}$ Static disorder

$p = 6$ $\quad l < \lambda_{ph}$ Vibrating disorder

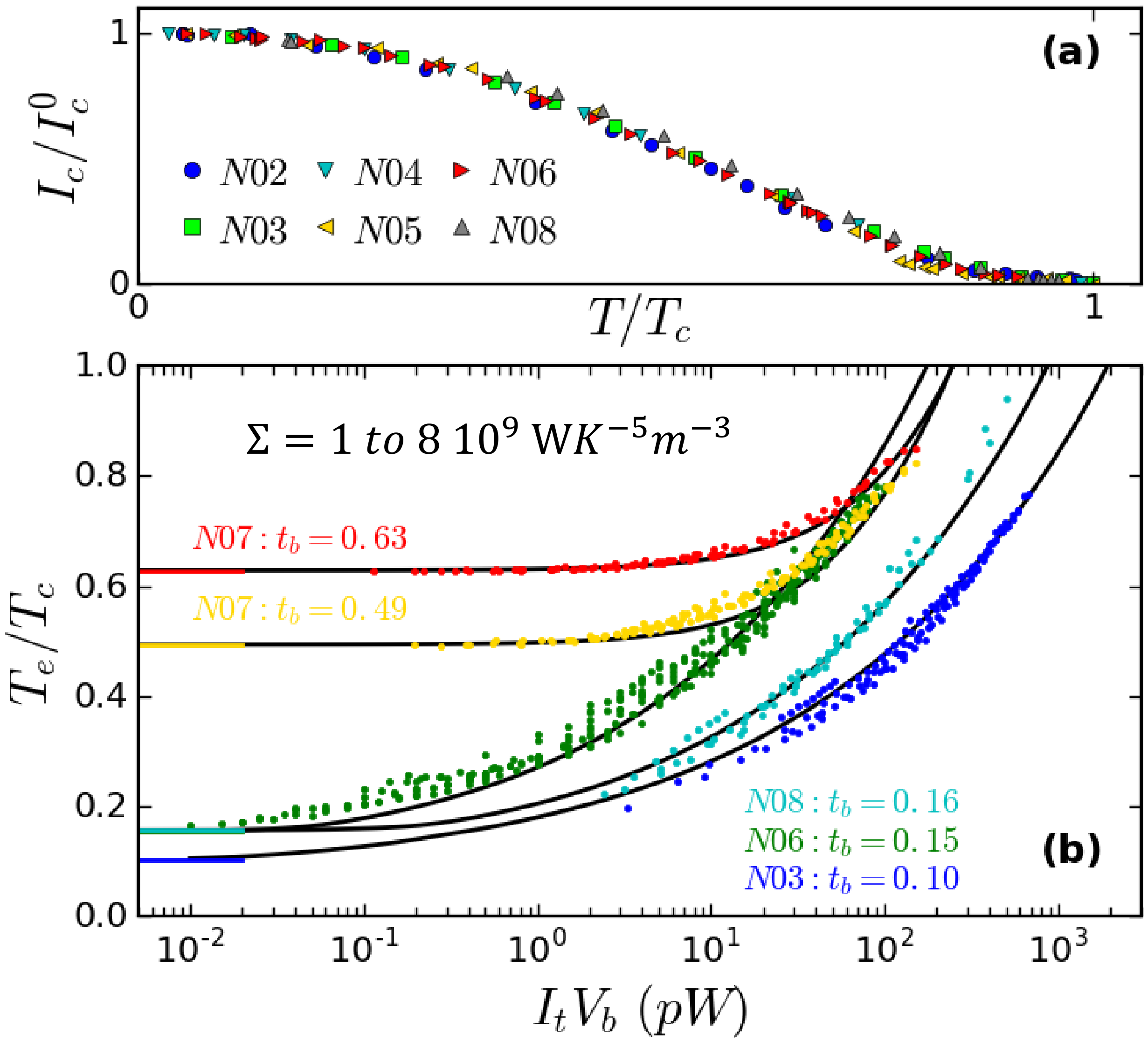
$p = 5$ $\quad l > \lambda_{ph}$

$l \approx \lambda_{ph}$ for $V_b = 20$ meV



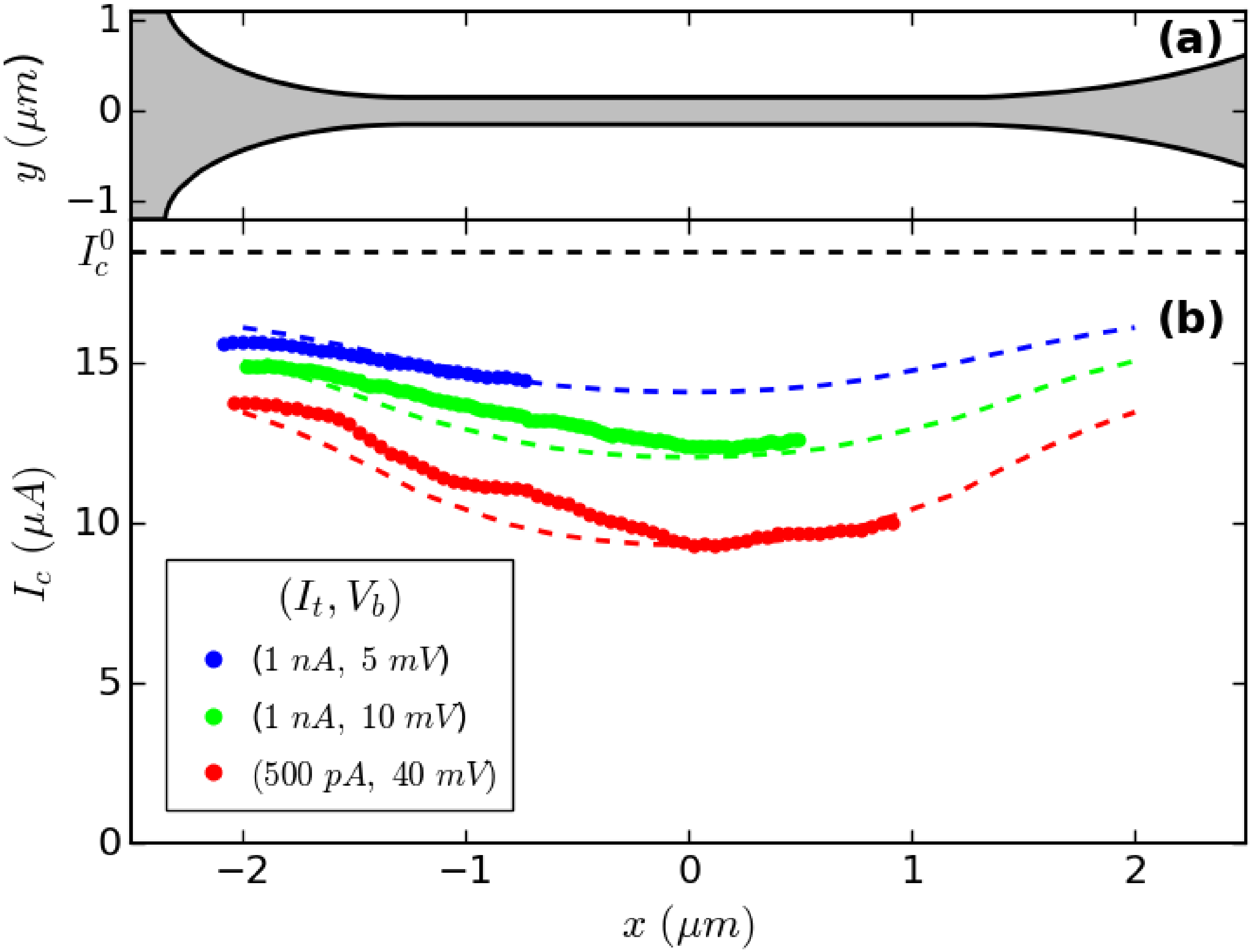
F. C. Wellstood, C. Urbina, and John Clarke, Phys. Rev. B 49 (1994)

