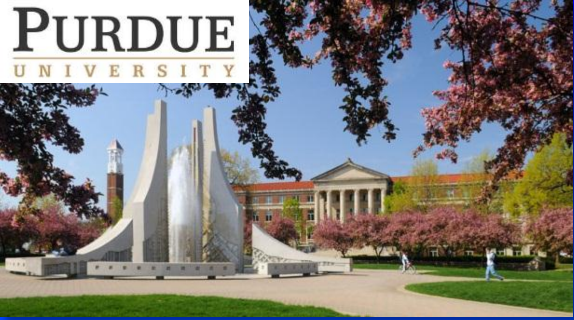

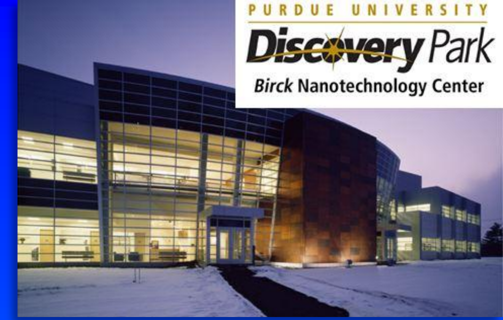

Fractional ac Josephson effect: the signature of Majorana particles

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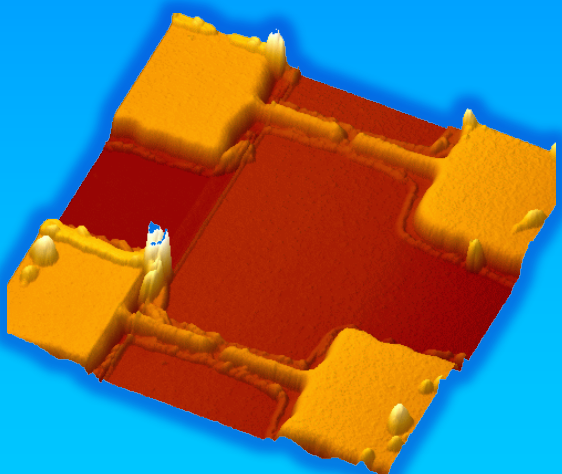
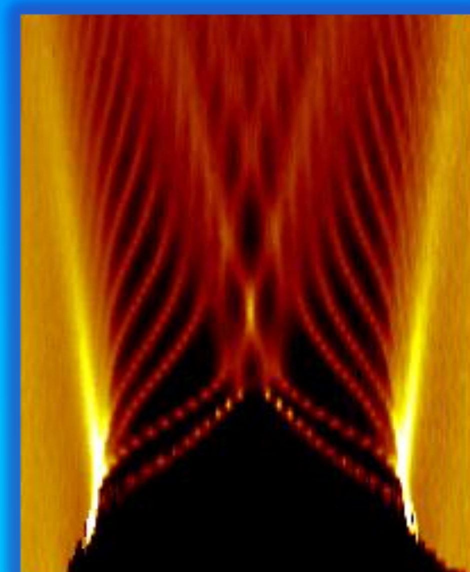




Jacek Furdyna *(Notre Dame)*
Xinyu Liu *(Notre Dame)*

KITP, November 10, 2012

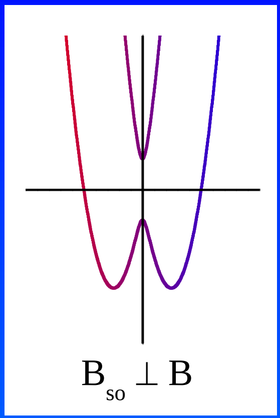
choice of material

		GaAs	InAs	InSb
Dresselhaus, [eV·Å^3]	γ_e	27.6	27.2	760
Dresselhaus, [eV·Å^3]	γ_h	-81.6	-50.2	-934
Rashba, [eVÅ^2]	r_{41}	5.2	117	523
Dresselhaus, [eV·Å]	α_D^e	0.55	0.055	1.54
Dresselhaus, [eV·Å]	α_D^h	0.17	0.1	1.9
Rashba, [eV·Å]	α_R		0.12	
effective mass, m_0	m_e	0.067	0.023	0.014
effective mass, m_0	$\langle m_h \rangle$	0.57	0.41	0.43
Landé g-factor	g^*	0.44	16	50
$\kappa\mu_B B$ (holes)	κ	1.2	7.6	15.6

← 15 nm QW

← 10^5 V/cm

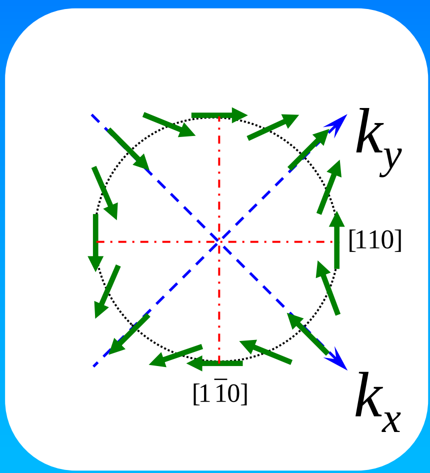
parameter space

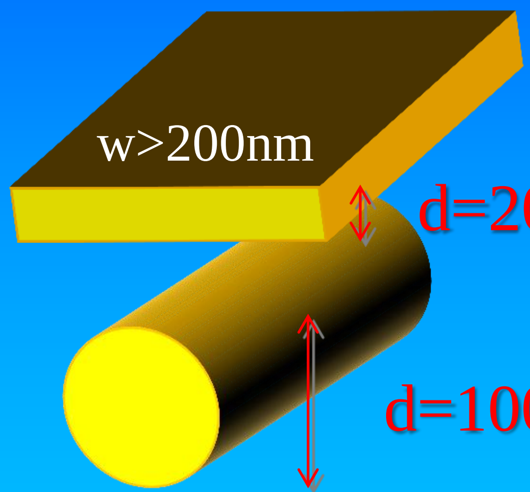


single-spin condition: $E_Z > \sqrt{\Delta^2 + E_F^2}$

to protect superconductivity: $E_Z \sim E_{SO}$

$$E_{SO} = \sqrt{2}\gamma_D \langle k_z^2 \rangle k = \sqrt{2}\gamma_D (\pi / d)^2 k$$





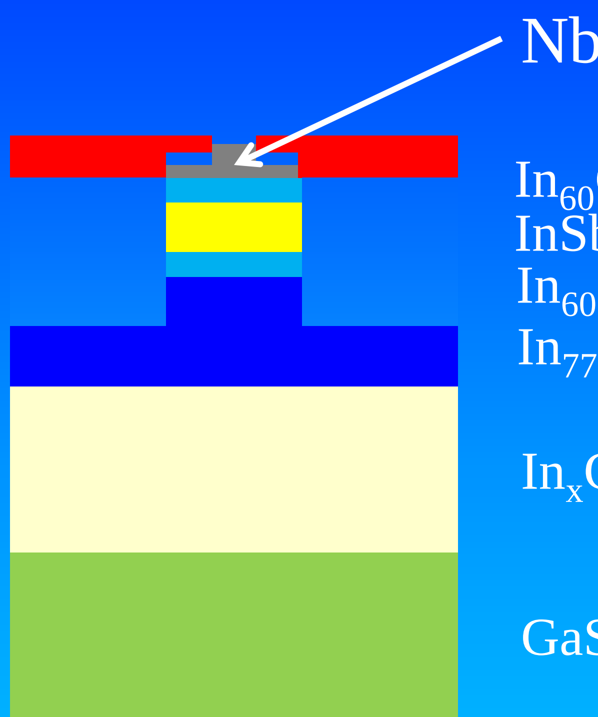
d=20nm $E_{SO} \approx 2.6 \cdot k$ [meV], $k[10^6\,\mathrm{cm}^{-1}]$

d=100nm $E_{SO} \approx 0.1 \cdot k$ [meV], $k[10^6\,\mathrm{cm}^{-1}]$

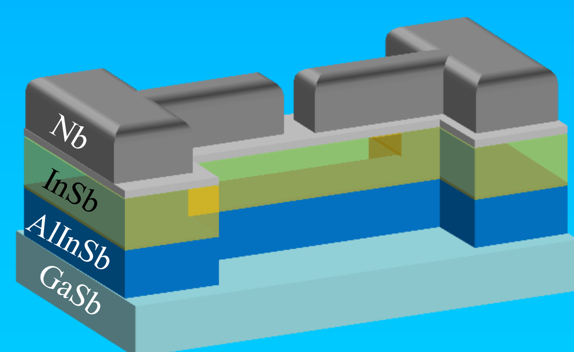
smallest dimension defines E_{so}:

small d ⇒ large E_{so} ⇒ large E_F ⇒ less localization

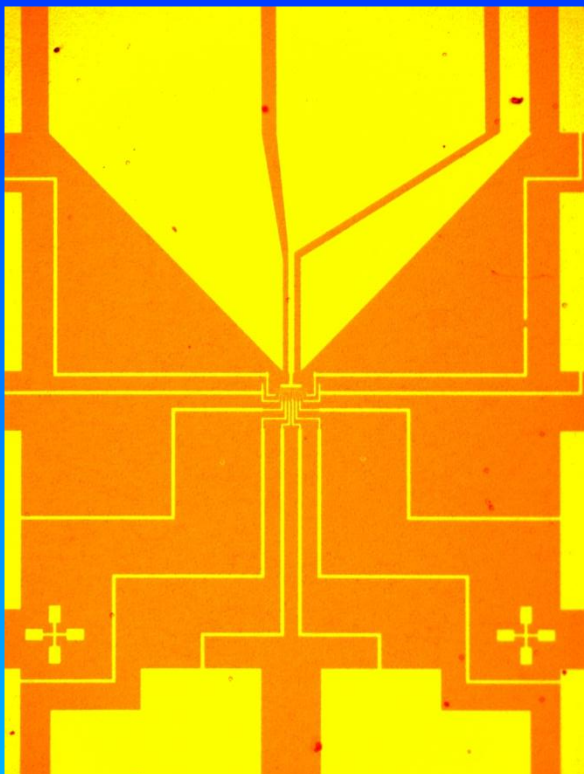
wafers



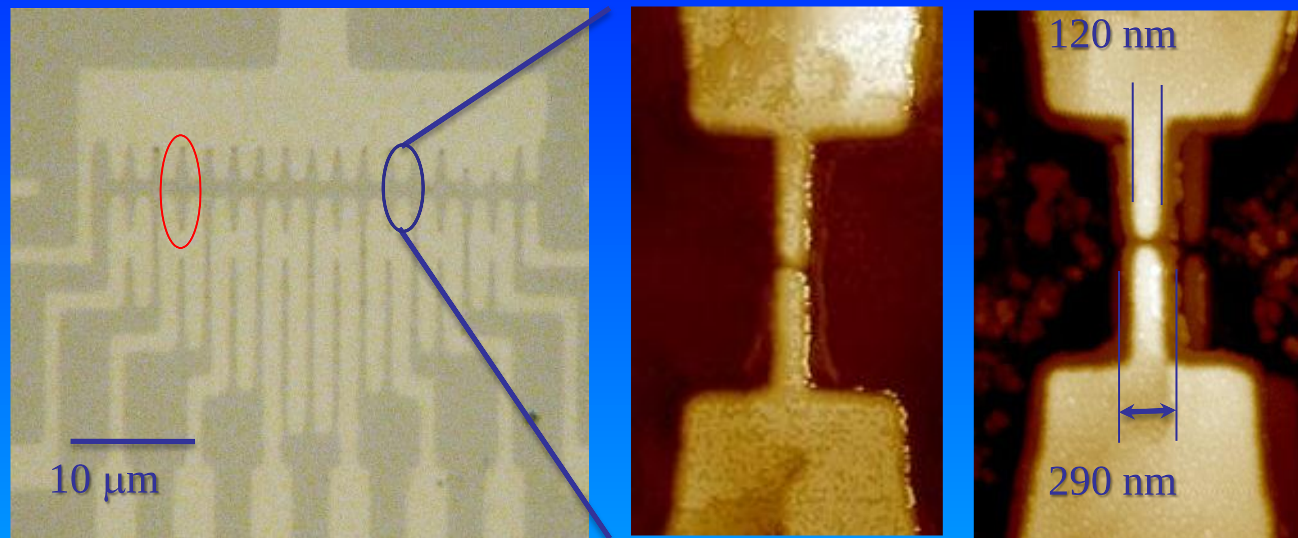
$In_{60}Ga_{30}Sb$	3 nm
InSb	20 nm
$In_{60}Ga_{30}Sb$	3 nm
$In_{77}Al_{23}Sb$	120 nm
$In_xGa_{1-x}Sb$ graded	1280 nm
GaSb:Te substrate	

