

Сверхпроводниковая адиабатическая логика и «летающие» кубиты

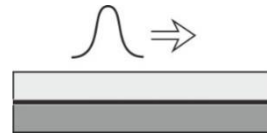
Клёнов Н.В.

МГУ имени М.В. Ломоносова

- Physical foundations of SCE

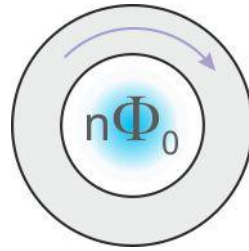
- **Superconductivity:**

- Coherent state of electrons in metals characterized by superconducting order parameter
- Zero resistance for constant current flow. Ballistic signal transfer



- **Quantization of magnetic flux:**

- Single Flux Quantum (SFQ) is $\Phi_0 = h/2e = 2 \cdot 10^{-15}$ Wb.



- **Josephson effects** (correspond to a current tunneling through a weak link between two superconducting banks - the Josephson junction):

Parameters: I_c, R_n

$$\phi_1 - \phi_2 = \varphi$$

$$I = I_c \sin(\varphi)$$

$$V = \frac{\hbar}{2e} \frac{d\varphi}{dt} = \frac{\Phi_0}{2\pi} \frac{d\varphi}{dt} \Rightarrow \int_0^T V dt = \Phi_0$$

Switching time:

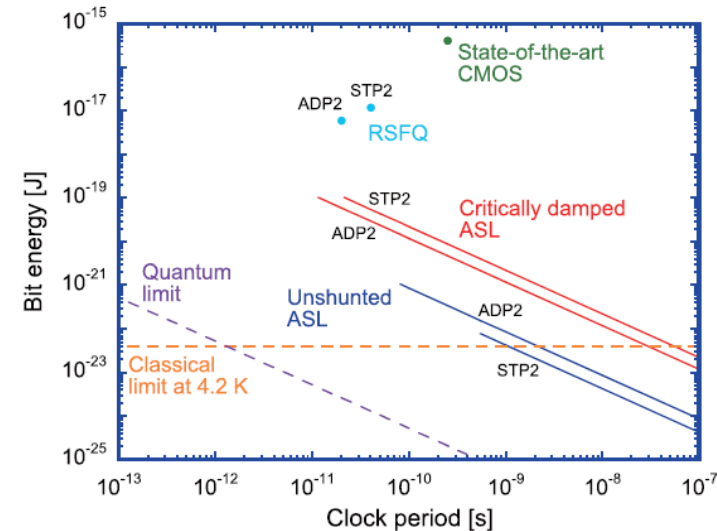
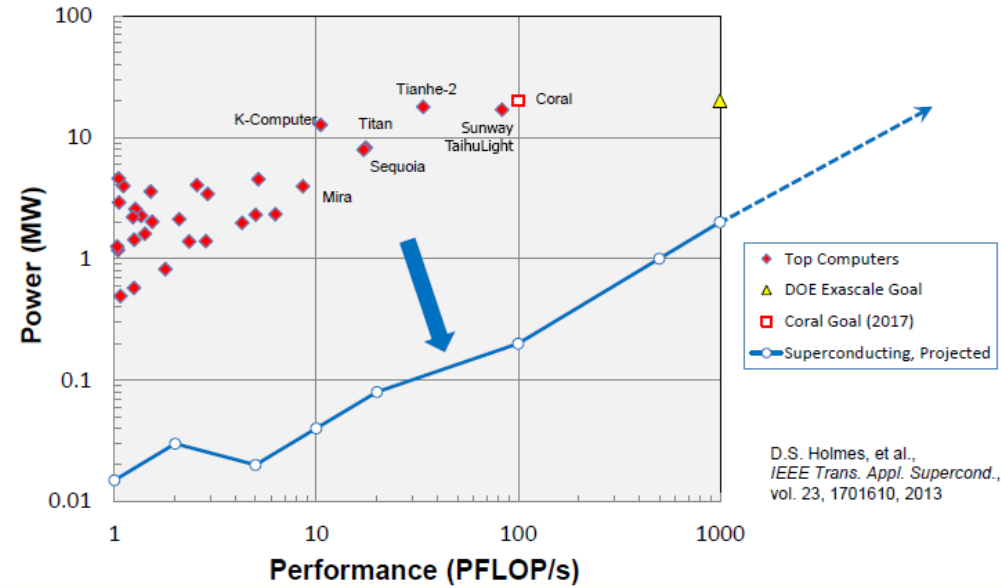
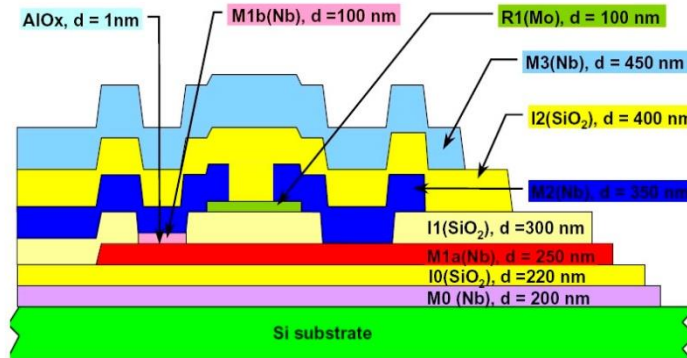
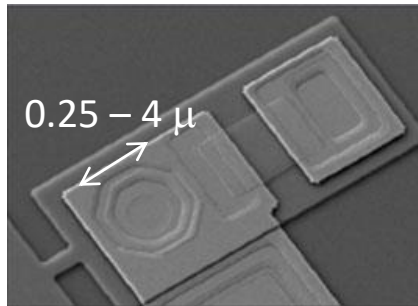
$$\tau_j = 2 \dots 4 \text{ [ps]}$$

Characteristic voltage:

$$V_c = 0.5 - 1 \text{ [mV]}$$

Characteristic energy:

$$E_j = 2 \times 10^{-19} \text{ [J]}$$

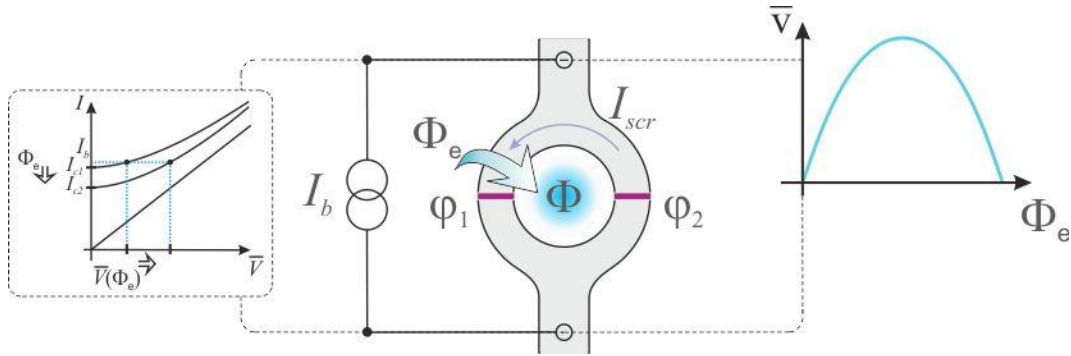


Magnetometric systems

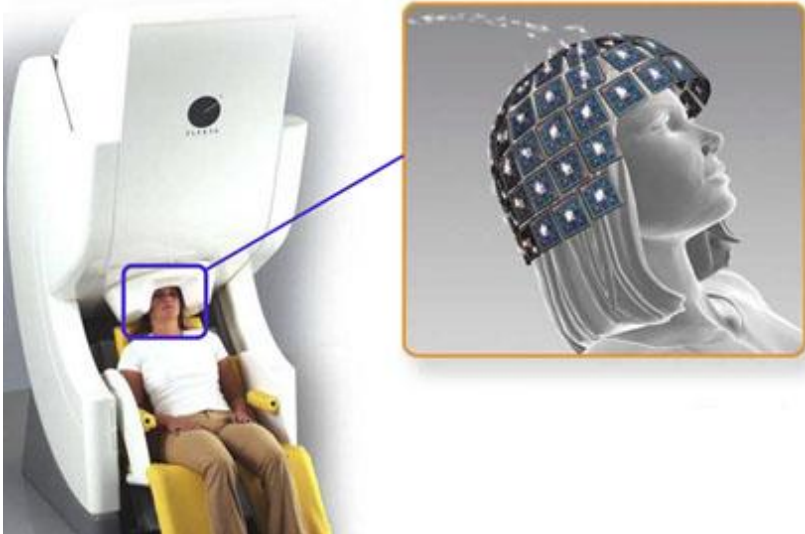
Superconducting QUantum Interferometric Devices - SQUIDS

Medical equipment

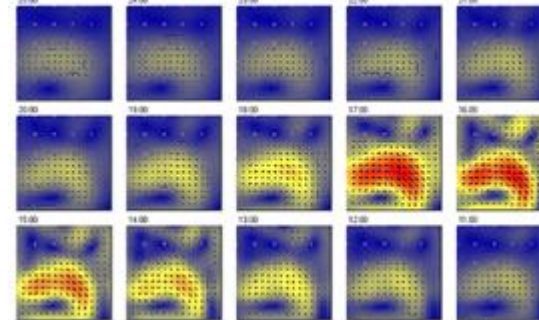
Voltage response



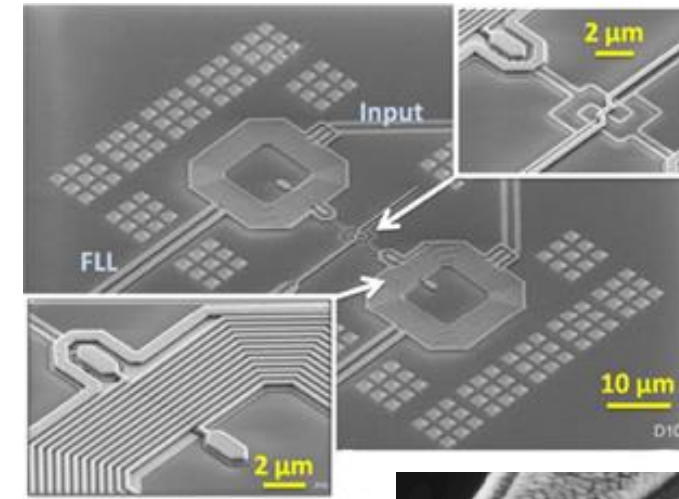
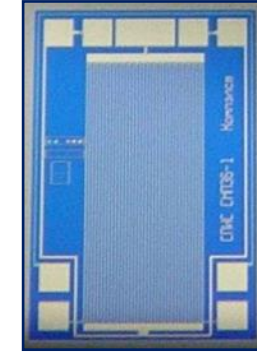
Magnetoencephalography (MEG), Elekta Neuromag



