Mechanisms of 0-p transition in SFS Josephson junctions

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Outline

p –junctions:

general properties and possible applications

- **Proximity effect in ferromagnet-superconductor (FS) structures**:

  oscillating nature of the order parameter in F

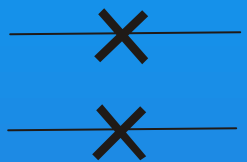
- **Mechanisms of 0- p transitions in SFS junctions**:

  theory and experiment

- **Complex current-phase relations SFcFS point contacts:**

  theory

Fundamental equations for ‘0’ and ‘p’ junction

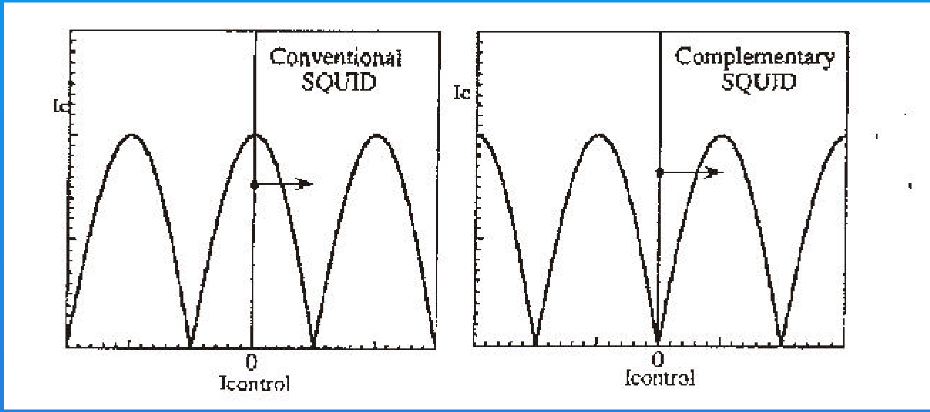


$J = J_{c0}\sin\varphi$

$J = J_{c\pi}\sin\varphi$

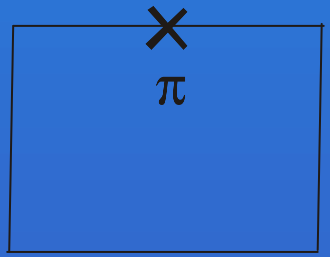
π

$J_{c\pi} = -J_{c0}$



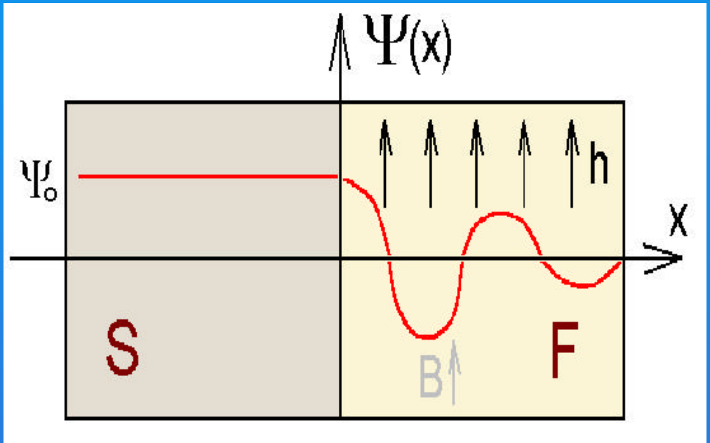
Bulaevskii et al (1977):
Possibility of spontaneous flux in the loop

$$J = \sqrt{J_{c0}^2 + J_{cp}^2 + 4J_{c0}J_{cp}\cos^2\frac{p\Phi}{\Phi_0}}$$

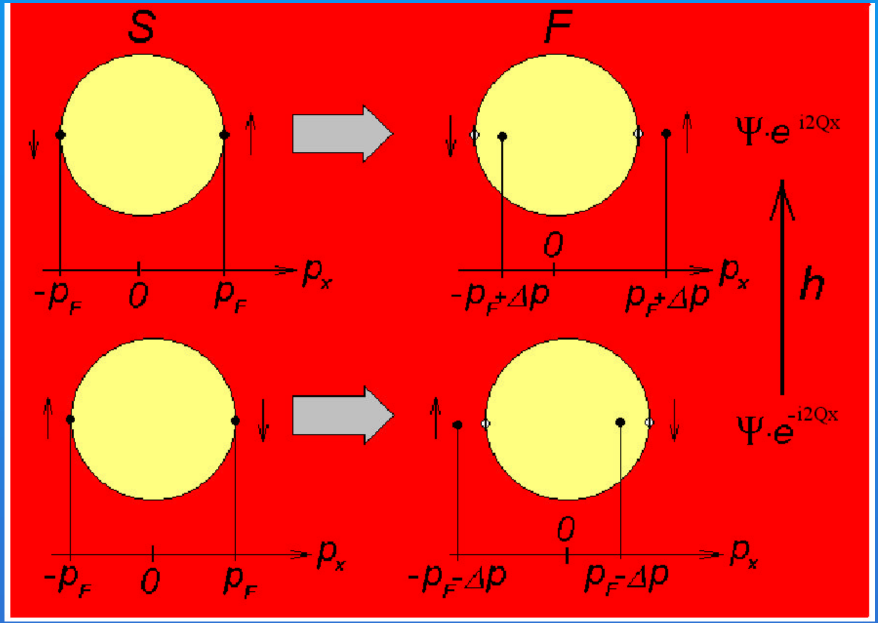


Beasley et al (1998), Blatter et al (2000): proposals for application of p-juncitons in RSFQ and qubit structures

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



Buzdin & Kupriyanov (1991)
Radovic' *et al.* (1991)



