CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

ESPCI
ParisTech

HTc Josephson nano-junctions : physics and applications

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Collège de France 2008

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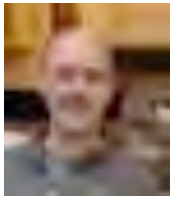
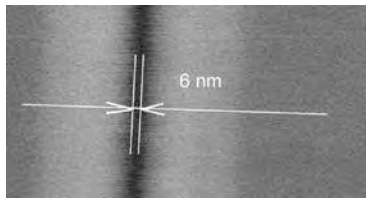
Giancarlo Faini 

Martin Sirena 



Thomas Wolf 

Rozenn Bernard, Javier Briatico, Denis Crété

THALES

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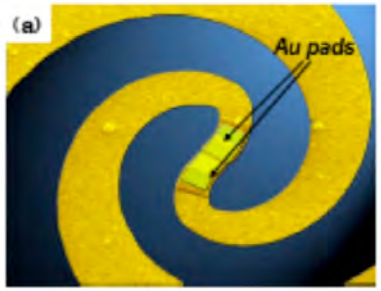
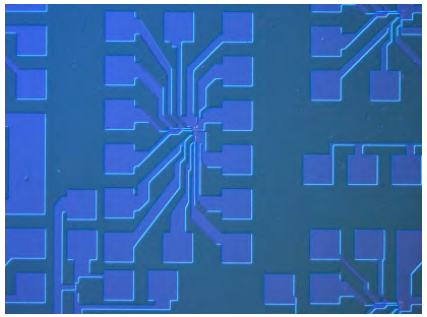
LAHC

Nicolas Bergeal
Martin Sirena
Thomas Wolf
Alexandre Zimmers

THz

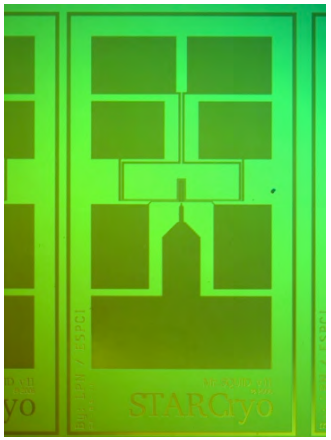


RSFQ



THALES

Denis Crété



SQUID

Etalon du Volt

LNE
Le progrès, une passion à partager

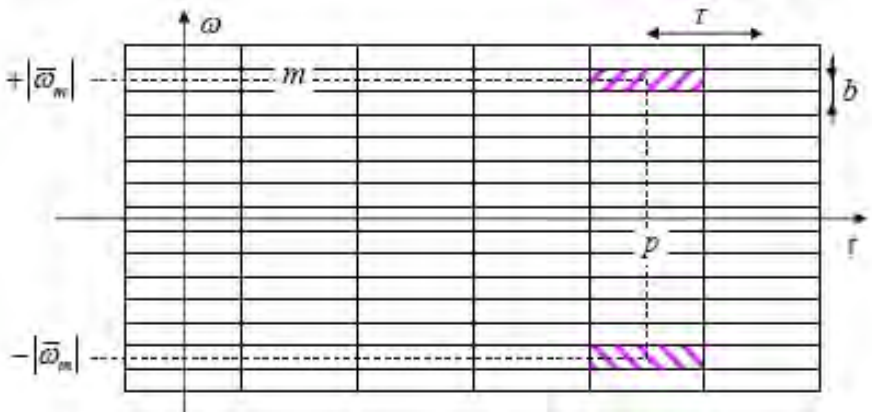
Robin Cantor

STAR Cryoelectronics

Sophie Djordjevic

Quantum circuits ?

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



1st

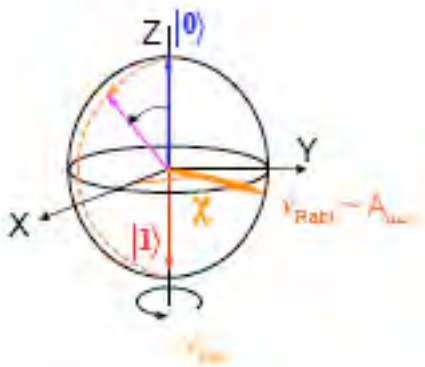
$$\left\{A^{\mp}_{m_1 p_1}, A^{\mp}_{m_2 p_2}\right\}_{PB} = -\frac{i}{2}\bar{\omega}_{m_1}\delta_{m_1+m_2}\delta_{p_1-p_2}$$

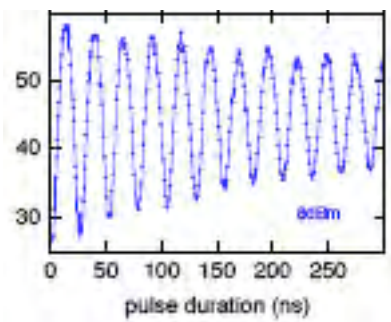
2d

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

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

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





Phase properties and superconducting circuits

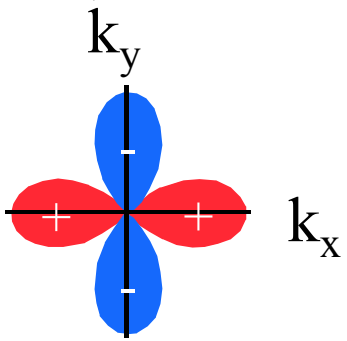
- Phase rigidity of the condensate

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

$$\oint d\varphi = 0$$

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

- Intrinsic phase structure in High Tc SC



$d_{x^2-y^2}$

Josephson nano-junctions

π-junctions

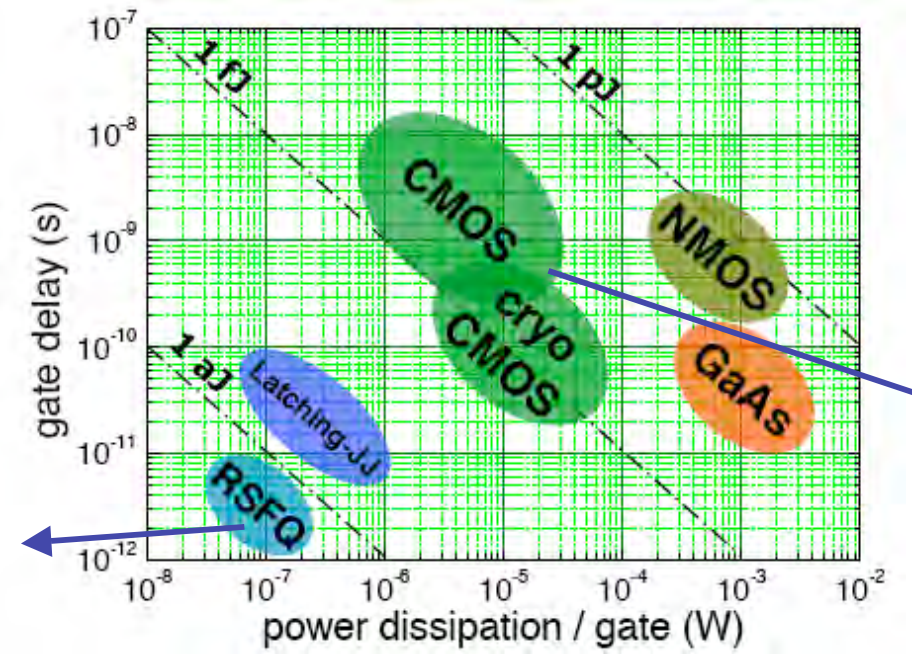
- High speed applications

Analog to Digital converters

Communication systems

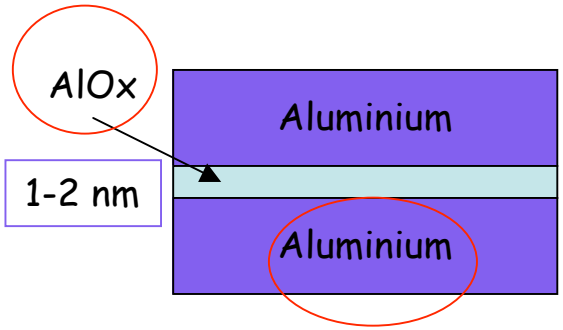
PetaFLOPS computer …

Superconductive electronics



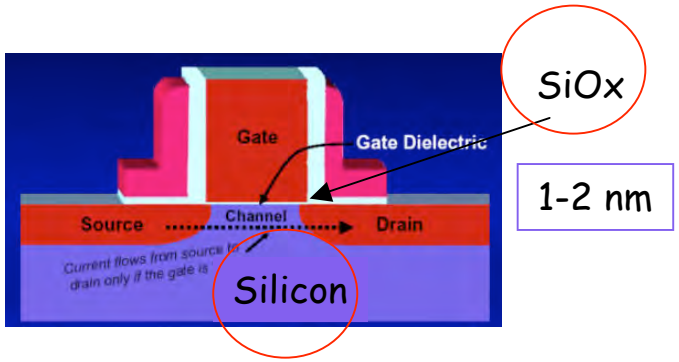
Superconductors

Semiconductors



Josephson Junction

Quantum circuit

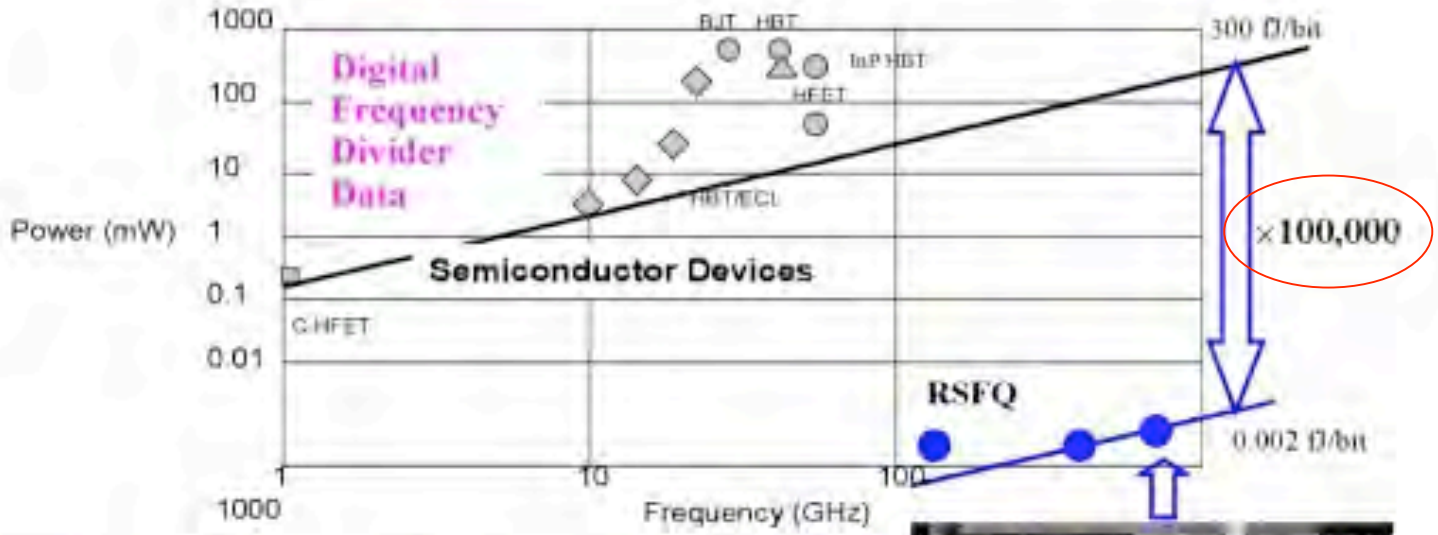


CMOS transistor

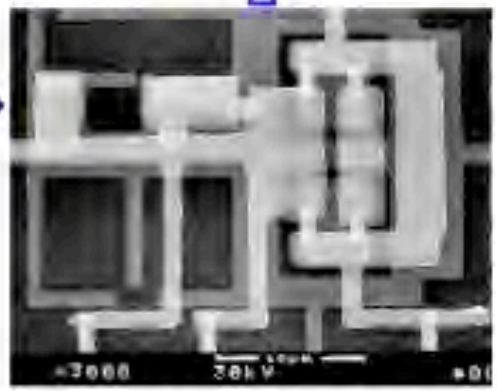
Dream or reality ?

➢ An example : a digital frequency divider

Technology : Nb/Al/AlOx/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



RSQF- SUNY Frequency divider

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

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

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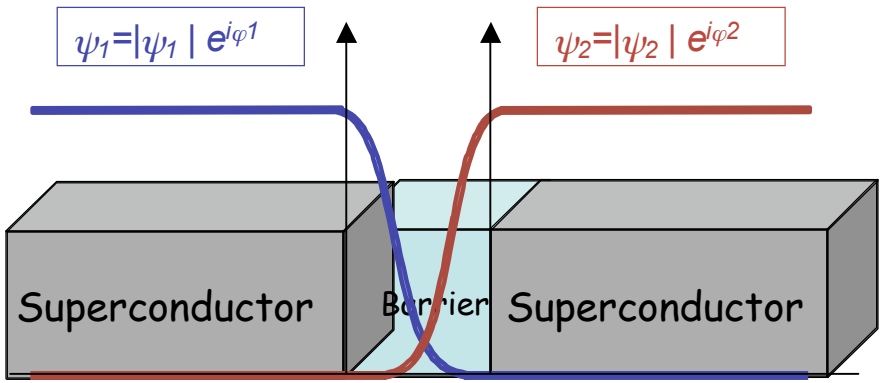
Josephson Junctions

➢ Josephson Junctions



➡ Josephson equations

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

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

483 597,9 GHz/V

Barrier : insulator, normal metal, constriction …

➡ Josephson Energy

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

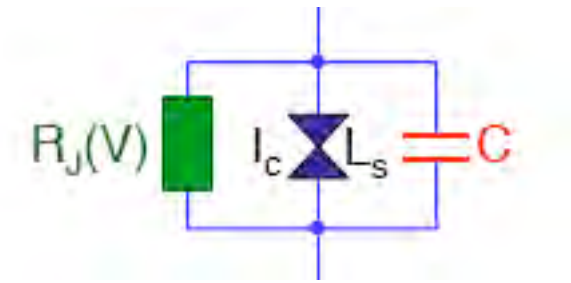
➢ Applications : superconductive electronics

- 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

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



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

➢ Josephson Junction : a non-linear inductance

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

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

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

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

The mechanical analogy

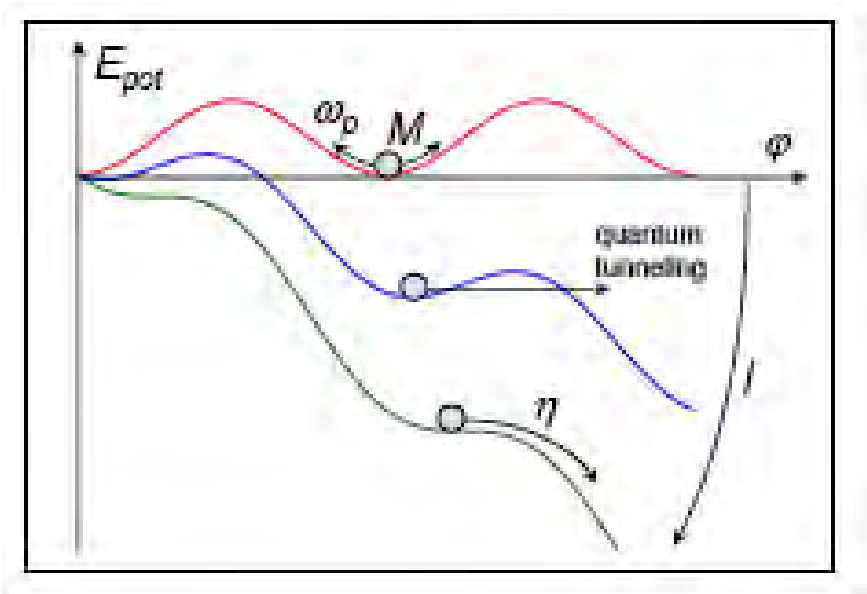
➢ Normalized equation

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

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

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

➢ « 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

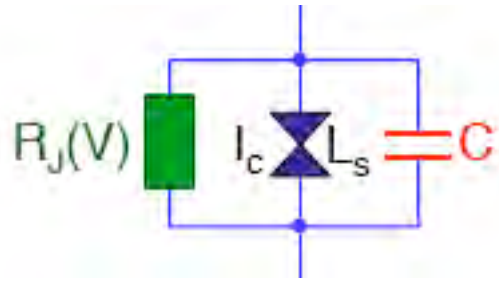
➢ Characteristic times

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

$$\tau_p = \sqrt{\frac{2\pi\phi_0 C_J}{I_c}} \qquad \tau_{LR} = \frac{\phi_0}{2\pi I_c R_J} \qquad \tau_{RC} = R_J C_J$$

➢ Mc Cumber parameter

$$\tau = \frac{t}{\tau_{LR}} \qquad \beta_C = \frac{\tau_{RC}}{\tau_{LR}} = \frac{2\pi I_C C_J R_J^2}{\phi_0}$$



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

$\beta_C >> 1$ underdamped

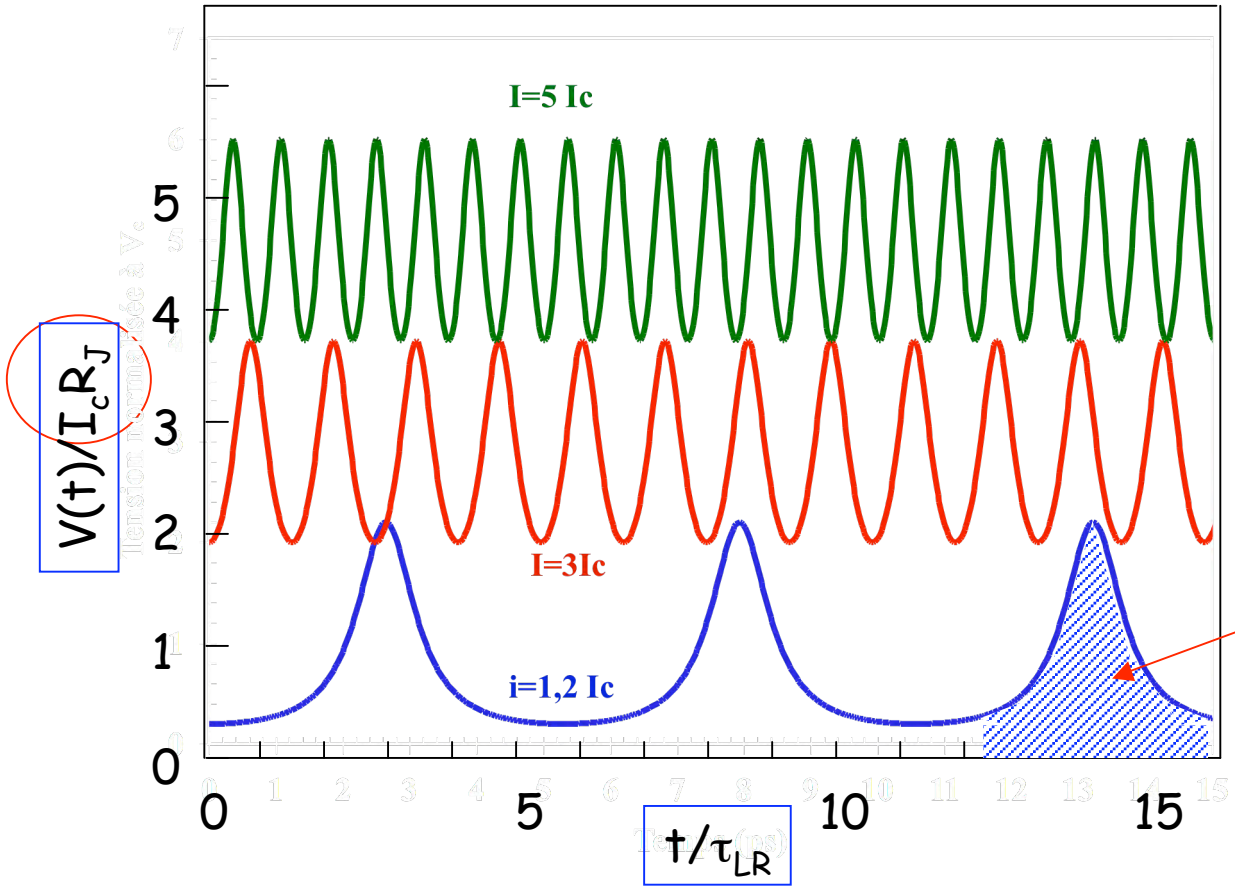
$\beta_C \leq 1$ overdamped

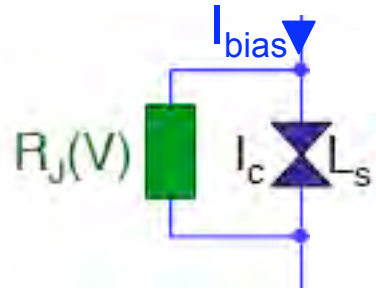
R & C small

No tunnel

Voltage and current across a current biased JJ

➢ Current biased overdamped Josephson Junction





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

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

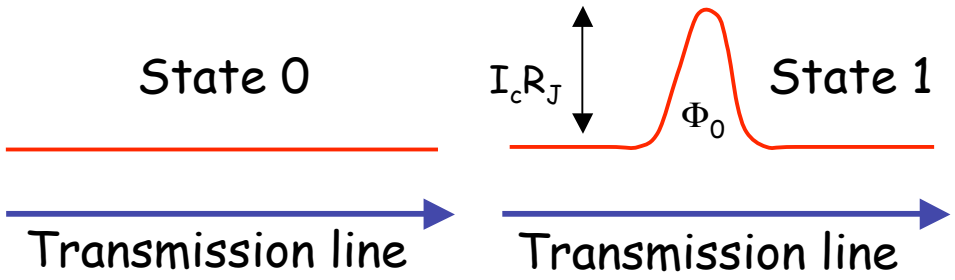
τ_{LR}

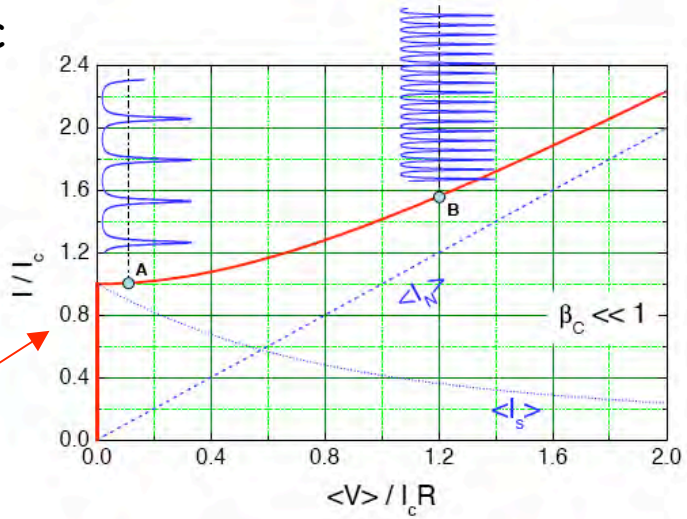
$$\tau_{LR} = \frac{\phi_0}{2\pi I_c R_J}$$

