Современное состояние в сверхпроводниковой спинтронике

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Квантовой наноэлектроники

Наноэлектроника квантовых сверхпроводящих систем

* Теория сверхпроводимости

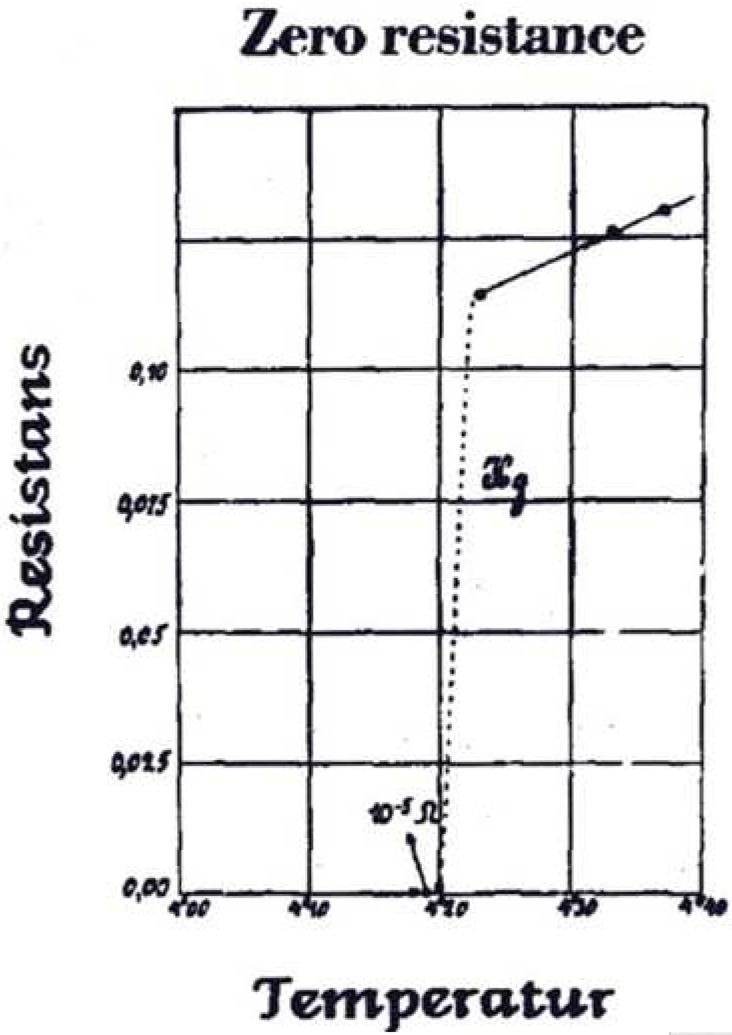
* Макроскопическое квантовое туннеллирование (эффект Джозефсона)

* Антагонизм и сосуществование сверхпроводимости и магнетизма

* Триплетная сверхпроводимость

* Квантовые свойства нанообъектов для вычислительных систем

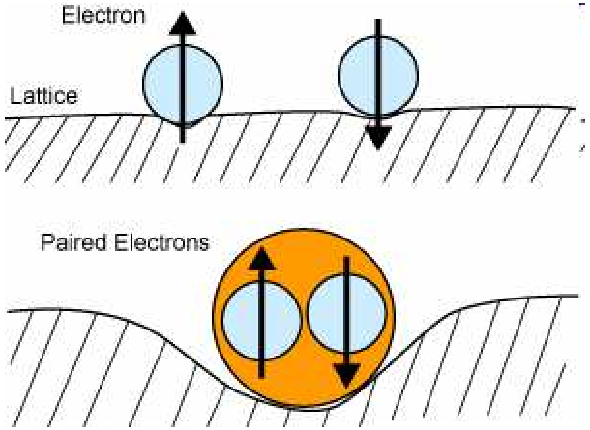
Сверхпроводимость



1913

1972

BCS theory: Electron phonon attraction



Fermi surface in the momentum space

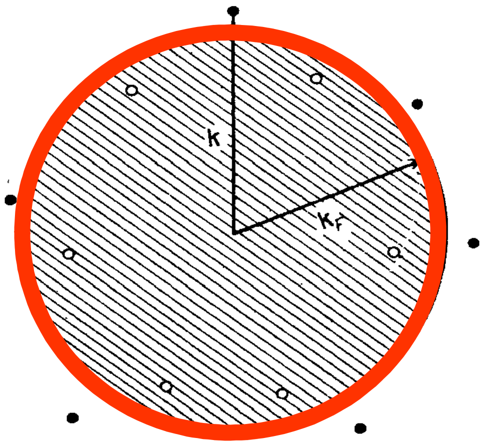
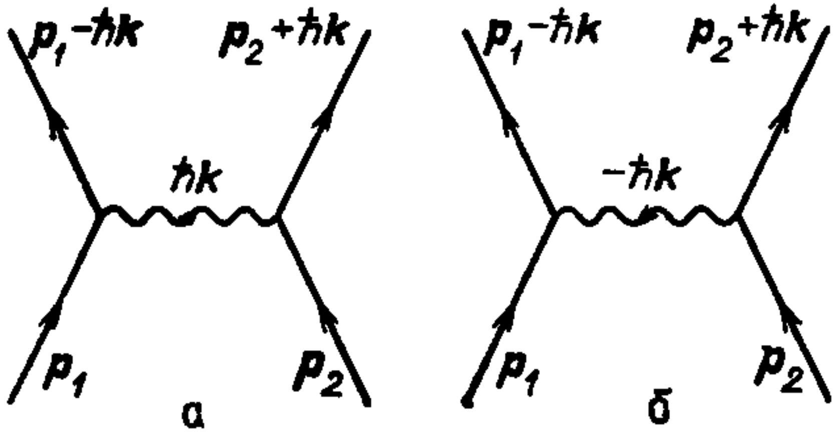


Рис. 3. Типичная возбужденная конфигурация нормального состояния.

Квазичастичные возбуждения — заполненные состояния над поверхностью Ферми и дырки под поверхносью Ферми.