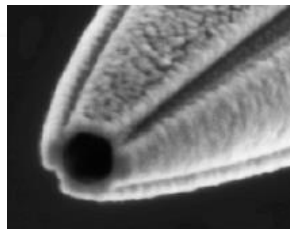
1 SQUID:
€ 0.5 – 1 K



DC SQUID, NIIFP
Chip size from 3x3 mm²



DC SQUID /
nanoSQUID

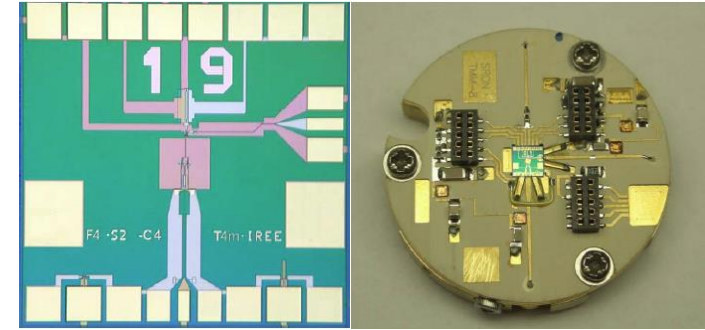


Detectors & Receivers (RF & sub-THz & THz)

THz receivers and photon counters

Cryptography

Superconductor Single Photon Detector (SSPD), Scontel

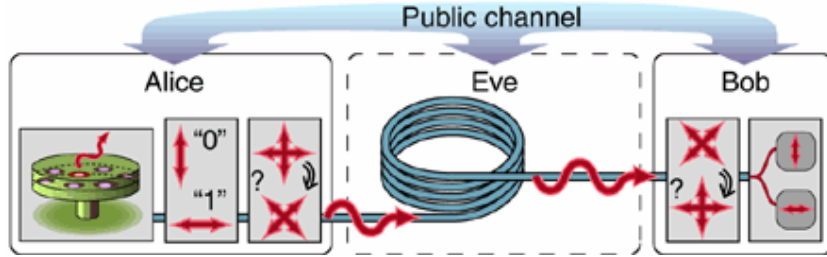
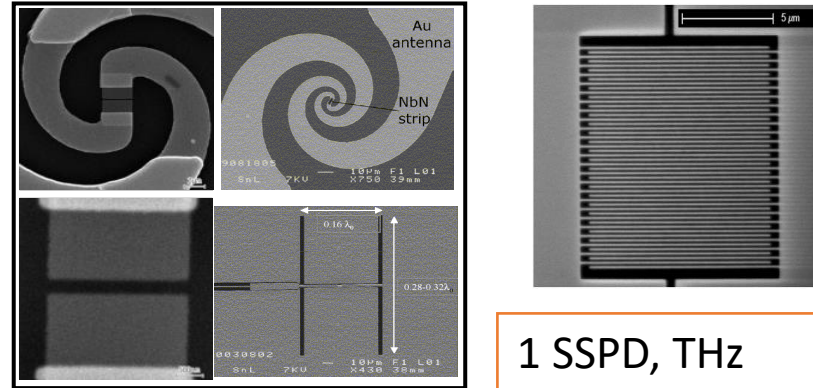


IRE RAS

1 SSPD, THz detector: ~ \$ 80 K

32 Gs/s X-band All-Digital Receiver (ADR) HYPRES, Inc.

1 ADR: ~ \$ 0.5 M



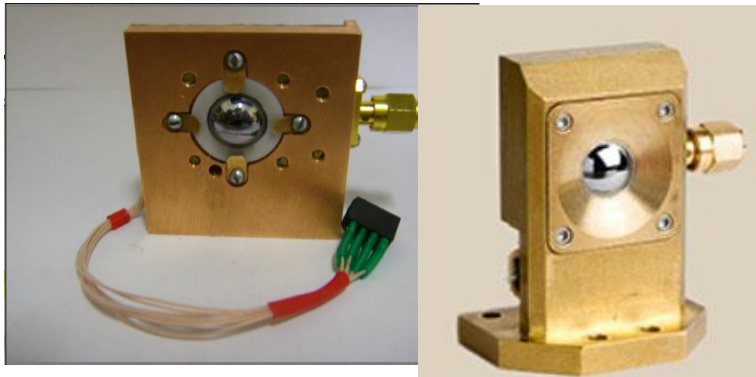
Radioastronomy

Space communications



Medicine

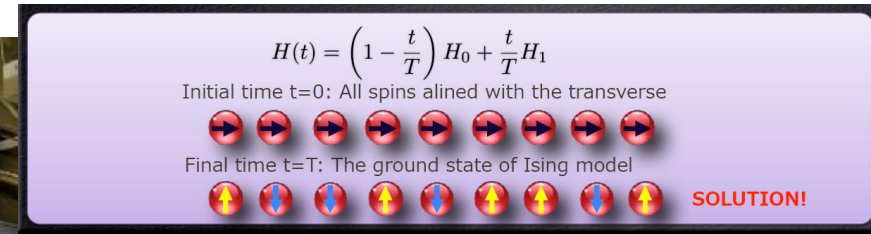
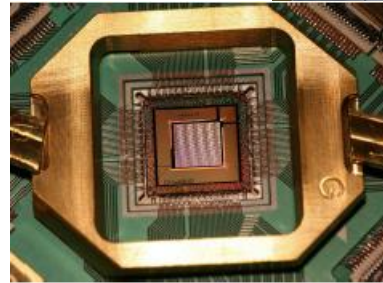
Security



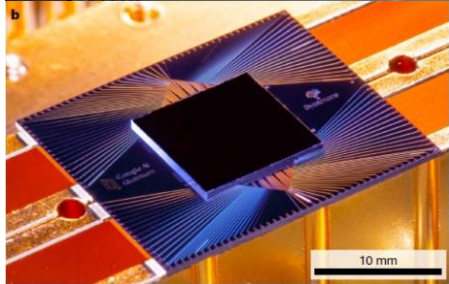
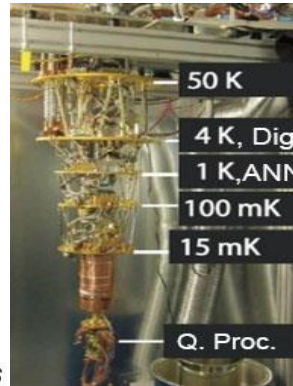
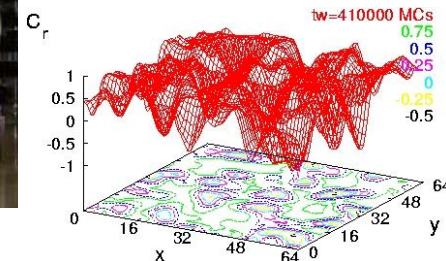
Quantum computers and neuromorphic processors



1 QC:
~ \$ 20 M

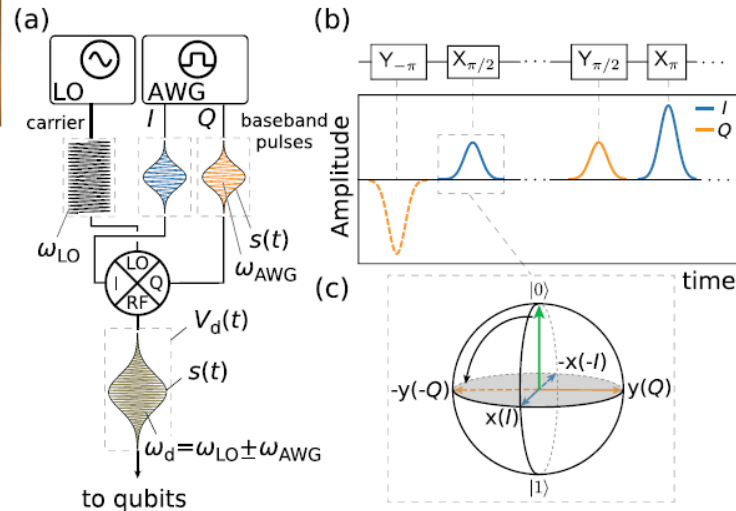


Quantum annealer,
D-Wave

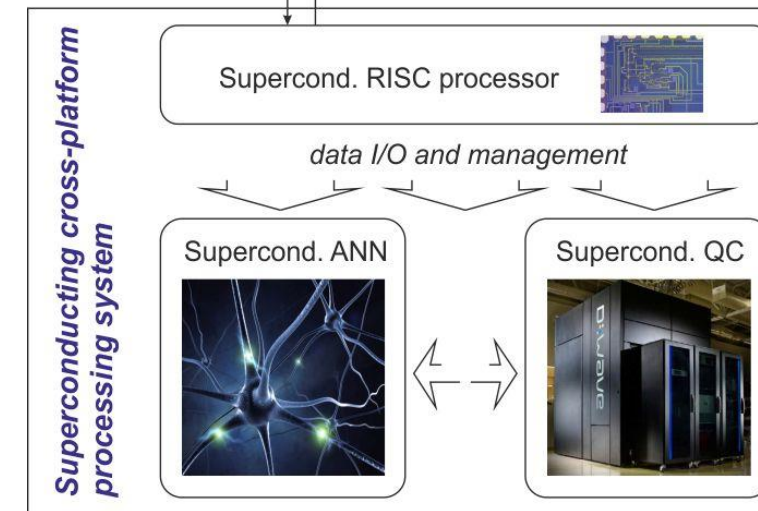
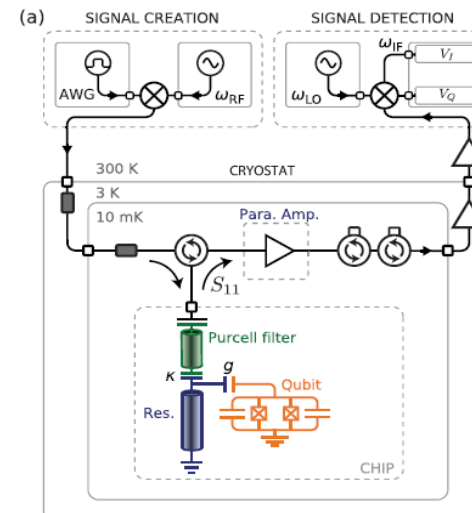


Sycamore quantum processor,
Google Hardware lab.