- ➢ Quantized pulses
- ➢ Timescale $\tau_{LR} \approx$ ps
- ➢ Vmax$\approx 2 I_c R_J \approx$ mV
- ➢ Energy$\approx I_c \Phi_0 \approx$ aJ

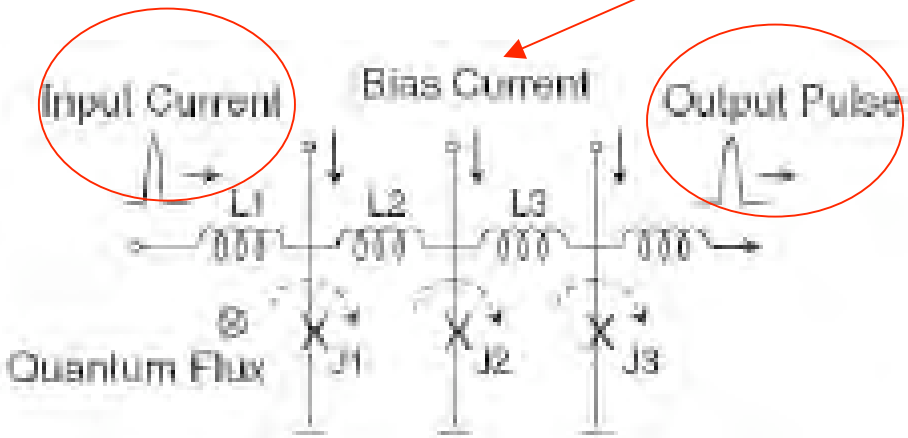
Rapid Single Flux Quanta logic

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



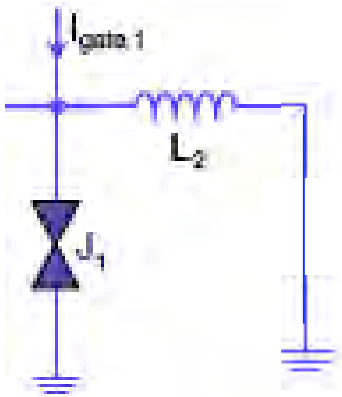


➢ Current biased overdamped JJ (Ib < Ic)



Josephson transmission line

➢ Inductance (RF SQUID)



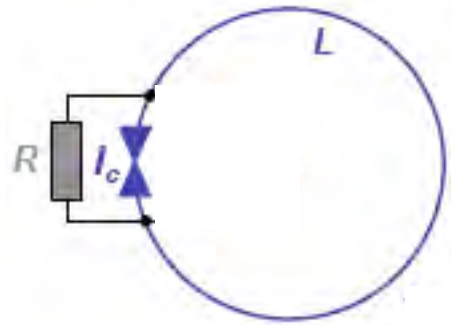
$$\beta_L = \frac{2L I_C}{\phi_0}$$

Dynamics of an RF SQUID

➢ Fluxoid quantification

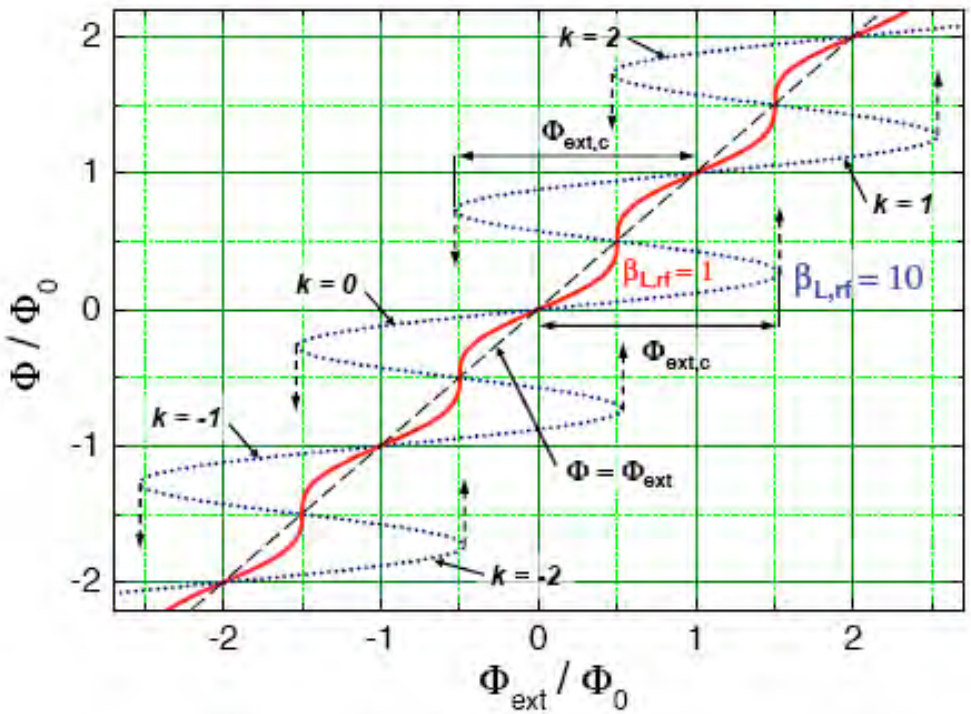
$$\frac{\phi}{\phi_0} = \frac{\phi_{ext}}{\phi_0} - \frac{\beta_L}{2\pi}\sin\left(2\pi\frac{\phi}{\phi_0}\right)$$

$$\beta_L = \frac{2L I_C}{\phi_0}$$



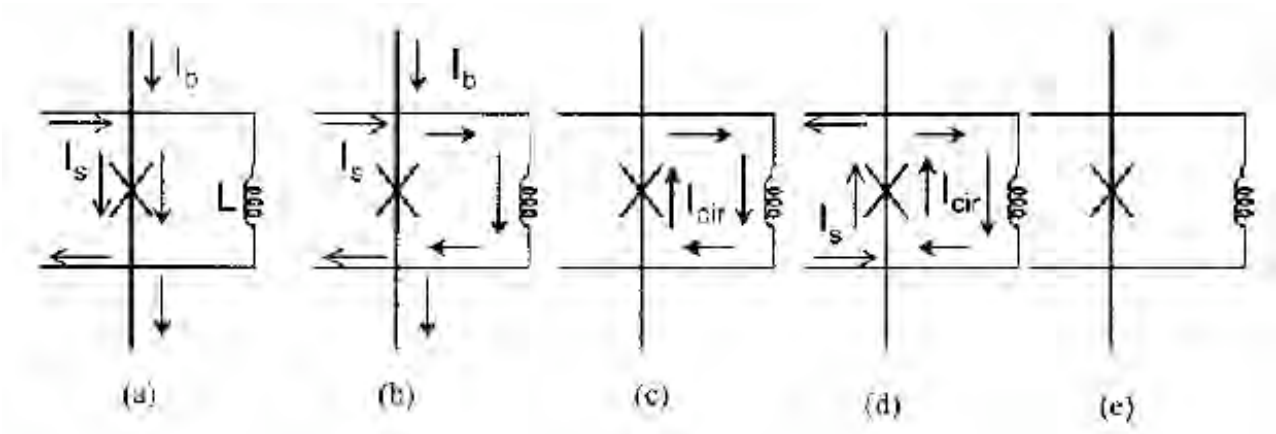
$\beta_L << 1$ Non-hysteretic

$\beta_L >> 1$ Hysteretic



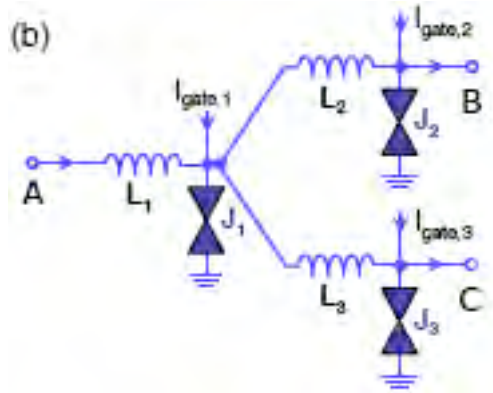
Storing and manipulating pulses

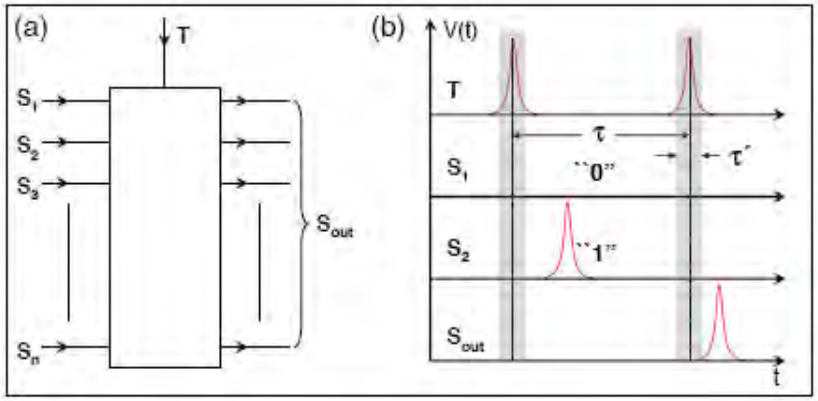
➢ Storing a pulse



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

➢ Manipulating pulses





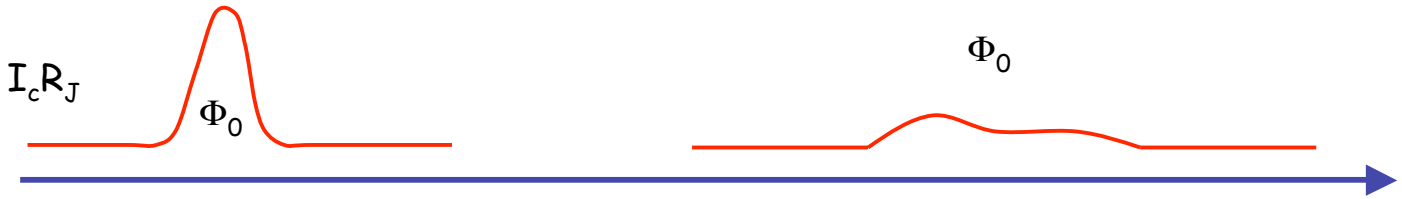
➢ RSFQ circuits : JJ and inductances

$$\Phi_0 < LIc$$

$$\Phi_0 > LIc$$

Advantages of RSFQ logic

- Robust pulse along the way



- Intrisinc speed : THz frequency

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

Ic ≈ 0.1 - 1 mA

R_J ≈ 1 - 10 Ω

$1/\tau_{LR}$ ≈ 1-10 THz

- Low power consumption

Energy ≈ $Ic\Phi_0$

f ≈ 0.1 - 1 THz

P ≈ 0.1 - 1 nW

N ≈ 10^6 gates

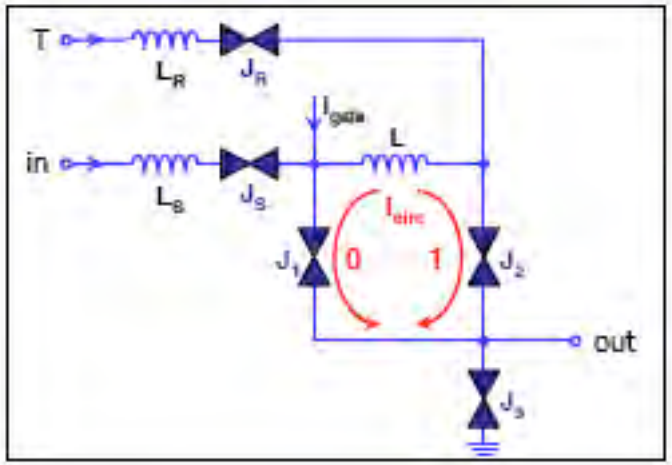
P ≈ 0.1 - 1 mW

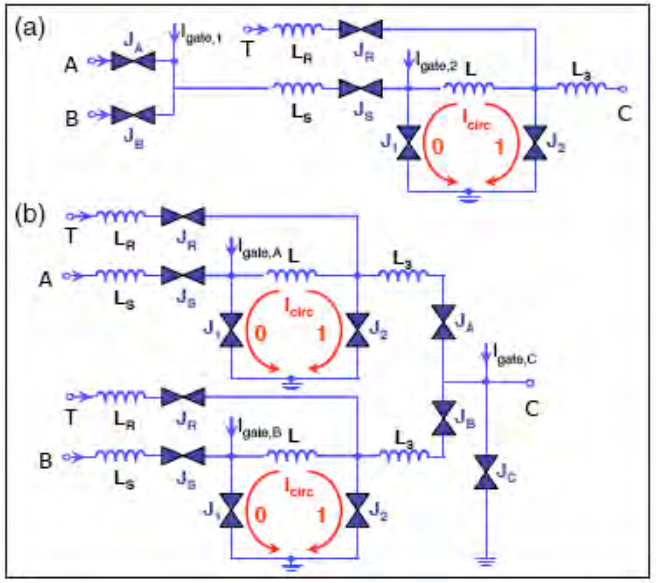
- Overdamped : no tunnel junctions

A complete logic library

➢ All logic elements possible

NOT

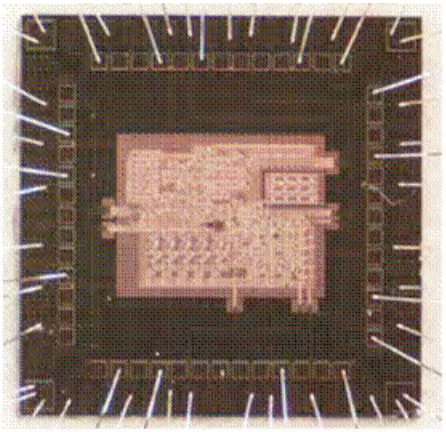




T-NOR

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

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

Increasing current density j_C

~~Today Low Tc~~

Tomorrow High Tc

- Temperature ~~4.2 K~~ 100 K
- Current density >>10 kA/cm²
- SC gap ~~1 mV~~ 20-30 mV
- 5 to 10% spread
- 30000 JJ

?????

Increasing superconducting gap $I_c R_N$

Decreasing the JJ characteristic spread

High Tc Superconductive electronics … today

➢ High Tc A/D convertor (ISTEC Japan)

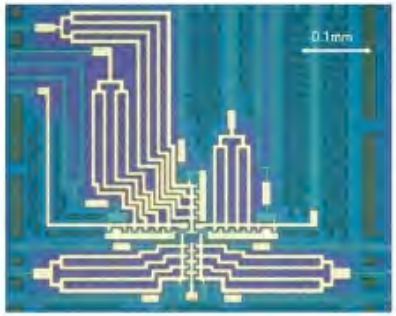


Fig.1. Photomicrograph of the 1:2 switch test circuit

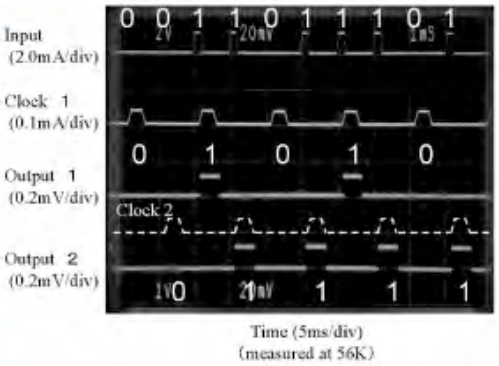


Fig.2. Example of output waveform of the 1:2 switch test circuit

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

➢ Complex materials

➢ Multi-component oxides ($YBa_2Cu_3O_7$)

➢ High temperature processing (700-800°C)

➢ Very sensitive to disorder …

HTSc Josephson Junctions technology :

reliability, ageing, integration, cost effective

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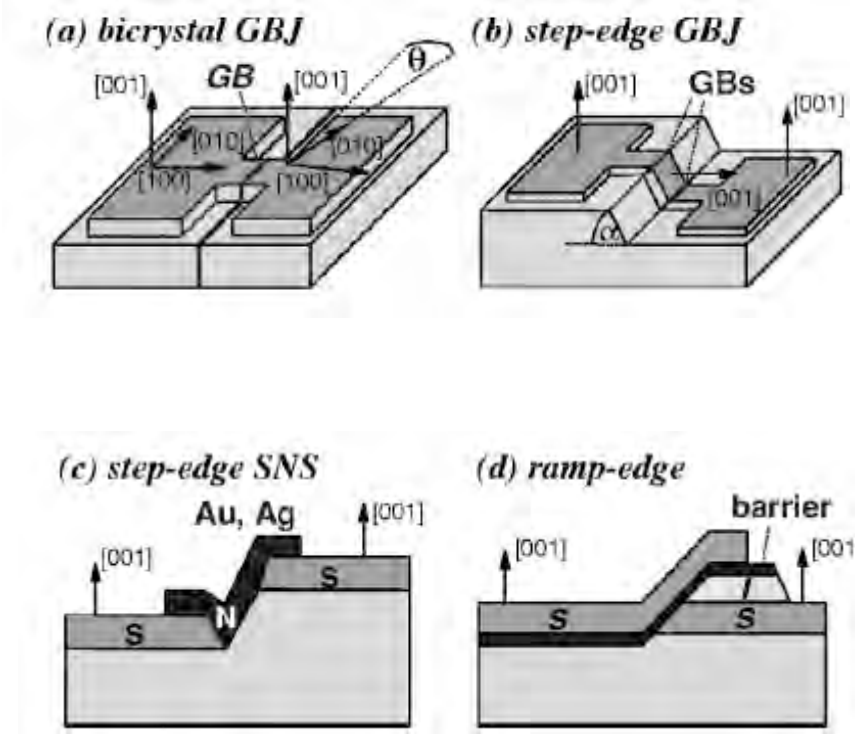
« Standard » High Tc Josephson junctions