Elementary excitations

e-e attraction is due to exchange of 'virtual phonons'

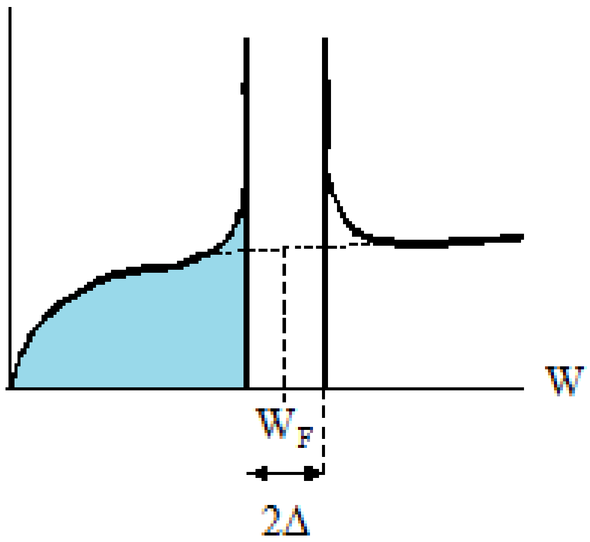


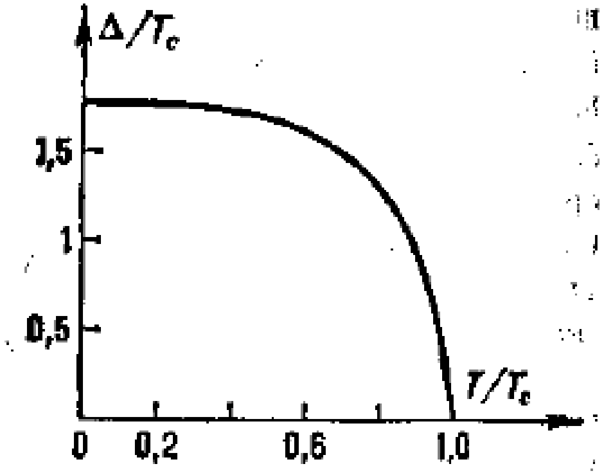
Cooper pairs

Cooper pair: Two electrons with Opposite momentums $\boldsymbol{p}'=-\boldsymbol{p}$

Orbital momentum of electrons relative movement l=0, (s-pairing) => central interaction => they may appear in the same point of space =>
Two electrons have **opposite spins** ↑+↓

BCS Superconductivity: no gap – no supercurrent!





$$\Delta = \hbar\omega_D \exp\left[-2/(g\nu(\mu))\right].$$

The order parameter Ψ has a physical meaning of the wave function of the superconducting condensate and the gap in the quasi-particle spectrum determines its modulus:

$$\Psi = \Delta e^{i\phi}$$

In normal state $\Psi = 0$

The characteristic length of the superconducting interaction : coherenc length

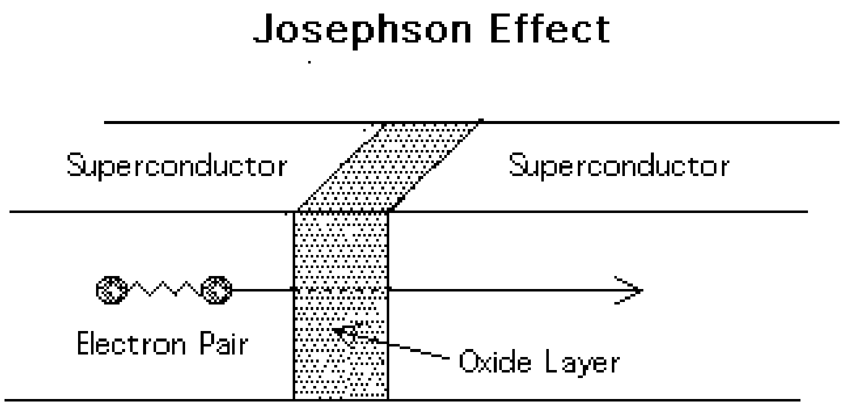
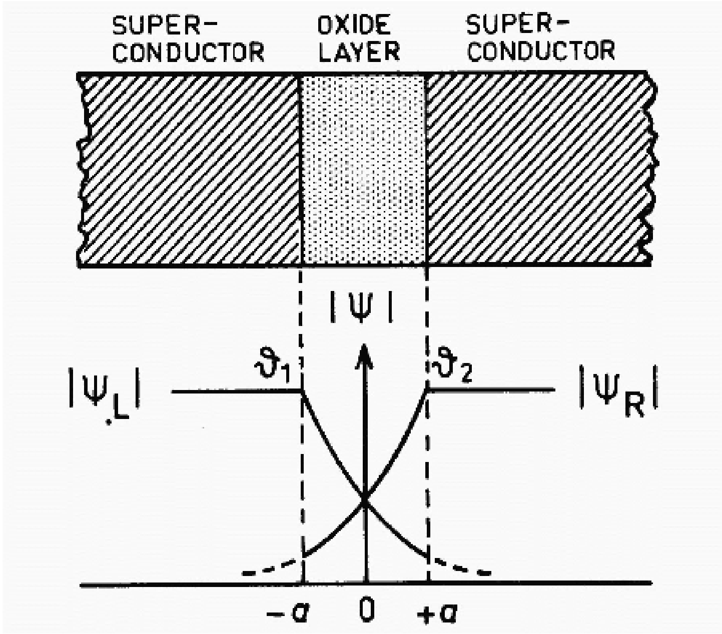


Fig. 13



$I(\Theta)$, $\Theta = \varphi_2 - \varphi_1$

1) Periodic function

2) Odd function $I(-\Theta) = -I(\Theta)$

$I = I_c \sin(\varphi_2 - \varphi_1) = I_c \sin(\Theta)$ stationary eff.

$$I_c = \frac{\pi \Delta(T)}{2eR_n} \tanh \frac{\Delta\ (T)}{2T}.$$

SIS Josephson junc.

$I = I_c \sin(\Theta(t))$ nonstationary eff.