A. Sergeev and V. Mitin, Phys. Rev. B 61 (2000)

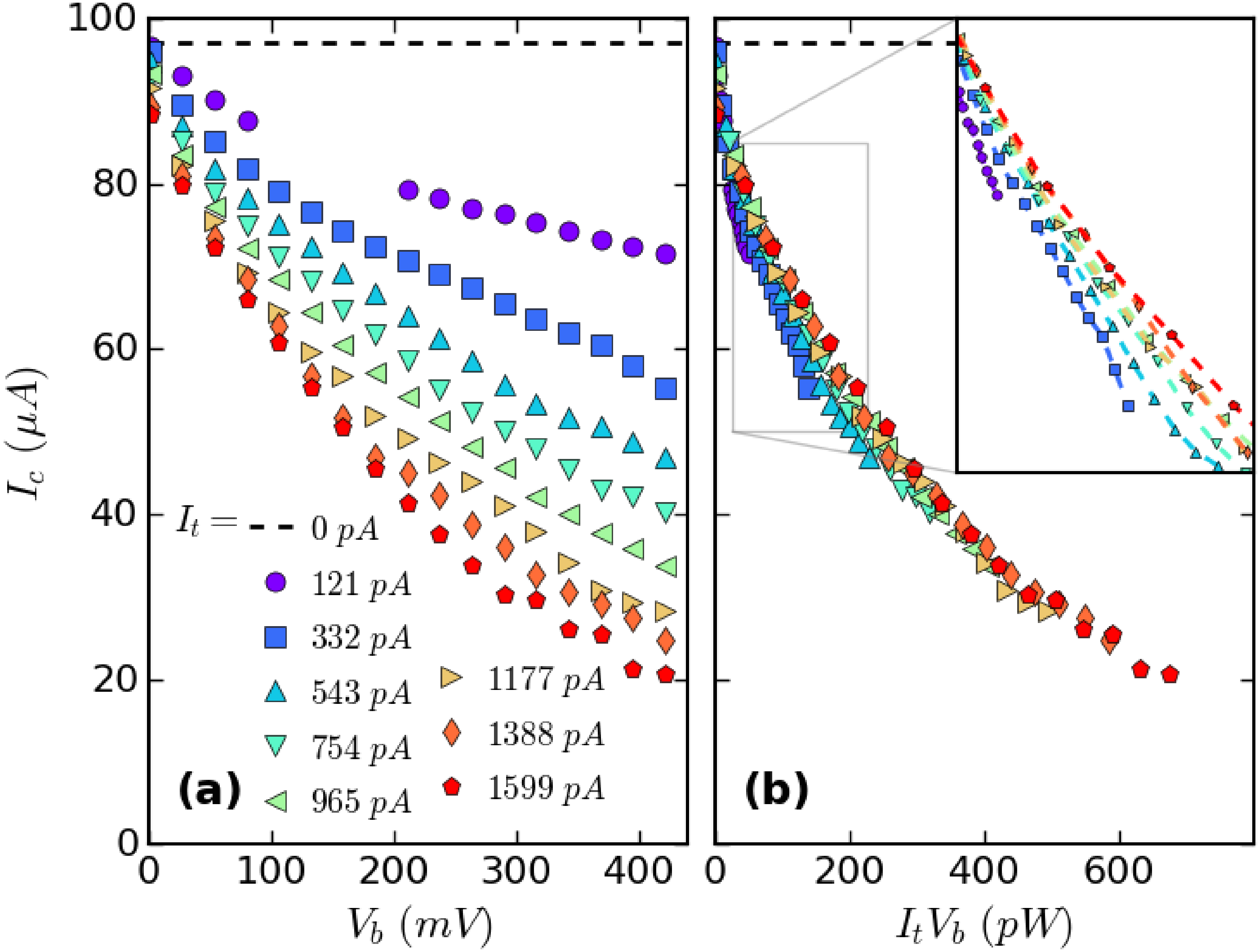


$$\nabla\left(twk_e\frac{\partial T_e(x)}{\partial x}\right) = \Sigma wt(T_e^5(x) - T_{ph}^5) - P_0\delta(x - x_0)$$

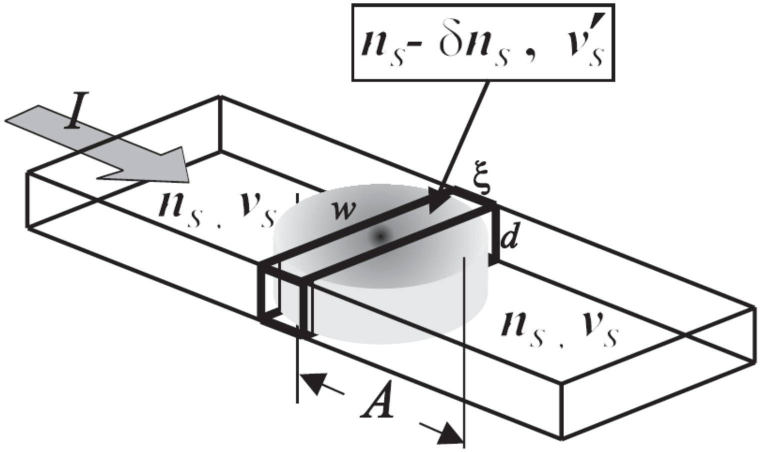
Spatial dependence



$$\nabla(twk_e \frac{\partial T_e(x)}{\partial x}) = \Sigma wt(T_e^5(x) - T_{ph}^5) - P_0\delta(x - x_0)$$


100
80
60
40
20
0
I_c (μA)
0
100
200
300
400
V_b (mV)
I_t = 0 pA
121 pA
332 pA
543 pA
754 pA
965 pA
1177 pA
1388 pA
1599 pA
(a)
0
200
400
600
$I_t V_b$ (pW)
(b)

