Proximity Effect in SF-Structures and Josephson π-Junction Networks

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OUTLINE

- **Proximity effect in SF-bilayers**

  - Spatial oscillations of the induced superconducting order parameter in F- layer
  - F-layer thickness dependence.
    SF-bilayer $T_c(d_F)$-oscillations

- **0-π-transition in SFS Josephson junctions**

  - Reentrant behavior of the $I_c(T)$ and $I_c(d_F)$ dependences

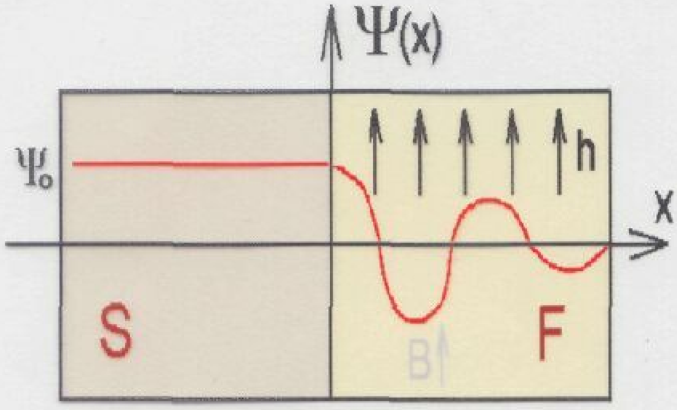
- **π-shift in triangular array at 0-π-transition**

  - Two-cell triangular array of SFS junctions
    π-shift of the $I_c(H)$ dependence

- **"0"-π-bi-stability of SFS junction arrays in magnetic field**

  - "0"-π - transition in magnetic field

Spatial oscillations of induced superconducting order parameter in ferromagnets in close proximity to a superconductor



h is exhange field

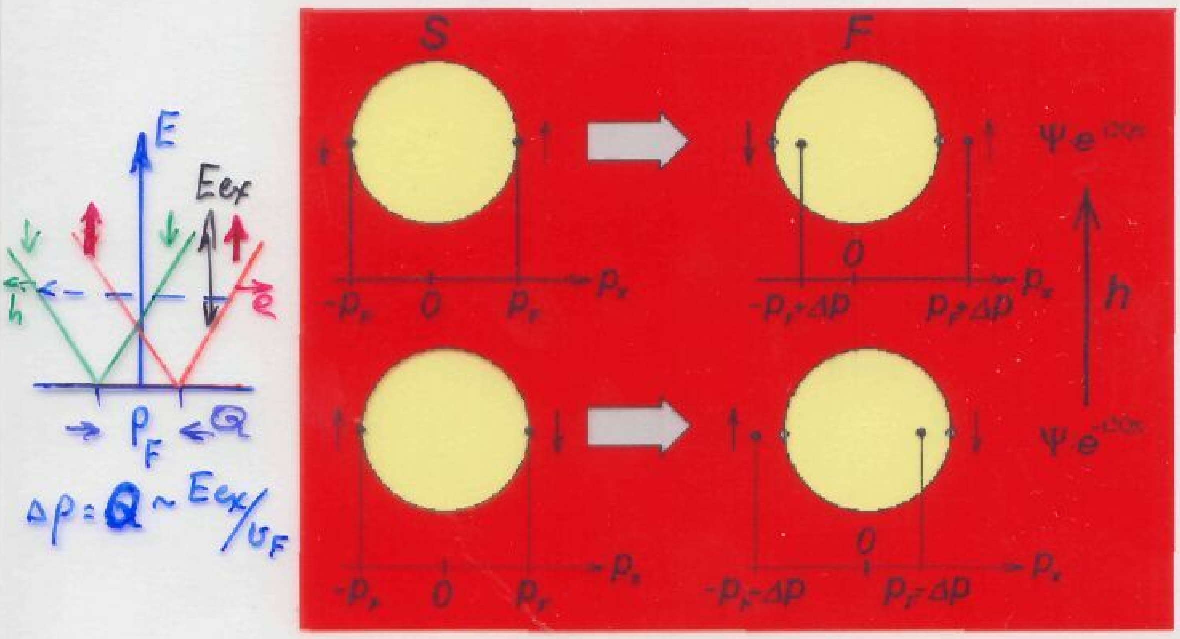
$\Psi(x) = \Psi_0 Cos(2Qx)$

• exp. decay

$Q \sim E_{ex}/v_F$

$Q \neq 0$ is center of pair mass momentum

Demler, Arnold, Beasley, *Phys. Rev. B.* **55**, 15174 (1997).



$$\Psi(x) = \Psi_0\,(e^{i2Qx}+e^{-i2Qx})/2 = \Psi_0 Cos(2Qx)$$

$$p'^2/2m - p^2/2m = E_{ex}; \qquad Q \sim E_{ex}/v_F$$

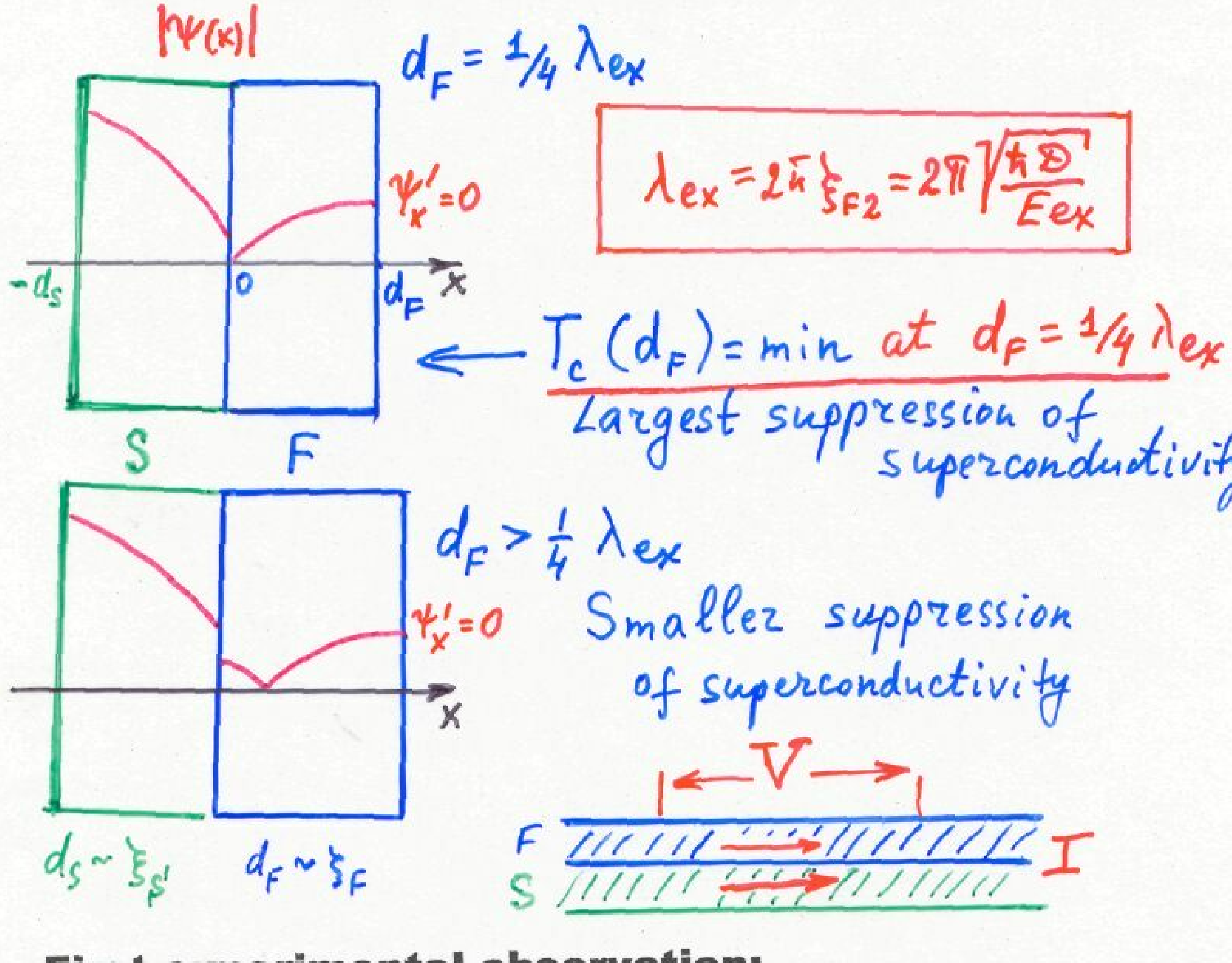
Order parameter at SF-interface in a SF-bilayer. SF-bilayer T_c-jscillations