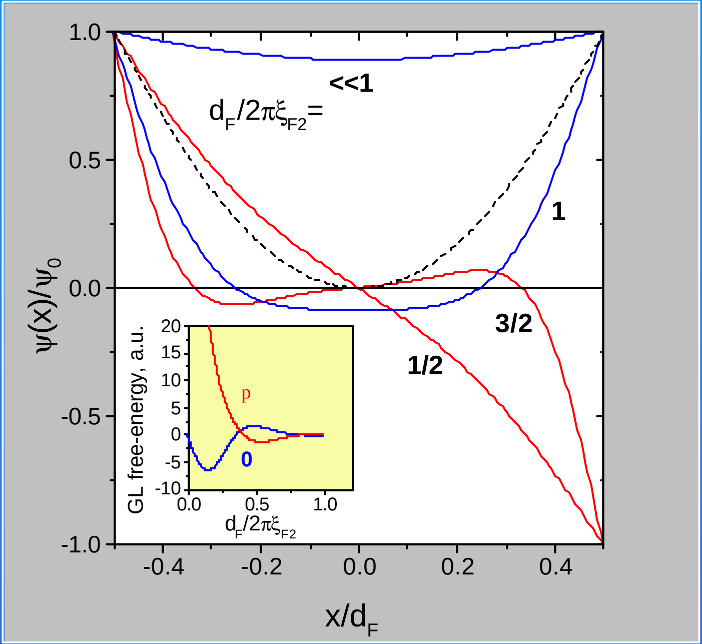
? (x) = ? $_0$ *cos*(2Qx)

Q ~ E_{ex}/v_F is center of pair mass momentum

Demler, Arnold & Beasley (1997)

LOFF state in *SFS* Josephson junction

The spatial distribution of the order parameter in the F-layer of the SFS junction calculated for various $d_F/2\pi\xi_{F2}$ ratios



The inset shows calculations of Ginzburg-Landau (GL) free-energy in the F-layer for the 0- and p-phase states. Ginzburg-Landau free-energy consists of negative condensation energy (~ Y^2) and positive gradient energy ({ grad Y }^{2}).

red lines – p state favorable
blue lines – 0 state favorable

Spatial dependence of the order parameter in the F-layer

$$\Psi_{GL} = \Psi_0 \exp(-\frac{x}{x_1}) \exp(-i\frac{x}{x_2})$$

Spatial oscillations of the order parameter in a ferromagnet: formal description

Larkin-Ovchinnikov-Fulde-Ferrel (LOFF) state in a ferromagnet: complex coherence length

$$\Psi = \Psi_0 e^{-x/x_F} \qquad x_F = \left[\frac{D_F}{2(pk_B T + iE_{ex})} \right]^{1/2} = x_{F1} + i x_{F2}$$

$$x_{F1,2} = \left[\frac{D_F}{\left[(pk_B T)^2 + E_{ex}^2 \right]^{1/2} \pm pk_B T} \right]^{1/2}$$

Supercurrent across the SFS junction

$$J_s(j) \sim \Psi \nabla \Psi^* - \Psi^* \nabla \Psi \quad \sim \quad \Psi_0^2 e^{-d_F/x_{F1}} \sin(d_F / x_{F2}) \sin j$$

the oscillation period x_{F2} decreases with decreasing T, thus 0 -> p crossover is possible for fixed F-layer thickness with variation of T

Quasiclassical theory:
linearized Usadel equations (dirty limit)

Supercurrent is given by

$$J_s(j) = ieN_F(0)D_F pT \sum_{n=-\infty}^{n=\infty} (F(w_n)\nabla F^*(-w_n) - F^*(-w_n)\nabla F(w_n))$$

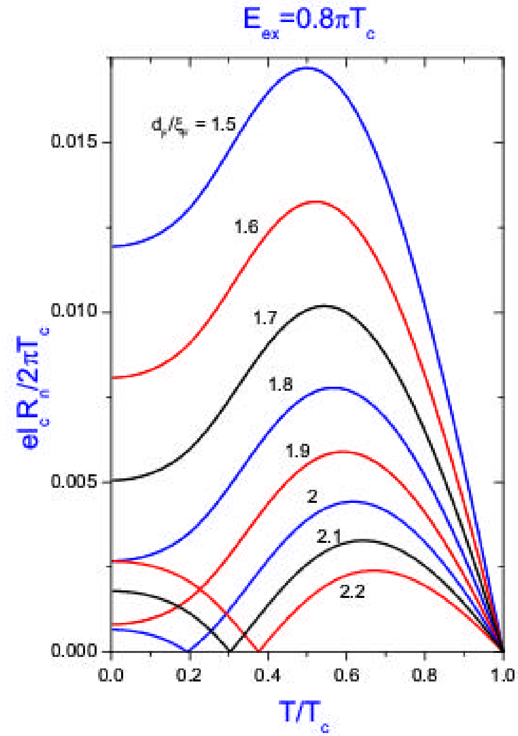
Functions F have spatial scale

$$x_F(w_n) = \sqrt{\frac{\hbar D_F}{2(w_n + iE_{ex})}}, \quad w_n = pT(2n+1)$$

The resistivity parameter of SF interfaces
(assumed large in this calculation)

$$g_B = \frac{2}{3}\frac{l_F}{x_F}\left\langle \frac{1-D}{D} \right\rangle >> 1$$

$$\tilde{d}_F = d_F / x_F$$

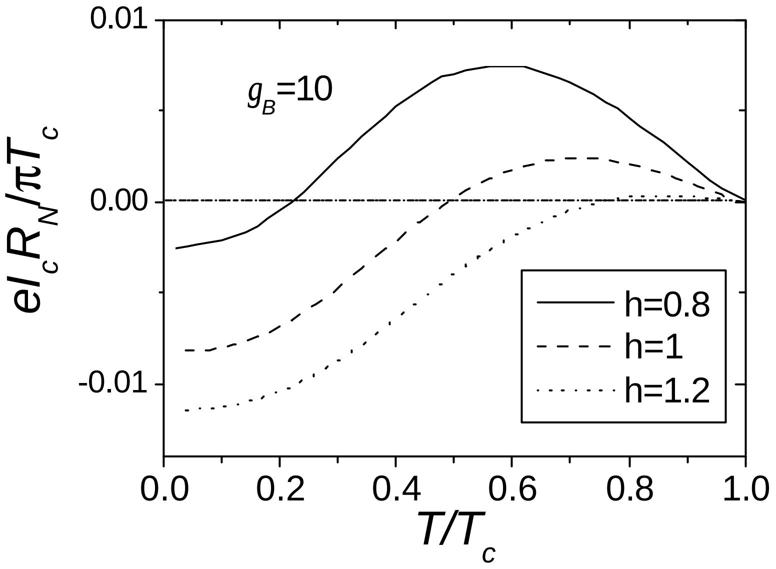


$$I_S = \frac{4\pi T}{eR_N}\frac{d_F}{\gamma_B \xi_F} \mathrm{Re} \sum_{\omega>0} \frac{\Delta^2 \sin(\varphi)}{(\omega^2 + \Delta^2)\tilde{d}_F \sinh \tilde{d}_F}$$