Qubit control



Readout



ASL. Information representation

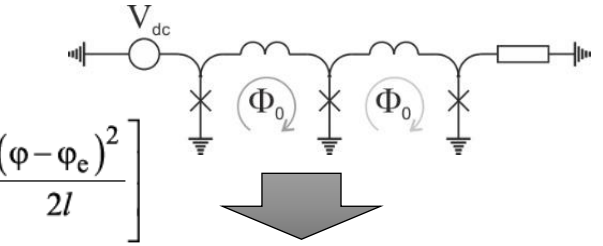
Non-adiabatic switching

Adiabatic switching

Parametric qantron

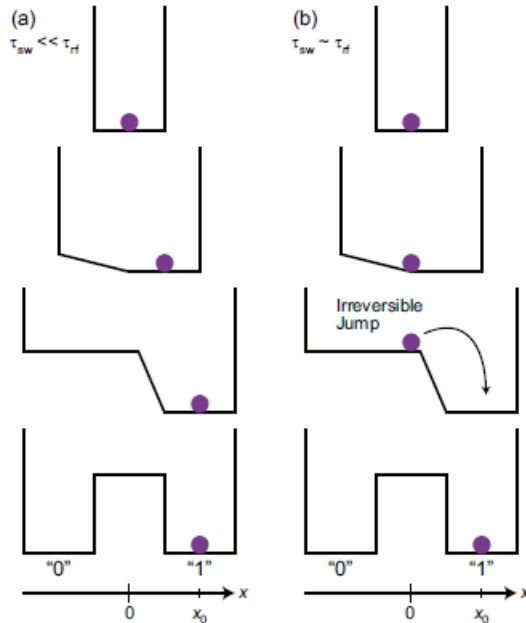
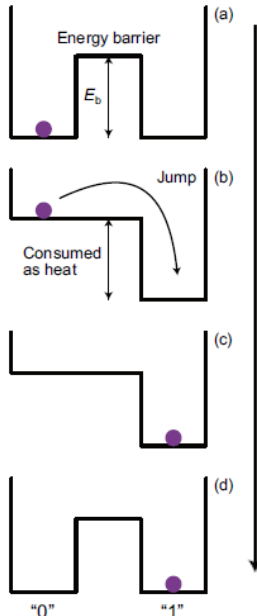
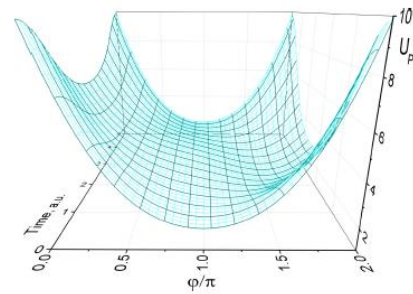
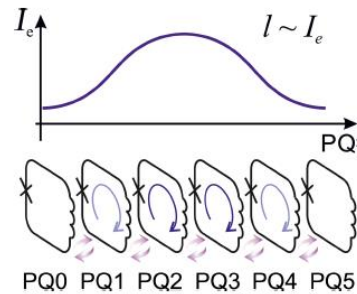
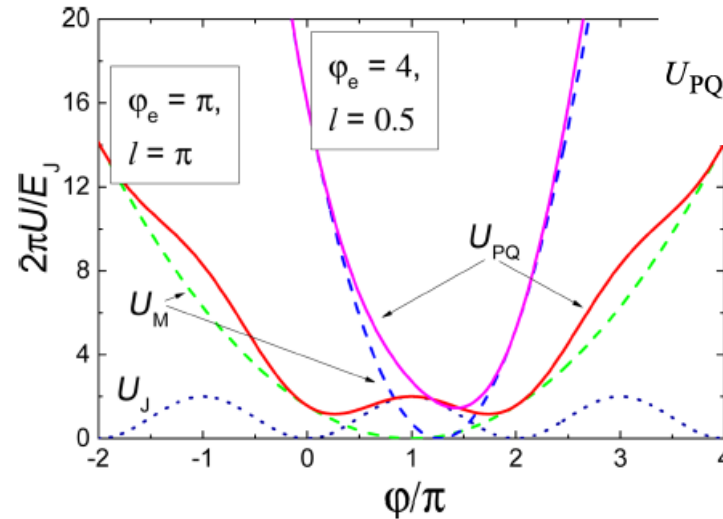
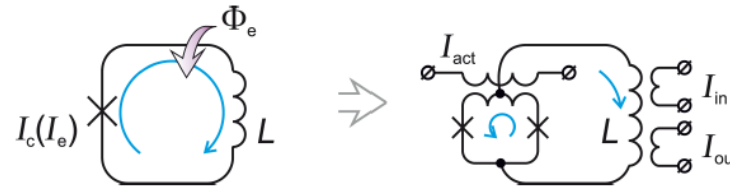
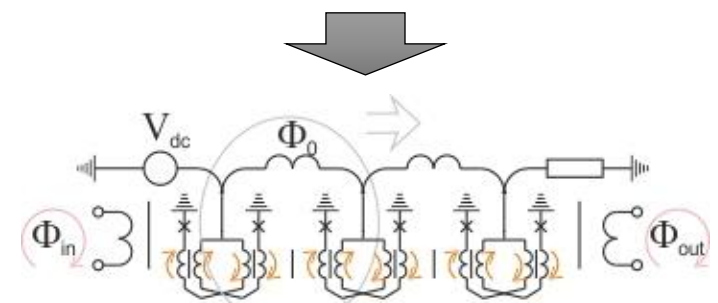
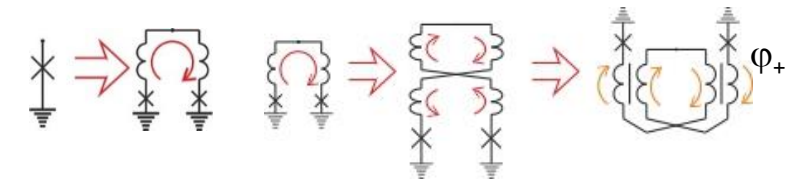
nSQUIDs

Josephson transmission line



Data domain

nSQUID



- N. Takeuchi et al. Supercond. Sci. Technol. 28, 015003 (2015); PhD Thesis "Extremely Energy-Efficient Integrated Circuits Using Adiabatic Superconductor Logic", 2014.

- V. K. Semenov et al. IEEE Trans. Appl. Supercond. 13, 938 (2003); IEEE Trans. Appl. Supercond. 17, 455 (2007);
- J. Ren, V. K. Semenov et al. IEEE Trans. Appl. Supercond. 19, 961 (2009); IEEE Trans. Appl. Supercond. 21, 780 (2011)

ASL. Information representation + add-ons

Adiabatic Quantum Flux Parametron (AQFP)

