



CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

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HTc Josephson nano-junctions made by ion irradiation

Jérôme Lesueur

Phd thesis : Nicolas Bergeal, Thomas Wolf

Collaborators : M. Sirena ESPCI-UPR5 CNRS

T. Kontos LPA-ENS

G. Faini, LPN-CNRS

J-P. Contour, J. Briatico, R. Bernard UMR THALES/CNRS

Support : CNRS post-doc grant

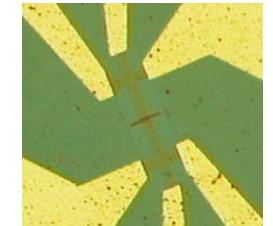
Phasme team : www.lpem.espci.fr/phasme



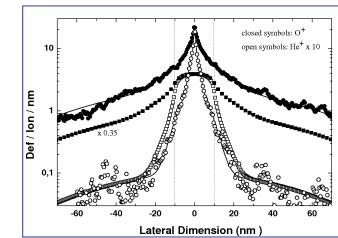
Outline

A route towards HTSc SNS Josephson Junctions

HTSc Josephson nano-Junctions



Optimization of the process



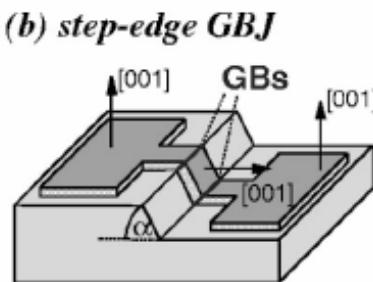
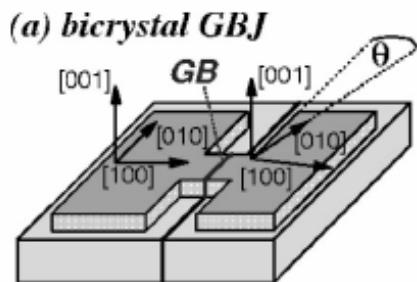
Quasi-classical approach of the proximity effect

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

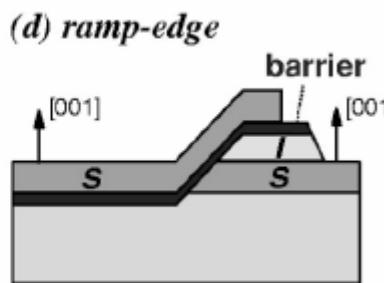
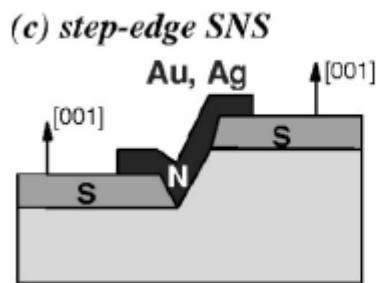
Conclusions

« Standard » High Tc Josephson junctions

↖ Complex materials ...



■ Grain boundary junctions



Special substrates
Design constraints
Lack of reproducibility

■ Ramp junctions

↖ Alternative technology



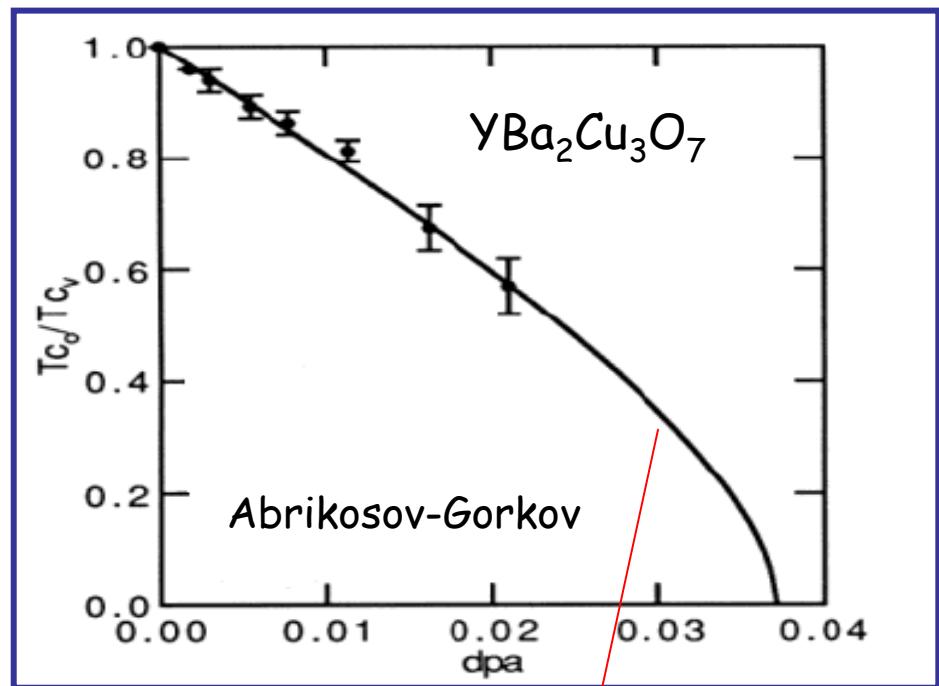
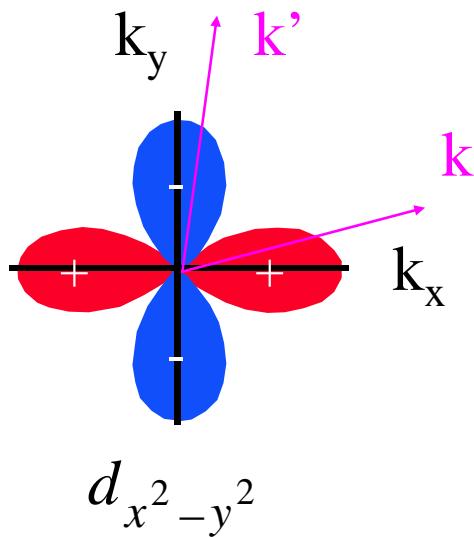
Ion irradiation

Kahlmann et al & Katz et al APL'98

Disorder in High Tc Superconductors

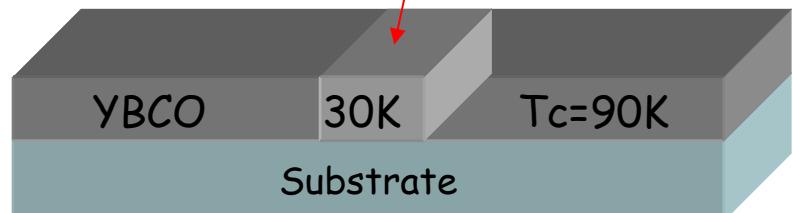
↖ Defect in $d_{x^2-y^2}$ superconductor

→ depairing



↖ Local control of the disorder

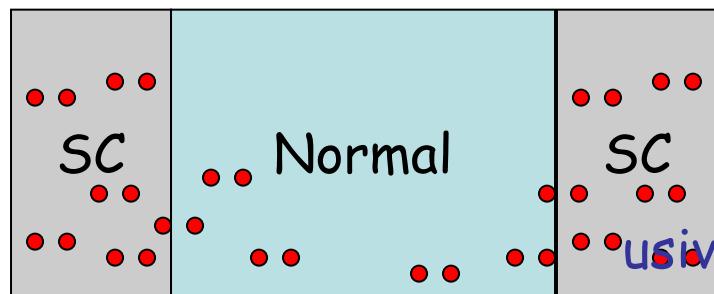
↖ Nanoscale engineering (ξ_N)



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

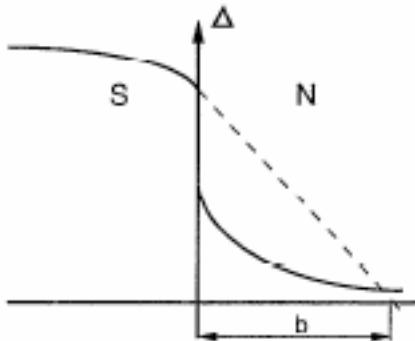
Proximity effect based Josephson Junctions

↖ Phase coherence through normal metal : Josephson coupling



Diffusive case

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



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

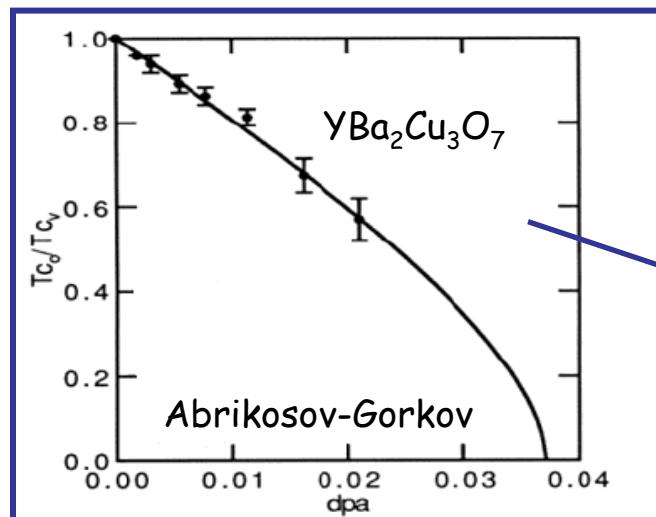
$$\xi_N = \sqrt{\frac{\kappa D}{2\pi k_B T}}$$

→ A few 10 nm

De Gennes : Rev Mod Physics 1964

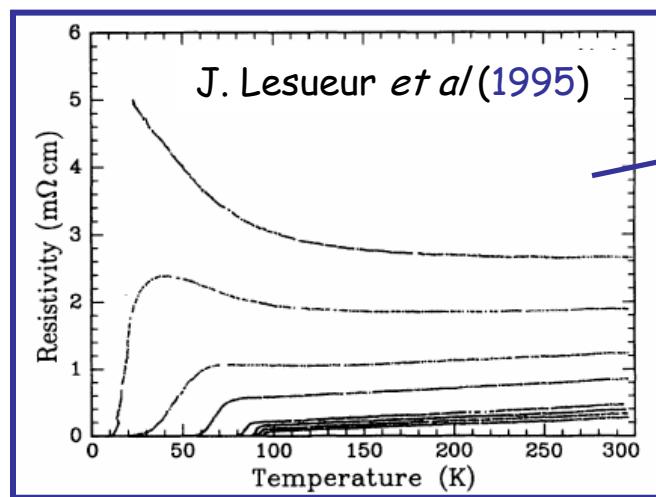
Fabrication of High Tc nano-Junctions

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



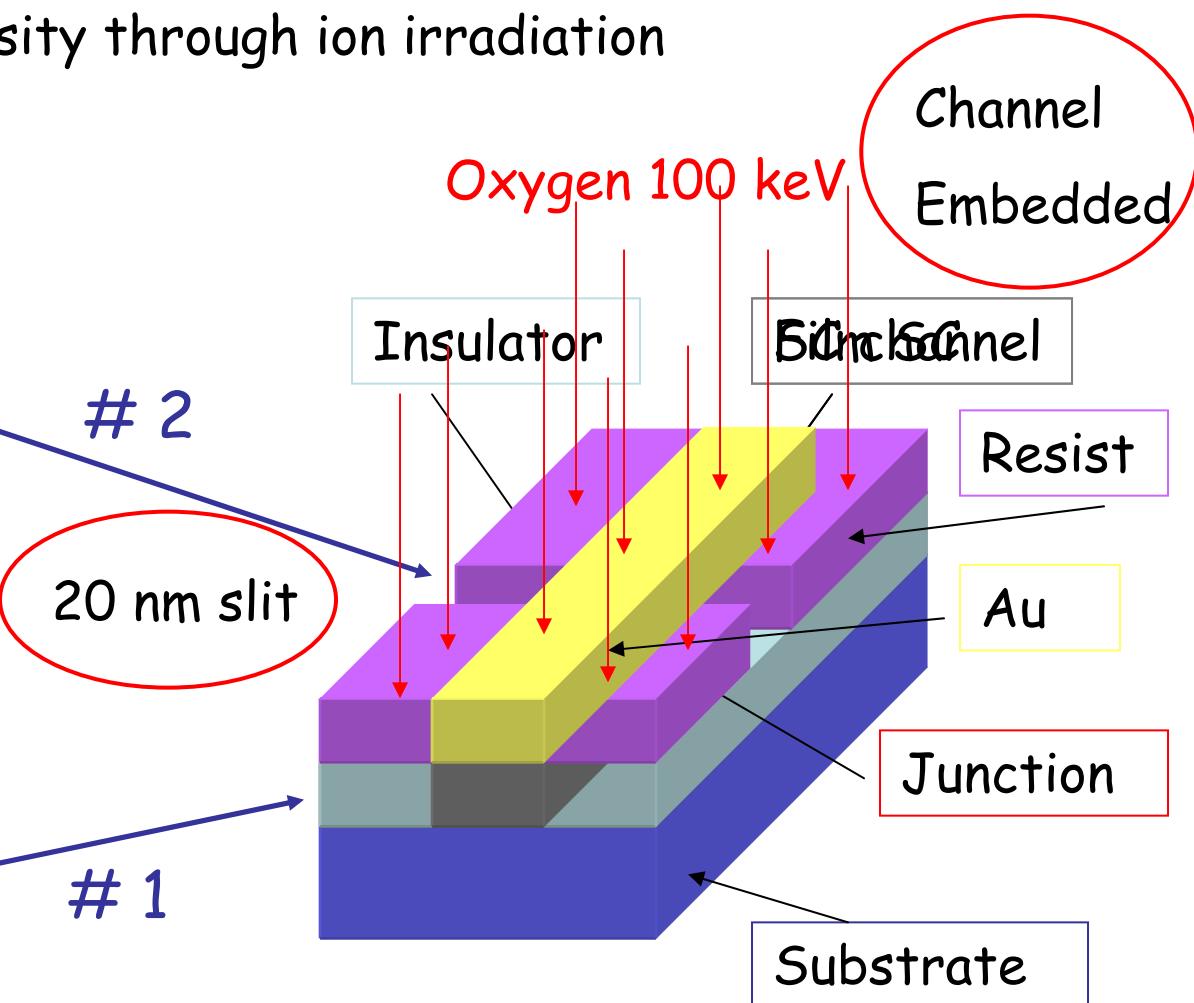
2

20 nm slit



1 : drawing channels : (10^{15} at/cm²)