Selfconsistent theory

Nonlinear Usadel equations are solved numerically,

no limitation for layer thicknesses and barrier resistivity



SFS junction:

$$h = E_{ex}/pT_C$$

$$d_F = 2x_F$$

$$g_B = \frac{2}{3}\frac{l_F}{x_F}\left\langle\frac{1-D}{D}\right\rangle = 10$$

0 - π crossover at low T

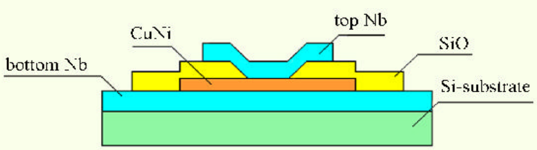
Experimental realization of SFS junctions:

V.Ryazanov *et al.*, Chernogolovka, Russia
J. Aarts, Leiden

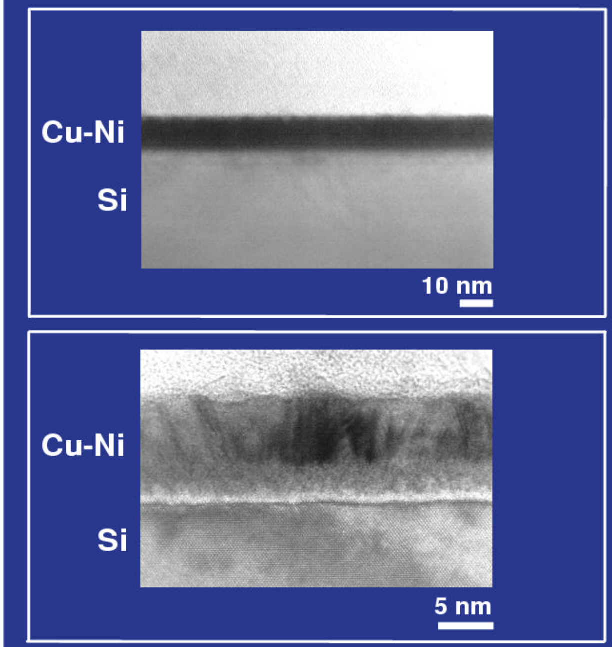
Samples fabrication

- *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

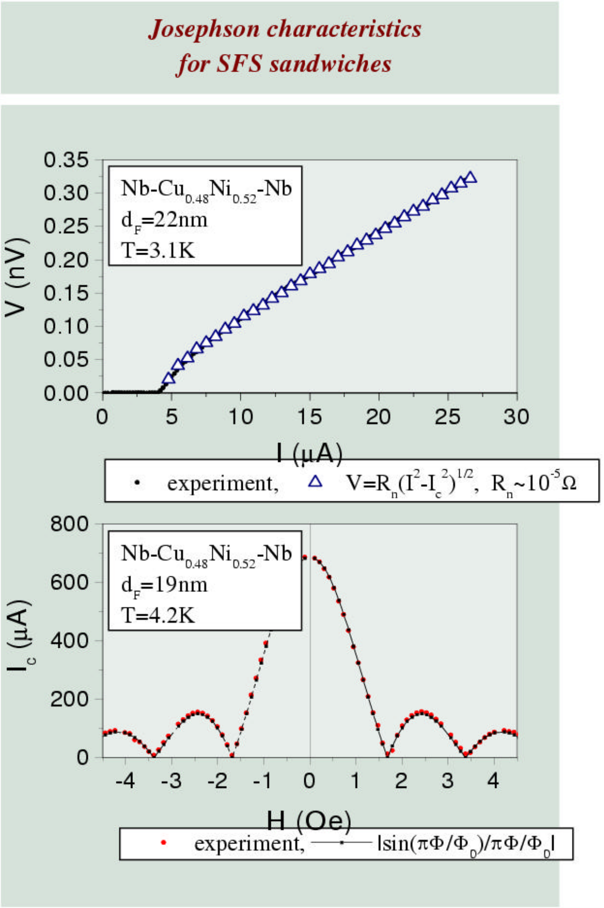


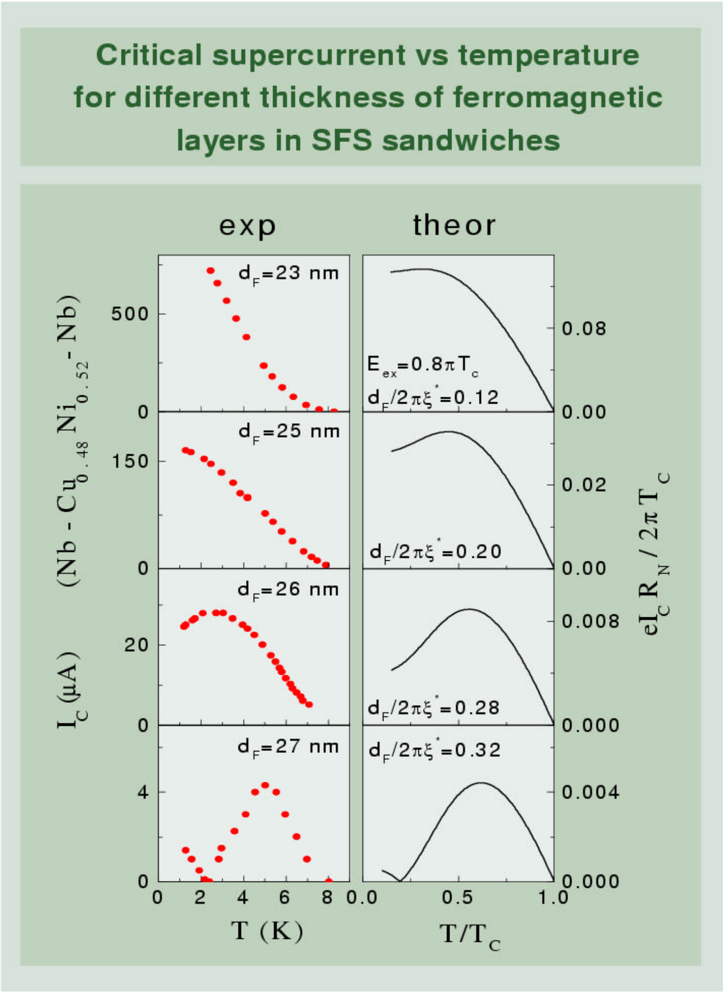
Cross-sectional TEM micrograph of $Cu_{0.43}Ni_{0.57}$ film on Si-substrate