➢ Complex materials …



■ Grain boundary junctions

Special substrates

Design constraints

Lack of reproducibility

■ Ramp junctions

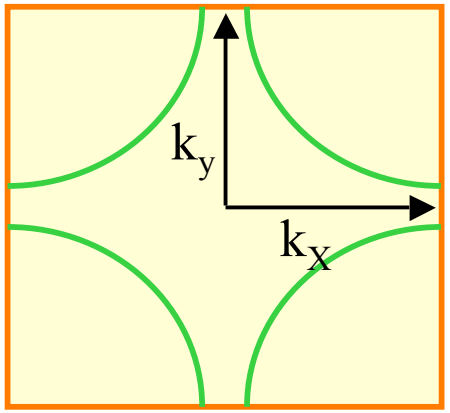
➢ Alternative technology

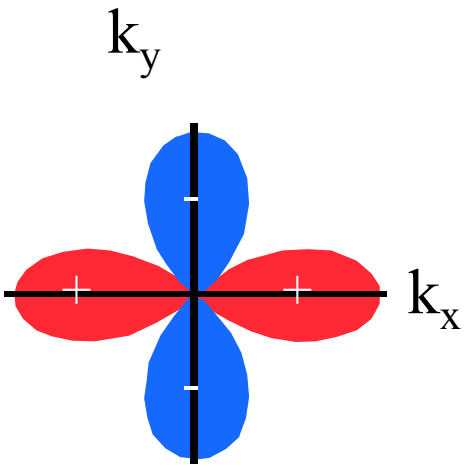
➡ Ion irradiation

Kahlmann et al & Katz et al APL'98

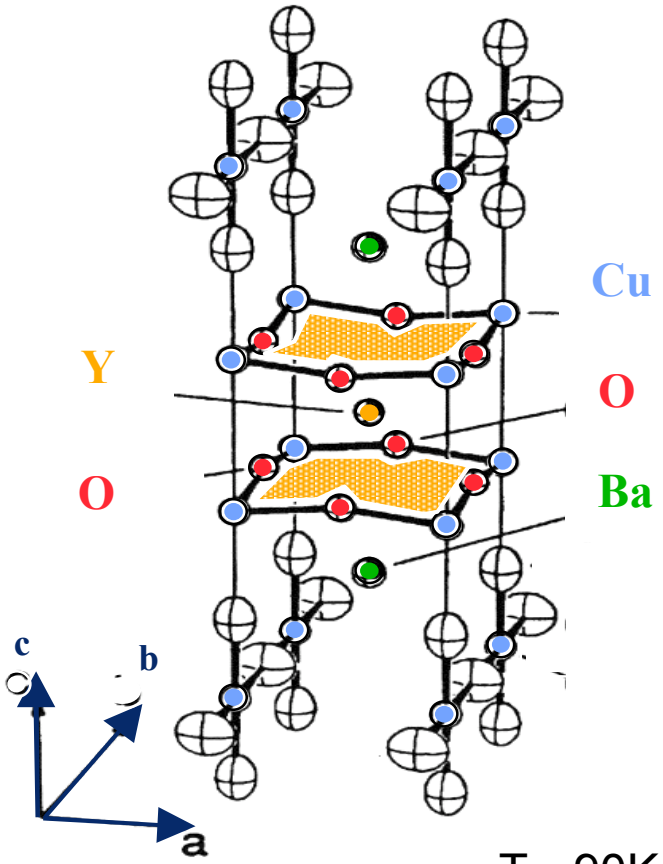
High Tc cuprate superconductors

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





$YBa_2Cu_3O_{6+x}$

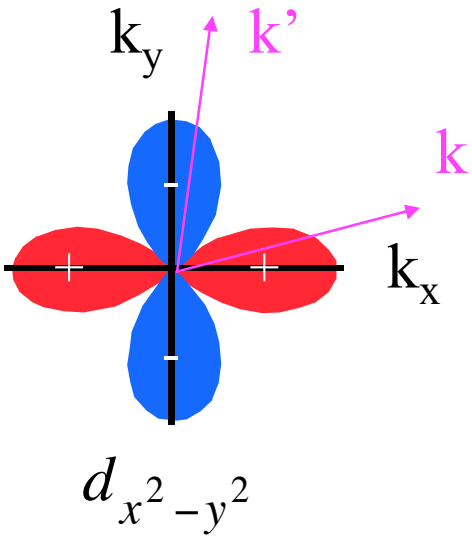


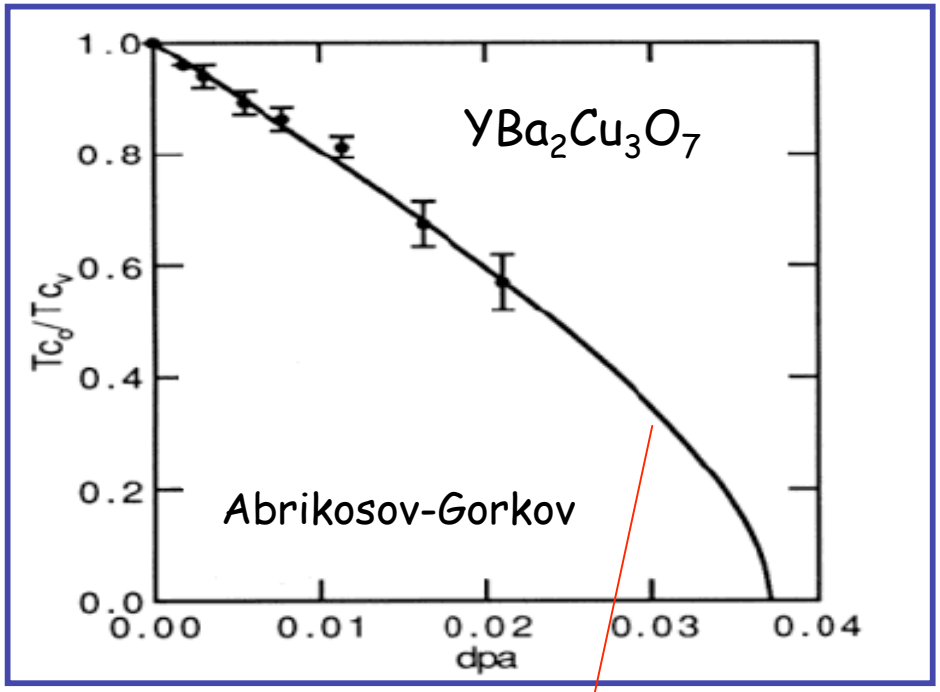
T_c=90K

- Order parameter symmetry : d_{x2-y2}

Disorder in High Tc Superconductors

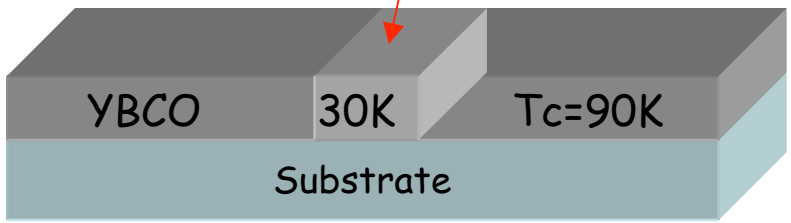
➢ Defect in d_{x2-y2} superconductor ➡ depairing





➢ Local control of the disorder

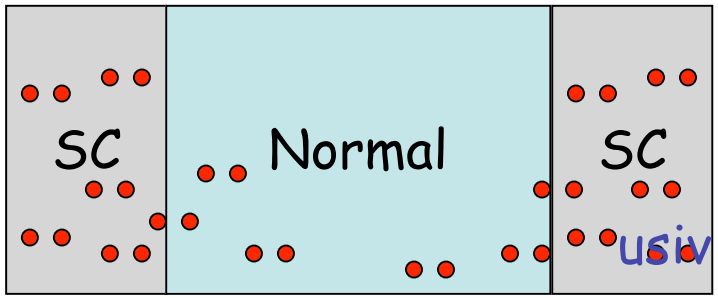
➢ Nanoscale engineering (ξ_N)



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

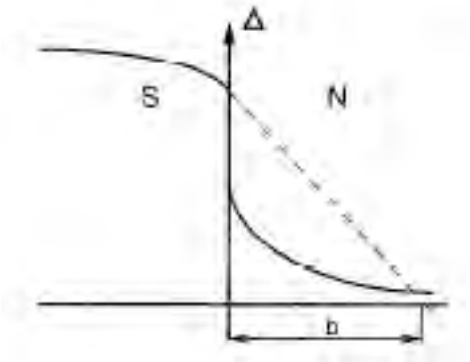
Proximity effect based Josephson Junctions

➢ Phase coherence through normal metal : Josephson coupling



Diffusive case

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



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

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

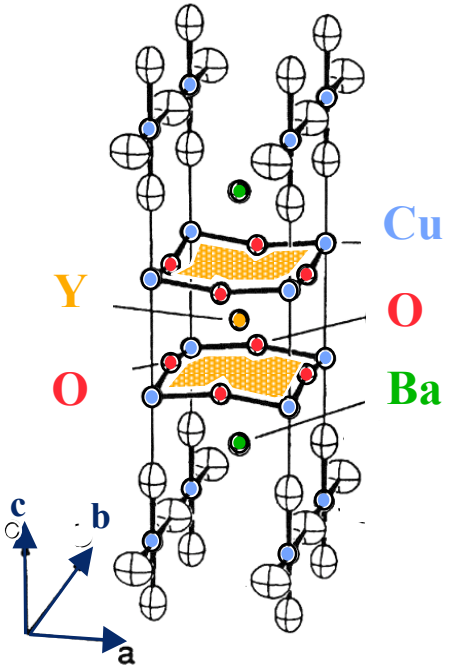
→ A few 10 nm

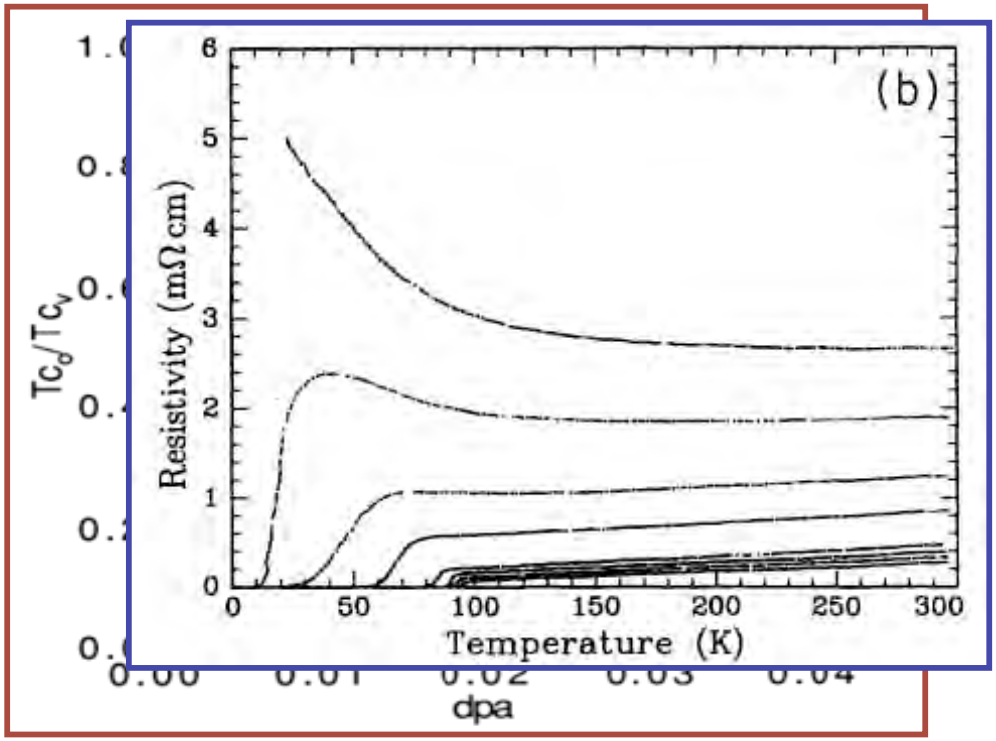
De Gennes : Rev Mod Physics 1964

Towards the insulator

➢ Defect in d_{x2-y2} superconductor ➡ depairing

➢ High defect concentration: T_c decreases

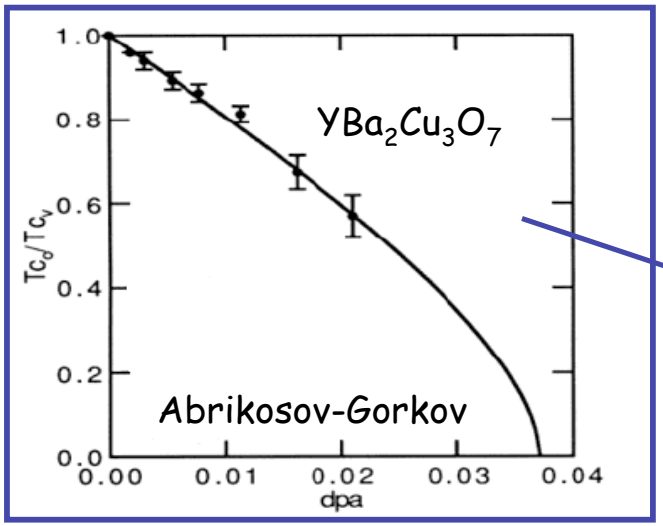


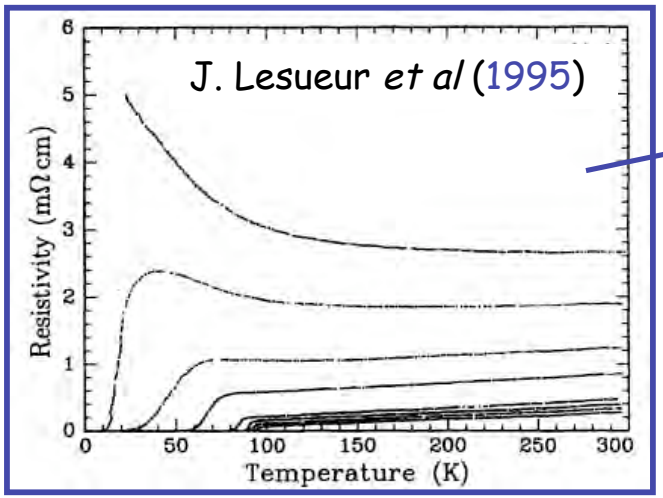


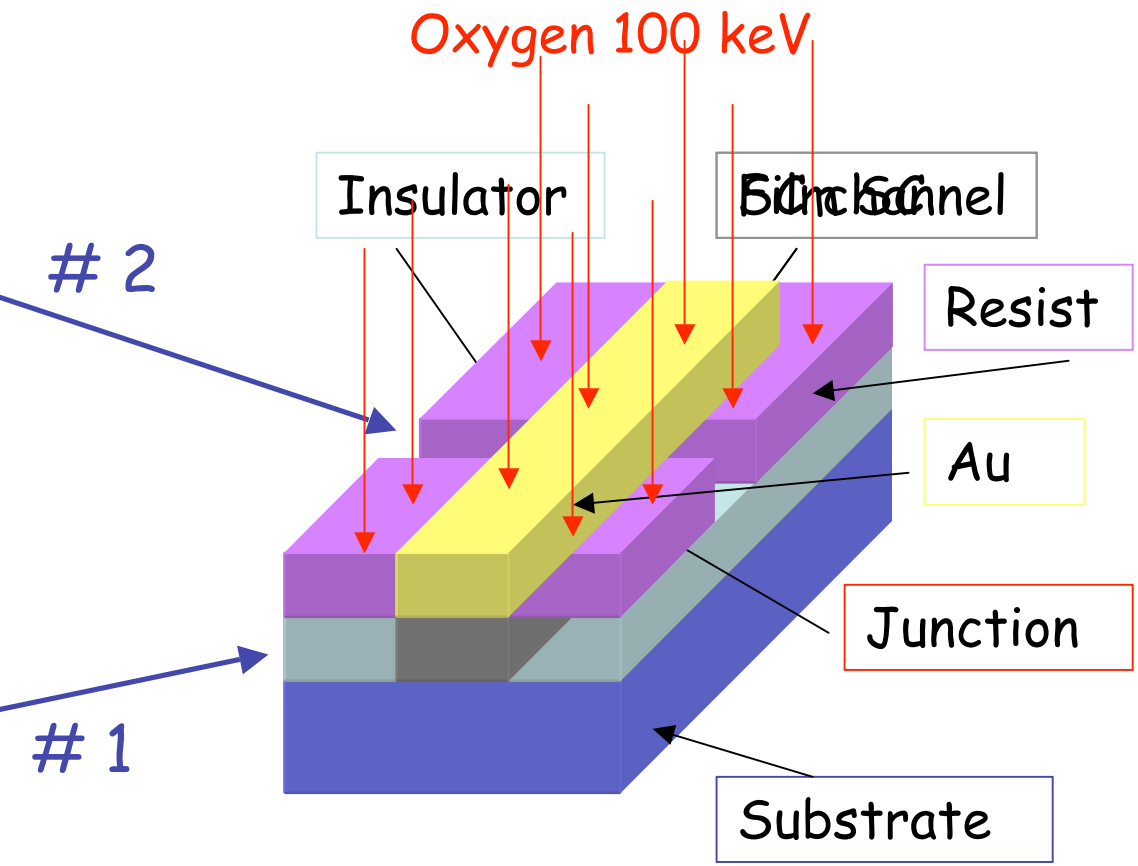
Lesueur *et al* (1995)

Fabrication of High Tc nano-Junctions

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





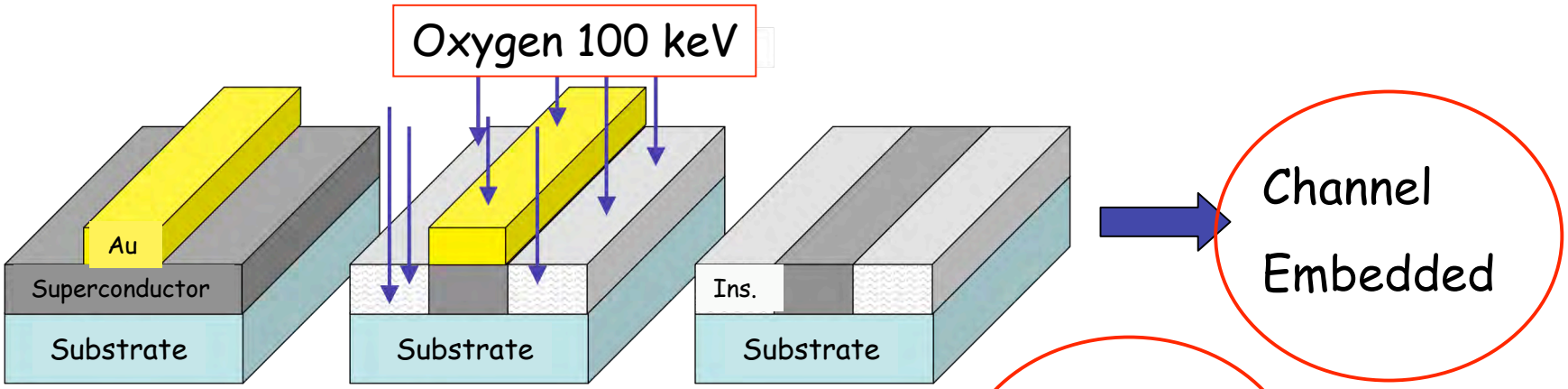


1 : drawing channels : (10^{15} at/cm^2)

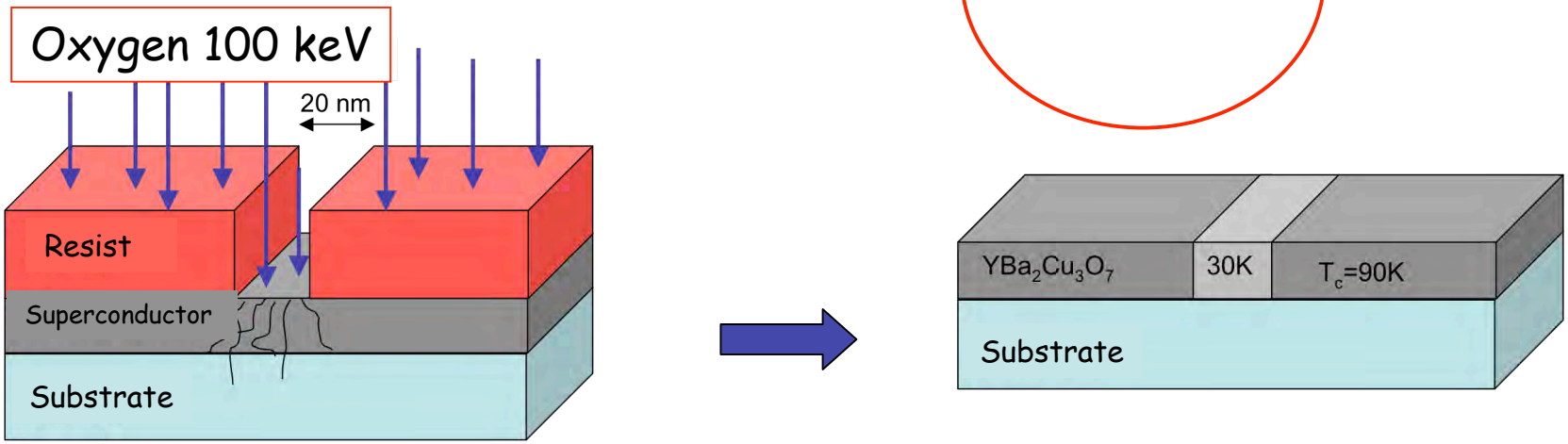
2 : creating nanoJunctions : (10^{13} at/cm^2)

Tailoring at a nanoscale

➢ First step : channel in a $YBa_2Cu_3O_7$ film (thickness = 1500Å)