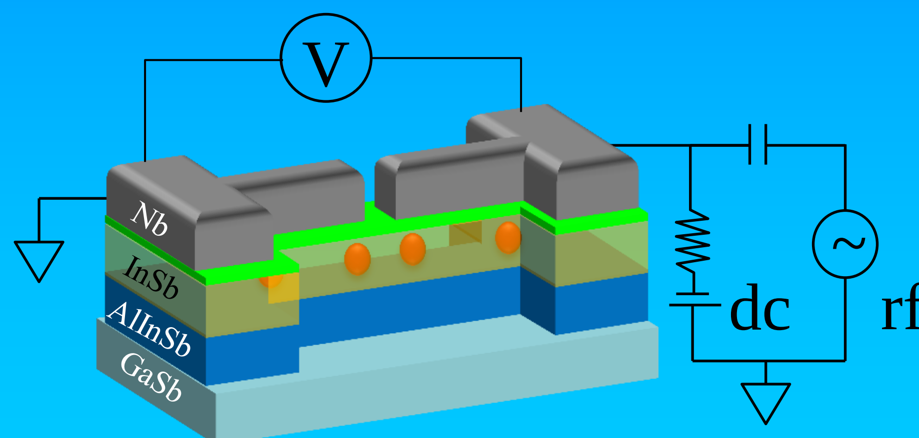


fabrication

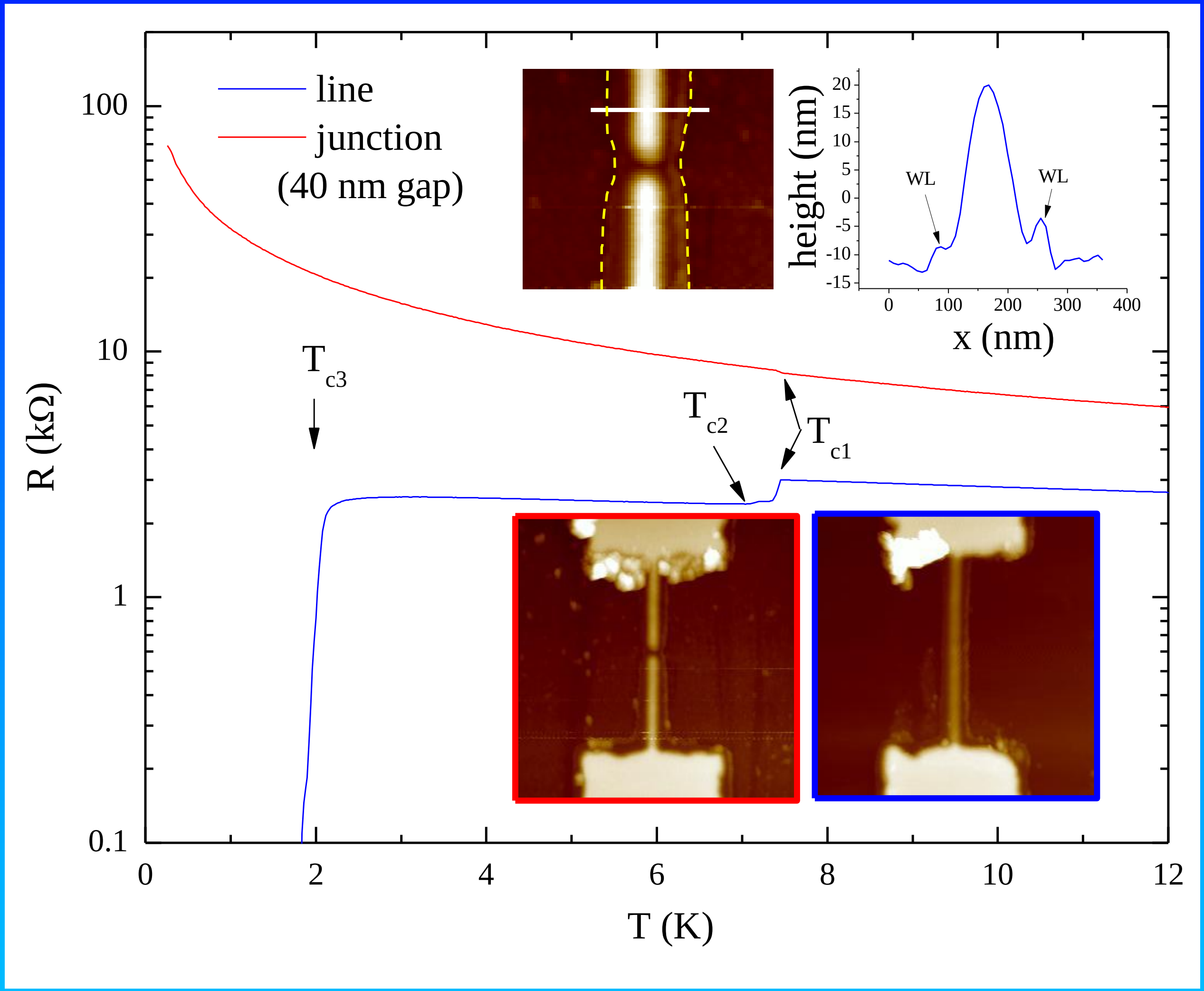


etch ~50 nm





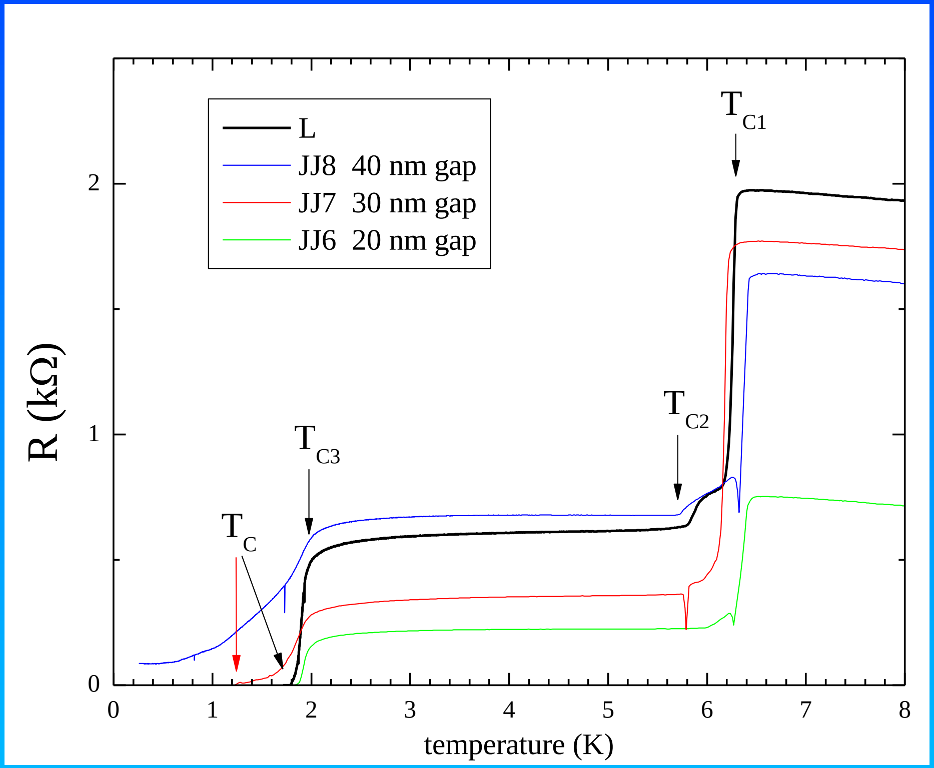
junctions on i-GaAs



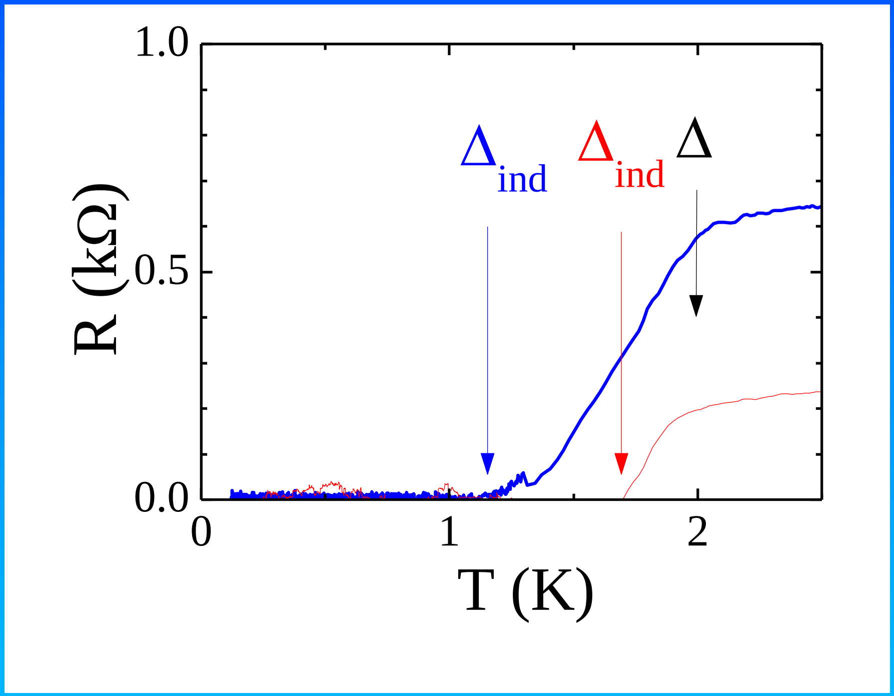
devices with the gap > 20 nm are insulating

T-dependence of JJs

^{3}He system



dilution fridge



T_{C1} – w>6 μm
T_{C2} – w=1 μm
T_{C3} – w=0.1 μm
T_C – proximity gap

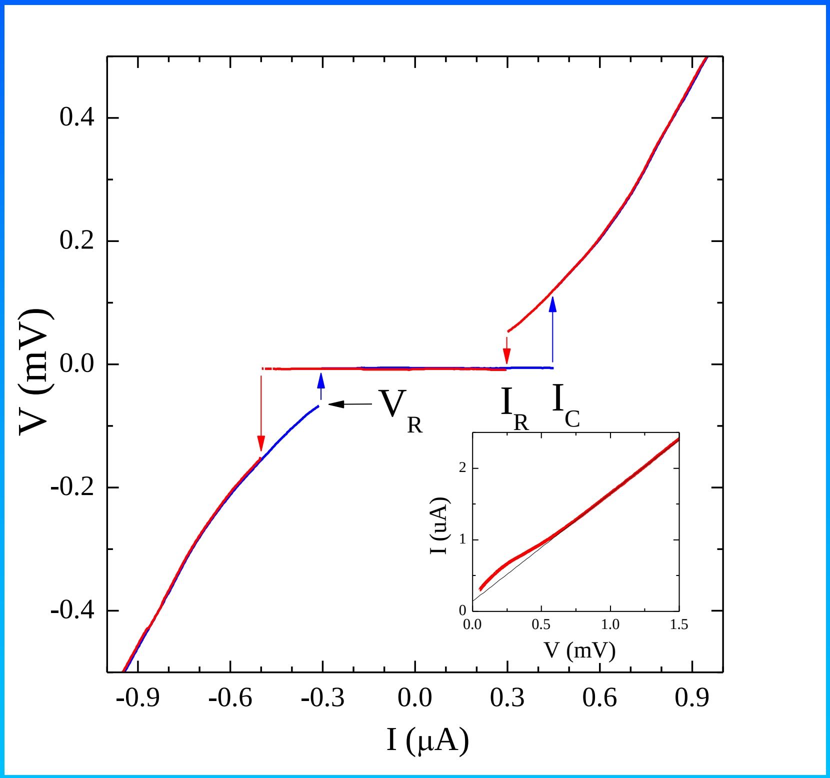
$$\Delta_{ind} = \Delta \frac{\Gamma}{\Gamma + \Delta}$$

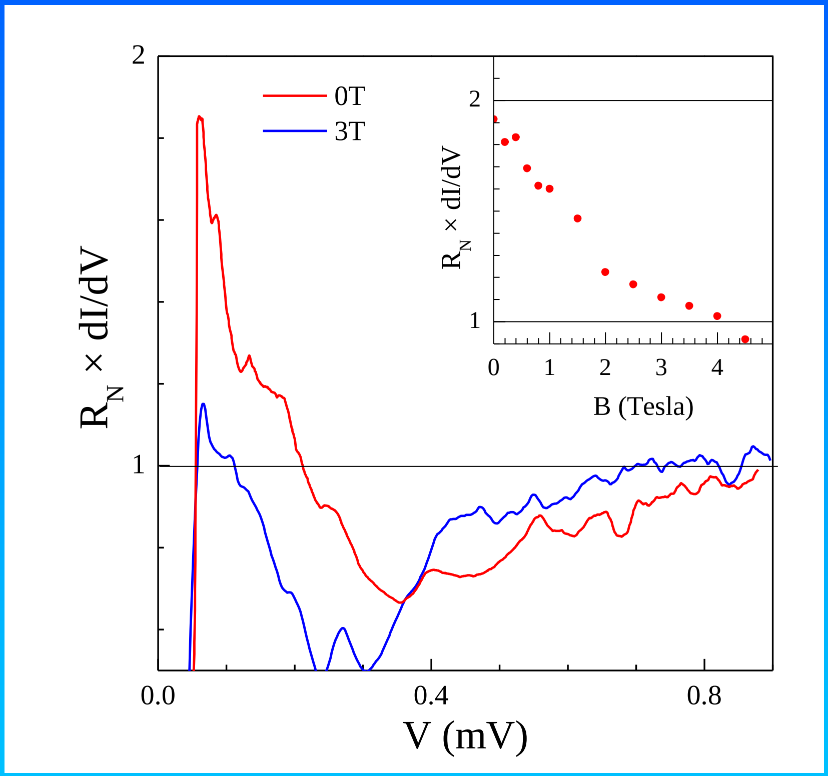
Δ =1.76 $k_B T_{C3}$/e = 310 μeV
Δ_{ind} =1.76 $k_B T_C$/e = 180 μeV
$\Gamma \sim \Delta_{ind}$