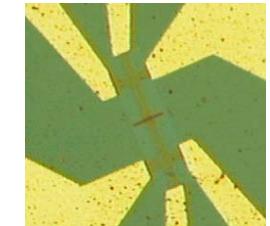
2 : creating nanoJunctions : (10^{13} at/cm²)



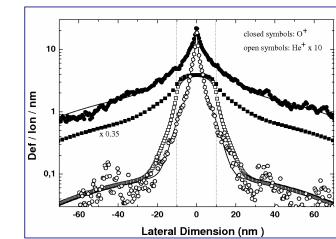
Outline

A route towards HTSc SNS Josephson Junctions

HTSc Josephson nano-Junctions



Optimization of the process

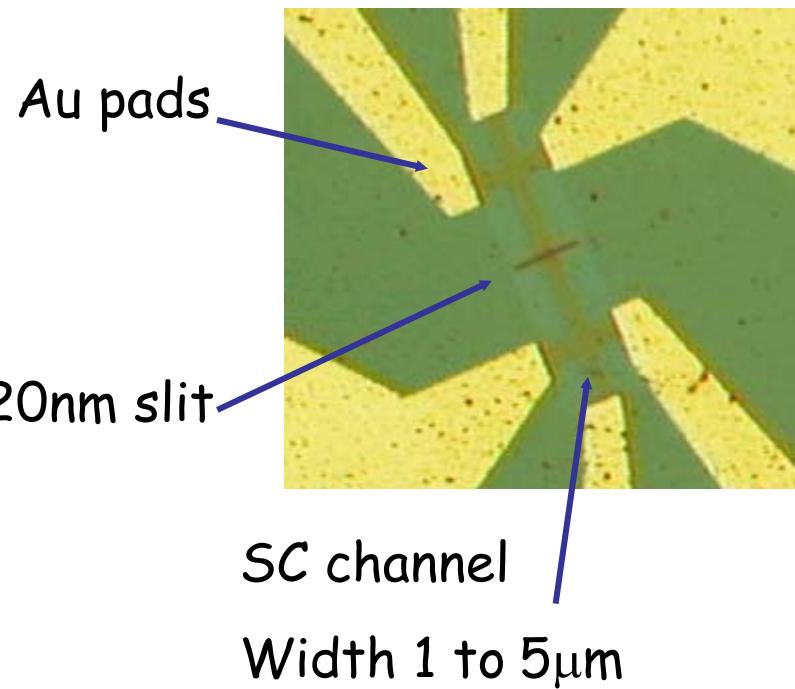


Quasi-classical approach of the proximity effect

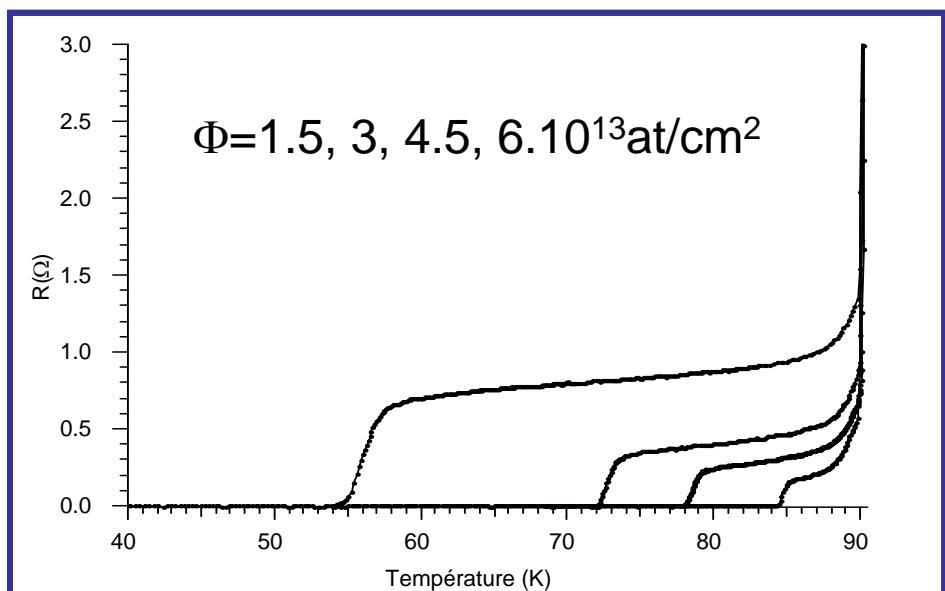
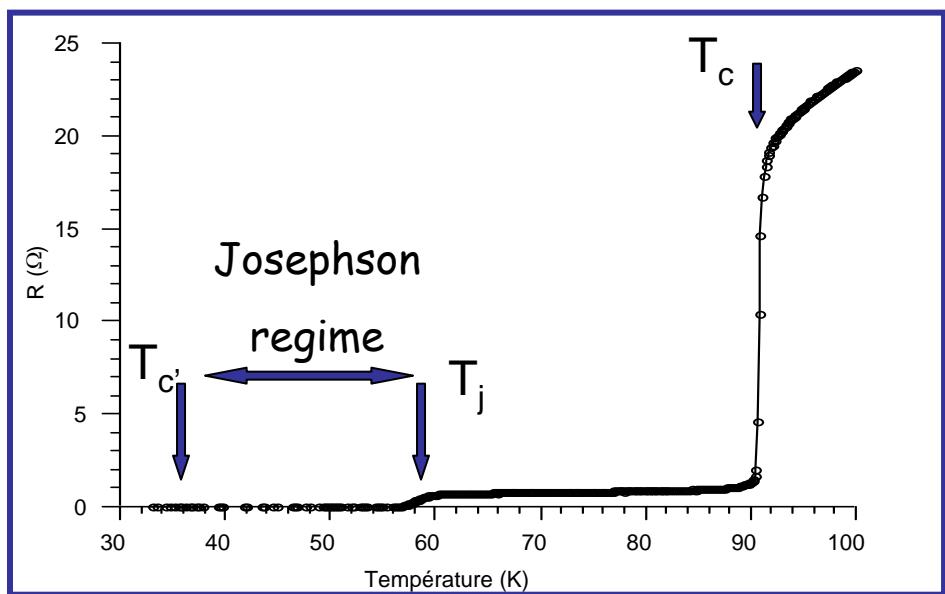
$$\frac{\kappa D(x)}{2} \frac{\partial^2 \theta_n}{\partial x^2} - \omega_n \sin \theta_n + \Delta(x) \cos \theta_n - \Gamma_{AB}(x) \sin \theta_n \cos \theta_n = 0$$

