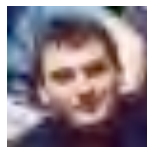


HTc Josephson nano-junctions : physics and applications

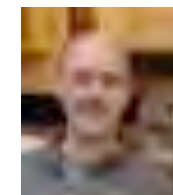
Jérôme Lesueur



Nicolas Bergeal



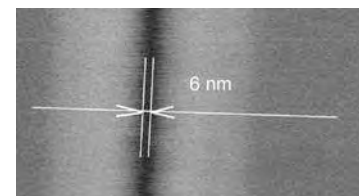
Giancarlo Faini



Martin Sirena



Thomas Wolf

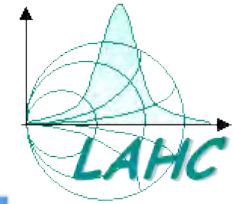


Rozenn Bernard, Javier Briatico, Denis Crété

THALES

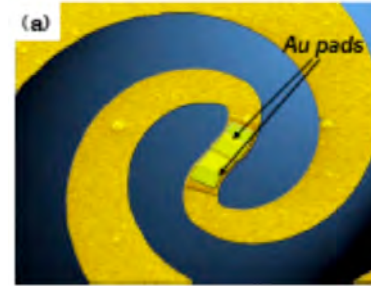


Pascal Febvre

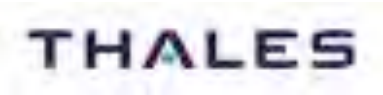
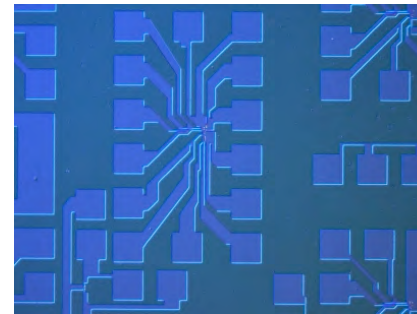


Nicolas Bergeal
Martin Sirena
Thomas Wolf
Alexandre Zimmers

THz



RSFQ



Denis Créte

SQUID



Etalon du Volt

Robin Cantor

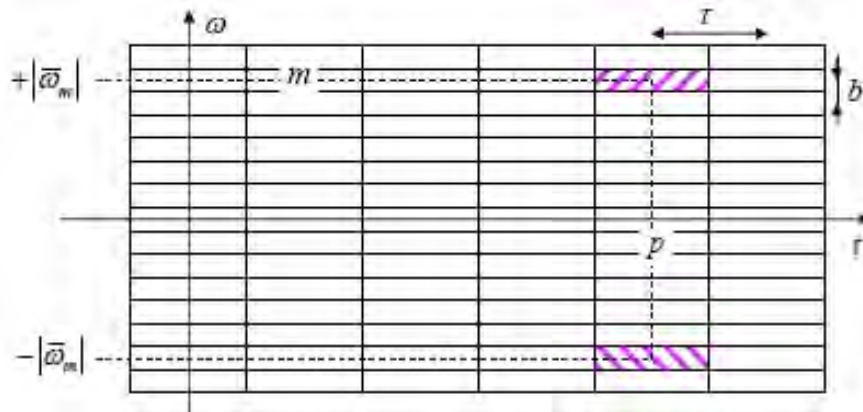


Sophie Djordjevic



Quantum circuits ?

➤ No quantification of the EM field (cf M. Devoret's lecture)



1st

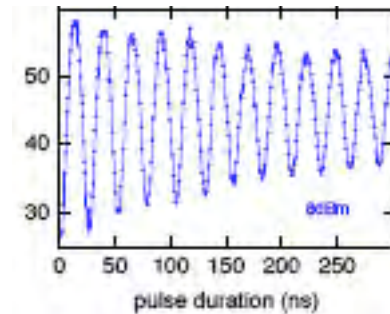
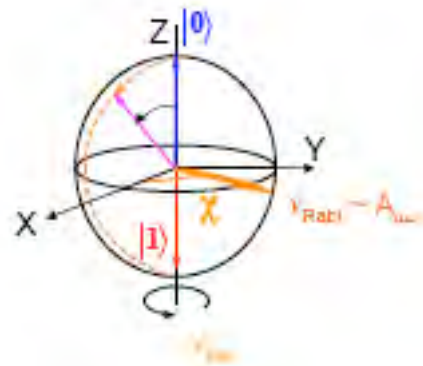
$$\left\{ \hat{A}_{m_1 p_1}^{\leftarrow}, \hat{A}_{m_2 p_2}^{\leftarrow} \right\}_{\text{P.B.}} = -\frac{i}{2} \bar{\omega}_{m_1} \delta_{m_1+m_2} \delta_{p_1-p_2}$$

2d

$$\left[\hat{A}_{m_1 p_1}^{\leftarrow}, \hat{A}_{m_2 p_2}^{\leftarrow} \right] = \frac{\hbar \bar{\omega}_{m_1}}{2} \delta_{m_1+m_2} \delta_{p_1-p_2}$$

➤ No quantum states manipulation (cf O. Buisson's seminar)

$$\frac{|0\rangle + |1\rangle}{\sqrt{2}}$$



Phase properties and superconducting circuits

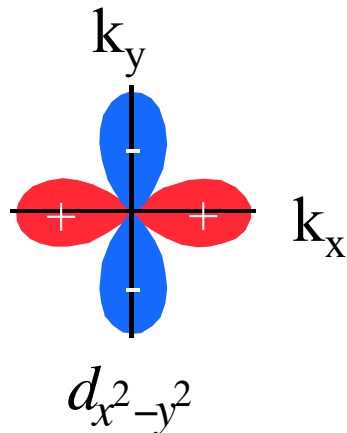
- Phase rigidity of the condensate

$$\Psi = \Psi_0 e^{i\varphi}$$

$$\oint d\varphi = 0$$

$$\int_0^T V(t) dt = \phi_0$$

- Intrinsic phase structure in High Tc SC



Josephson nano-junctions

π -junctions

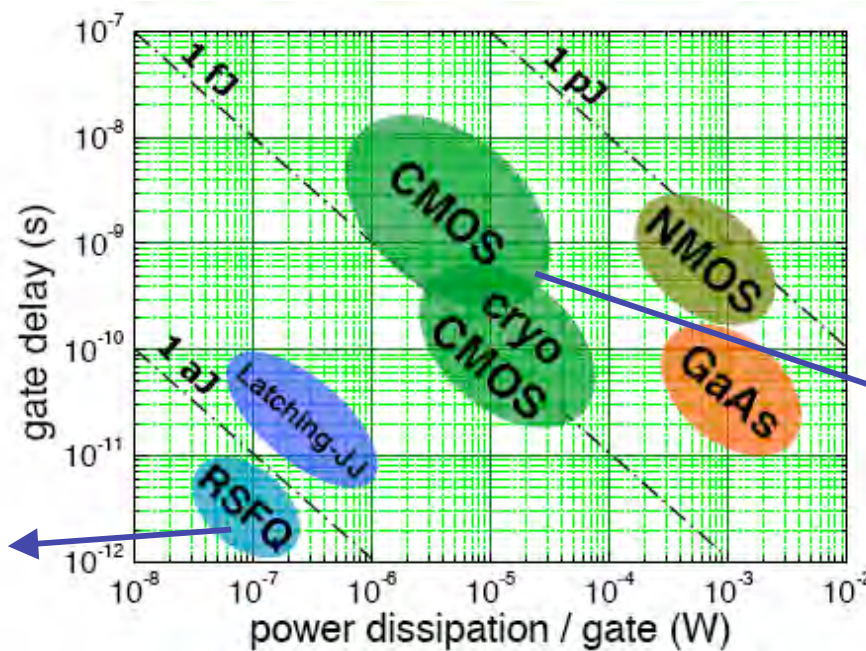
- High speed applications

Analog to Digital converters

Communication systems

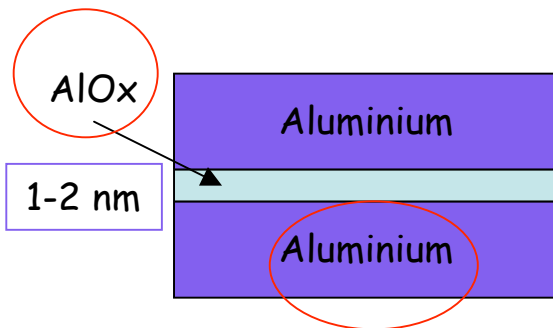
PetaFLOPS computer ...

Superconductive electronics



Superconductors

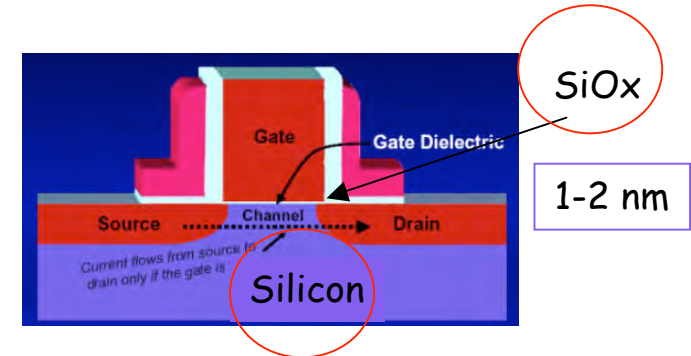
Semiconductors



Josephson Junction



Quantum circuit

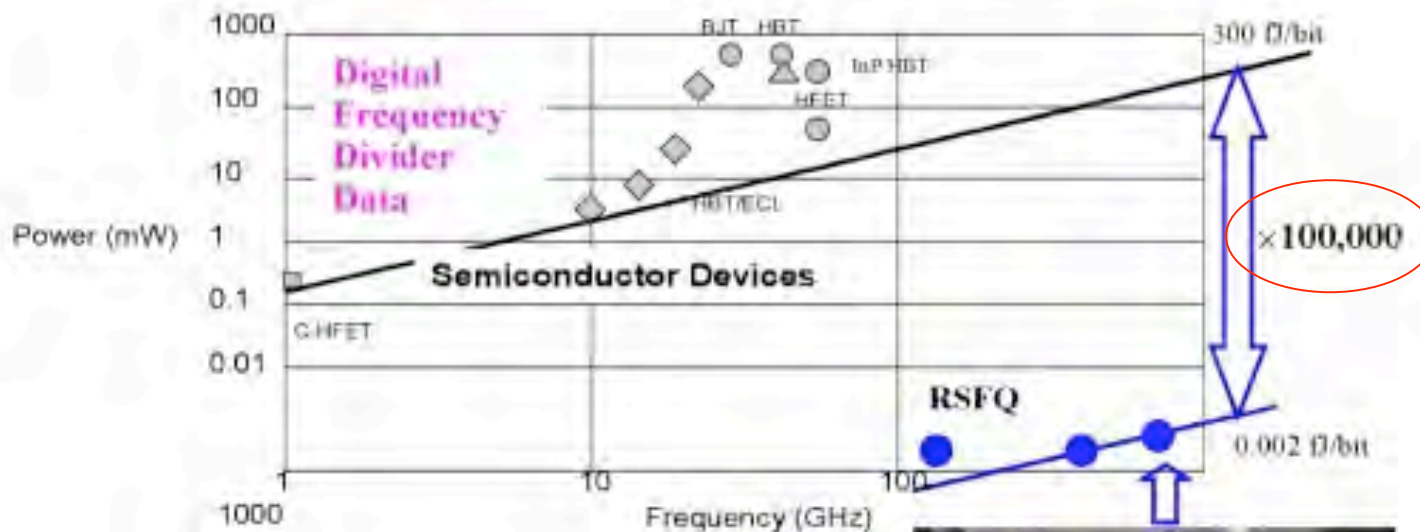


CMOS transistor

Dream or reality ?

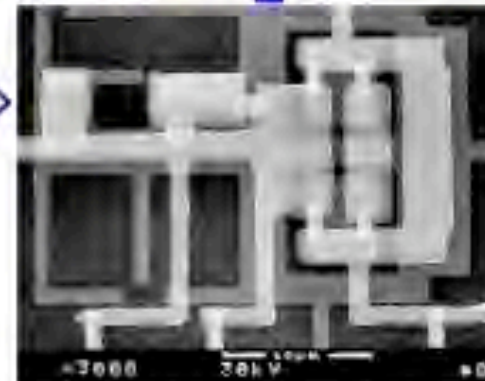
➤ An example : a digital frequency divider

Technology : Nb/Al/AlO_x/Nb @4.2 K



A very simple fabrication technology:
2 metalization layers & 0.5 μm lithography
for a 770 GHz, 1.5 μW digital device

BOTTOM LINE:
RSFQ is the *fastest*, the *simplest*, and the *lowest-power* digital technology available



RSFQ- SUNY Frequency divider

Outline

1. Superconductive electronics

Dynamics of Josephson Junctions

Rapid Single Flux Quanta logic

Actual RSFQ devices

2. High T_c Josephson nanoJunctions

Ion irradiation of High T_c Superconductors

Making Nanojunctions

Major characteristics of the Nanojunctions

A few applications

3. Physics of High T_c nanojunctions

Proximity effect

Quasi-classical diffusive approach

D-wave order parameter symmetry

π -junctions and RSFQ devices

4. Conclusions

Outline

1. Superconductive electronics

Dynamics of Josephson Junctions

Rapid Single Flux Quanta logic

Actual RSFQ devices

2. High T_c Josephson nanoJunctions

Ion irradiation of High T_c Superconductors

Making Nanojunctions

Major characteristics of the Nanojunctions

A few applications

3. Physics of High T_c nanojunctions

Proximity effect

Quasi-classical diffusive approach

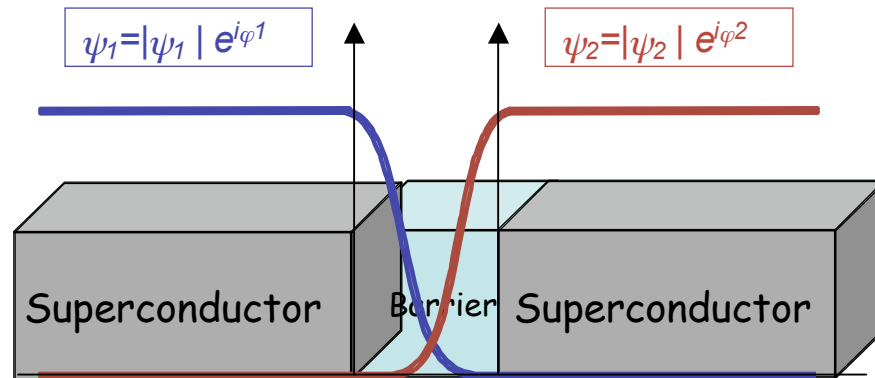
D-wave order parameter symmetry

π -junctions and RSFQ devices

4. Conclusions

Josephson Junctions

➤ Josephson Junctions



➔ Josephson equations

$$I = I_c \sin(\varphi) \quad \varphi = \varphi_1 - \varphi_2$$

$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar} = \frac{2\pi V}{\phi_0}$$

$$483\,597,9 \text{ GHz/V}$$

Barrier : insulator, normal metal, constriction ...

➔ Josephson Energy

$$E_J = \frac{\phi_0 I_c}{2\pi} (1 - \cos(\varphi))$$

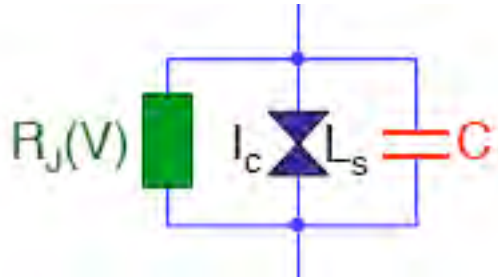
➤ Applications : superconductive electronics

- Photon detection : 1 junction
- SQUID for magnetometry, voltmetry ... : 2 junctions
- Rapid Single Flux Quantum (RSFQ) logic : from 10 to millions junctions !

Modeling a Josephson Junction

➤ RC Shunted Junction Model

$$I(t) = I_J(t) + I_R(t) + I_C(t)$$



$$I(t) = I_c \sin(\varphi(t)) + \frac{V(t)}{R_J} + C_J \frac{\partial V(t)}{\partial t}$$

➤ Josephson Junction : a non-linear inductance

$$V(t) = \frac{\phi_0}{2\pi} \frac{\partial \varphi(t)}{\partial t}$$

$$V(t) = L_J \frac{\partial I_J(t)}{\partial t}$$

$$L_J = \frac{\phi_0}{2\pi I_c \cos \varphi(t)}$$

$$\frac{I(t)}{I_c} = \sin(\varphi(t)) + \frac{L_{J0}}{R_J} \frac{\partial \varphi(t)}{\partial t} + L_{J0} C_J \frac{\partial^2 \varphi(t)}{\partial t^2}$$

The mechanical analogy

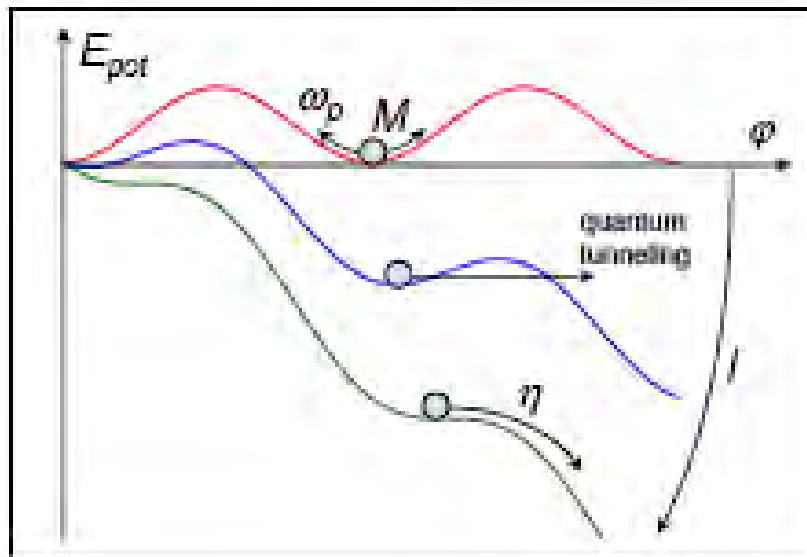
➤ Normalized equation

$$E_{J0} \frac{\partial}{\partial \varphi} (1 - \cos(\varphi) - i\varphi) + \left(\frac{\hbar}{2e}\right)^2 \frac{1}{R_J} \frac{\partial \varphi}{\partial t} + \left(\frac{\hbar}{2e}\right)^2 C_J \frac{\partial^2 \varphi}{\partial t^2} = 0$$

$$E_J = \frac{\hbar I_c}{2e} (1 - \cos(\varphi))$$

$$i(t) = I(t) / I_c$$

➤ « Washboard » potential : phase difference motion



$$\nabla U + \eta \frac{\partial x}{\partial t} + M \frac{\partial^2 x}{\partial t^2} = 0$$

« damping »

« mass »

Dynamics of a Josephson Junction

➤ Characteristic times

$$\frac{I(t)}{I_c} = \sin(\varphi(t)) + \frac{L_{J0}}{R_J} \frac{\partial \varphi(t)}{\partial t} + L_{J0} C_J \frac{\partial^2 \varphi(t)}{\partial t^2}$$

$$\tau_p = \sqrt{\frac{2\pi\phi_0 C_J}{I_c}}$$

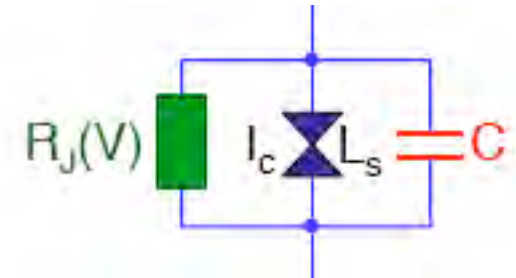
$$\tau_{LR} = \frac{\phi_0}{2\pi I_c R_J}$$

$$\tau_{RC} = R_J C_J$$

➤ Mc Cumber parameter

$$\tau = \frac{t}{\tau_{LR}}$$

$$\beta_c = \frac{\tau_{RC}}{\tau_{LR}} = \frac{2\pi I_c C_J R_J^2}{\phi_0}$$



$$\sin \varphi - i + \frac{\partial \varphi}{\partial \tau} + \beta_c \frac{\partial^2 \varphi}{\partial \tau^2} = 0$$