samples

Typical V(I) characteristics

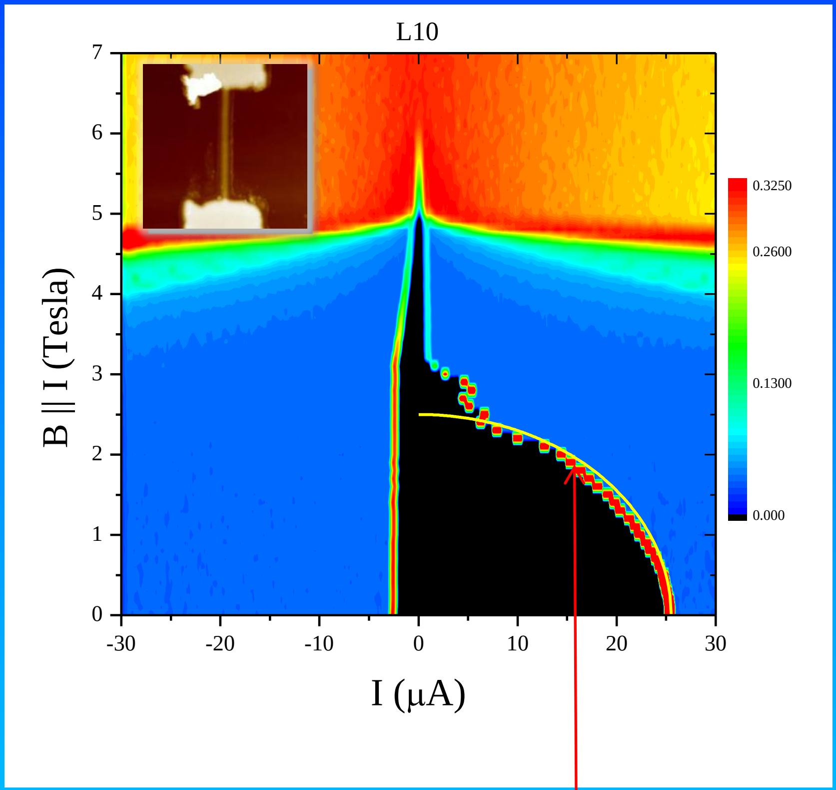
excess current – Andereev reflection
sign of coherent transport



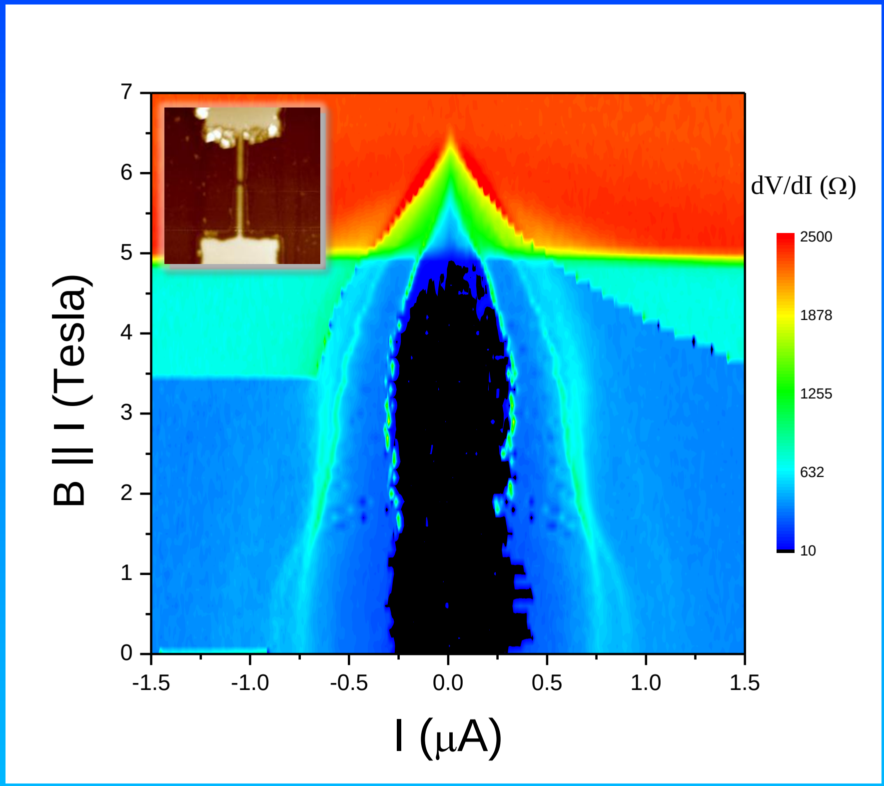


field dependence of I_c

0.1 μm - wide line



JJ



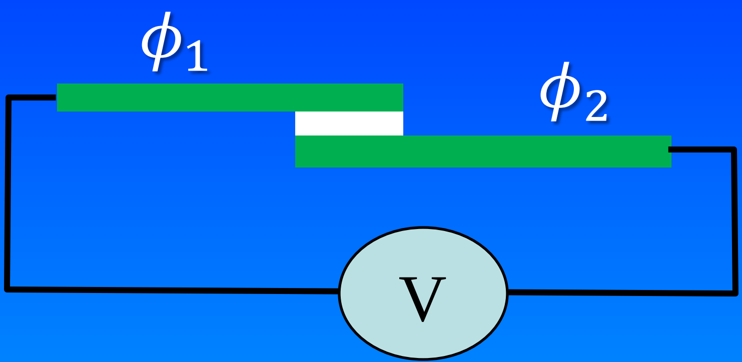
$$I_c \propto \sqrt{1-\left({}^{B}/_{B_{c1}}\right)^2}$$