Conclusions

$R(T)$ measurements



N. Bergeal et al, APL 2005
JAP 2007



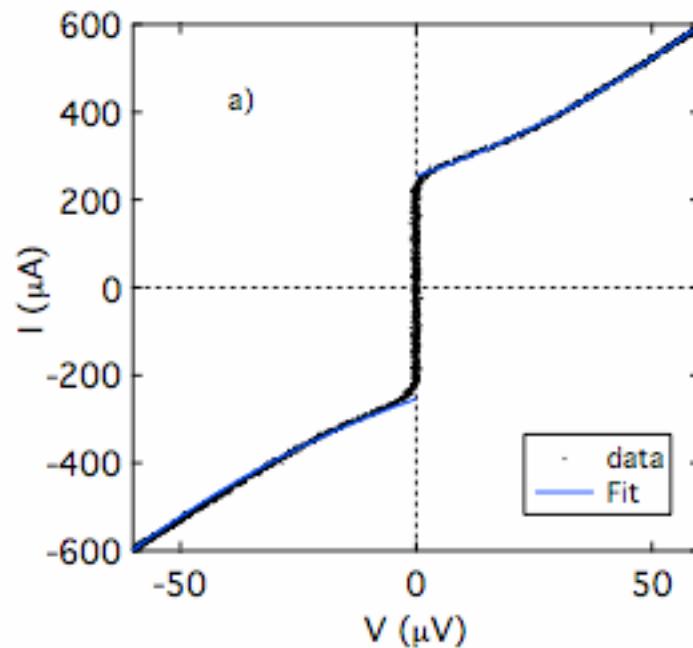
$I(V)$ characteristics

Overdamped JJ

$$\Phi = 3 \cdot 10^{13} \text{ at/cm}^2$$

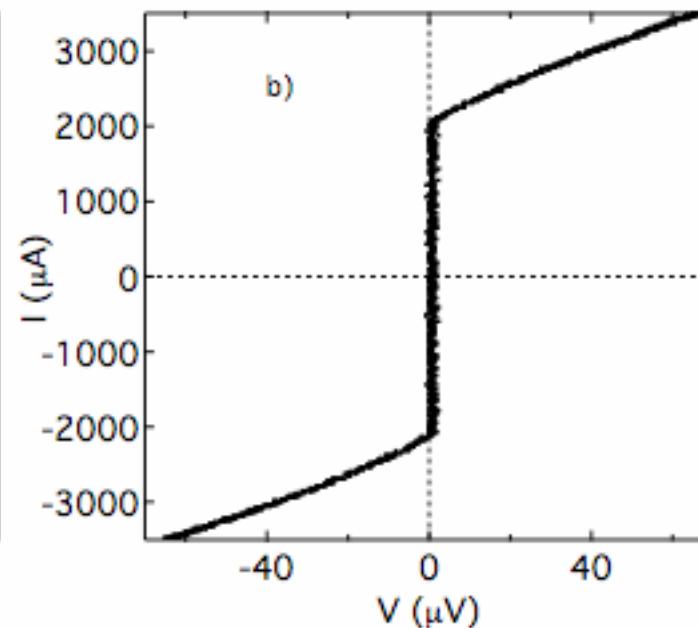
$$T_J > T > T_{c'}$$

$$72.5 \text{ K}$$



$$T < T_{c'}$$

$$70 \text{ K}$$



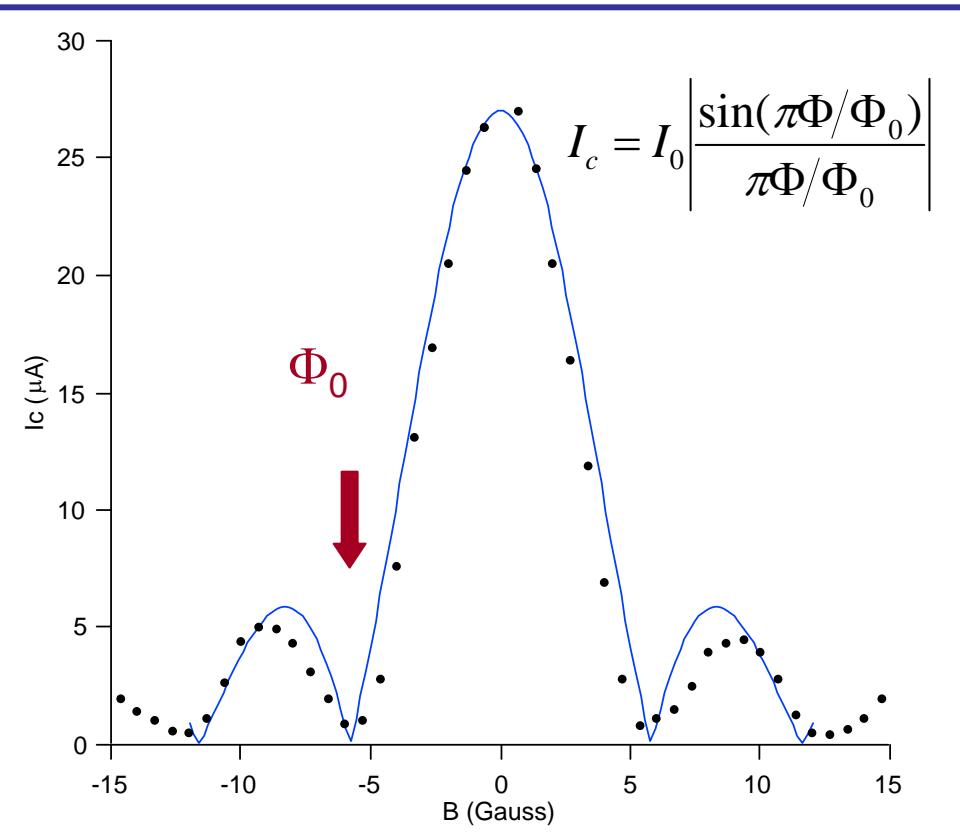
↖ RSJ behavior

↖ Flux flow behavior

↖ Resistance R_n ranging from $200\text{m}\Omega$ to a few Ω

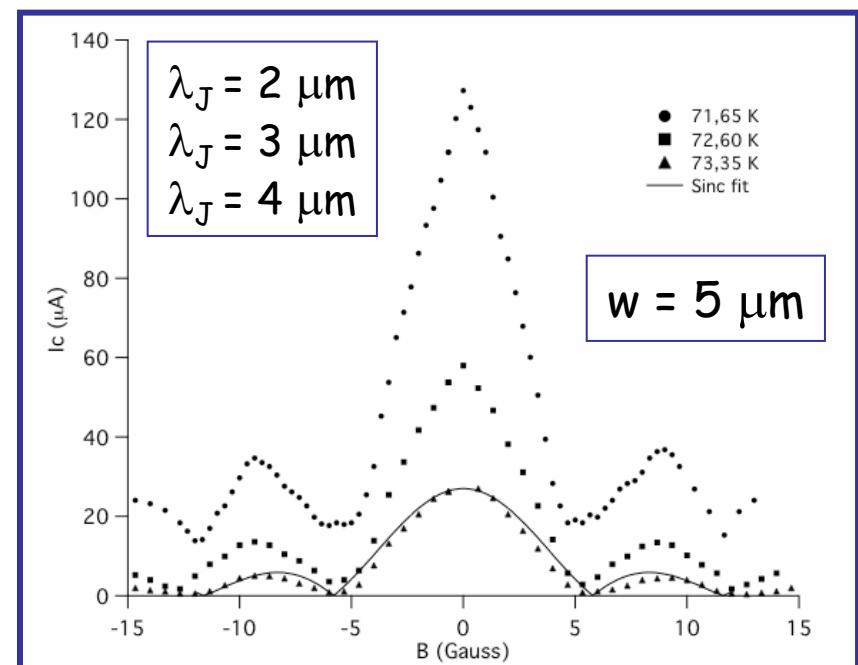
Fraunhofer pattern $I_c(B)$

▷ Phase control by the vector potential



Josephson length λ_J

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

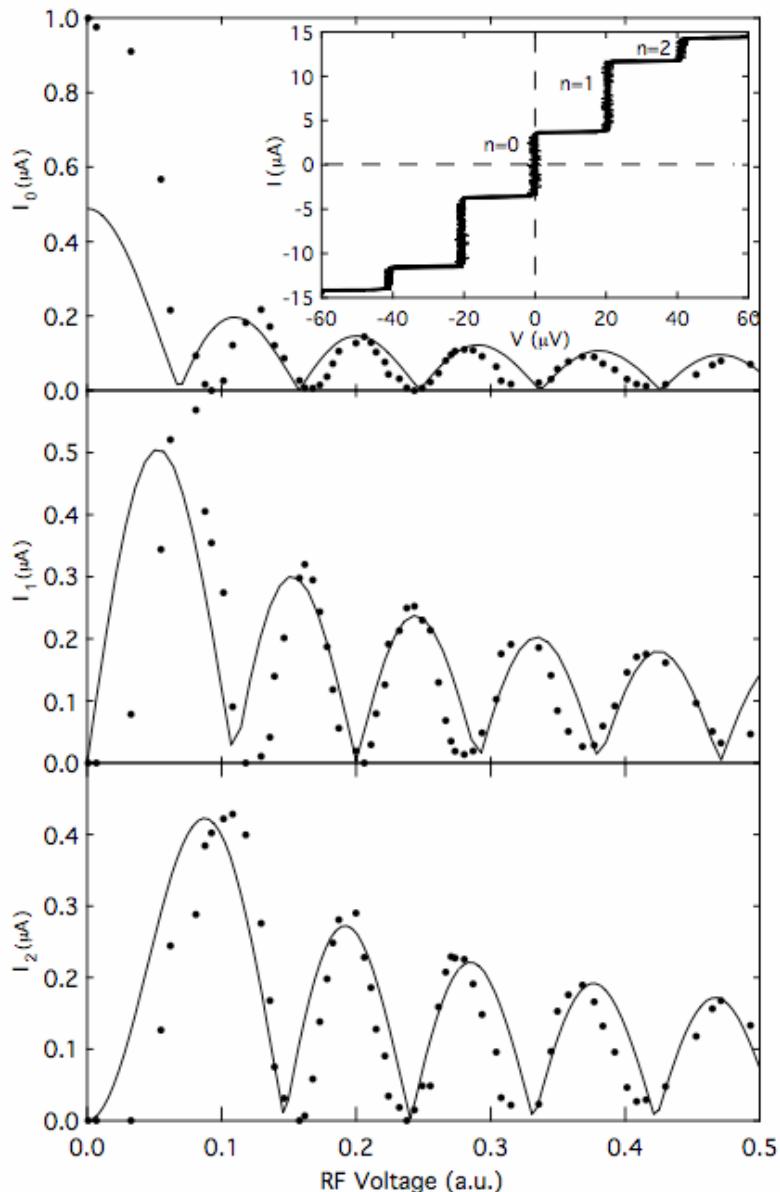
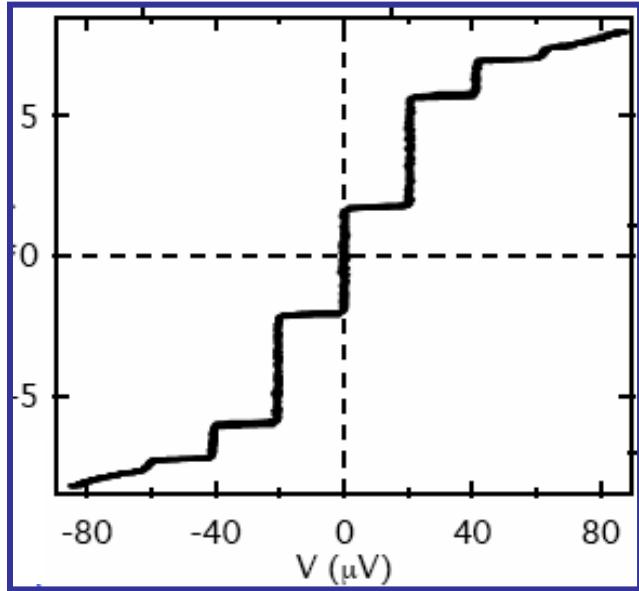


Shapiro Steps

► Phase controlled by microwaves

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

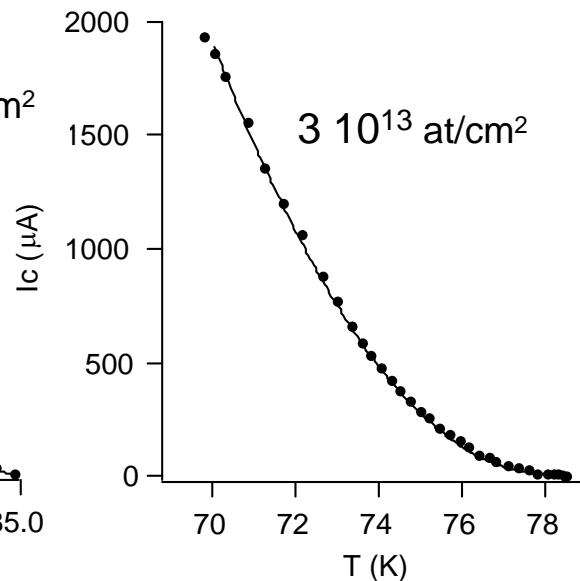
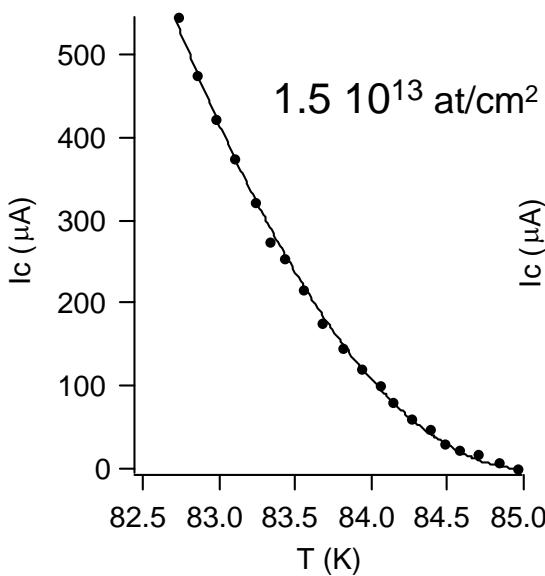
483 597,9 GHz/V



► Almost ideal Bessel functions

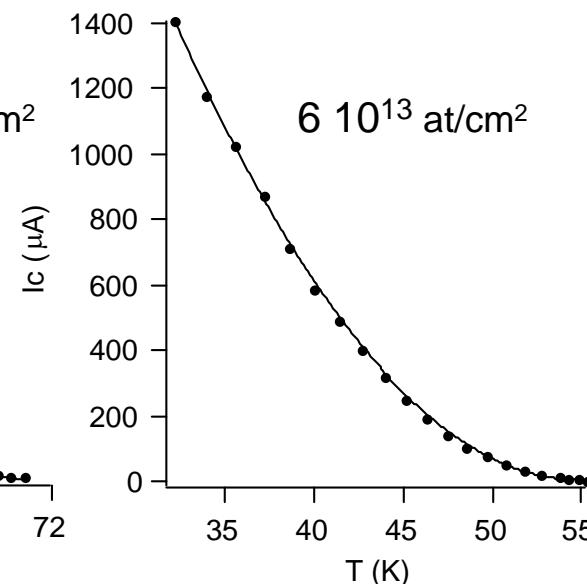
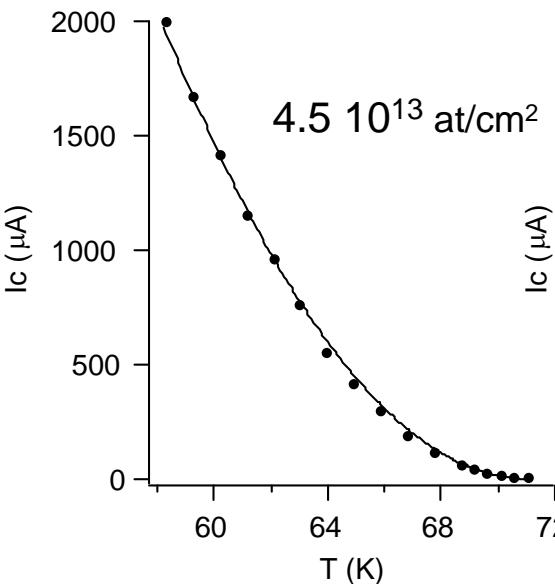
N. Bergeal, JAP 2007

$I_c(T)$ measurements



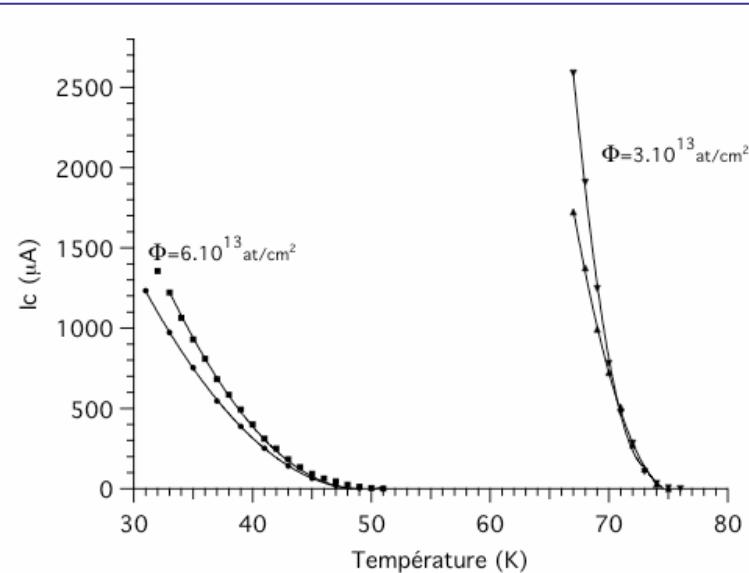
↖ De Gennes-Werthamer model of proximity effect

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

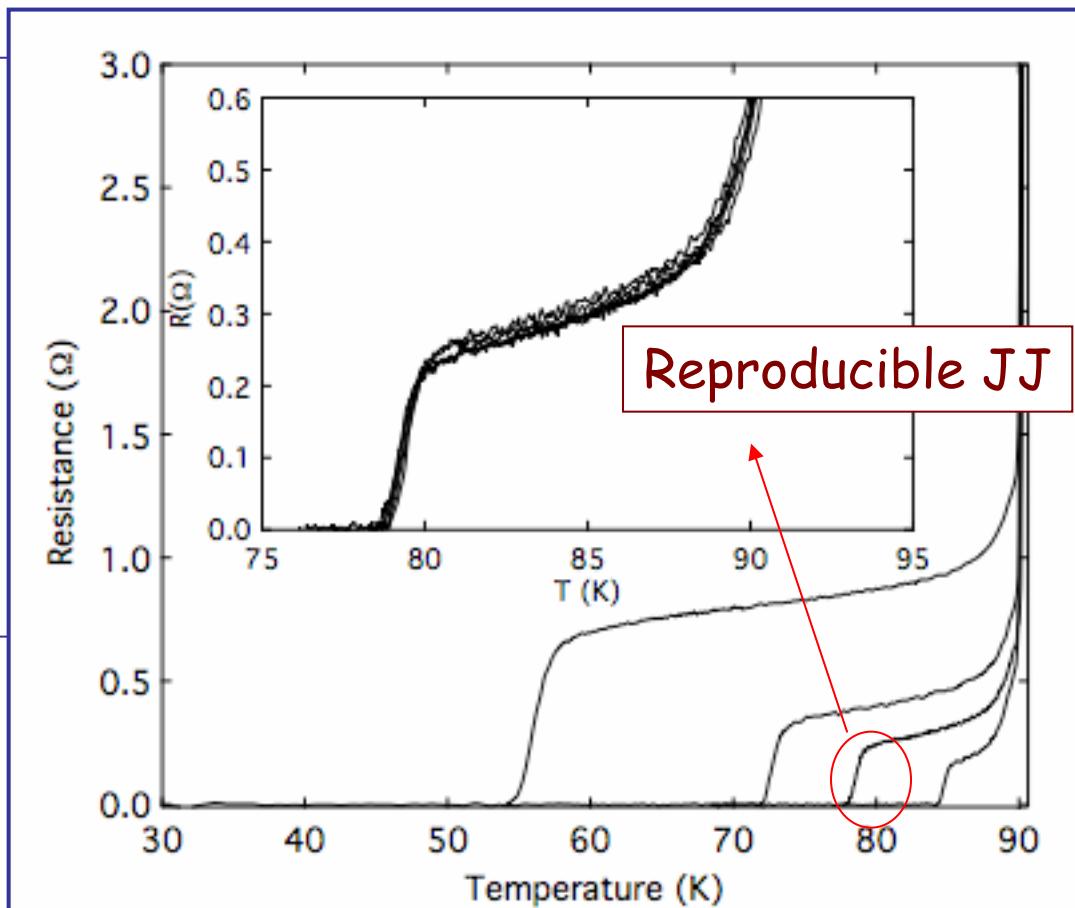


↖ $I_c R_n \sim \text{a few } 100 \text{ }\mu\text{V}$

Major characteristics and reproducibility



N. Bergeal, APL 2005,
JAP 2007



Sample	Fluence	T_j	$T_{c'}$	$R_n(0.9T_j)$	$I_c(0.9T_j)$	$I_cR_n(0.9T_j)$	$J_c(0.9T_j)$
M11	$6 \cdot 10^{13}$ at/cm ²	49 K	32 K	1.2 Ω	72 μA	90 μV	10 kA/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