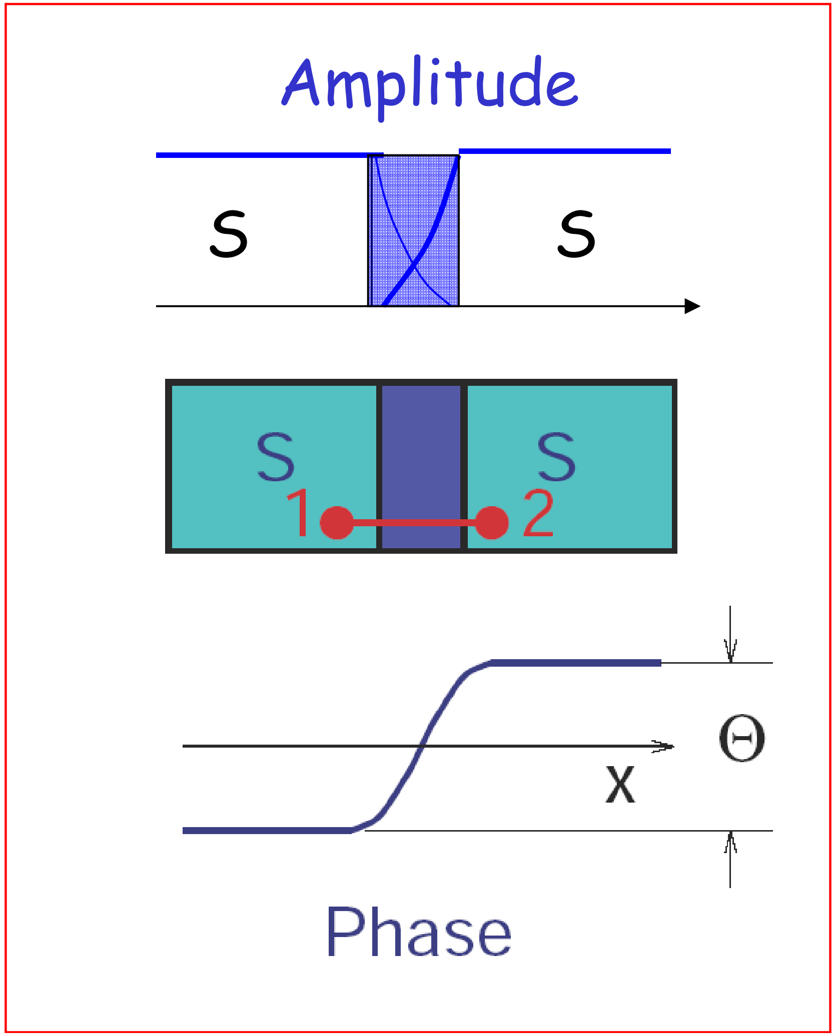
$$2eV(t) = \hbar\omega = \hbar \frac{d\Theta}{dt}$$

$V(t)$ - voltage

Josephson effect – the effect of MACROSCOPIC quantum tunneling of superconducting condensate (Cooper pairs) through a nonsuperconducting barrier

Explanation of the Josephson effect

$$\Psi = \Psi_0 \exp(i\varphi), \quad \varphi_1 - \varphi_2 = \Theta$$



the finite phase difference must create persistent current transferring Cooper pairs between the leads

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

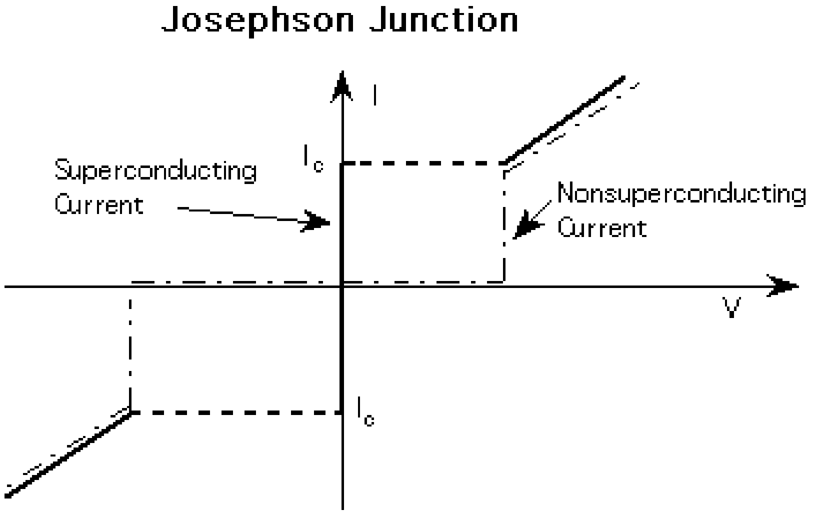
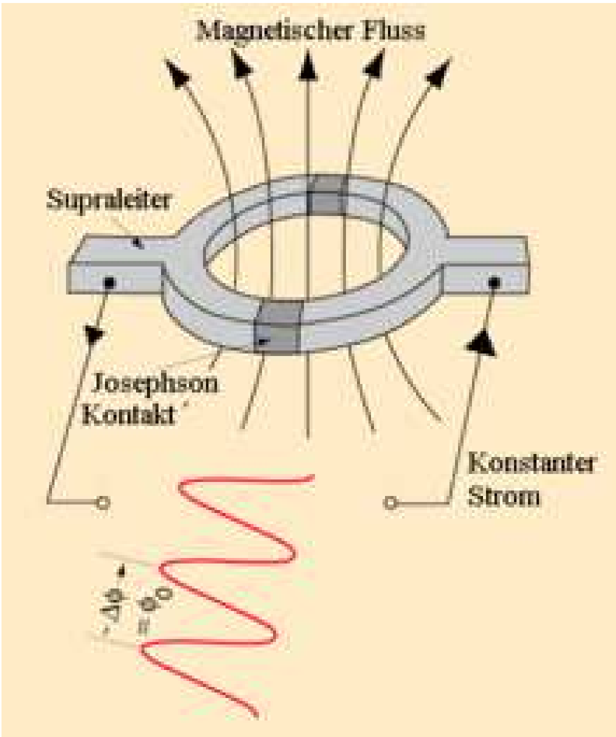
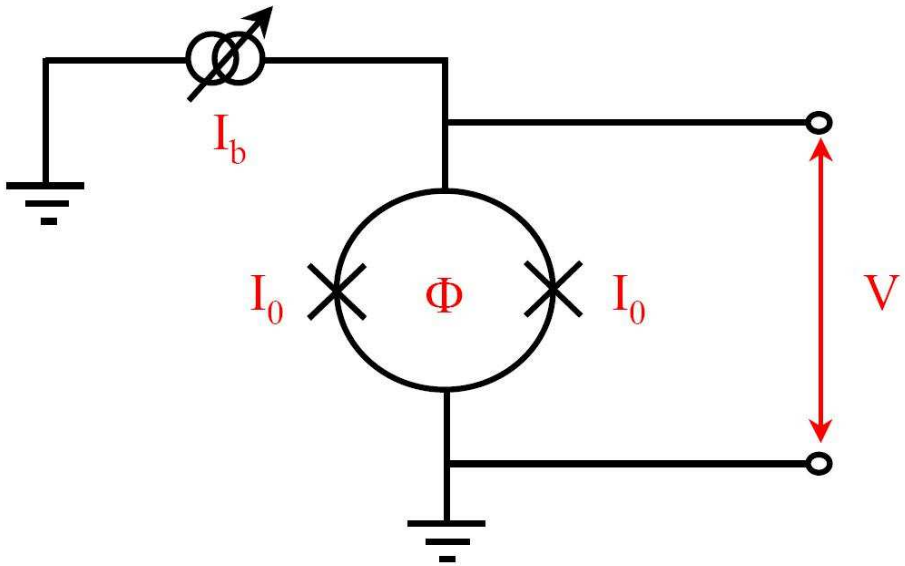