B_{c1} ~ 2.5 Tesla

B_{c2} ~ 5 Tesla

ac Josephson effect

direct

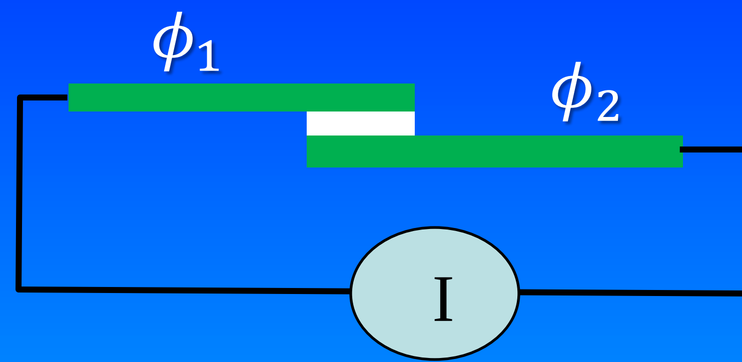


$$\frac{d(\Delta\phi)}{dt} = \frac{2eV}{\hbar}$$

$$I_s = Ic\sin(\omega_J t) = I_c \sin\left(\frac{2eV}{\hbar}t\right)$$

Current oscillates with frequency $\propto V$

inverse



$$I = I_0 + I_\omega \sin(\omega t)$$

$$V = \left(\frac{h\omega}{2e}\right)$$

Constant voltage steps $\propto \omega$

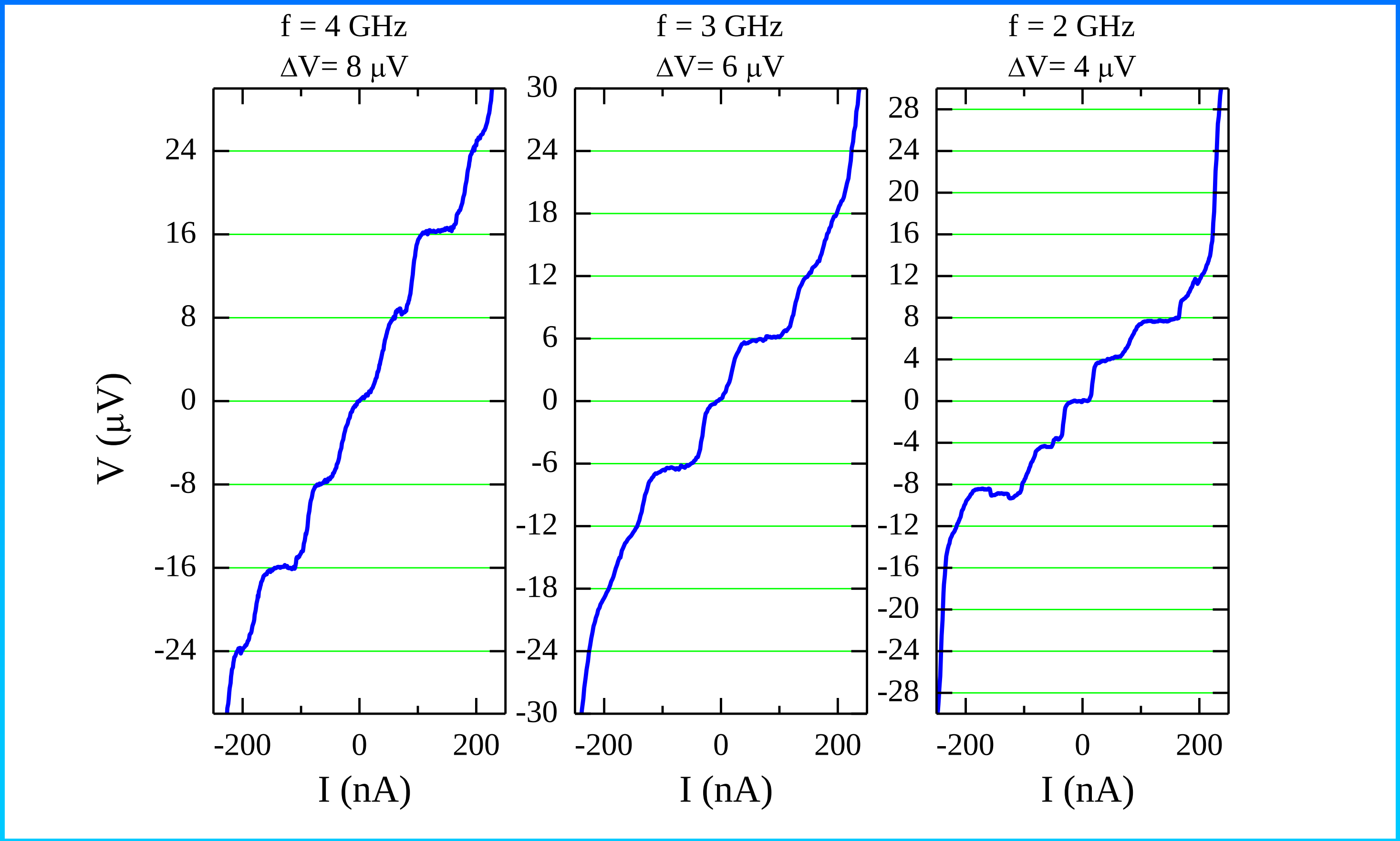
inverse ac Josephson effect

phase locking between external rf and Josephson frequency

$$V_n = n\left(\frac{h\omega_{rf}}{q}\right)$$

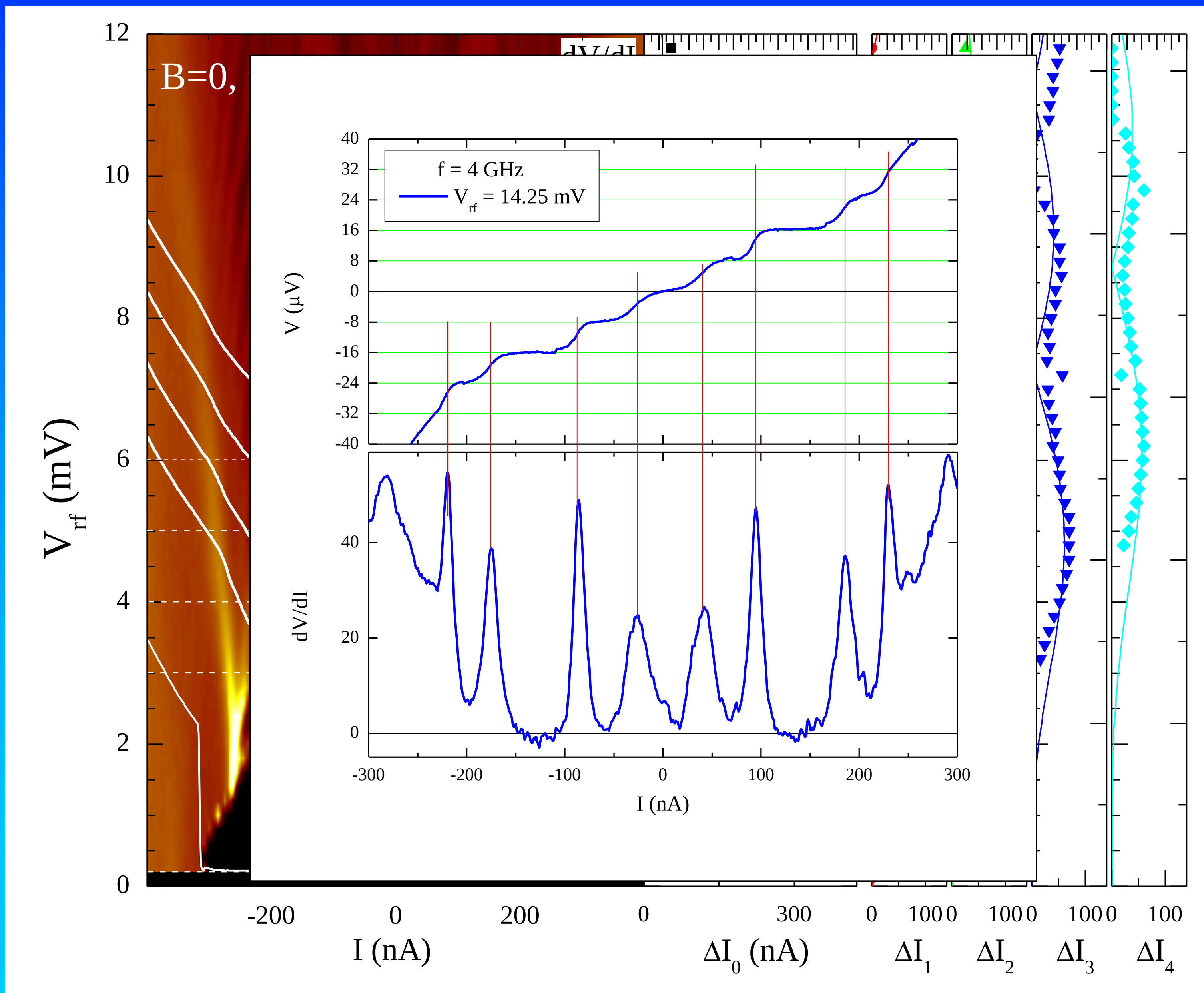
Shapiro steps (Shapiro '63)