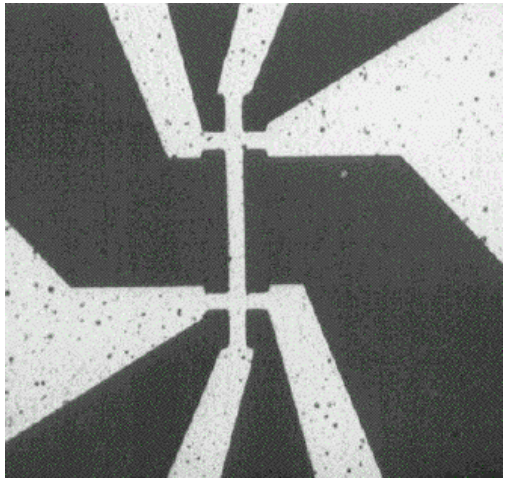
➢ Second step : nanojunction through a 20 nm slit



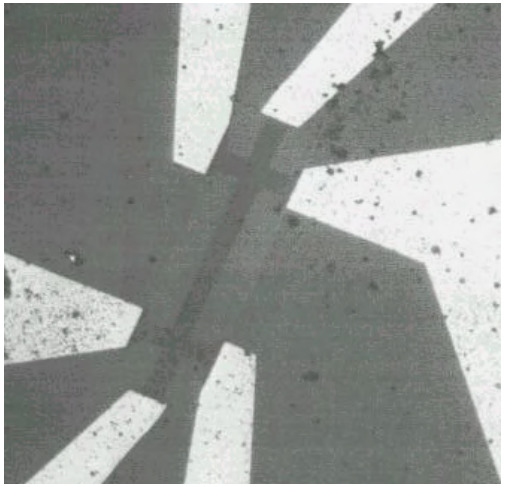
30K<T<90K jonction Super/Normal/Super

Fabrication of nanojunctions

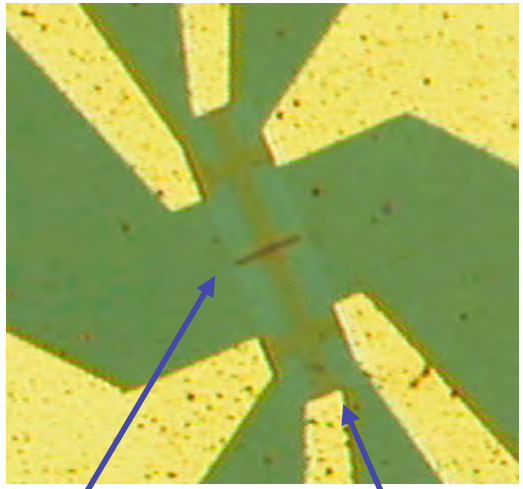
Irradiation
through Au mask



Au IBE removed



Irradiation
through Resist mask



N. Bergeal et al, APL 2005

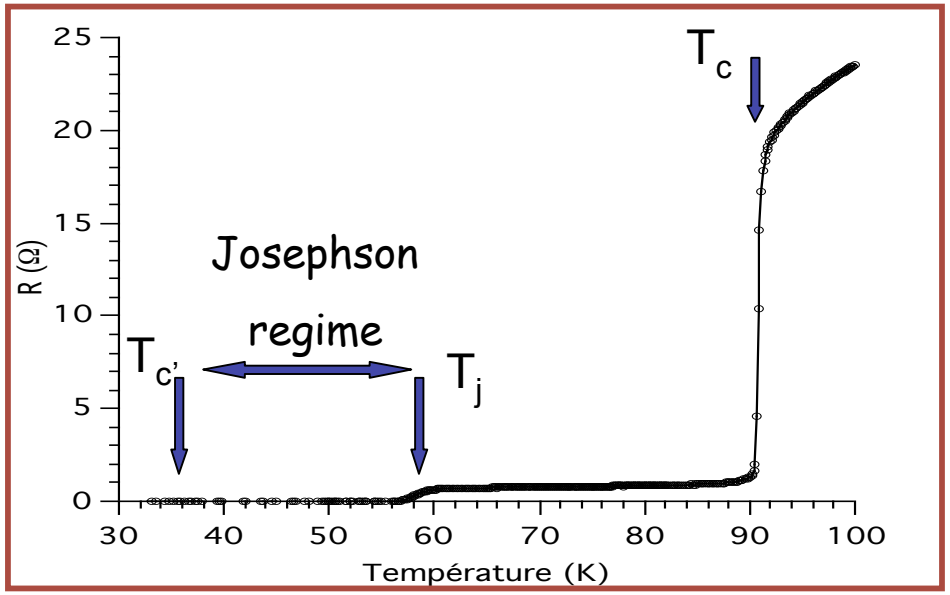
JAP 2007

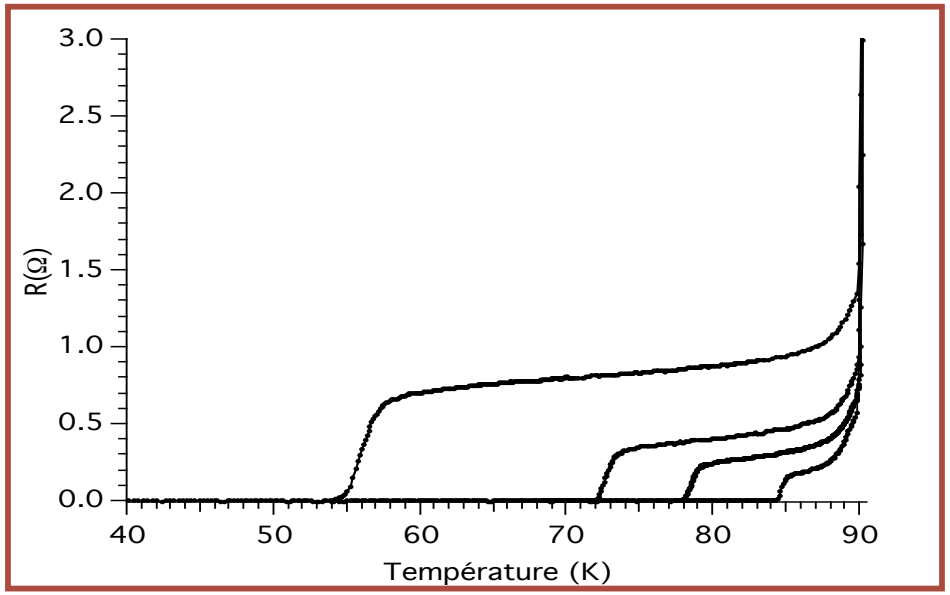
20nm slit

Hall cross

Width 1 to 5μm

R(T) measurements





High operating T

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

- $T_{c'}<T<T_j$ Josephson regime
- $T<T_{c'}<T_j$ Flux flow regime

L=5μm, E=100keV

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

- Extension of the Josephson regime

$\Delta T=7K \rightarrow \Delta T=20K$

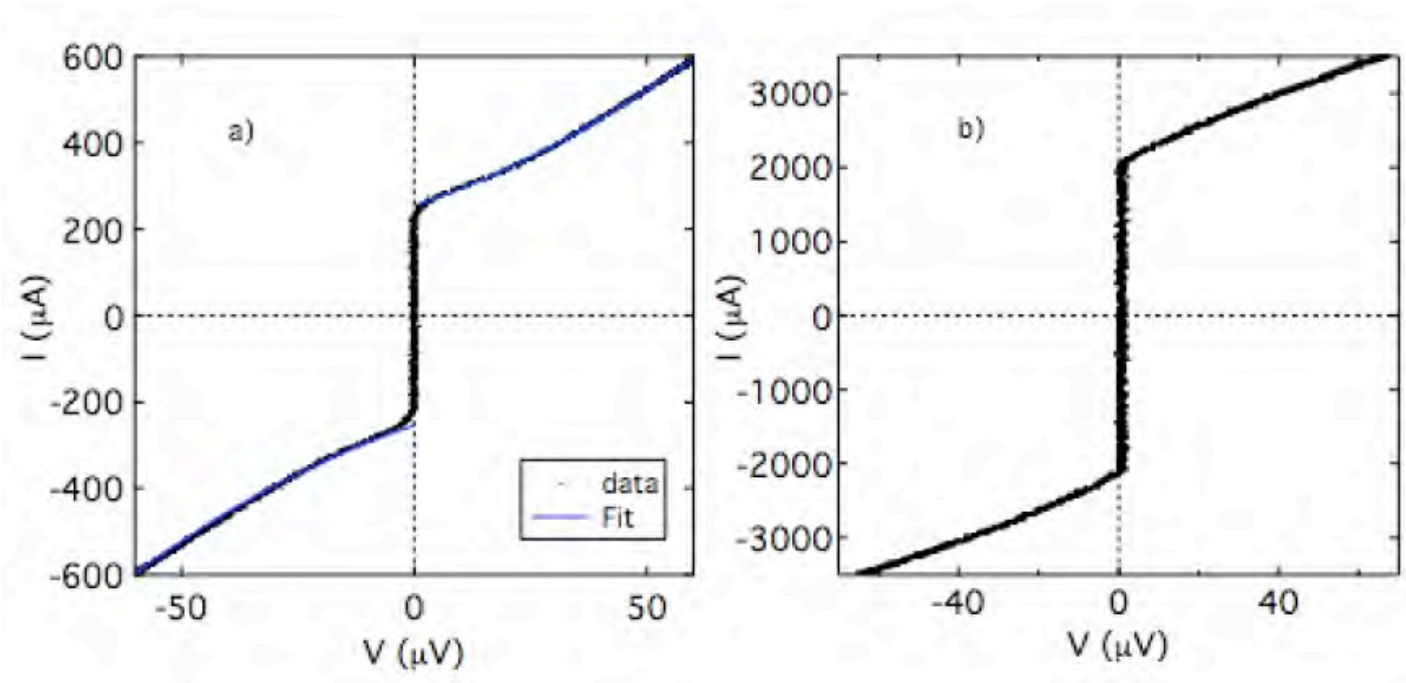
I(V) characteristics

Overdamped JJ

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

$T_J > T > T_{c'}$ 72.5 K

$T < T_{c'}$ 70 K



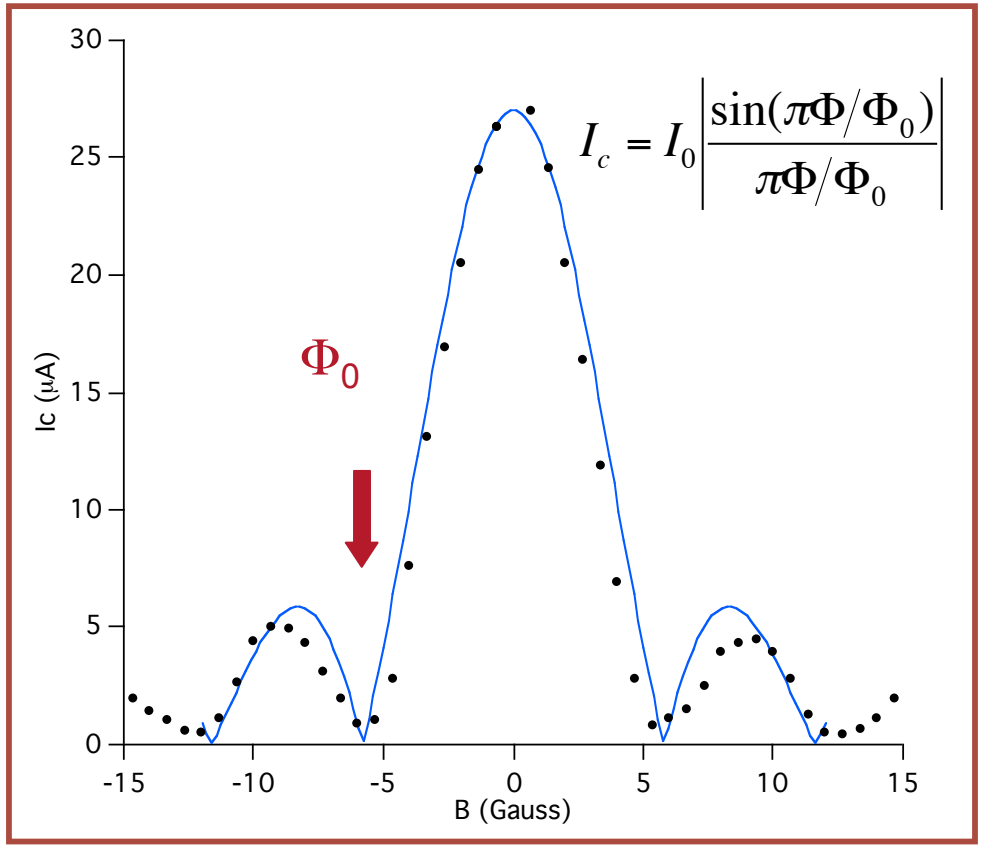
➢ RSJ behavior

➢ Flux flow behavior

➢ Resistance Rn ranging from 200mΩ to a few Ω

Fraunhofer pattern $I_c(B)$

➢ Phase control by the vector potential

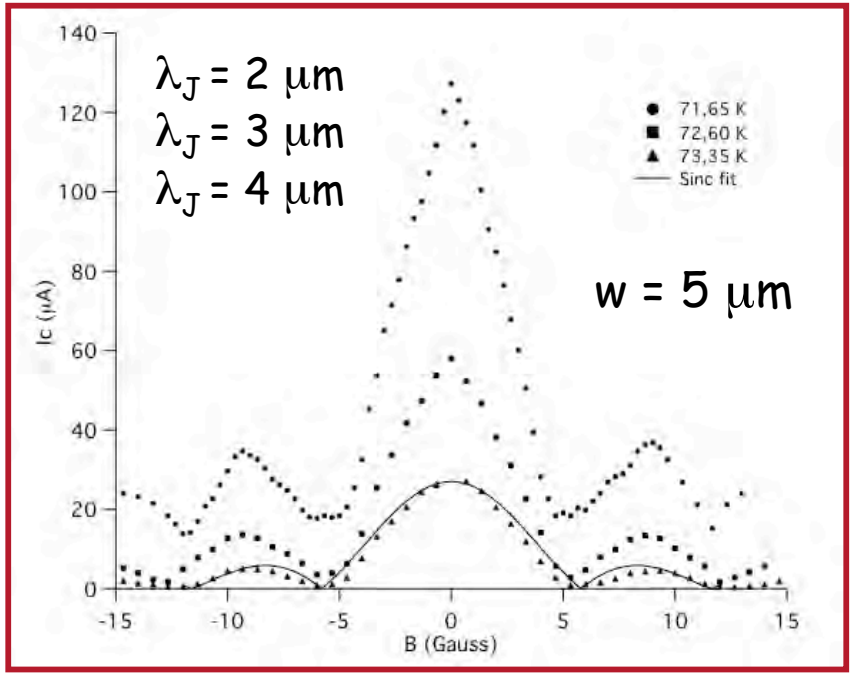


$$I = I_c \sin(\varphi) \qquad \varphi = \varphi_1 - \varphi_2$$

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

Josephson length λ_J

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

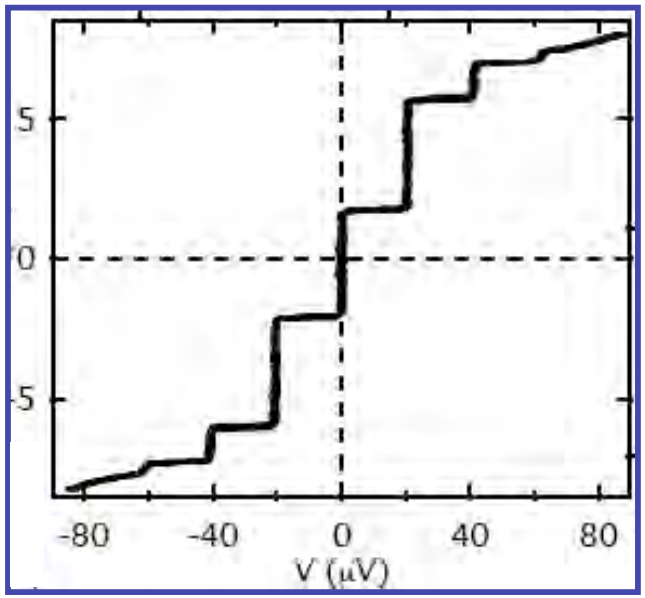


Shapiro Steps

➢ Phase controlled by microwaves

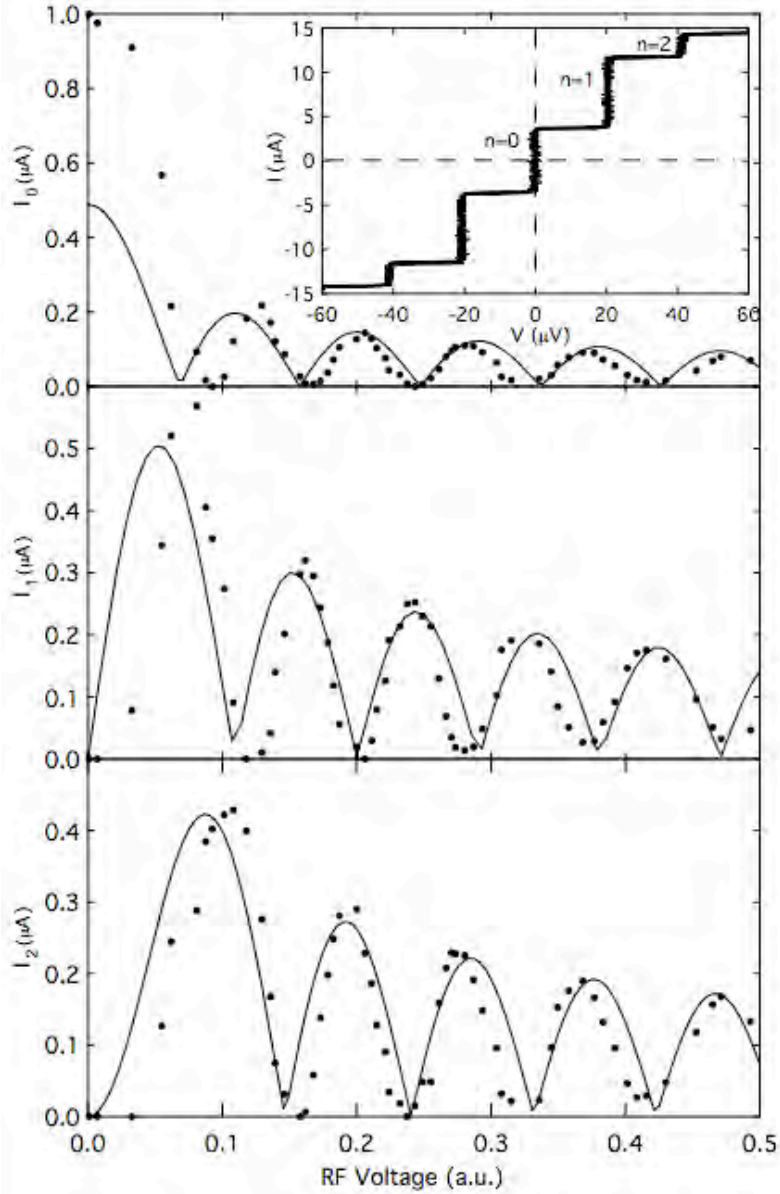
$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar}$$