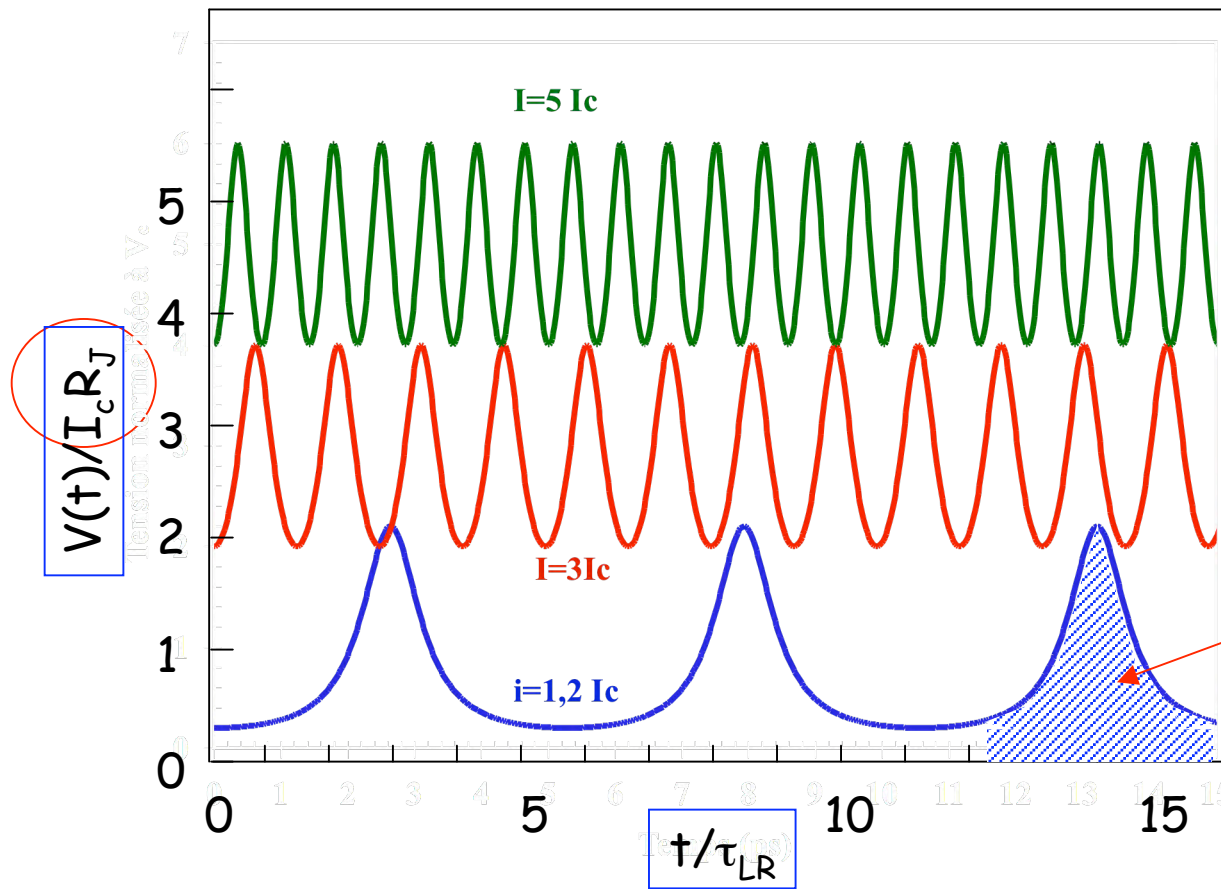
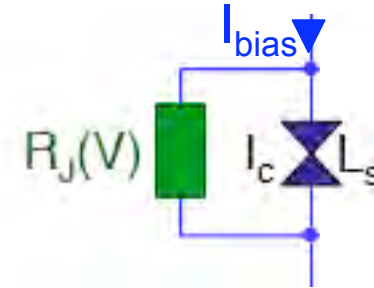
$\beta_c \gg 1$ underdamped

$\beta_c \leq 1$ overdamped

R & C small
No tunnel

Voltage and current across a current biased JJ

➤ Current biased overdamped Josephson Junction



$$\langle V \rangle = \frac{1}{T} \int_0^T V(t) dt = \frac{\phi_0}{T}$$

➤ Quantized pulses

➤ Timescale $\tau_{LR} \approx ps$

➤ $V_{max} \approx 2I_c R_J \approx mV$

➤ Energy $\approx I_c \Phi_0 \approx aJ$

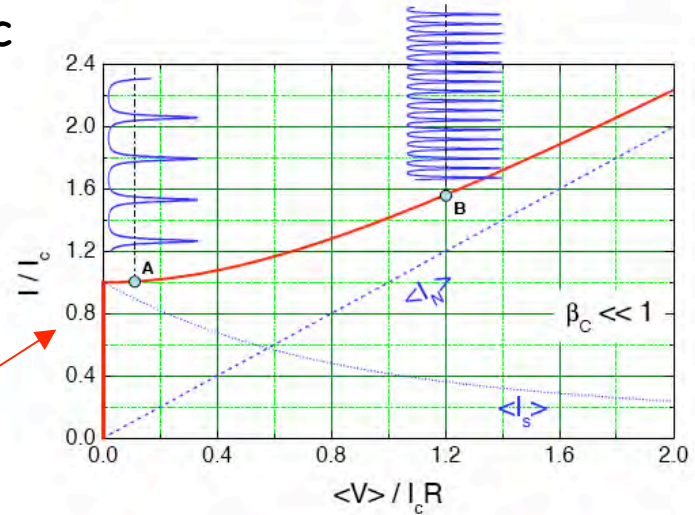
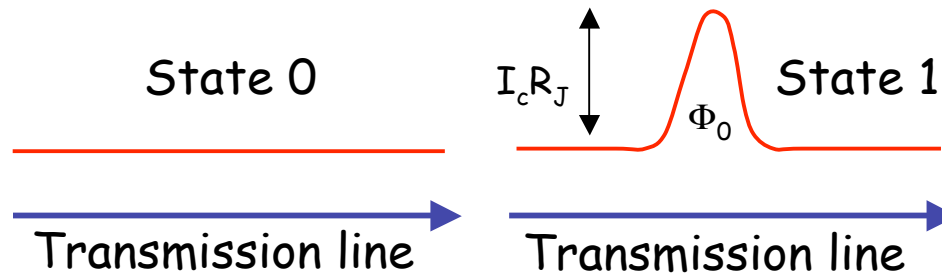
$$T = \frac{2\pi \tau_{LR}}{\sqrt{i^2 - 1}}$$

$$\tau_{LR}$$

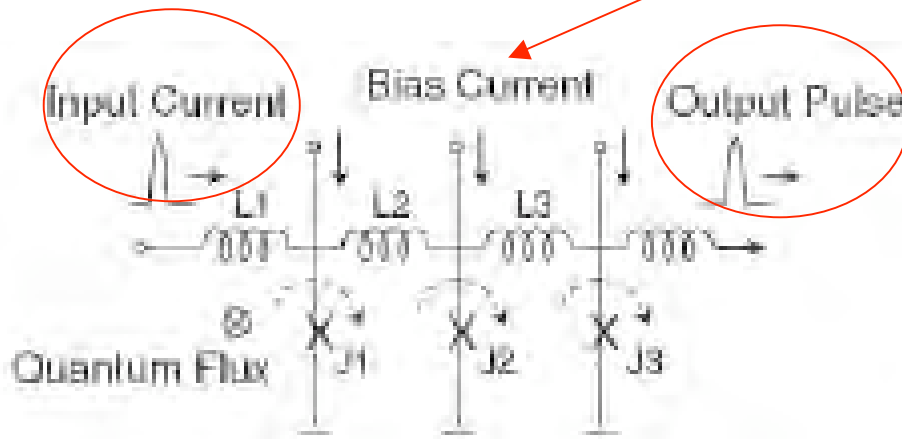
$$\tau_{LR} = \frac{\phi_0}{2\pi I_c R_J}$$

Rapid Single Flux Quanta logic

➤ Likarev's basic idea (1985) : dynamical logic

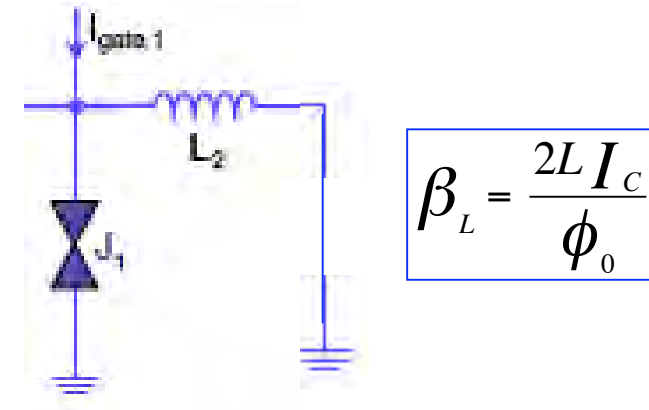


➤ Current biased overdamped JJ ($I_b < I_c$)



Josephson transmission line

➤ Inductance (RF SQUID)

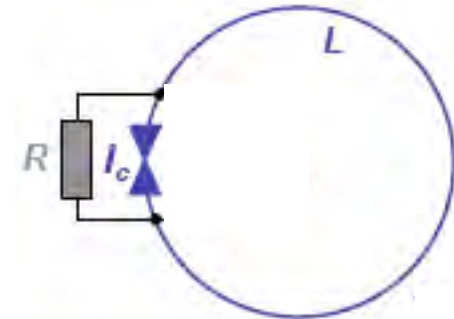


Dynamics of an RF SQUID

➤ Fluxoid quantification

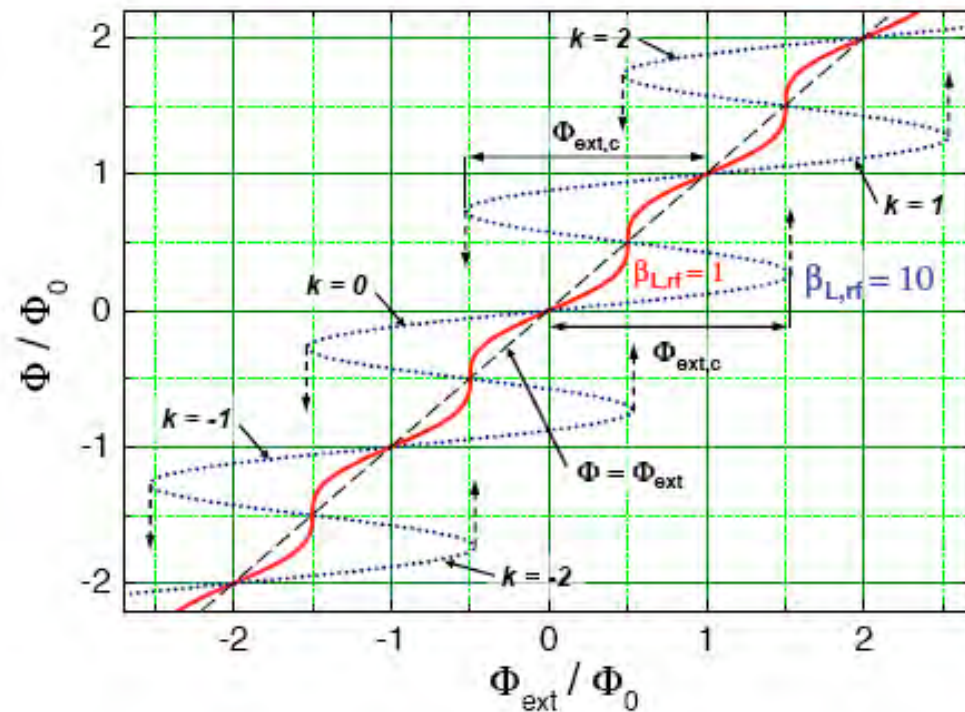
$$\frac{\phi}{\phi_0} = \frac{\Phi_{ext}}{\phi_0} - \frac{\beta_L}{2\pi} \sin\left(2\pi \frac{\phi}{\phi_0}\right)$$

$$\beta_L = \frac{2LI_C}{\phi_0}$$



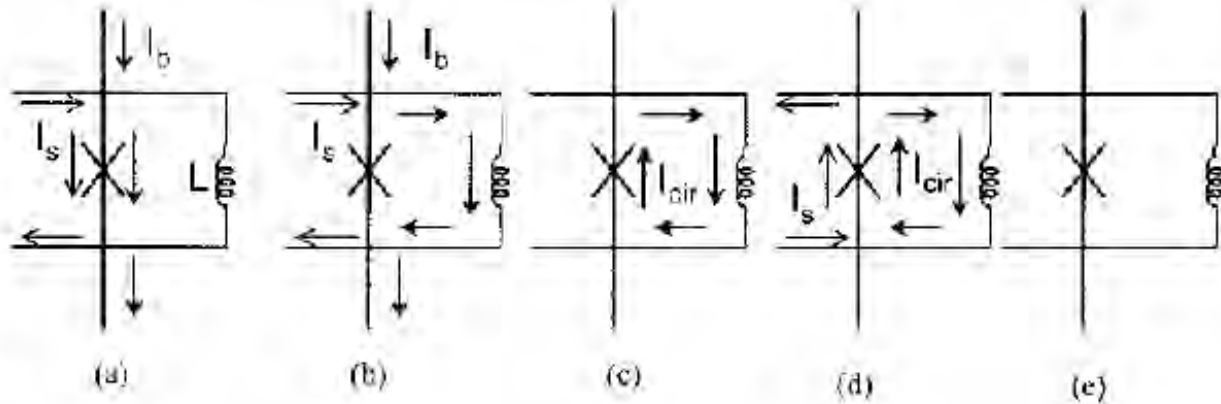
$\beta_L \ll 1$ Non-hysteretic

$\beta_L \gg 1$ Hysteretic



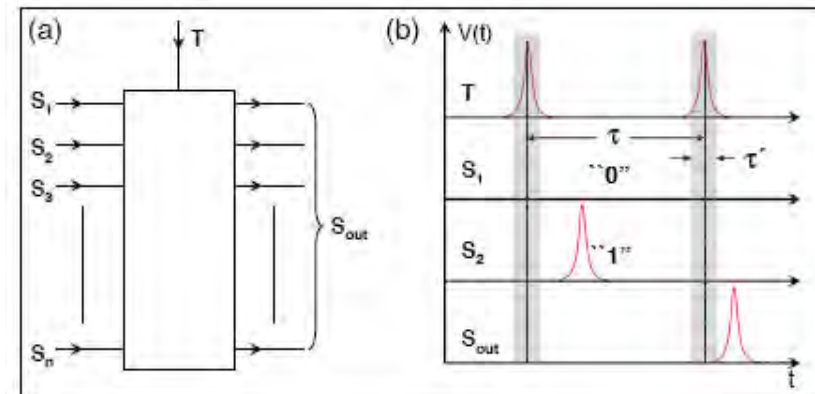
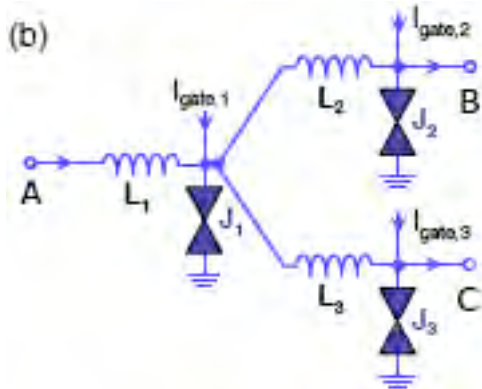
Storing and manipulating pulses

➤ Storing a pulse



$$\Phi_0 < LIc < 2\Phi_0$$

➤ Manipulating pulses



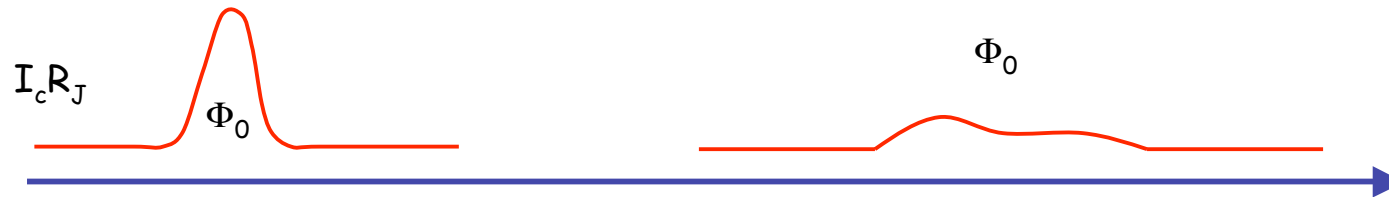
➤ RSFQ circuits : JJ and inductances

$$\Phi_0 < LIc$$

$$\Phi_0 > LIc$$

Advantages of RSFQ logic

- Robust pulse along the way



- Intrinsic speed : THz frequency

$$\tau_{LR} = \frac{\phi_0}{2\pi I_c R_J}$$

$$I_c \approx 0.1 - 1 \text{ mA}$$

$$R_J \approx 1 - 10 \Omega$$

$$1/\tau_{LR} \approx 1-10 \text{ THz}$$

- Low power consumption

$$\text{Energy} \approx I_c \Phi_0$$

$$f \approx 0.1 - 1 \text{ THz}$$

$$P \approx 0.1 - 1 \text{ nW}$$

$$N \approx 10^6 \text{ gates}$$

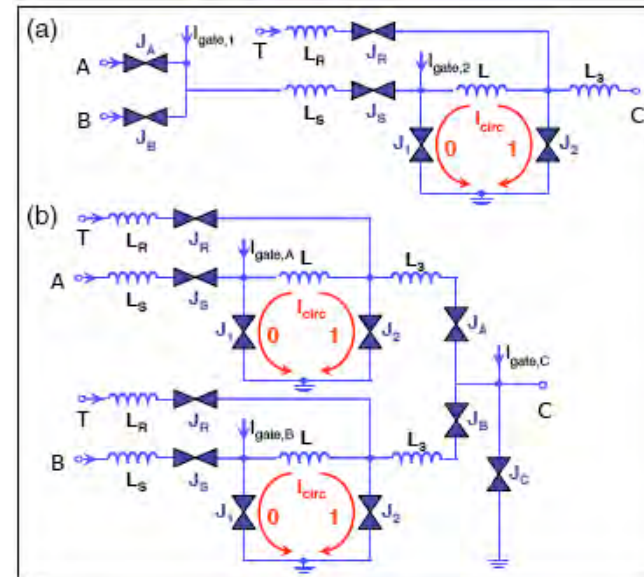
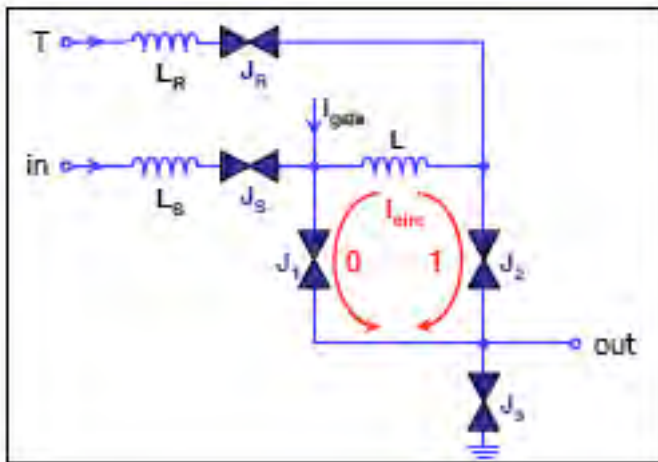
$$P \approx 0.1 - 1 \text{ mW}$$

- Overdamped : no tunnel junctions

A complete logic library

➤ All logic elements possible

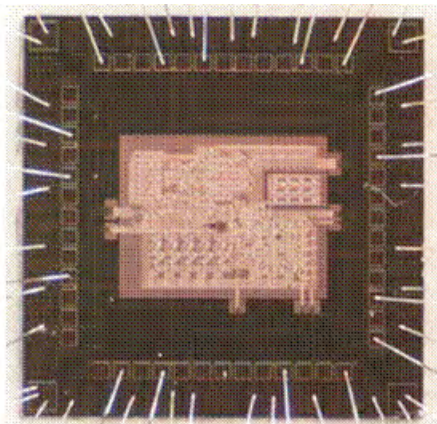
NOT



T-NOR

T-AND

➤ Low Tc Micro processor (ISTEC Japan)



An SFQ micro-processor

15.5 GHz

1.6 mW

- Technology : Nb/Al/AlOx/Nb @4.2 K
- 8000 to 30000 junctions
- Max speed : 770 GHz, sampler

Superconductive electronics : the Holy Graal ?

➤ Important parameters

$$\tau_{LR} = \frac{\phi_0}{2\pi I_c R_J}$$

$$\beta_c = \frac{\tau_{RC}}{\tau_{LR}} = \frac{2\pi I_c C_J R_J^2}{\phi_0}$$

→ unity $\tau_{LR} \propto \sqrt{\frac{C_J}{I_c}}$

Robust against thermal fluctuations

$$I_c > \frac{k_B T}{\phi_0}$$

~~Today Low Tc~~
~~Tomorrow High Tc~~

- Temperature ~~4.2 K~~ 100 K
- Current density $\gg 10 \text{ kA/cm}^2$
- SC gap ~~1 mV~~ 20-30 mV
- 5 to 10% spread
- 30000 JJ

?????

Increasing current density j_c

Increasing superconducting gap $I_c R_N$

Decreasing the JJ characteristic spread

High Tc Superconductive electronics ... today

- High Tc A/D convertor (ISTEC Japan)

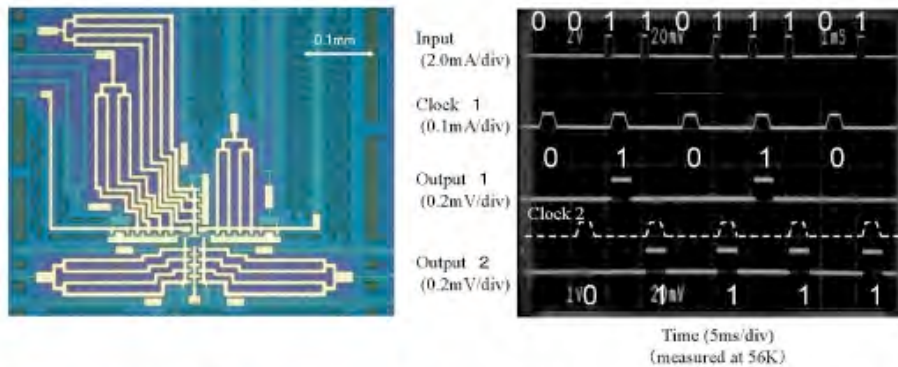


Fig.1. Photomicrograph of the 1:2 switch test circuit

Fig.2. Example of output waveform of the 1:2 switch test circuit

- Technology : YBCO @77.7 K
- 10 to 15 junctions

- Complex materials
- Multi-component oxides ($\text{YBa}_2\text{Cu}_3\text{O}_7$)
- High temperature processing (700-800°C)
- Very sensitive to disorder ...