$$q = 2e$$

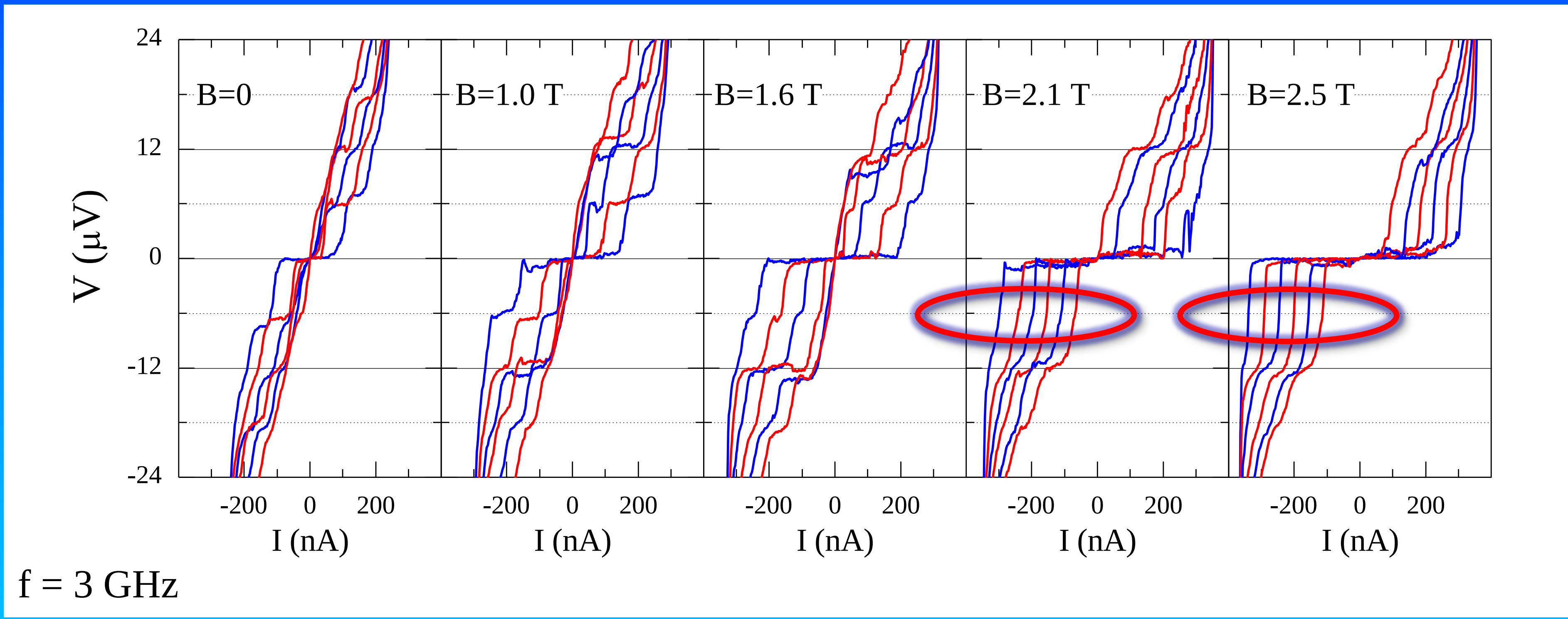


Shapiro steps

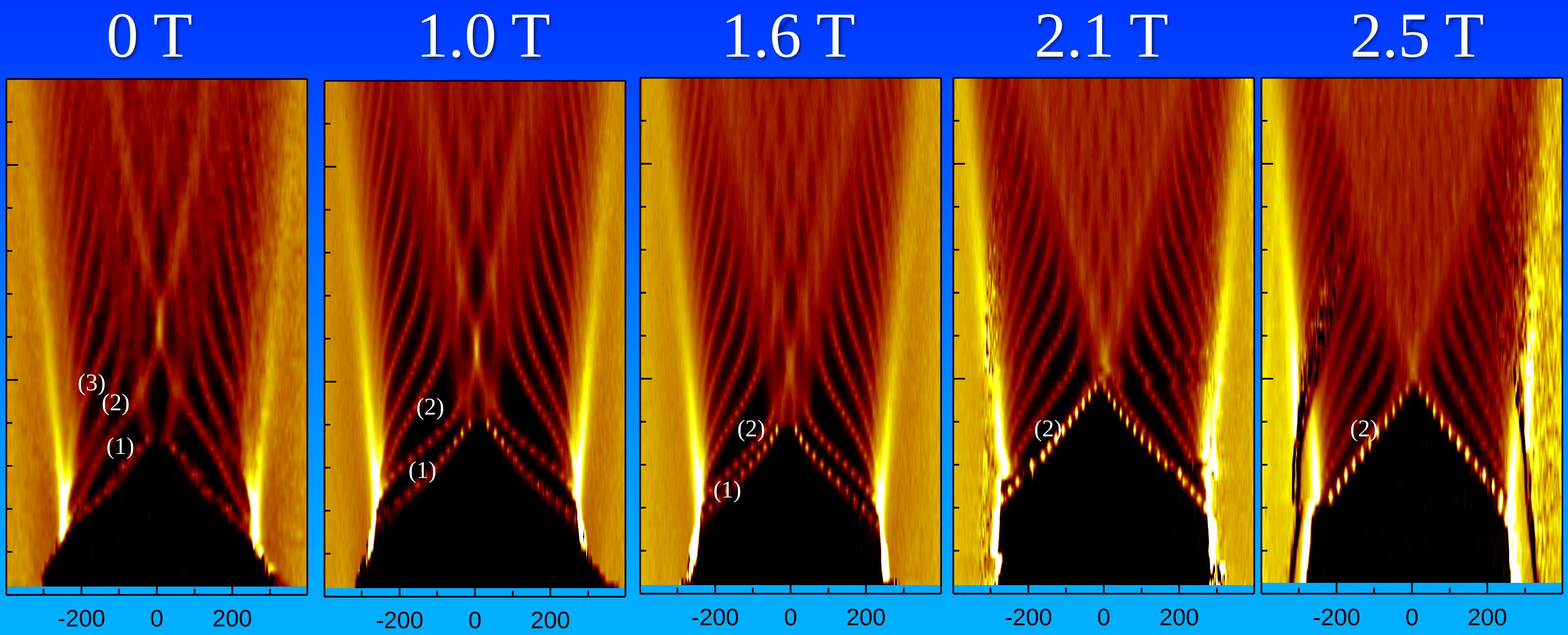
$$\Delta I_n = A\left|J_n\left(\frac{2ev_{rf}}{\hbar\omega_{rf}}\right)\right|$$