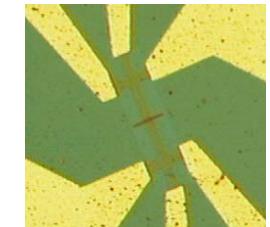
- ↖ Low dispersion in $I_c R_n$ (<10%)
- ↖ Self-shunted junctions
- ↖ High values of J_c (a few 10^4 A/cm²)
- ↖ Excellent thermal cycling and aging

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

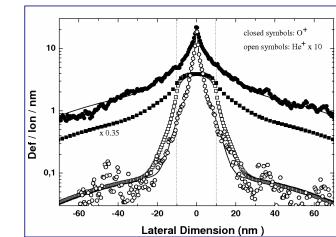
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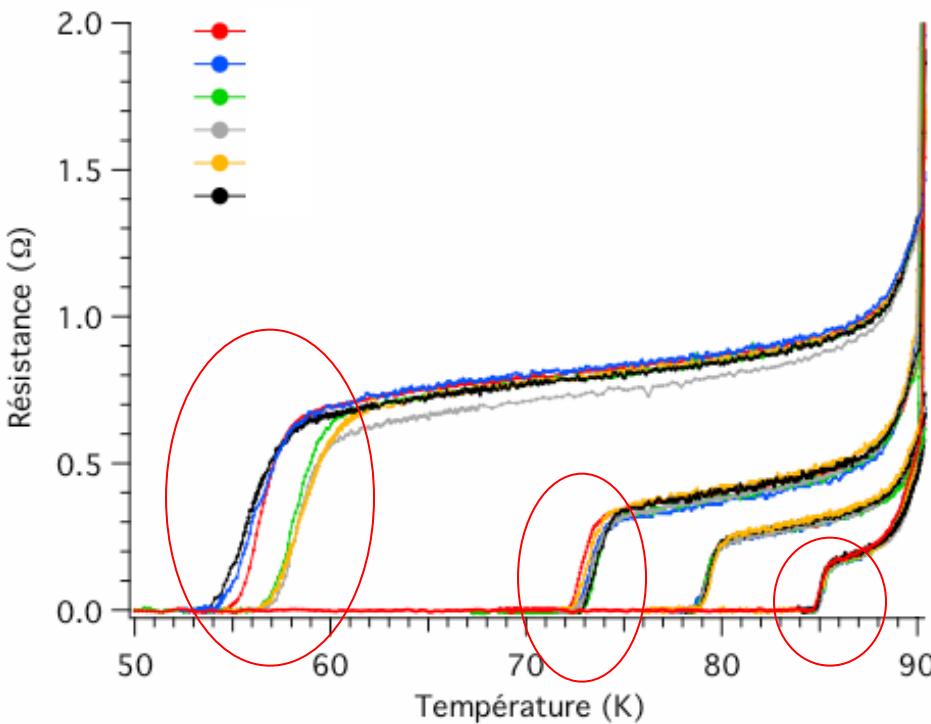


Quasi-classical approach of the proximity effect

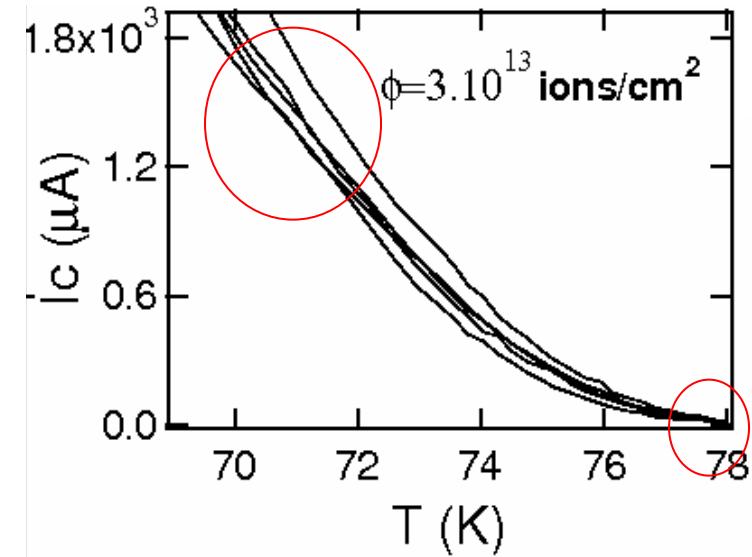
$$\frac{\kappa D(x)}{2} \frac{\partial^2 \theta_n}{\partial x^2} - \omega_n \sin \theta_n + \Delta(x) \cos \theta_n - \Gamma_{AB}(x) \sin \theta_n \cos \theta_n = 0$$

Conclusions

Reproducibility ... can we do better ?



- ↖ I_c very sensitive to temperature
- ↖ Spread in T_c' increases with Φ

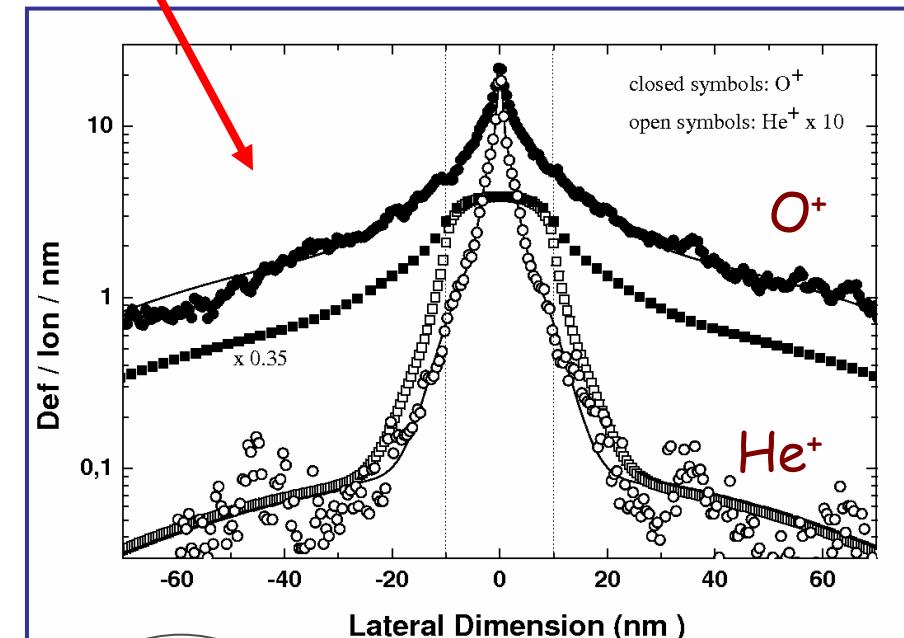
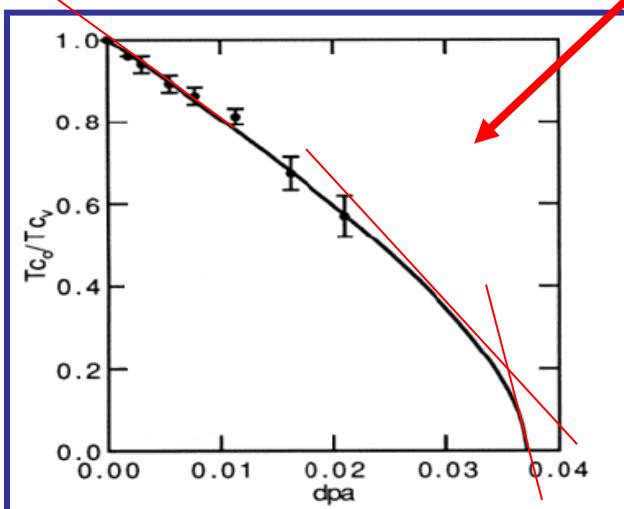


Where does the spread come from ?

↖ Tc' is the critical parameter

$$\Delta Tc' = \frac{\partial Tc'}{\partial dpa} \cdot \frac{\partial dpa}{\partial d} \Delta d$$

Slit width



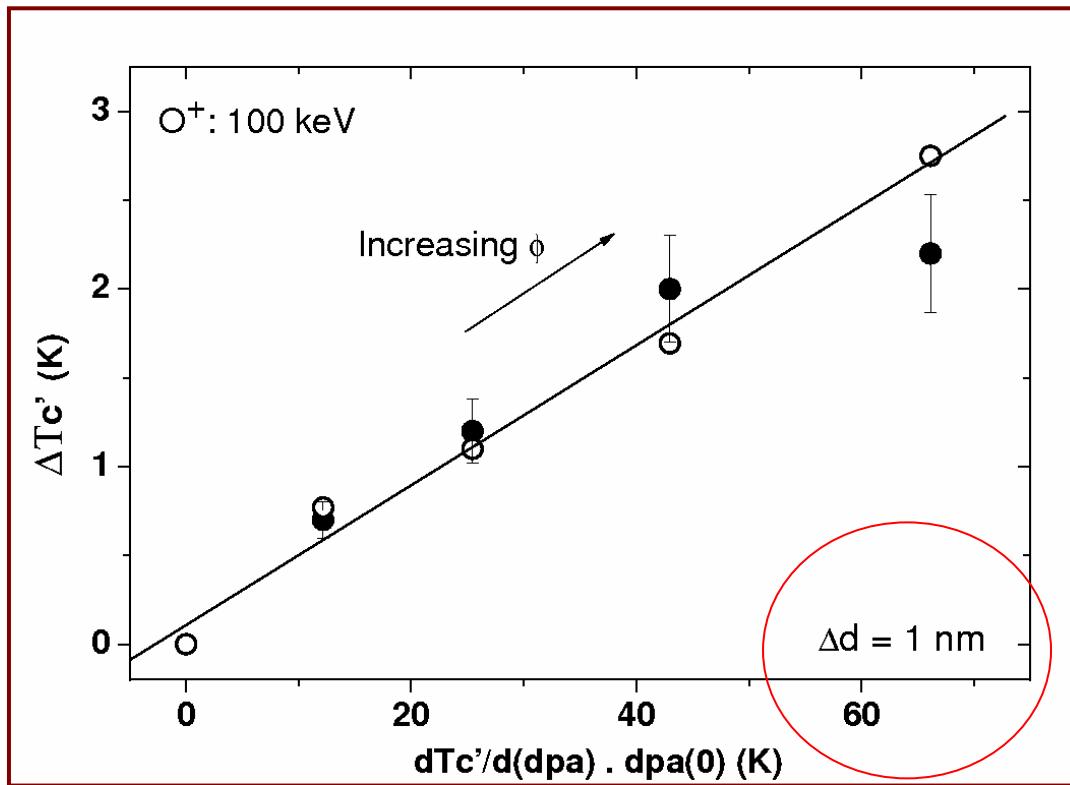
Intrinsic

$$\Delta Tc' = \frac{\partial Tc'}{\partial dpa} \cdot dpa(0) \cdot \frac{C(d/2)}{I^d(0)} \Delta d$$

Defects profile

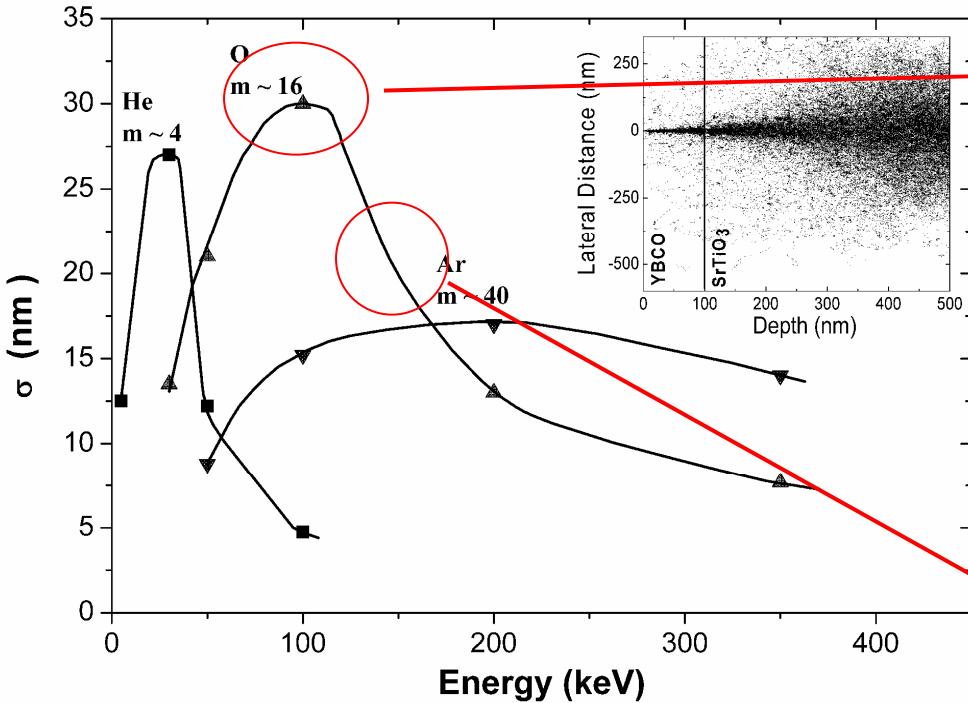
Slit width limitation ...