Fig. 14

Applications of the Josephson effect

- Volt standard
- SHF (microwave) generators
- Single-electron transistors (Coulomb blockade)
- **SQUID**s (Superconducting Quantum Interference Devices) (magnetometry)





Summary RSFQ

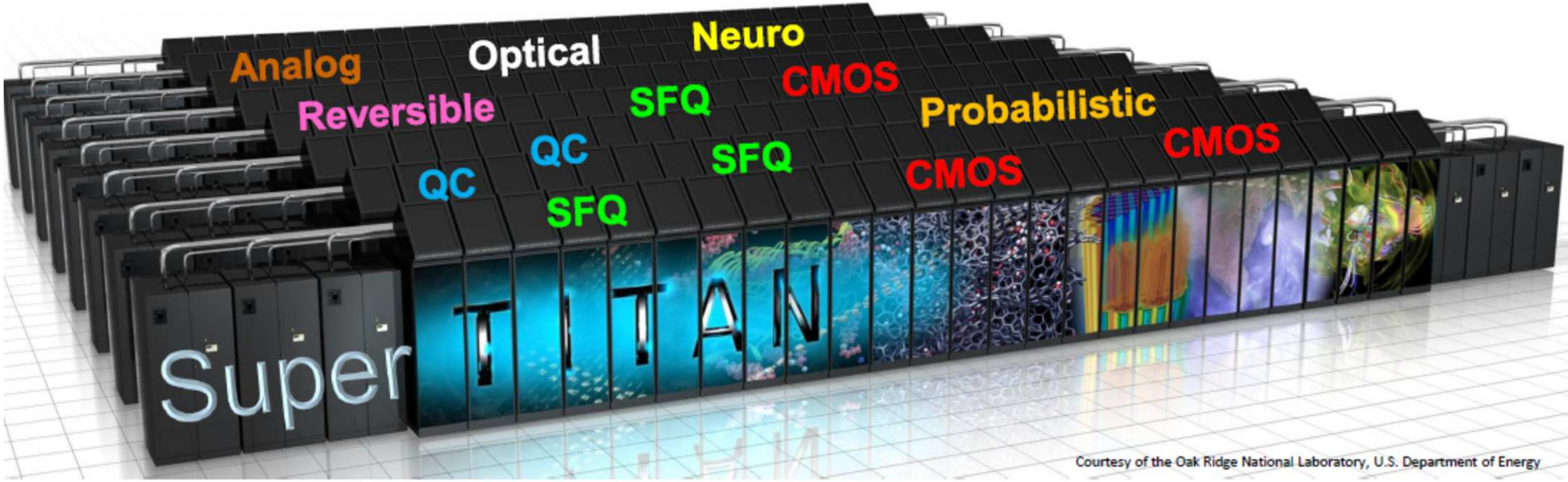
STONY BROOK
STATE UNIVERSITY OF NEW YORK

Superconductor electronics:

- very useful for niche applications, including
  - numerous physics experiments,
  - ultrasensitive radiation/photon receivers/detectors,
  - fundamental standards.
- digital applications hard because of:
  - need in liquid refrigeration,
  - current focus on communications / entertainment
- still, unbeatable opportunity for low-latency, low-power supercomputing

Keeps me (cautiously) optimistic about the future prospects of the field

Future Supercomputing Vision



- Hybrid technologies: digital (CMOS, SFQ), probabilistic, analog, neuromorphic, reversible, and quantum computing (QC)
  — whatever works best!
- SFQ digital platform supports multiple cryogenic technologies
- Requires optical interconnects between room temperature and cryogenic nodes

SF proximity effect and FFLO states

What happens when the Cooper pair ↑↓ penetrates into F?

In F the sum momentum of the pair ↑↓ cannot be zero.

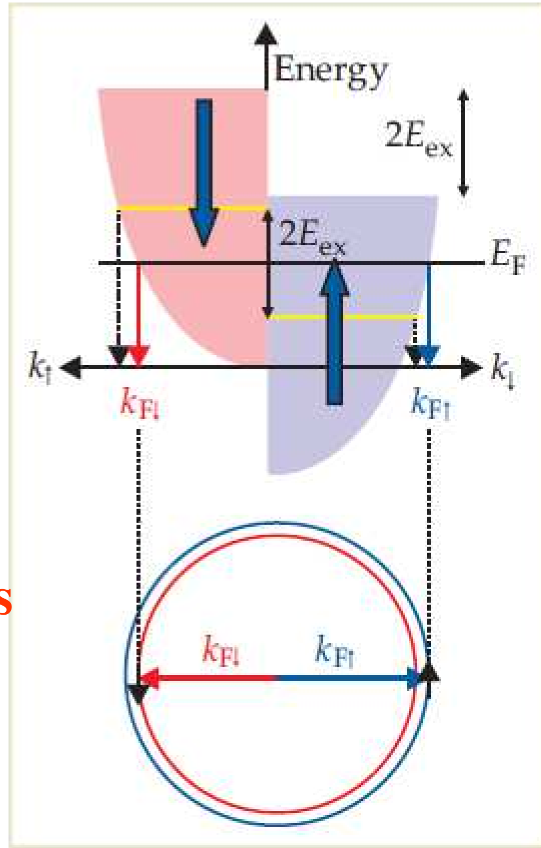
$k_{F\uparrow} \neq k_{F\downarrow}, k_{F\uparrow} - k_{F\downarrow} \sim h$, ***h*** **-** exchange field, $\mu_B \boldsymbol{h} > \Delta$,