$$E_{bit} \sim 10^{-21} \text{ Дж} = 10^{-2} E_{bitminSFQ}$$

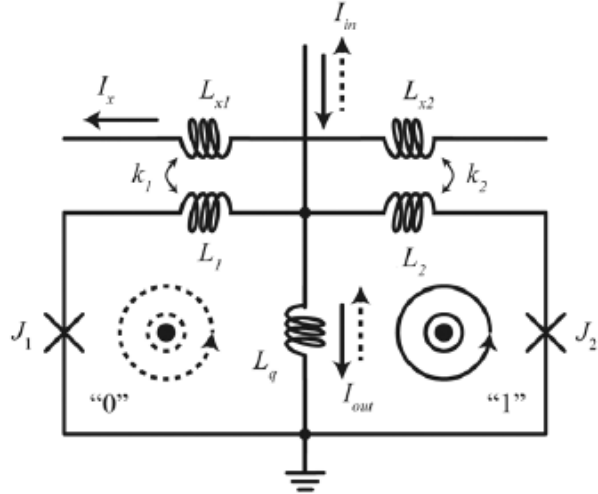
$$f = 5 \text{ ГГц}$$

$$T = 4.2 \text{ К}$$

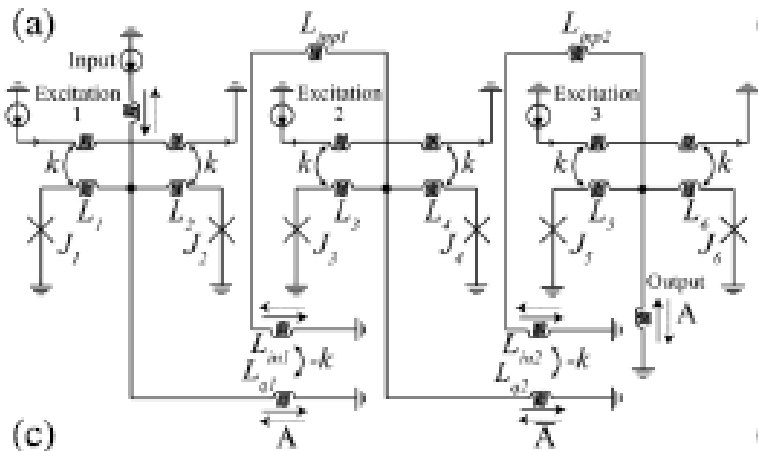
$$N_{cell} \text{ до } 10^4$$

$$(N_{JJ} = 20000)$$

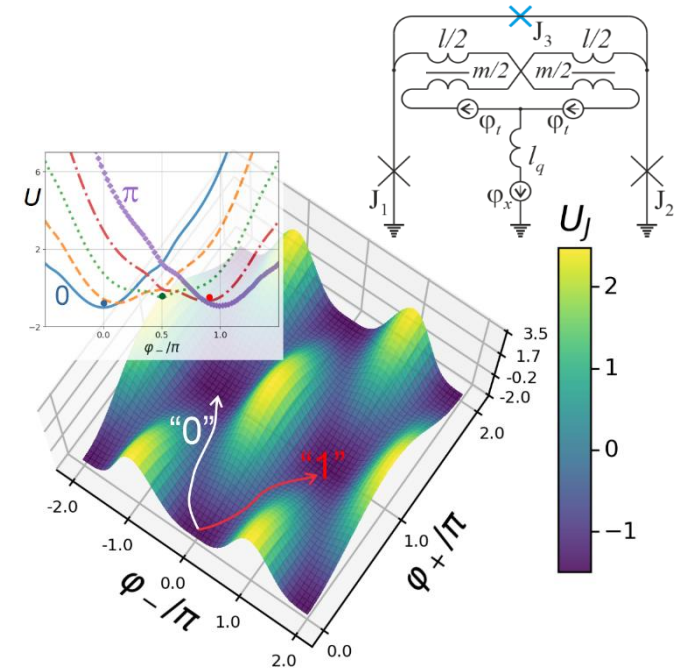
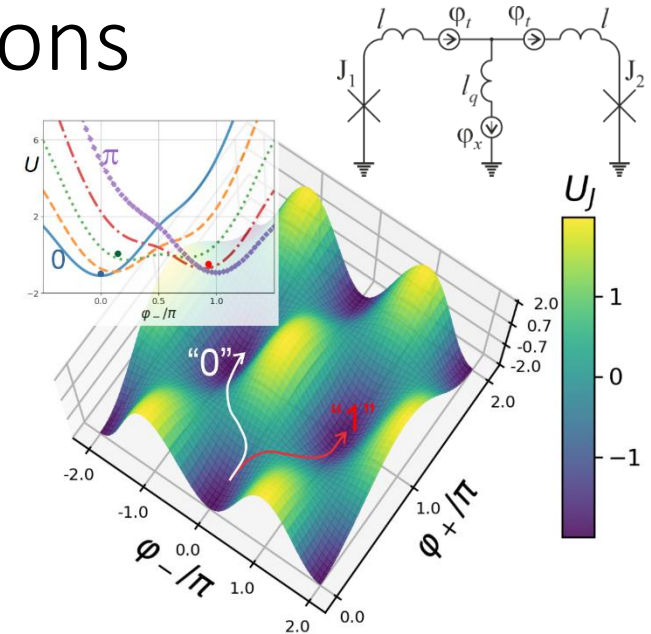
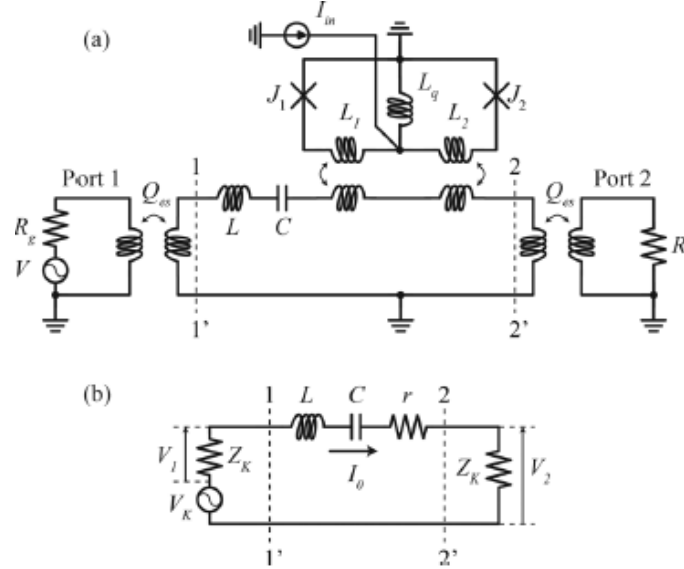
$$f_{max} = 5 \text{ ГГц}$$



Inverter "NO"

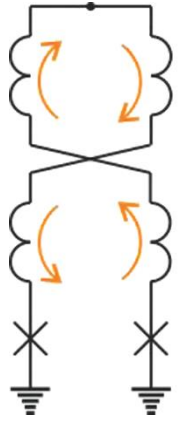


Измерение потребляемой энергии



- N. Takeuchi et al. Appl. Phys. Lett. 102, 052602 (2013);
- Appl. Phys. Lett. 102, 052602 (2013);
- Sci. Rep. 4, 6354 (2014);
- J. Appl. Phys. 117, 173912 (2015);
- Supercond. Sci. Technol. 28, 015003 (2015)

Оптимизация базового элемента потокового адиабатического управления



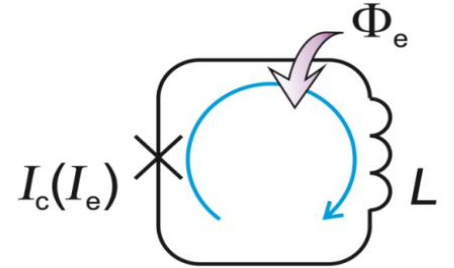
СКВИД

Расчет потенциальной энергии и динамических процессов при переключении СКВИДа при увеличении ведущей фазы φ_c : 0 (а), $\pi/2$ (б), π (в), $3\pi/2$ (г).

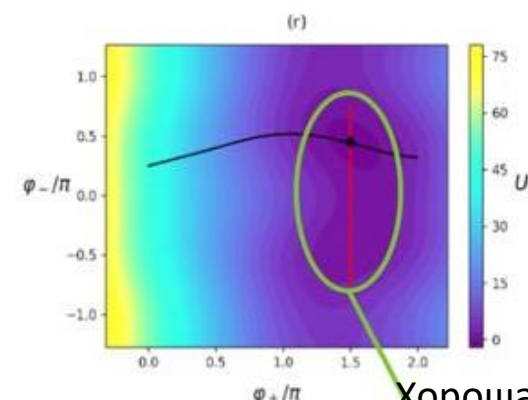
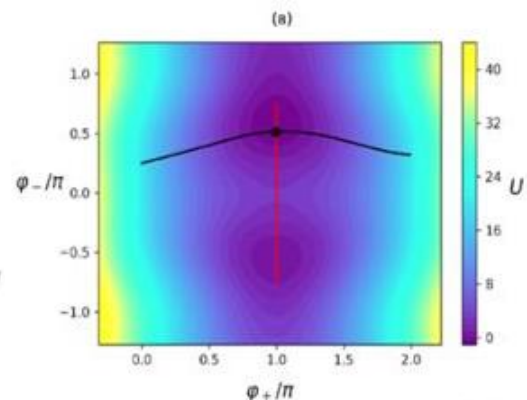
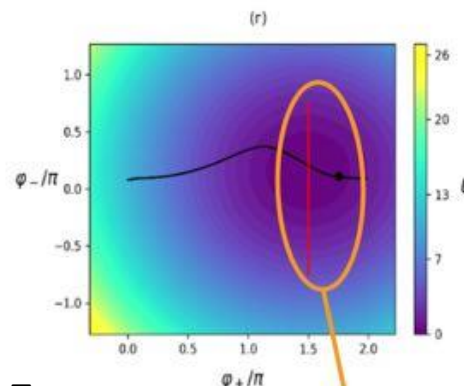
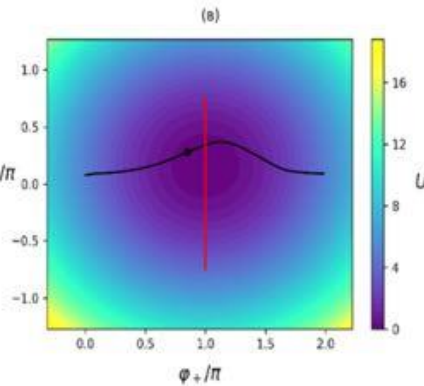
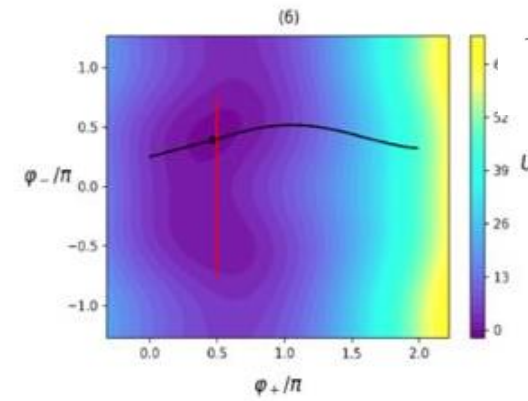
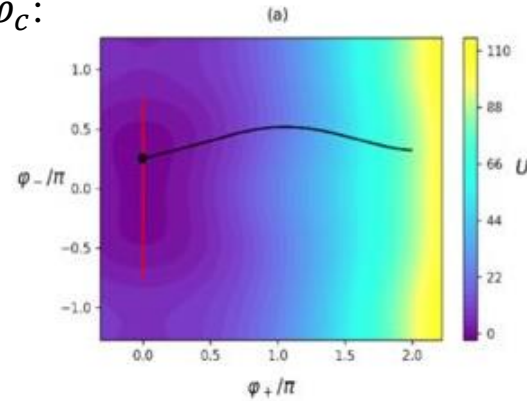
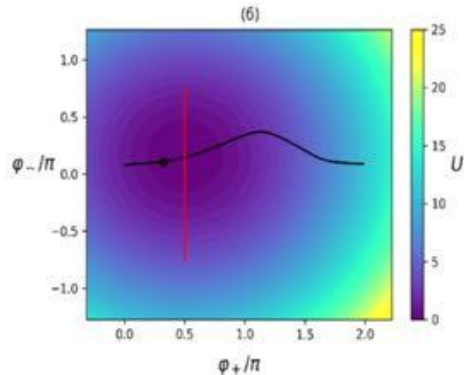
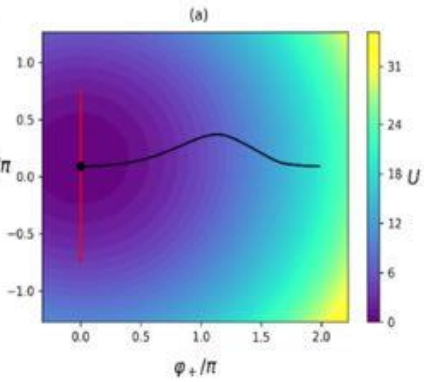
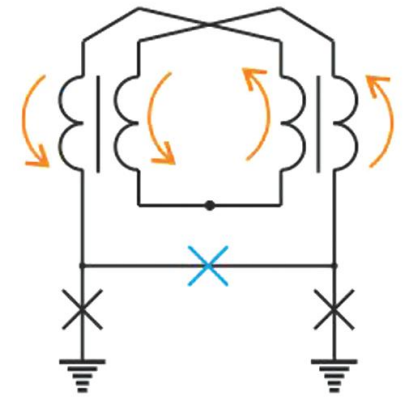
φ_c - отвечает за тактируемость ячейки,
 φ_e - отвечает за передачу информации.

Расчет потенциальной энергии и динамических процессов при переключении н-би-СКВИДа с пи-контактом между устойчивыми состояниями при увеличении ведущей φ_c : 0 (а), $\pi/2$ (б), π (в), $3\pi/2$ (г).