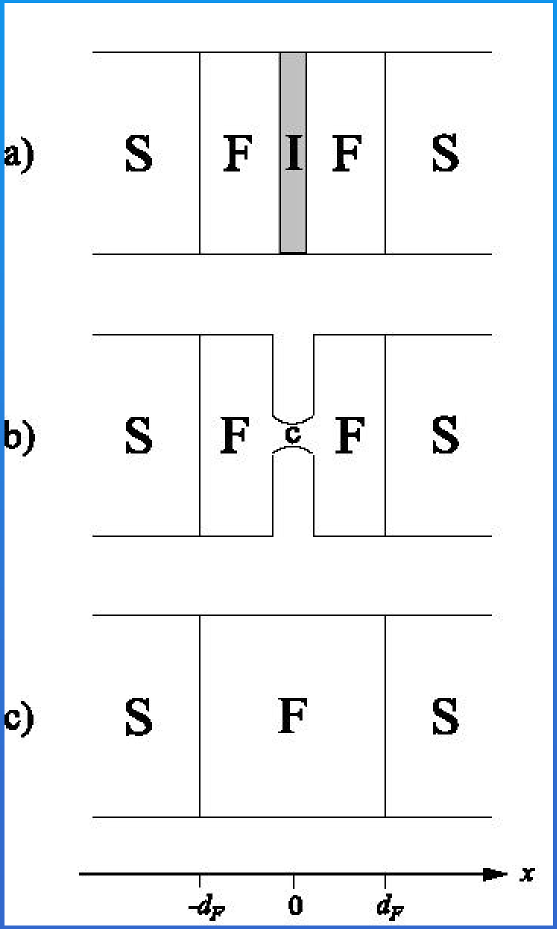
0 - p transition in SFS junctions: theory and experiment

V.Ryazanov, V.Oboznov, A.Rusanov,A.Veretennikov, A.Golubov, and J.Aarts, PRL 86, 2427 (2001)





Different junction geometries

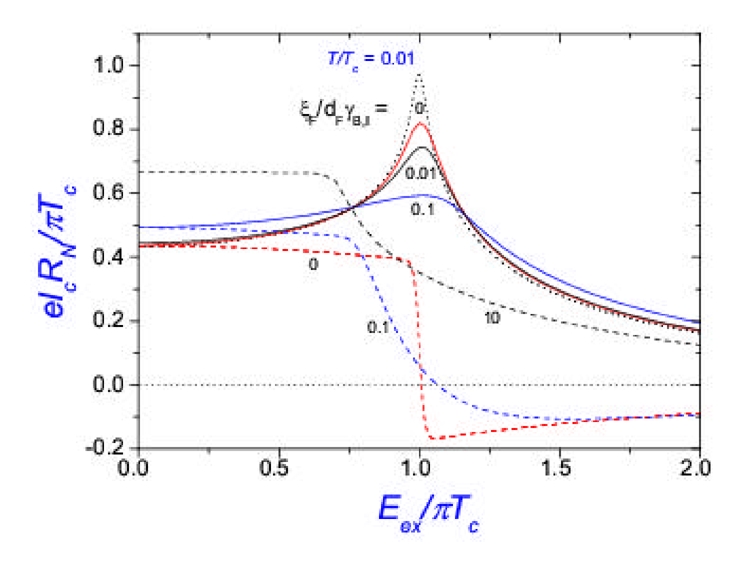


a) planar SFIFS tunnel junction

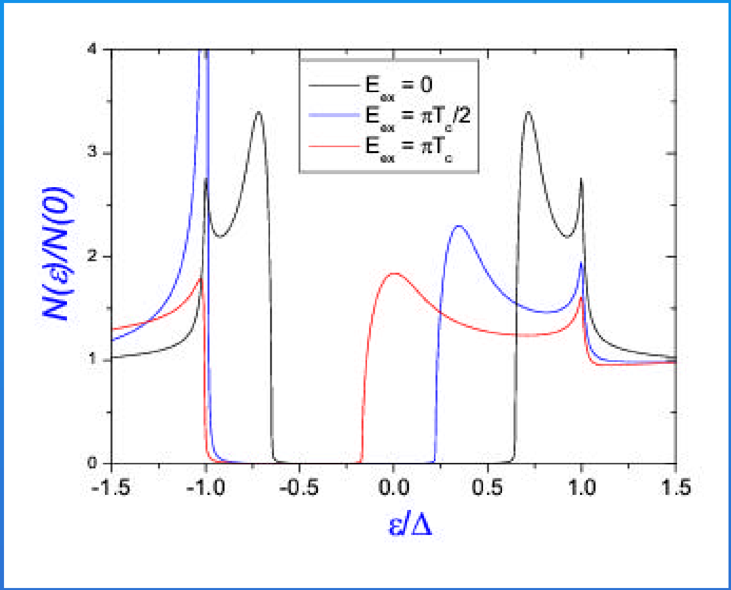
b) SFcFS point contact (ballistic or diffusive)

