COHERENT QUANTUM STATE CONTROL

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Structure:

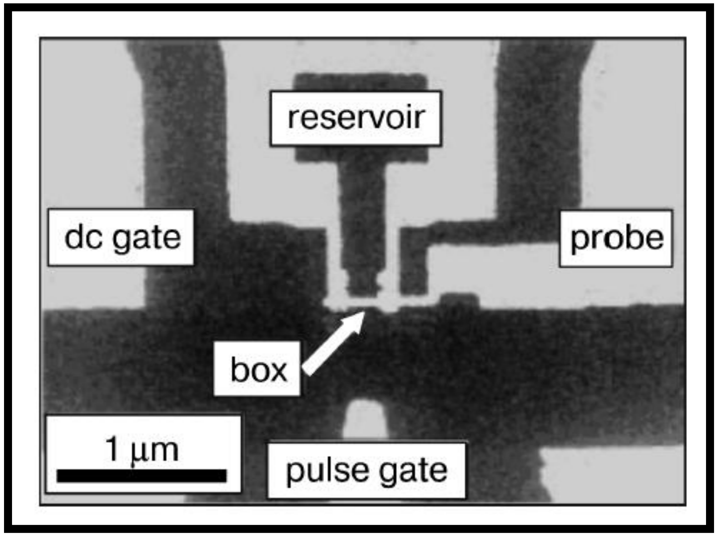
1. Josephson qubit as a quantum system
2. Qubits for superconducting quantum processor: problems and design solutions
3. Qubit coupling methods
4. Analogue control of the quantum processor (Rabi technique)
5. Digital control of the quantum processor (SFQ technique)

Josephson qubit as a quantum system

Josephson qubits are extensively used in modern day quantum processors (Intel, Google, Rigetti, IBM, etc.)

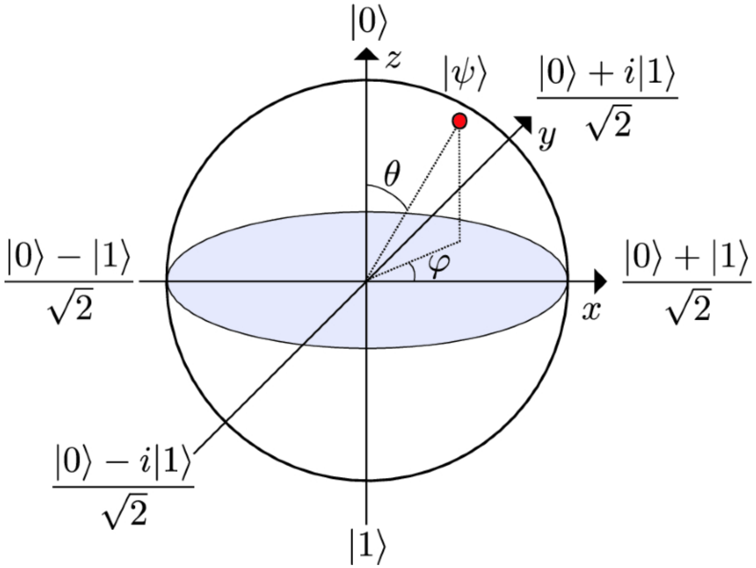
Josephson qubit

- superconducting circuit
- acts as an artificial atom
- quantum anharmonic oscillator



Nakamura Y. et al., Nature 398, 786 (1999)

Bloch sphere



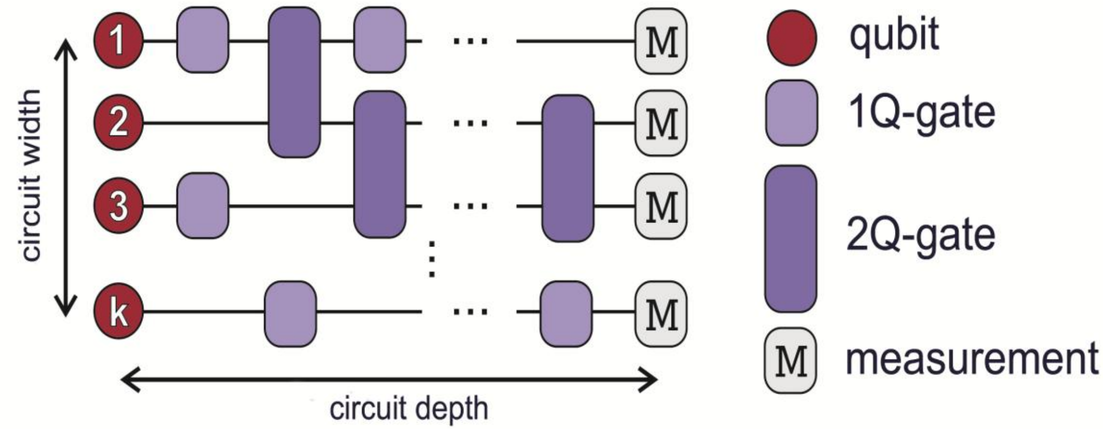
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$\alpha = e^{-i\varphi/2}\cos\frac{\theta}{2}, \quad \beta = e^{i\varphi/2}\sin\frac{\theta}{2}.$$

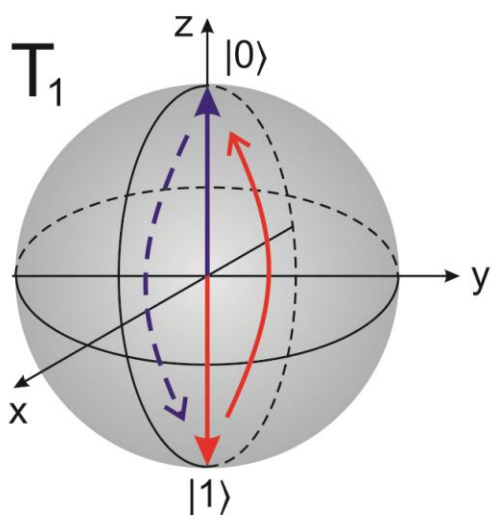
Josephson qubit lifetime restrictions

Main sources of noise in qubits:

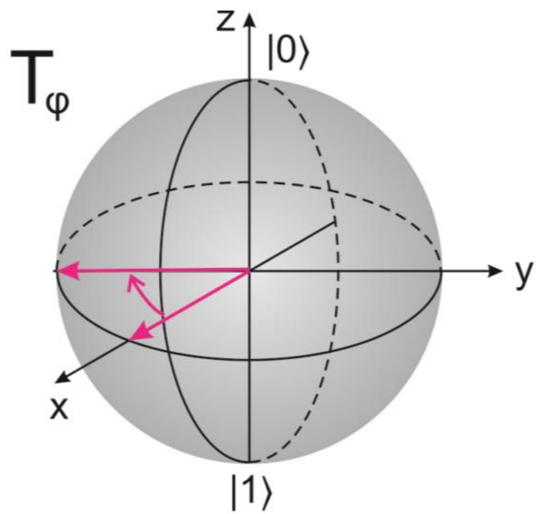
- charge noise
- flux noise
- photon noise
- quasiparticle poisoning