Параметрический квантрон



Н-БИ-СКВИД
с пи-контактом

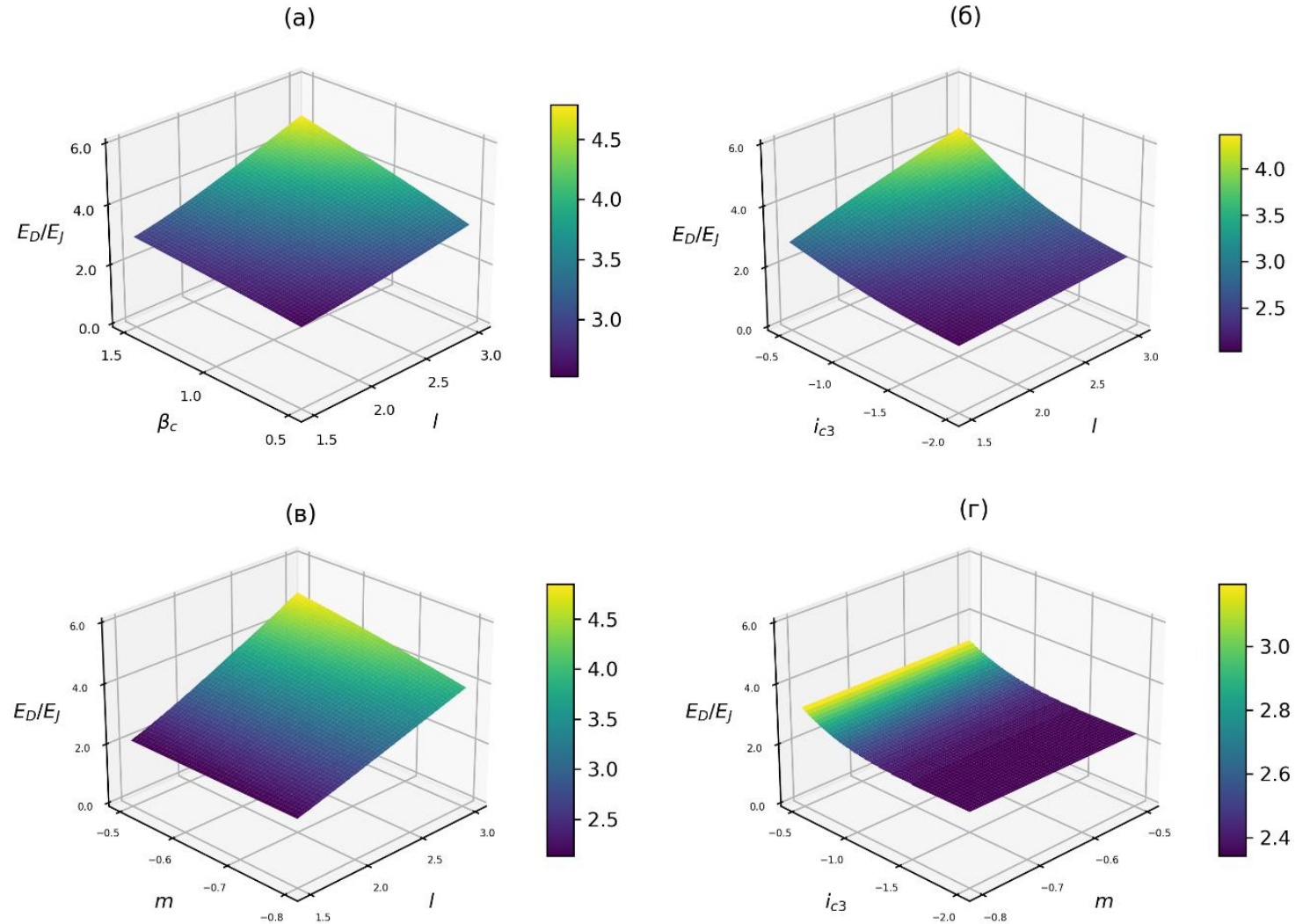
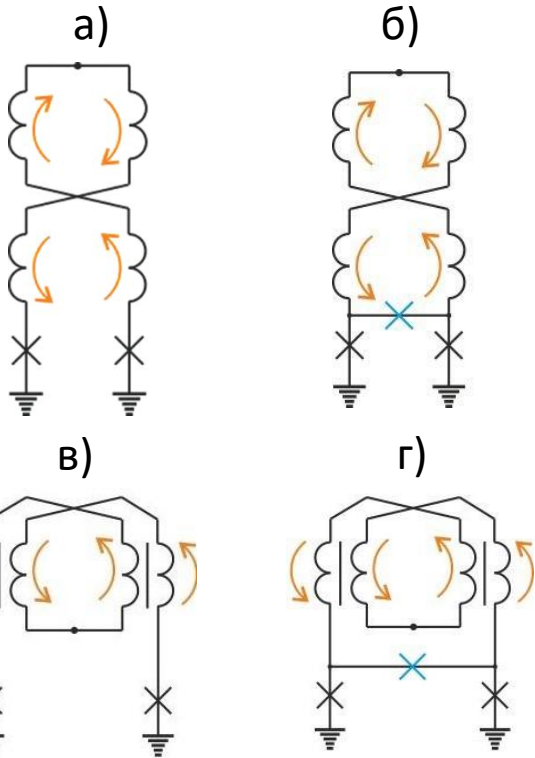


Хорошая тактируемость

Плохая тактируемость

Soloviev, I.I., Khismatullin, G.S., Klenov, N.V. et al, π Junctions in Adiabatic Superconductor Logic Cells. J. Commun. Technol. Electron. 67, 1479–1491 (2022).

Сравнение ячеек по их энергоэффективности



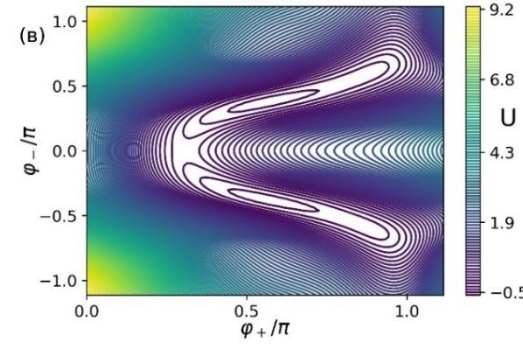
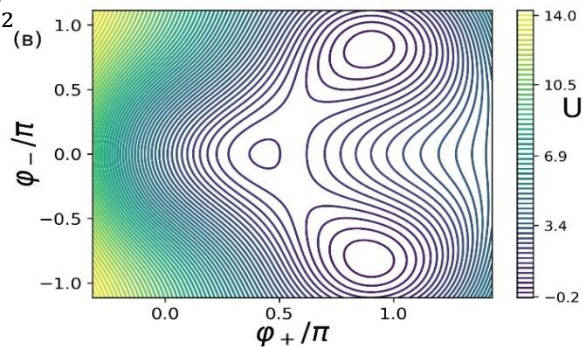
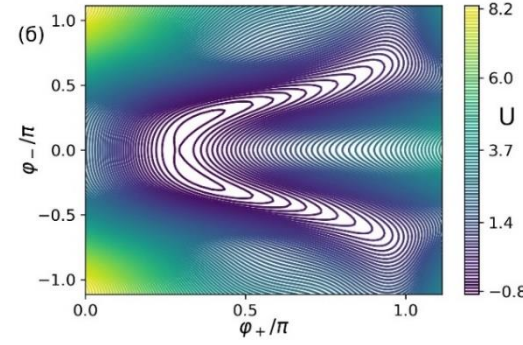
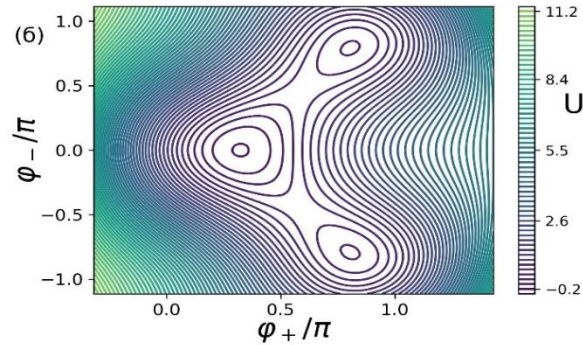
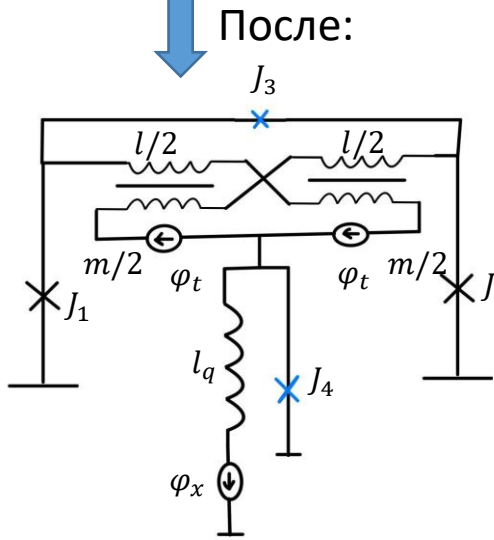
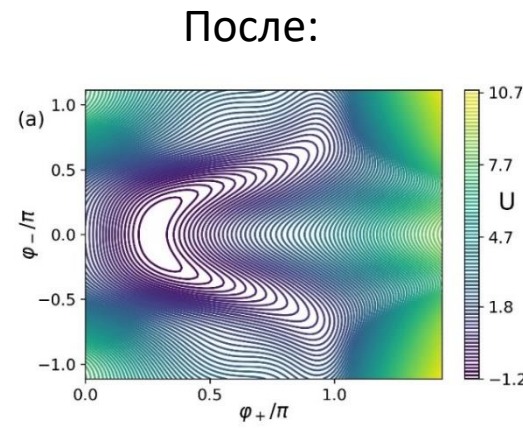
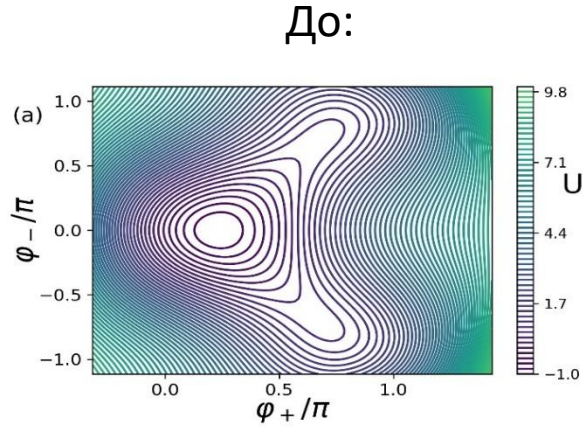
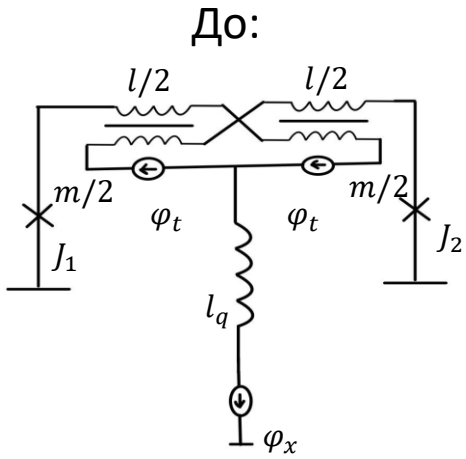
Расчет рассеиваемой за однократное переключение энергии в: СКВИДе (а), би-СКВИДе с пи-контактом (б), н-СКВИДе (в), н-би-СКВИДе с пи-контактом (г).