483 597,9 GHz/V

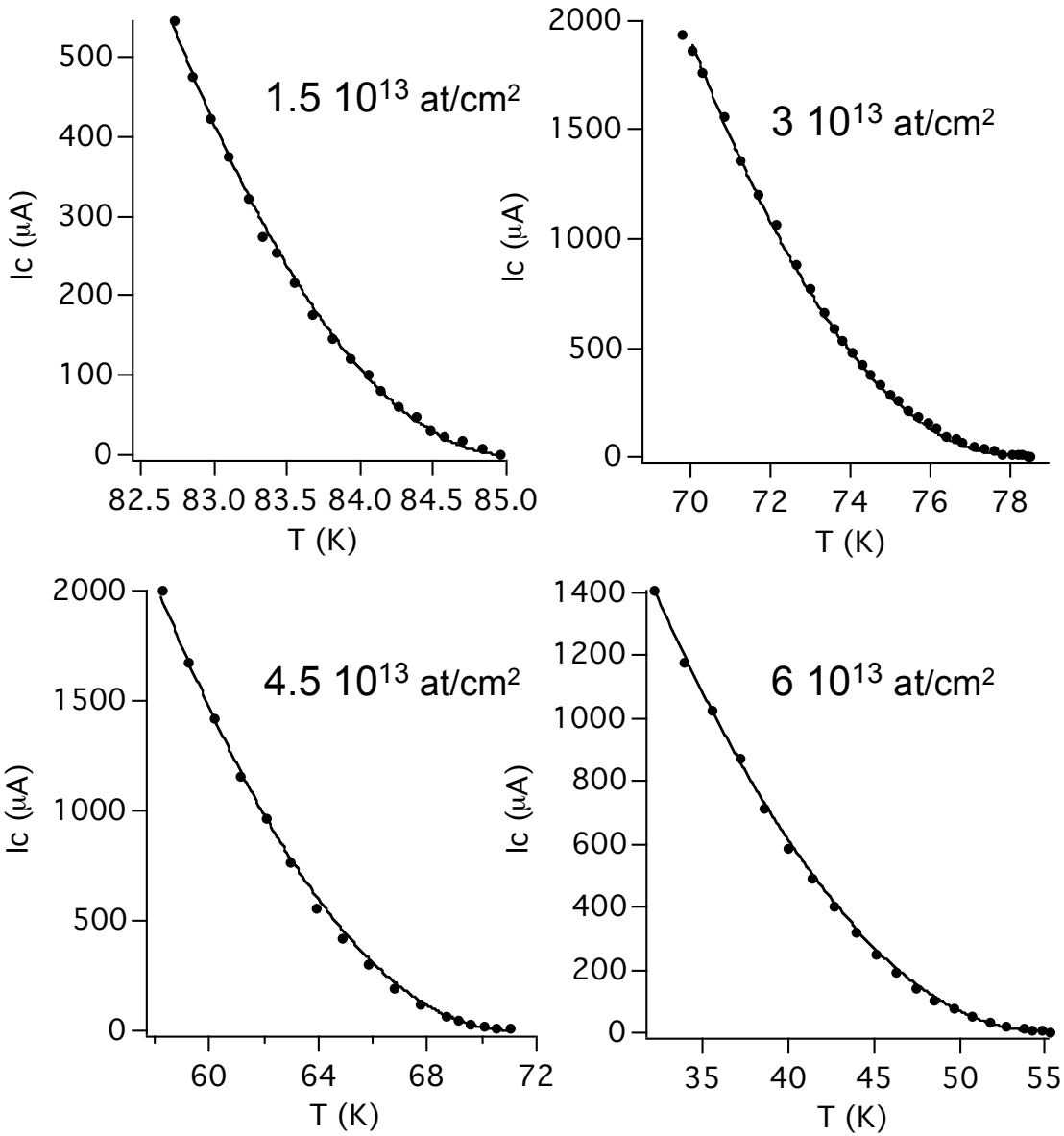


➢ Almost ideal Bessel functions

N. Bergeal, JAP 2007



$I_c(T)$ measurements

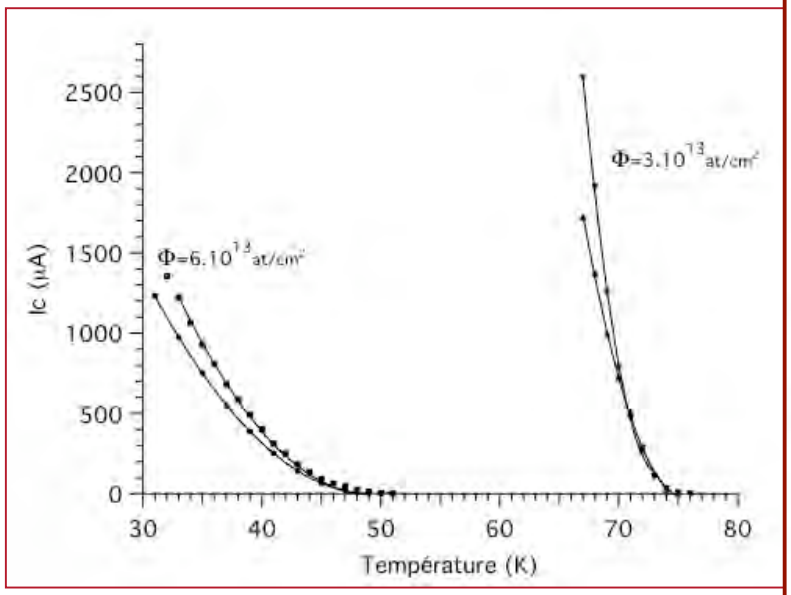


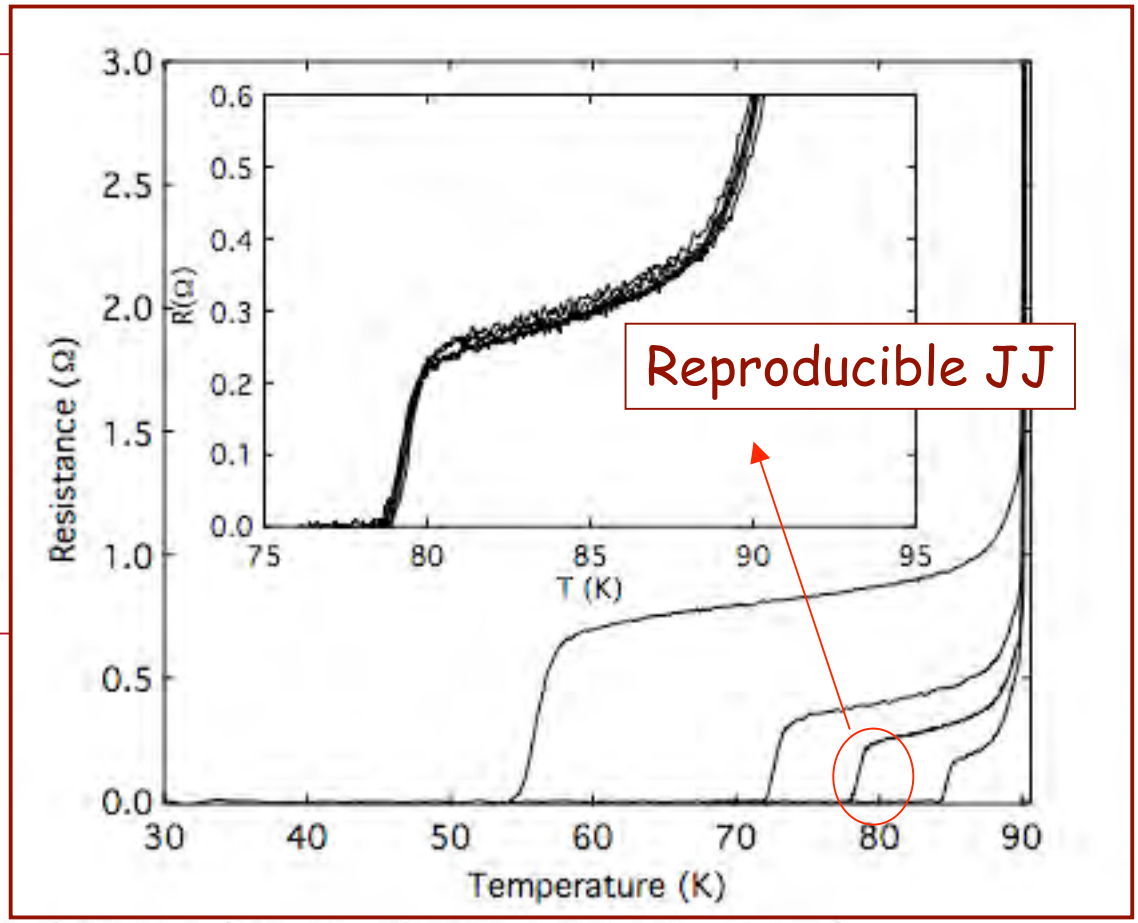
- De Gennes-Werthamer model of proximity effect

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

- I_cR_n ~ a few 100 μV

Major characteristics and reproducibility





N. Bergeal, APL 2005, JAP 2007

Sample	Fluence	Tj	Tc'	Rn (0.9Tj)	Ic(0.9Tj)	IcRn (0.9Tj)	Jc (0.9Tj)
M11	6 10^{13} at/cm^2	49 K	32 K	1.2 Ω	72 μA	90 μV	10 k A/cm^2
M13	6 10^{13} at/cm^2	48 K	31 K	1.2 Ω	90 μA	72 μV	12 kA/ cm^2
M21	3 10^{13} at/cm^2	75 K	57 K	0.35 Ω	772 μA	270 μV	100 kA/cm^2
M25	3 10^{13} at/cm^2	75 K	61 K	0.25 Ω	1100 μA	272 μV	140 kA/cm^2

High Jc

Clues for reproducibility and reliability

N. Bergeal et al, APL 2005

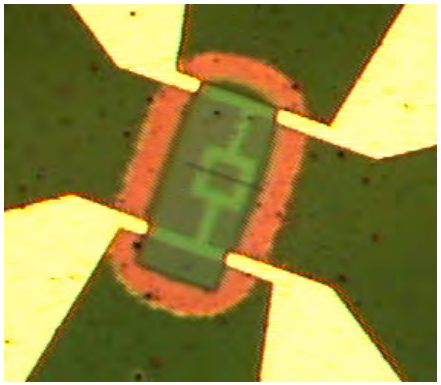
- Low dispersion in IcRn (<10%)
- Self-shunted junctions
- High values of Jc (a few 10^4 A/cm^2)
- Excellent thermal cycling and aging

- 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

10μm* 10μm

W ~ 5μm

L = 32 pH

φ_0 for B~0.08 G

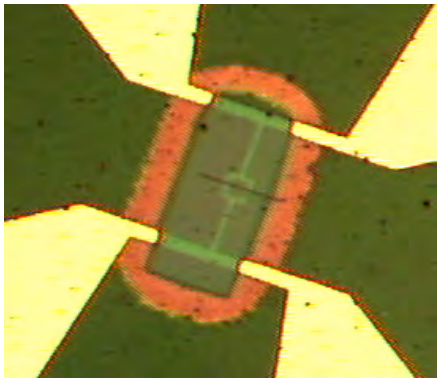
Geometry #2

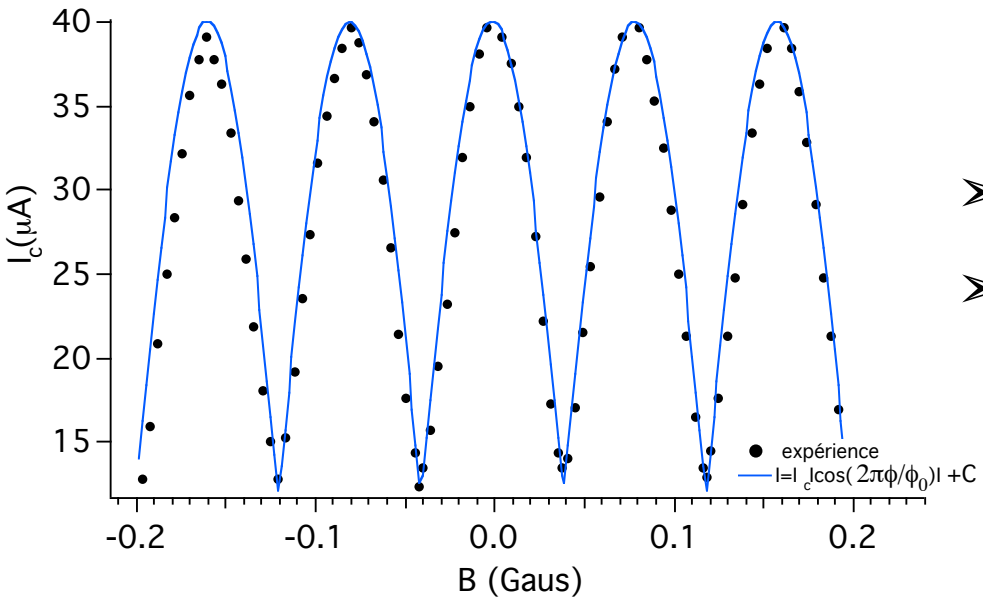
6μm* 6μm

W ~ 2μm

L = 17 pH

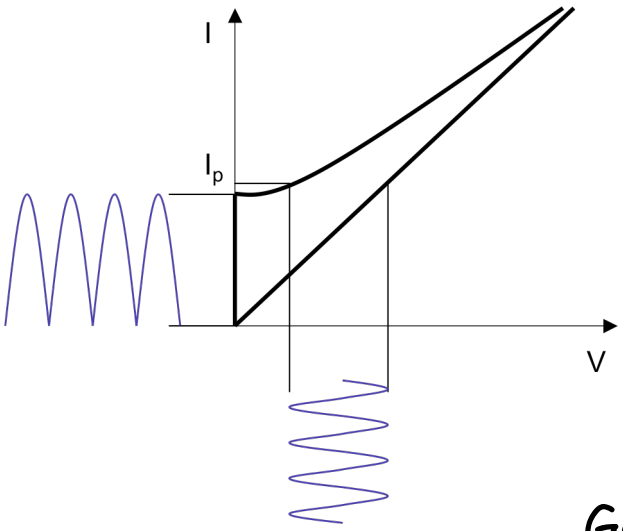
φ_0 for B~0.3 G





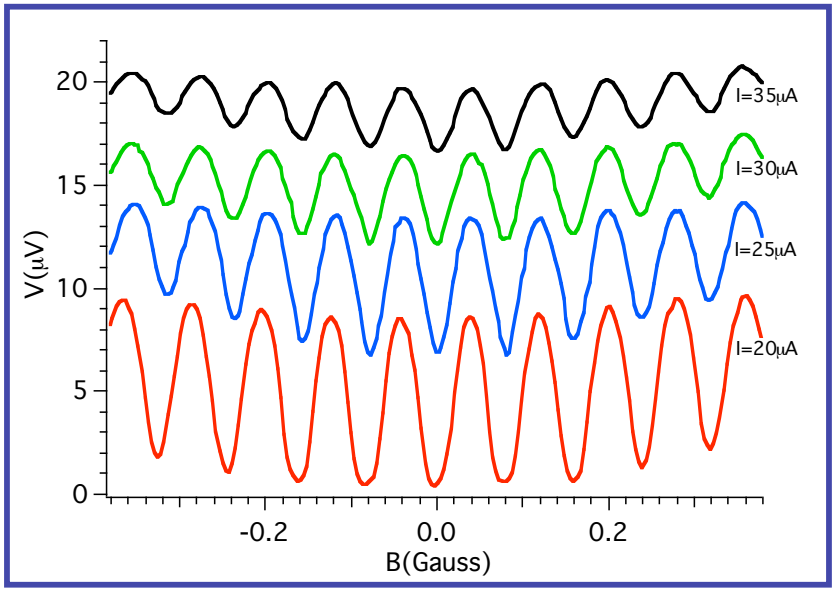
- Ic(B) modulation
- Cosinus fit with a period 0.08 G

SQUID modulations

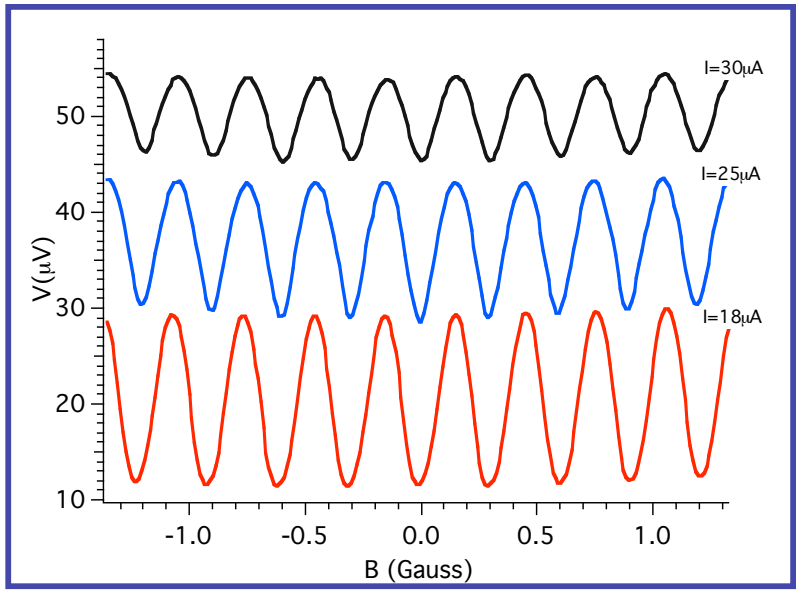


- Modulation of I -> modulation of V
- Sensitivity : $dV/d\Phi = 60\ \mu V/\Phi_0$
- Temperature = 77.7 K

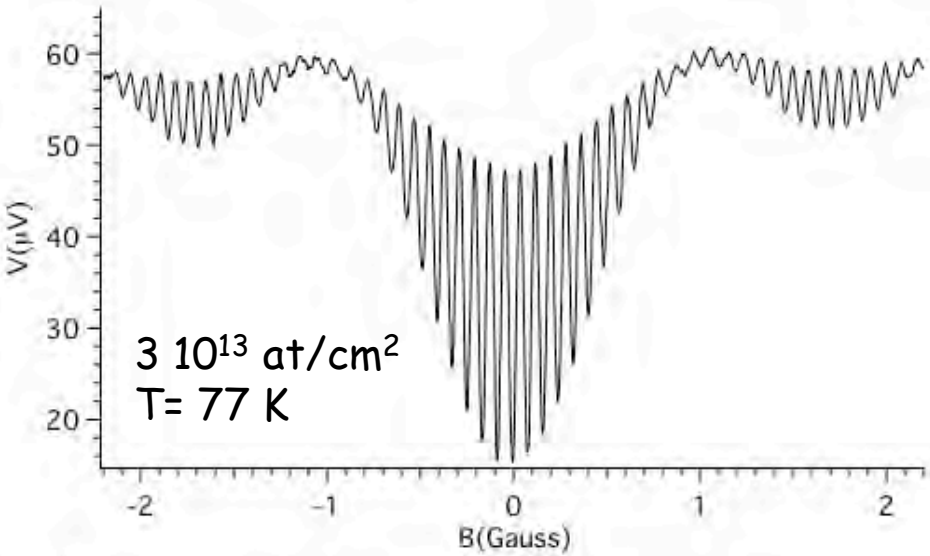
Geometry #1

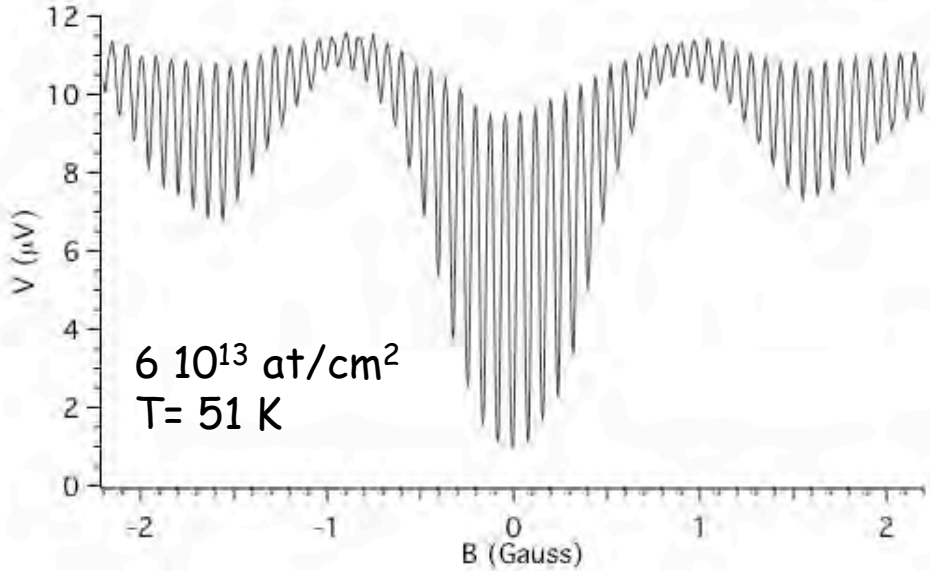


Geometry #2



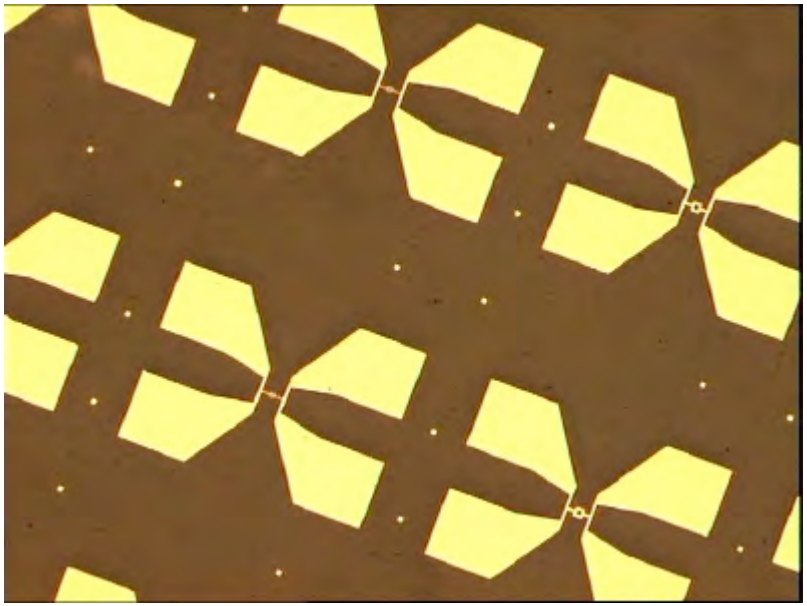
SQUID characteristics





N. Bergeal, APL 2006 ; APL 2007

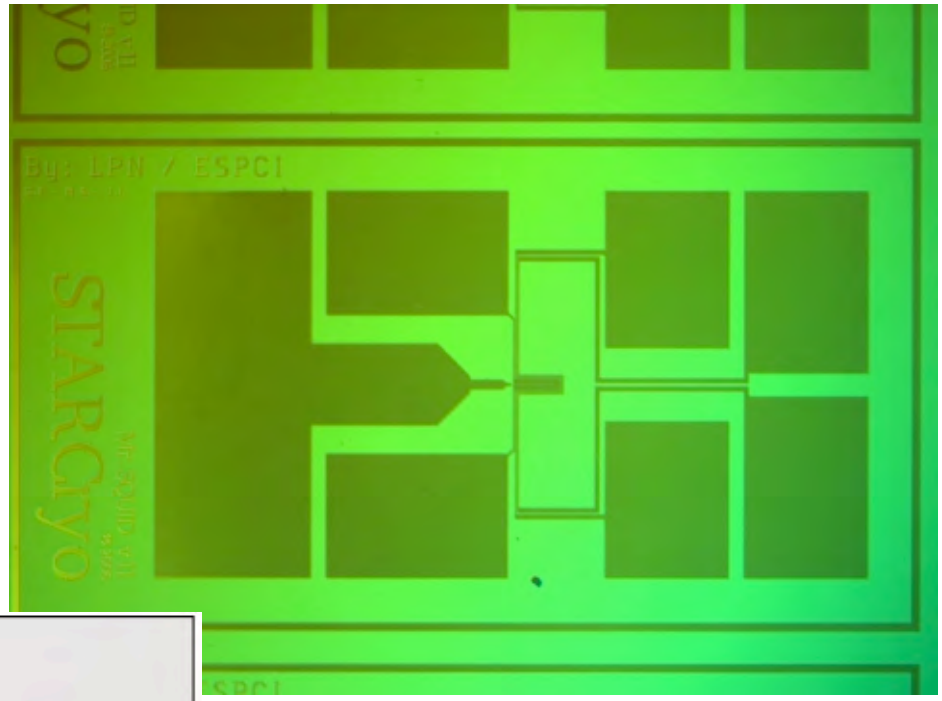
- ➢Fraunhofer + SQUID modulation
- ➢Noise < 100pV/√Hz (at 100 Hz)
- ➢Sensitivity ≈ qq 10^{-4} Φ_0
- ➢Excellent cycling and aging
- ➢Networks