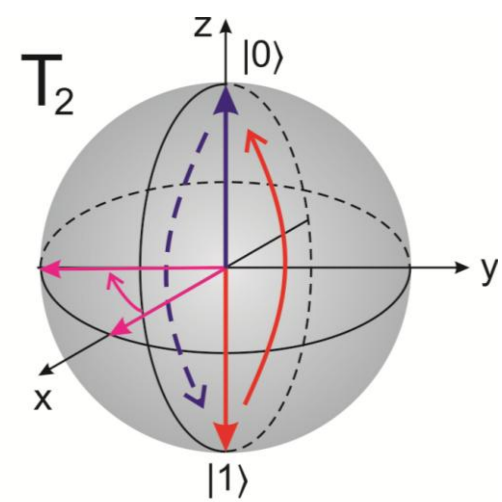
relaxation



pure dephasing

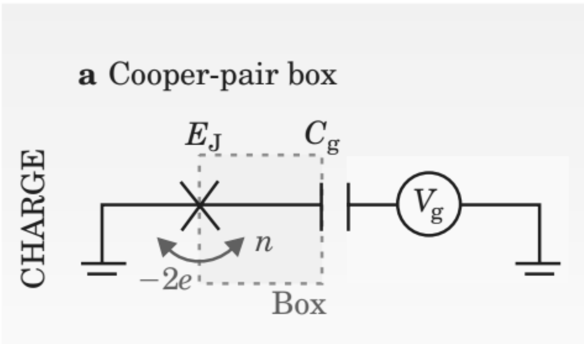


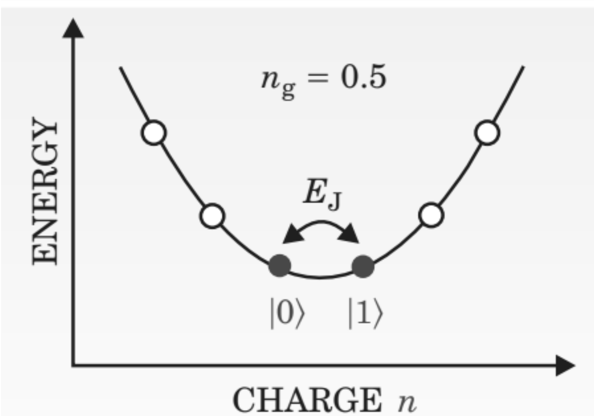
dephasing



Josephson qubit as a quantum system

Charge qubit



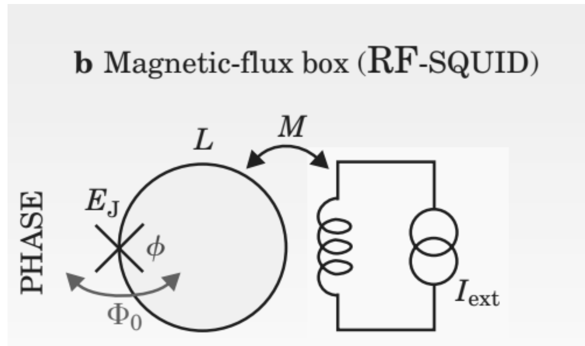


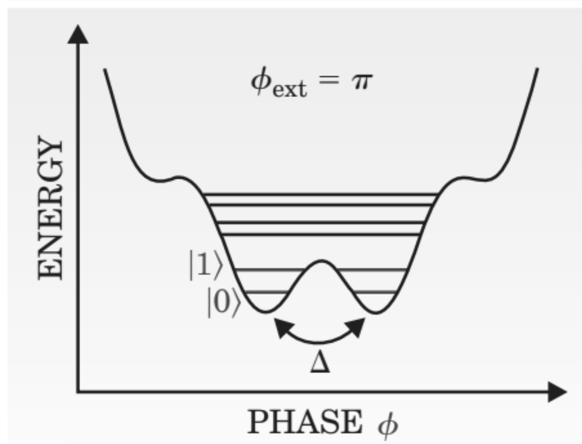
$$H = E_C (N - N_g)^2 - E_J \cos\phi,$$

$$N_g = CV_0/2e$$

$$E_C = (2e)^2/2(C_J + C)$$

Flux qubit

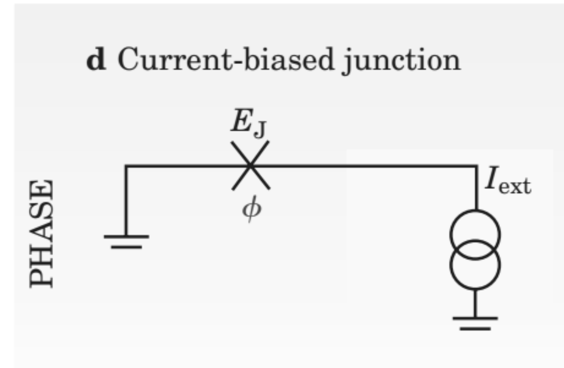


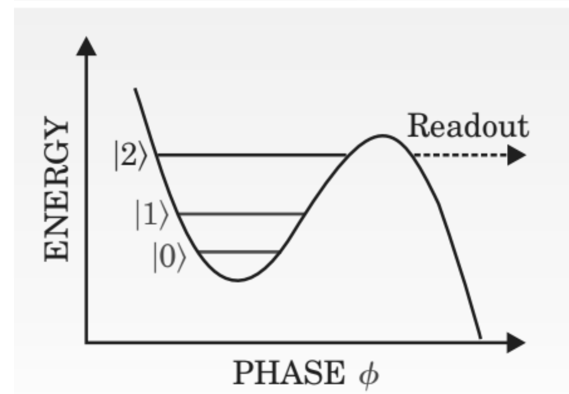


$$H = \frac{q^2}{2C_J} + \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{\phi^2}{2L} -$$