c) planar SFS double barrier junction

SFIFS junctions with thin F-layers

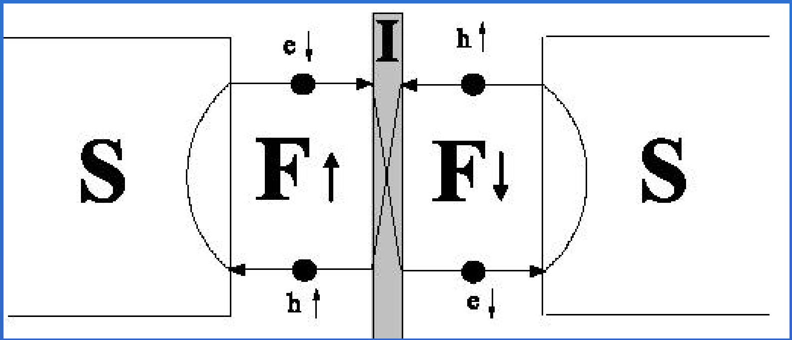


the mechanism of Ic enhancement:
DoS splitting by an exchange field

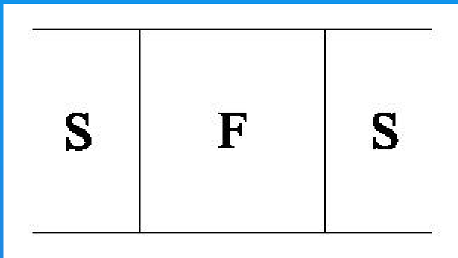


Solid lines: Ic enhancement for ***antiparallel magnetizations***, Bergeret *et al*, Schelkachev *et al (2001*)

Dashed lines: 0- π transition for ***parallel magnetizations*** due to phase shift π/2 at each SF interface



Phase rotation at the SF interface



Green's function in SF bilayer

$$\Phi_F = \frac{\tilde{\omega}\Phi_S G_S}{\omega\left(G_S + \tilde{\omega}\gamma_{BM}/\pi T_C\right)}, \quad \gamma_{BM} = \gamma_B \frac{d_F}{\xi_F}.$$

$$\chi = \frac{1}{2}\arctan\frac{q}{p} + \frac{\pi}{4}(1 - \operatorname{sgn} p)\operatorname{sgn} H,$$

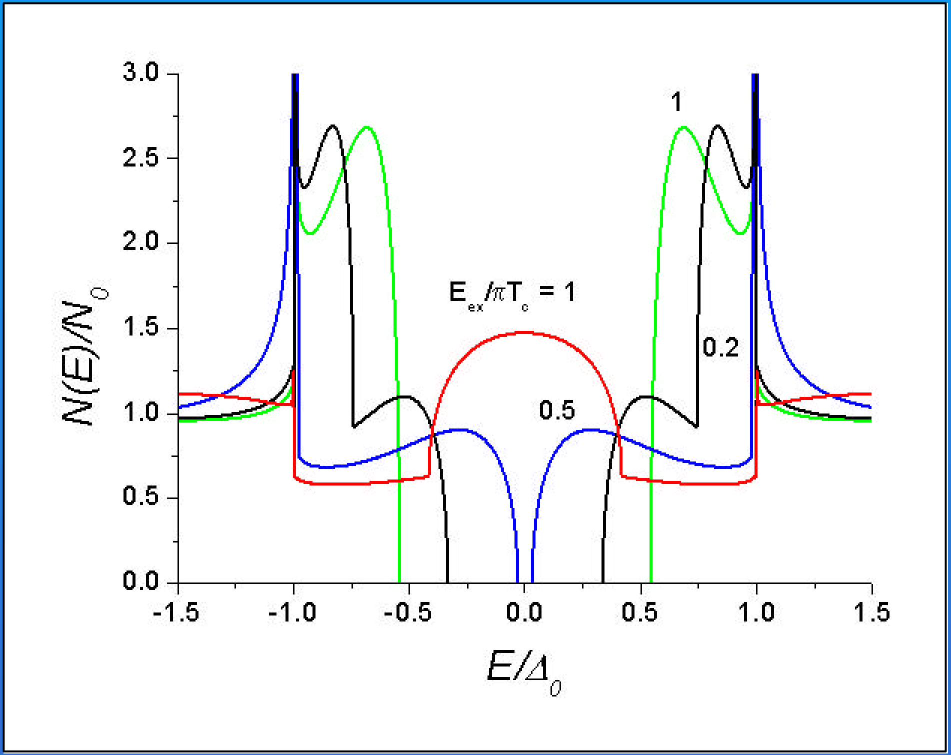
where

$$p = 1 + \frac{\omega^2 - H^2}{(\pi T_C)^2}\gamma_{BM}^2 + 2\frac{\omega^2\gamma_{BM}}{\pi T_C\sqrt{\omega^2 + \Delta_0^2}},$$

$$q = 2\gamma_{BM}\frac{H\omega}{\pi T_C}\left(\frac{\gamma_{BM}}{\pi T_C} + \frac{1}{\sqrt{\omega^2 + \Delta_0^2}}\right).$$

p/2 phase shift at the SF interface occurs at large H

Oscillating density of states in a ferromagnet



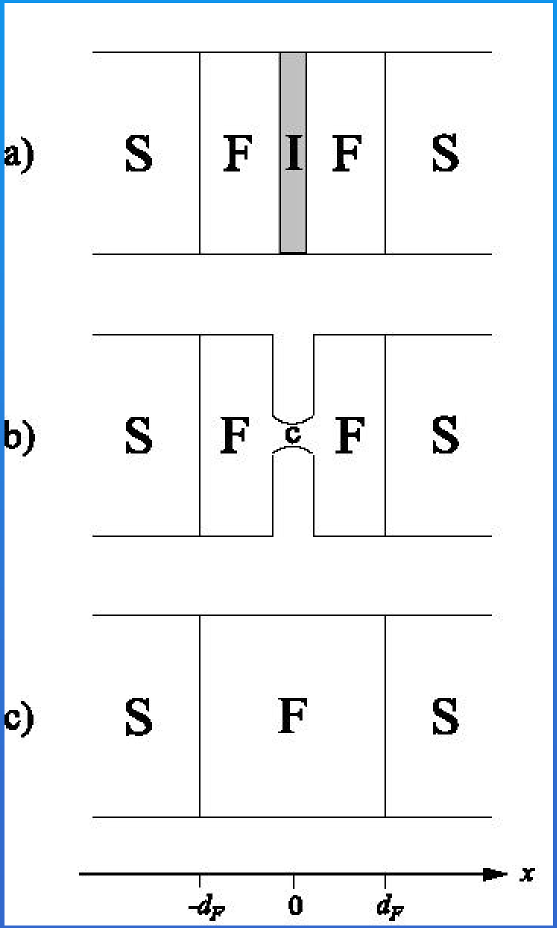
Thin F layer
DoS for both spin direction