M. Sirena et al, JAP 2007



↖ Spread is dominated by slit width dispersion ... very low !!

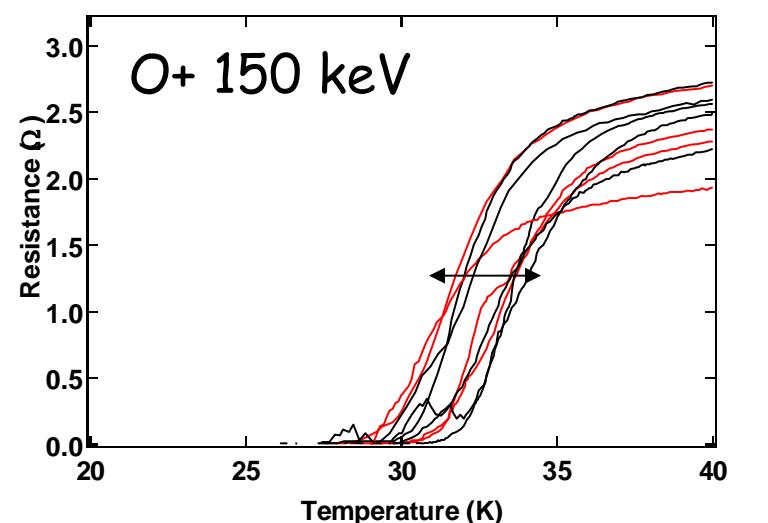
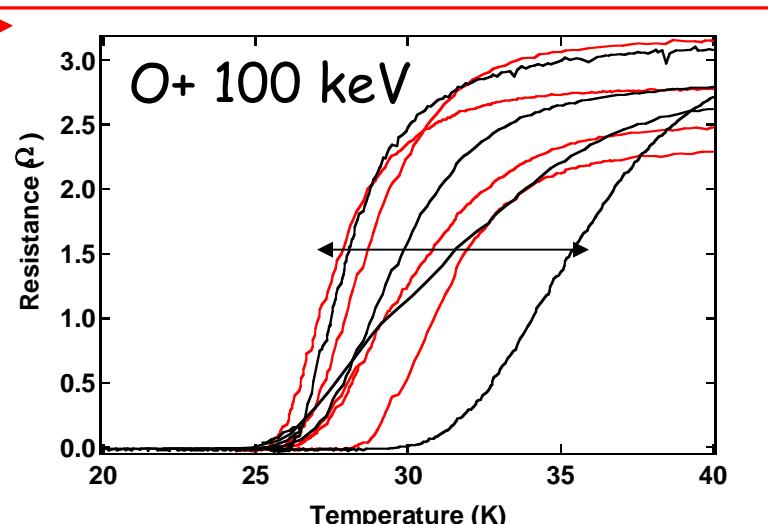
Choosing the energy ...



M. Sirena et al, JAP 2007

↖ $\Delta T_c'$ 3 times smaller

M. Sirena et al, APL 2007

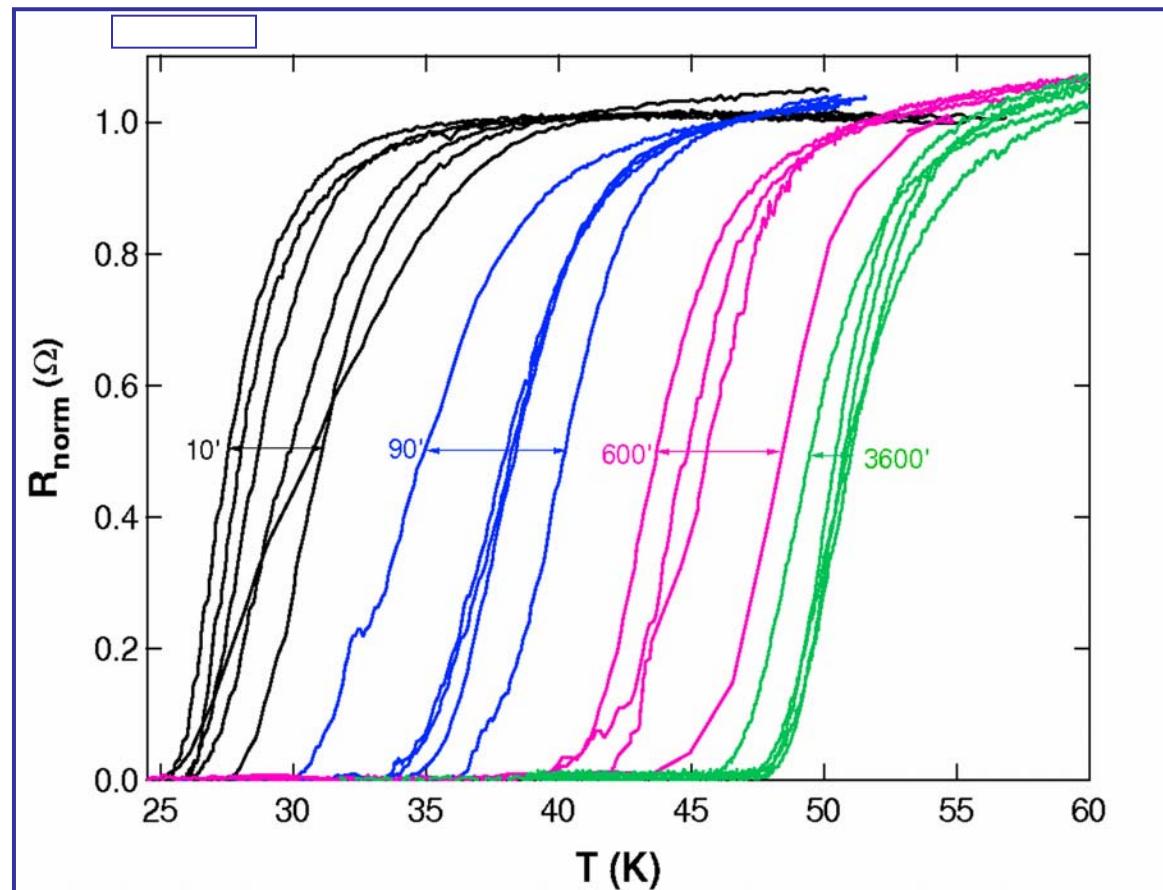


Annealing ... increases homogeneity

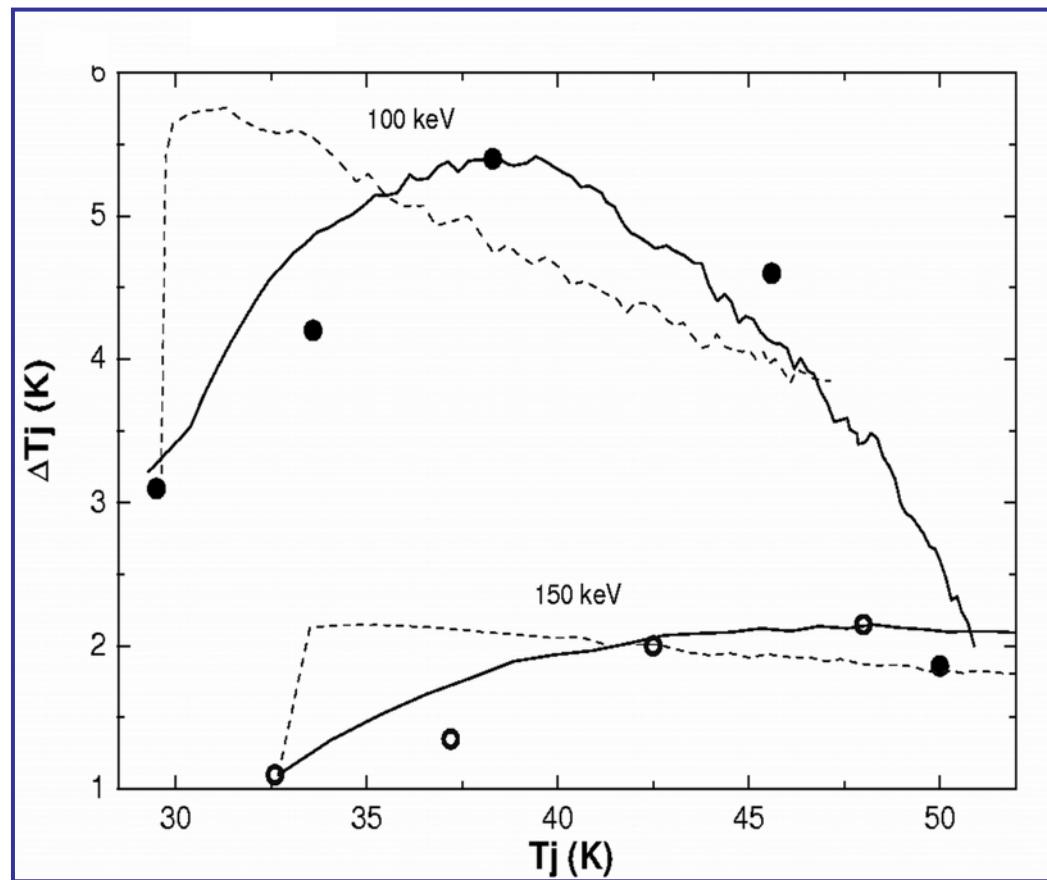
- ↖ Increases homogeneity ? YES
- ↖ Increases $I_c R_n$ product ? YES
- ↖ Long term stability ? YES

Tinchev et al

80 °C
From 10 to 3600'



Simulations ... and experiments



↖ ~~Oxygen Diffusion~~

↖ Vacancies - interstitials annealing

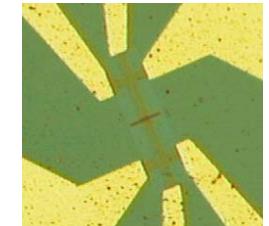
QuickTime™ et un décompresseur TIFF (non compressé) sont requis pour visionner cette image.

M. Sirena et al, APL 2007

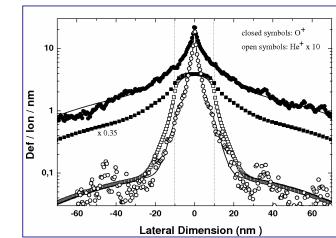
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Quasi-classical approach of the proximity effect

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

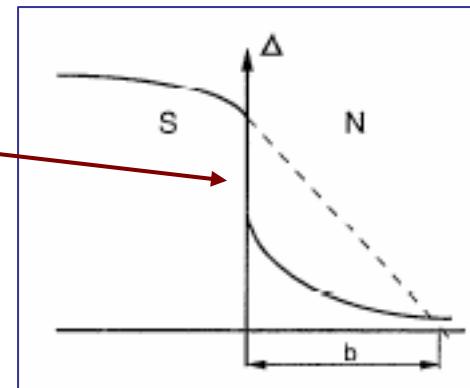
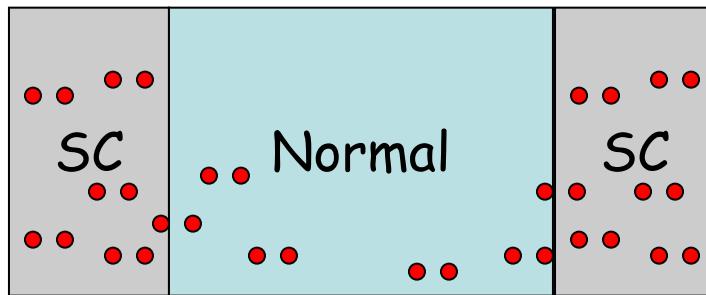
Conclusions