$$- E_J \cos\left[\phi - \Phi \frac{2\pi}{\Phi_0}\right]$$

Phase qubit



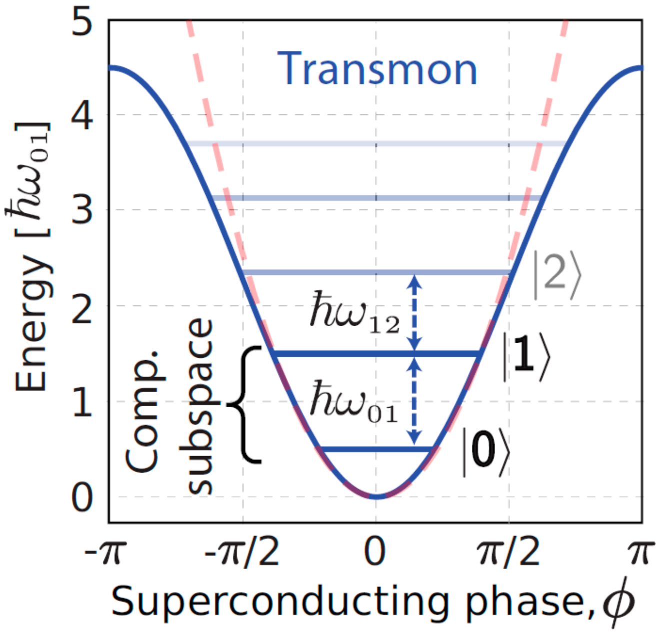


$$H = \frac{(2e)^2}{2C_J} q^2 - I_0 \frac{\Phi_0}{2\pi} \phi -$$

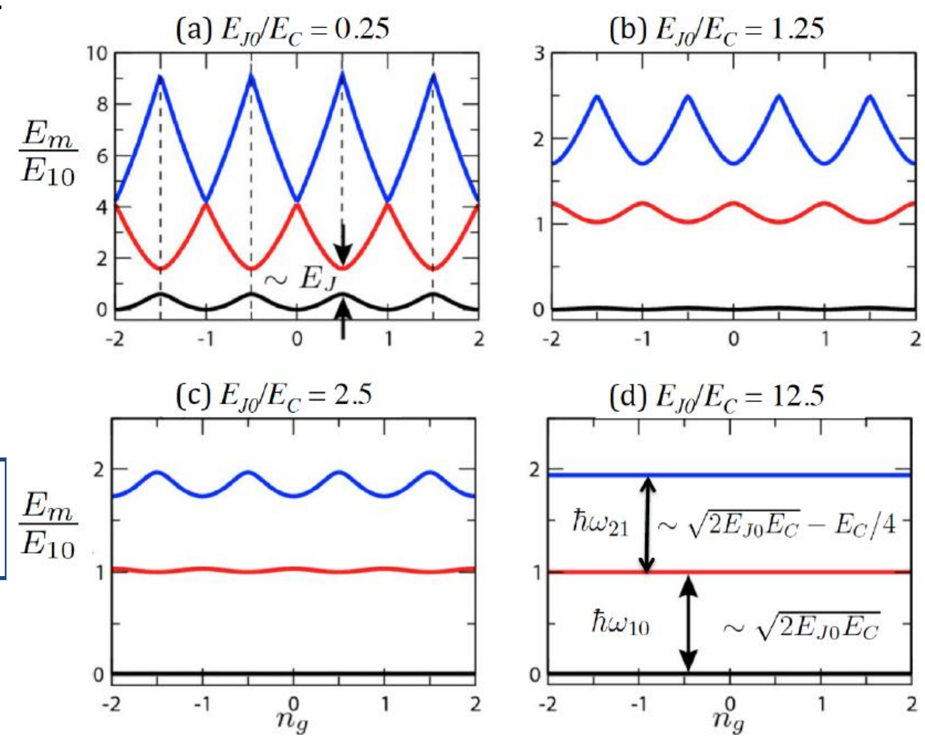
$$- E_J \cos\phi,$$

Transmons

Transmon spectrum



- Persistent to charge and flux noise (lifetimes up to 100 μs)
- Small anharmonicity rate – leakage to the higher level states might be an issue



Transmon hamiltonian

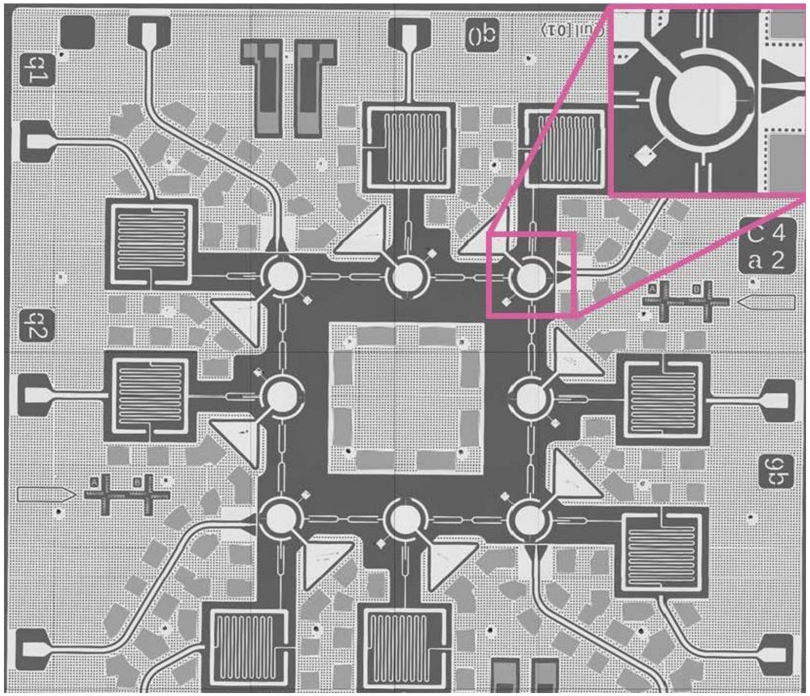
$$H = \omega_{01} a^{\dagger} a + \alpha \left(a + a^{\dagger}\right)^4 - \varepsilon(t)\left(a + a^{\dagger}\right)$$

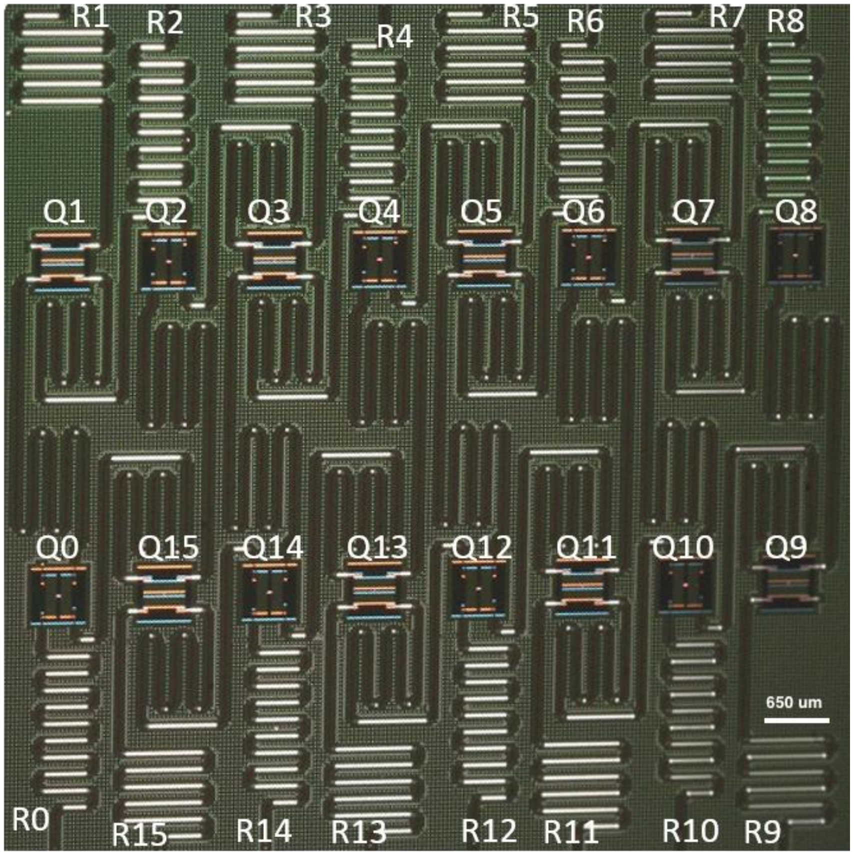
$$\omega_{01} = \sqrt{8E_J E_C} \qquad \alpha = -E_C/12$$

J. Koch et al. Phys. Rev. A 76, 042319

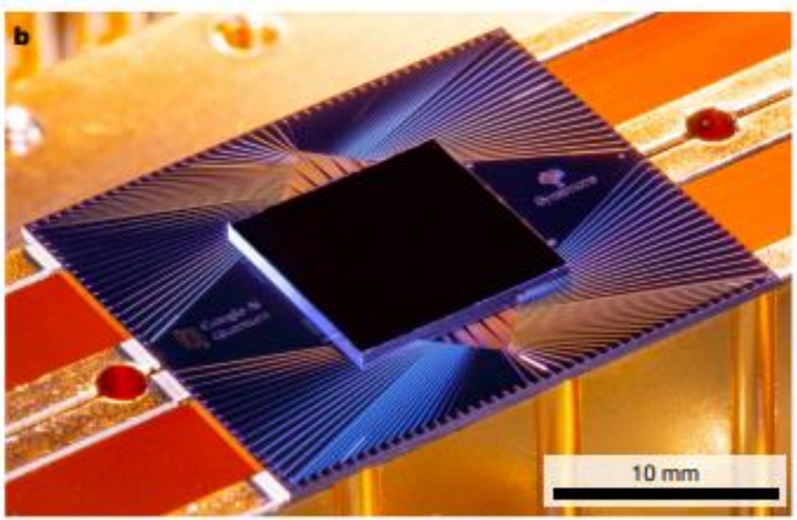
Transmon–based quantum proccessors

Rigetti 8Q Agave





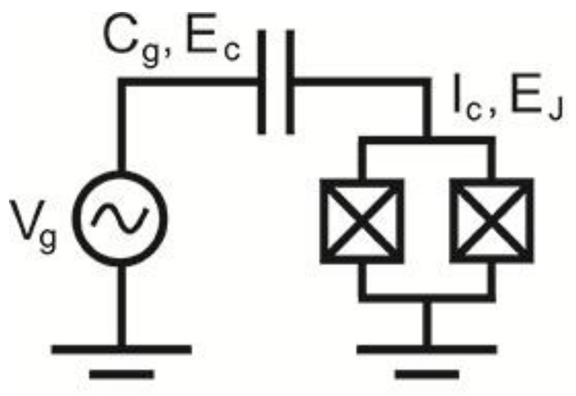
IBM 16Q Rueschlikon



Google Sycamore

Transmon design

Transmon scheme



Transmon topology solutions:

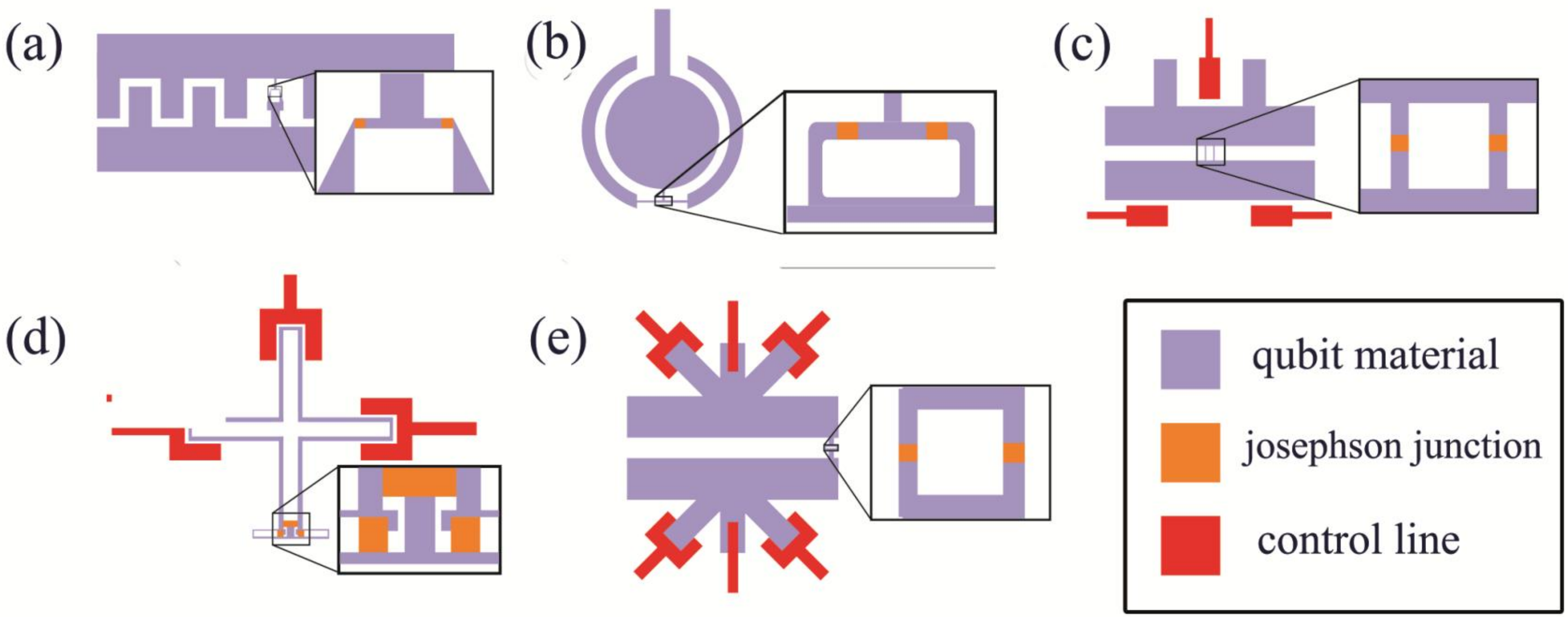
(a) Classic transmon

(b) Radial transmon (Rigetti)

(c) IBM transmon

(d) Xmon (Google)

(e) Starmon (Intel)

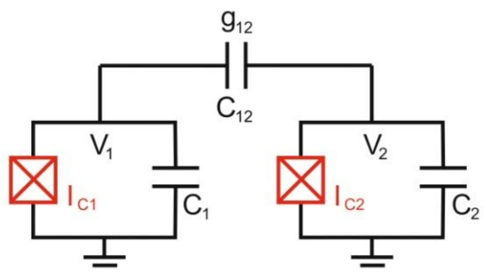


Vozhakov V., Bastrakova M. et al. 10.3367/UFNr.2021.02.038934

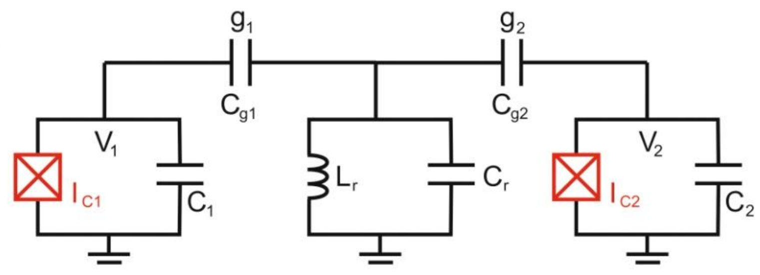
Connecting qubits

- 1Q-gates require qubit to be **isolated** from its neighbors
- 2Q-gates require qubit to be **connected** with its neighbors