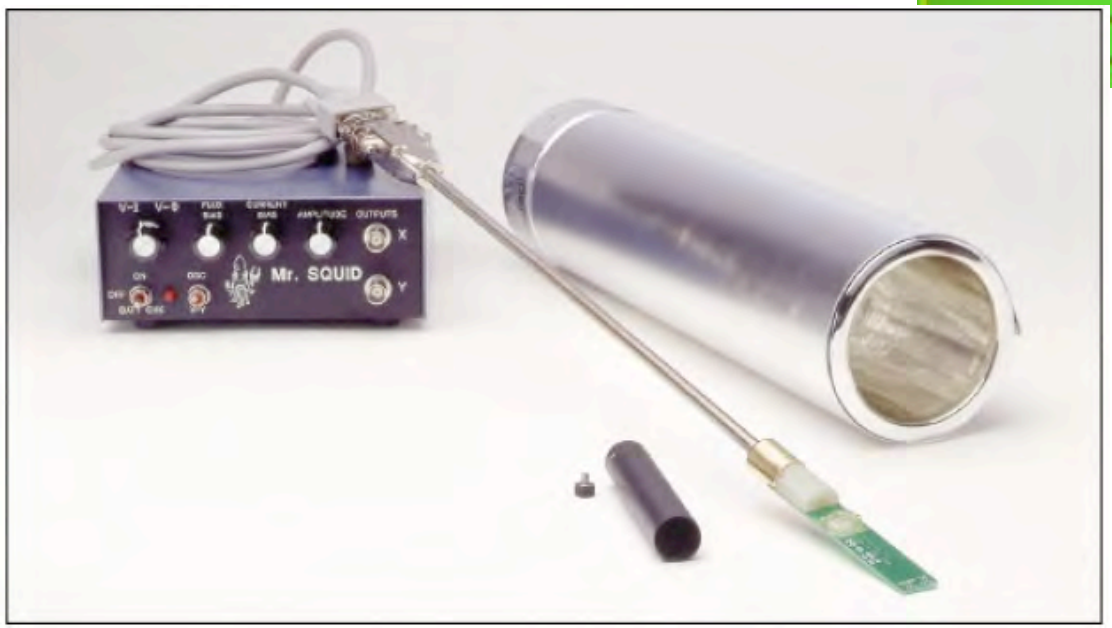


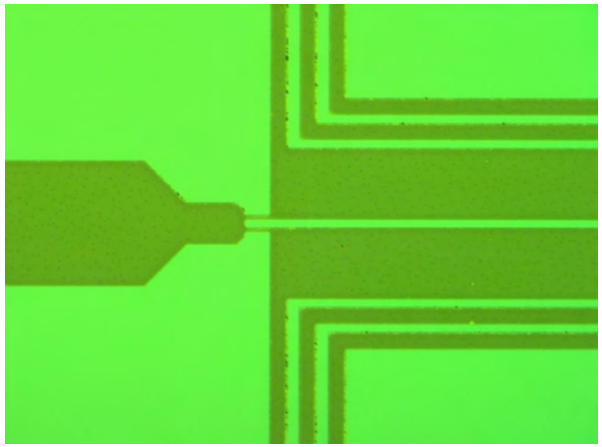
SQUID for « Mr SQUID »

STAR Cryoelectronics

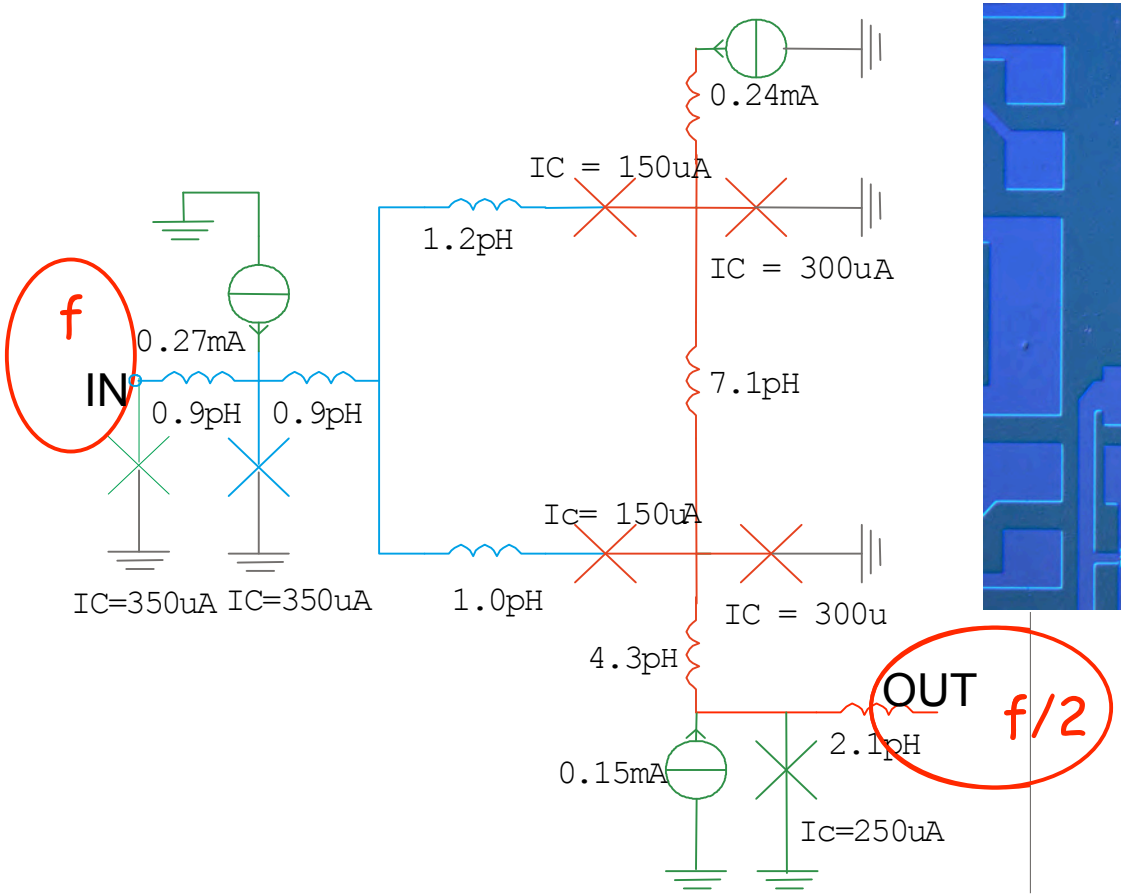
Mr. SQUID®

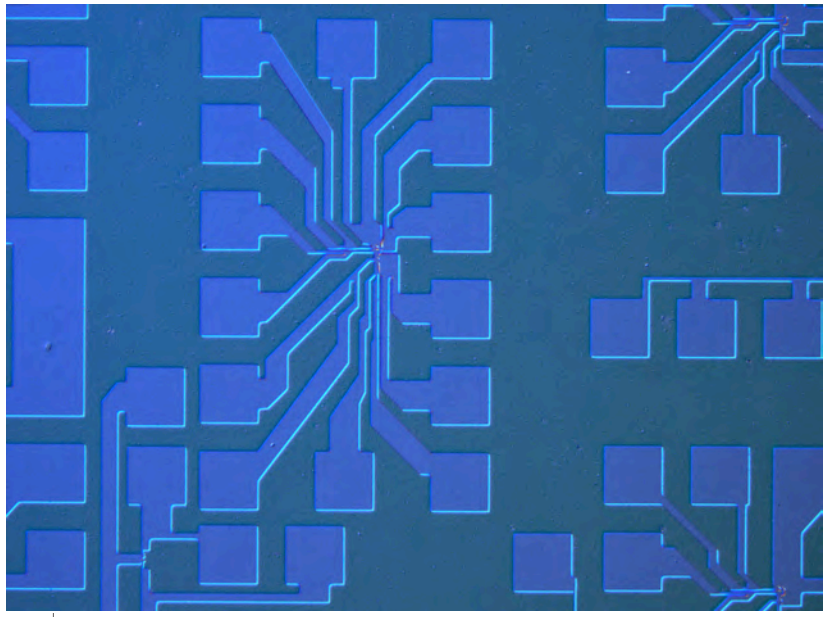






RSFQ T Flip-Flop



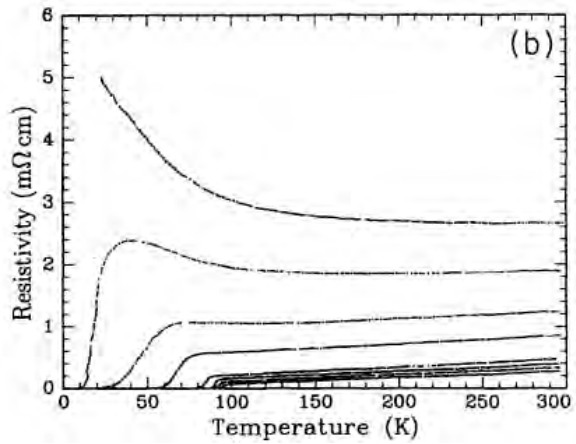


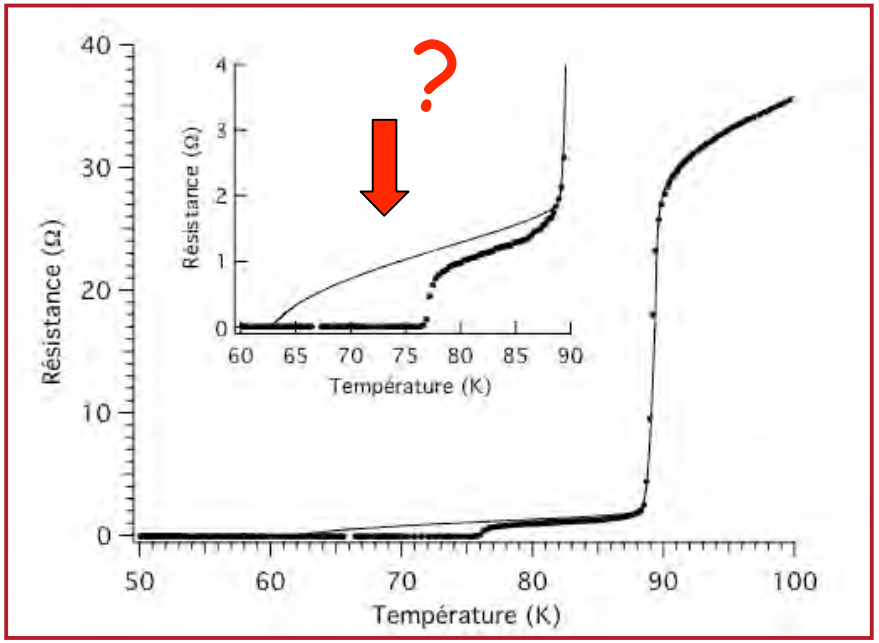
- Design D. Crété (Thales)
- Kim et al (2002) 100 GHz @ 12K

Outline

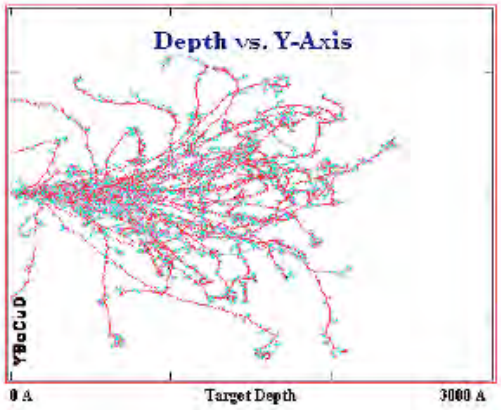
1. Superconductive electronics
    - Dynamics of Josephson Junctions
    - Rapid Single Flux Quanta logic
    - Actual RSFQ devices
2. High Tc Josephson nanoJunctions
    - Ion irradiation of High Tc Superconductors
    - Making Nanojunctions
    - Major characteristics of the Nanojunctions
    - A few 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

A bit of physics …

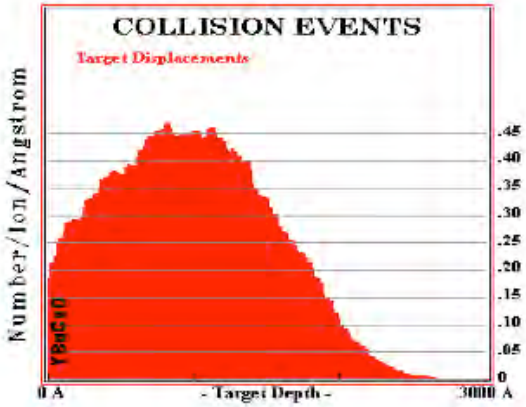




- Tc , resistivity r(T) vs defects
- Damage profile (SRIM)



a)



b)

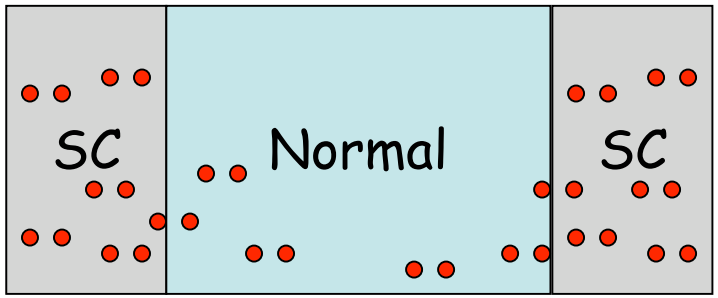
- Reduced size ?

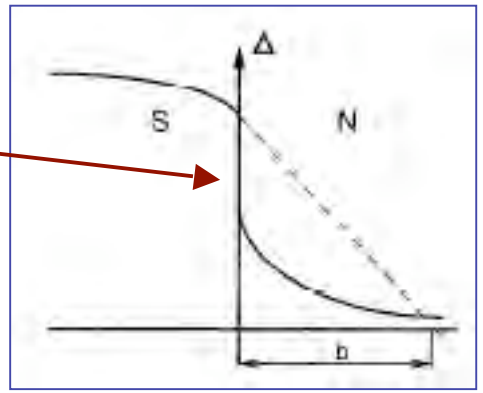
« No-interface » Josephson Junctions

- 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 Ic(T) for all temperatures

Quasi-classical approach of the proximity effect

➢ Usadel equations parametrized in θ

$$\begin{cases} G=\cos\theta & \text{Quasiparticles} \\ F=\sin\theta & \text{Pairs} \end{cases}$$

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 $\tan\theta_N = \dfrac{\Delta}{\omega_N}$

➢ Self-consistant gap equation

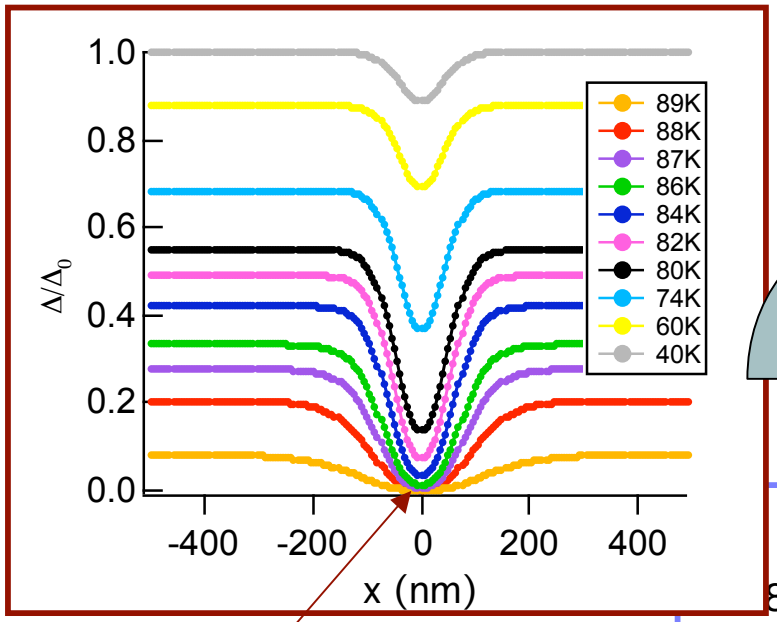
$$\Delta(x) = \lambda_S 2\pi K_B T \sum_{\omega_n} \sin\theta_n$$

In the limit of vanishing current

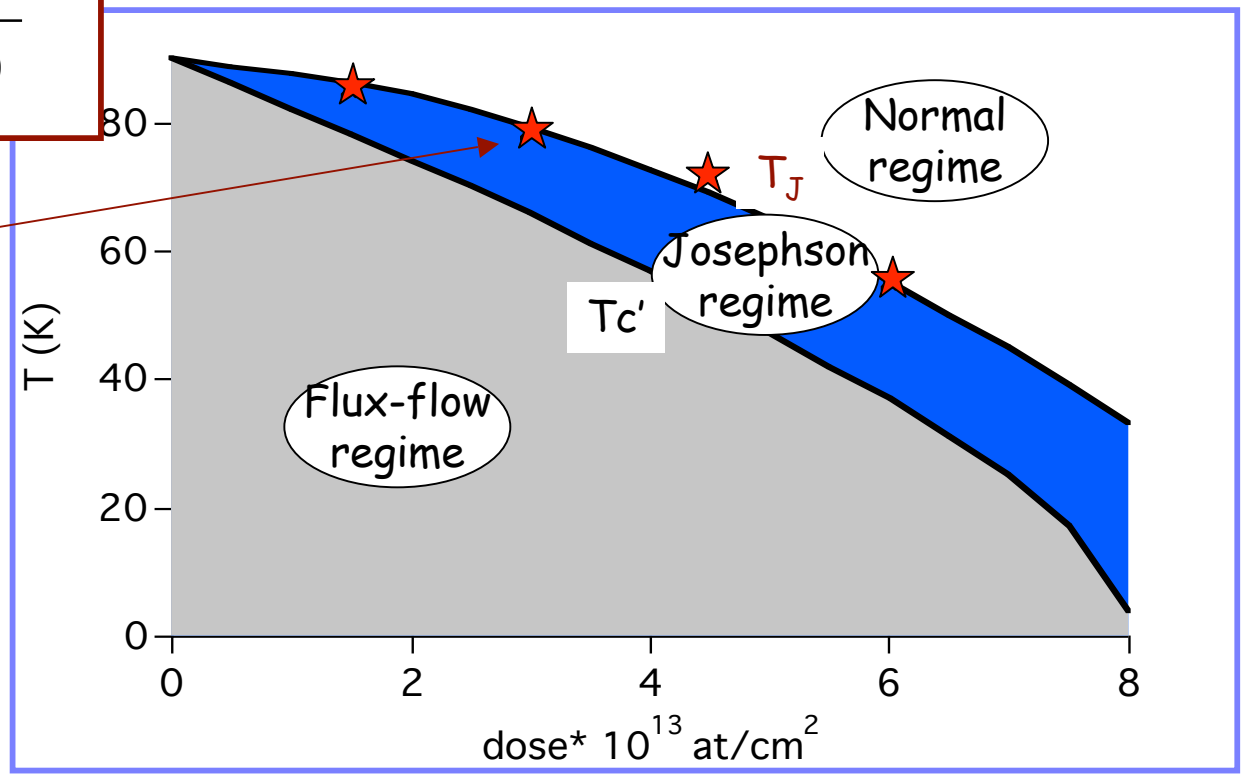
$\Delta(x)$ profil along the junction

Computing the Josephson coupling temperature

N. Bergeal et al, submitted to PRL



T_J



Computing the critical current density

➢ Usadel equations parametrized in θ

$$\begin{cases} G=\cos\theta & \text{Quasiparticles} \\ F=\sin\theta & \text{Pairs} \end{cases}$$