Z.Radovic, M.Ledvij, L.Dobrosavljevic-Grujic, A.I.Buzdin and J.R.Clem. PR B **44**, 759 (1991) } SF-multi-layers

J.Aarts, J.M.E.Geers, E.Bruck, A.A.Golubov, and R.Coehoorn. PR B **56**, 2779 (1997)

L.Lazar, K.Westerholt, H.Zabel, L.R.Tagirov et al. PR B **61**, 3711 (2000) } SF-bilayer

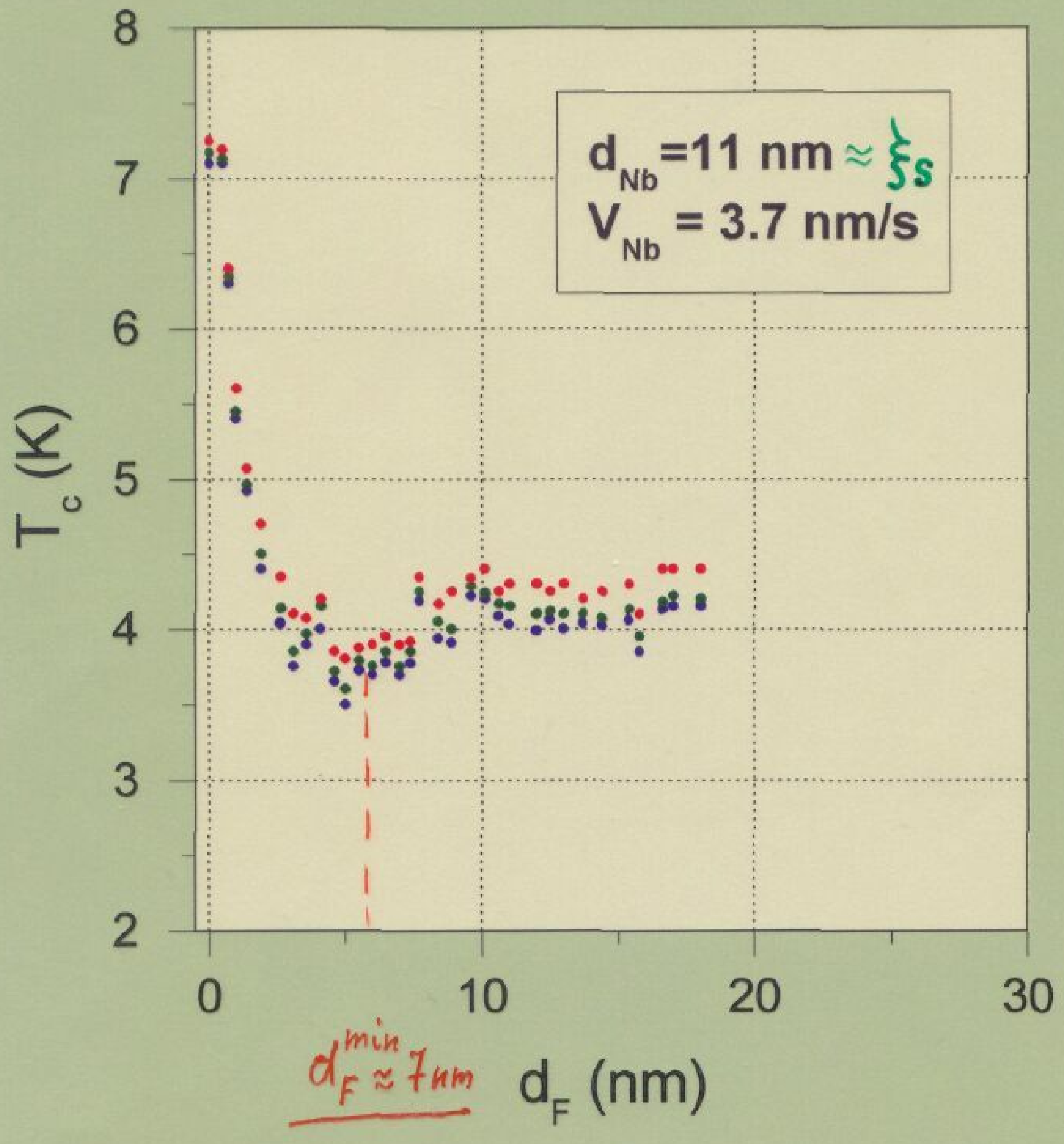
Fominov, Chtchelkatchev, Golubov. PRB 66, 014507 (2002)



First experimental observation:

Nb/Gd – Jiang, Davidovich et al. PRL 74, 314 (1995)

Critical temperature T_c of Nb-$Cu_{0.43}Ni_{0.57}$ bilayer vs ferromagnetic layer thickness d_F



- Superconducting transition initial point
- Superconducting transition middle point
- Superconducting transition final point

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Samples fabrication

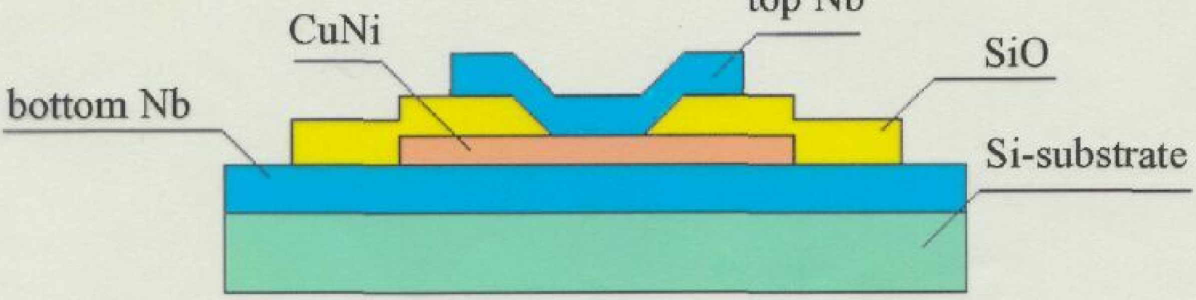
- *forming of the bottom Nb strip (width 100 μm) by Nb film dc-magnetron sputtering (110 nm thickness), photolithography and chemical etching*

- *Nb - surface ion etching and CuNi alloy film deposition by rf-diode sputtering*

- *forming of SiO-isolation layer (170 nm) with the "window" (50x50) μm by photolithography, thermal evaporation and "lift-off" process*

- *forming of the upper Nb strip (240 nm thickness and 80 μm width) by photolithography, CuNi-alloy surface ion etching, Nb film dc-magnetron sputtering and "lift-off" process*

Sample side view



Nb - Cu/Ni - Nb (SFS) sandwich

Temperature dependence of the order parameter spatial oscillations for $E_{ex} \sim k_B T$

Complex pair coherence length in ferromagnet for $E_{ex} >> k_B T$:

typical for SFS's with Co, Ni, Fe interlayers

$$\xi_F = \sqrt{\hbar D / i2E_{ex}}$$

$$\xi_{F1} = \xi_{F2} = \sqrt{\hbar D / E_{ex}}$$

ξ_{F1} is *the pair decay length,*

$2\pi\xi_{F2}$ is *a wavelength of the spatial oscillations*

Complex pair coherence length in ferromagnet for $E_{ex} \sim k_B T$:

$$\xi_F = \sqrt{\frac{\hbar D}{2(\pi k_B T + iE_{ex})}}$$

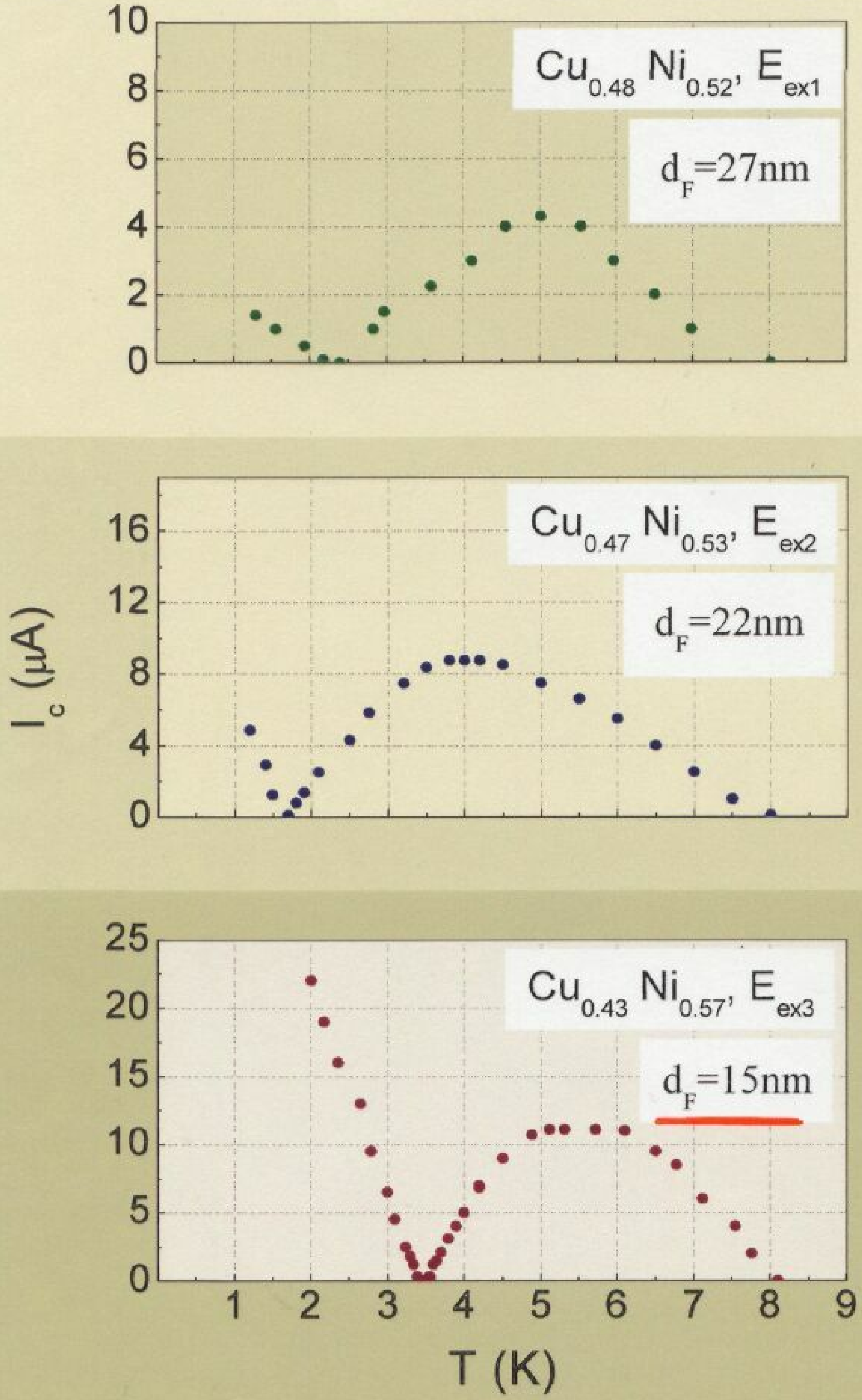
$$\xi_{F1} = \sqrt{\frac{\hbar D}{\sqrt{E_{ex}^2 + (\pi k_B T)^2} + \pi k_B T}}$$

$$\xi_{F2} = \sqrt{\frac{\hbar D}{\sqrt{E_{ex}^2 + (\pi k_B T)^2} - \pi k_B T}}$$

The period of the spatial oscillations decreases with temperature !

Temperature crossover from '0-' to 'π'-state at T_π where d_F is about $\pi\xi_{F2}(T)$

Critical currents vs temperature for different exchange fields in F-layers of SFS structures