- DoS is splitted with increase of exchange energy

(b) Zero energy DoS oscillates as a function of exchange energy

DoS oscillations also take place as a function of coordinate
Theory: Buzdin (2000), Zareyan *et al* (2001)
Experiment: Kontos *et al* (2001)

Current-phase relations in SFS: high transparency



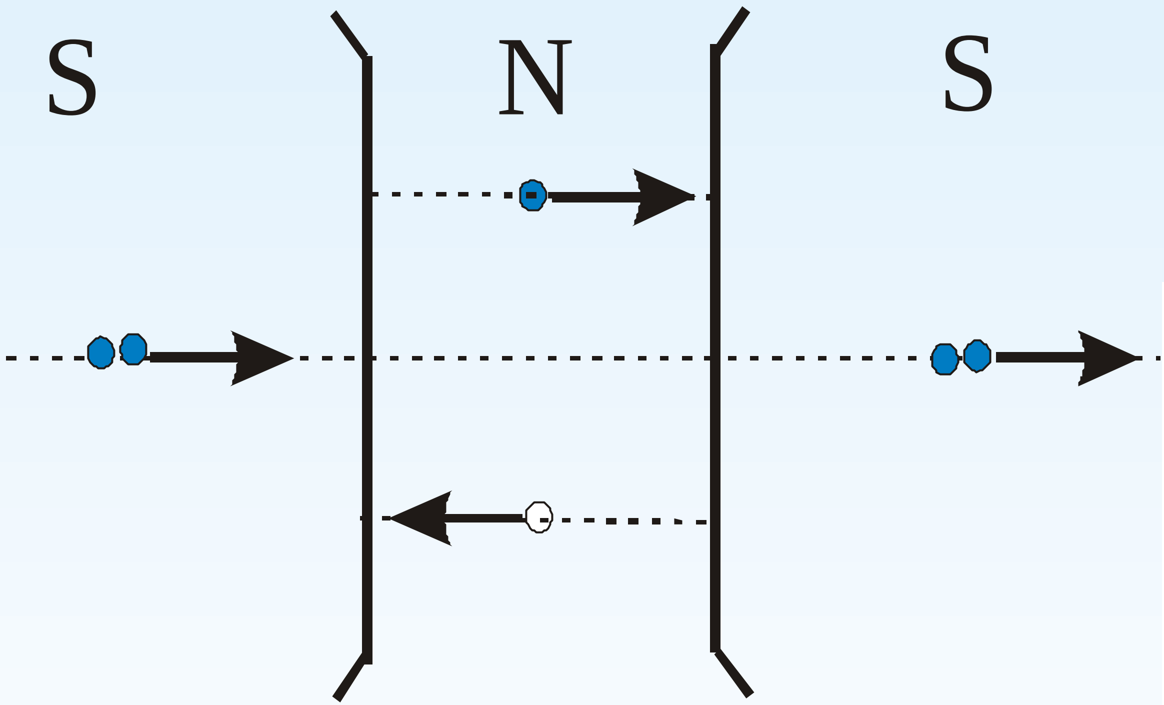
Consider the cases

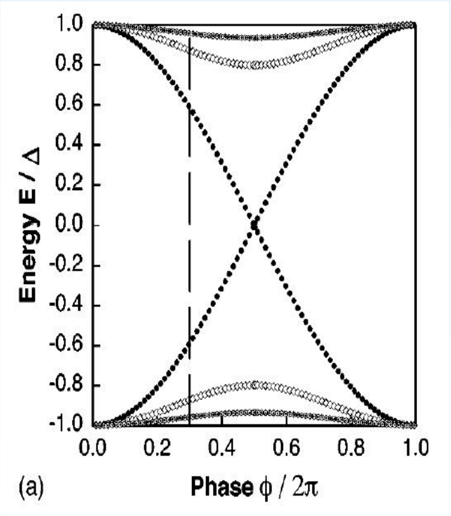
(b) SFcFS point contact (ballistic or diffusive)

c) planar SFS double barrier junction

(SFIFS)

Andreev Bound State





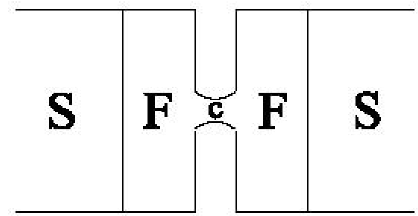
Andreev bound state energy

$$E_B = \Delta\sqrt{1 - D\sin^2\varphi/2}$$

Current-phase relations in more complex geometry:
ballistic SFcFS junction

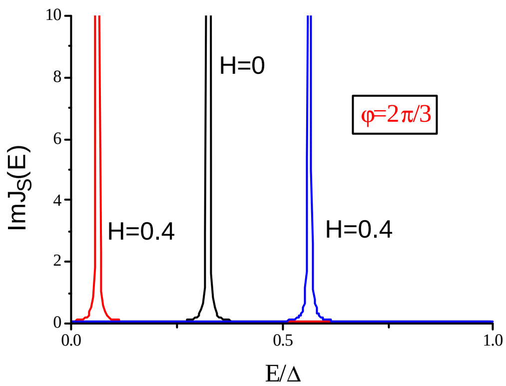
$$J_S = \frac{4pT}{eR_N} \mathrm{Re} \sum_{w>0} \frac{\Delta^2 \sin j}{D^{-1}(W^2+\Delta^2) - \Delta^2 \sin^2 j/2}, \qquad g_{BM} = g_{BM} d / x_F$$