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

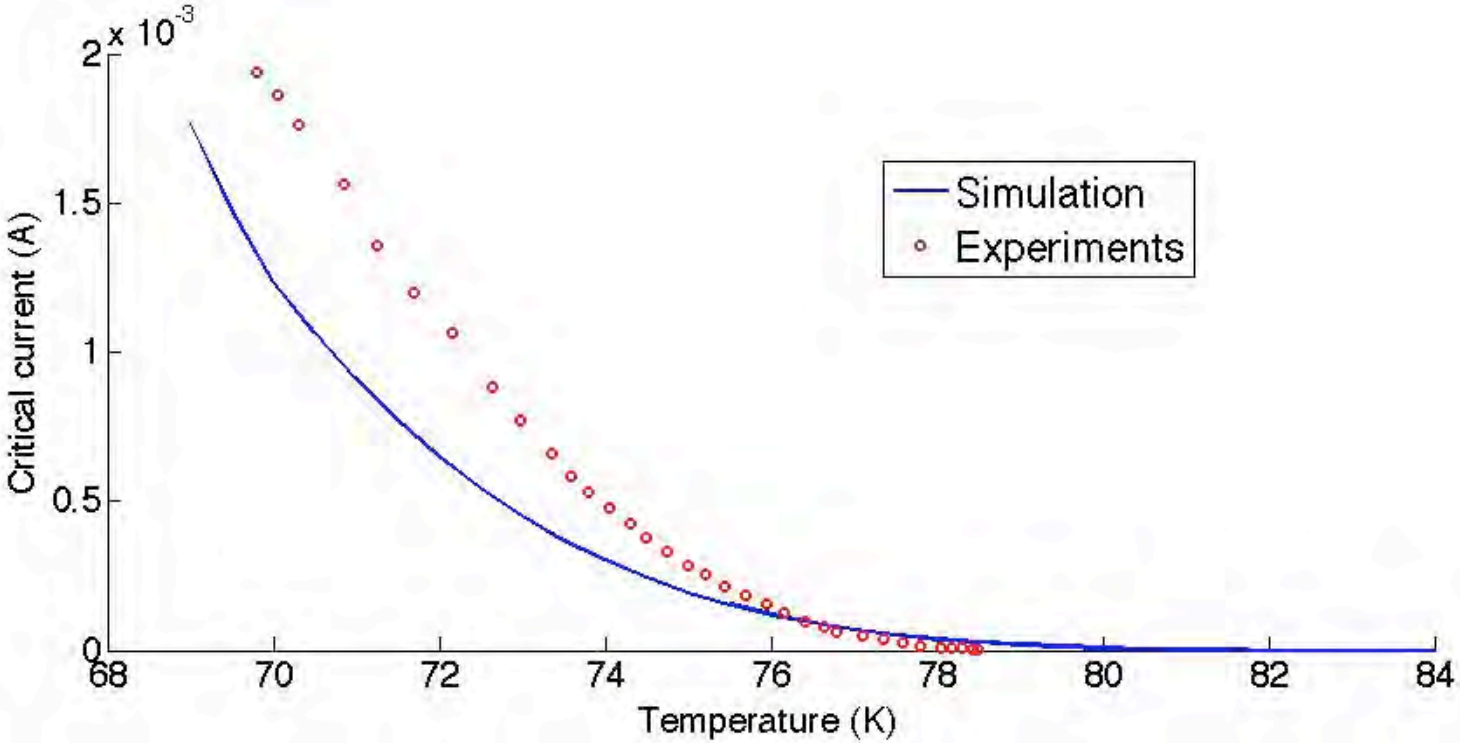
Supercurrent inside the junction

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

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

Comparison with eperiments

➢ Quantitative results for the critical current of our Josephson junctions



➢ With **NO adjustable parameters**

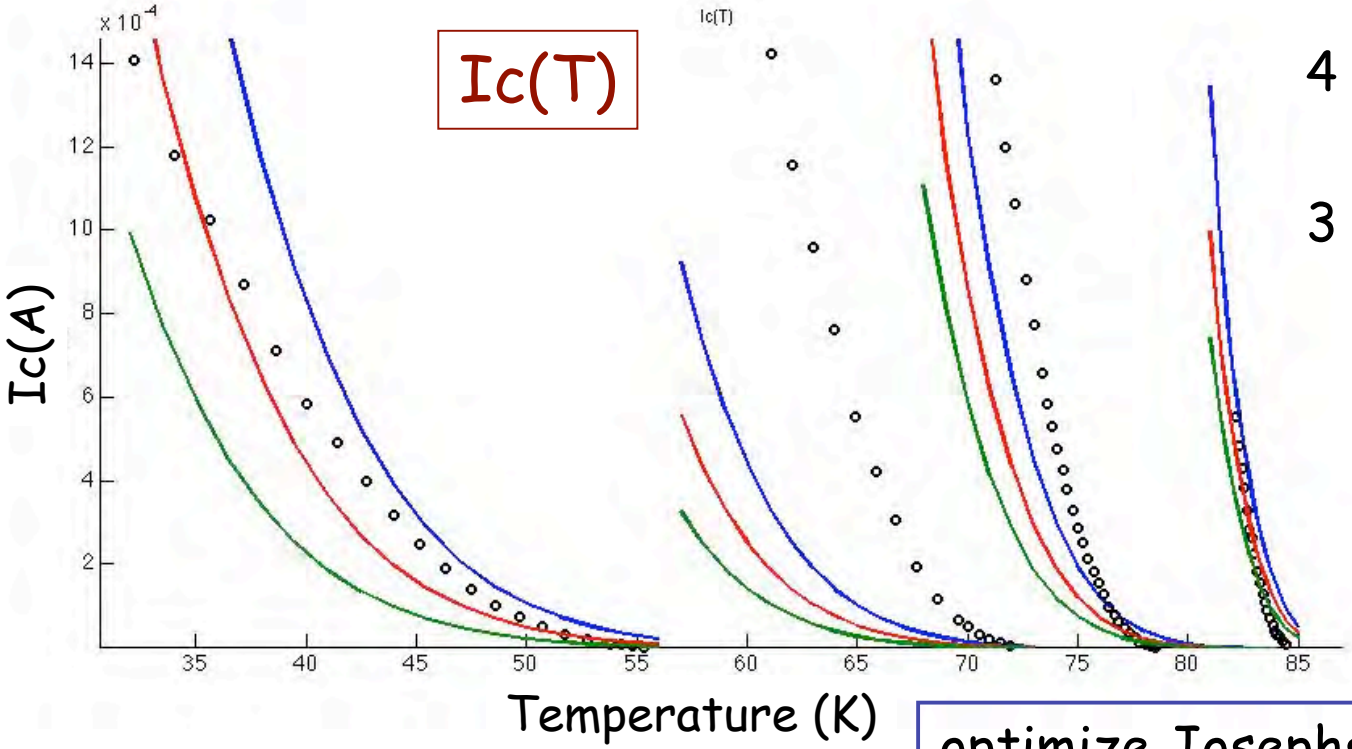
- Irradiations on full films
- SRIM simulations

➢ Depairing coefficient

➢ Defects profile

Changing the junctions parameters

- Importance of the slit size and irradiation doses



4 different doses

3 different slit size

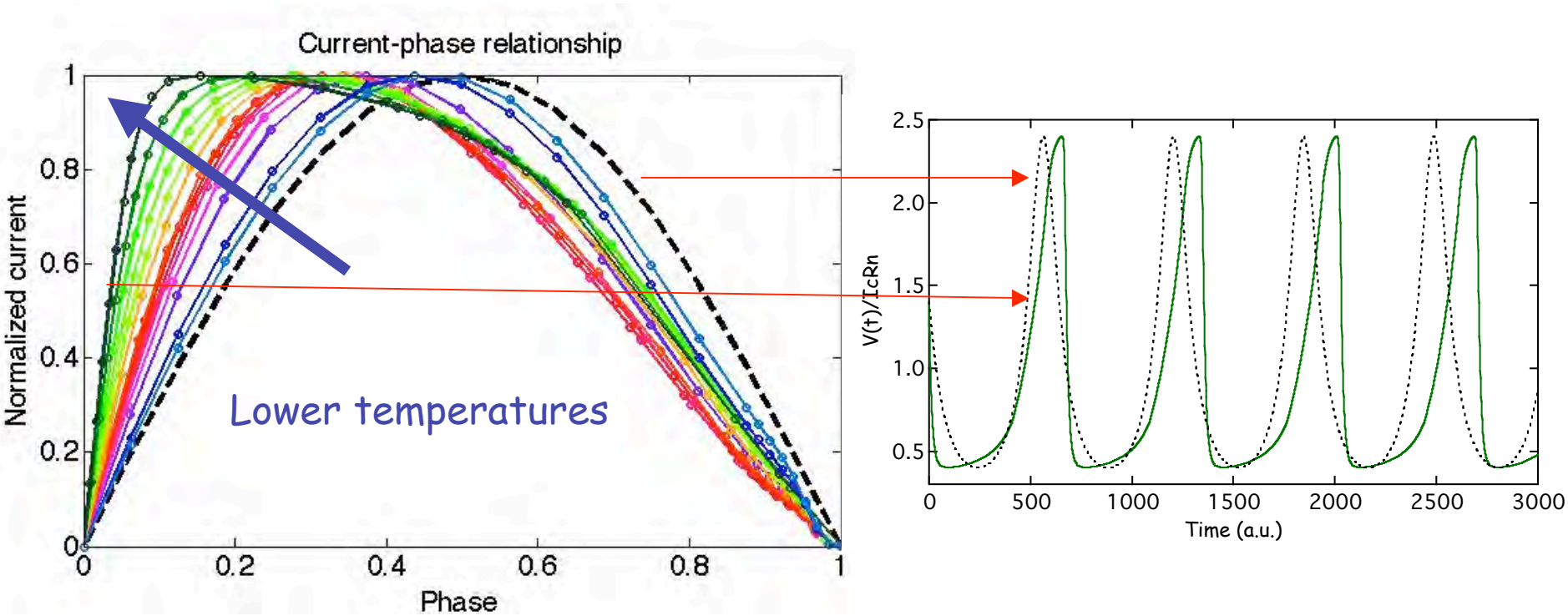
- Simulate various
  - slit size
  - film thickness
  - irradiation dose, …

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 → **lower** temperature
- Strong anharmonicity develops …

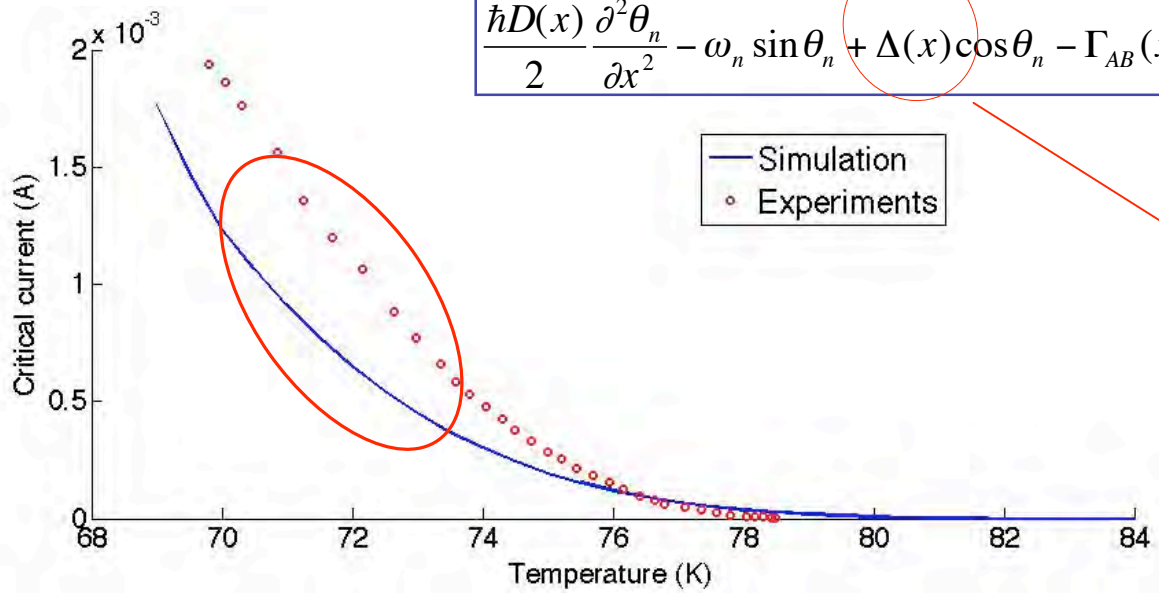


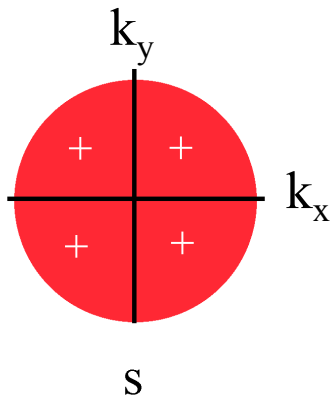
- RSFQ pulses robust against anharmonicity

A d-wave order parameter

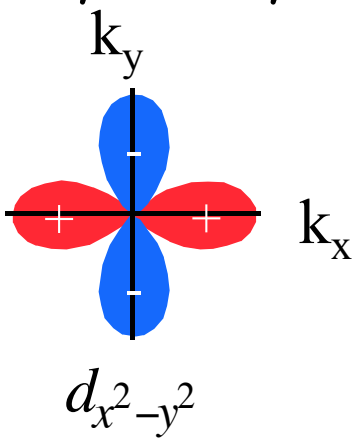
➢ 1D Quasi-classical equations with an isotropic order parameter

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



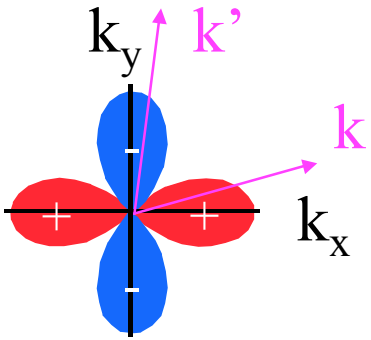


➢ 2D symmetry of the d-wave order parameter



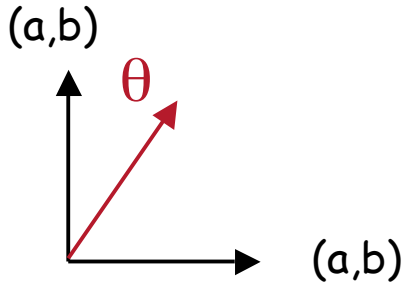
- Anisotropy of the order parameter
- Sign change : Andreev Bound States
- π-junctions and RSFQ circuits

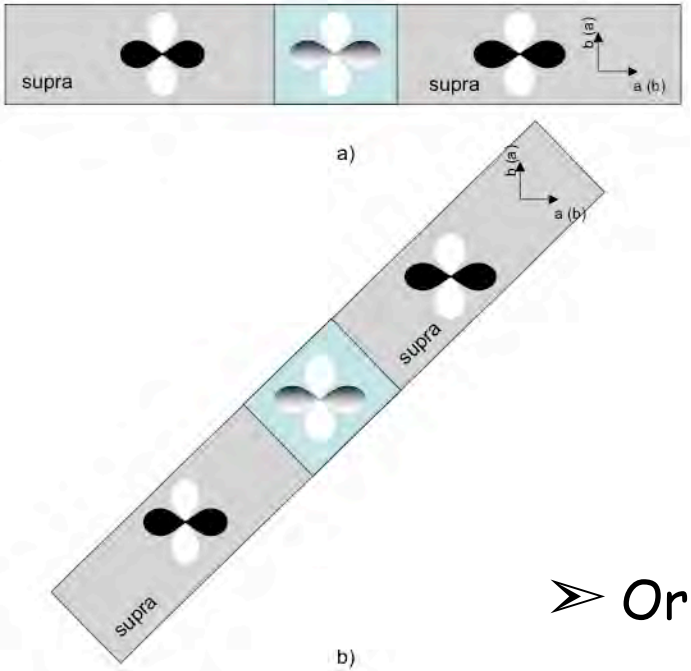
Order parameter anisotropy ?

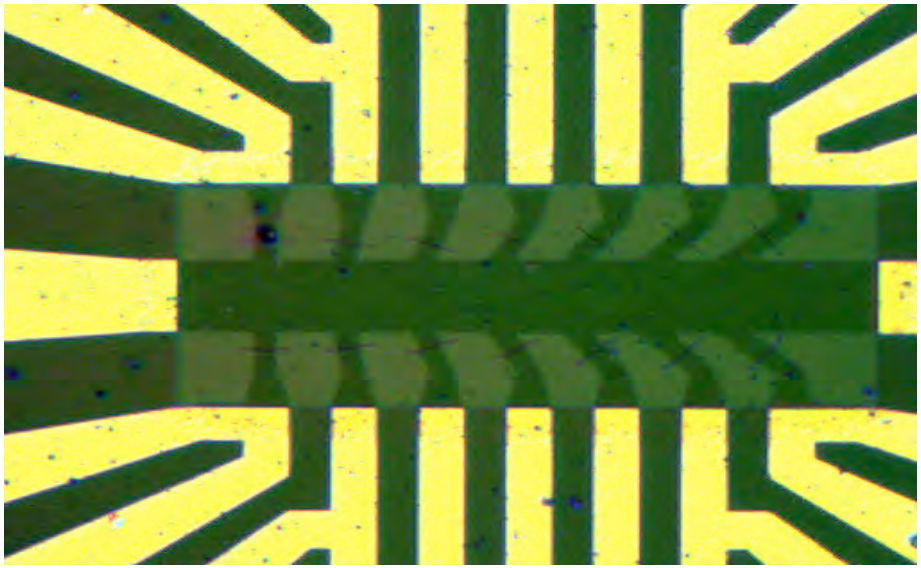


$d_{x^2-y^2}$

➢ D-wave order parameter

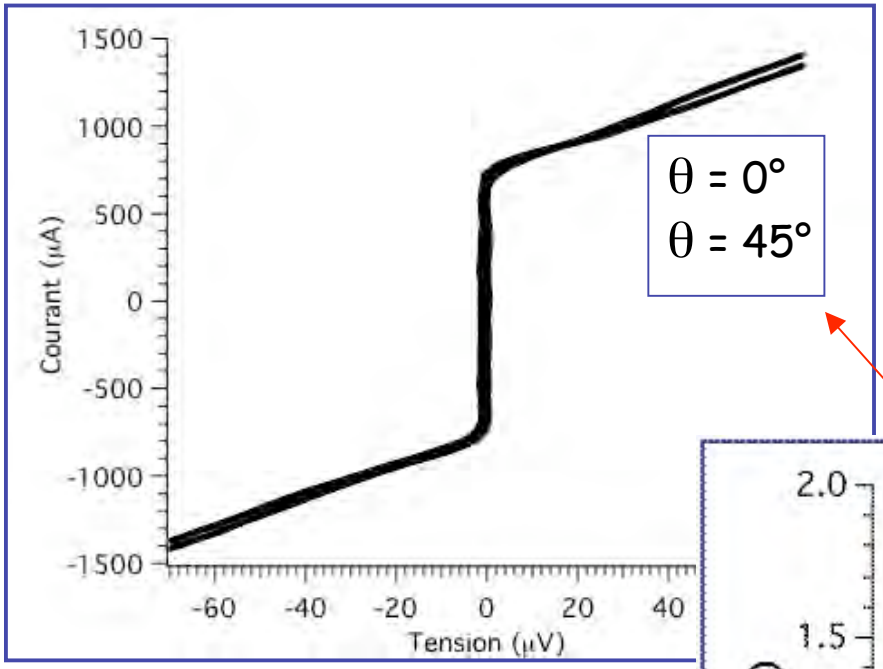






➢ Orientations θ = 0 °,10 °,20 °,30 °,40 °,45°

Order parameter anisotropy ?