HTSc Josephson Junctions technology :
reliability, ageing, integration, cost effective

Outline

1. Superconductive electronics

Dynamics of Josephson Junctions

Rapid Single Flux Quanta logic

Actual RSFQ devices

2. High Tc Josephson nanoJunctions

Ion irradiation of High Tc Superconductors

Making Nanojunctions

Major characteristics of the Nanojunctions

A few applications

3. Physics of High Tc nanojunctions

Proximity effect

Quasi-classical diffusive approach

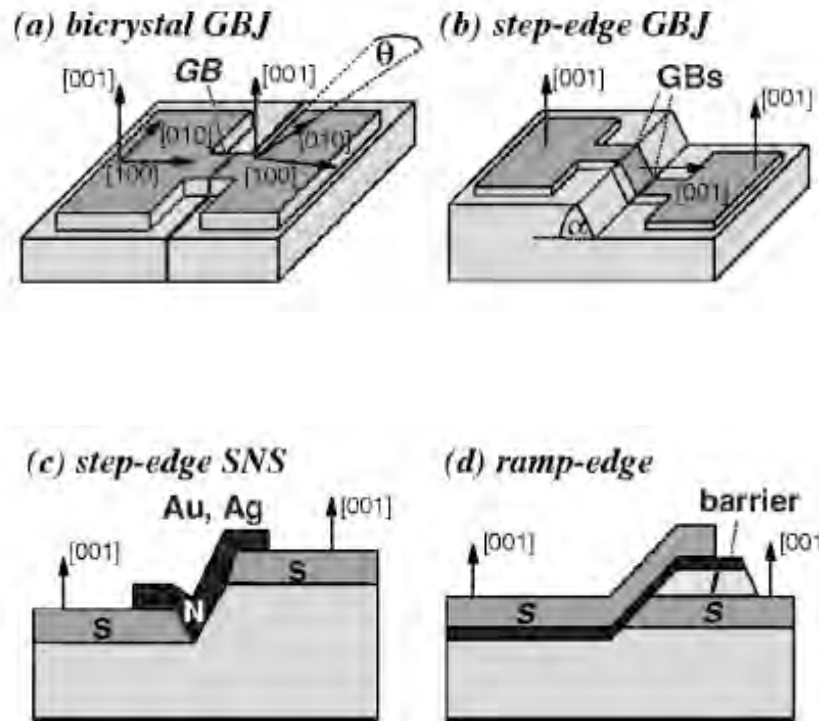
D-wave order parameter symmetry

π -junctions and RSFQ devices

4. Conclusions

« Standard » High Tc Josephson junctions

➤ Complex materials ...



■ Grain boundary junctions

Special substrates
Design constraints
Lack of reproducibility

■ Ramp junctions

➤ Alternative technology

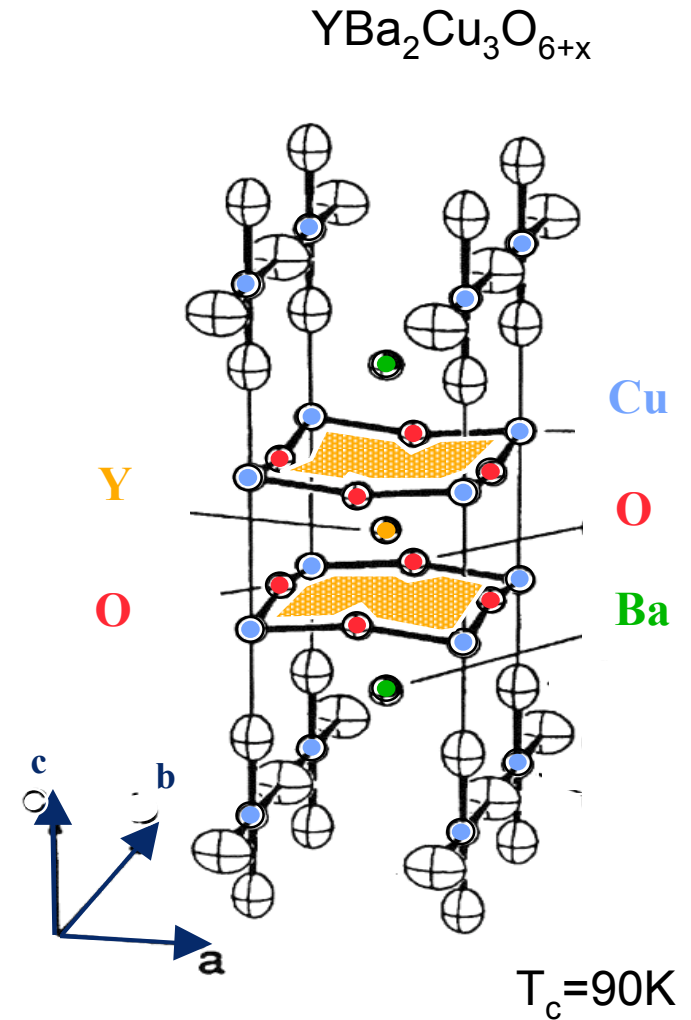
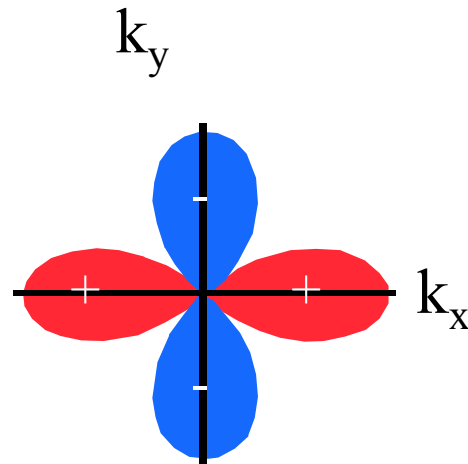
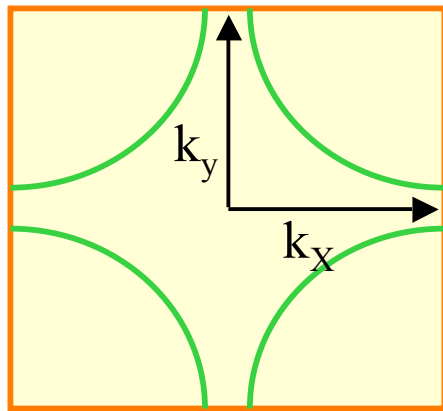


Ion irradiation

Kahlmann et al & Katz et al APL'98

High Tc cuprate superconductors

- High Tc superconductors
- Hole-doped in the CuO_2 plane
- Anisotropic 2D Fermi Surface

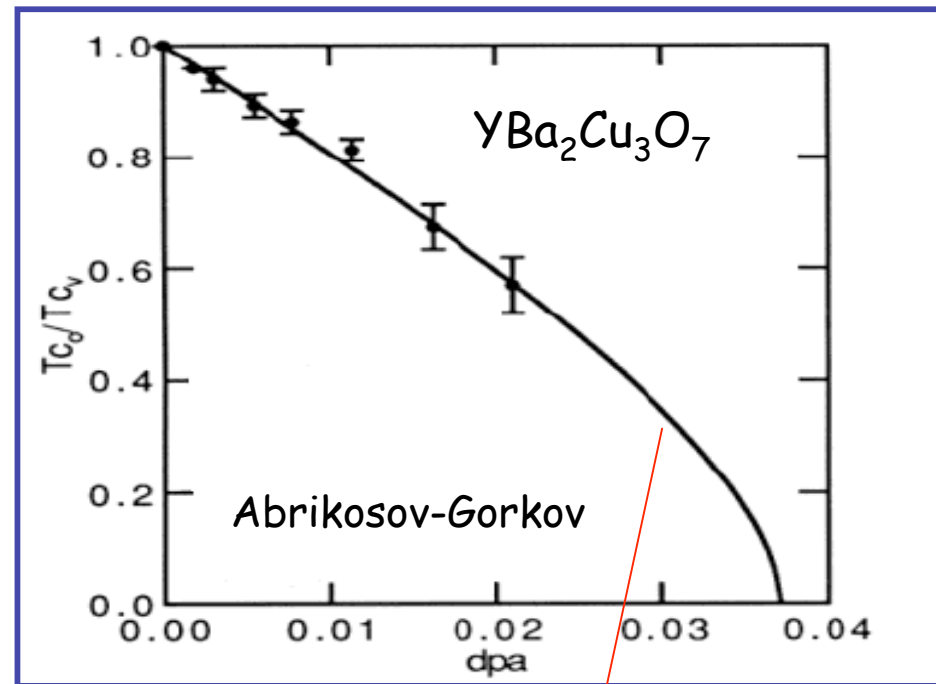
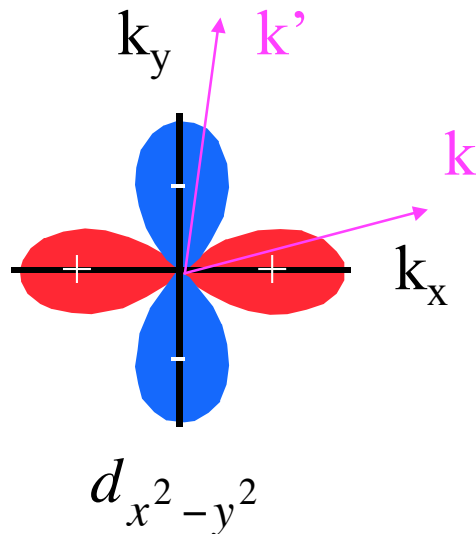


- Order parameter symmetry : $d_{x^2-y^2}$

Disorder in High Tc Superconductors

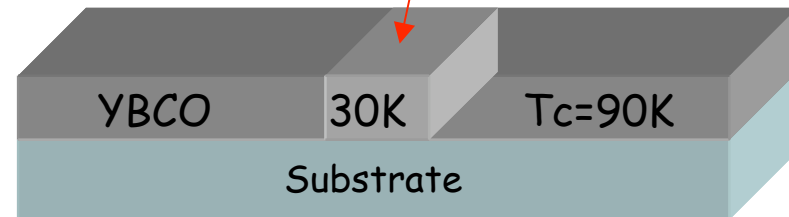
➤ Defect in $d_{x^2-y^2}$ superconductor

➔ depairing



➤ Local control of the disorder

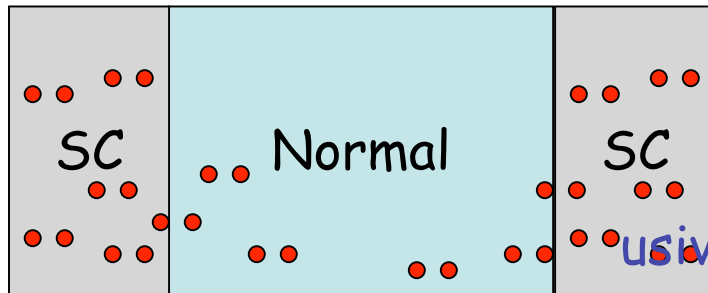
➤ Nanoscale engineering (ξ_N)



30K < T < 90K Super/Normal/Super Josephson junction

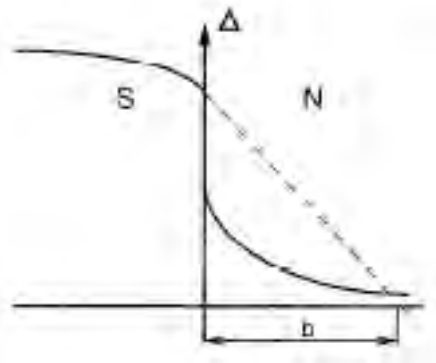
Proximity effect based Josephson Junctions

➤ Phase coherence through normal metal : Josephson coupling



Diffusive case

$$I_c = I_0 \left(1 - \frac{T}{T_c}\right)^2 \frac{l/\xi_N}{\sinh(l/\xi_N)}$$



$$\psi_N(x) \approx \psi_N(0^+) e^{-\frac{x}{\xi_N}}$$

$$\xi_N = \sqrt{\frac{\hbar D}{2\pi k_B T}}$$



A few 10 nm

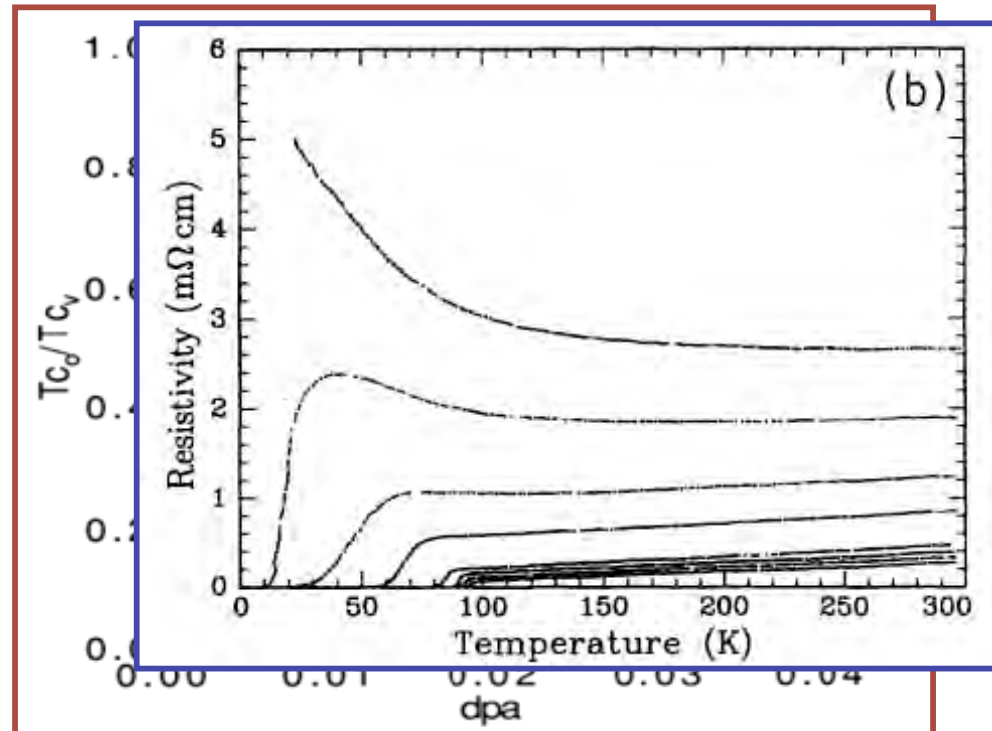
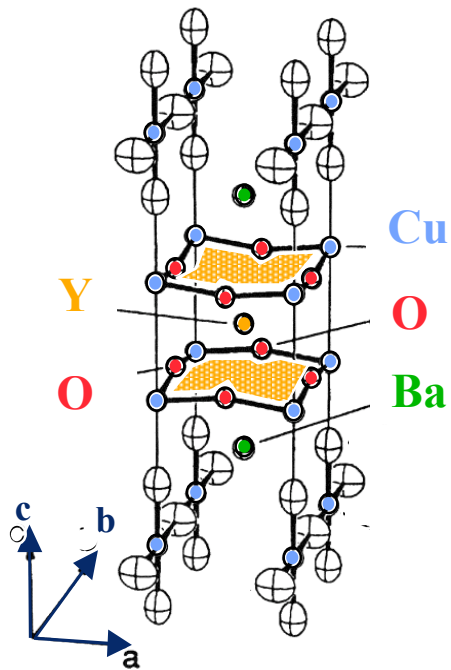
De Gennes : Rev Mod Physics 1964



Towards the insulator

➤ Defect in $d_{x^2-y^2}$ superconductor ➔ depairing

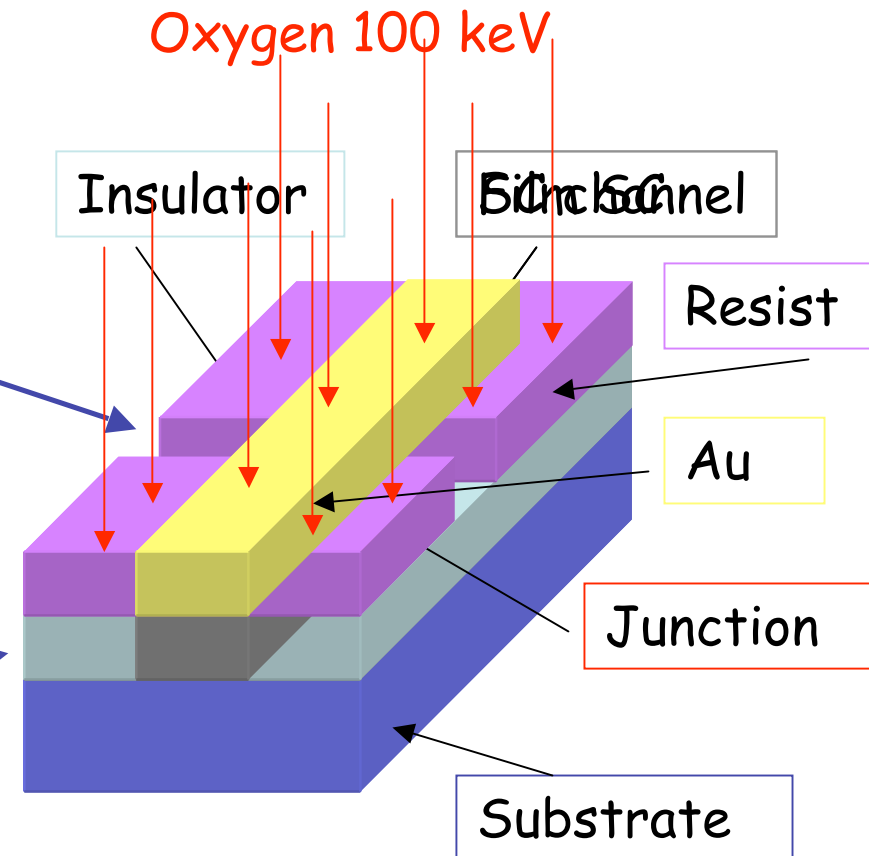
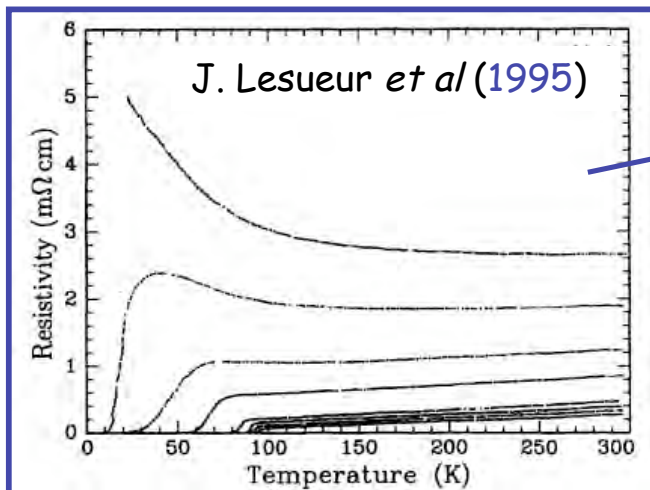
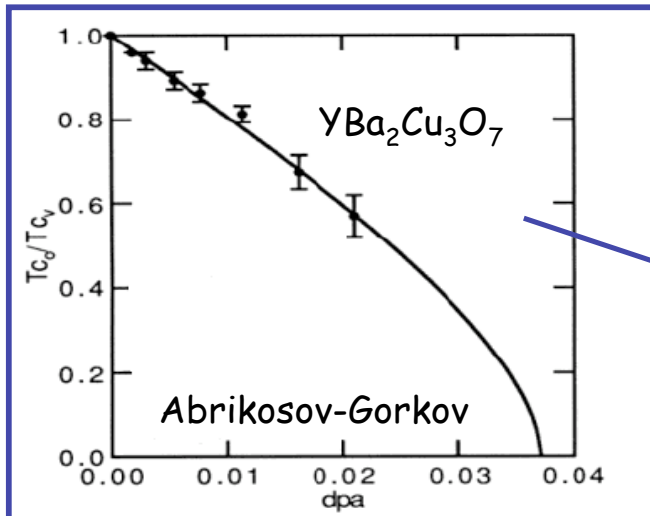
➤ High defect concentration in insulator increases



Lesueur *et al* (1995)

Fabrication of High Tc nano-Junctions

- Control the defect density through ion irradiation
- two-steps strategy :



2

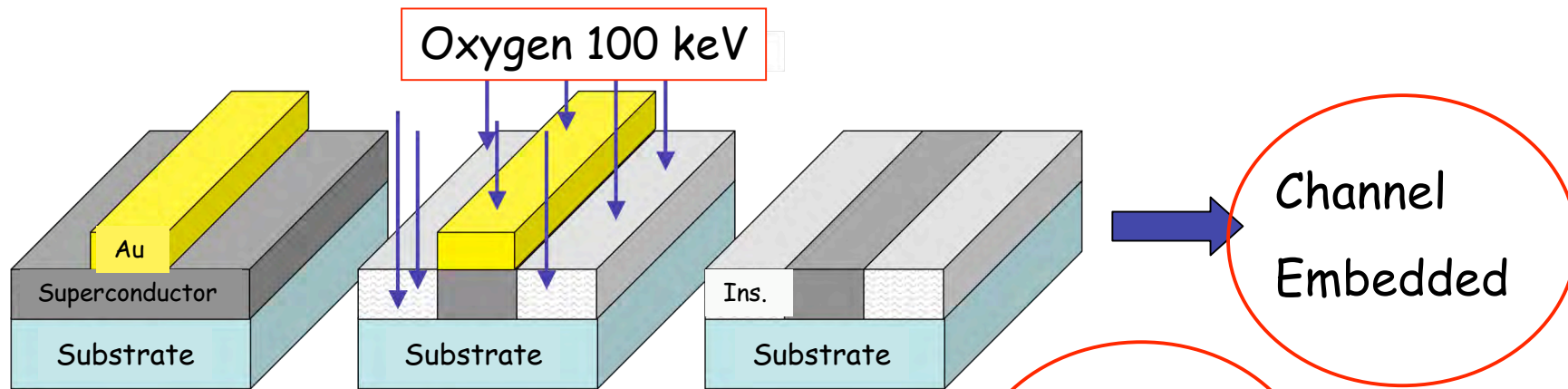
1

1 : drawing channels : (10^{15} at/ cm^2)