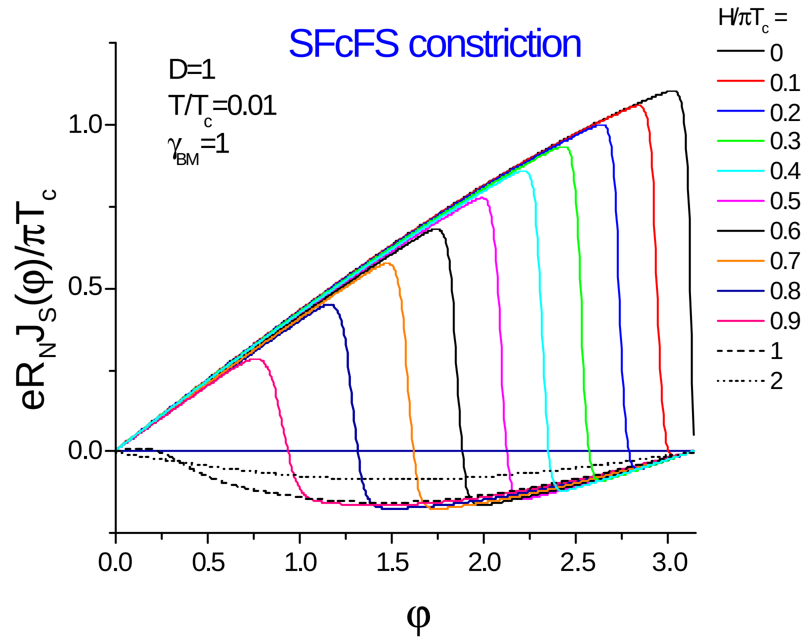
$$W = w + g_{BM}\sqrt{w^2+\Delta^2}(w+iH),$$



Andreev bound state splitting

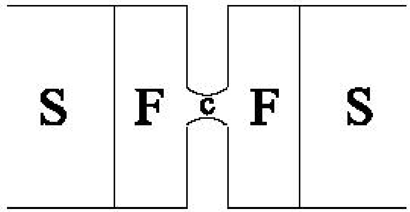
$$E_B = \Delta\sqrt{1 - D\sin^2 j/2}, \quad H = 0$$





$$E_B \text{ crosses zero at } j_C = 2\arcsin\sqrt{[1-(H/pT_c)^2]/D}$$

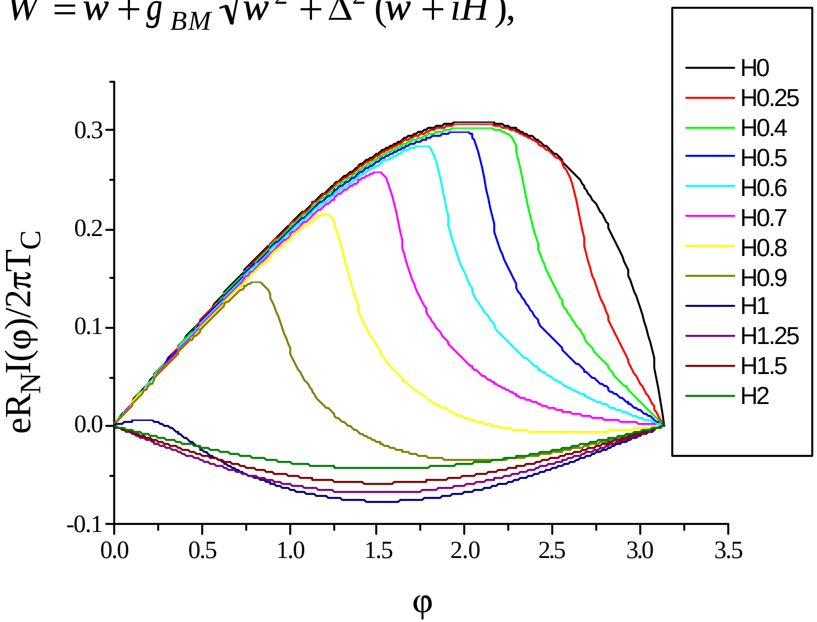
Diffusive SFcFS junction

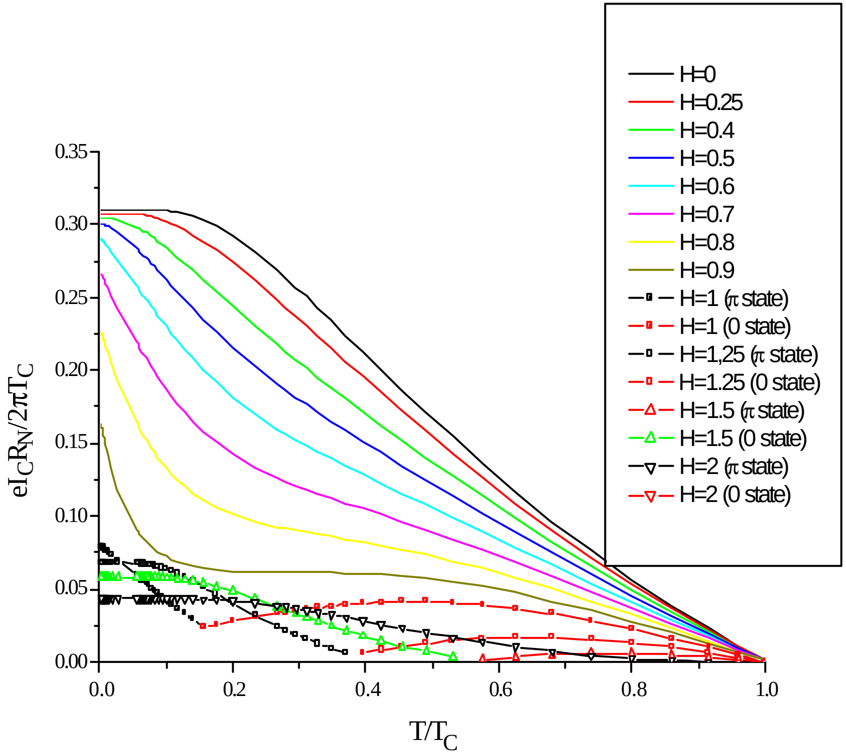


$$J(j) = \int_0^1 r(D) J_S(D) dD, \quad r(D) = 1/2D^{-1}(1-D)^{-1/2} - Dorokhov \quad density \quad function$$

$$J_S = \frac{4pT}{eR_N} \mathrm{Re} \sum_{w>0} \frac{\Delta \cos j/2}{R} acr \tan \frac{\Delta \cos j/2}{R}, \quad R = \sqrt{W^2 + \Delta^2 \cos^2 j/2}$$

$$W = w + g_{BM}\sqrt{w^2 + \Delta^2}(w + iH),$$

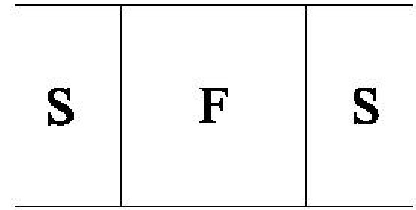




Current reversal is weaker than in ballistic case due to admixture of closed channels (D<1)