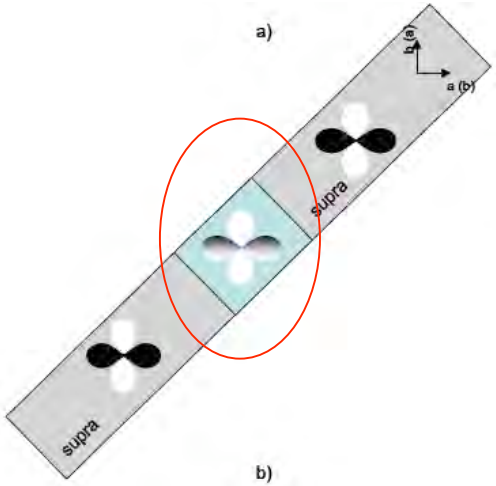


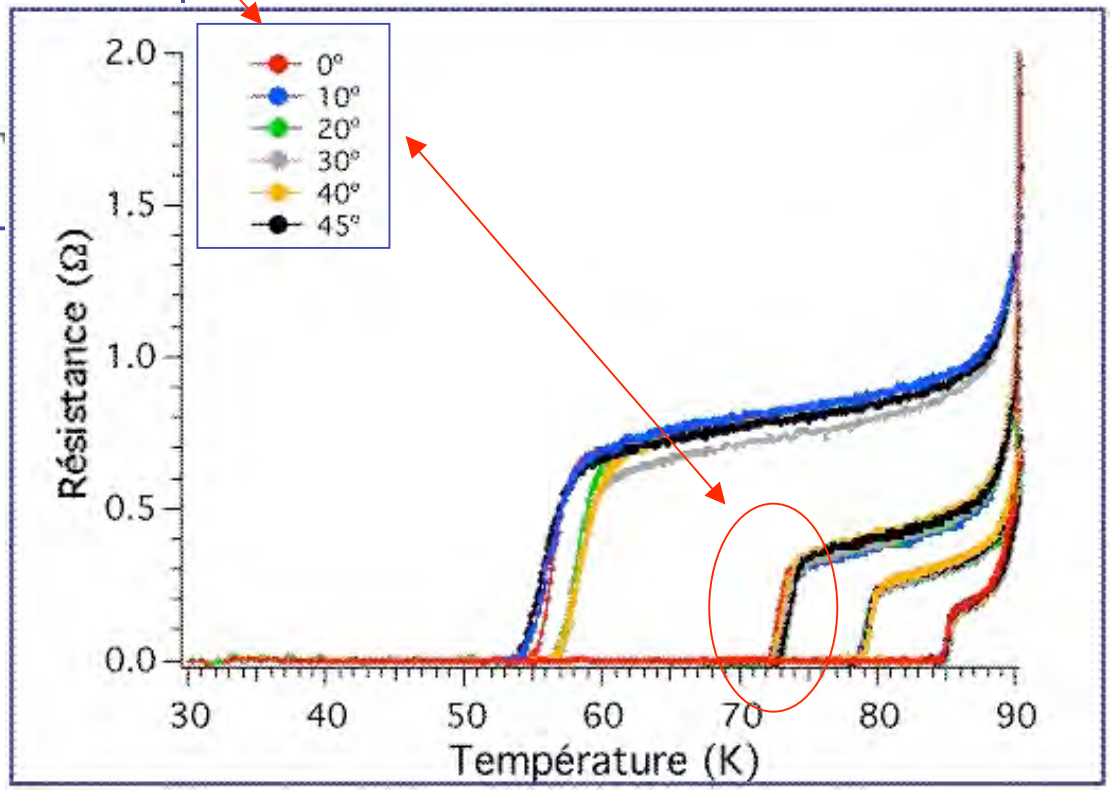
➢ No effect !!

➢ Diffusion ?

➢ 2d order parameter ?

➢ Anisotropic pairing !





Back to Eilenberger equations …

➢ No diffusion approximation

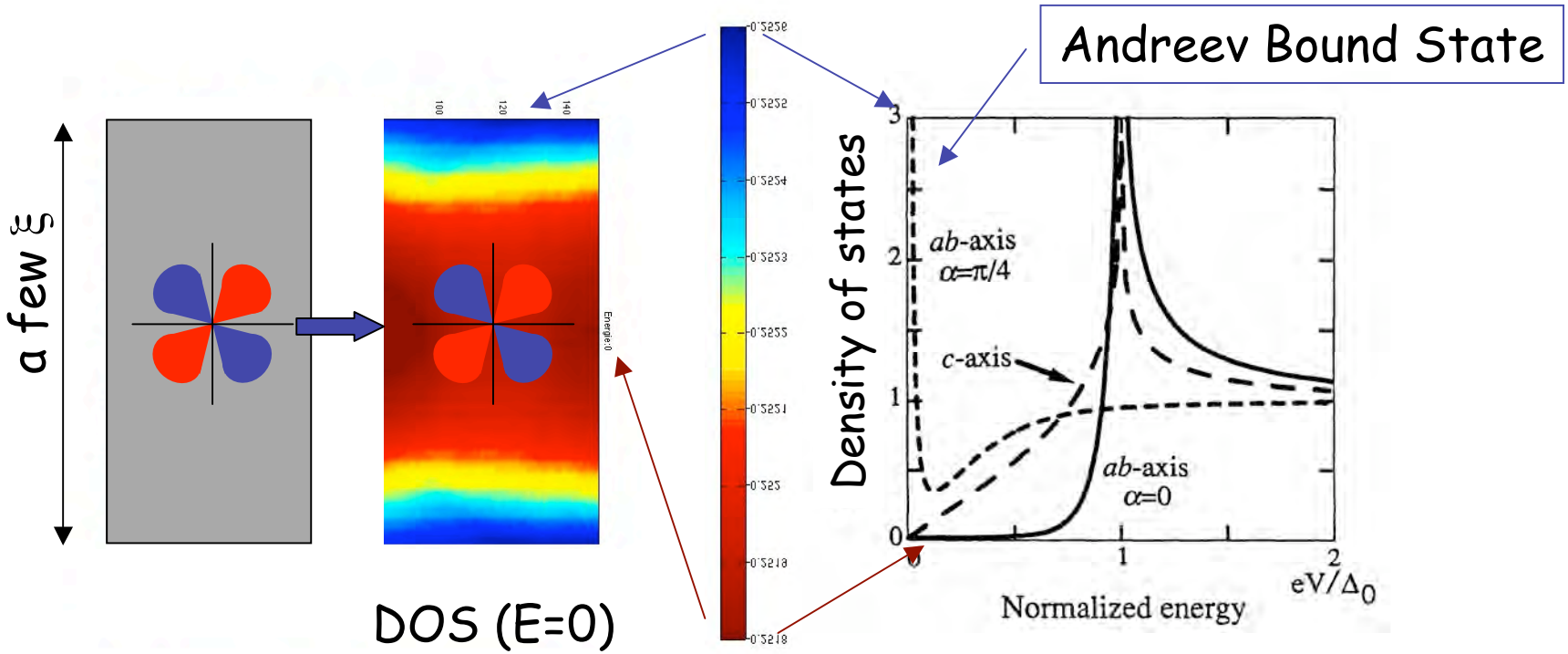
Usadel : l < ξ

No wave vector dependence

Eilenberger : l >< ξ

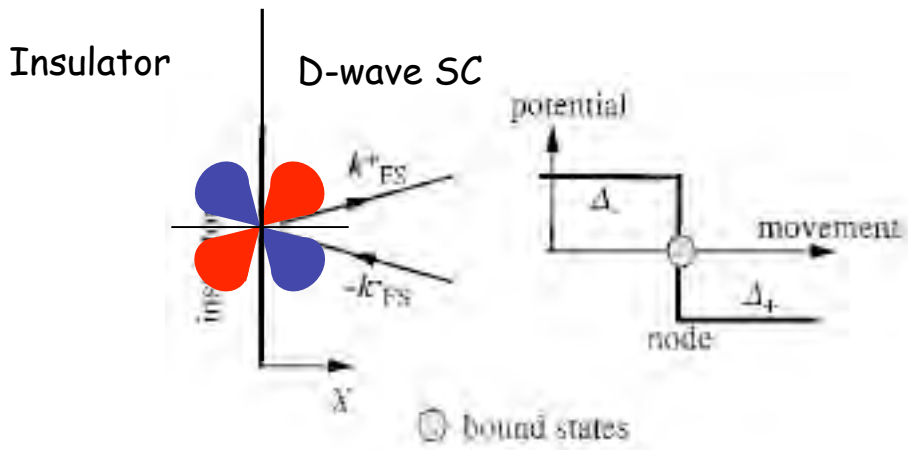
$$-\hbar v_F\left[\tilde{\partial}, \hat{g}_\omega(v_F, r)\right] = \left[\omega\hat{\tau}_3 + \hat{\Delta} + \frac{1}{2\tau}\langle\hat{g}_\omega(v_F, r)\rangle, \hat{g}_\omega(v_F, r)\right]$$

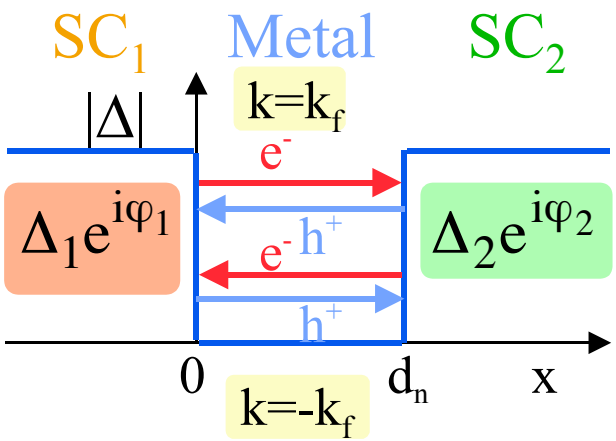
➢ Confined geometry : full d-wave calculation in a channel



Andreev Bound State

➢ Surface Bound State

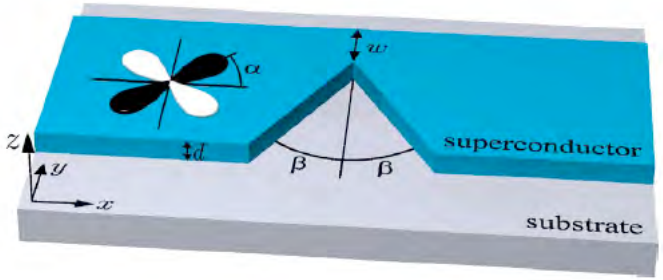




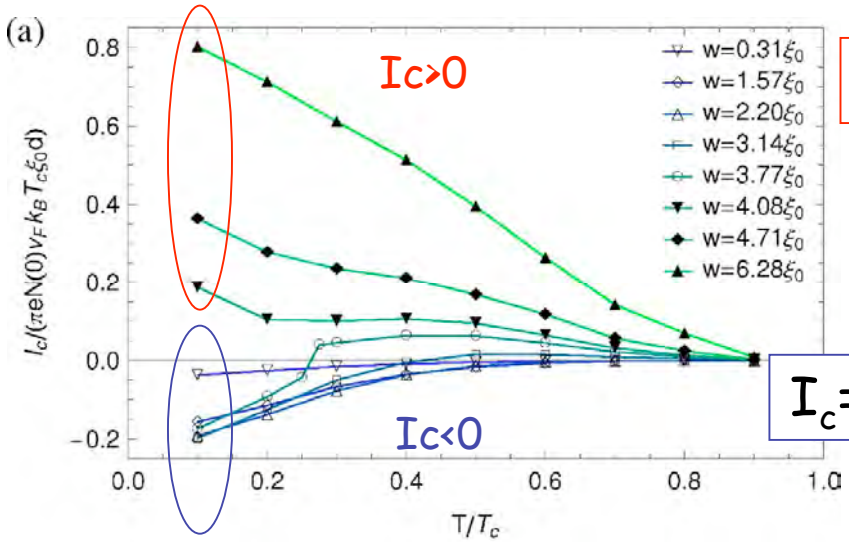
$\varphi_1-\varphi_2=\pi$ → Bound State E=0

➢ Making a π junction

w = a few ξ



Gumann et al APL 2007



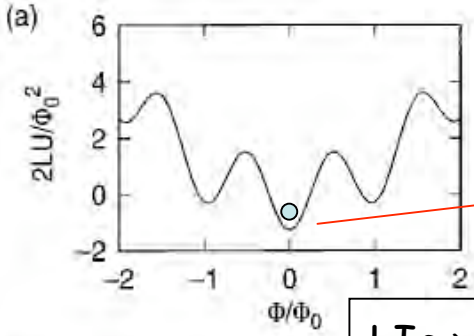
$I_c=I_0\sin(\Delta\varphi)$

$I_c=I_0\sin(\Delta\varphi+\pi)$

Spontaneous super-current

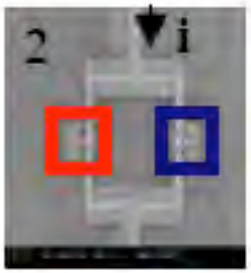
➢ π SQUID

0 junction

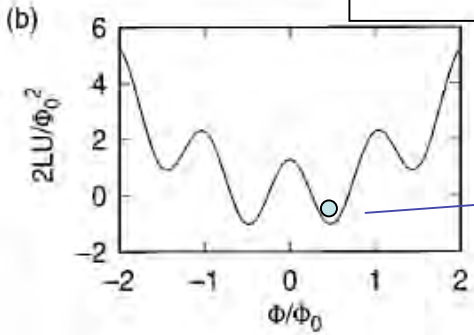


Ground state j=0
Flux = 0

LIc > ϕ_0



π junction



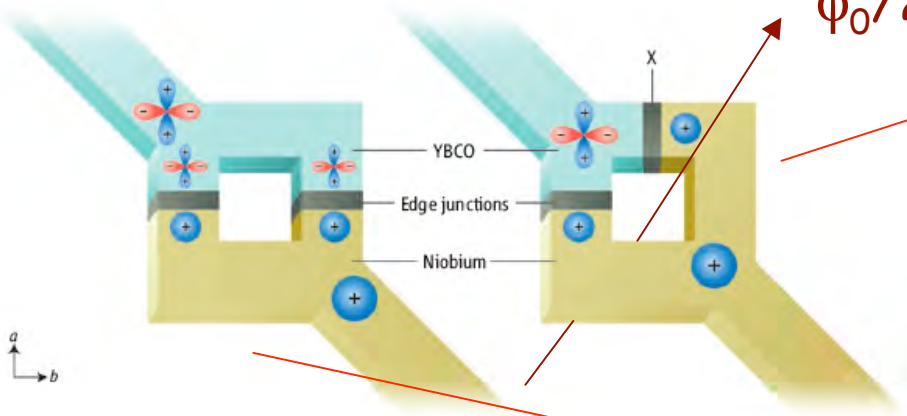
Ground state j≠0
Flux = $\phi_0/2$

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

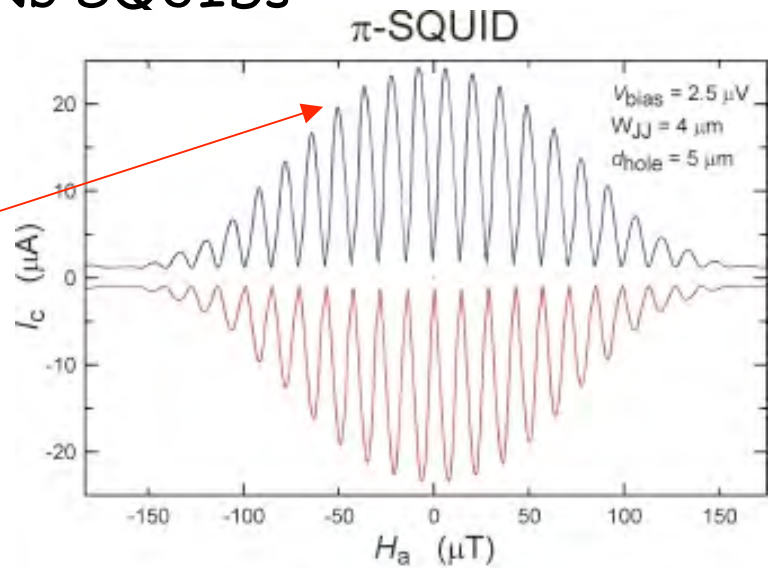
Spontaneous current

π-SQUID in RSFQ circuits

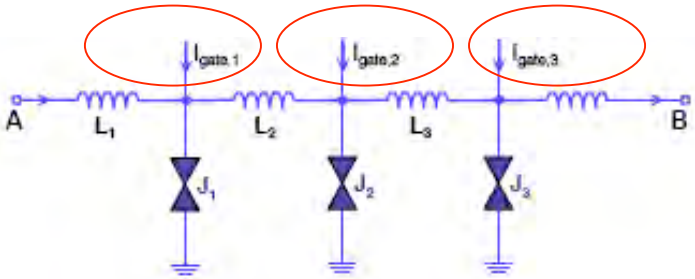
- Spontaneous half flux quanta in YBCO/Nb SQUIDs



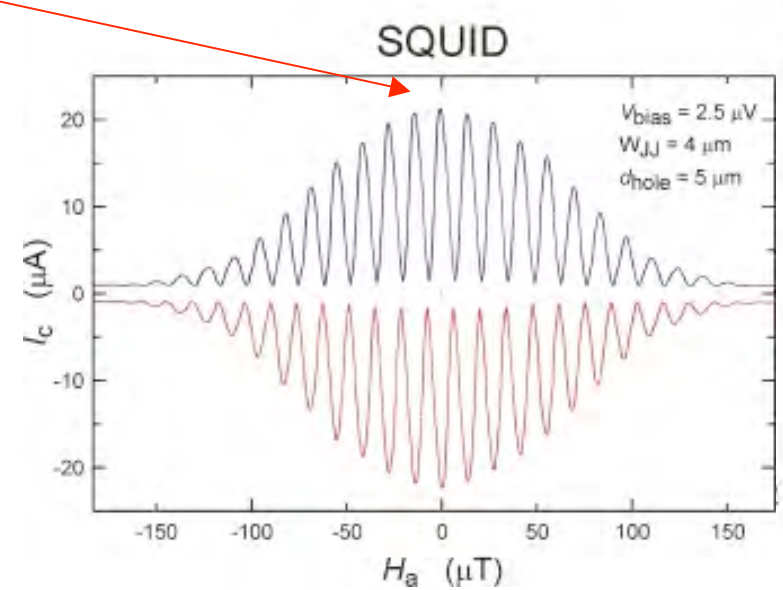
$\phi_0/2$



- Numerous bias leads in RSFQ circuits

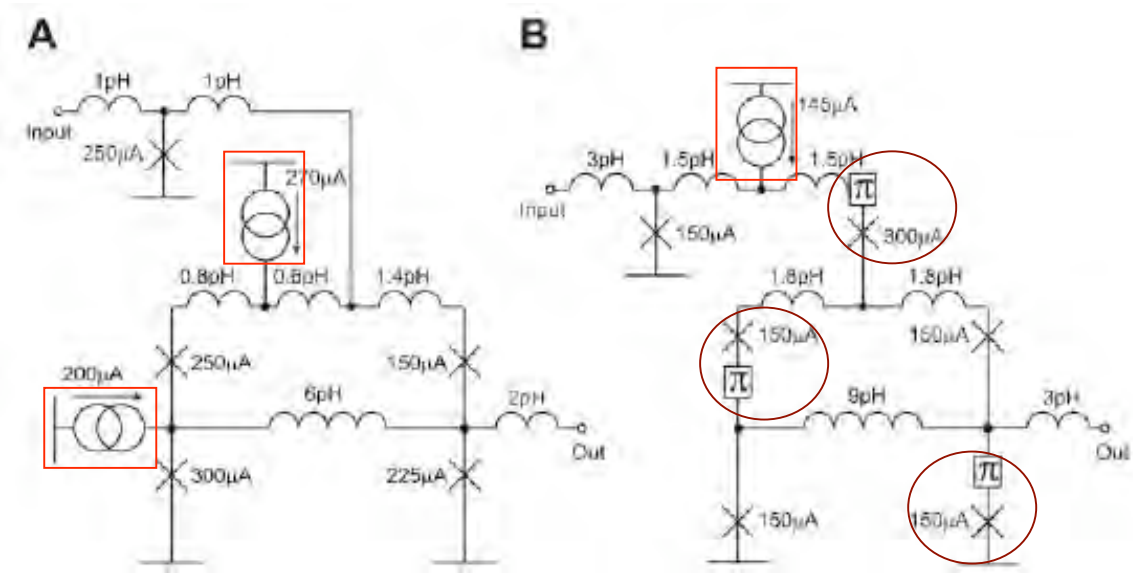


Ortlepp et al Science 2006

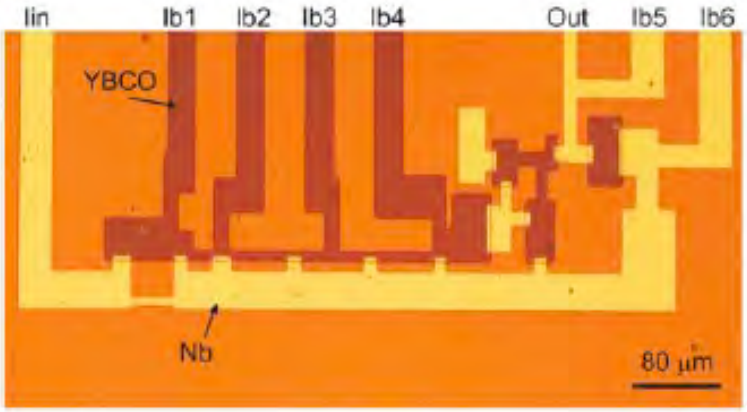


Toggle flip-flop

- 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 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

Conclusions

- RSFQ logic : a promissing technology
- High Tc Josephson nano-Junctions : a promissing 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)