Работа над рассмотрением новых способов подстройки использованием потокового адиабатического контроллера была продолжена: *Soloviev, I.I., Khismatullin, G.S., Klenov, N.V., Optimization of adiabatic superconducting logic device cells with Josephson pi-contacts, JETP Letters (2023) – to be published.*

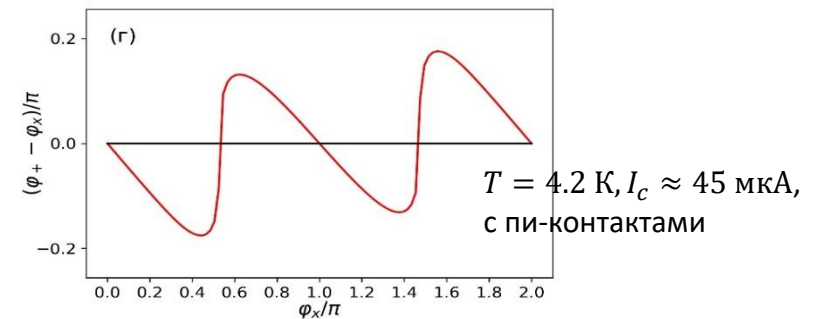
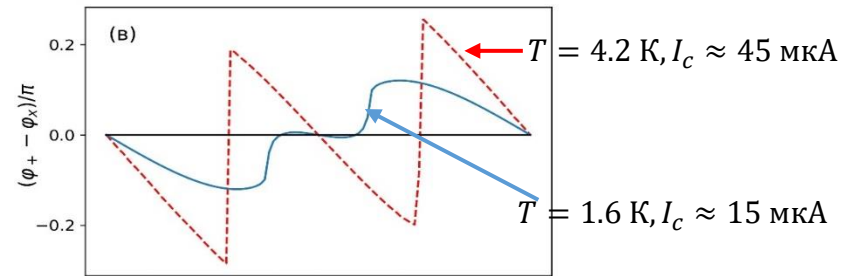
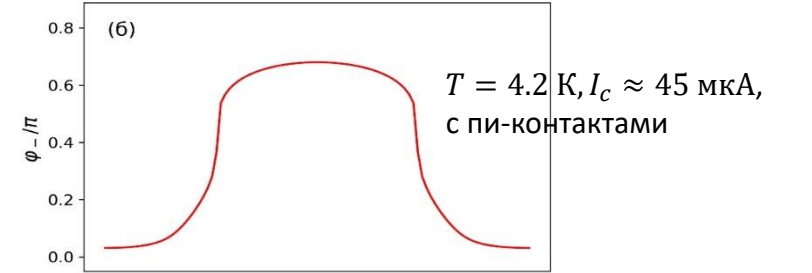
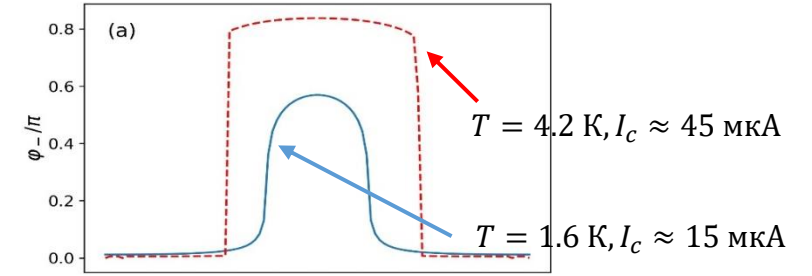
Оптимизация н-СКВИДА

Шумовой ток: $I_T = \left(\frac{2\pi}{\Phi_0}\right) k_B T$

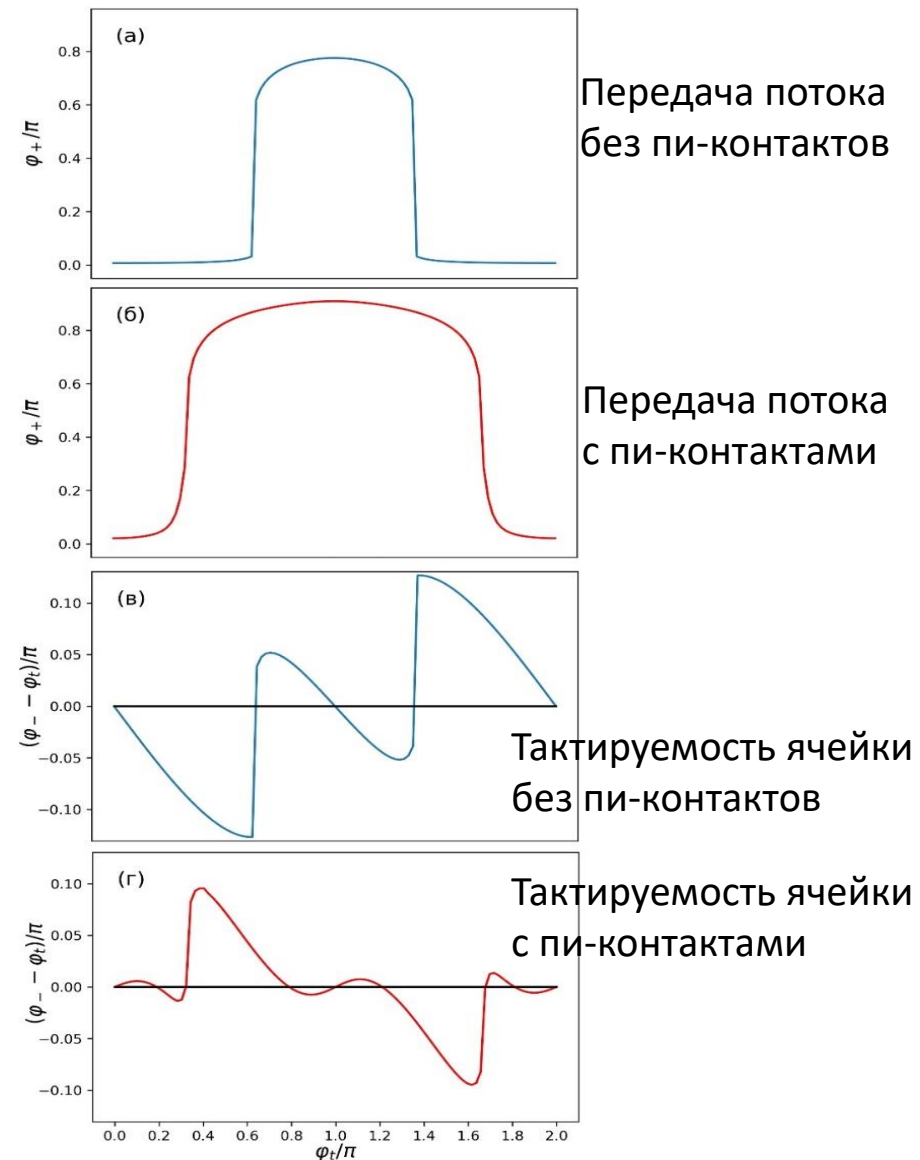
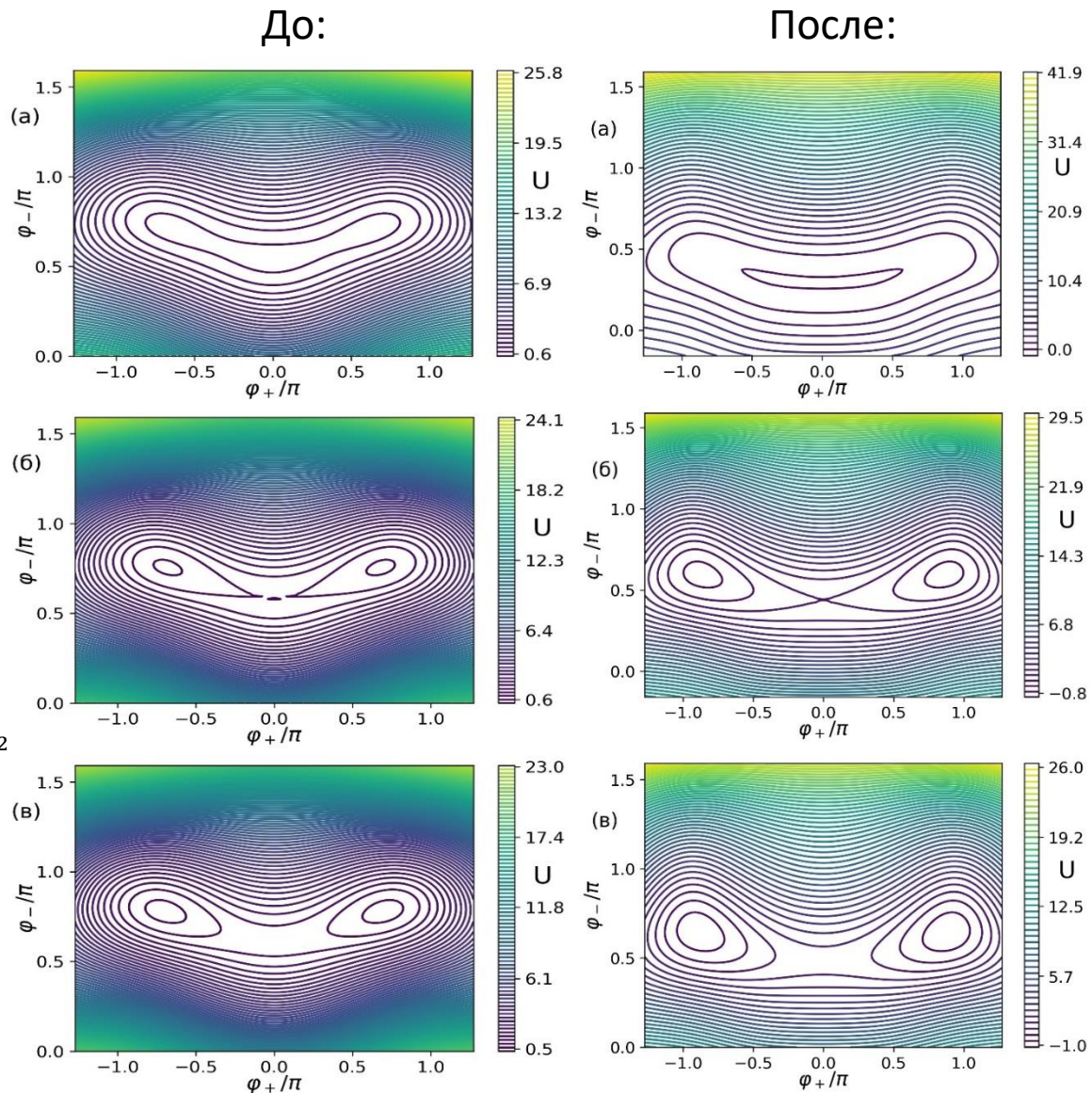
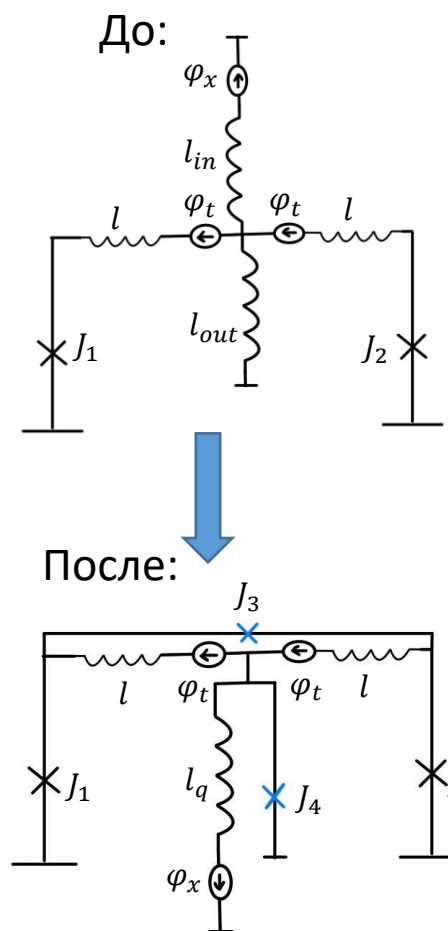
$T = 4.2 \text{ К}, I_T \approx 18 \text{ мкА}, I_c \approx 50 \text{ мкА}$