Hot spot model



A. Semenov, et al., Eur. Phys. J. B 47 (2005)

$$n_s \approx N_0\, \Delta$$

$$j_s = n_s\, v_s\, \mathrm{e} \qquad j'_s = (n_s - \delta n_s)\, v'_s\, \mathrm{e}$$

$$I_s = j_s\, \mathrm{d\, w} = n_s\, v_s\, \mathrm{e\, d\, w}$$

$$I_s = I'_s \Rightarrow v'_s = \frac{n_s}{n_s - \delta n_s} v_s$$

$$I_c = n_s\, v_c\, \mathrm{e\, d\, w}$$

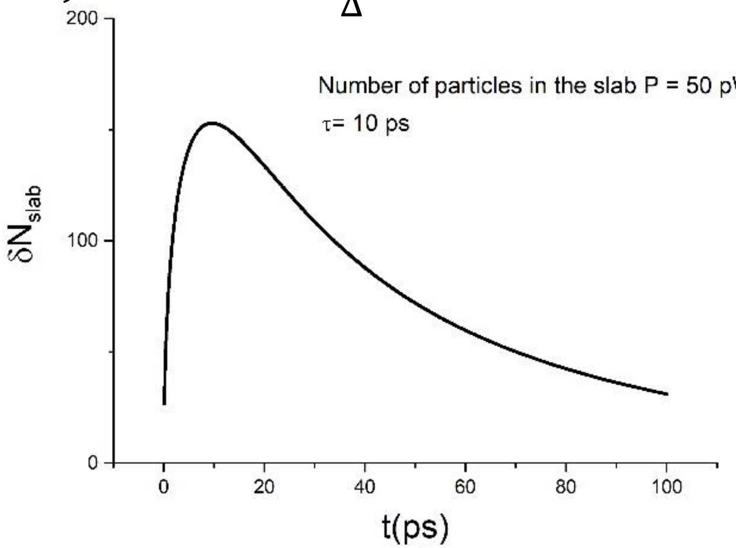
Superconducting transition : $v'_s = v_c \Rightarrow \delta n_s = n_s\left(1 - \frac{I_c}{I_{c0}}\right)$

Out-of-equilibrium quasiparticles in the slab at the transition : $\delta N_c = N_0 \Delta\, \xi \mathrm{w\, d} \left(1 - \frac{I_c}{I_{c0}}\right)$

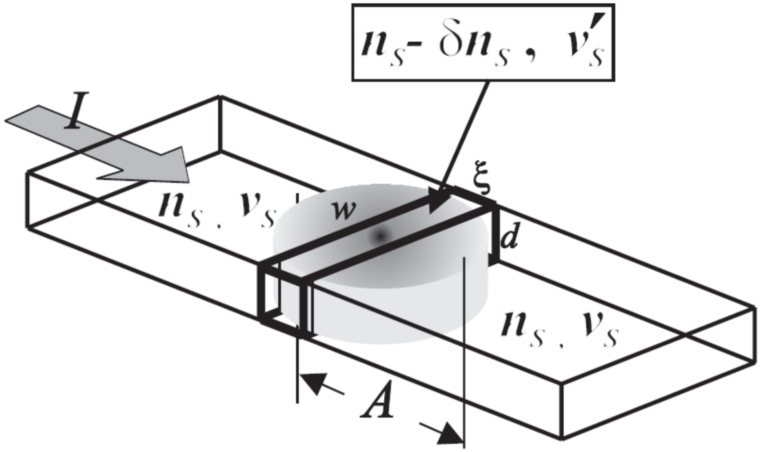
Generation of quasiparticles : $M(t) = K\,(1 - e^{-\frac{t}{\tau}})$ with $K \approx \frac{e\, V_i}{\Delta}$

Hot spot radius : $A(t) = 4\sqrt{D\, t\, ln(M(t))}$

$$\delta N_{slab} = \frac{K\,(1 - e^{-\frac{t}{\tau}})\,\xi}{\sqrt{\pi\, D\, t}}$$



Hot spot model



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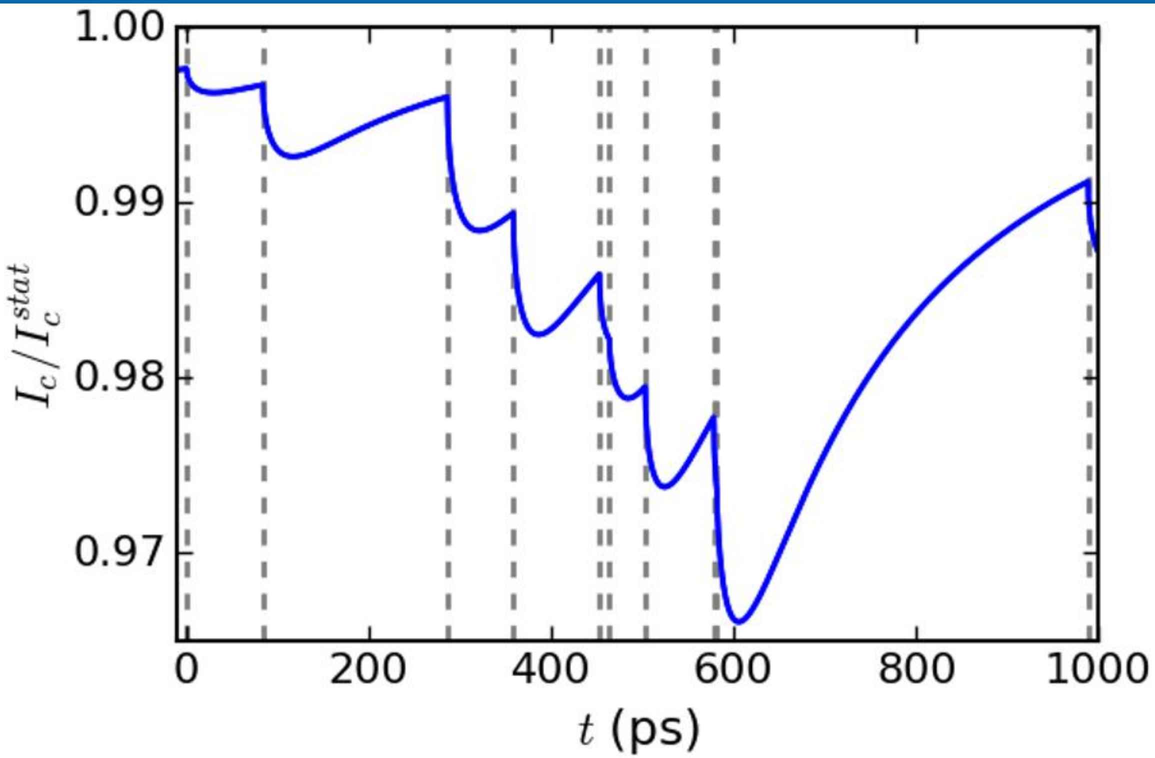
Hot spot radius : $A(t) = 4\sqrt{D\, t\, ln(M(t))}$

$$\delta N_{slab} = \delta N_c \Rightarrow I_c = I_{c0} \left(1 - \frac{\tau_{inj}\, P_i\, (1 - e^{-\frac{t}{\tau}})}{N_0 \Delta^2\, \mathrm{w\,d} \sqrt{\pi\, D\, t}}\right) \qquad P_i = I_t\, V_i \quad \tau_{inj} = \frac{e}{I_t}$$