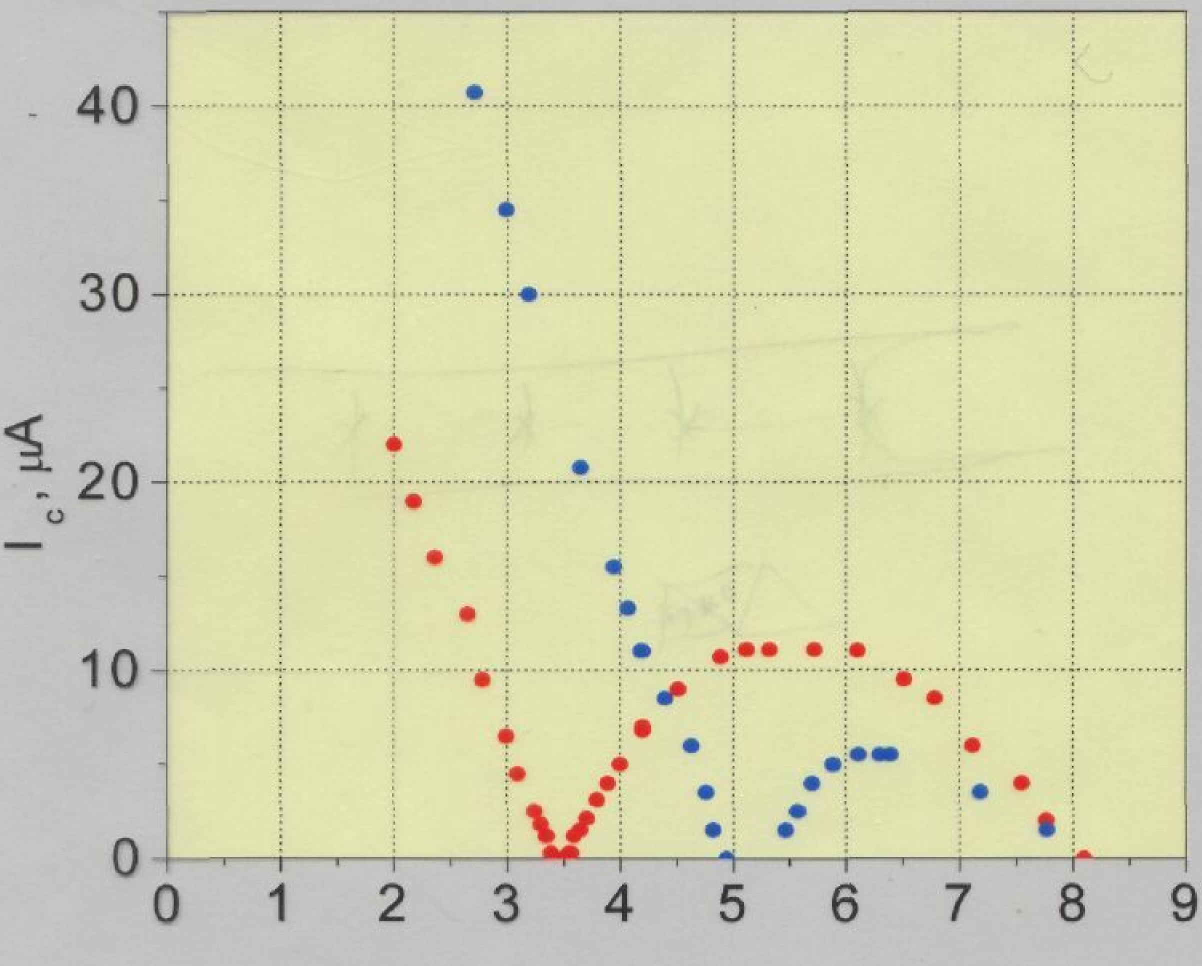


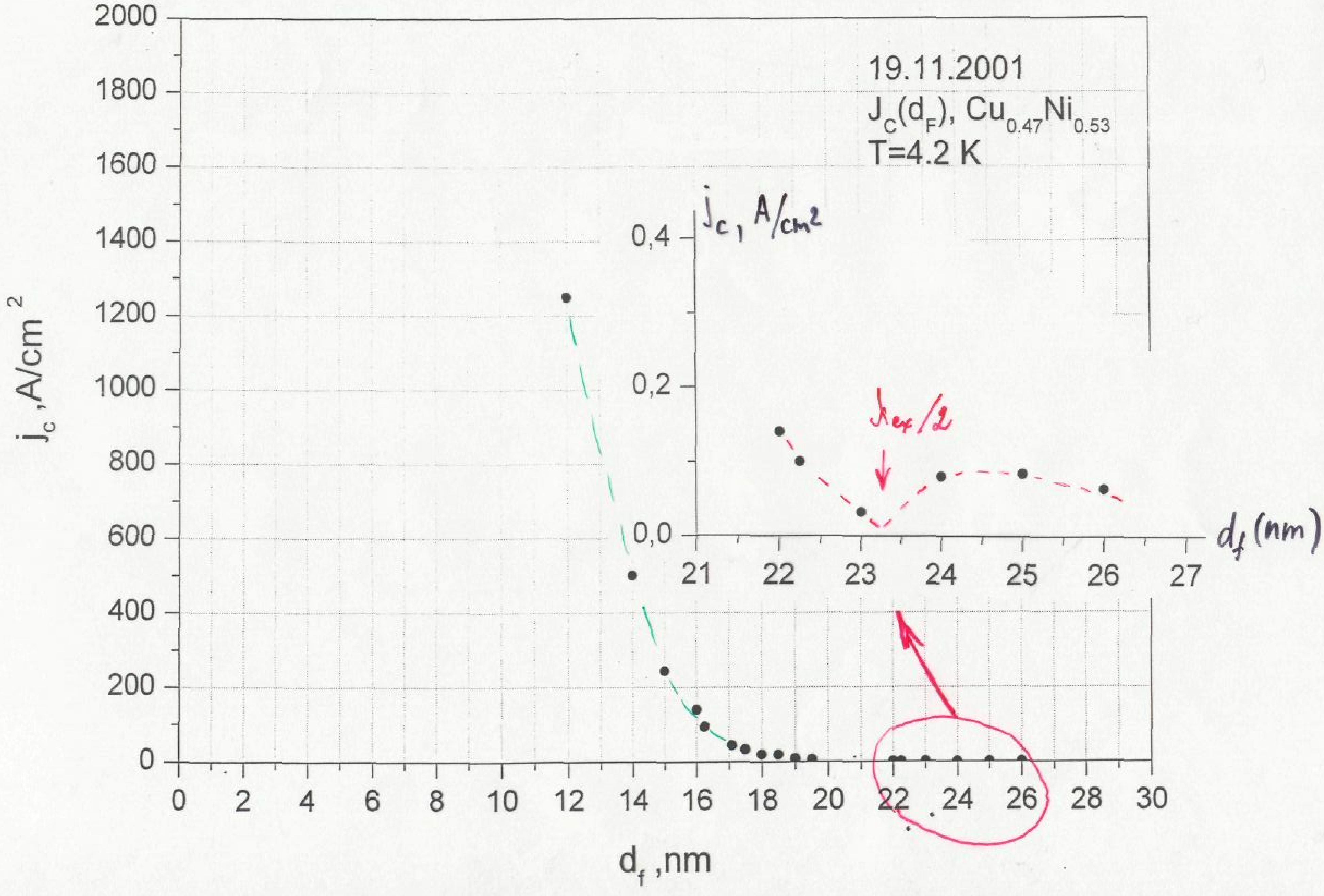
$$E_{ex1} < E_{ex2} < E_{ex3}$$

$d_F \simeq \pi \xi_{F2} \sim \sqrt{1/E_{ex}}$

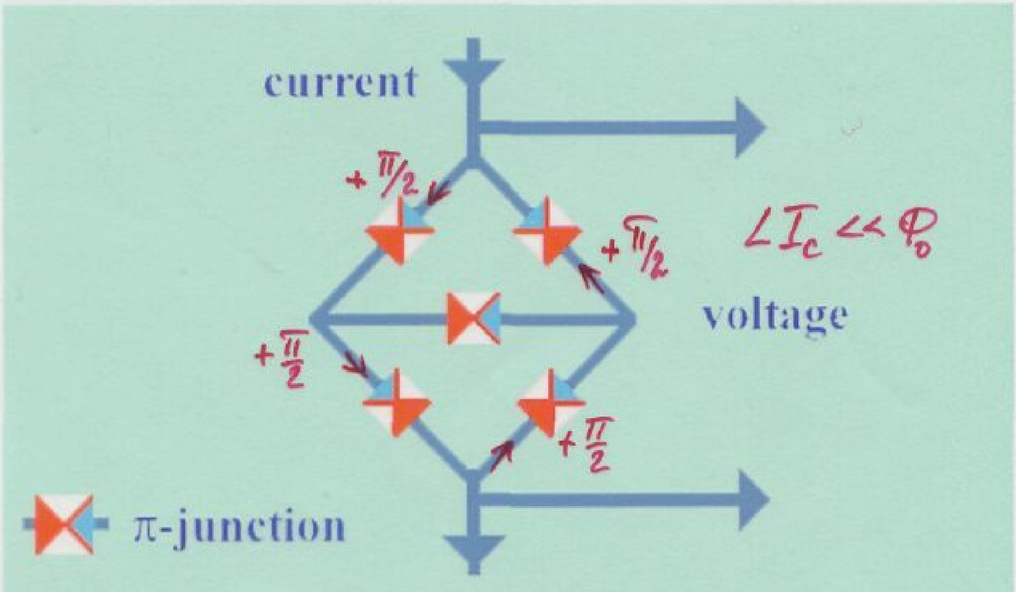
$I = I_c \sin(\varphi + \pi) = -I_c \sin\varphi$

Critical current vs temperature in Nb-$Cu_{0.43}Ni_{0.57}$-Nb SFS structures, d_F=15nm, sample 1 & sample 2