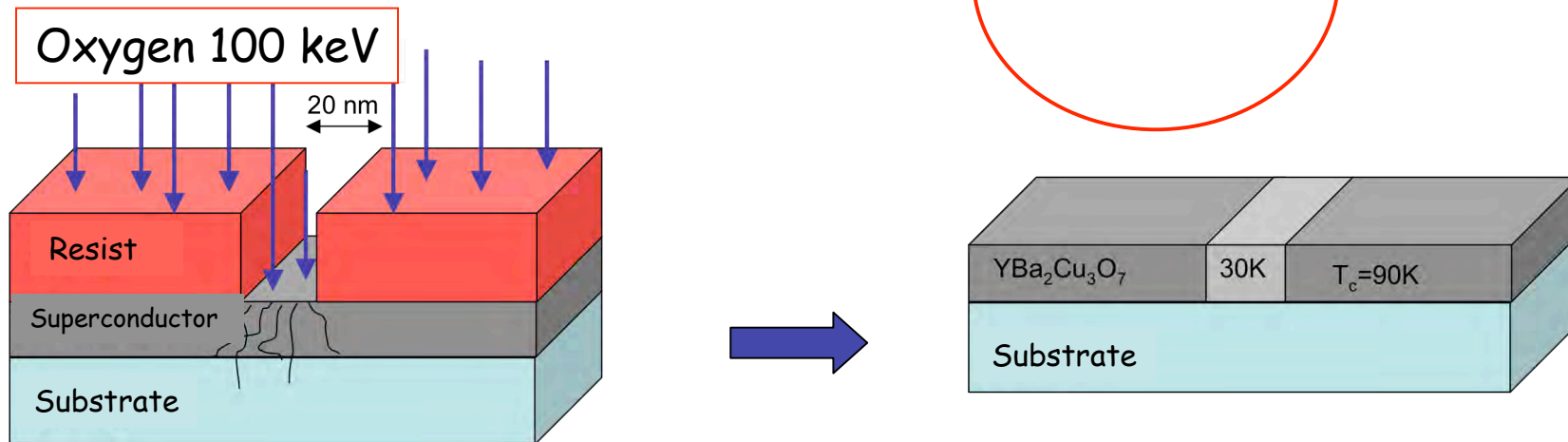
2 : creating nanoJunctions : (10^{13} at/ cm^2)

Tailoring at a nanoscale

➤ First step : channel in a $\text{YBa}_2\text{Cu}_3\text{O}_7$ film (thickness = 1500\AA)



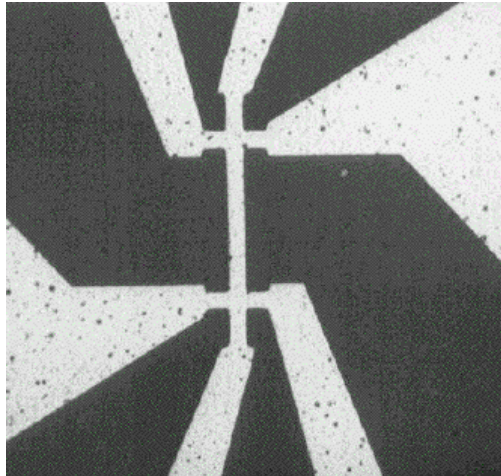
➤ Second step : nanojunction through a 20 nm slit



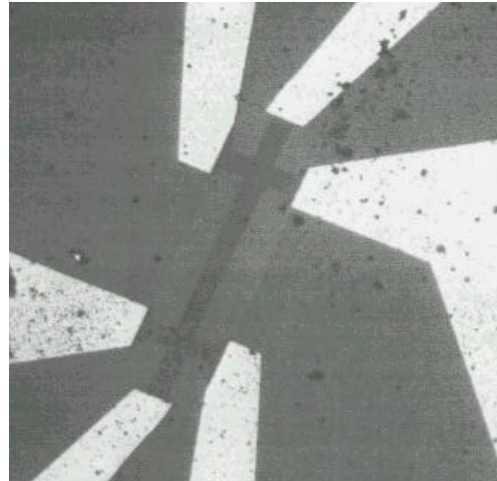
$30\text{K} < T < 90\text{K}$ junction Super/Normal/Super

Fabrication of nanojunctions

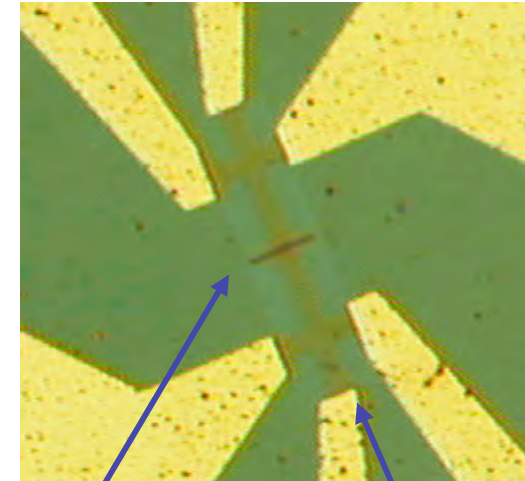
Irradiation
through Au mask



Au IBE removed



Irradiation
through Resist mask



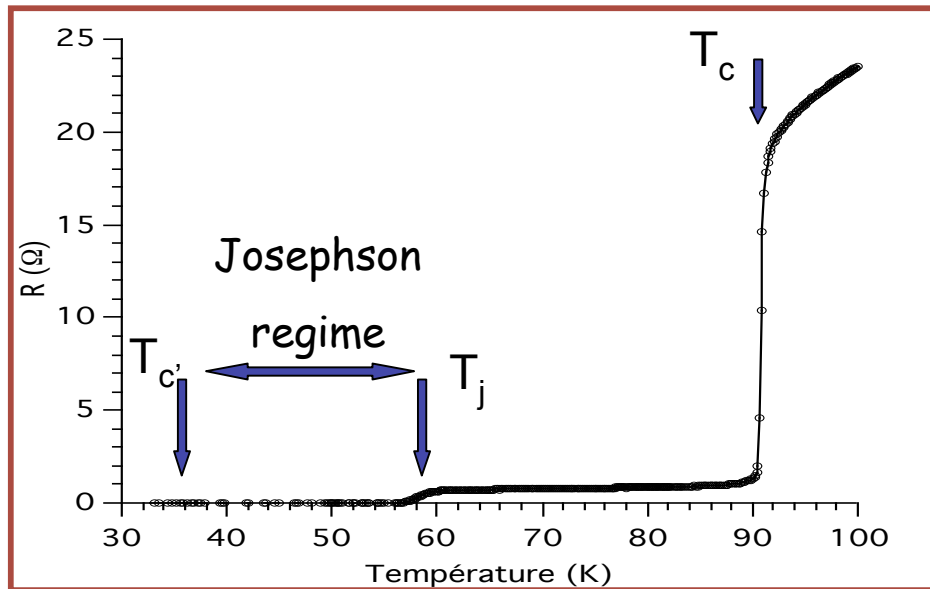
N. Bergeal et al, APL 2005
JAP 2007

20nm slit

Hall cross

Width 1 to 5 μ m

R(T) measurements

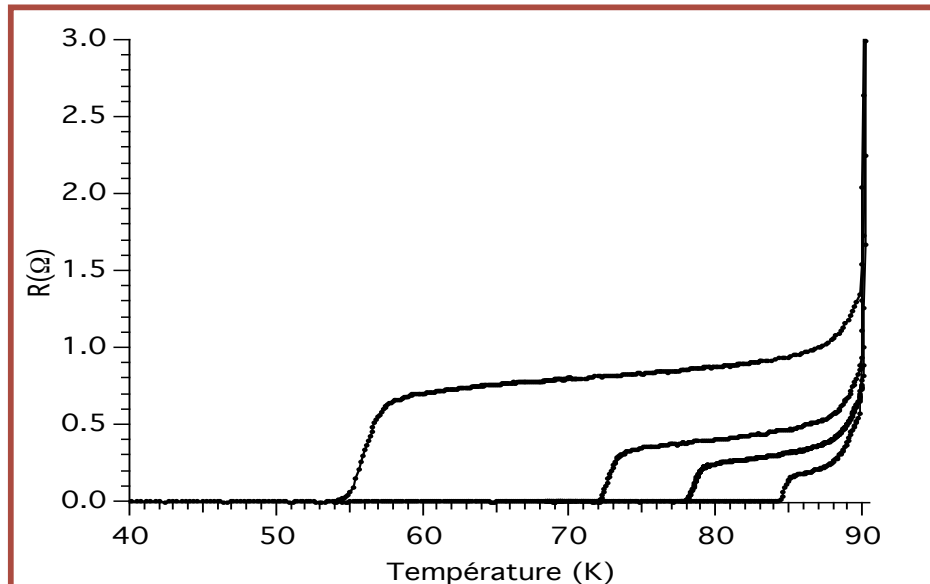


High operating T

$L=5\mu\text{m}$, $E=100\text{keV}$ $\Phi=6.10^{13}\text{at}/\text{cm}^2$

➤ $T_{c'} < T < T_j$ Josephson regime

➤ $T < T_{c'} < T_j$ Flux flow regime



$L=5\mu\text{m}$, $E=100\text{keV}$

$\Phi=1.5, 3, 4.5, 6.10^{13}\text{at}/\text{cm}^2$

➤ Extension of the Josephson regime

$\Delta T=7\text{K} \rightarrow \Delta T=20\text{K}$

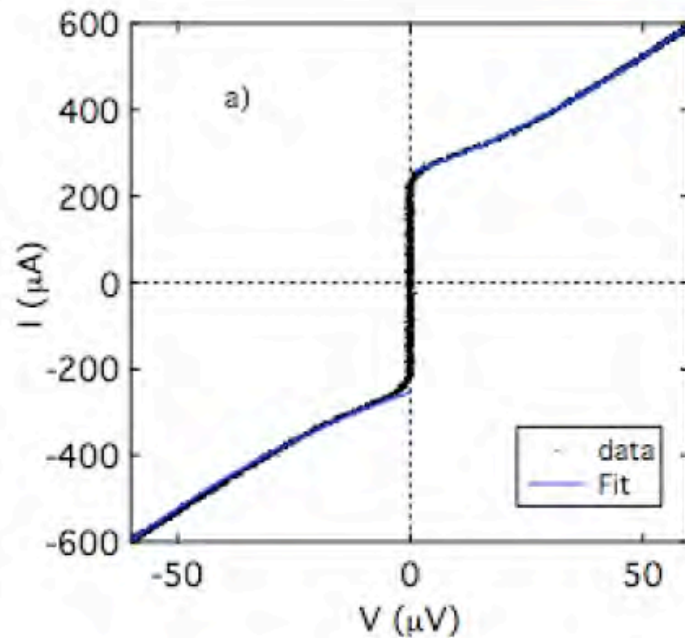
I(V) characteristics

Overdamped JJ

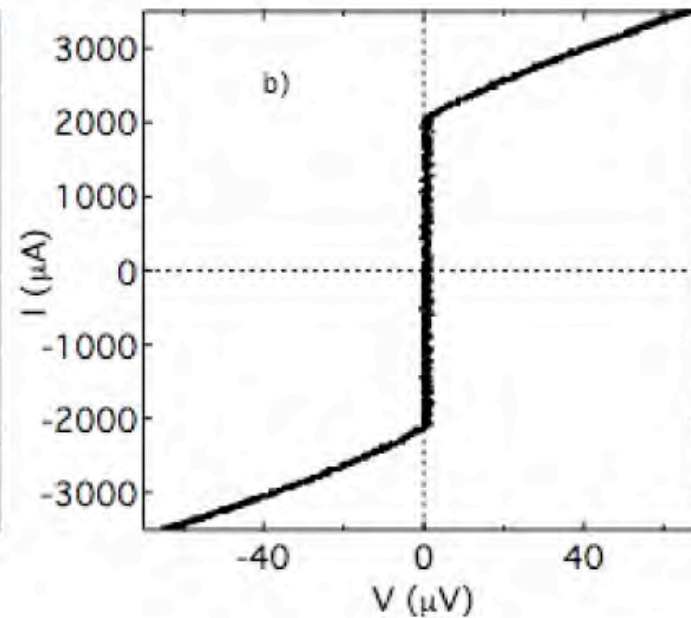
$$\Phi = 3.10^{13} \text{at/cm}^2$$

$T_J > T > T_c$
72.5 K

$T < T_c$
70 K



➤ RSJ behavior



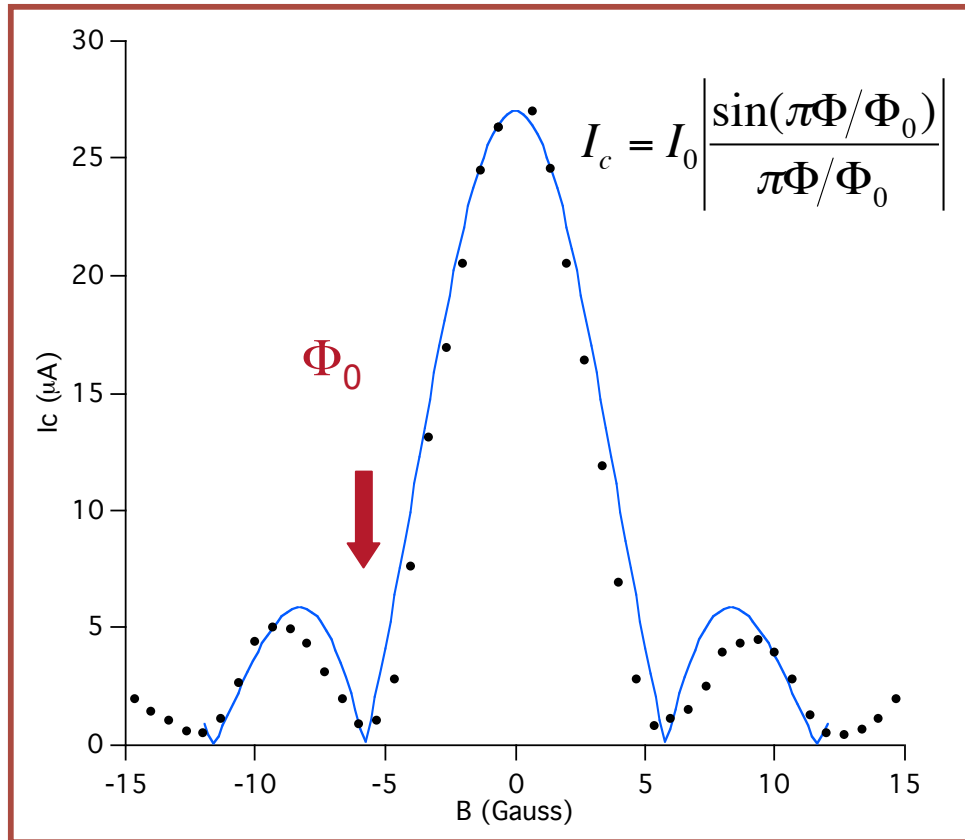
➤ Flux flow behavior

➤ Resistance R_n ranging from 200m Ω to a few Ω

Fraunhofer pattern $I_c(B)$

➤ Phase control by the vector potential

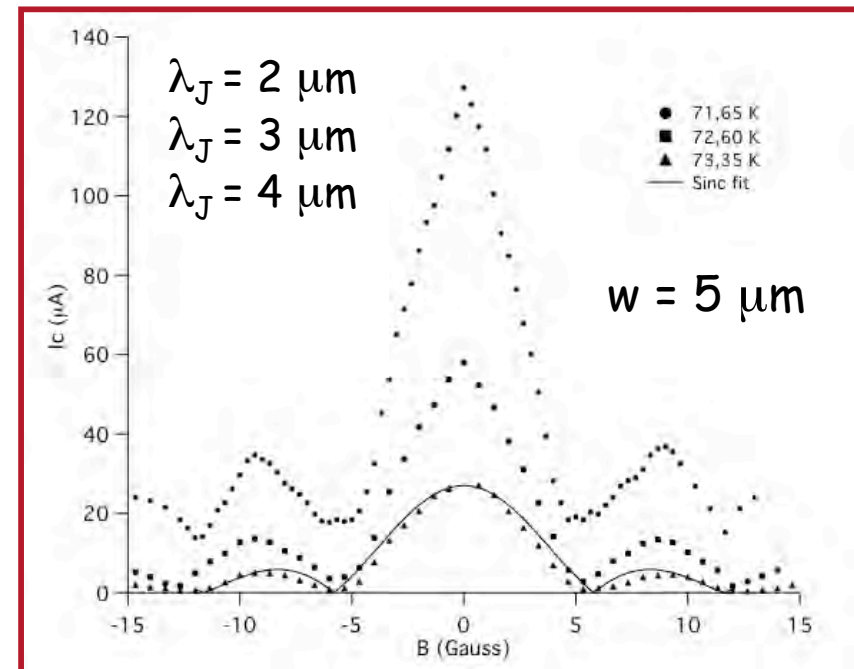
Josephson length λ_J



$$\lambda_J = \left(\frac{\hbar}{2\mu_0 e} \right)^{\frac{1}{2}} \sqrt{\frac{tL}{I_c(2\lambda + d)}}$$

$$I = I_c \sin(\varphi) \quad \varphi = \varphi_1 - \varphi_2$$

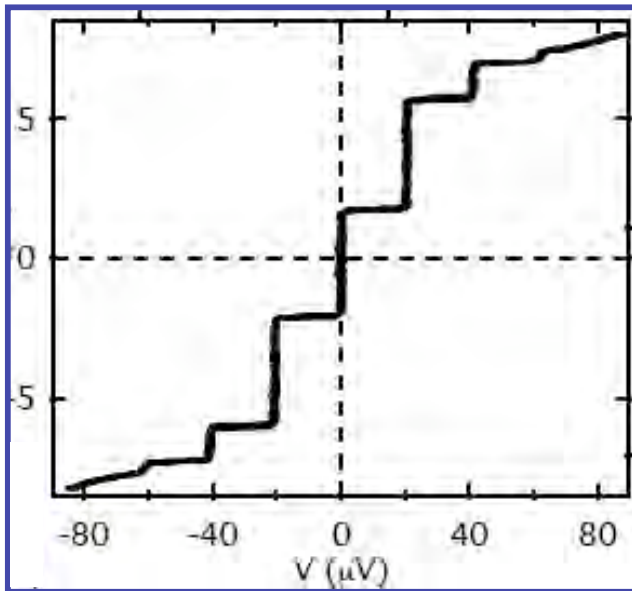
$$\nabla\varphi = \text{Cste } J_S + 2\pi\phi_0^{-1} A$$



Shapiro Steps

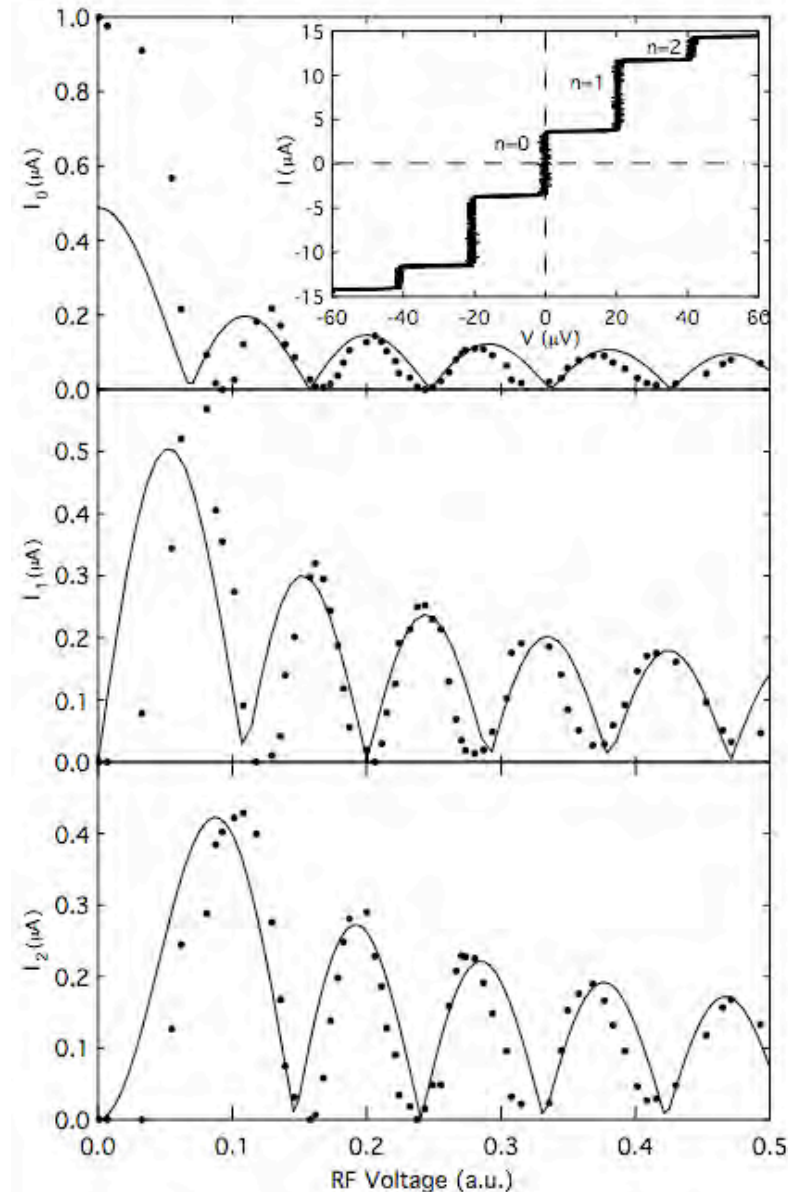
➤ Phase controlled by microwaves

$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar} \quad \boxed{483\,597,9 \text{ GHz/V}}$$