$N_0 = 31\; 10^{46}\; J^{-1} m^{-3}$ $\Delta = 370\; \mu eV$ $\xi = 35\; nm$ w = 300 nm d = 10 nm D = 6.8 $10^{-4}\; m^2 s^{-1}$

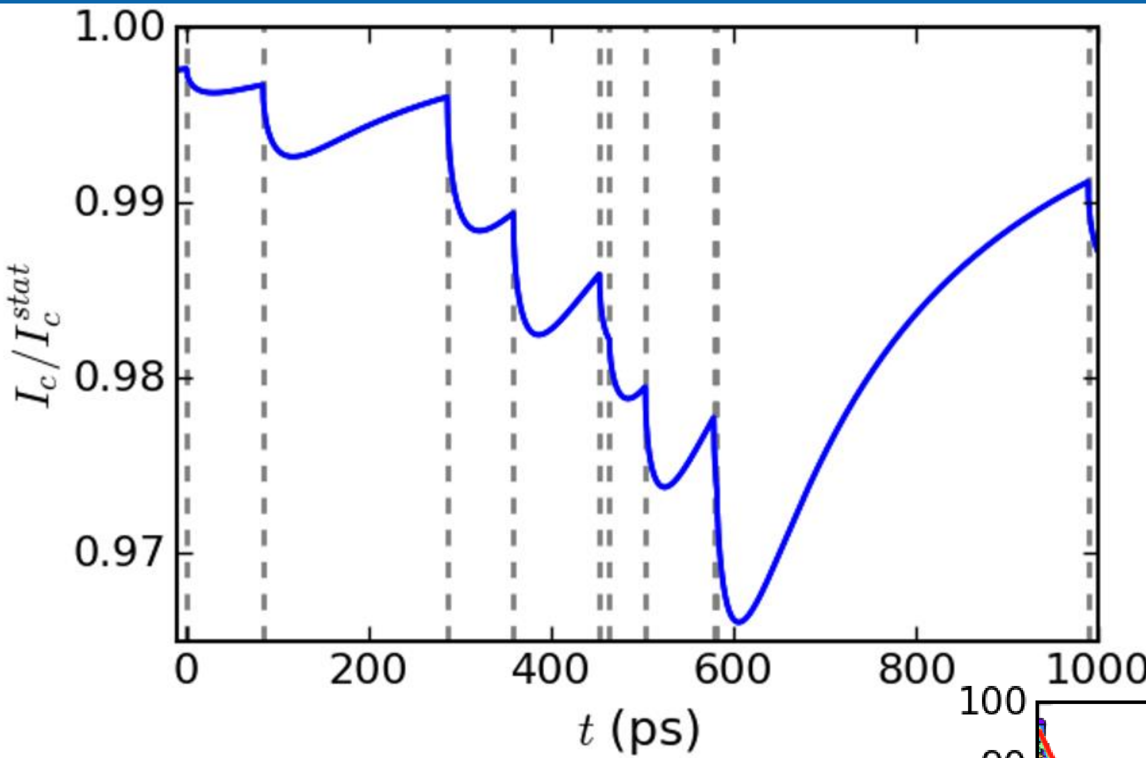
Numerical simulation of the hot spot dynamics



$$\delta N_{slab} = \delta N_c \Rightarrow I_c = I_{c0}\left(1 - \frac{\tau_{inj}\, P_i\, (1 - e^{-\frac{t}{\tau}})}{N_0 \Delta^2\, \mathrm{w}\, \mathrm{d} \sqrt{\pi\, D\, t}}\right)$$

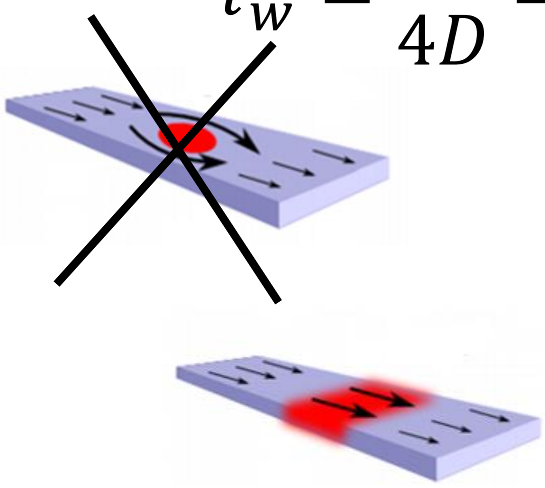
$N_0 = 31\ 10^{46}\ J^{-1} m^{-3}$ $\Delta = 370\ \mu eV$ $\xi = 35\ nm$ w $= 300\ nm$ d $= 10\ nm$ D $= 6.8\ 10^{-4}\ m^2 s^{-1}$

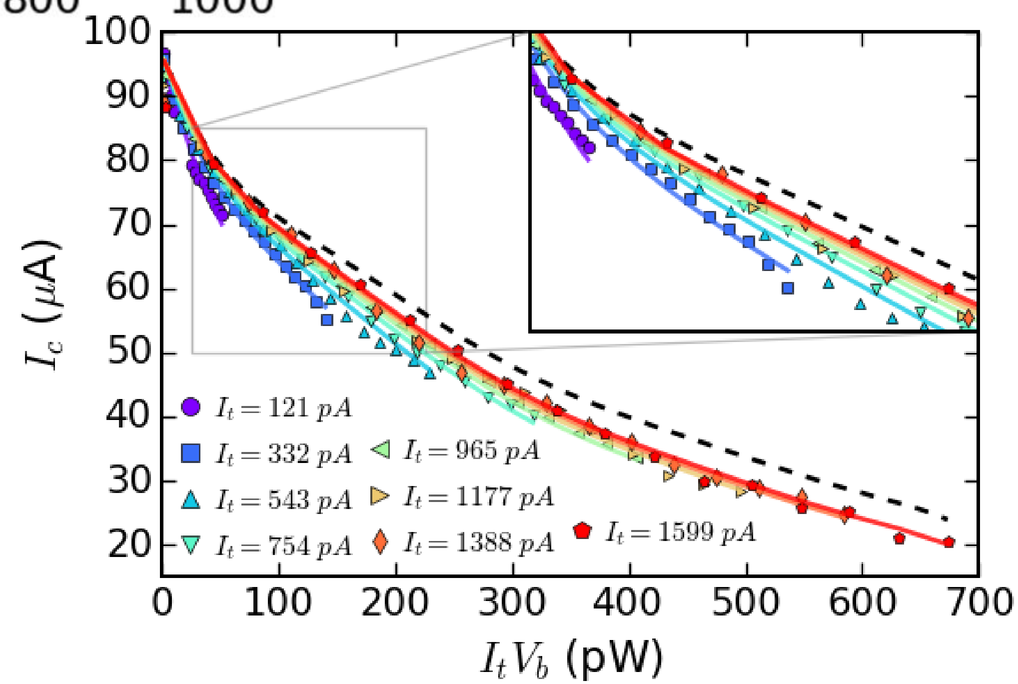
Numerical simulation of the hot spot dynamics