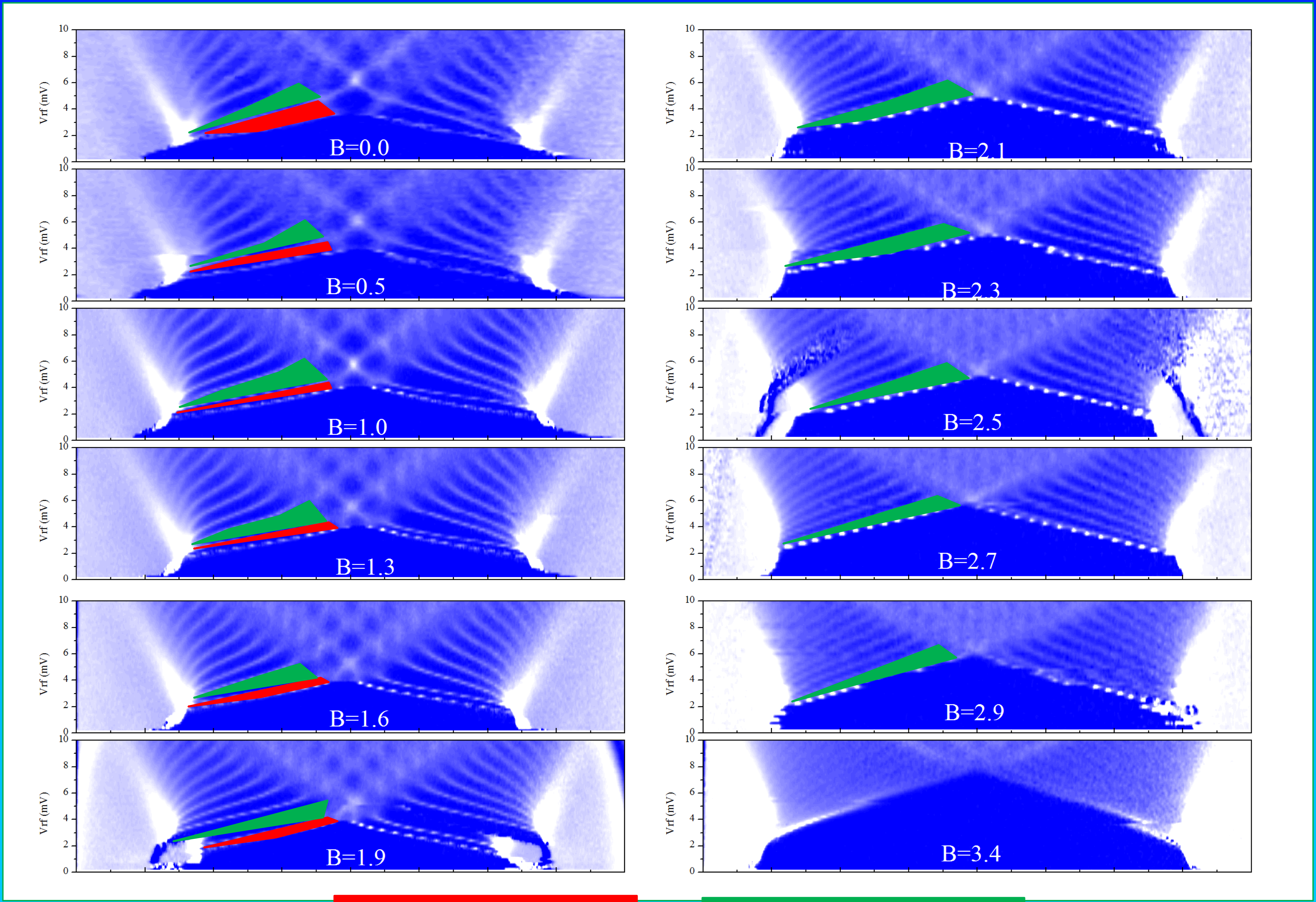
Disappearance of the first Shapiro step



more fields



dV/dI vs B

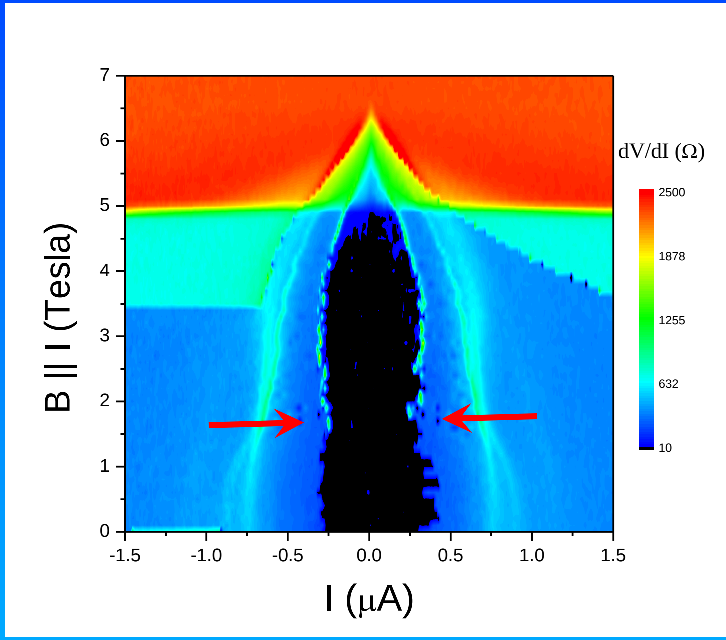


step @ 6 μV

step @ 12 μV

Gap closing at the quantum phase transition

reduction of the I_c at 2 Tesla:



gappless superconductivity?

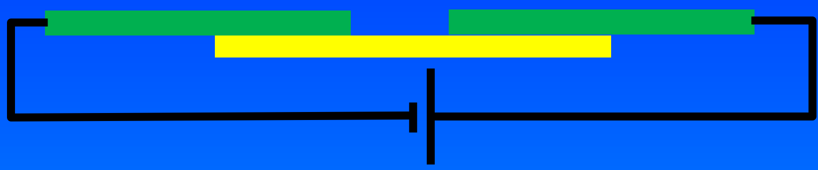
when density of gappless excitation small compared to the gapped ones

$\Delta = 0$ but $I_c > 0$

2π or 4π periodicity?

$$I(\varphi) = I_M \sin(\varphi/2) + I_c \sin(\varphi)$$

voltage bias



$$V(t) = V_0 + V_1 \cos(\omega_{ac} t),$$

$$\varphi(t) = \varphi_0 + \omega_0 t + \frac{2eV_1}{\hbar} \sin(\omega_{ac} t)$$

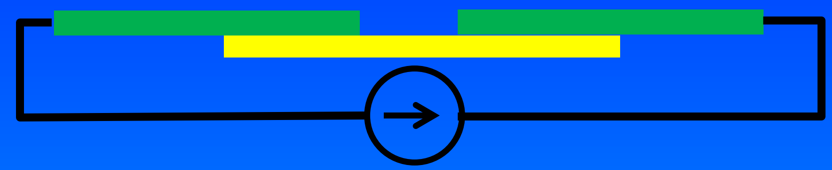
$$I_\pm = \pm \frac{e\Gamma}{2h} \sin(\Delta\varphi/2) - \frac{3e\Gamma^2}{16ht} \sin(\Delta\varphi)$$

I_M I_C

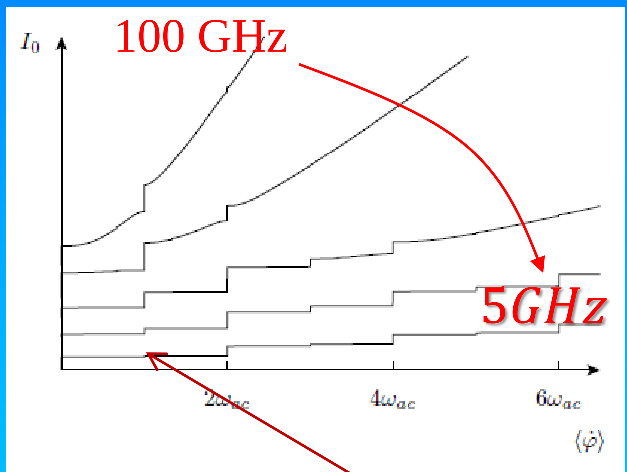
For $\Gamma \sim \Delta$ $I_M \sim I_C$

Lutchyn, Sau & das Sarma '10
Alicea, *et al*, '11

current bias



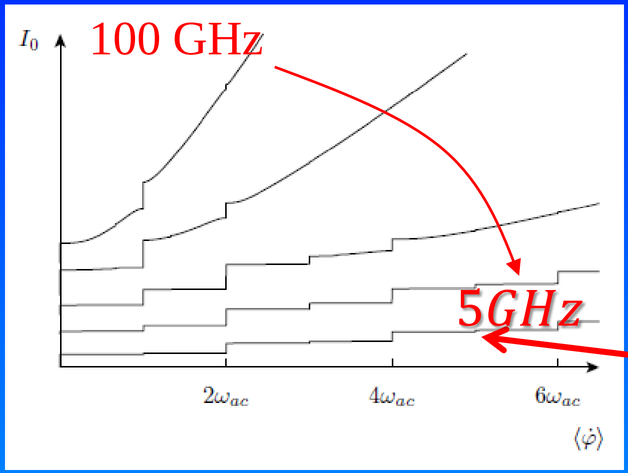
$$I_0 + I_1 \sin(\omega_{ac} t) = I(\varphi(t)) + \frac{\hbar}{2eR} \dot{\varphi}(t).$$