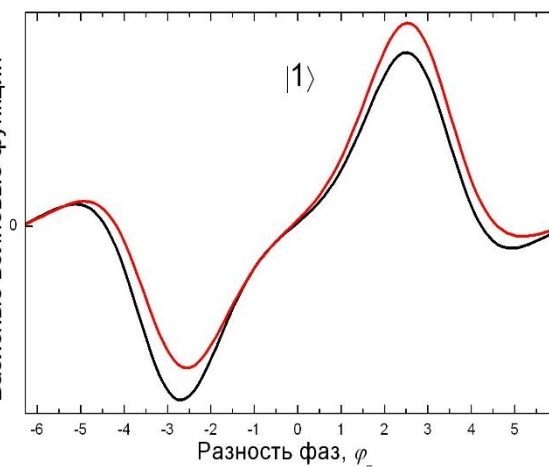
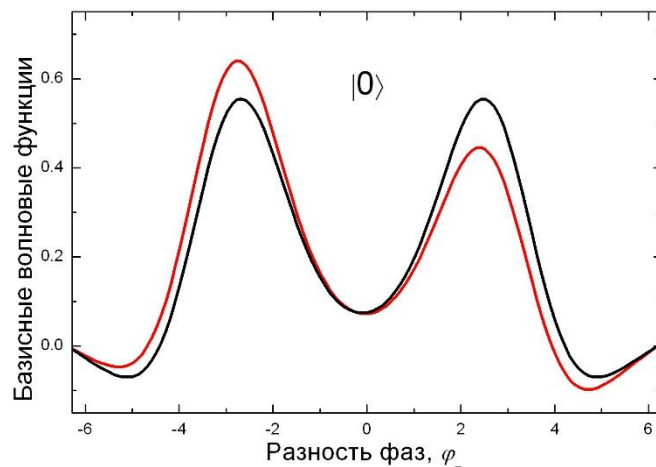
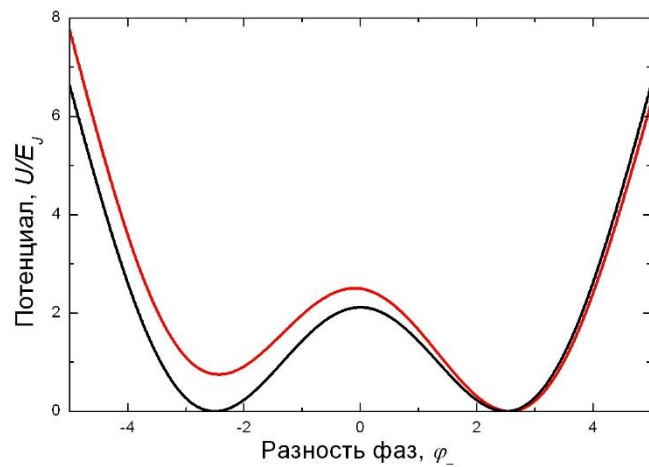
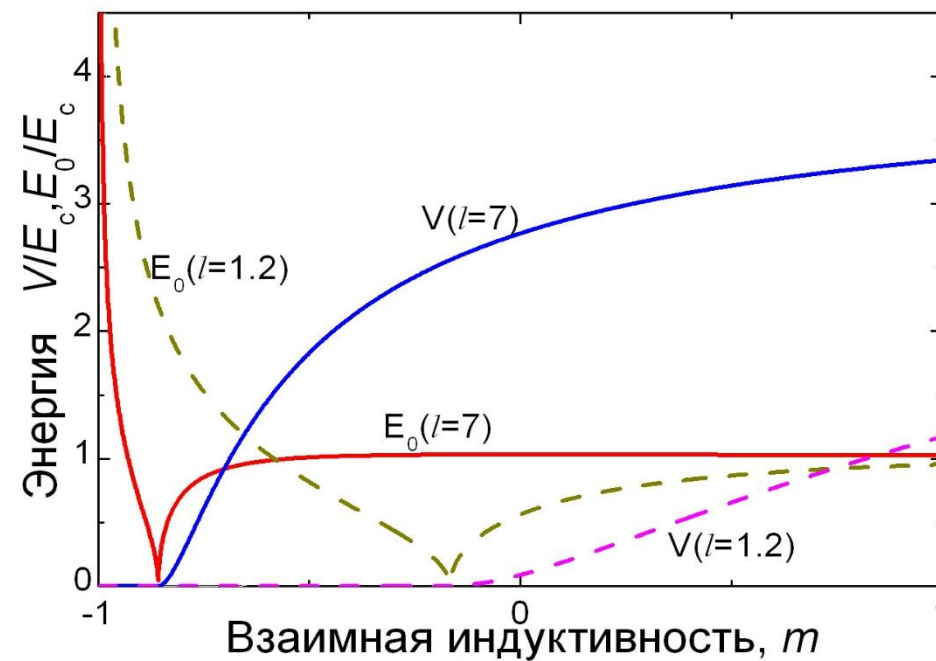
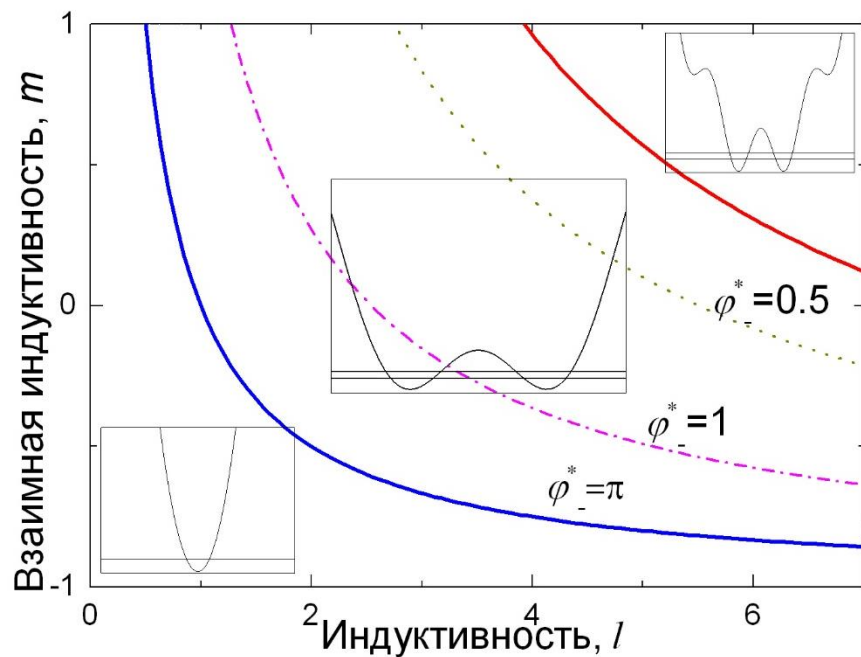
Передача магнитного потока (а, б),
Контролируемость ячейки (в, г)



Оптимизация адиабатического квантового потокового параметрона (АКПП)