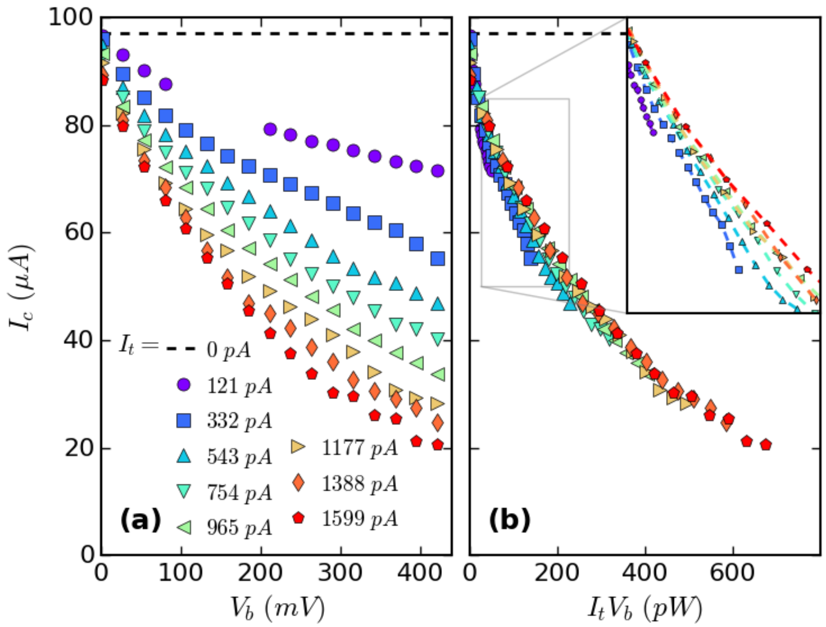
$\tau = 40\ ps$

$$\tau_w = \frac{w^2}{4D} = 40\ ps$$



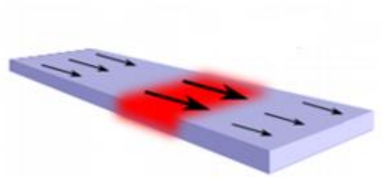


- $\frac{I_c}{I_t} \sim 10^6$
- Thermal effect

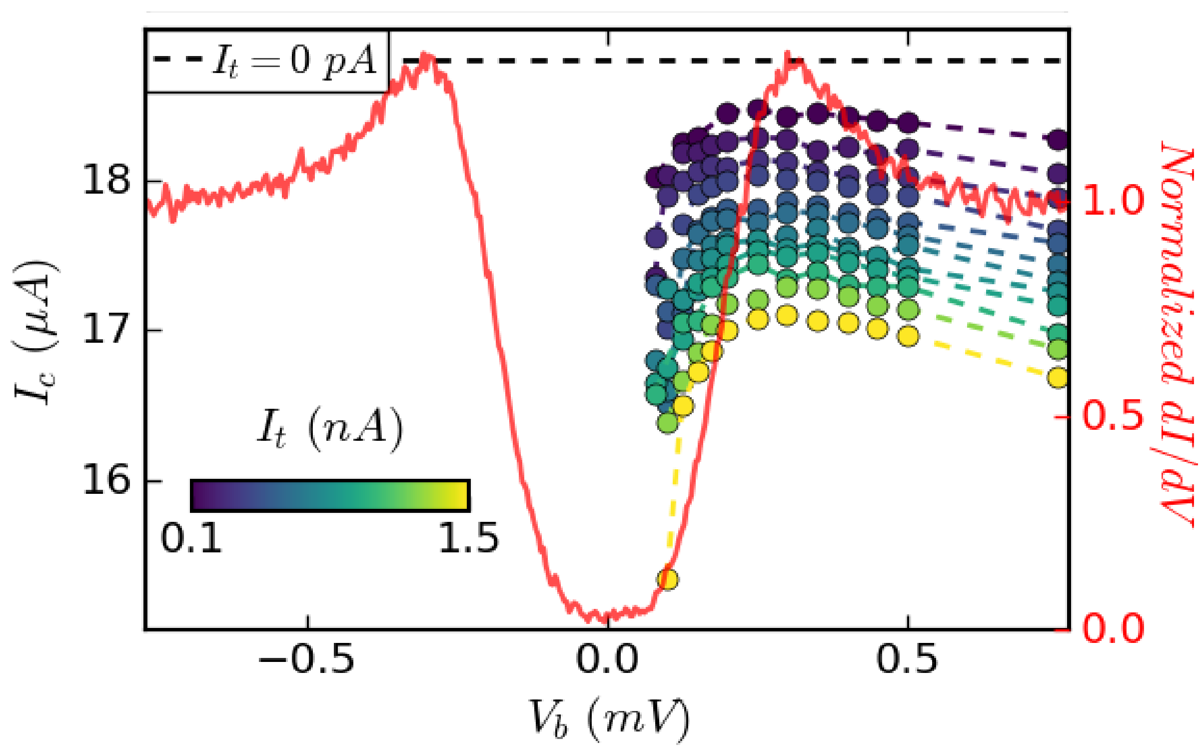


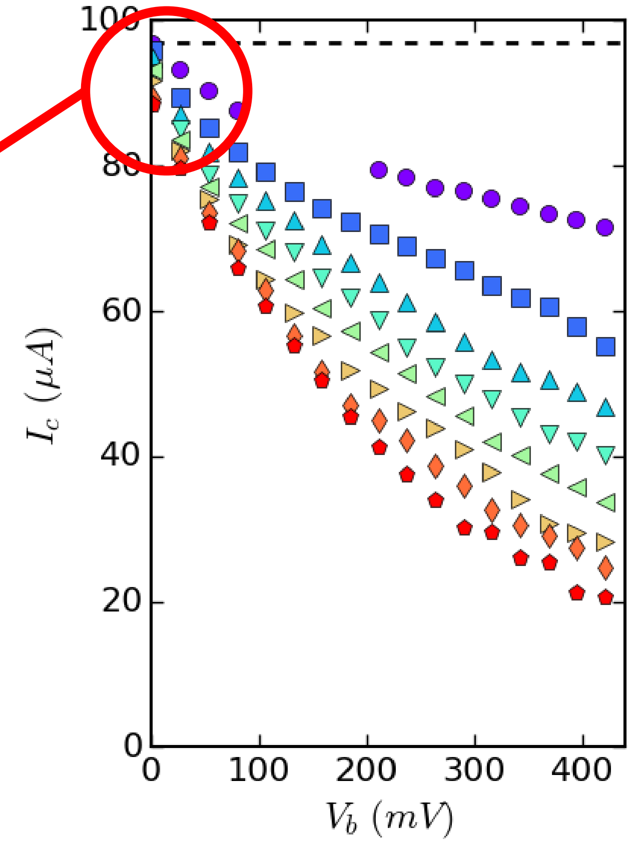
T. Jalabert, et al., Nat. Phys. (2023)