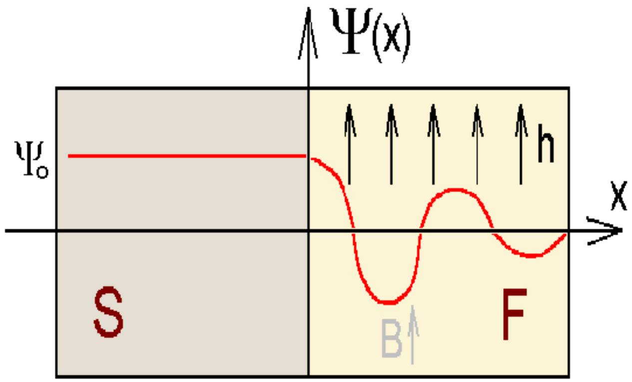
nonzero pair momentum

Non-uniform superconducting order parameter in F

$$\Psi = \Psi_0 \cos(Qr),$$

Q is wave-vector, **Q ~ *h*/*v*$_F$,**



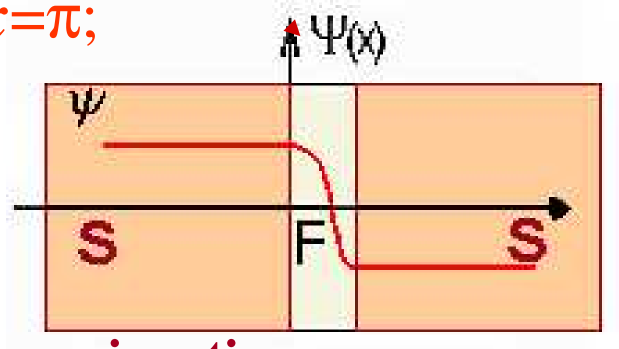


spatially nonuniform states

Fulde, Ferrel (1964),

Larkin, Ovchinnikov (1964)

Q*x*=π;



π-junction

Does the exchange magnetic field strongly suppresses the BCS correlation and destroys the Cooper pairs in F?

It is true, but not whole.

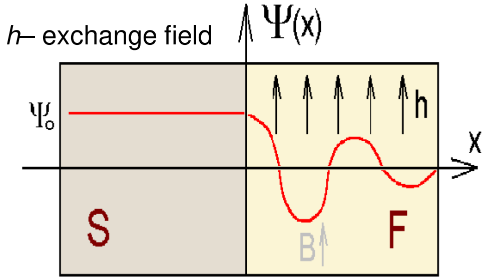
Nonuniform exchange field may produce the spin triplet (↑↑) superconducting correlation!

*A.F. Volkov PRB (2001)

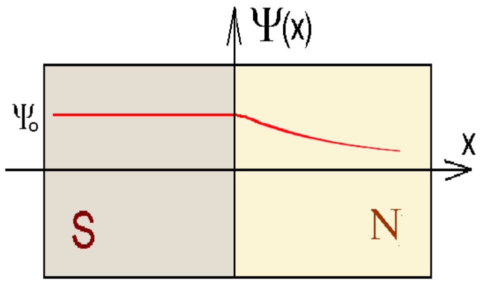
Oscillating superconductivity, FFLO states

SF and SN proximity effect

SF



SN



Non-uniform superconducting order parameter in F

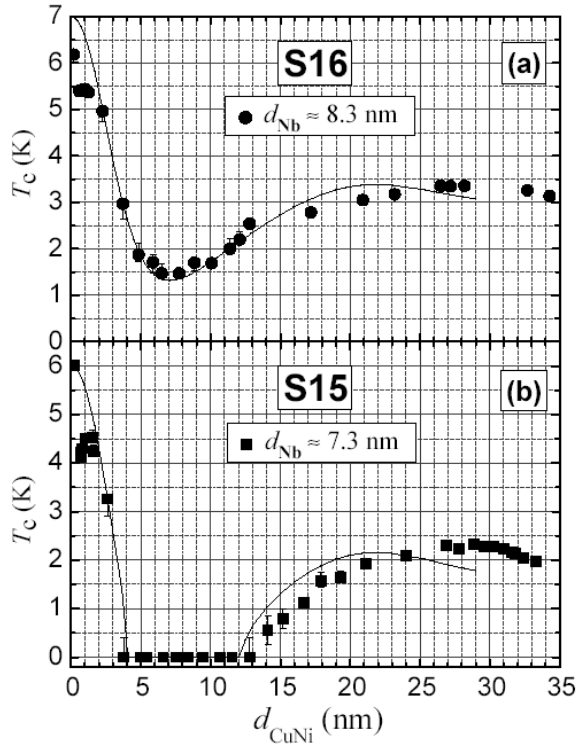
$\Psi(x) \sim \exp(-kx)\cos(-Qx)$ It decays with oscillations –

FFLO states (Fulde-Ferrell- Larkin-Ovchinnikov)

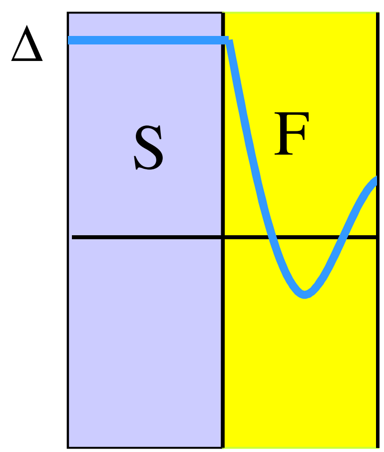
$\xi_{F1,F2} \sim (\hbar D/h_{ex})^{1/2} \approx$ **1-4 nm** $(h_{ex} >> k_B T)$,