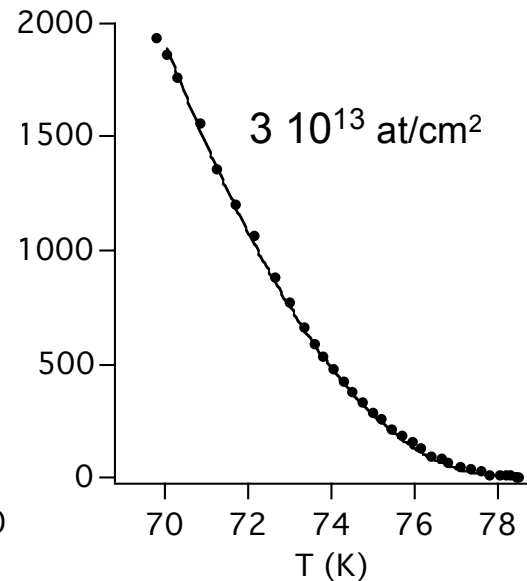
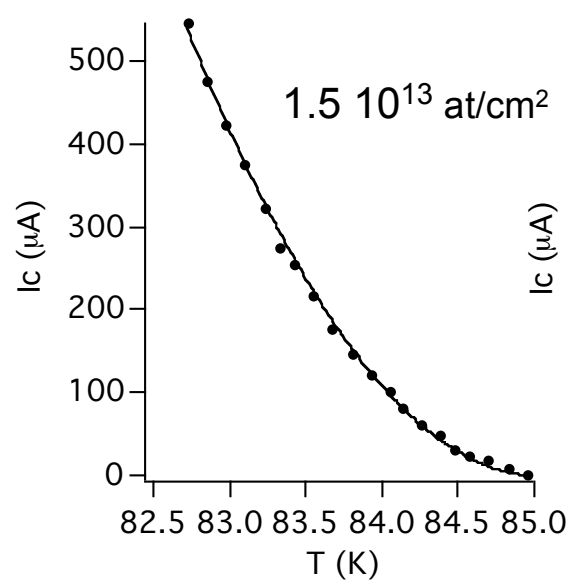


➤ Almost ideal Bessel functions

$\boxed{\text{N. Bergeal, JAP 2007}}$

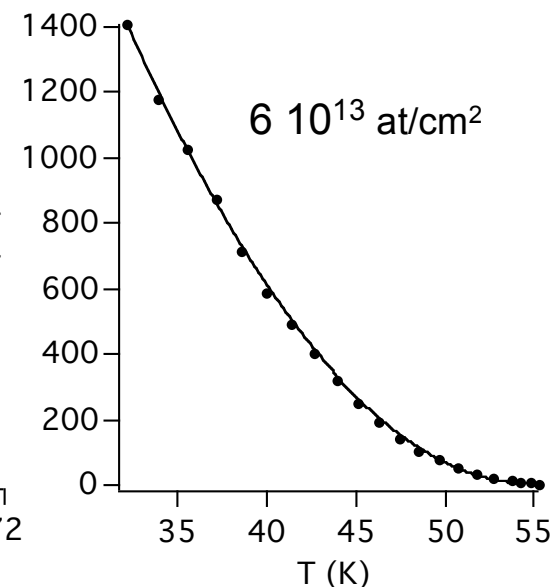
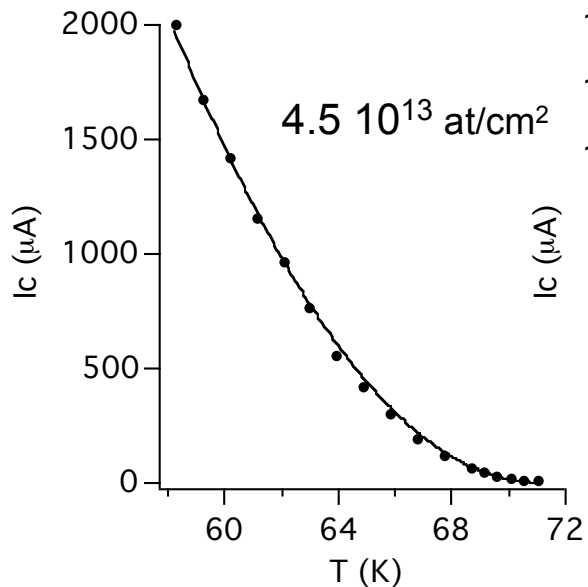


$I_c(T)$ measurements



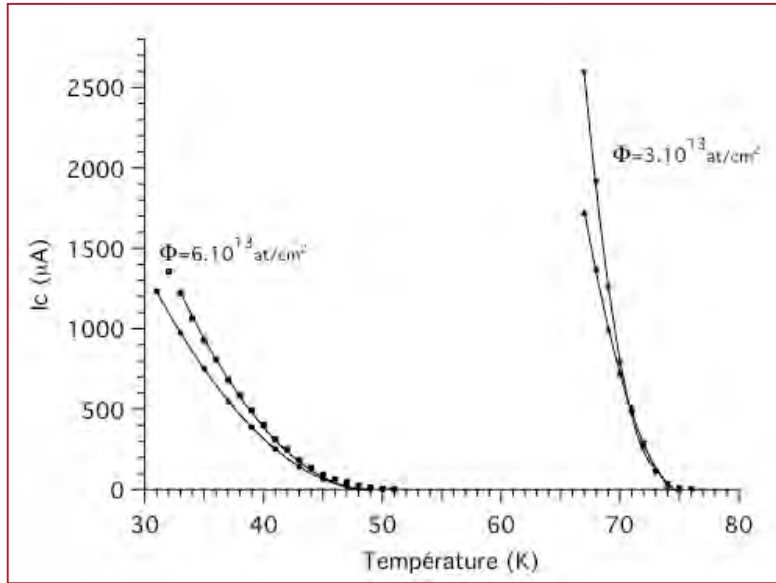
➤ De Gennes-Werthamer model of proximity effect

$$I_c = I_0 \left(1 - \frac{T}{T_j} \right)^2 \frac{l/\xi_N}{\sinh(l/\xi_N)}$$

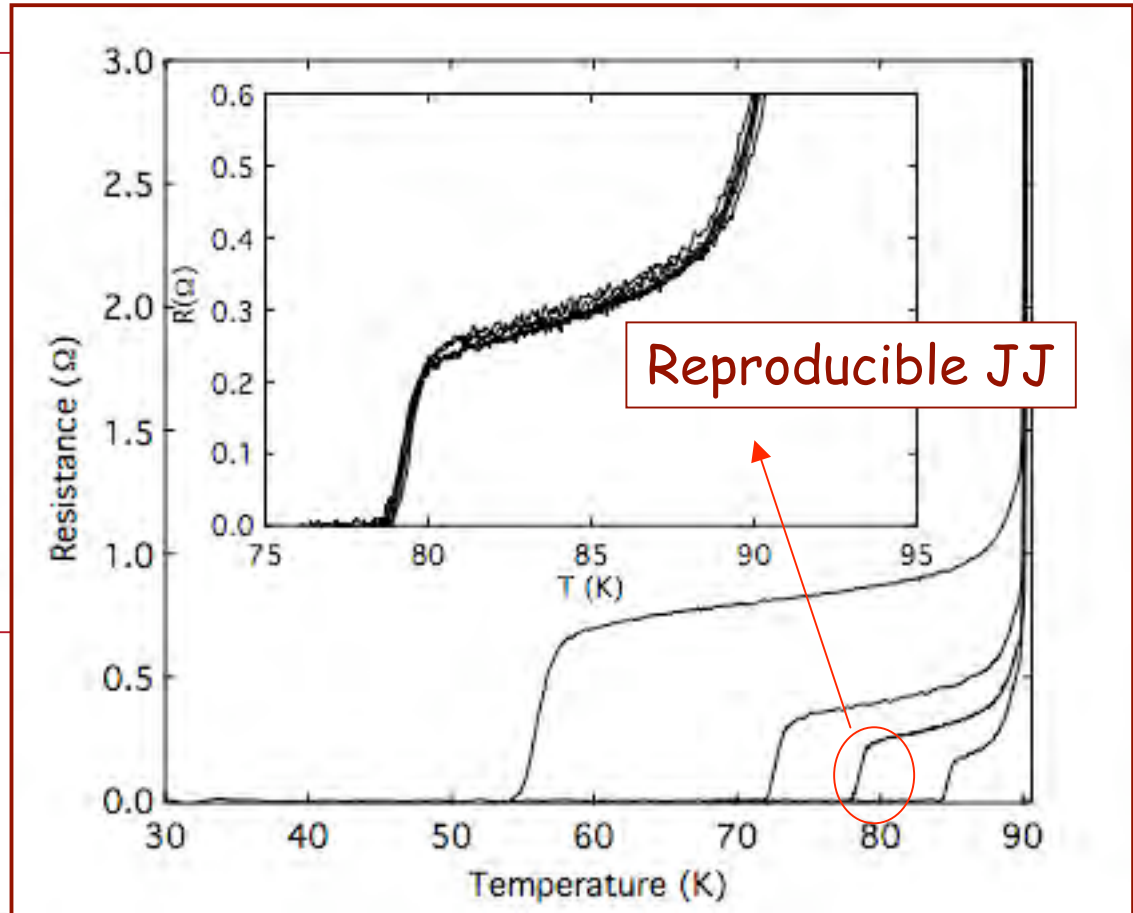


➤ $I_c R_n \sim$ a few 100 μ V

Major characteristics and reproducibility



N. Bergeal, APL 2005,
JAP 2007



Sample	Fluence	T_j	T_c'	$R_n(0.9T_j)$	$I_c(0.9T_j)$	$I_c R_n(0.9T_j)$	$J_c(0.9T_j)$
M11	$6 \cdot 10^{13}$ at/cm ²	49 K	32 K	1.2 Ω	72 µA	90 µV	10 k A/cm ²
M13	$6 \cdot 10^{13}$ at/cm ²	48 K	31 K	1.2 Ω	90 µA	72 µV	12 kA/ cm ²
M21	$3 \cdot 10^{13}$ at/cm ²	75 K	57 K	0.35 Ω	772 µA	270 µV	100 kA/cm ²
M25	$3 \cdot 10^{13}$ at/cm ²	75 K	61 K	0.25 Ω	1100 µA	272 µV	140 kA/cm ²

High J_c

Clues for reproducibility and reliability

N. Bergeal et al, APL 2005

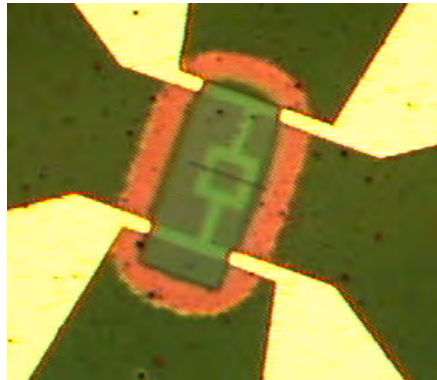
- Low dispersion in $I_c R_n$ ($<10\%$)
- Self-shunted junctions
- High values of J_c (a few 10^4 A/cm²)
- Excellent thermal cycling and aging

- Embedded junctions
- No annealing of the junctions
- In-situ Gold protected YBCO films
- All dry process

- THz detectors
- Voltage standard
- SQUIDS
- RSFQ : T flip-flop

DC SQUIDS with nanojunctions

N. Bergeal et al, APL 2006



Geometry #1

10 μm * 10 μm

W ~ 5 μm

L = 32 pH

φ_0 for
B ~ 0.08 G

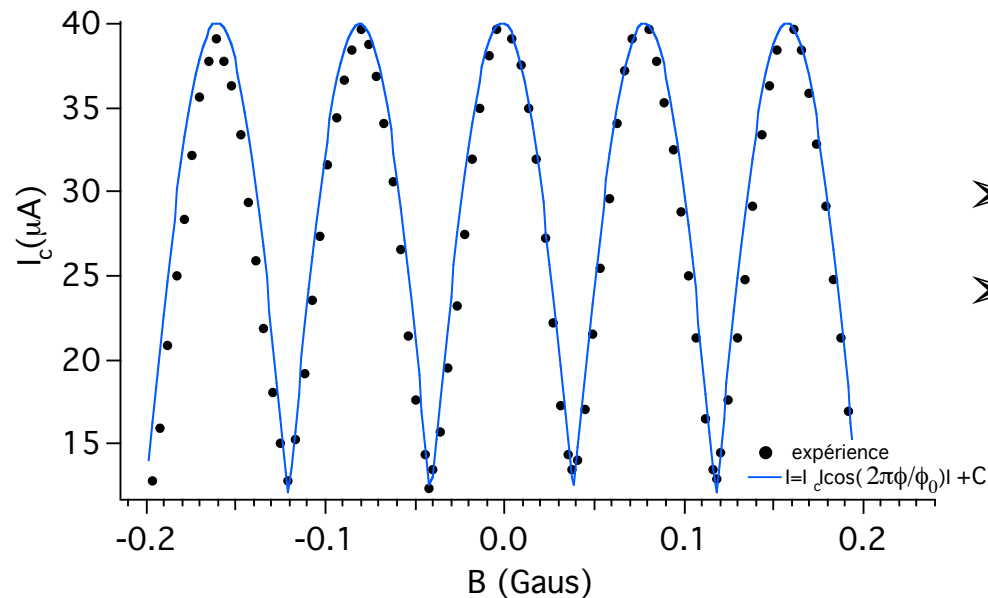
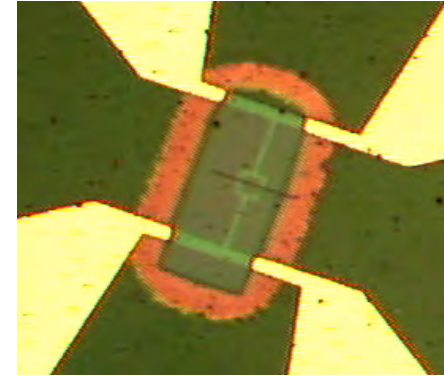
Geometry #2

6 μm * 6 μm

W ~ 2 μm

L = 17 pH

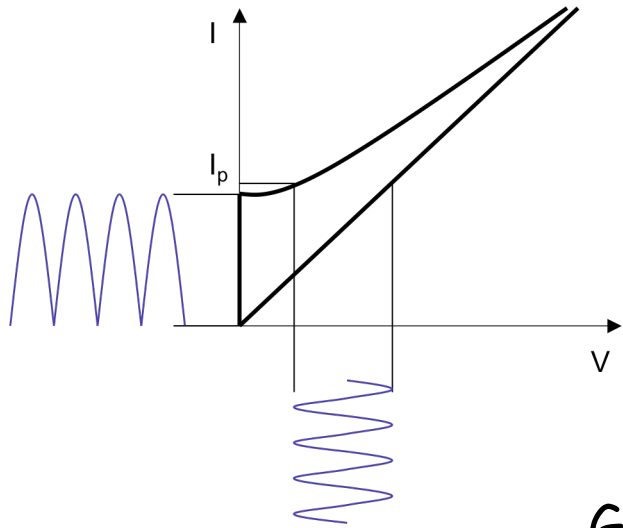
φ_0 for
B ~ 0.3 G



➤ $I_c(B)$ modulation

➤ Cosinus fit with a period 0.08 G

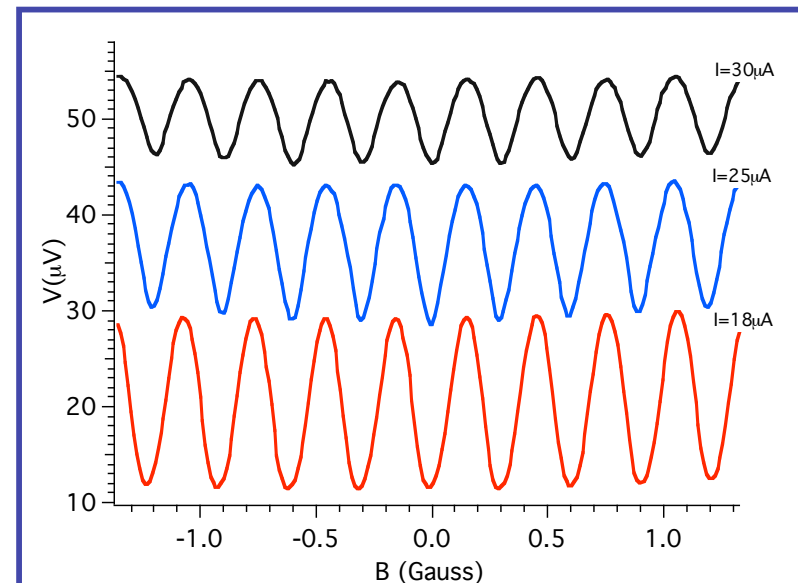
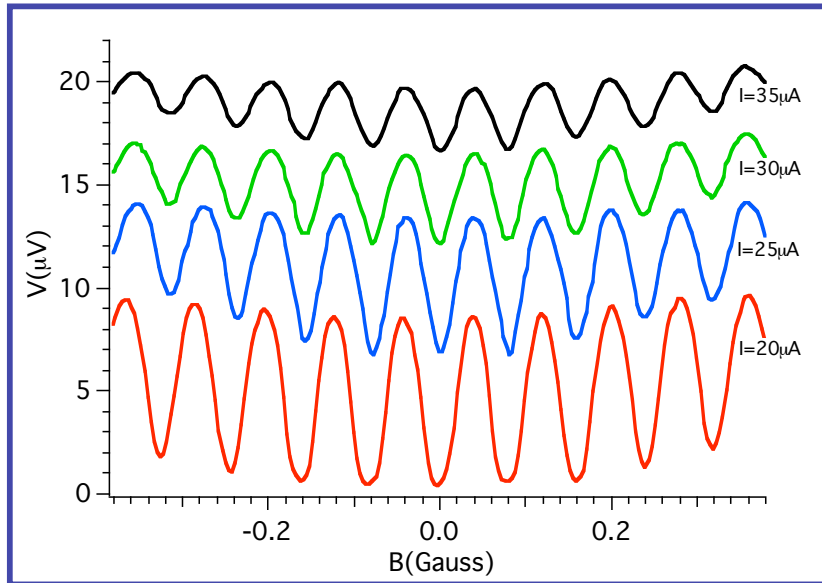
SQUID modulations



- Modulation of $I \rightarrow$ modulation of V
- Sensitivity : $dV/d\Phi = 60 \mu V/\Phi_0$
- Temperature = 77.7 K

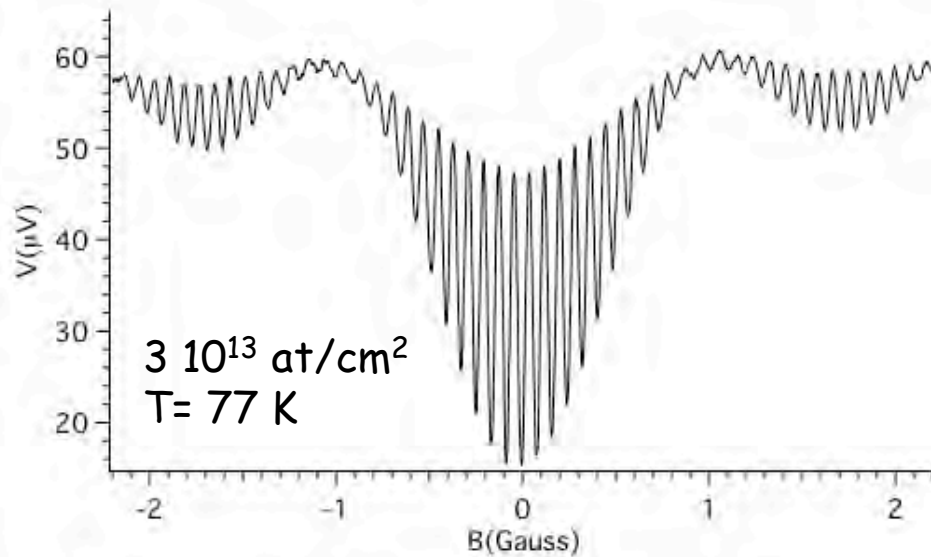
Geometry #1

Geometry #2

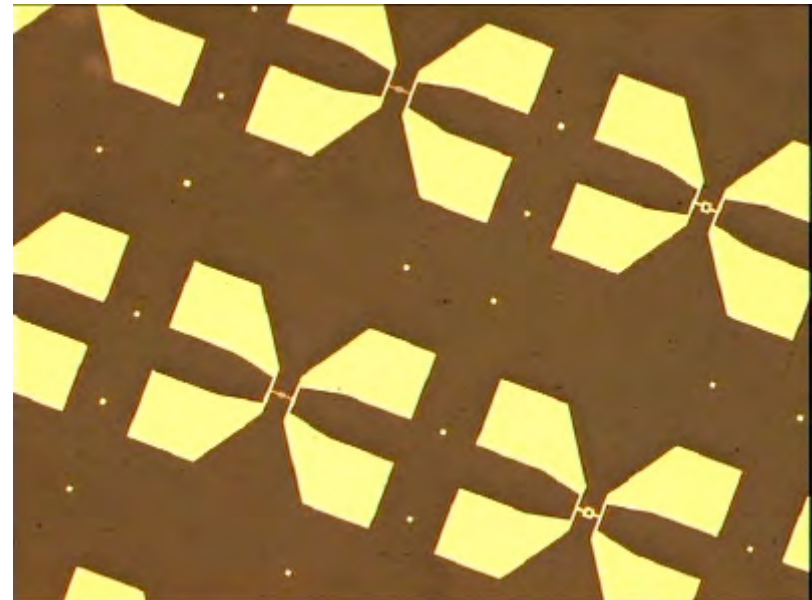
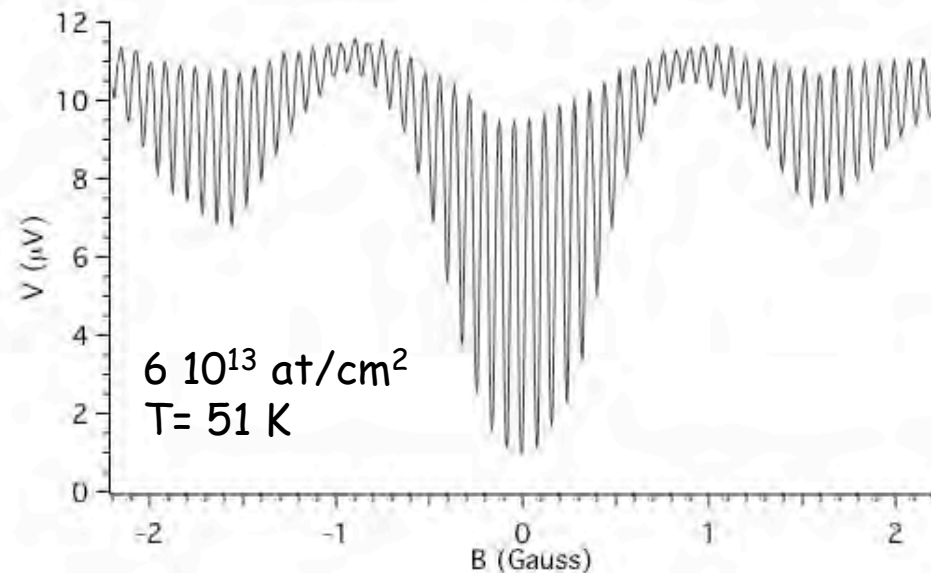