- Quasiparticle dynamics
- $\tau \sim 40\ ps$



Low bias injection





Non-thermalized quasiparticles :

- No electronic temperature
- Non-Fermi-Dirac distribution function

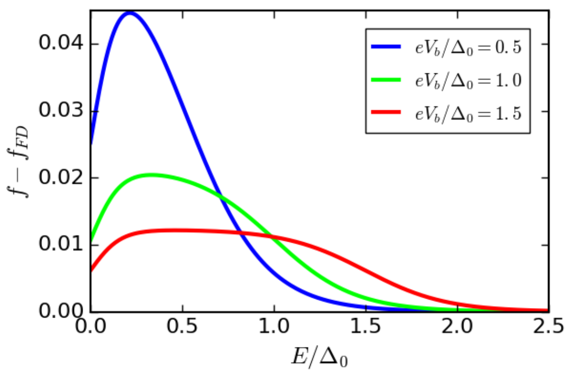
$$\frac{1}{N_0 V_{eff}} = \int_0^{\omega_D} dE\, \frac{1 - 2f(E)}{\sqrt{E^2 - \Delta^2}}$$

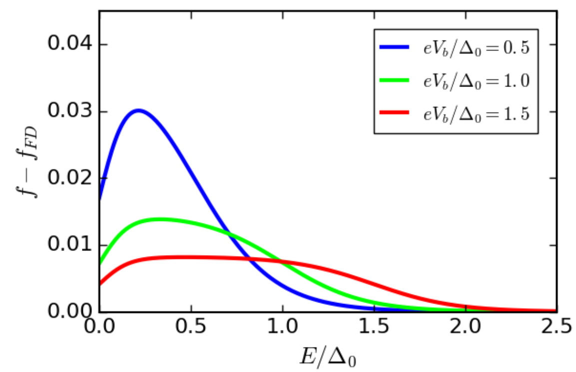
Low bias injection

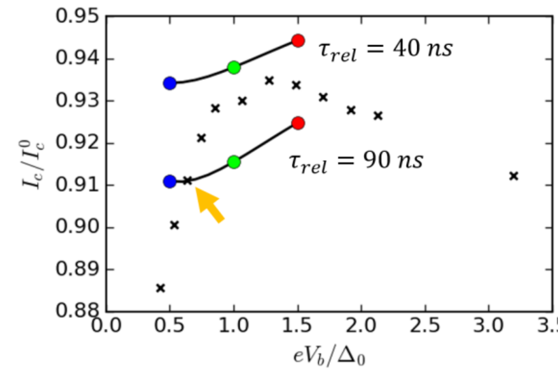
$$I_t(V_b) = \frac{1}{eR_T} \int dE\, N_s(E)\big(f_s(E) - f_{tip}(E - eV_b)\big)$$

$$\frac{1}{e\,R_T} N_S(E)(f_S(E) - f_{tip}(E - eV_b)) = -e\Omega N_0 N_S(E) \frac{f_S(E) - f_{FD}(E)}{\tau_{rec}}$$

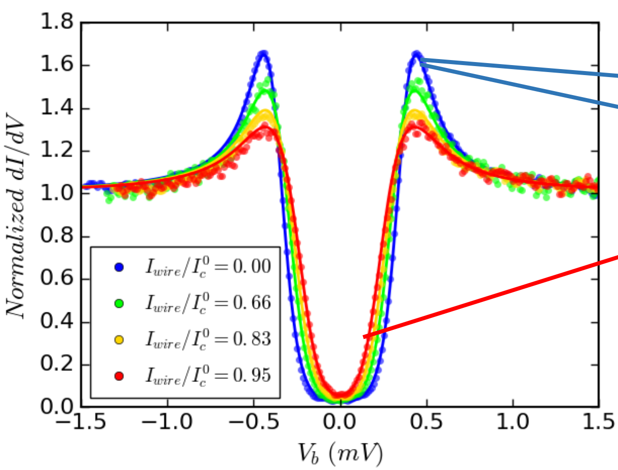
$$f_S(E) = \frac{\Gamma\, f_{tip}(E - eV_b) + f_{FD}(E)}{\Gamma + 1} \qquad \Gamma = \frac{\tau_{rec}}{e^2 R_T \Omega N_0} \qquad \Omega = \sqrt{D\tau_{rec}}\, wd$$

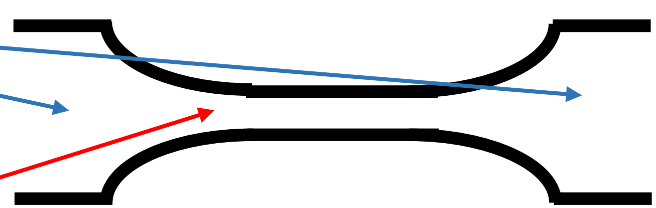






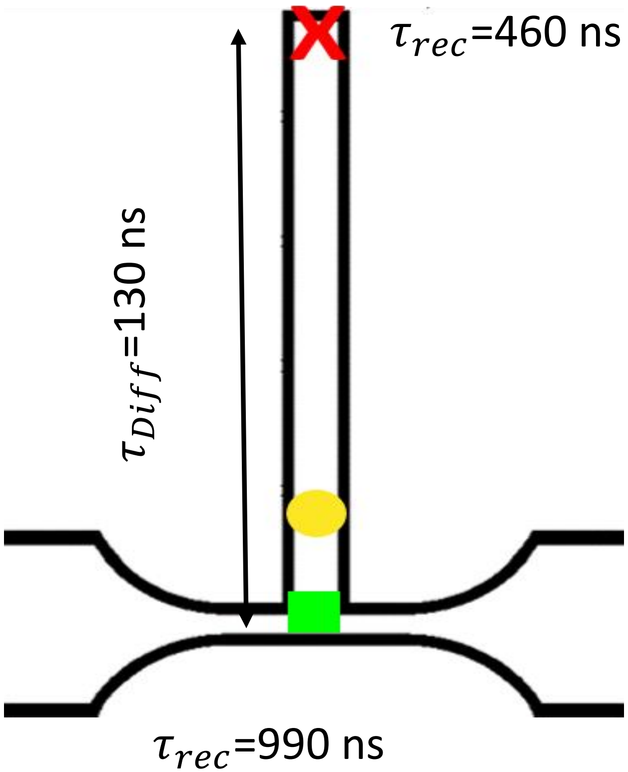
At the spectral gap $eV_b \sim 0.45\,\Delta_0$ τ_{rec}= 100 – 600 ns