« No-interface » Josephson Junctions

↖ Strength of the coupling

Low interface resistance

Fermi Velocities match



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

↖ Beyond De Gennes's approximation

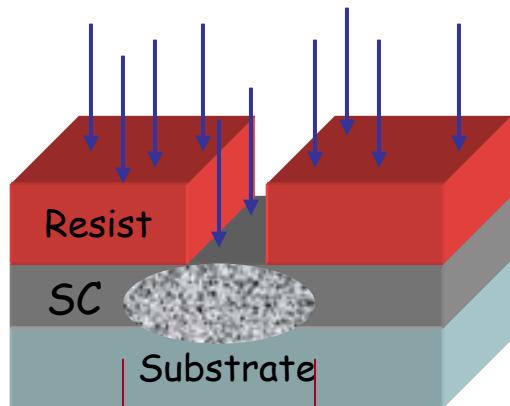
No true interface

Self-consistent calculation of the local gap

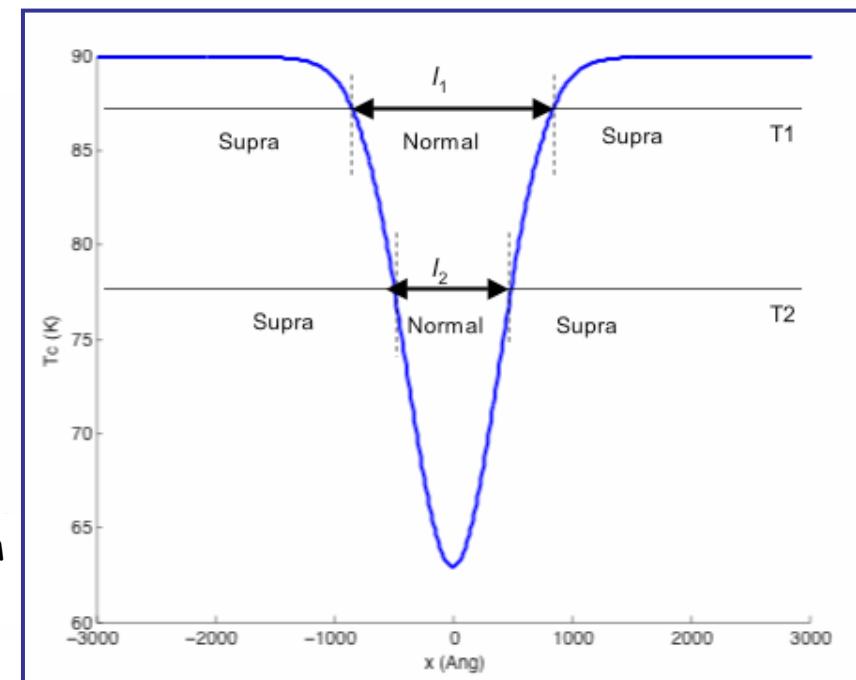
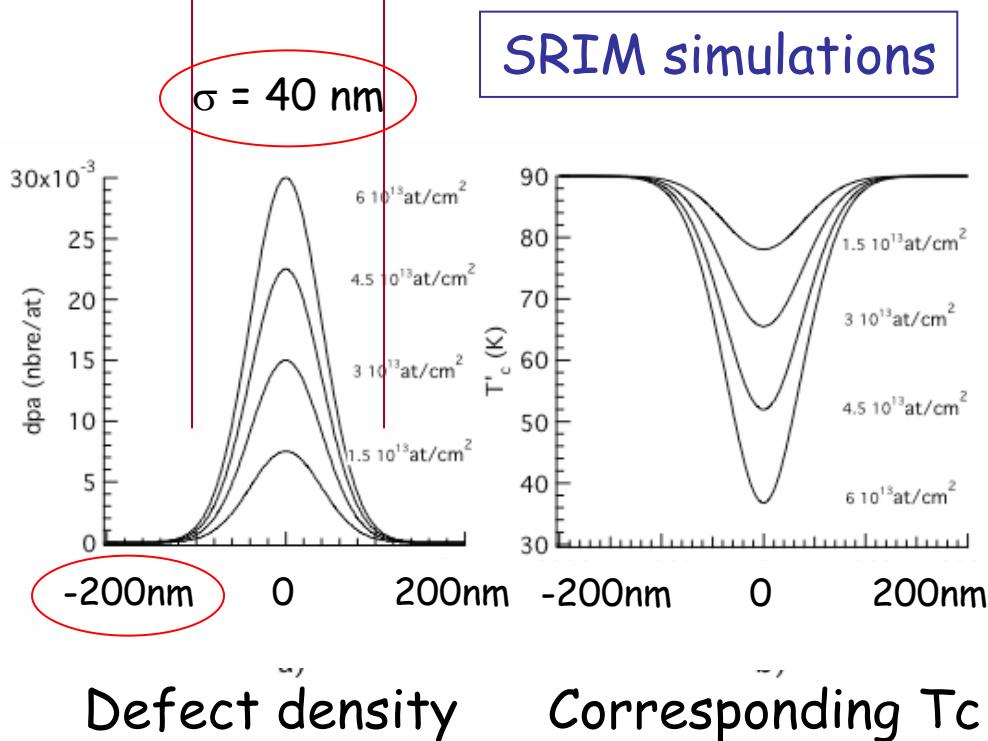
Calculating the Josephson critical temperature

Calculating $I_c(T)$ for all temperatures

Modeling the junction



- ↖ « Ideal proximity system »
- ↖ Perfect Fermi velocities match
- ↖ No interface
- ↖ Long range Proximity Effect



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

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

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

Depairing Γ_{AB}

$$\Gamma_{AB}(x) \sin \theta_n \cos \theta_n = 0$$

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

↳ Self-consistent gap equation

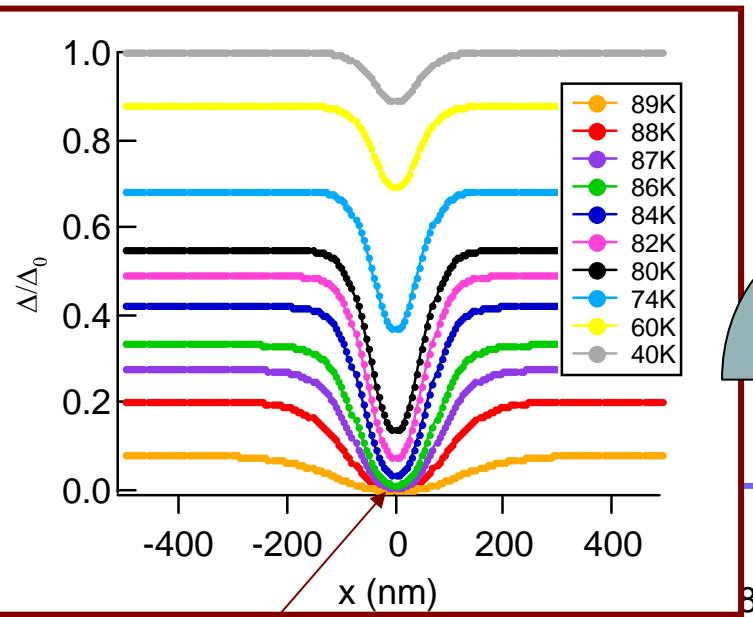
$$\Delta(x) = \lambda_s 2\pi K_B T \sum_{\omega_n} \sin \theta_n$$

In the limit of vanishing current



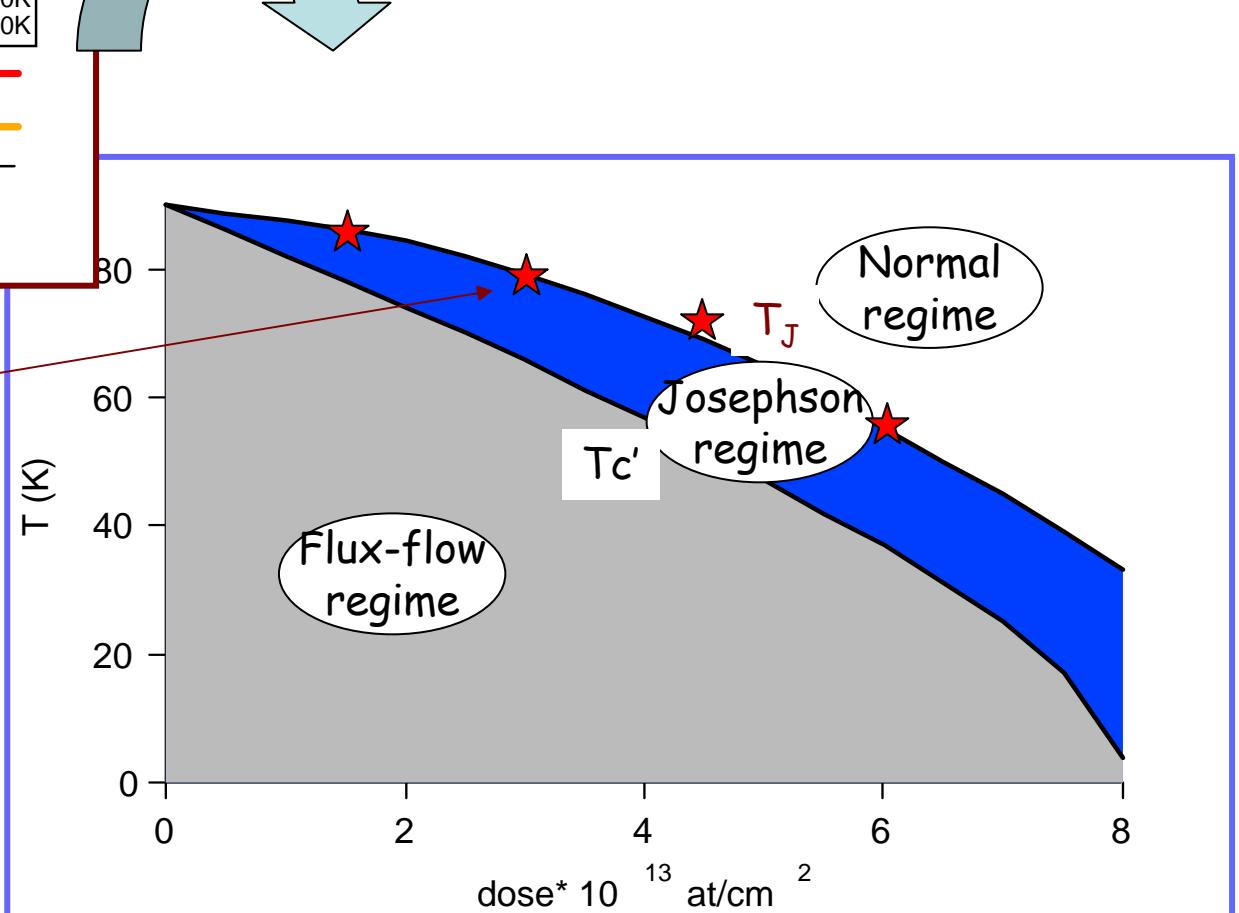
$\Delta(x)$ profil along the junction

Computing the Josephson coupling temperature



T_J

N. Bergeal et al, submitted to PRL



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

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

Depairing Γ_{AB}

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

Depairing by supercurrent χ



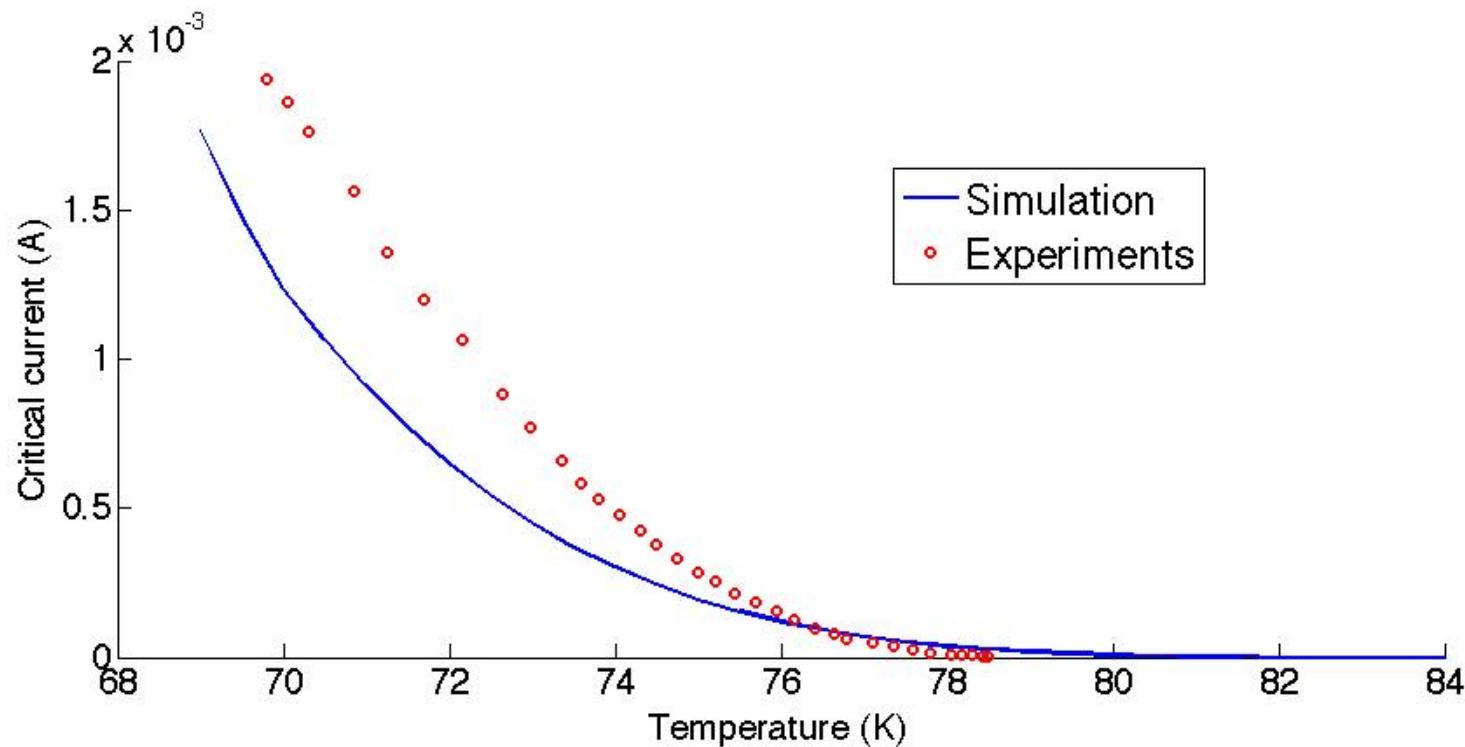
Supercurrent inside the junction

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

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

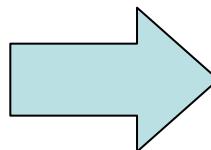
Comparison with experiments

↳ Quantitative results for the critical current of our Josephson junctions



↳ With NO adjustable parameters

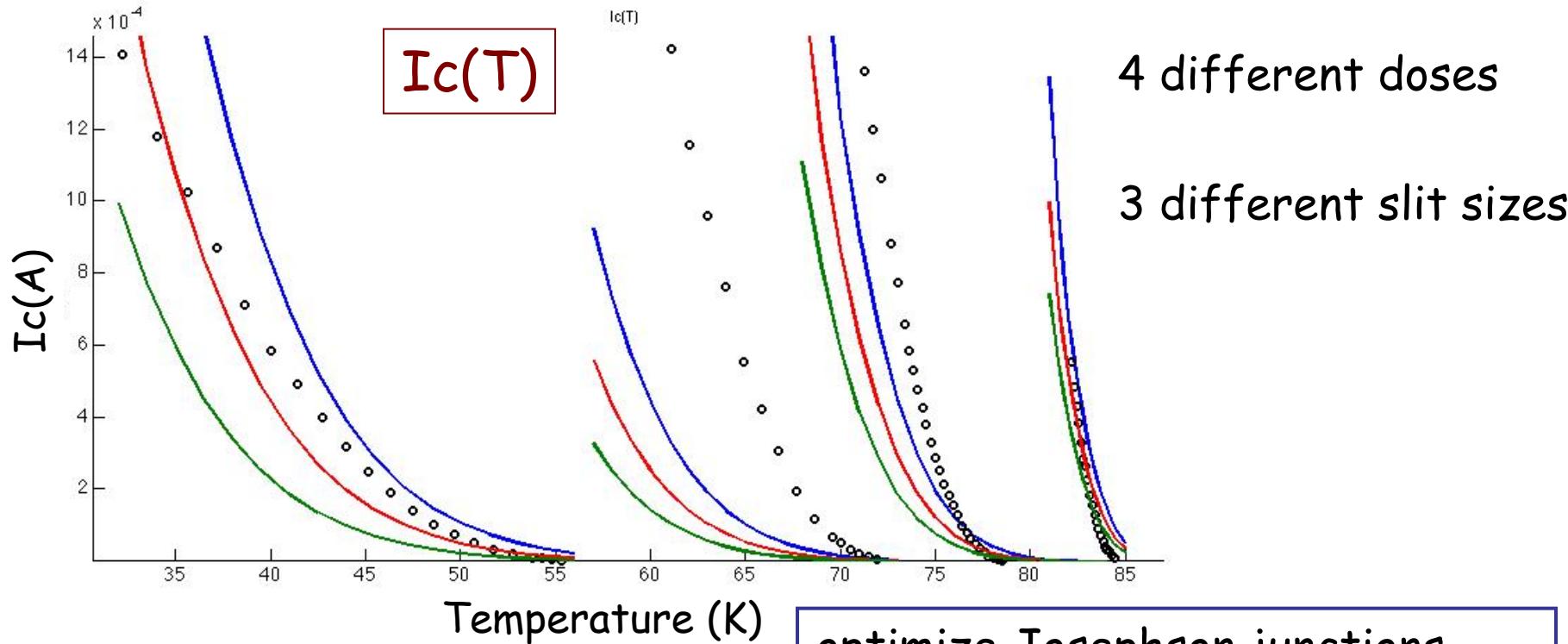
{ Irradiations on full films
SRIM simulations