$\xi_N = [\hbar D/(2\pi kT)]^{1/2} \sim= 10\text{-}100$ **nm**

much smaller compared to the ξ_N decay



S/F bilayer

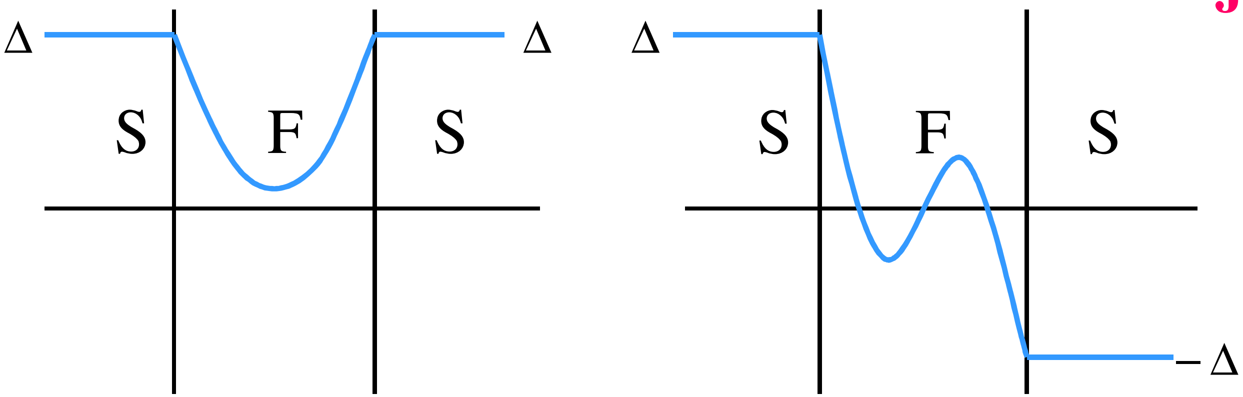


Reentrant superconductivity

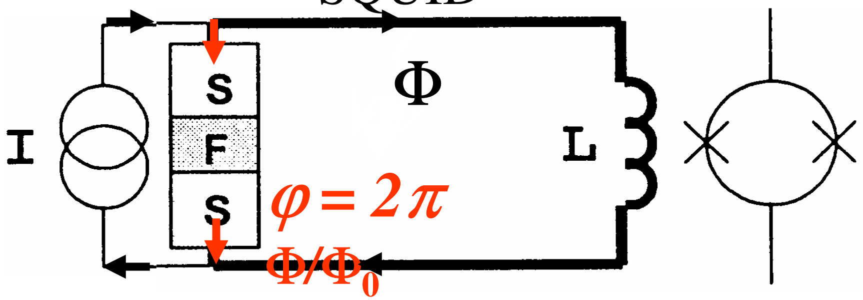
* Zdravkov et al.
PRL 97 (2006) 057004

Josephson π-junction

« 0 phase » « π phase »



SQUID



$\varphi = 2\pi \, \Phi/\Phi_0$

$\varphi = \pi = (2\pi/\Phi 0)\int A dl = 2\pi\Phi/\Phi_0$

$\Phi = \Phi_0 /2$

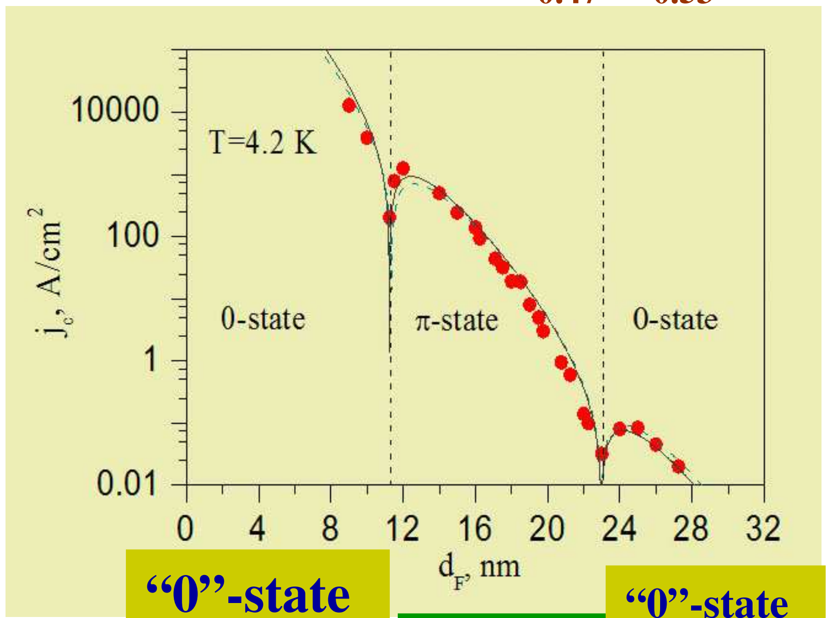
Spontaneous circulating current
in a closed superconducting loop

May be used as a phase battery,

We do not need an external magnetic field

Frolov, et.al. Nature Physics 4, 32 (2008)

$Nb\text{-}Cu_{0.47}Ni_{0.53}\text{-}Nb$



"0"-state
$I = I_c \sin\varphi$

π-state

"0"-state
$I = I_c \sin\varphi$

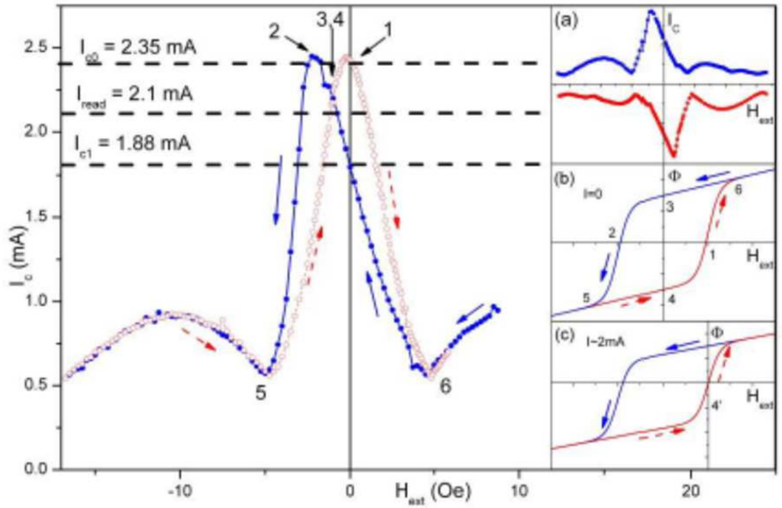
$I = I_c \sin(\varphi + \pi) = - I_c \sin(\varphi)$

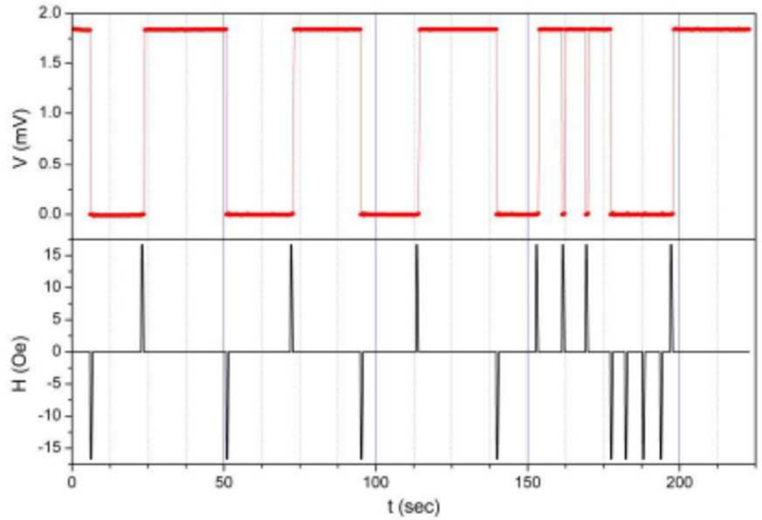
$E = E_J[1 - \cos(\pi + \varphi)] = E_J[1 + \cos\varphi]$