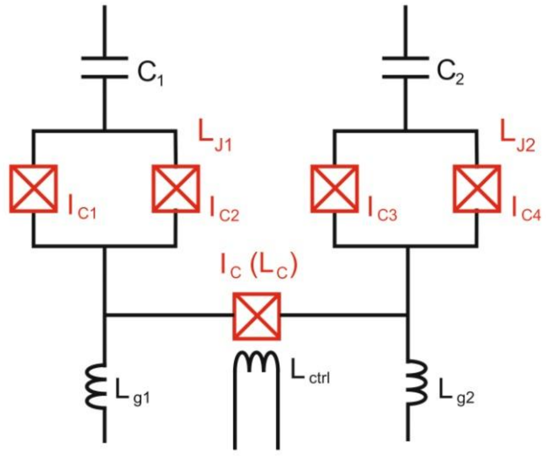
direct capacitive coupling



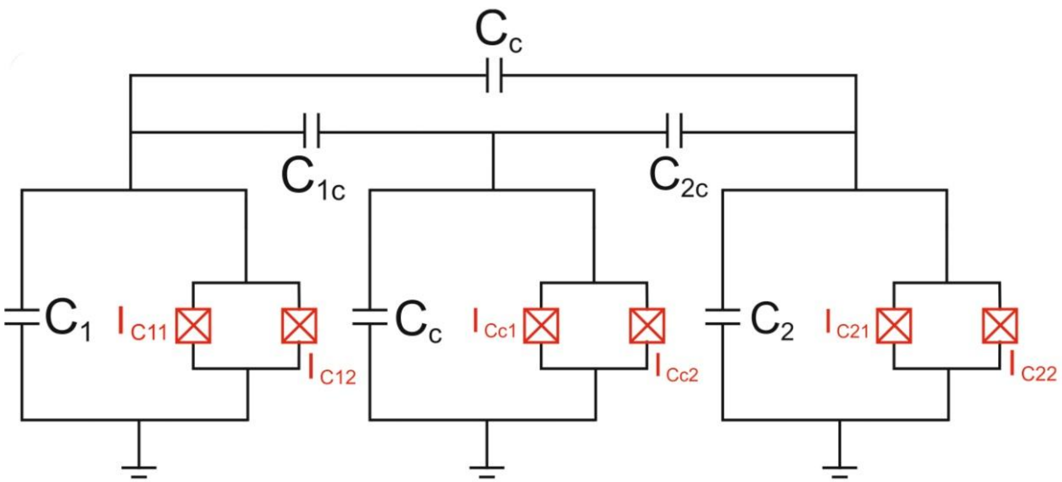
coupling via resonance



coupling via josephson junction

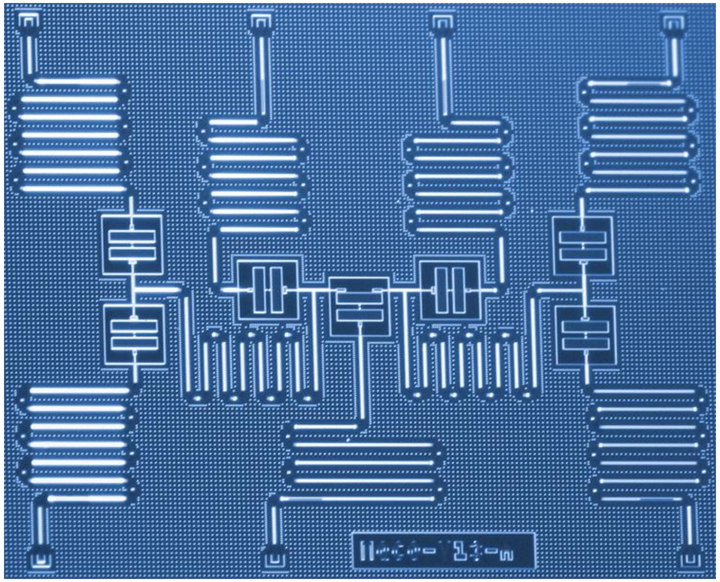


coupling via extra josephsion qubit



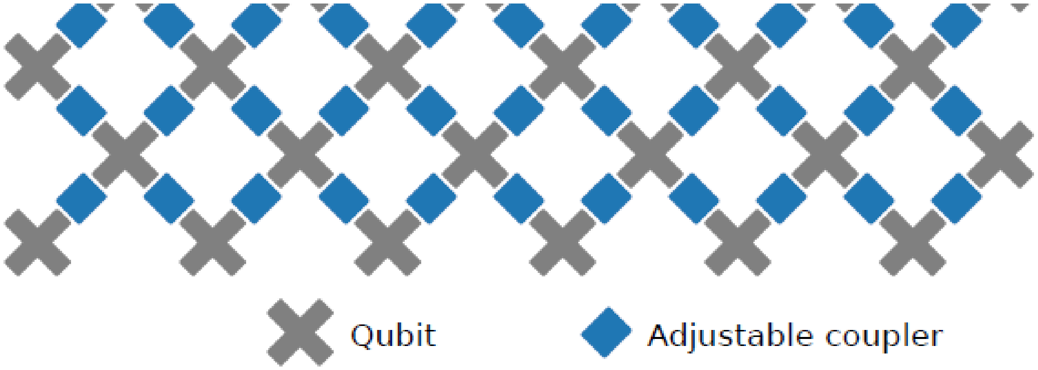
Connection examples

Rigetti 8Q
Capacitive coupling between non-tunable and tunable qubits



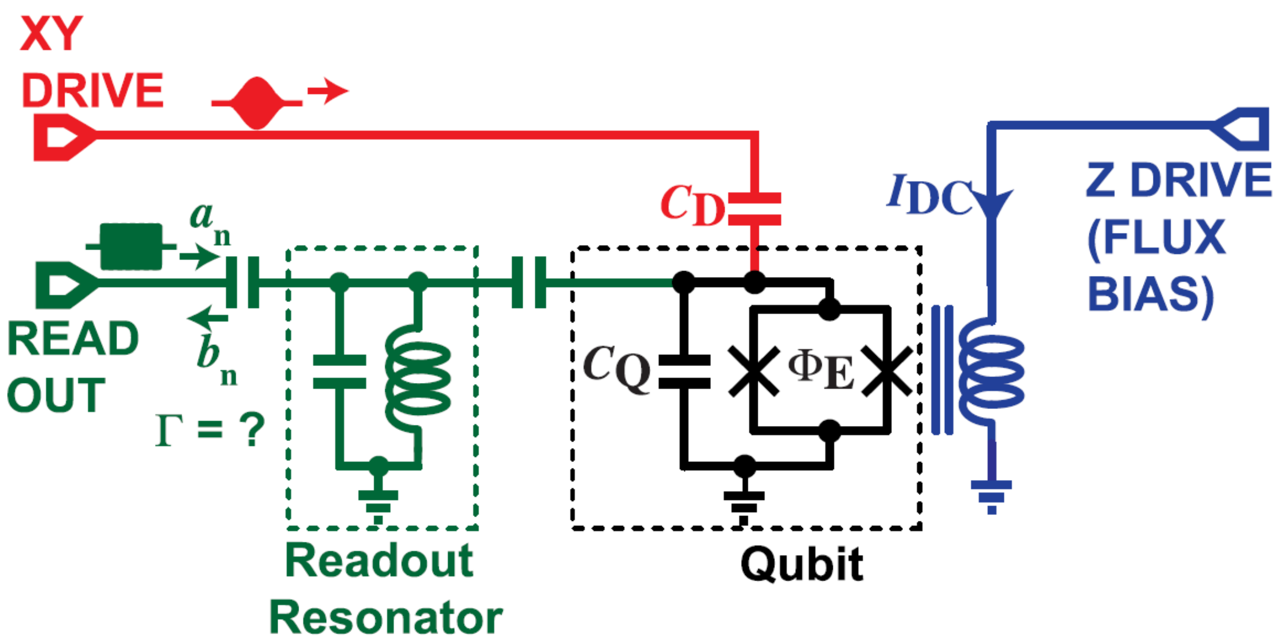
IBM 7Q
Resonance coupling between non-tunable qubits

Google Sycamore
Tunable qubits connected by tunable couplers



Quantum gates

- Operation length should be significantly less than qubit lifetimes $t_{op} \ll T_1, T_2$
- Qubit control can be implemented via microwave (XY-control) and flux lines (Z-control)
- Using both types of control makes control easier but leads to additional crosstalk



Quantum gates

	1Q-gate	2Q-gate
microwave only	X-, Y-rotations using arbitrary wave generator (AWG) and I/Q mixer Virtual Z-gate	bSWAP gate CR gate RIP gate MAP gate
microwave and flux	Z-rotations using flux control	CPHASE gate iSWAP gate Adiabatic Z-gate TQA gate