↳ Depairing coefficient
↳ Defects profile

Changing the junctions parameters

↖ Importance of the slit size and irradiation doses



↖ Simulate various

↖ slit size

↖ film thickness

↖ irradiation dose, ...



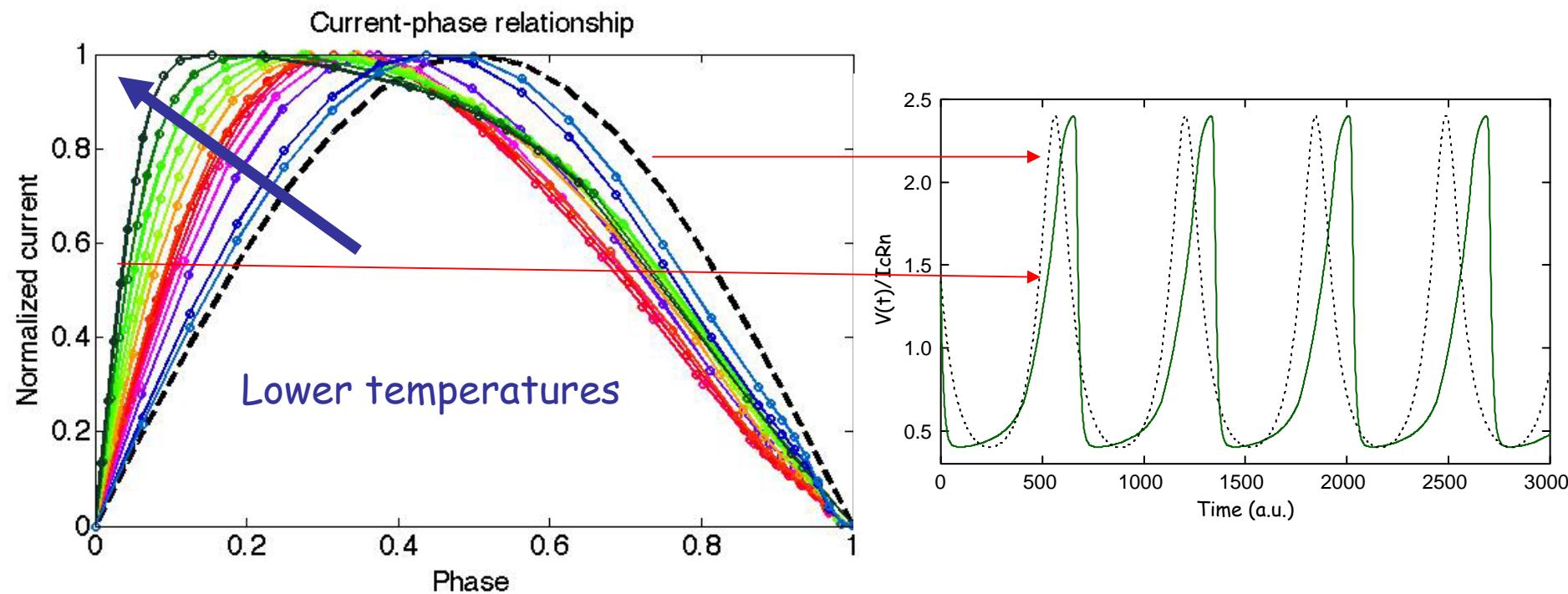
optimize Josephson junctions

↖ 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

Conclusions

- ↖ High Tc Josephson nano-Junctions : a promissing path
- ↖ Possible optimization of characteristics
- ↖ Proximity effect based Josephson Junctions
- ↖ Applications are on their way (SQUIDs, RSFQ, THz detection ...)

Thank you !

JnJ : Bergeal & al, APL 87, 102502 (2005),
JAP 102, 083903 (2007)

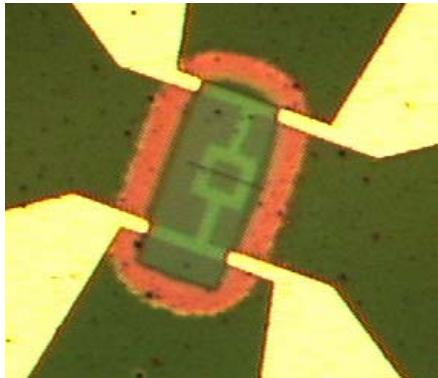
Squids : Bergeal & al, APL 89, 112515 (2006)
APL 90, 136102 (2007)

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)



DC SQUIDs with nanojunctions

N. Bergeal et al, APL 2006



Geometry #1

$10\mu\text{m} \times 10\mu\text{m}$

$W \sim 5\mu\text{m}$

$L = 32 \text{ pH}$

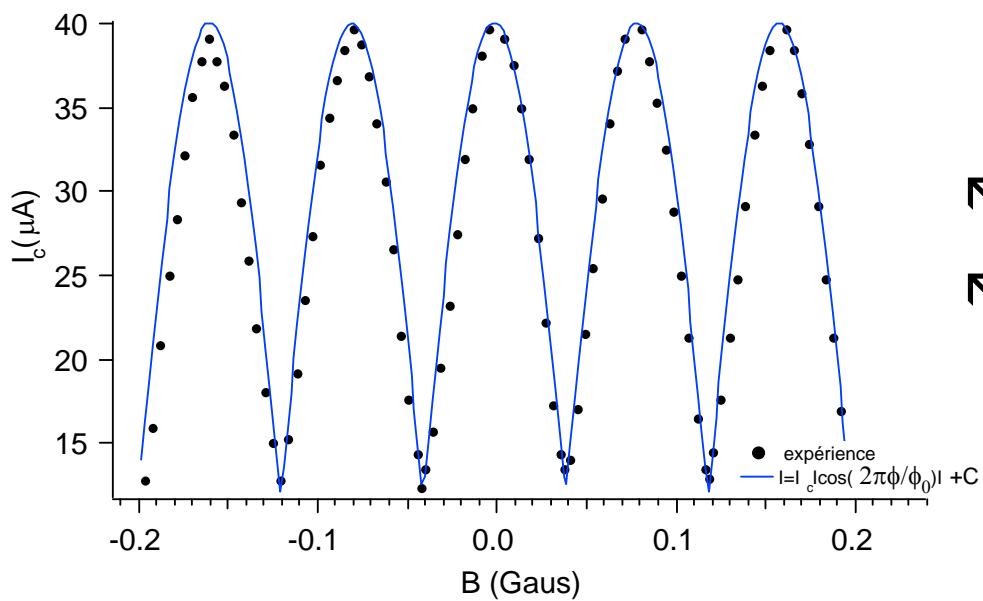
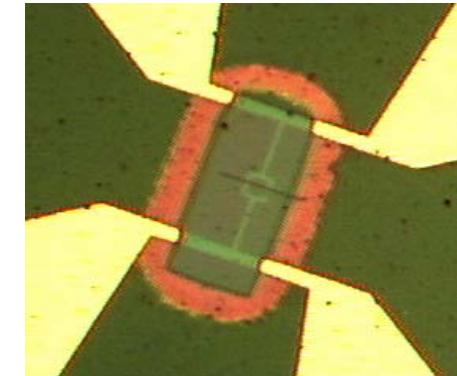
Φ_0 for
 $B \sim 0.08 \text{ G}$

Geometry #2

$6\mu\text{m} \times 6\mu\text{m}$

$W \sim 2\mu\text{m}$

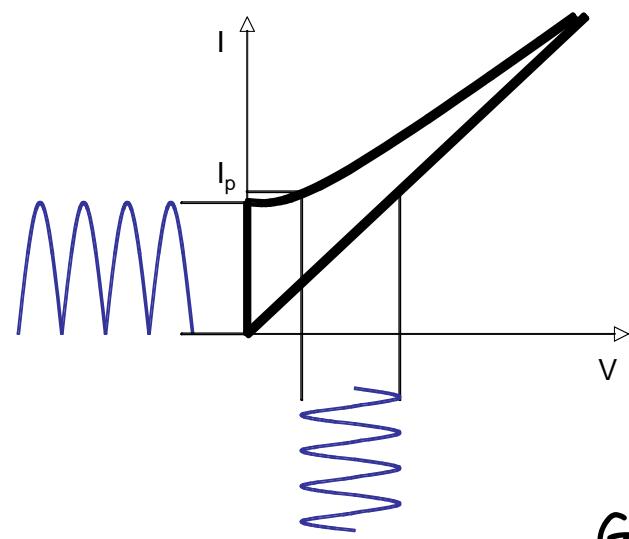
$L = 17 \text{ pH}$



↗ $I_c(B)$ modulation

↗ Cosinus fit with a period 0.08 G

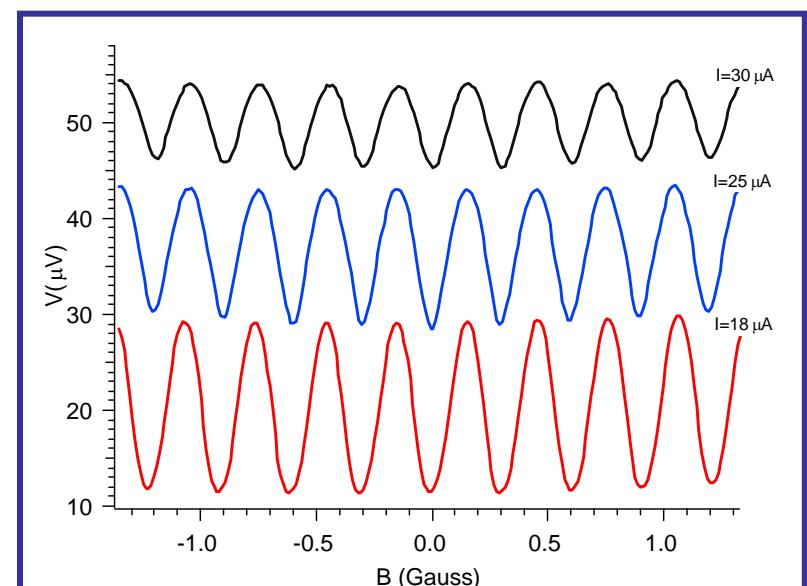
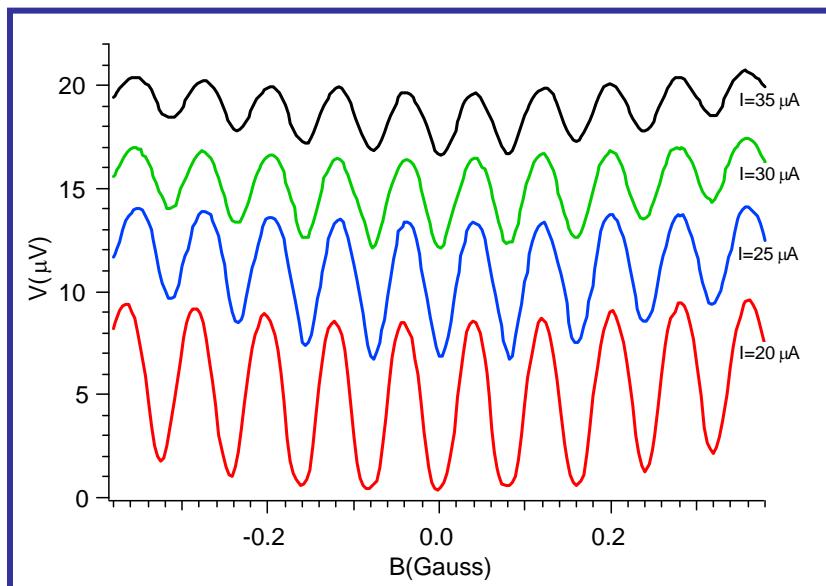
SQUID modulations