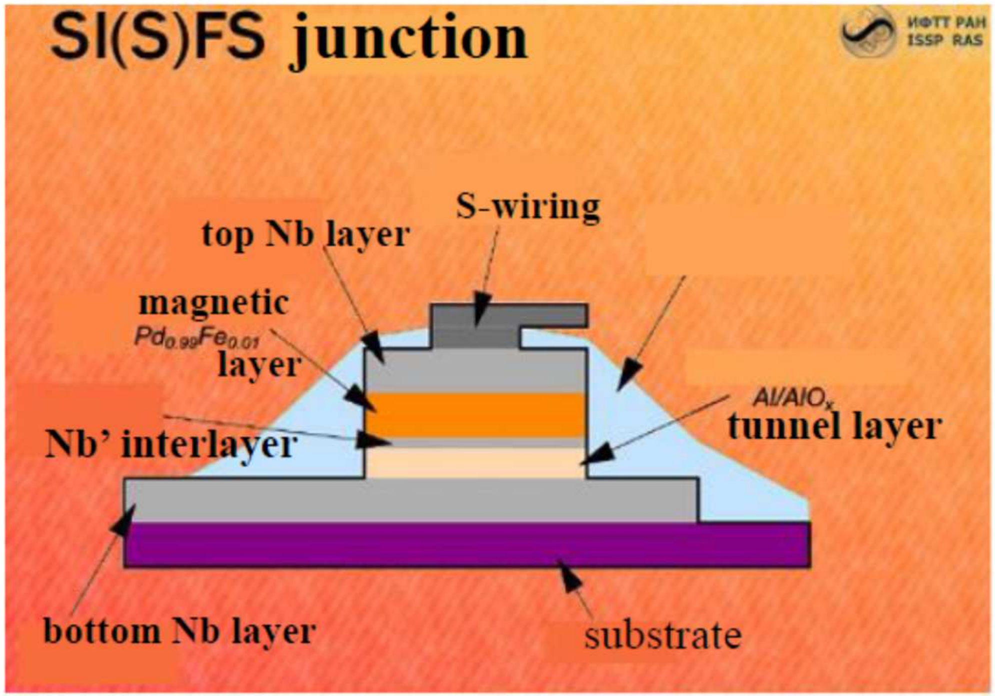
* V.R.. Oboznov. et al. PRL

Josephson Magnetic Memory with Fast Reading (in collaboration with HYPRES)

Magneto-hysteretic behavior of the critical current of Nb-PdFe-Nb Josephson junctions







SIsFS junction
with thin s-layer and tunnel junction I
d_s = 15 nm; $\xi_S < d_s \ll \lambda$
SIs tunnel junction "feels" F-layer remagnetization

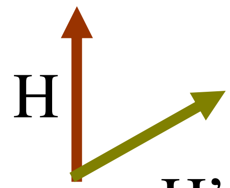
non-volatile switchable Magnetic Josephson junctions (MJJs) programmable using small field

V.R. et al, Phys. Procedia 36, 35 (2012)
Appl. Phys. Lett. 100, 222601 (2012)

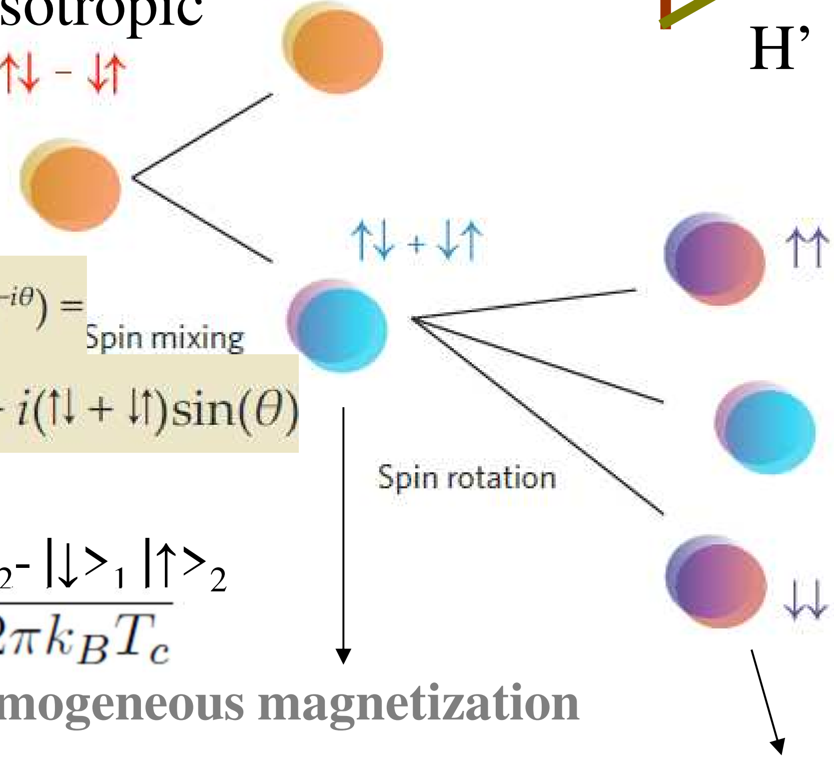
S. Bakurskiy, M.Yu. Kupriyanov, … N.P.
Appl. Phys. Lett. 2018

Prehistory: Long range proximity effect

Symmetry break -> H



isotropic



$$(\uparrow\downarrow - \downarrow\uparrow) \to (\uparrow\downarrow e^{i\theta} - \downarrow\uparrow e^{-i\theta}) =$$
$$= (\uparrow\downarrow - \downarrow\uparrow)\cos(\theta) + i(\uparrow\downarrow + \downarrow\uparrow)\sin(\theta)$$