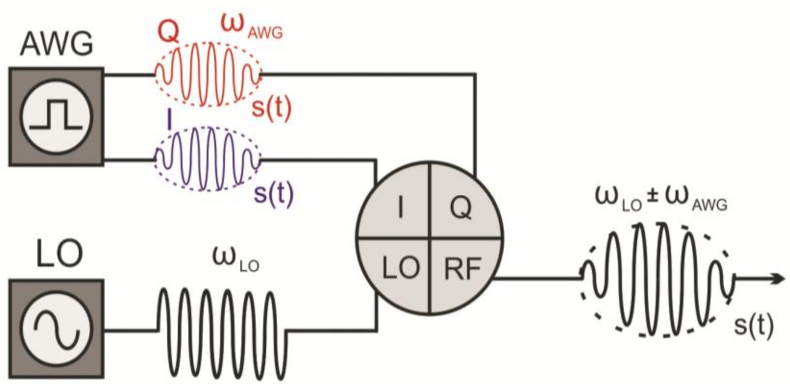
Transmon control using Rabi technique

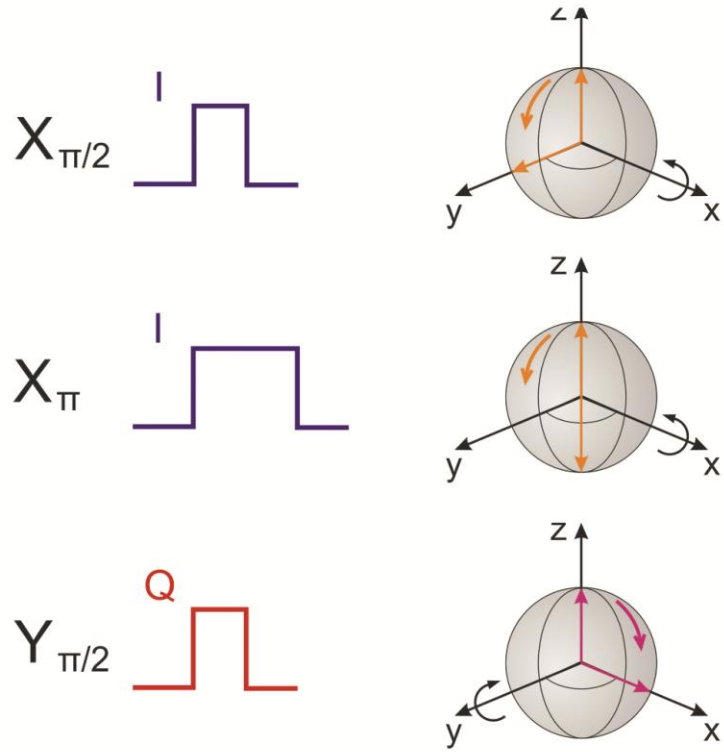
Control pulse: $\varepsilon(t) = A_R cos(\omega_R t)$

A_R – Rabi amplitude ω_R – Rabi frequency $\omega_R = \omega_{01} + \delta\omega$

ω_{01} – qubit frequency $\delta\omega$ – detuning

Qubit control connection scheme





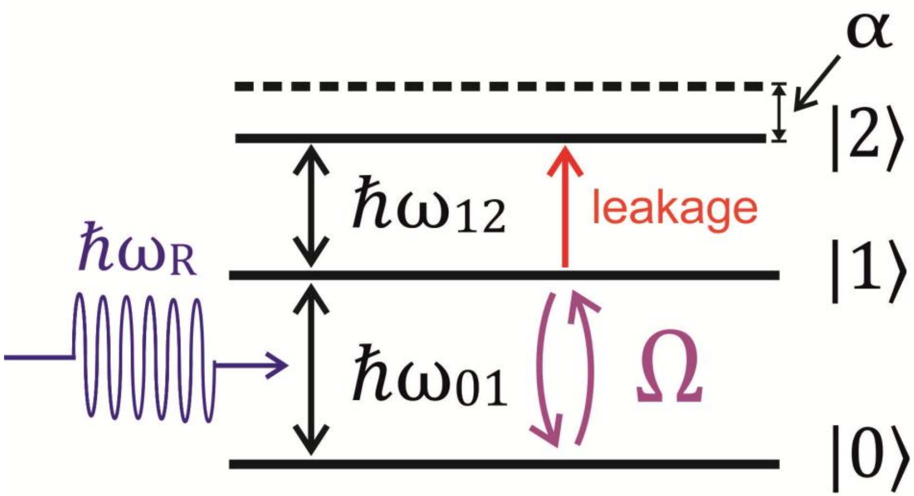
Implementation of the different qubit operations

$$H = -\frac{\omega_{01}}{2}\sigma_z + n_c V_d(t)\big(\cos(\omega_{01}t)\,\sigma_y - \sin(\omega_{01}t)\,\sigma_x\big)$$

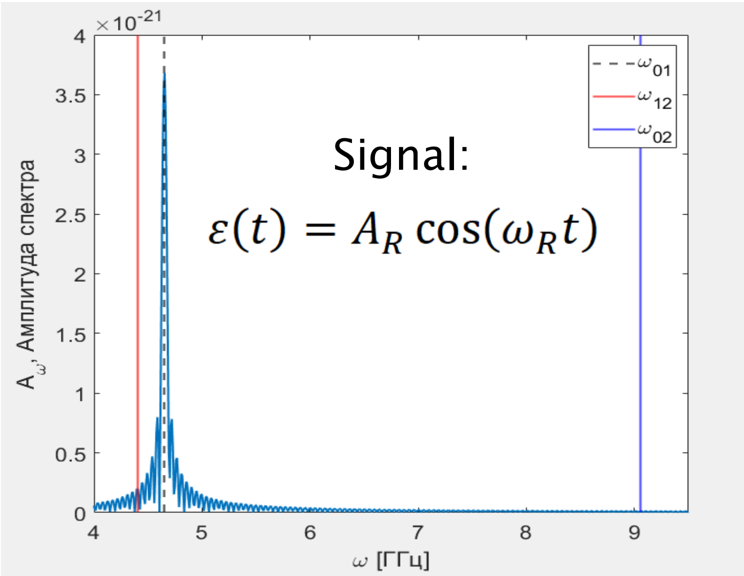
Implementing π/2 rotation using Rabi technique

Qubit parameters: $\omega_{01} = 4.652$ ГГц $\omega_{12} = 4.402$ ГГц

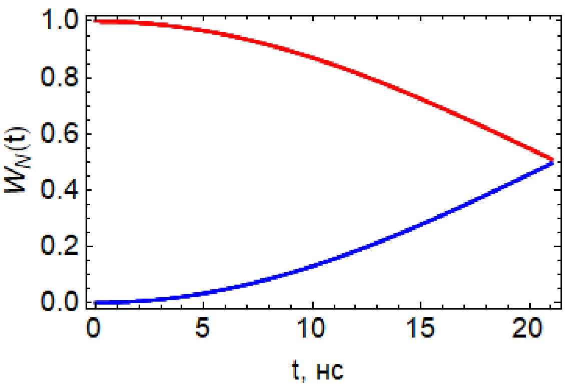
$\delta\omega = 0.001$ ГГц $A_R = 1{,}39 \cdot 10^{-26}$