SQUID characteristics

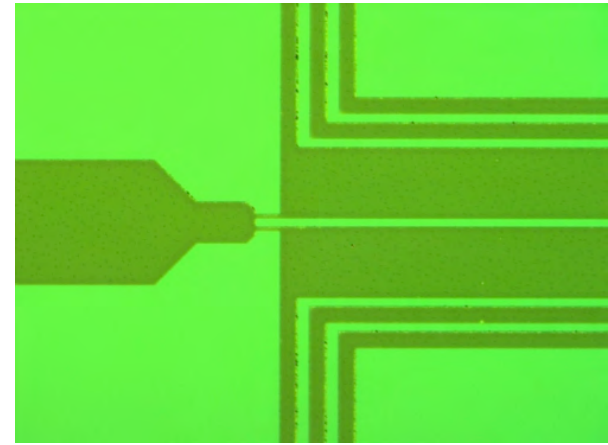
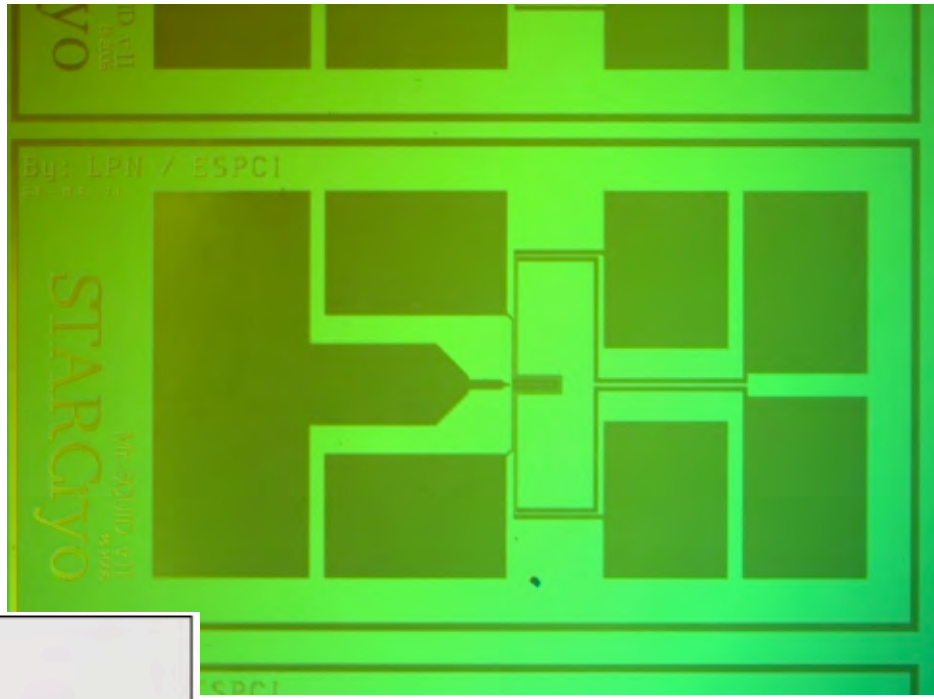
N. Bergeal, APL 2006 ; APL 2007



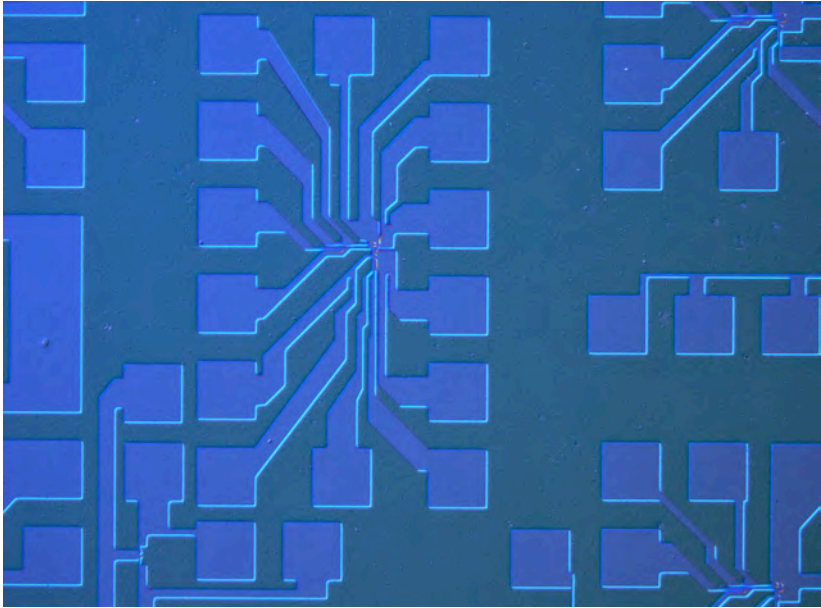
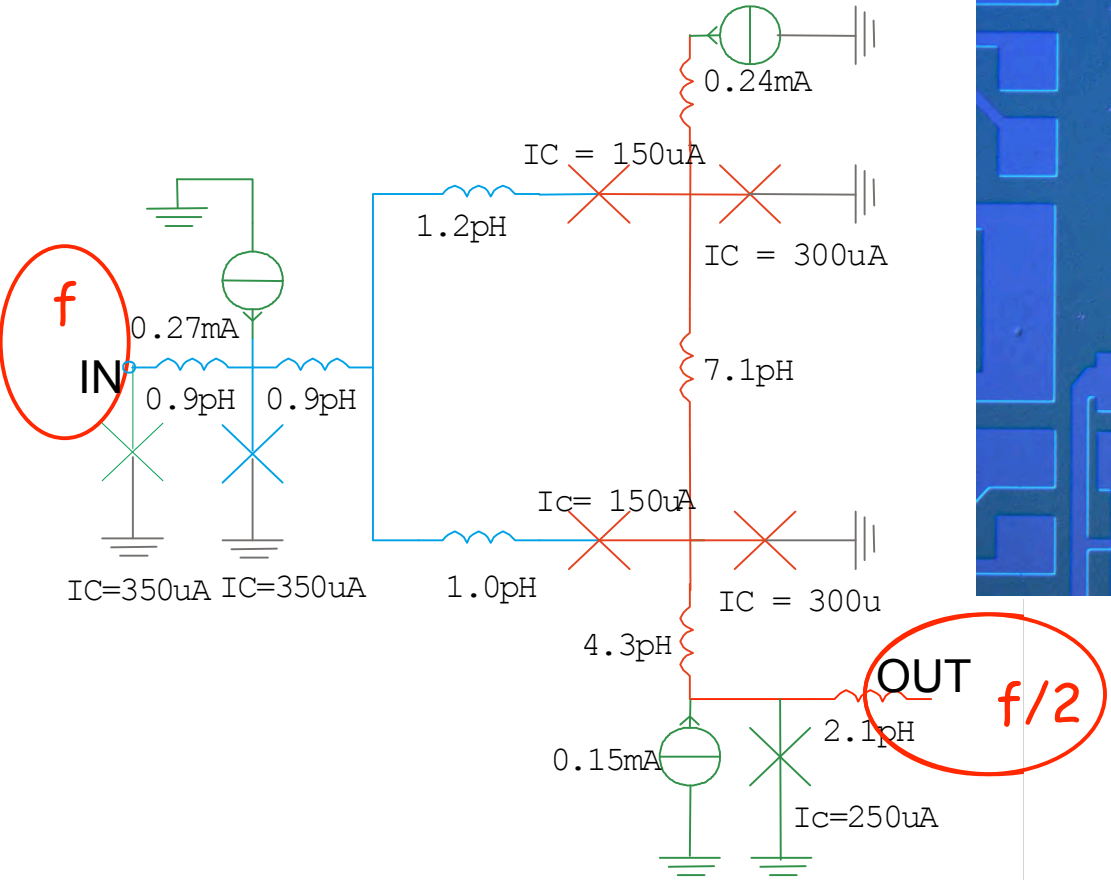
- Fraunhofer + SQUID modulation
- Noise < 100pV/√Hz (at 100 Hz)
- Sensitivity $\approx q \Phi_0$
- Excellent cycling and aging
- Networks



SQUID for « Mr SQUID »



RSFQ T Flip-Flop



- Design D. Crété (Thales)
- Kim et al (2002) 100 GHz @ 12K

Outline

1. Superconductive electronics

Dynamics of Josephson Junctions

Rapid Single Flux Quanta logic

Actual RSFQ devices

2. High T_c Josephson nanoJunctions

Ion irradiation of High T_c Superconductors

Making Nanojunctions

Major characteristics of the Nanojunctions

A few applications

3. Physics of High T_c nanojunctions

Proximity effect

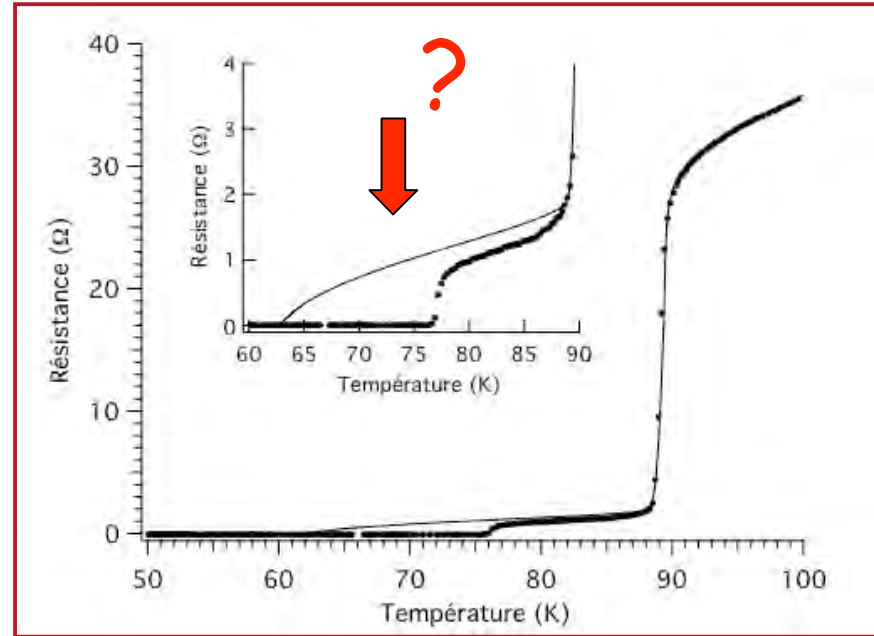
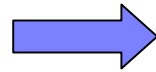
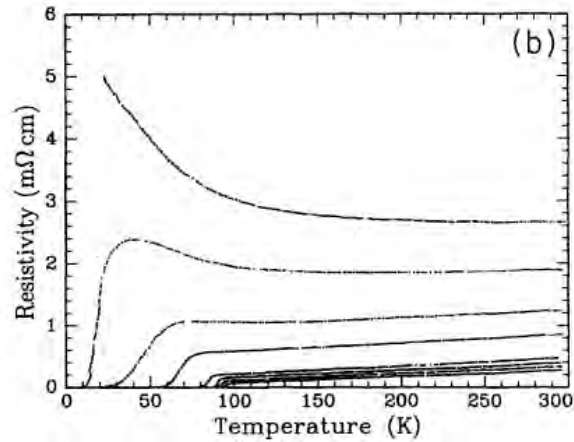
Quasi-classical diffusive approach

D-wave order parameter symmetry

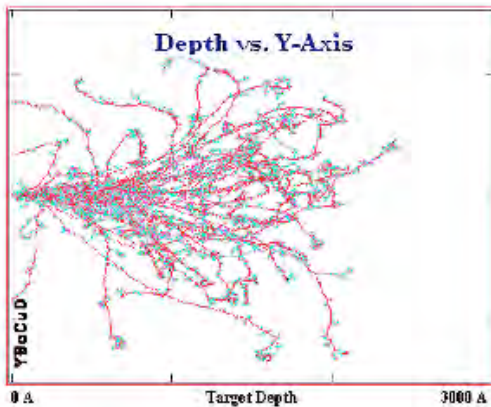
π -junctions and RSFQ devices

4. Conclusions

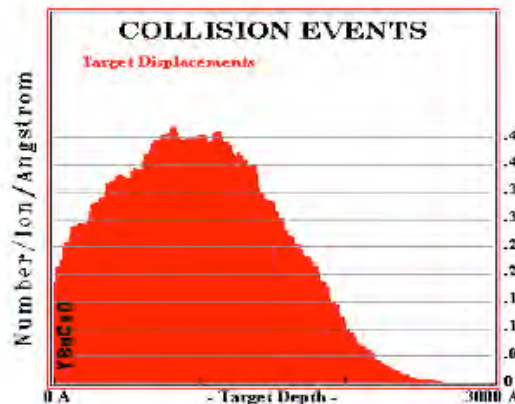
A bit of physics ...



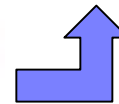
- T_c , resistivity $r(T)$ vs defects
- Damage profile (SRIM)



a)



b)



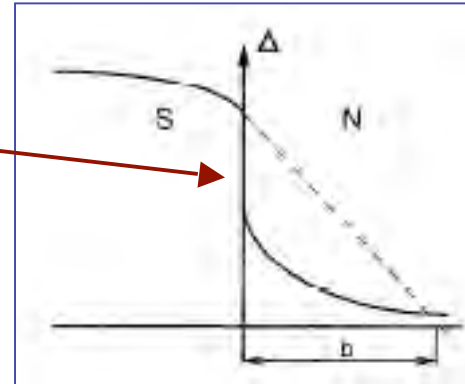
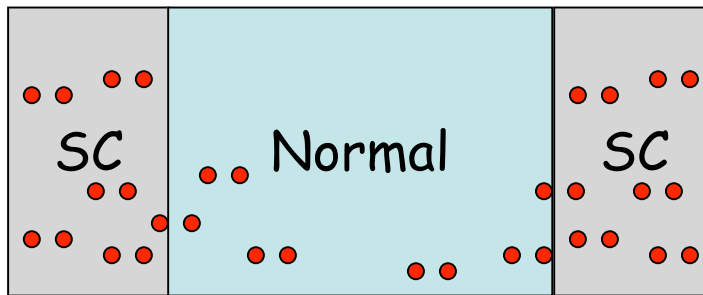
➤ Reduced size ?

« No-interface » Josephson Junctions

➤ Strength of the coupling

Low interface resistance

Fermi Velocities match



$$\xi_N = \sqrt{\frac{\hbar D}{2\pi k_B T}}$$

➤ Beyond De Gennes's approximation

No true interface

Self-consistent calculation of the local gap

Calculating the Josephson critical temperature

Calculating $I_c(T)$ for all temperatures

Quasi-classical approach of the proximity effect

- Usadel equations parametrized in θ $\left\{ \begin{array}{ll} G = \cos\theta & \text{Quasiparticles} \\ F = \sin\theta & \text{Pairs} \end{array} \right.$

Homogeneous SC

Depairing Γ_{AB}

$$\frac{\hbar D(x)}{2} \frac{\partial^2 \theta_n}{\partial x^2} - \omega_n \sin \theta_n + \Delta(x) \cos \theta_n - \Gamma_{AB}(x) \sin \theta_n \cos \theta_n = 0$$

$\omega_n = \pi k_B T (2n+1)$ Matsubara frequencies

Limits conditions $\tan \theta_N = \frac{\Delta}{\omega_N}$

- Self-consistent gap equation

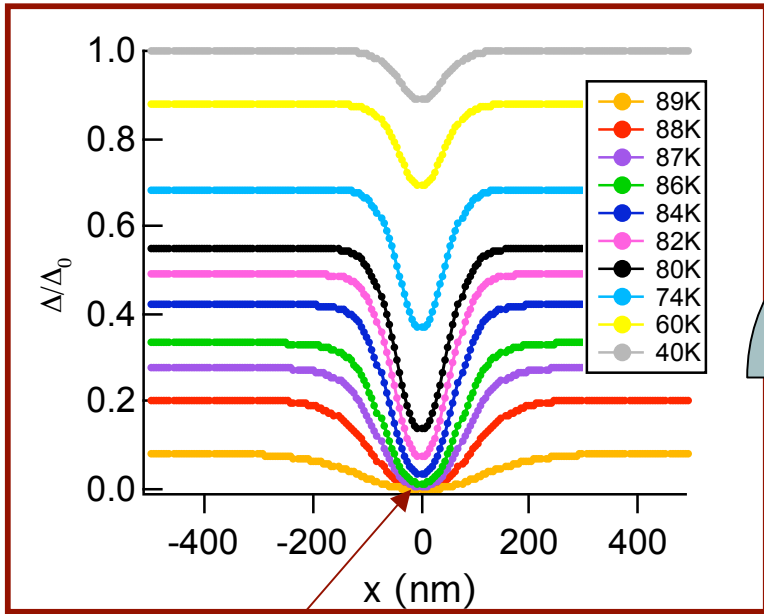
$$\Delta(x) = \lambda_S 2\pi K_B T \sum_{\omega_n} \sin \theta_n$$

In the limit of vanishing current

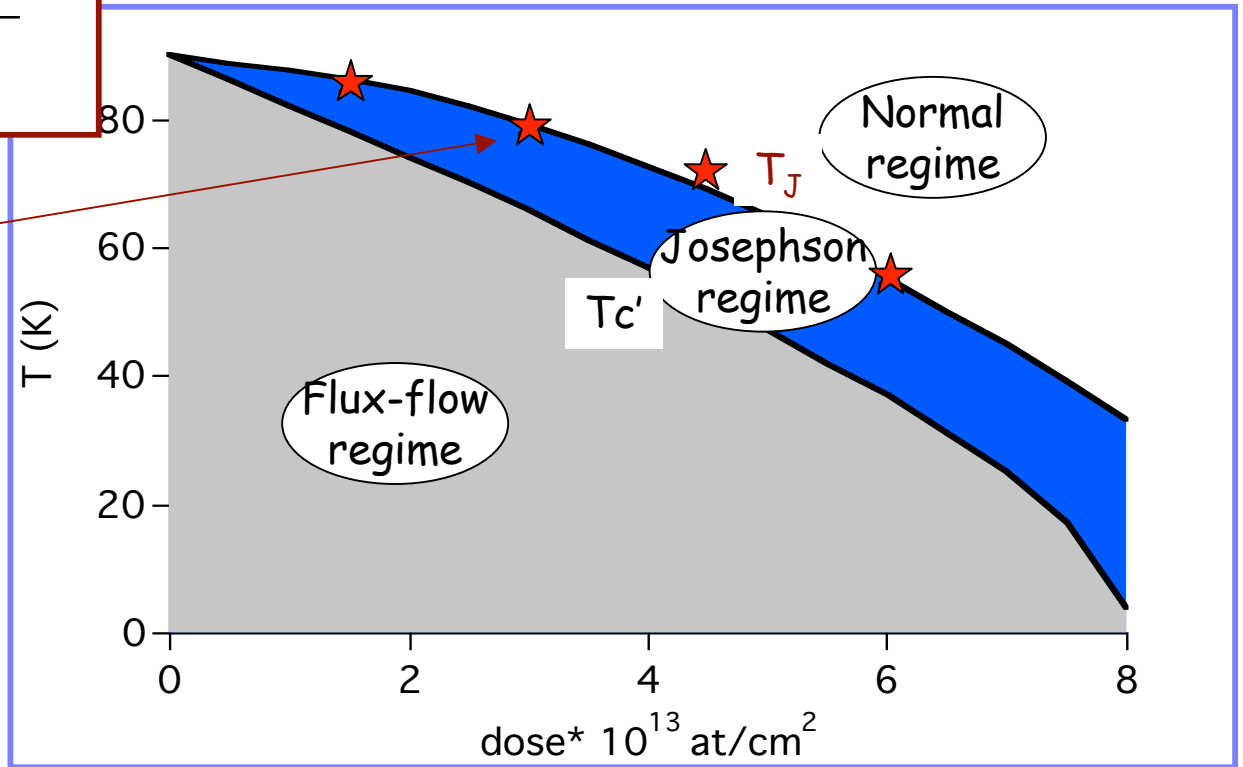
$\Delta(x)$ profil along the junction

Computing the Josephson coupling temperature

N. Bergeal et al, submitted to PRL



T_J



Computing the critical current density

➤ Usadel equations parametrized in θ $\left\{ \begin{array}{ll} G = \cos\theta & \text{Quasiparticles} \\ F = \sin\theta & \text{Pairs} \end{array} \right.$

Homogeneous SC

Depairing Γ_{AB}

$$\frac{\hbar D(x)}{2} \frac{\partial^2 \theta_n}{\partial x^2} - \omega_n \sin \theta_n + \Delta(x) \cos \theta_n - \Gamma_{AB}(x) \sin \theta_n \cos \theta_n = 0$$

$$-\frac{\hbar D(x)}{2} \left(\frac{\partial \chi}{\partial x} \right)^2 \sin(\theta) \cos(\theta) = 0$$