Normal metal

singlet: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$

$$\xi_0 = \sqrt{\hbar D_f / 2\pi k_B T_c}$$

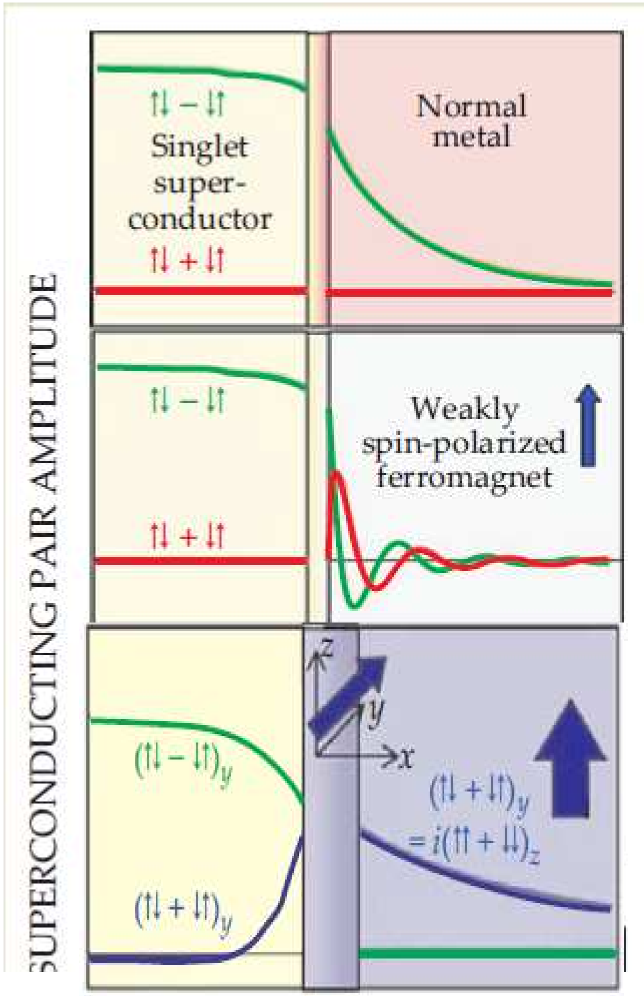
Homogeneous magnetization

singlet S=0: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$

triplet S_z=0: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2$

$$\xi^{-1} = \xi_1^{-1} + i\xi_2^{-1}$$

$$\xi_1 = \xi_2 = \sqrt{\hbar D_f / h}$$

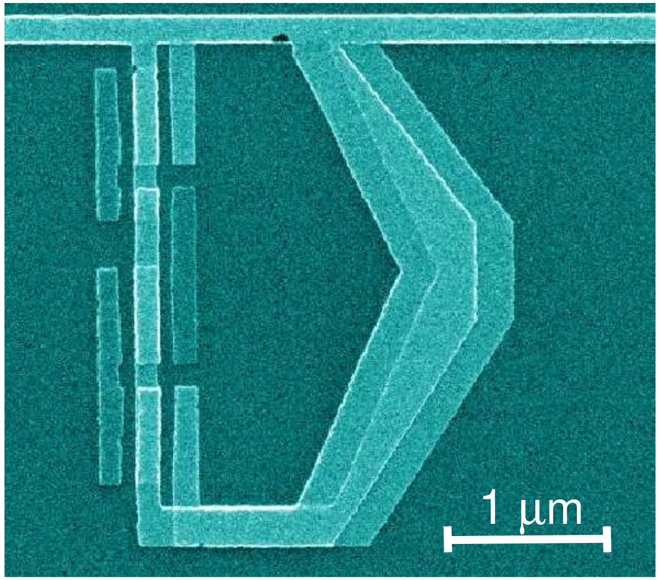


Nonhomogeneous magnetization

singlet S=0: $|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2$ } ξ_f
triplet S_z=0: $|\uparrow>_1|\downarrow>_2 + |\downarrow>_1|\uparrow>_2$

triplet S_z=1: $|\uparrow>_1|\uparrow>_2$, } ξ_0
triplet S_z= -1: $|\downarrow>_1|\downarrow>_2$

Изготовление кубитов в России

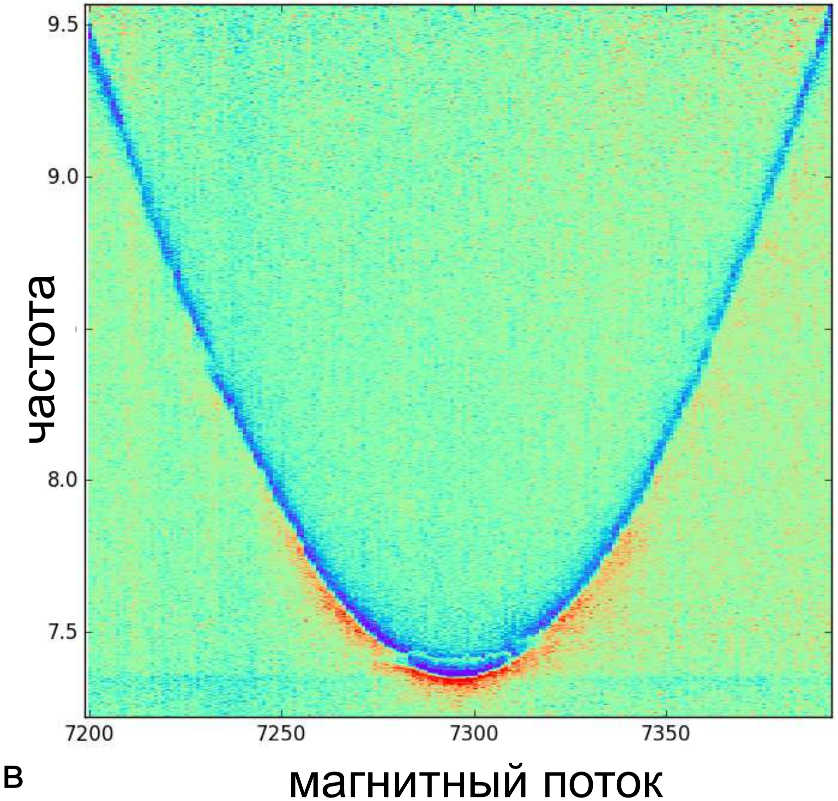


май 2015 г.
первый кубит,
изготовленный
в России

Олег Астафьев

Валерий Рязанов

спектр кубита



Ваши вопросы

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