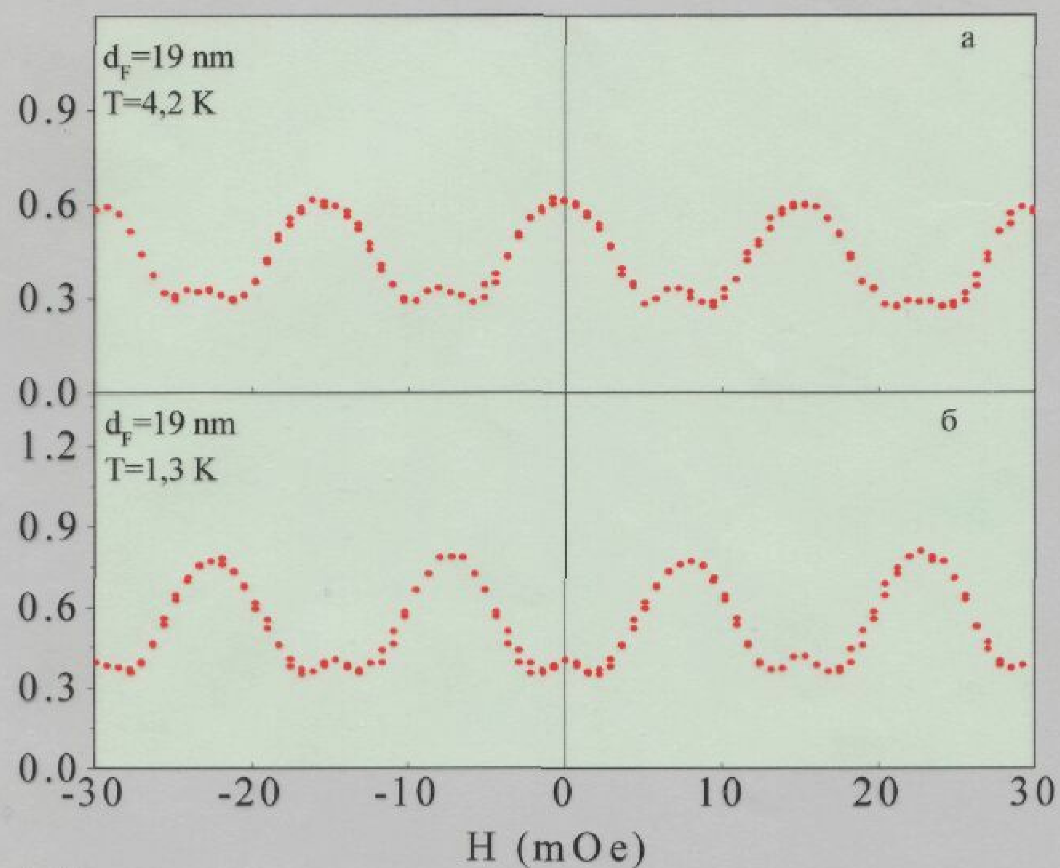


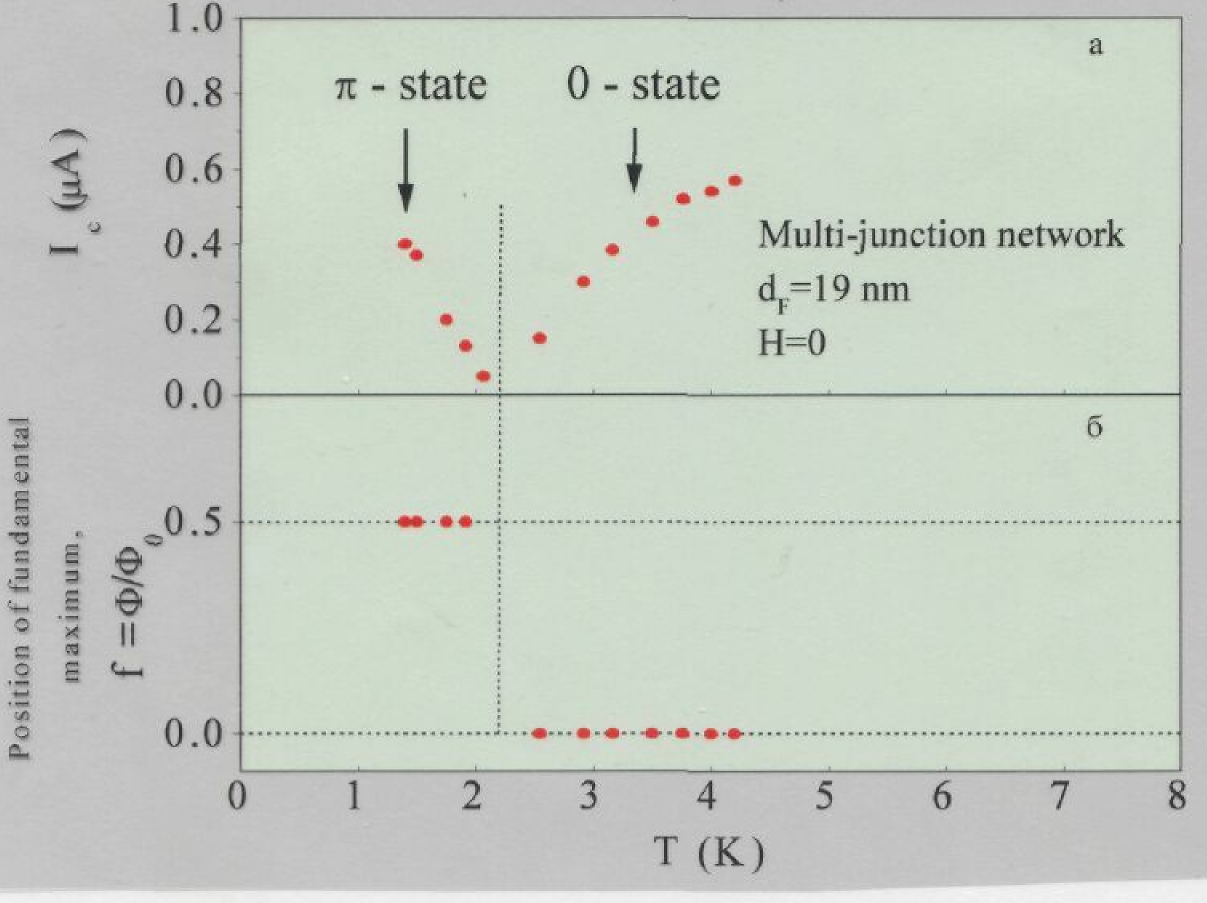

19.11.2001
$J_C(d_F)$, $Cu_{0.47}Ni_{0.53}$
T=4.2 K
j_c, A/cm²
d_f, nm
j_c, A/cm²
d_f (nm)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0,0
0,2
0,4
21
22
23
24
25
26
27

Triangular multi-π-junction network (Nb-$Cu_{0.46}Ni_{0.54}$-Nb junctions)



Multi-junction network





0-π bi-stability in magnetic field.

Two-contact interferometer with SFS junctions close to 0-π transition

$LI_c \sim \Phi_0$; $\Phi_e = \Phi_0/2$; $E = 2E_{J0} + LI_{sh}^2/2 = 2E_{J0} + \Phi_0^2/(4L)$

If one from the junction in π-state, and second one is in 0-sate:

$I_{sh} = 0$ and $E = E_{J\pi}$

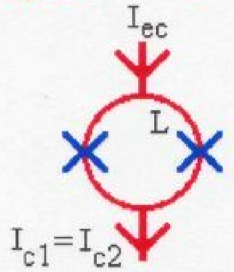
i.e. $I_{sh} = 0$ and $I_{ec} = max$ both for $\Phi_e = 0$ and $\Phi_e = \Phi_0/2$

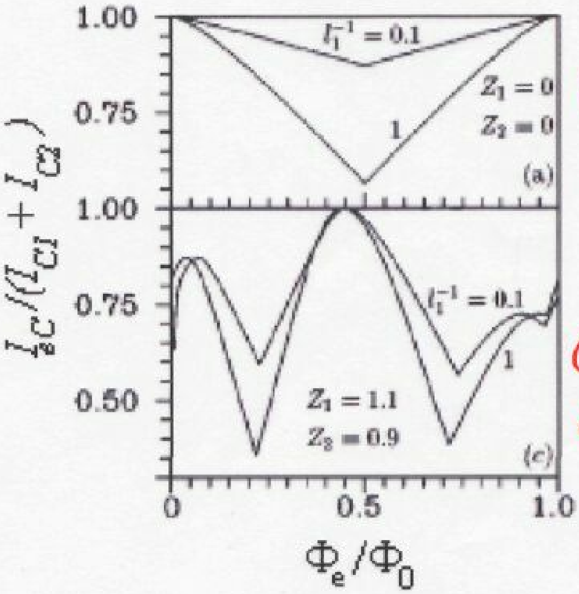
double-periodicity!!!

$\Delta\Phi = \Phi_0/2$

Close to π-transition free energy has two min: at $\varphi = 0$ and at $\varphi = \pi$ } $I = I_c \sin\varphi \rightarrow I = I_c \sin(2\varphi)$

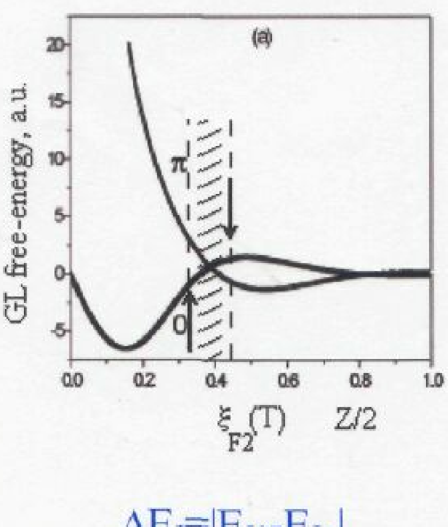
Proposition by Z.Radovic et al.
PRB 63,214512 (2001)





Far from 0-π-trans.

Close to 0-π trans.



$\Delta E_J = |E_{J0} - E_{J\pi}|$
is small

$l = 2\pi L i_c/\Phi_0$
is large enough

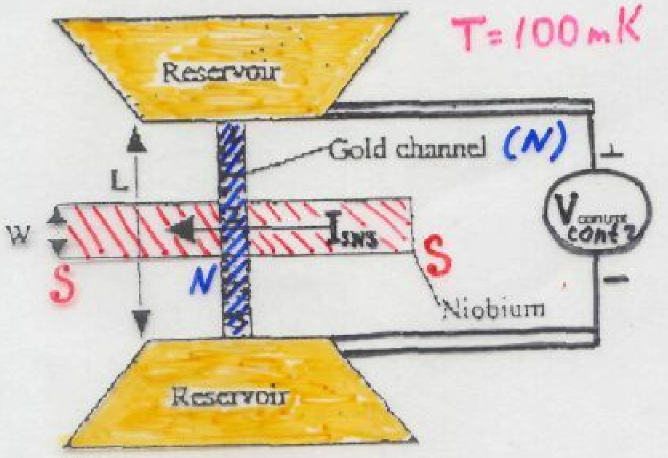
Mesoscopic SNS junction

Мезоскопические SNS-контакты, управляемые током через N-слой

А.Ф.Волков (1995)

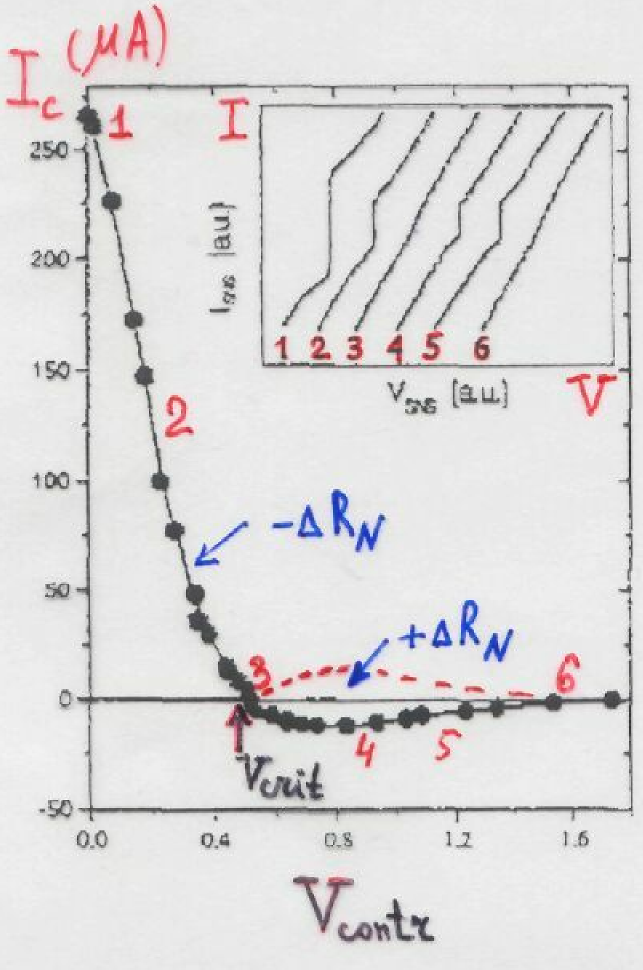
J.A.Baselmans, A.F.Morpurgo, B.J.van Wees, T.M.Klapwijk. Nature 397, *43 (1999)*

Напряжение на нормальном слое N меняет энергетическое распределение электронов и плотность токонесущих состояний, отвечающих за перенос сверхтока того или другого знака через N.