Depairing by supercurrent χ

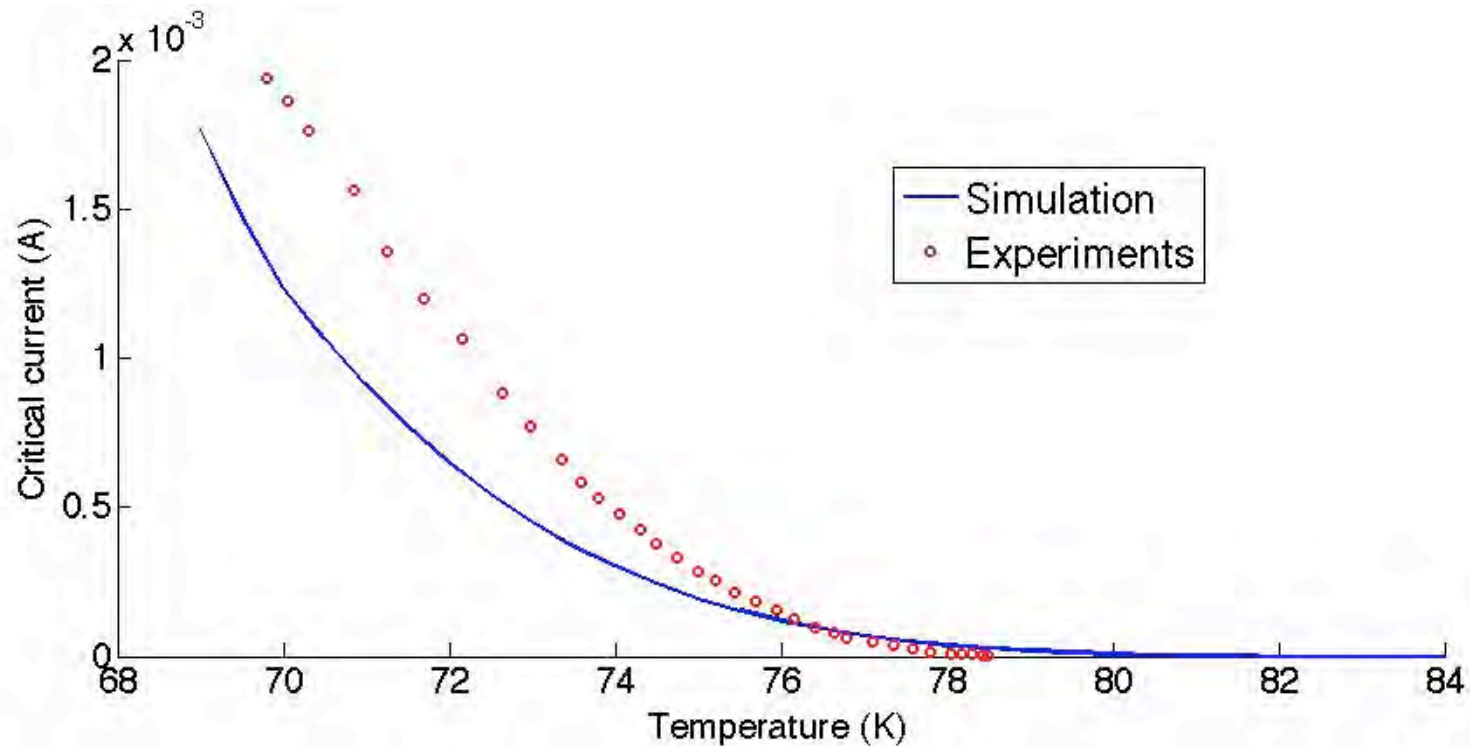
Supercurrent inside the junction

$\omega_n = \pi k_B T (2n+1)$ Matsubara frequencies

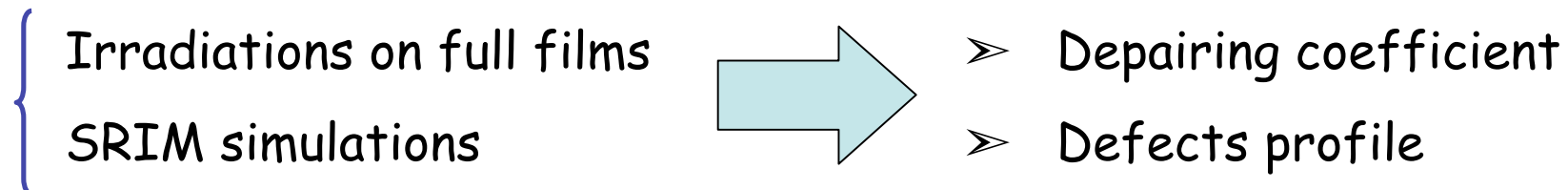
$$j(x) = -\pi e N D T \sum_{\omega} \frac{\partial \chi}{\partial x} \sin^2 \theta$$

Comparison with experiments

- Quantitative results for the critical current of our Josephson junctions

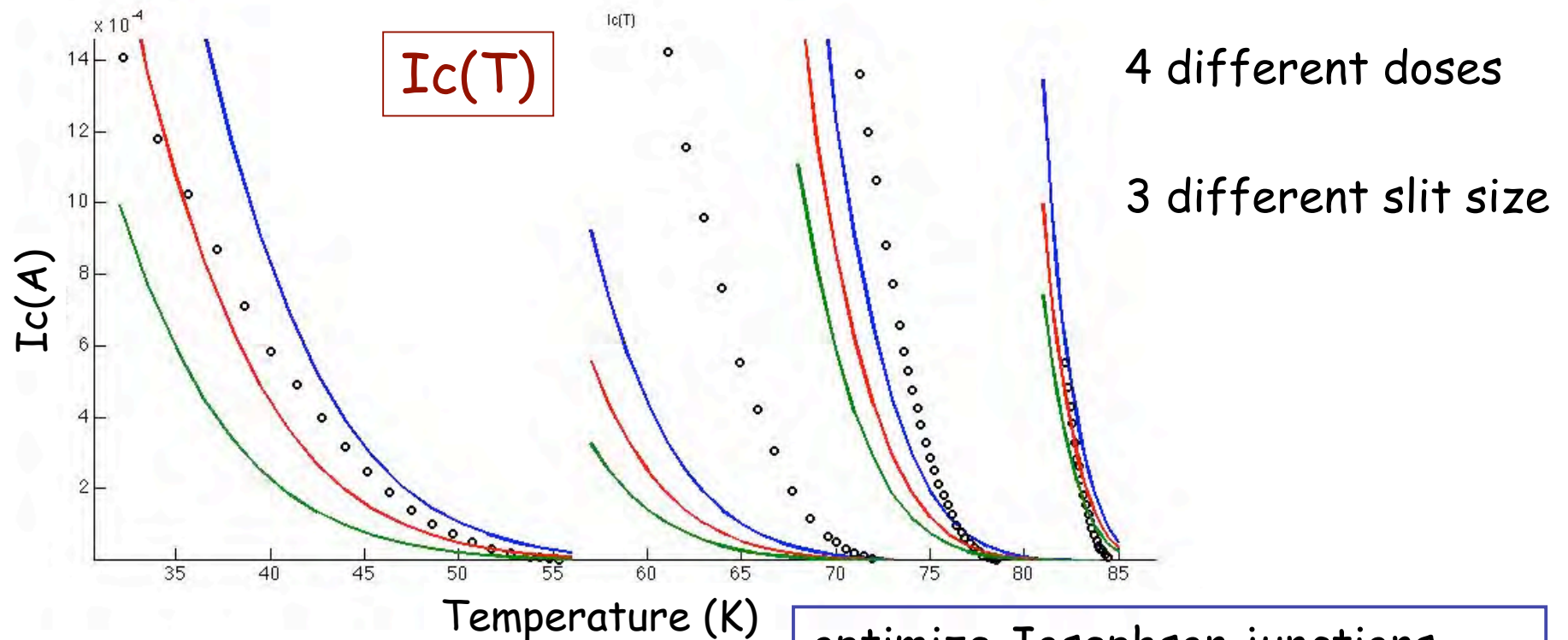


- With **NO** adjustable parameters



Changing the junctions parameters

- Importance of the slit size and irradiation doses



- Simulate various
 - slit size
 - film thickness
 - irradiation dose, ...

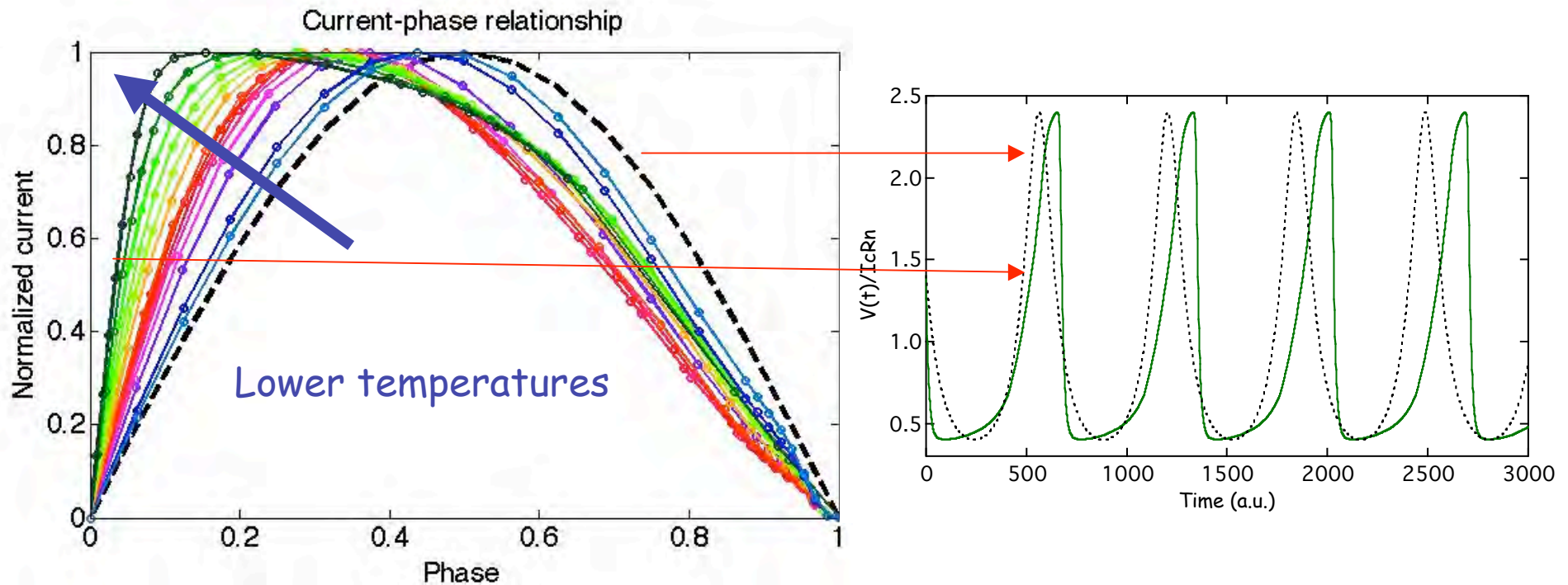


optimize Josephson junctions

- Specific temperatures
critical currents
- Reduce spread (identify
important parameters)

Deeper look in the low temperature regime

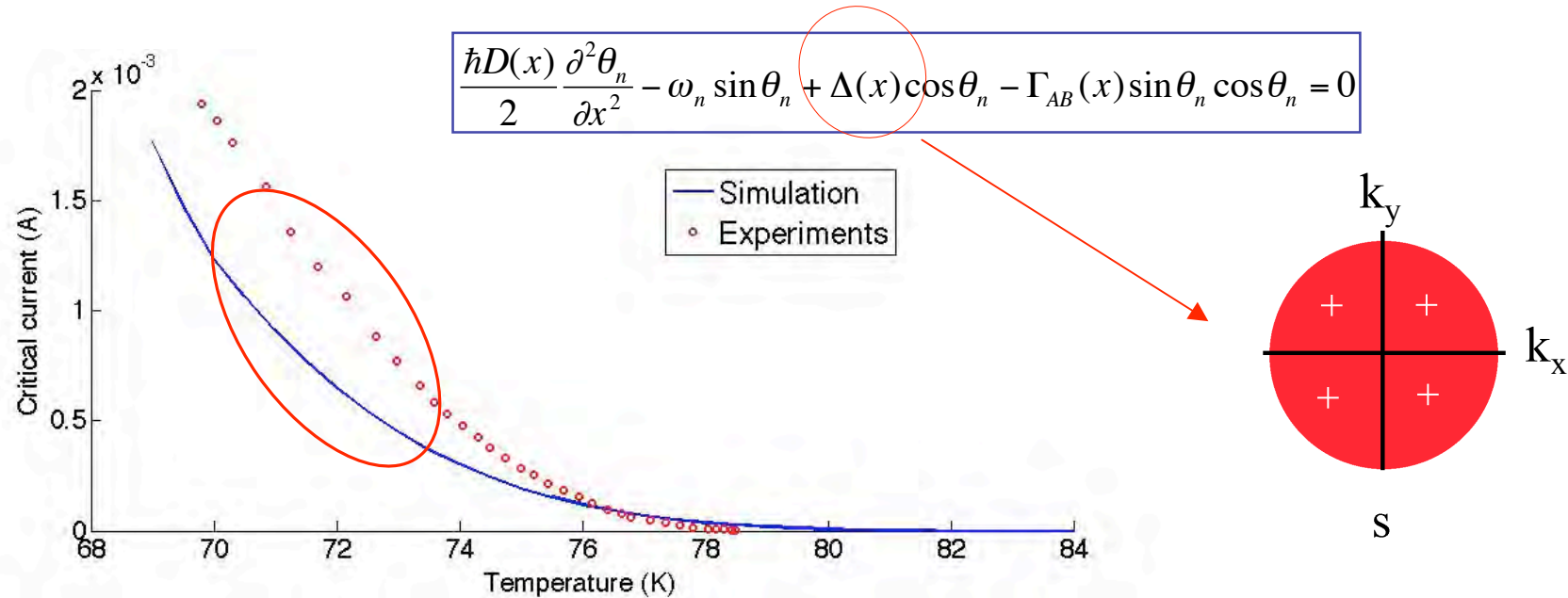
- Want to reach high critical current \rightarrow **lower** temperature
- Strong anharmonicity develops ...



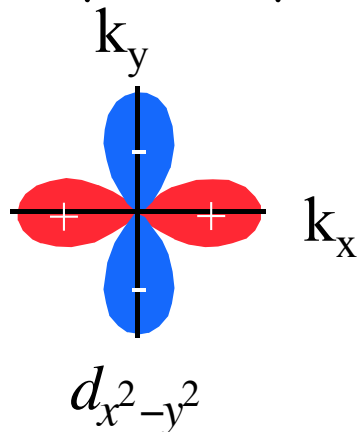
- RSFQ pulses robust against anharmonicity

A d-wave order parameter

➤ 1D Quasi-classical equations with an isotropic order parameter

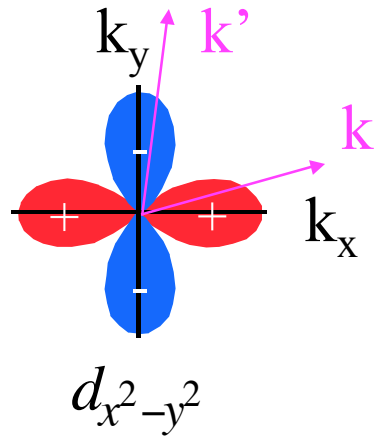


➤ 2D symmetry of the d-wave order parameter

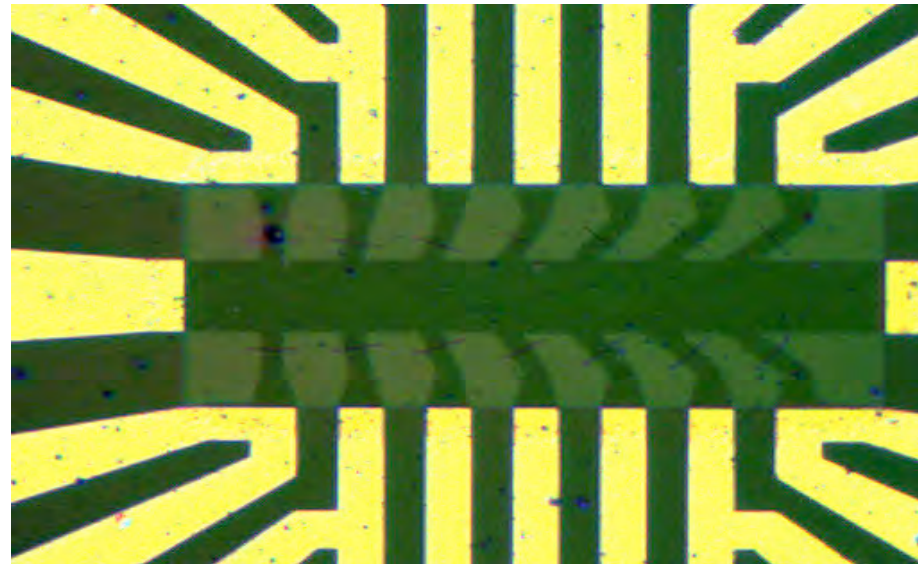
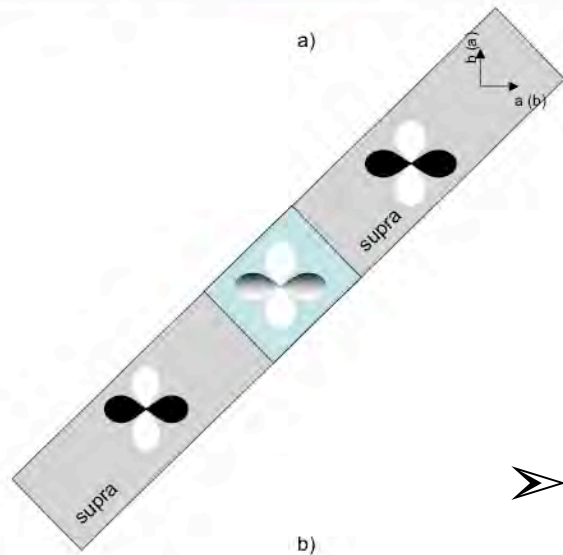
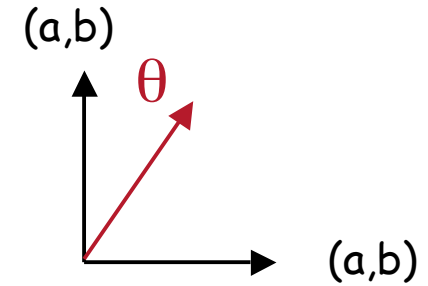


- Anisotropy of the order parameter
- Sign change : Andreev Bound States
- π -junctions and RSFQ circuits

Order parameter anisotropy ?

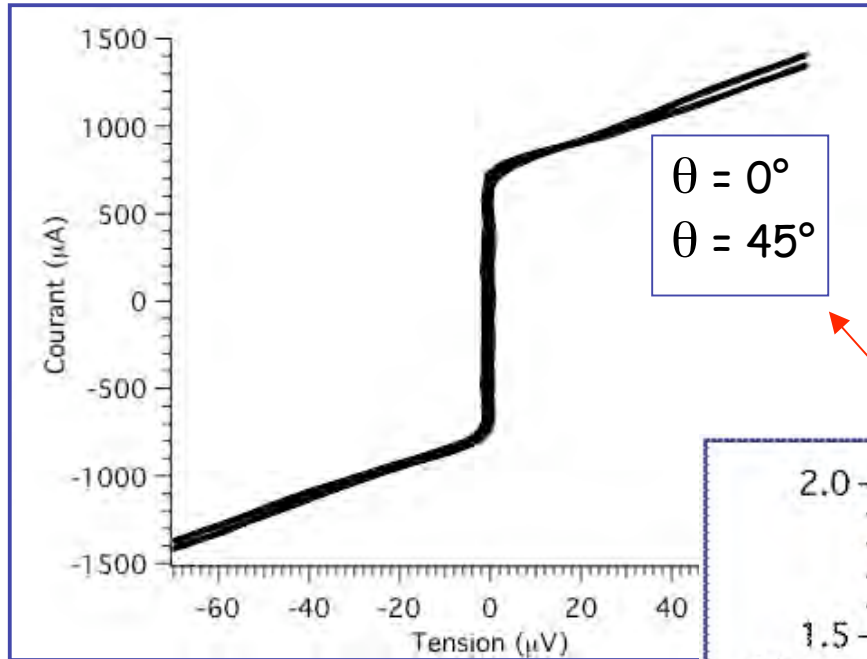


➤ D-wave order parameter



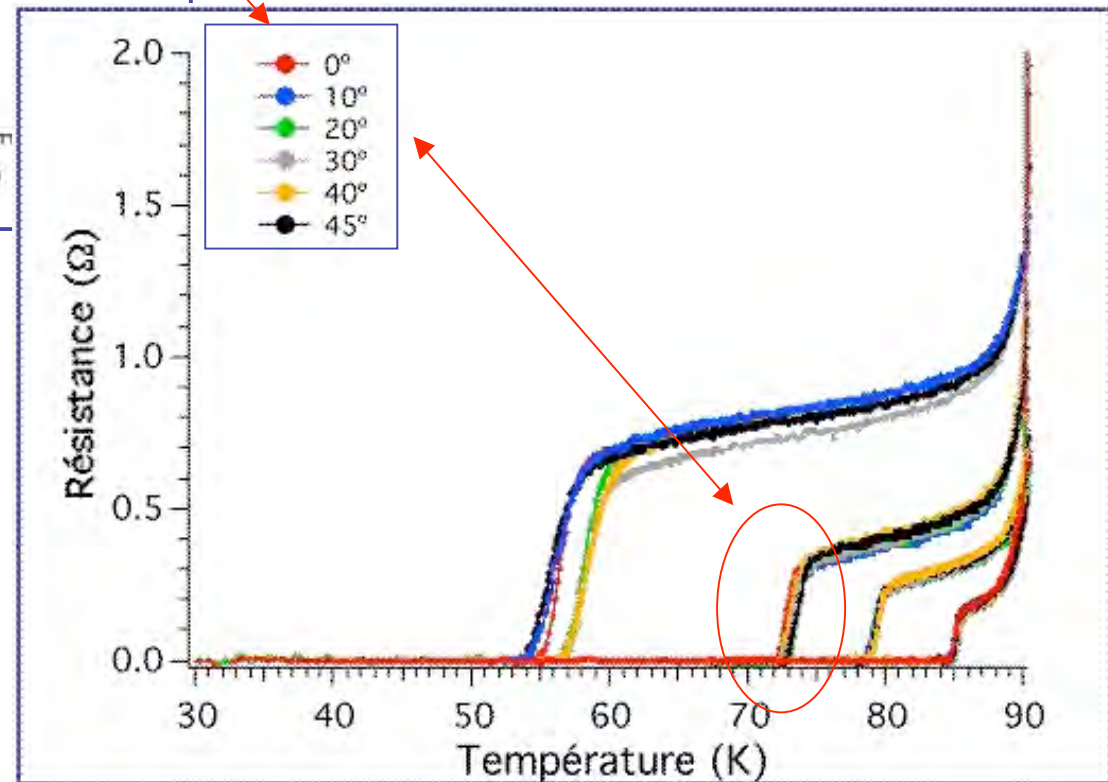
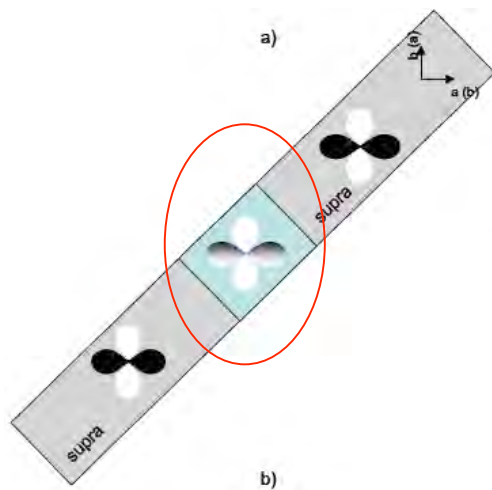
➤ Orientations $\theta = 0^\circ, 10^\circ, 20^\circ, 30^\circ, 40^\circ, 45^\circ$

Order parameter anisotropy ?