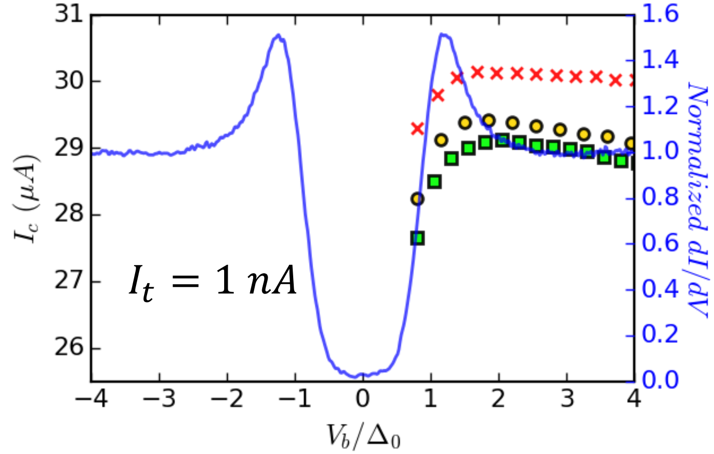


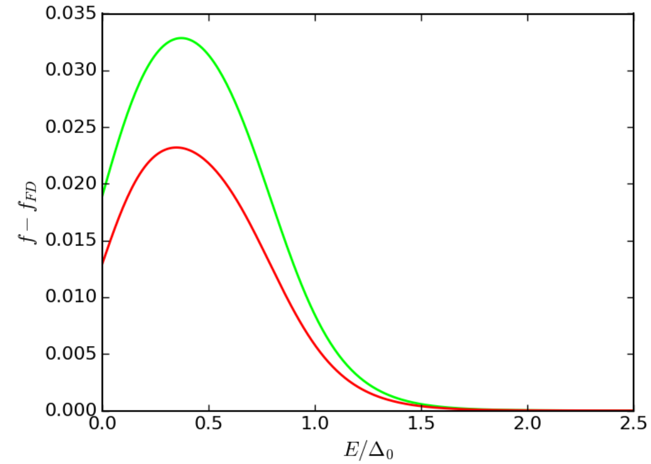


-Quasiparticles trapping $\Omega = Lwd$ τ_{rec}= 60 - 90 ns

Low bias injection

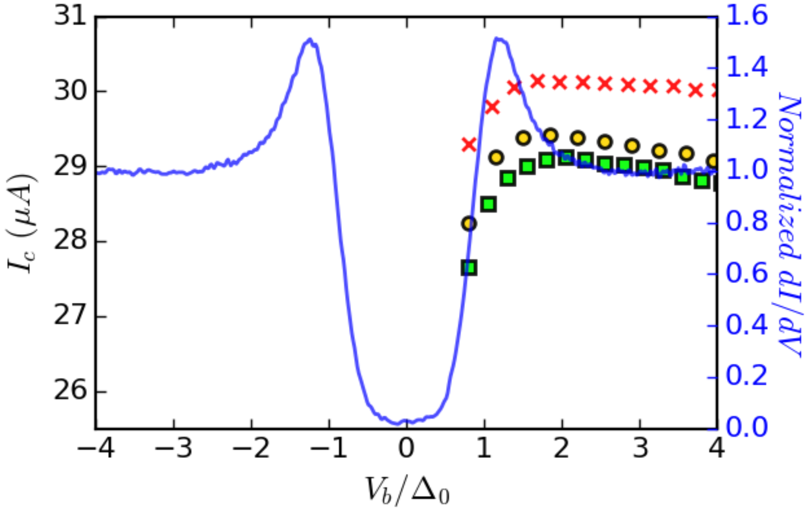




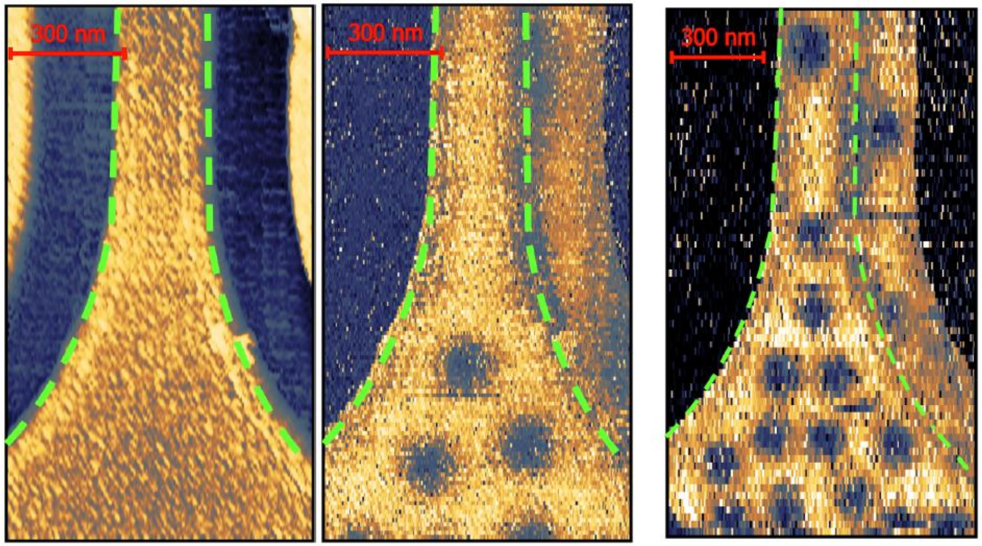


- Phonon trapping $\tau'_{rec} = \tau_{rec}(1 + \frac{\tau_{esc}}{\tau_{break}})^2$ A. Rothwarf and N.B. Taylor, Phys. Rev. Lett. (1967)

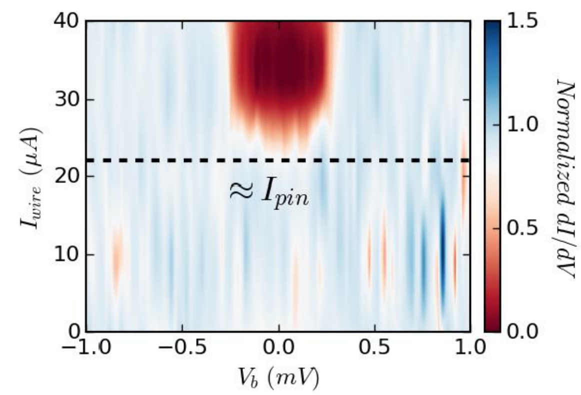
- Non-thermal quasi-particles
- Distribution function effect
- $\tau_{rec} \sim 100 - 500\, ns$