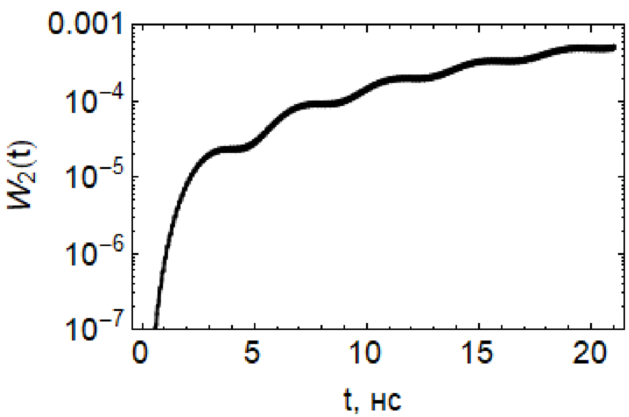
Fourier spectrum



State populations



Leakage to the second state



$$\Omega = \sqrt{A_R^2 + \delta\omega^2}$$

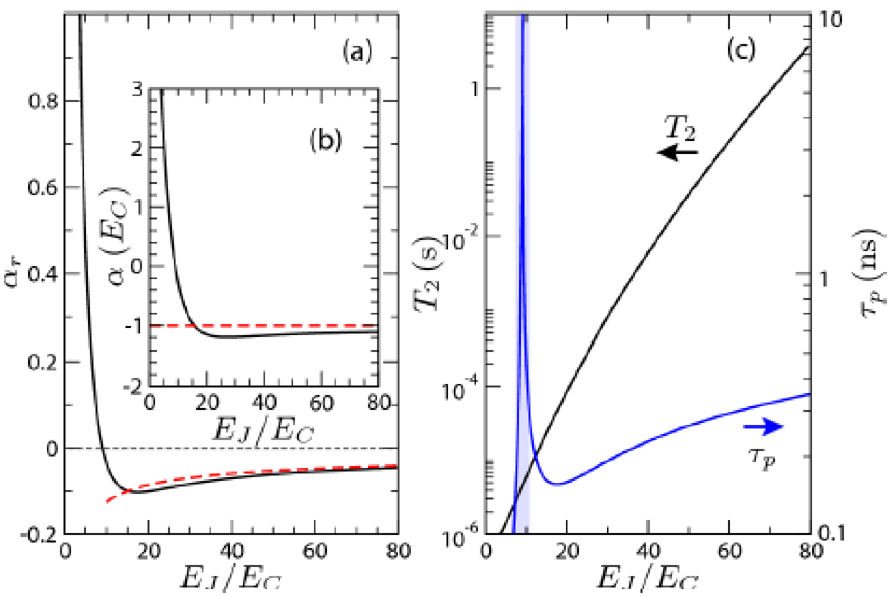
$$W_{|0\rangle \to |1\rangle} = \frac{A_R^2}{\Omega^2} \sin(\Omega t)$$

Rabi technique limitations

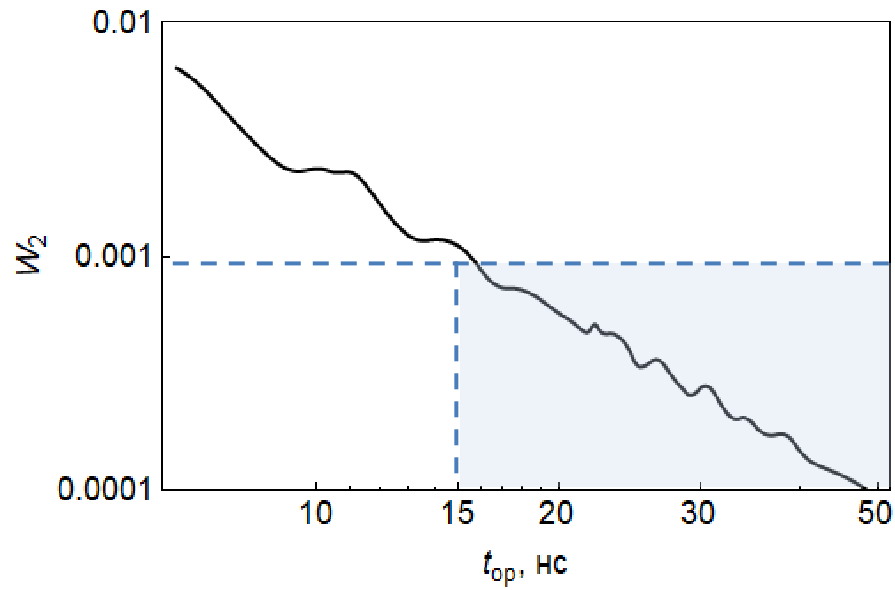
There are restrictions for Rabi pulse length defined by Duffing-Hubbard parameter α_r and qubit lifetime

$$\tau_p = 1/|\omega_{01}\alpha_r| \qquad \alpha_r = \alpha/\omega_{01}$$

$$\tau_p \ll T_1, T_2$$



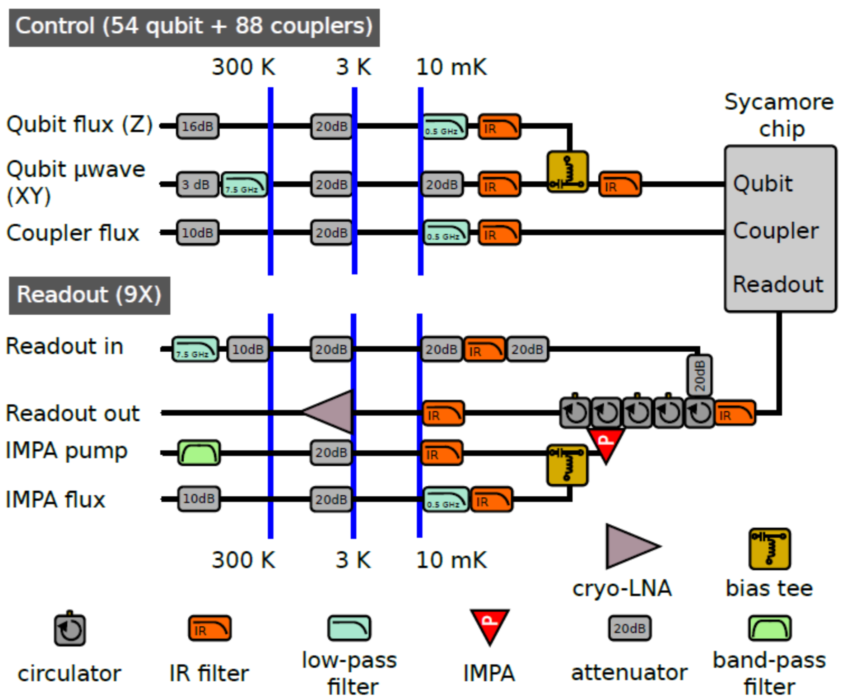
J. Koch et al.
Phys. Rev. A 76, 042319

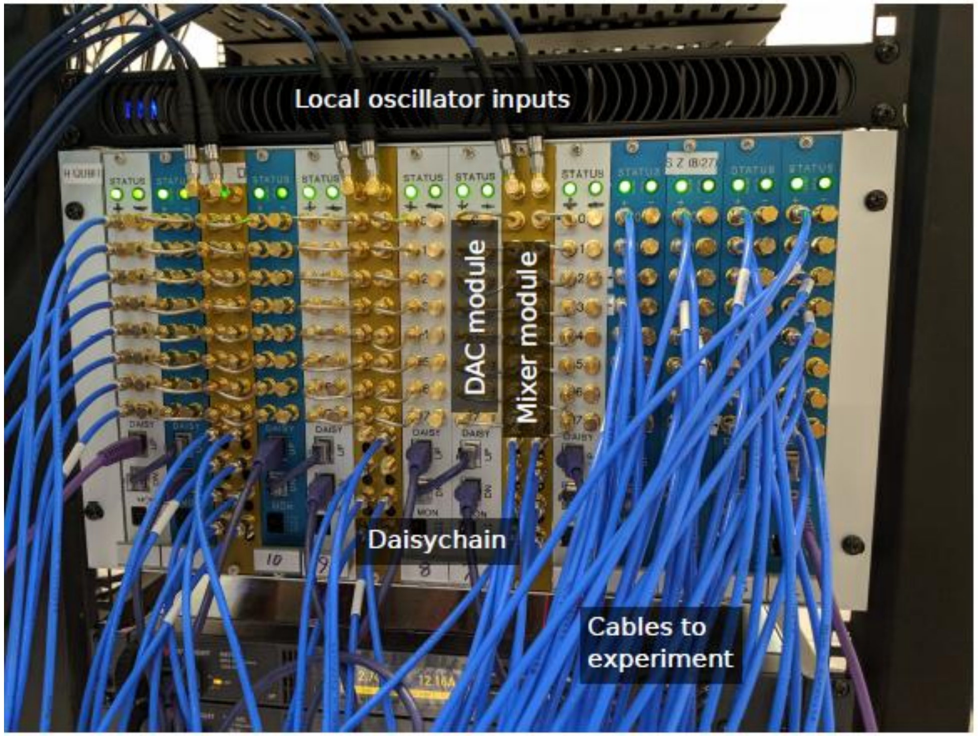


For the leakage less than 0.001, operation length should be about dozens of nanoseconds