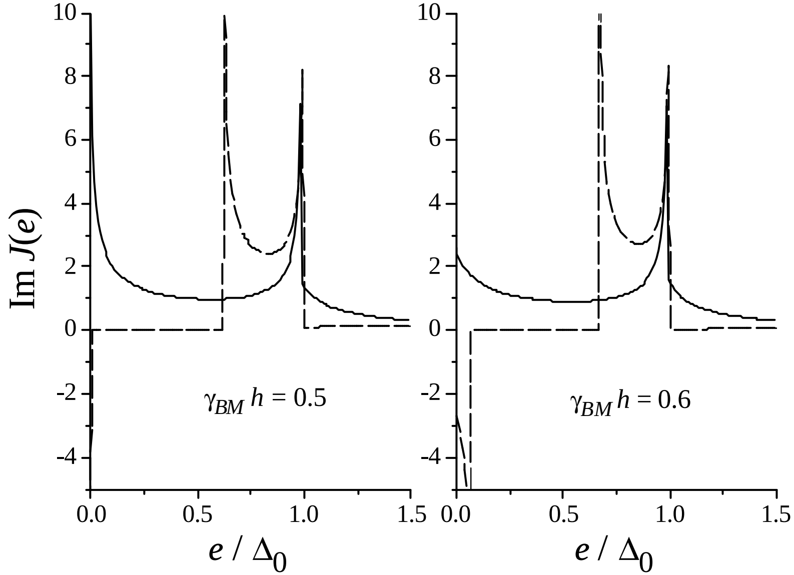
Reentrant behavior of Ic(T) minimum Ic is not zero

Double barrier SIFIS junction

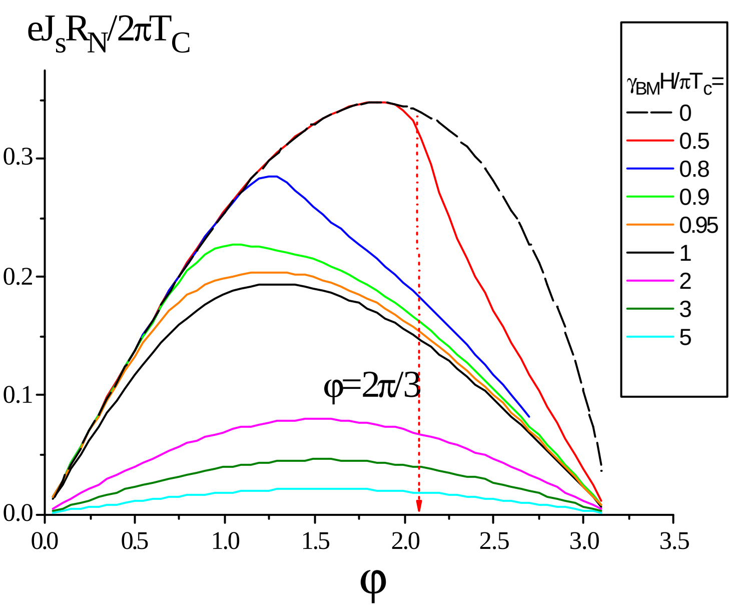


From solution of Usadel eqs $J_S = \frac{2\pi T}{eR_N} \mathrm{Re} \sum_{\omega>0} \frac{\Delta^2 \sin\varphi}{\sqrt{\omega^2+\Delta^2}\sqrt{W^2+\Delta^2\cos^2\varphi/2}}, \quad W = \omega + \gamma_{BM}\sqrt{\omega^2+\Delta^2}(\omega + iH)$

Spectral supercurrent



Current-phase relation

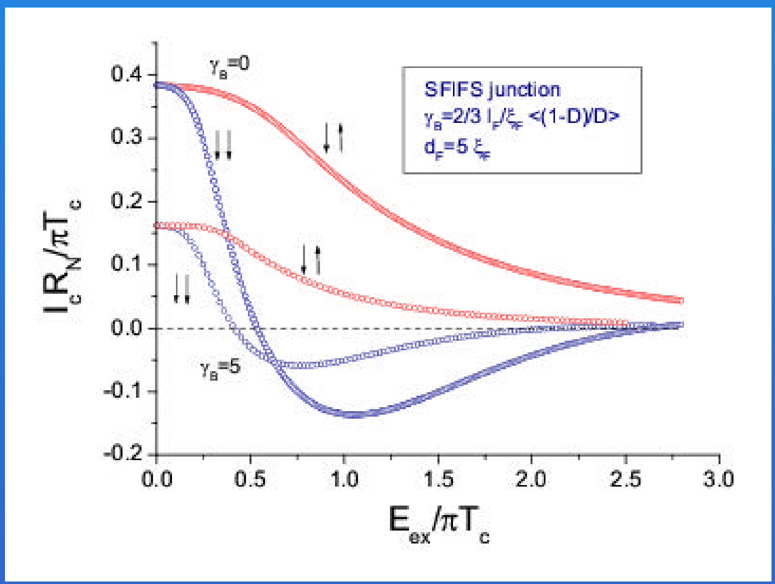


Supercurrents in multiterminal SF structures

Selfconsistent solution of Usadel equations:

no limitation for layer number, thicknesses and barrier resistivity

0 - p switching in multiterminal SF structures



Parallel orientation:
equivalent to a single SFS junction,
0 - π crossover with increasing E_{ex}

Antiparallel orientation:
order parameter oscillations
nearly compensated

Summary

The mechanisms of 0-p transition in SFS Josephson junctions:

- oscillating order parameter in a ferromagnet
- p/2 phase shifts at the SF interfaces in SFS junctions

SFS point contacts:

complex current-phase relations (mixture of 0 and p-states)

Multiterminal SF…FS structures:

0-p switching for parallel/antiparallel magnetization orientations

We thank V. Ryazanov, J. Aarts and A. Rusanov for stimulating discussions and communication of their experimental data