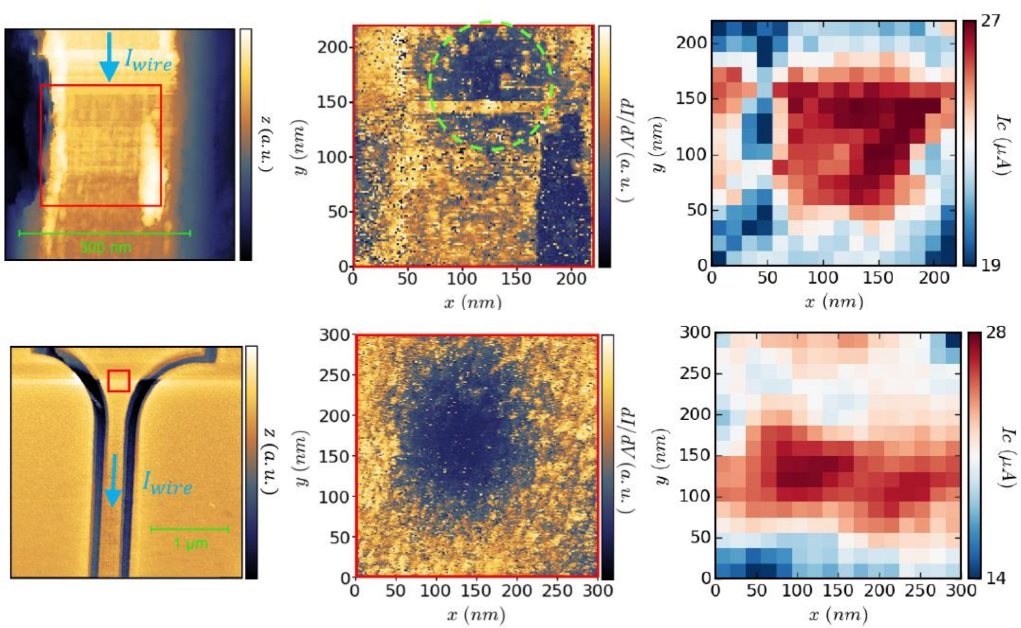
Scanning Critical Current Microscopy Outlook



(a) B=23 mT (b) B=23 mT (c) B=34 mT



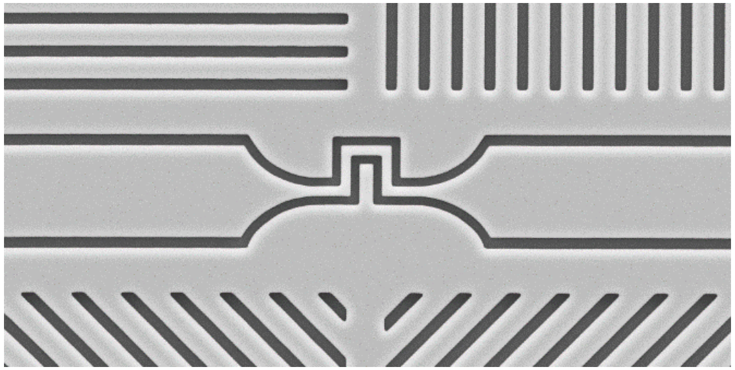
Vortex pinning



Quasi-particles trapping in a vortex

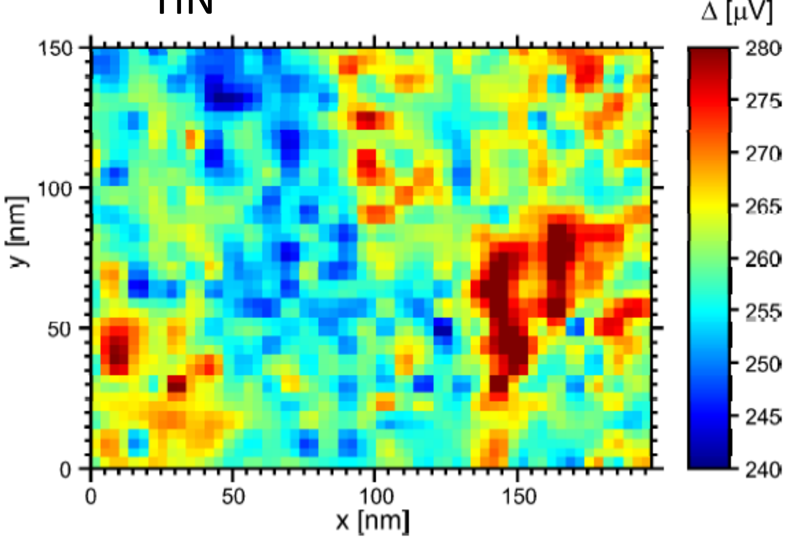
Scanning Critical Current Microscopy Outlook

Current crowding

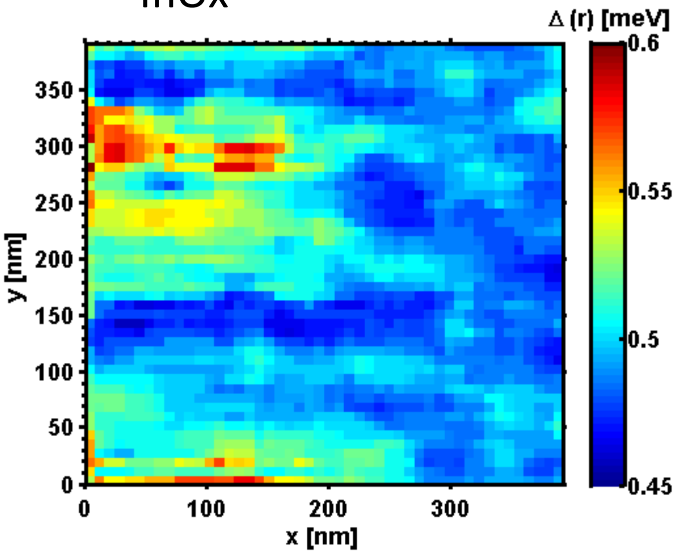


Highly disordered superconductors

TiN

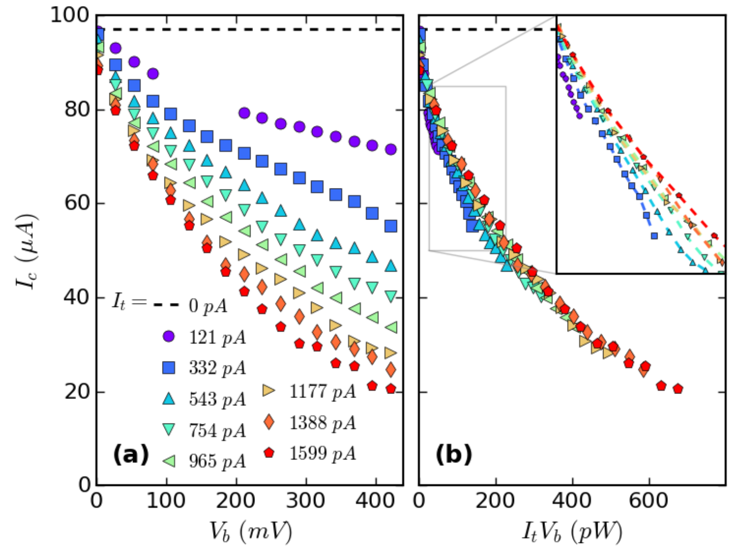


InOx



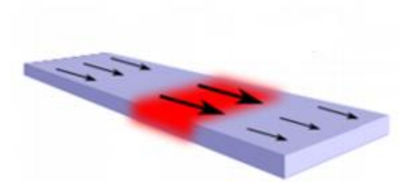
Conclusion

- $\frac{I_c}{I_t} \sim 10^6$
- Thermal effect



T. Jalabert, et al., Nat. Phys. (2023)

- Quasiparticle dynamics
- $\tau \sim 40\ ps$



- Non-thermal quasi-particles
- Distribution function effect
- $\tau_{rec} \sim 100\ - 500\ ns$