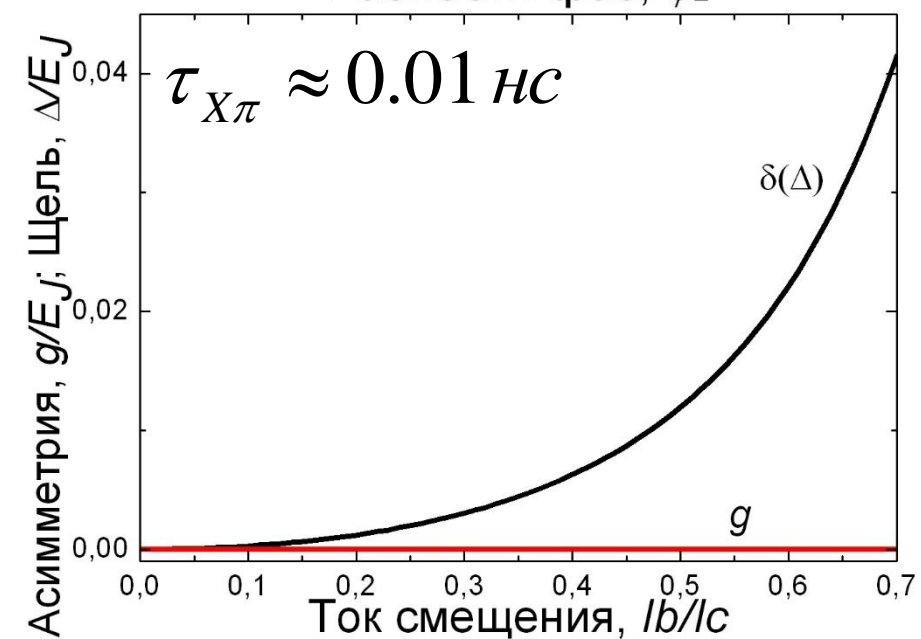
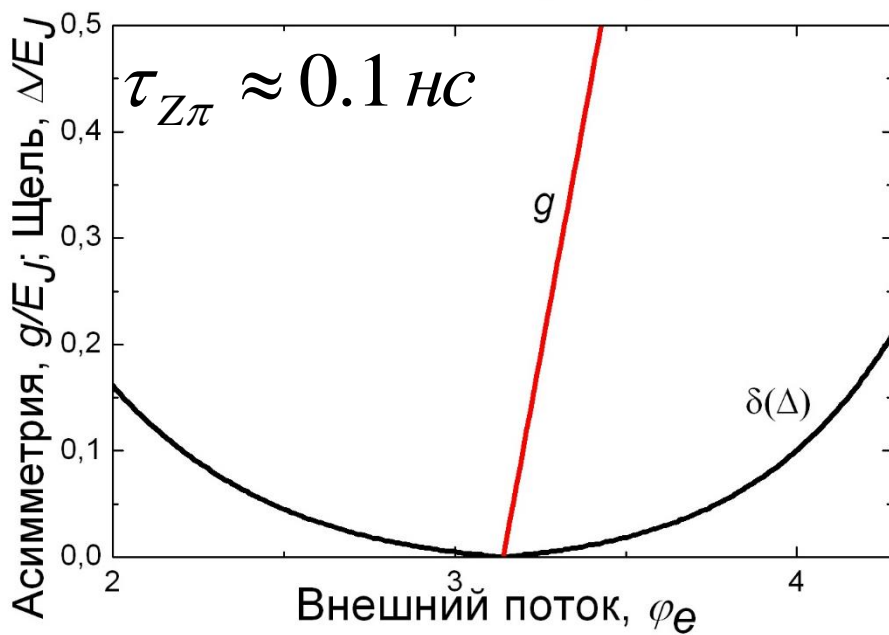
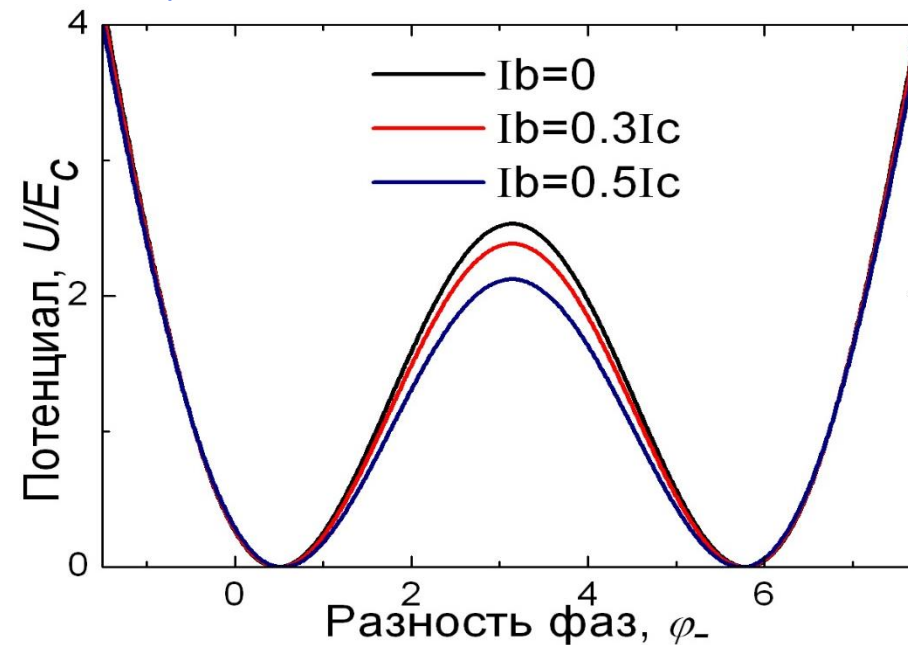
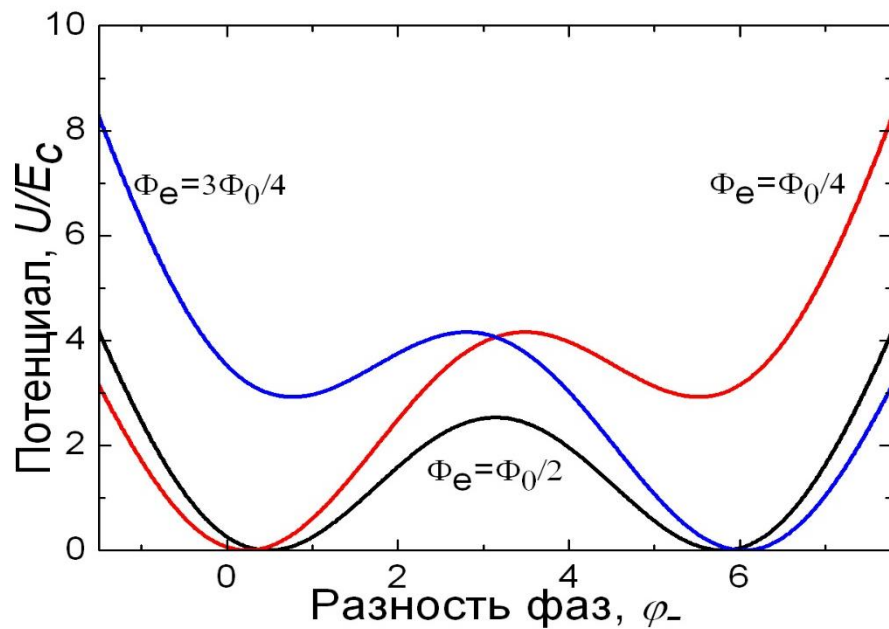


Зона двухъямности и область применения квазиклассики (n-СКВИД)

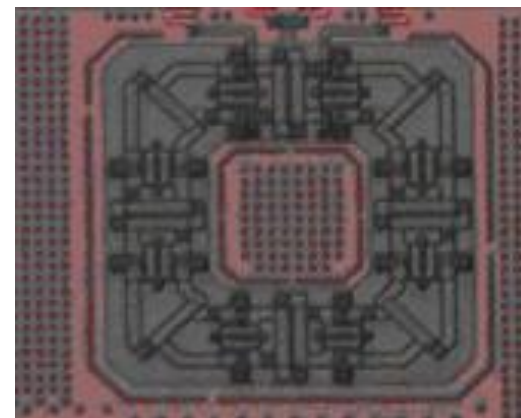
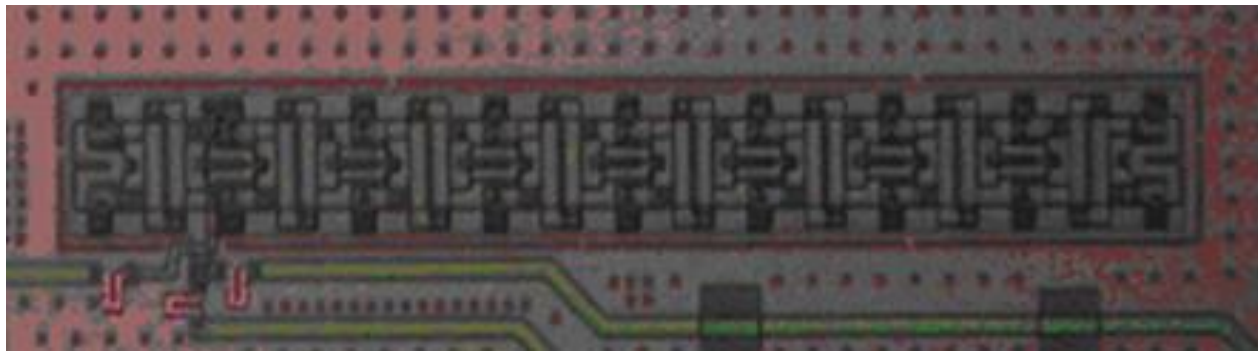
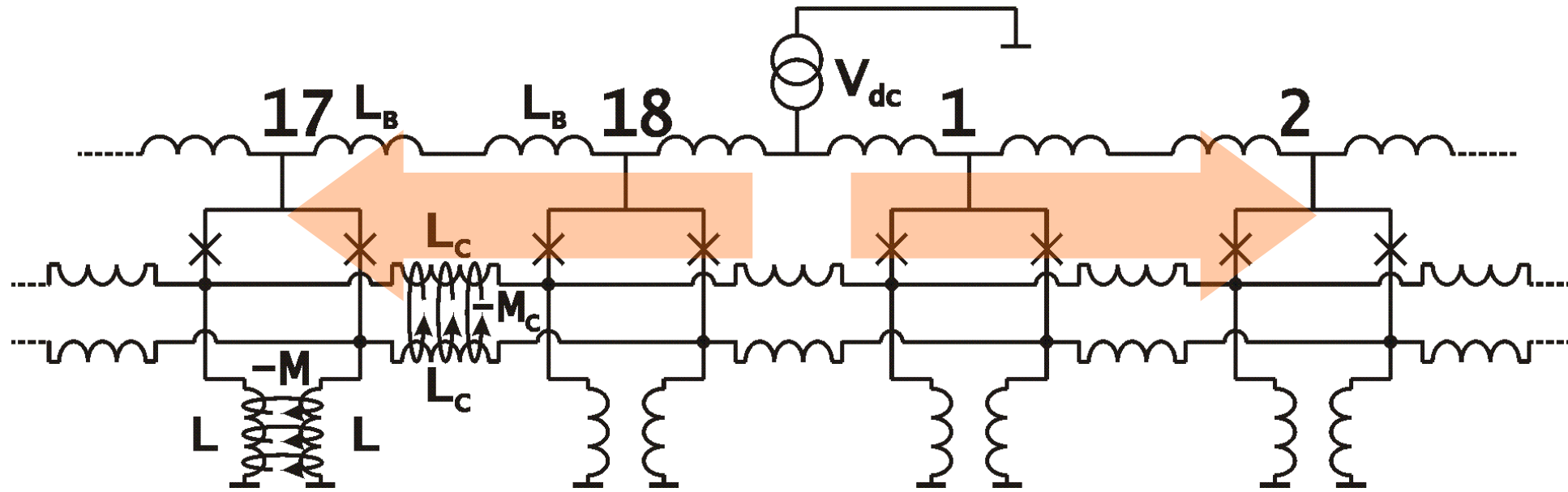


Логические операции в nSQUIDe

Два основных инструмента влияния: ток смещения и внешний поток.



Исследуемая схема реализации динамического кубита



Динамика режима