➤ No effect !!

- Diffusion ?
- 2d order parameter ?
- **Anisotropic pairing !**



Back to Eilenberger equations ...

- No diffusion approximation

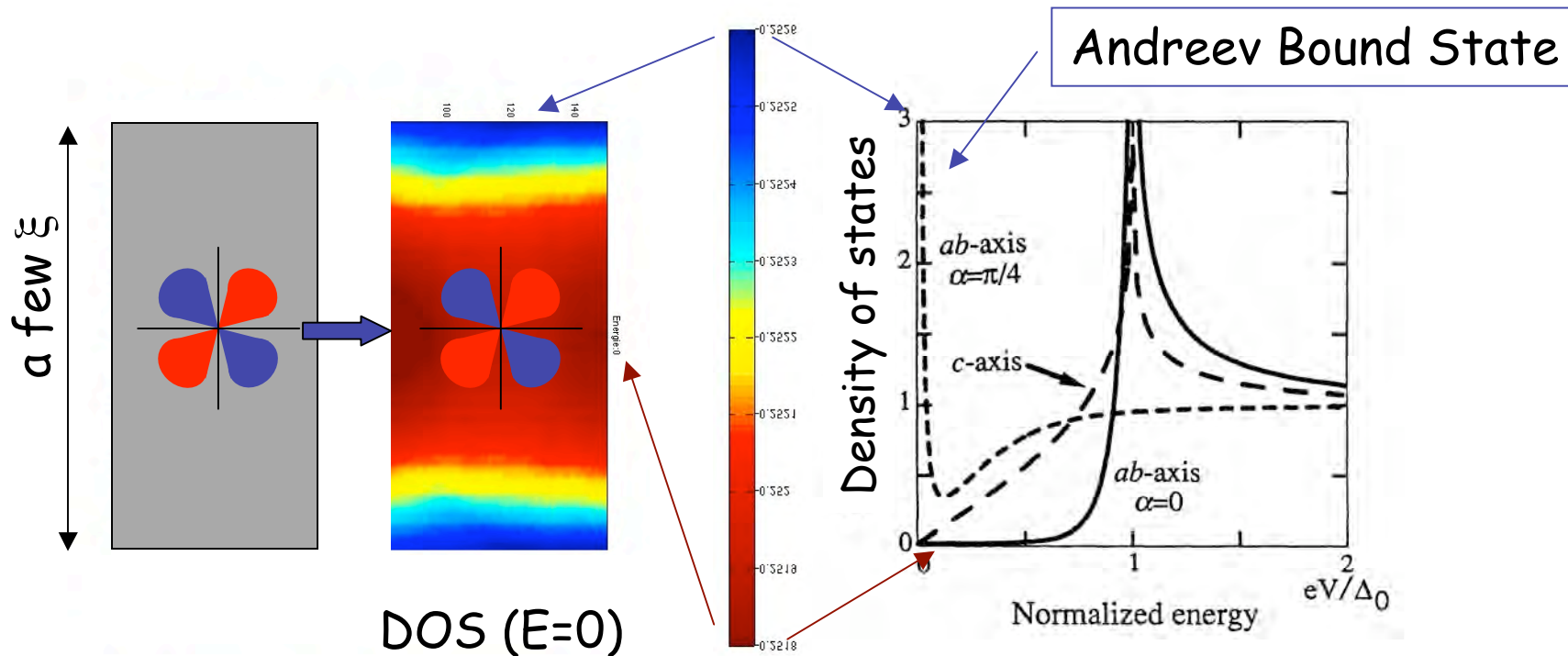
Usadel : $l < \xi$

No wave vector dependence

Eilenberger : $l \gg \xi$

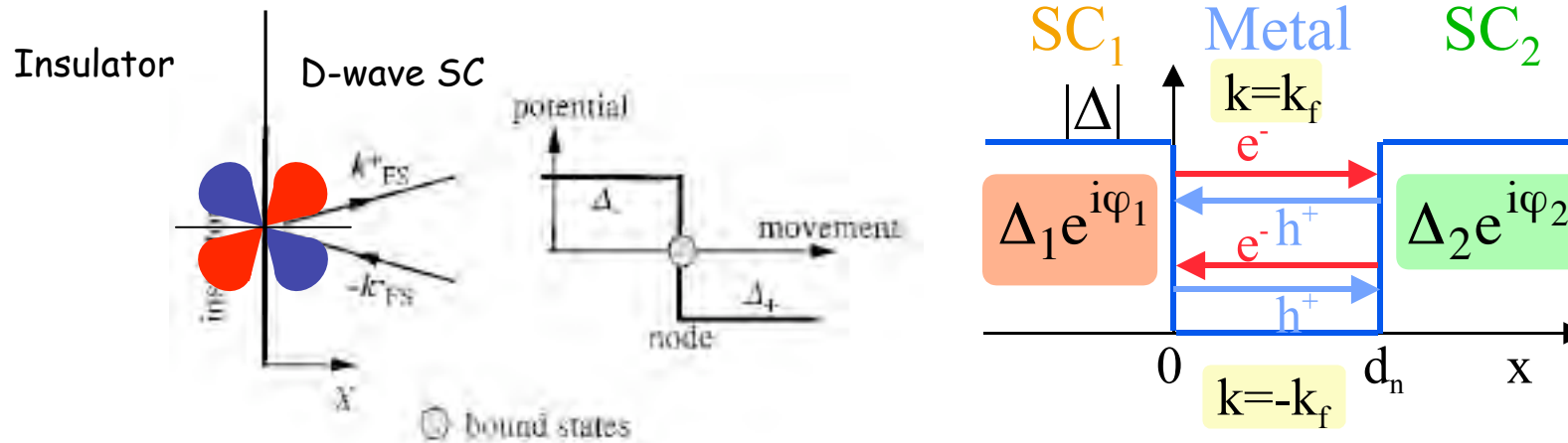
$$-\hbar v_F [\hat{D}, \hat{g}_\omega(v_F, r)] = [\omega \tau_3 + \hat{\Delta} + \frac{1}{2\tau} \langle \hat{g}_\omega(v_F, r) \rangle, \hat{g}_\omega(v_F, r)]$$

- Confined geometry : full d-wave calculation in a channel



Andreev Bound State

➤ Surface Bound State



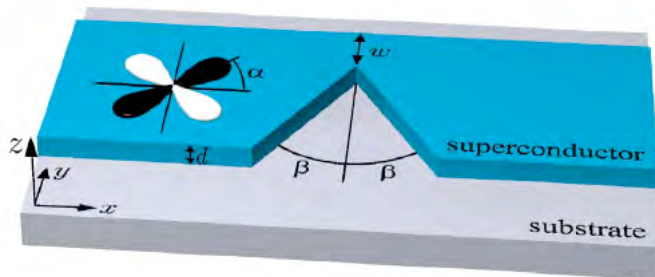
$$\varphi_1 - \varphi_2 = \pi$$



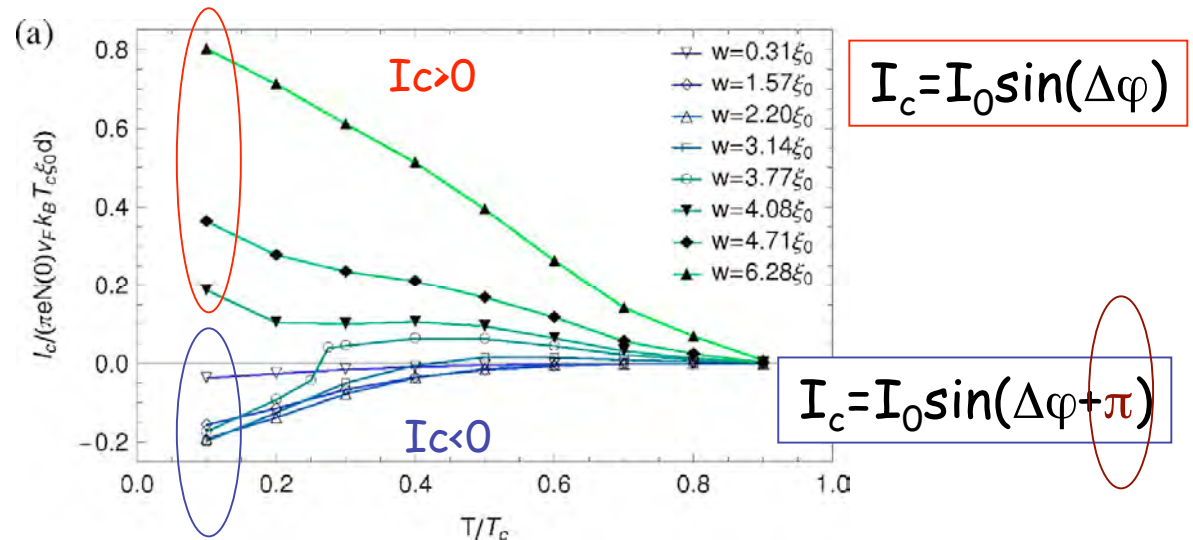
Bound State $E=0$

➤ Making a π junction

$$w = \text{a few } \xi$$

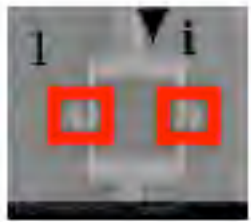


Gumann et al APL 2007

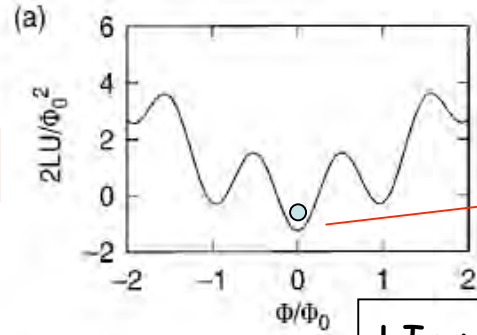


Spontaneous super-current

➤ π SQUID



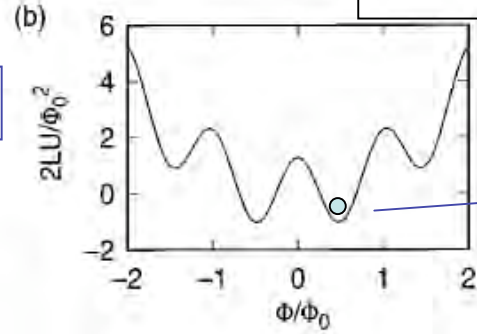
0 junction



Ground state $j=0$
Flux = 0



π junction



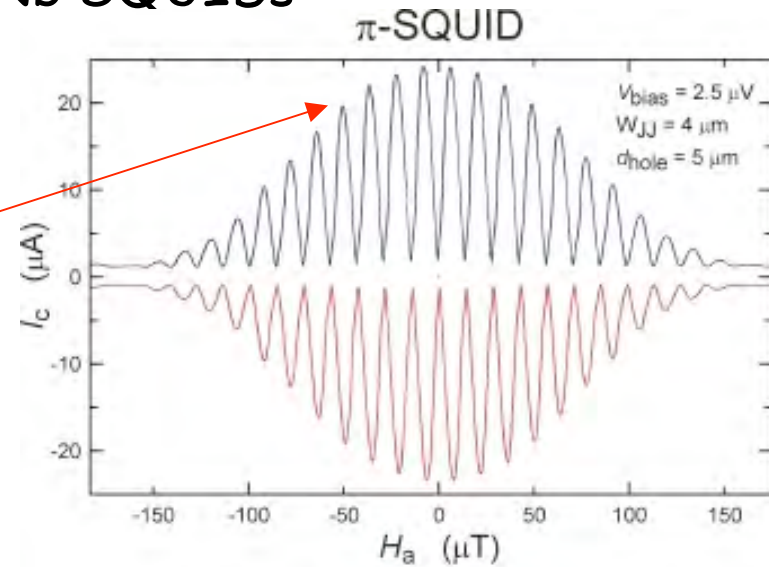
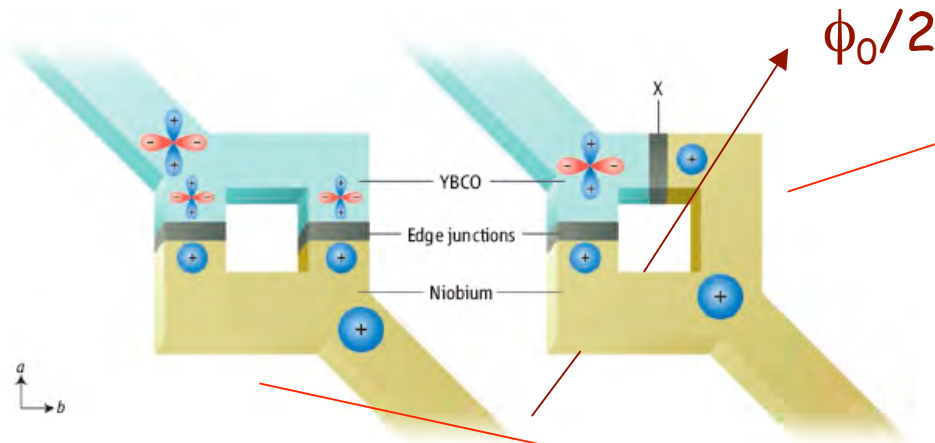
Ground state $j \neq 0$
Flux = $\phi_0/2$

Free energy
$$U(\Phi, \Phi_a) = \frac{\Phi_0^2}{2L} \left\{ \left(\frac{\Phi - \Phi_a}{\Phi_0} \right)^2 - \left(\frac{L|I_c|}{\pi\Phi_0} \right) \times \cos \left(\frac{2\pi}{\Phi_0} \Phi + \varphi \right) \right\}$$

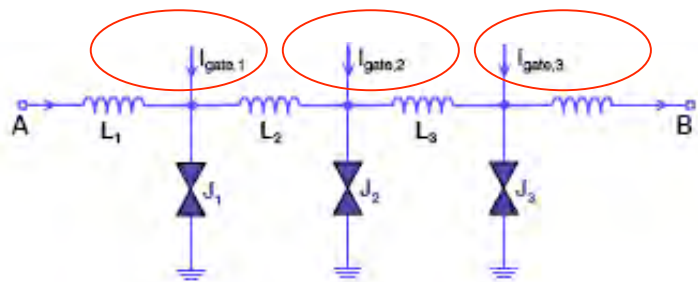
Spontaneous current

π -SQUID in RSFQ circuits

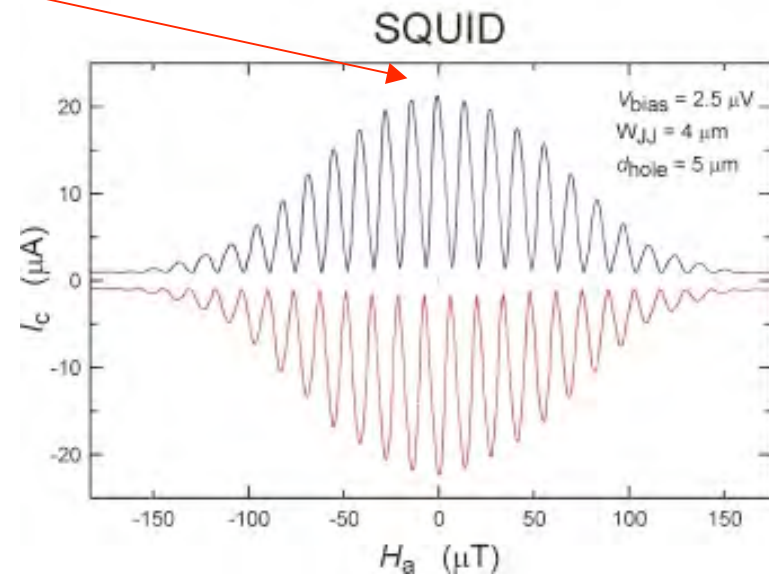
➤ Spontaneous half flux quanta in YBCO/Nb SQUIDS



➤ Numerous bias leads in RSFQ circuits

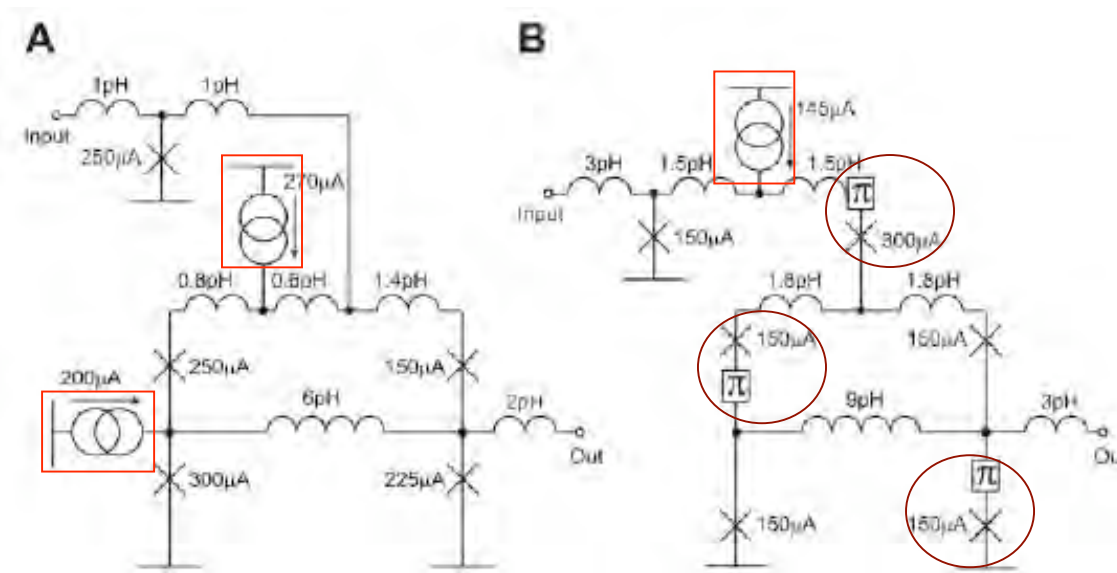


Ortlepp et al Science 2006

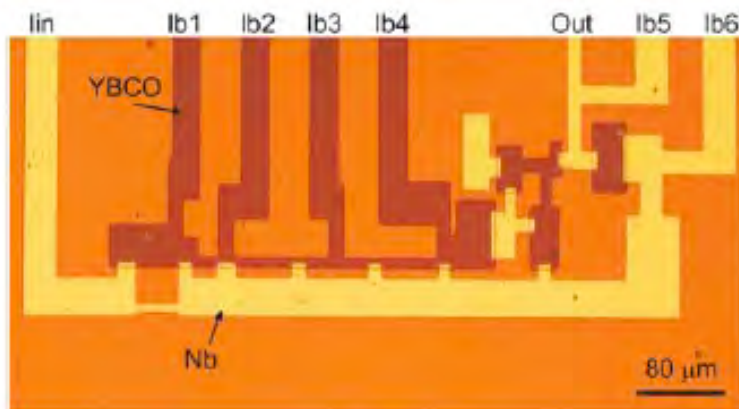


Toggle flip-flop

➤ Comparison with and without π -junctions



➤ Actual device



Outline

1. Superconductive electronics

Dynamics of Josephson Junctions

Rapid Single Flux Quanta logic

Actual RSFQ devices

2. High T_c Josephson nanoJunctions

Ion irradiation of High T_c Superconductors

Making Nanojunctions

Major characteristics of the Nanojunctions

A few applications

3. Physics of High T_c nanojunctions

Proximity effect

Quasi-classical diffusive approach

D-wave order parameter symmetry

π -junctions and RSFQ devices

4. Conclusions

Conclusions

- RSFQ logic : a promising technology
- High Tc Josephson nano-Junctions : a promising path
- Applications are on their way
- Proximity effect based Josephson Junctions
- D-wave order parameter : it matters !

Thank you !

JnJ : Bergeal & al, APL 87, 102502 (2005),
JAP 102, 083903 (2007)
Squids : Bergeal & al, APL 89, 112515 (2006)
APL 90, 136102 (2007)
Optimization : J. Lesueur & al,
IEEE Trans Appl Sup 17, 963 (2007)
M. Sirena & al, JAP 101, 123925 (2007)
M. Sirena & al, APL 91, 142506 (2007)
M. Sirena & al, APL 91, 262508 (2007)