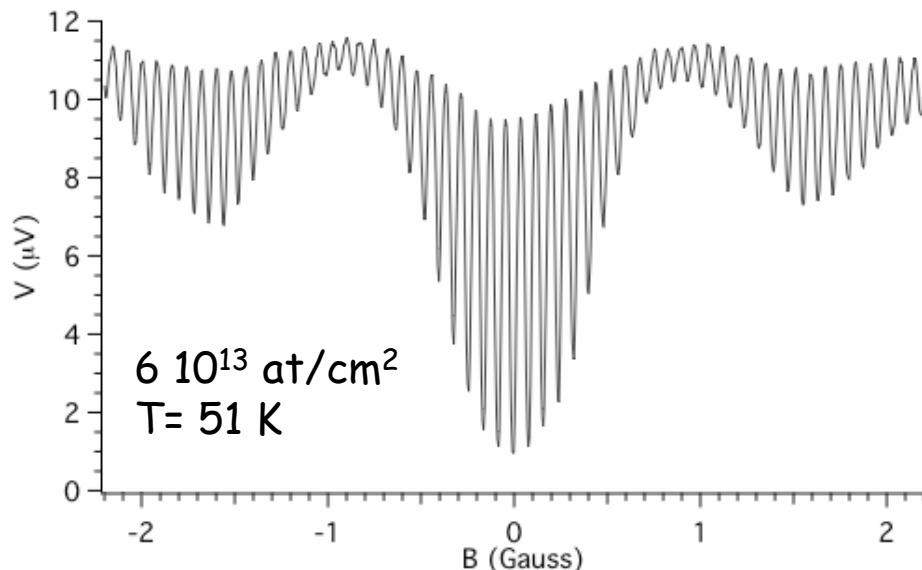
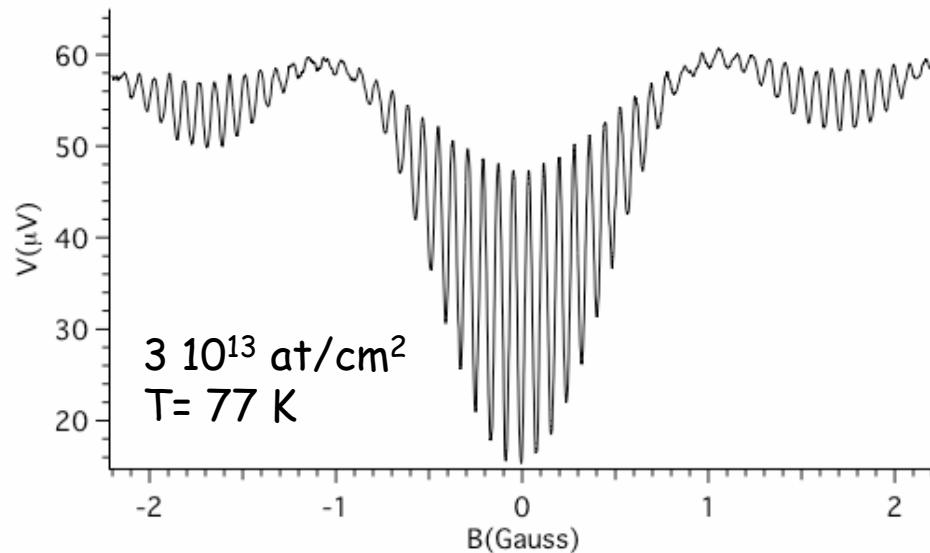
- ↖ Modulation of $I \rightarrow$ modulation of V
- ↖ Sensitivity : $dV/d\Phi = 60 \mu V/\Phi_0$
- ↖ Temperature = 77.7 K

Geometry #1

Geometry #2

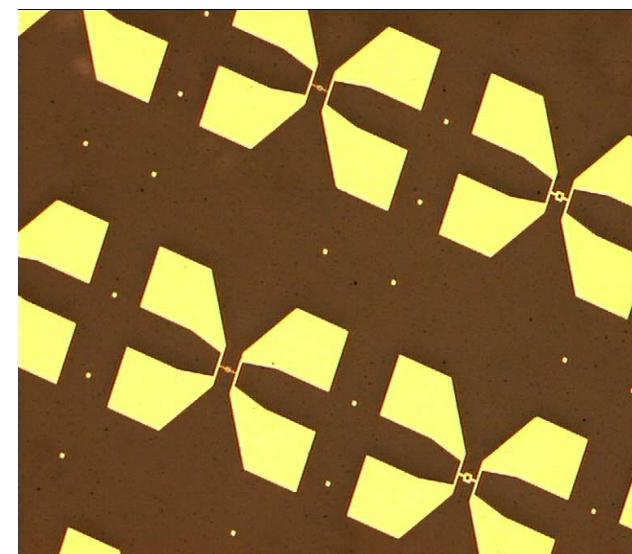


SQUID characteristics



N. Bergeal, APL 2006 ; APL 2007

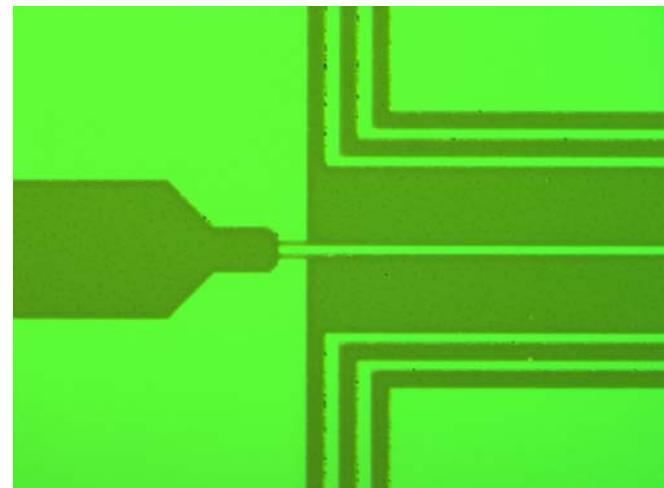
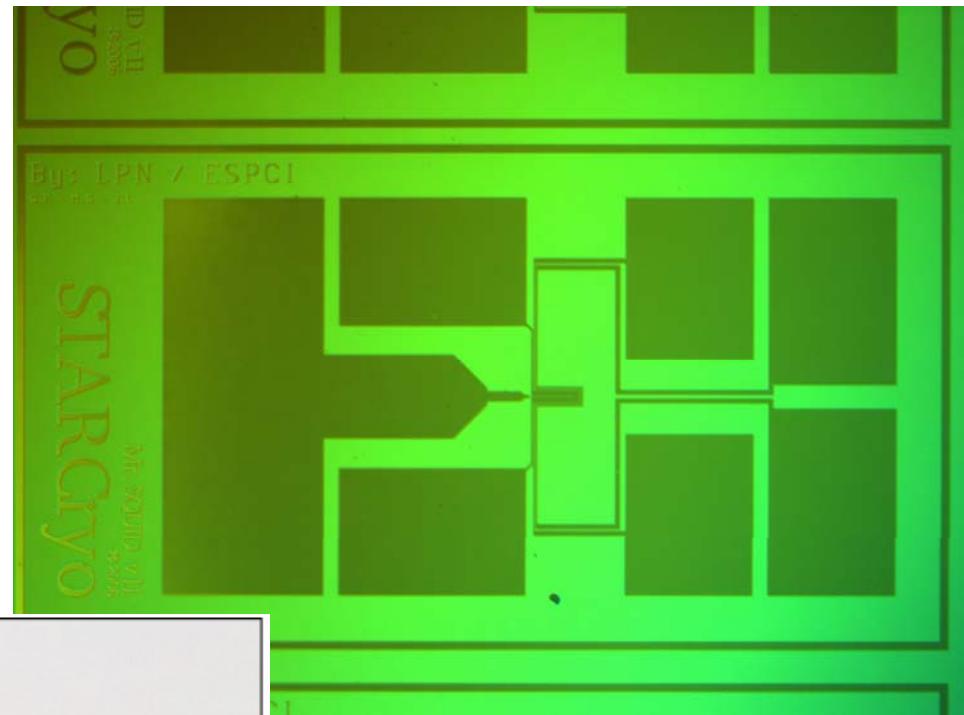
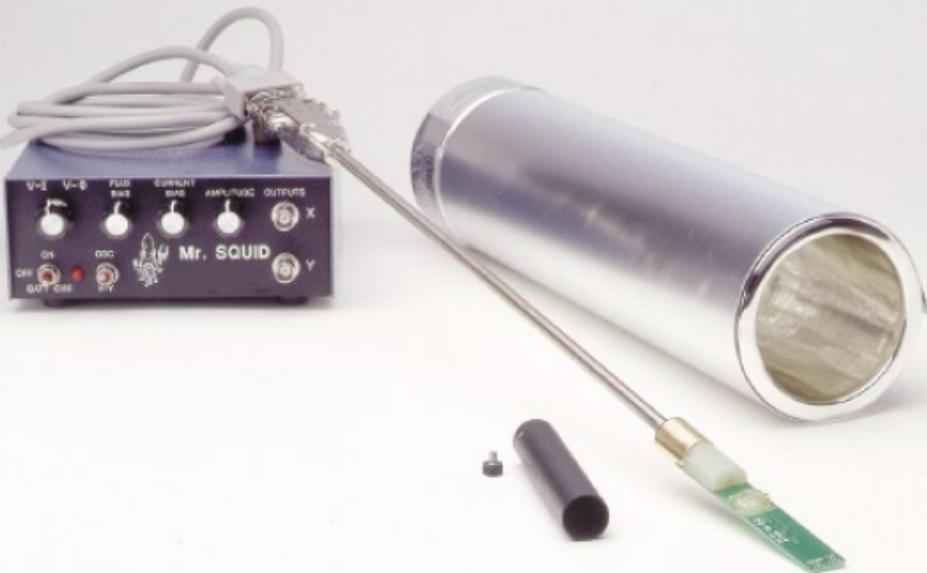
- ↳ Fraunhofer + SQUID modulation
 - ↳ Noise $< 100 \text{ pV}/\sqrt{\text{Hz}}$ (at 100 Hz)
 - ↳ Sensitivity $\approx q q 10^{-4} \Phi_0$
 - ↳ Excellent cycling and aging
- ↳ Networks



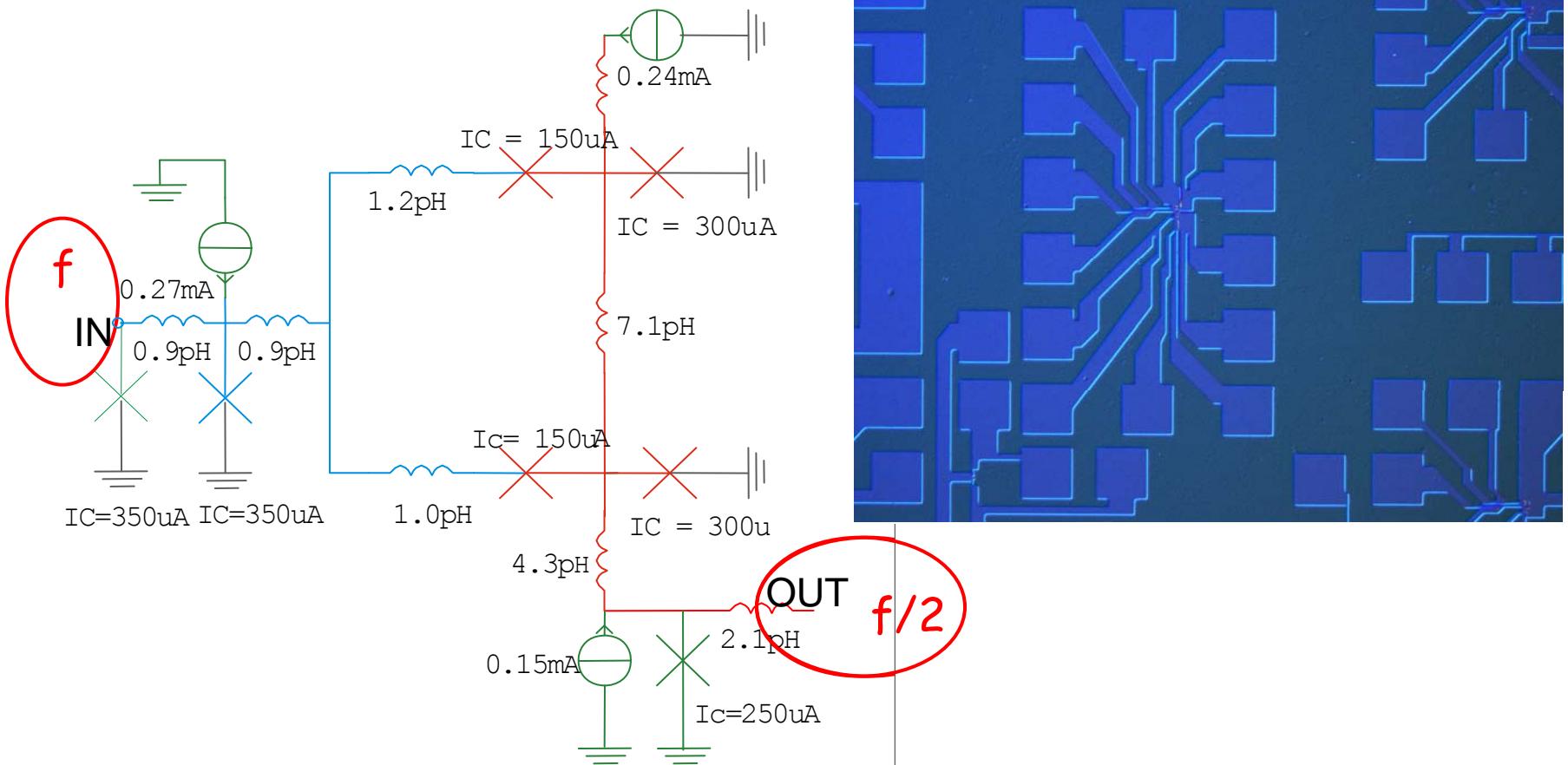
SQUID for « Mr SQUID »

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Cryoelectronics

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RSFQ T Flip-Flop



↖ Design D. Crété (Thales)

↖ Kim et al (2002) 100 GHz @ 12K