$V_{contr} > V_{crit}$

$I_{SNS} = I_c \cdot \sin\varphi \rightarrow I_c \sin(\varphi + \pi)$



Supercurrent reversal

= $I_c(V_{contr})$ oscillations

„0"- to „π"-junction crossover

Direct Observation of the Transition from the Conventional Superconducting State to the π State in a Controllable Josephson Junction

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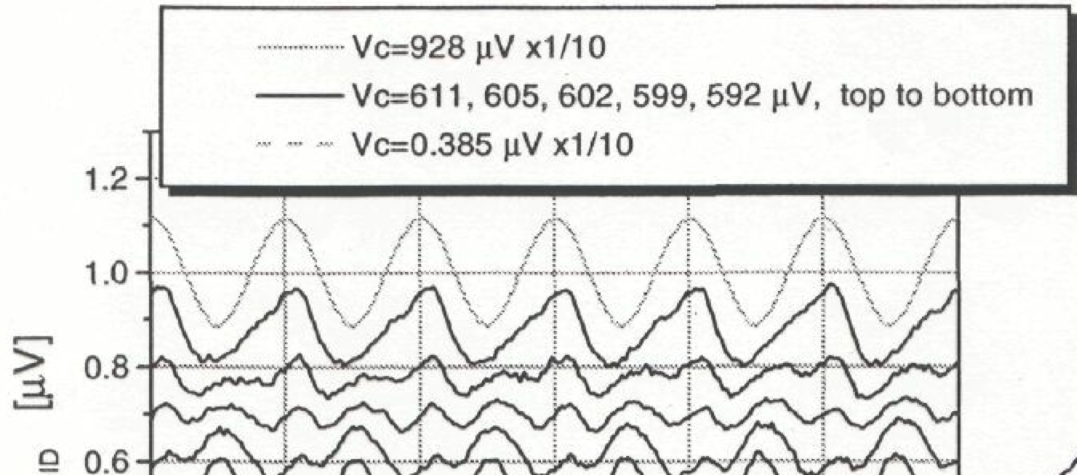


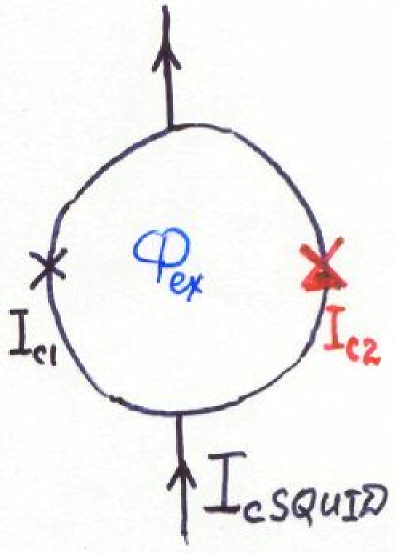


FIG. 2. Voltage over the SQUID (from contacts *A* to *B* in Fig. 1) at a bias current slightly larger than $I_{c,\mathrm{SQUID}}$ as a function of the ϕ_{ext} for different values of V_c. The amplitudes of the two grey curves are multiplied by 1/10. Around $V_{c,\mathrm{critical}} = 602\ \mu\mathrm{V}$, a doubling in periodicity of the voltage oscillations is observed.

$I_{c1} >> I_{c2}$

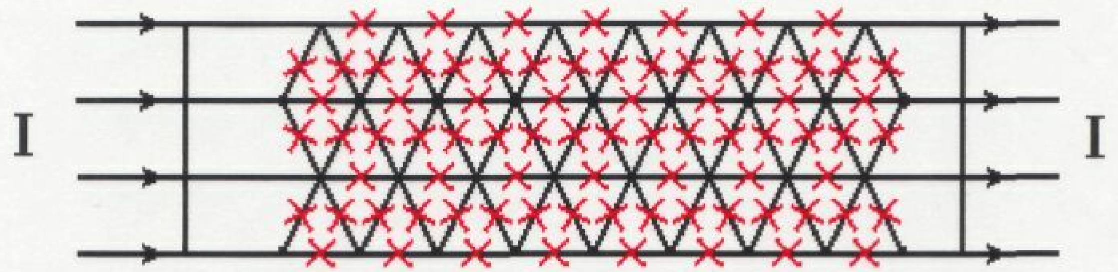
$I_{cSQUID} = I_{c1} + I_{c2}\left(\frac{\pi}{2} + 2\pi \frac{\Phi_{ex}}{\Phi_0}\right)$