no odd steps for

Domínguez, Hassler, and Platero , '12

current biased junction



$$I(\varphi) = I_M \sin(\varphi/2) + I_c \sin(\varphi)$$

simulations for $I_c = 10\ I_M$

no odd steps for $\omega_{rf} < \frac{2eR_N I_M}{\hbar} \approx 5\text{GHz}$

even step width $\Delta I_n = A|J_n(\beta V_{rf})|$

theory: $A = I_c + I_M/\sqrt{2}$

estimate: $I_M \lesssim {}^{e}/_{\hbar}\, \Delta_{ind} \approx 25\ \text{nA}$

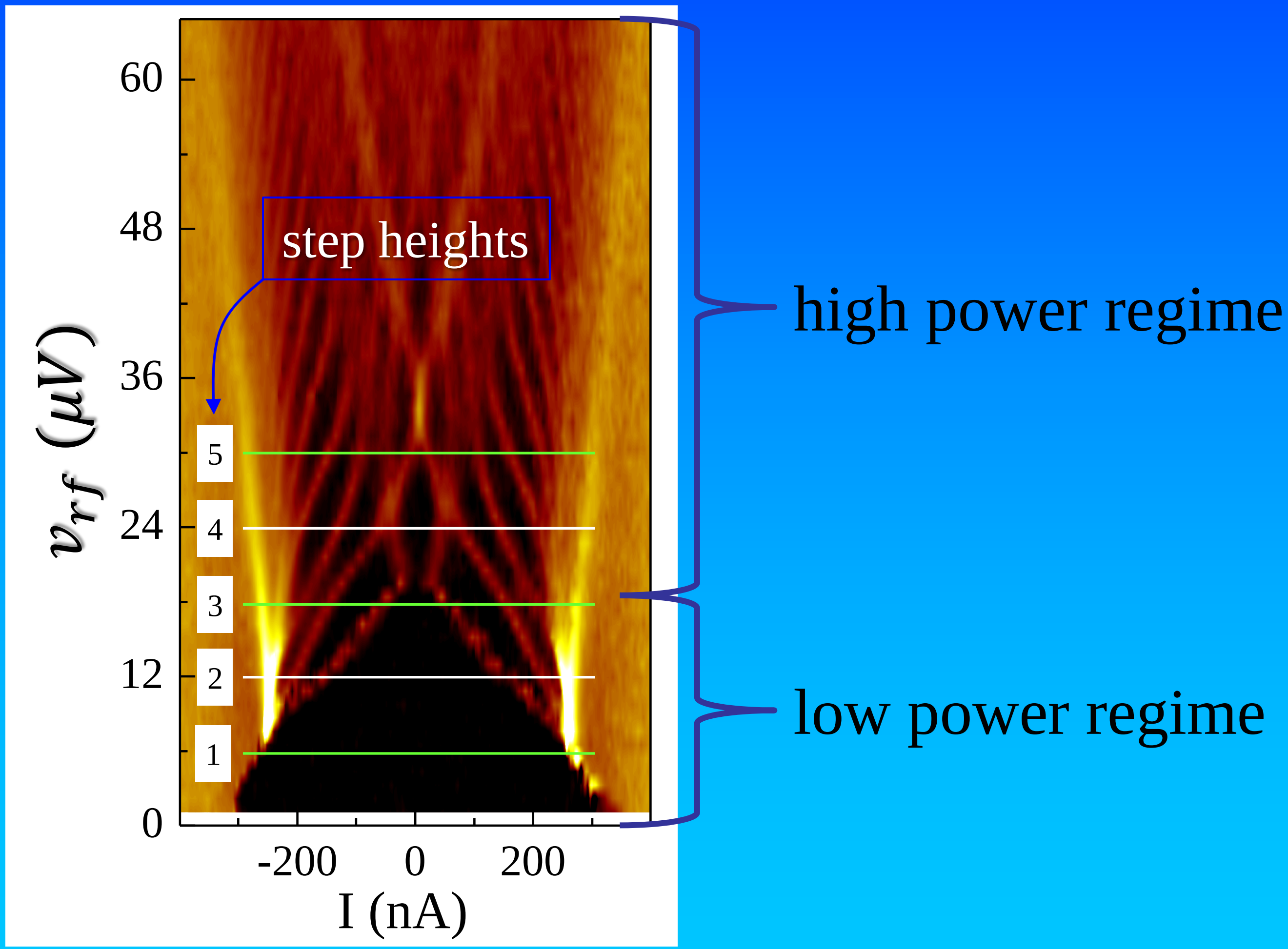
experiment: $A \approx 150\ \text{nA}$

consistent with wire size estimate (~5 modes)

Domínguez, Hassler, and Platero, PRB **86**, 140503 (2012)

3-rd and higher odd steps

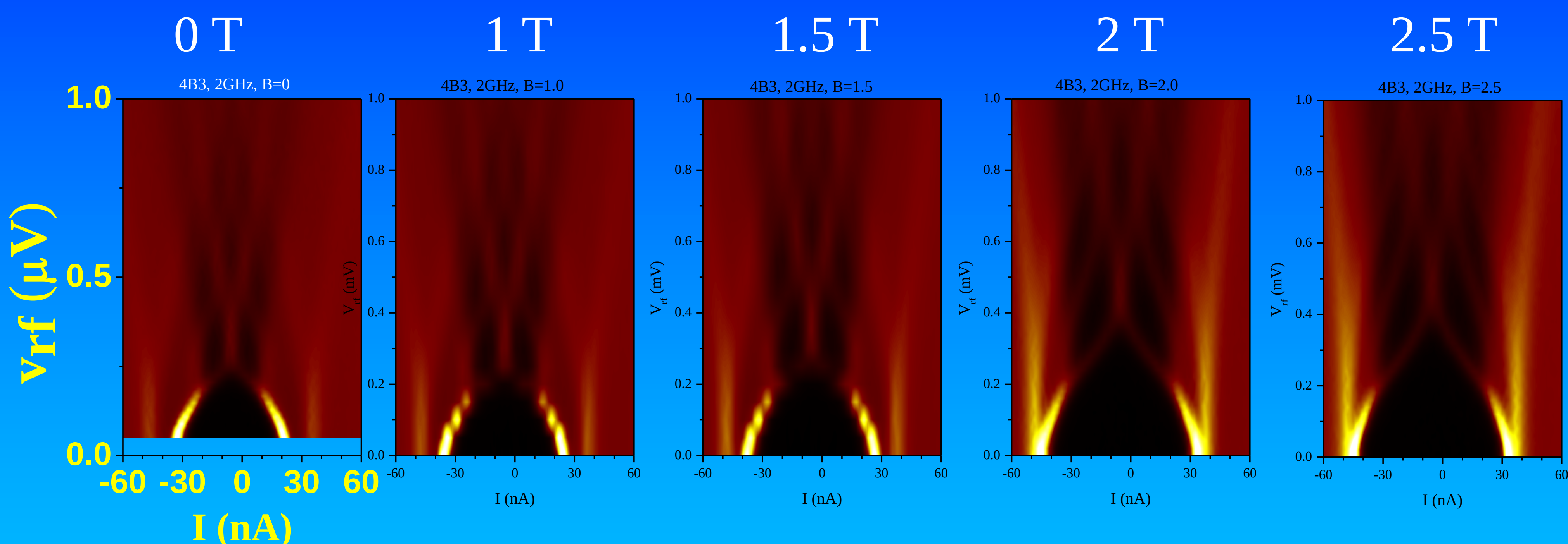
$\Delta I_n = A|J_n\left(\frac{2ev_{rf}}{\hbar\omega_{rf}}\right)|$ v_{rf} – ac voltage on the junction



2π periodicity restored in high power regime

Shapiro steps, different sample

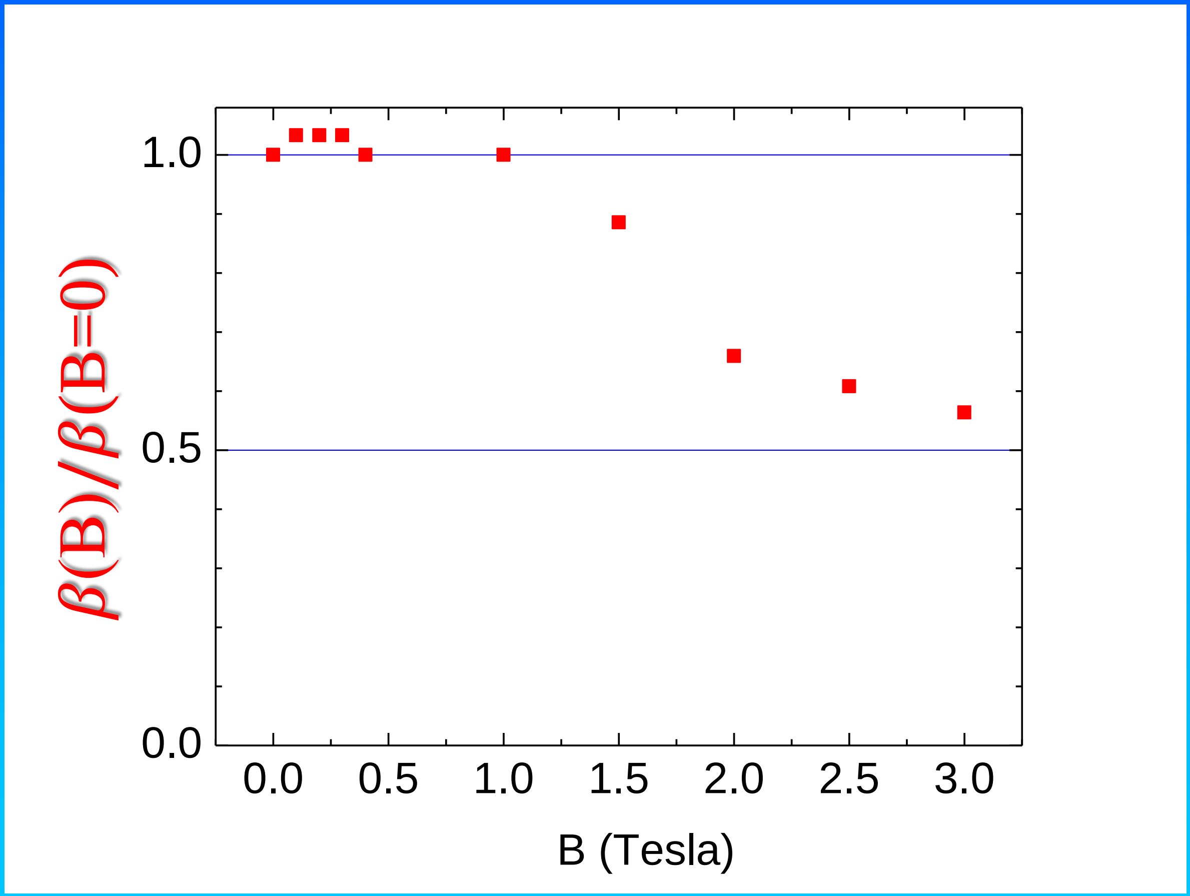
different sample & wafer (device 4B3), T_C = 0.3 K



low-high power transition @ v_{rf}=0.2 µV
first step @ 4 µV (2 GHz)
always at high power regime
all steps are visible

quasiparticle charge change?

$\Delta I_n \propto |J_n(\beta V_{rf})|$ $\beta = \frac{2eaV_{rf}}{\hbar\omega_{rf}}$, α – attenuation



$I_c = 30$ nA, $e/_{\hbar}\,\Delta_{ind} \approx 6$ nA, ~5 channels

conclusions

- 1D Josephson junction Nb/InSb/Nb
- Excess current - evidence of Andreev reflection
- Observe Shapiro steps with 2π periodicity
- At high field first step disappears: 4π periodicity

arXiv: 1204.4212; Nature Physics **8**, 795 (2012)

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

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Observation of the fractional ac Josephson effect: the signature of Majorana particles

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