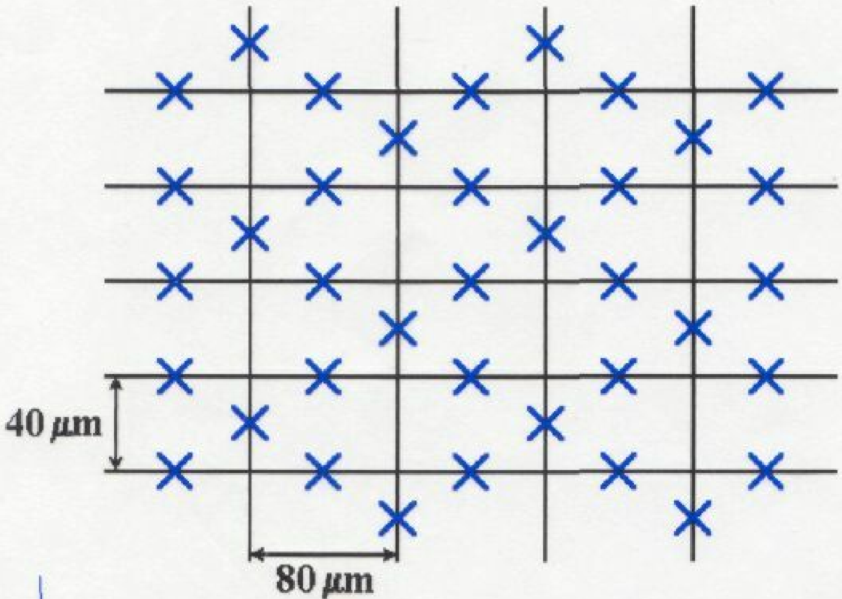
$T \approx T_\pi$ (our case) $V = V_c$

$I = I_c \sin\varphi \rightarrow I = I_c \sin 2\varphi$

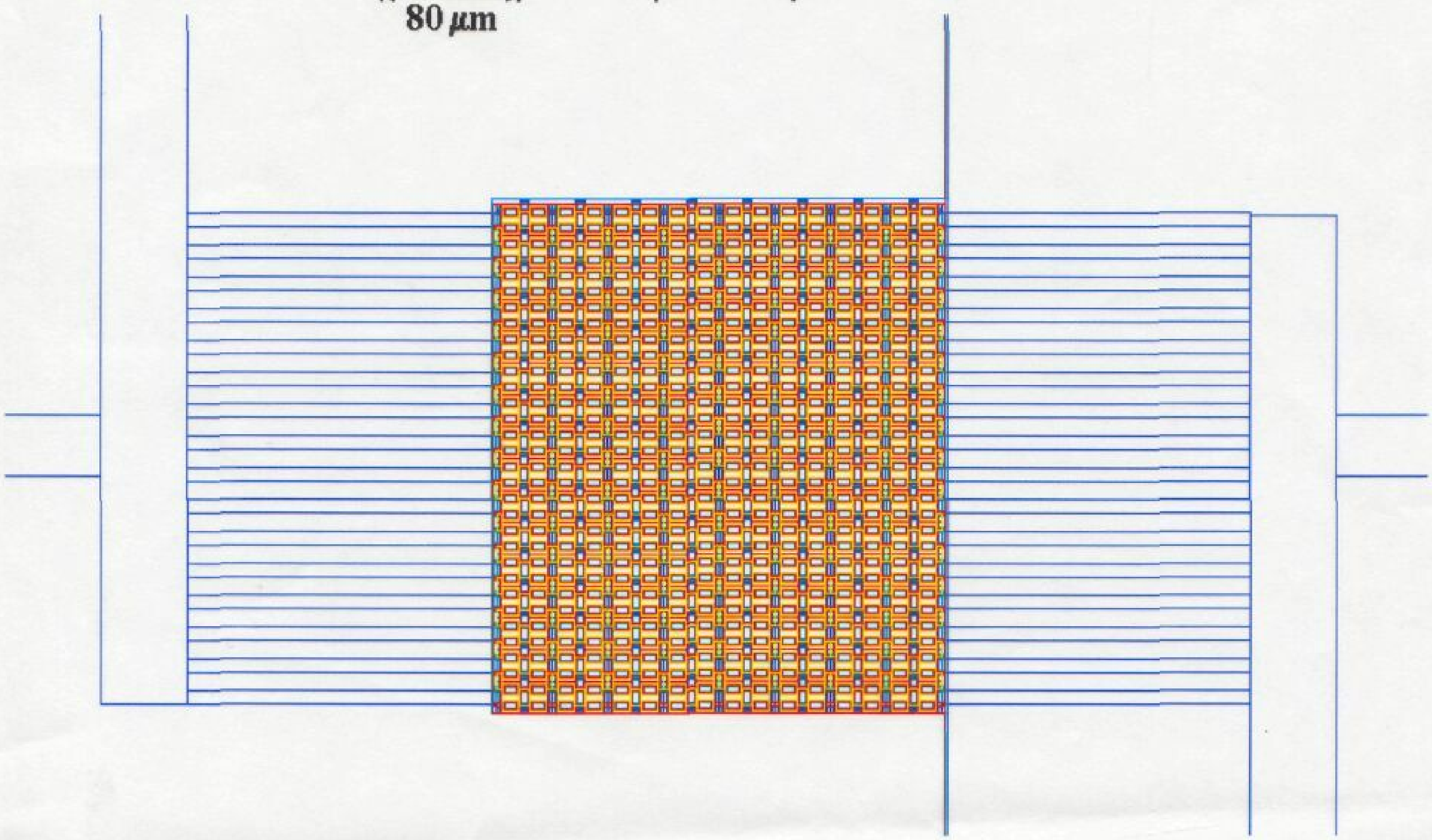
$I = I_c \sin(\varphi + \pi)$; $V > V_c$

Triangular n×m SFS junction array



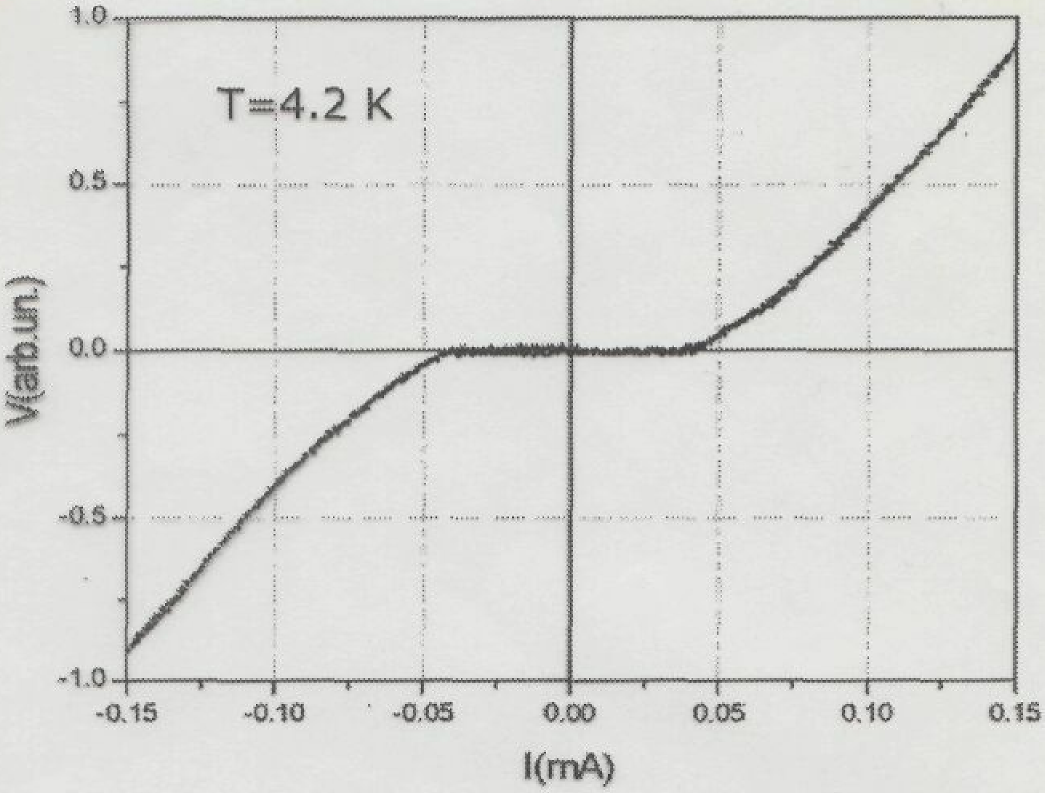


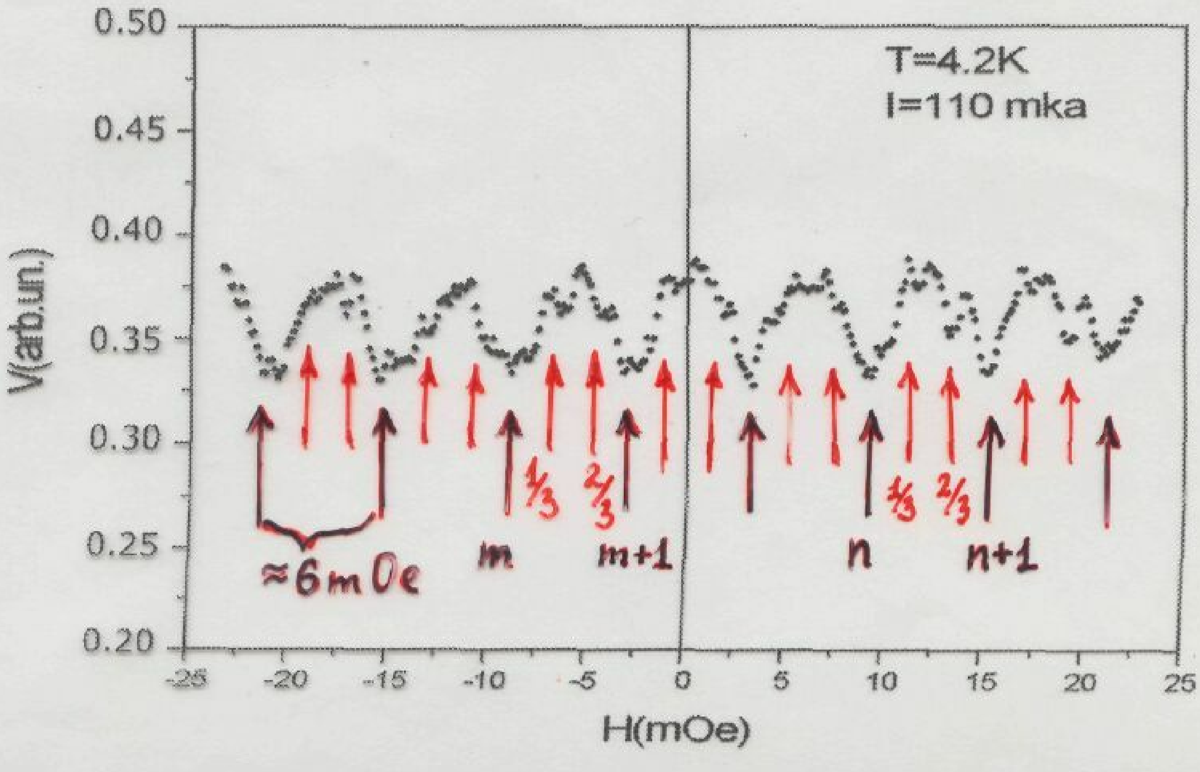
Quasi-triangular array 31×16



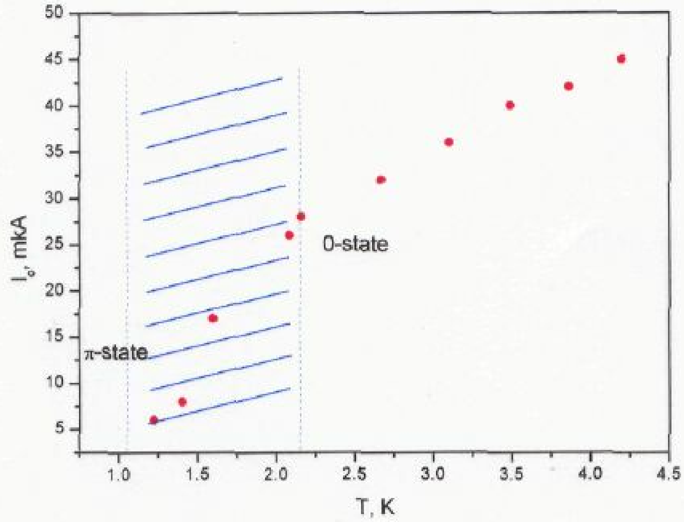
Triangular 31x16 SFS junction array

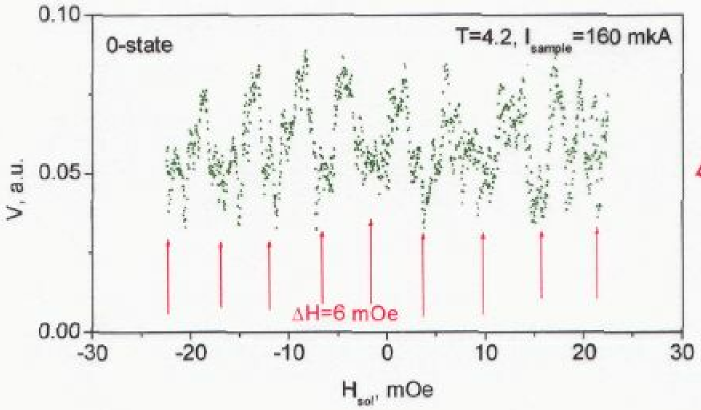
„0"-junction array. Far from „0-π" crossover!



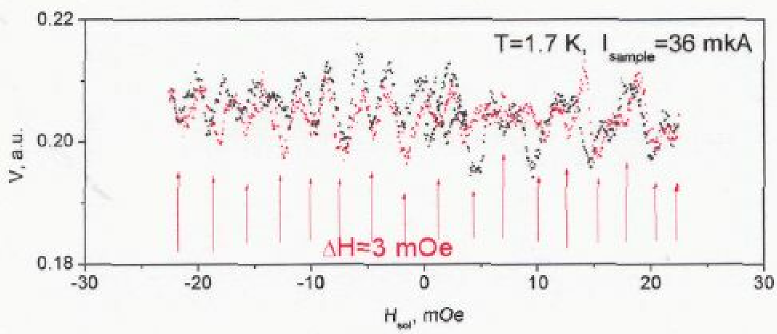


0-π bi-stability in SFS array
0-state close to 0-π-transition





$\Delta H_0 = \Phi_0 / S \approx 6\,mOe$

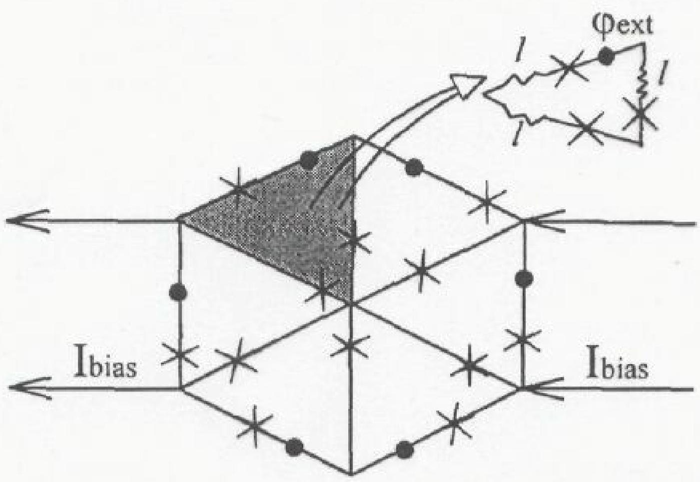


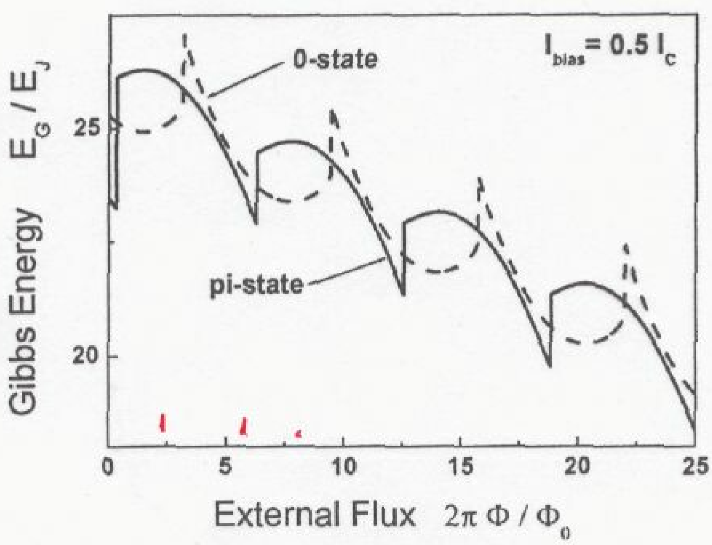
$\Delta H = \frac{1}{2} \Delta H_0$

"0"-π - transition in magnetic field

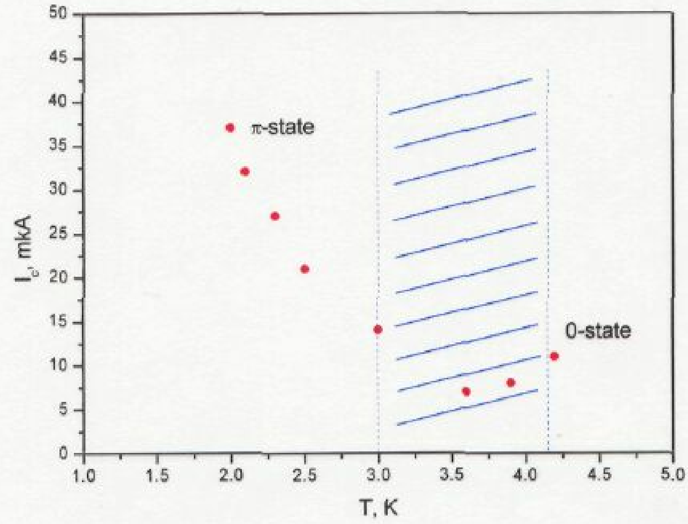
V.K.Kornev, N.V.Klenov

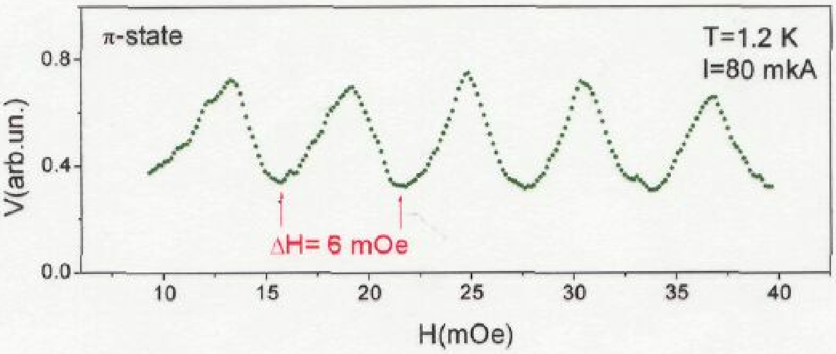
$$E_G=\Sigma E_{iJ}+\Sigma\Phi_j^2/(2L) - [\Phi_0/(2\pi)]\,\Sigma(I_b\,\varphi)$$

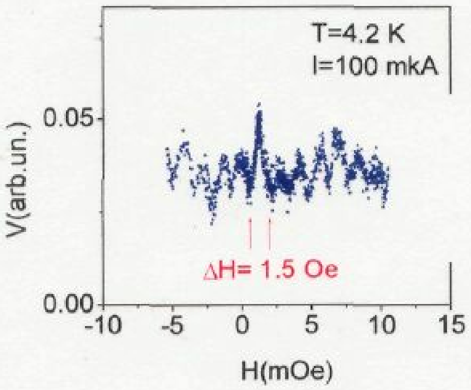




0-π bi-stability in SFS array
π-state close to 0-π-transition







$\Delta H = \frac{1}{4} \Delta H_0$

„Checkerboard state" in triangular array of π-junctions ?

$f = 1/4$!