Conclusion: Rabi technique has significant limitation in qubit control (w/o any additional procedures)

Rabi technique limitations



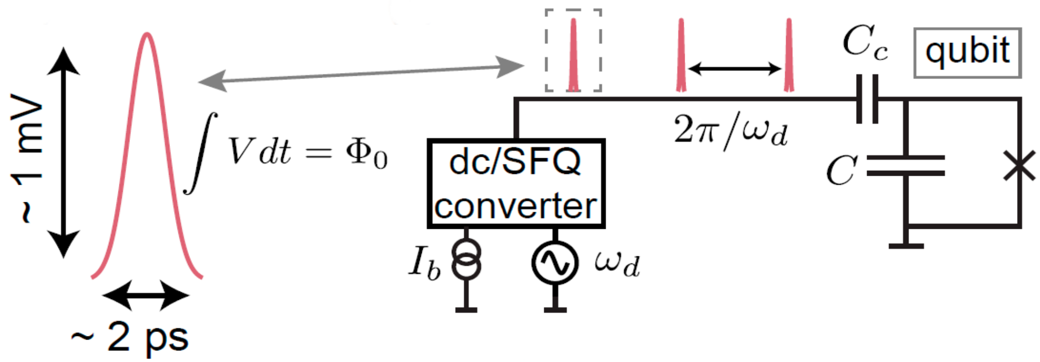


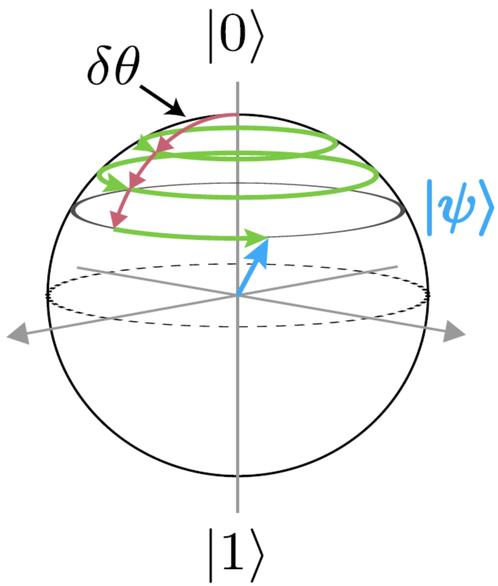
Processor with 53 qubits and 88 tunable couplers already needs extensive wiring. This problem can be resolved by withdrawal from HF control system.

Arute F et вl. Nature 574, 505–510 (2019).

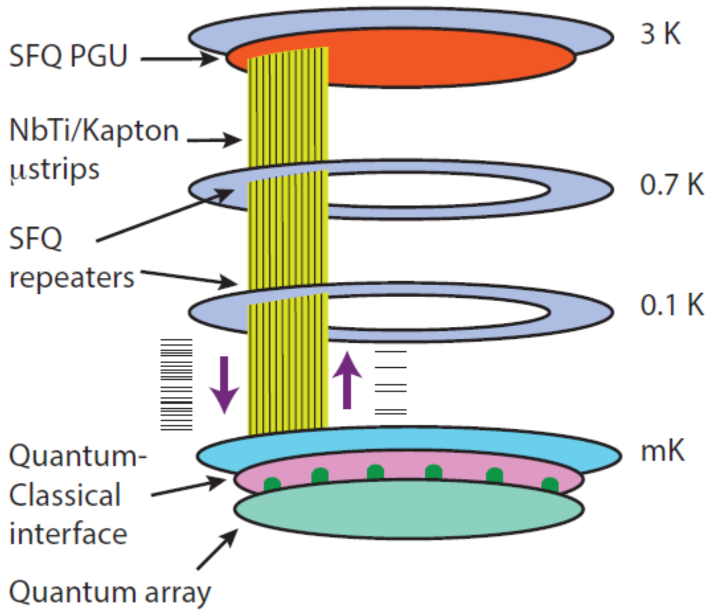
SFQ technique basics

Alternative idea: using single flux quantum (SFQ) pulses, every pulse induces rotation on the Bloch sphere by δθ.





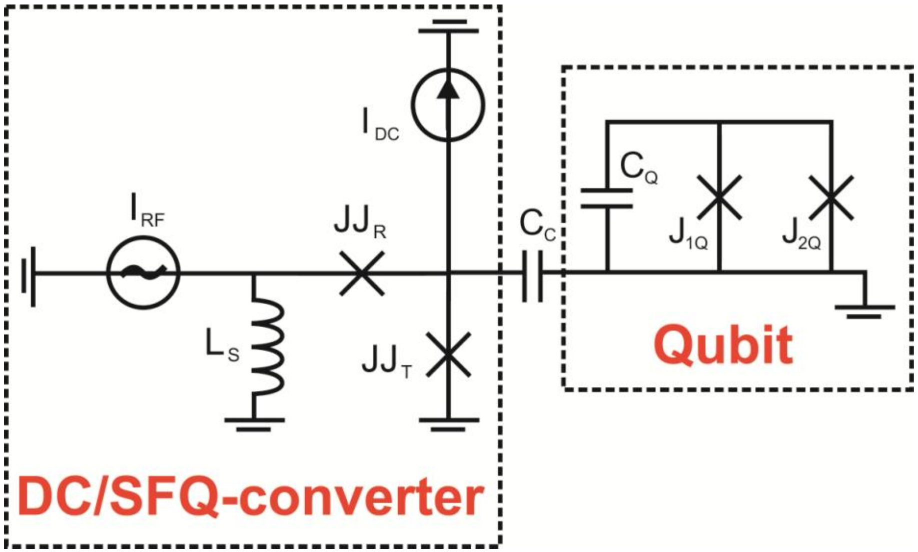
Quantum processor and classic interface connection scheme



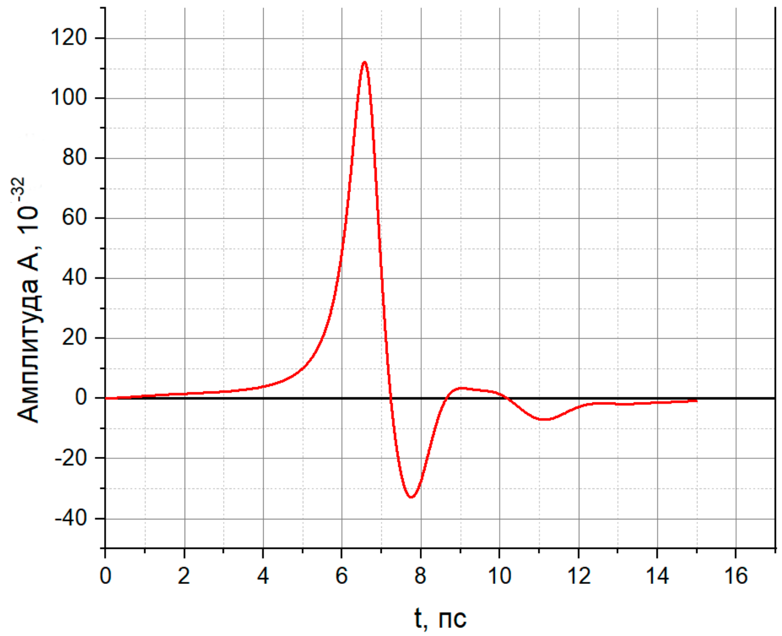
R. McDermott et al. 2018 Quantum Sci. Technol. 3 024004

DC/SFQ-converter

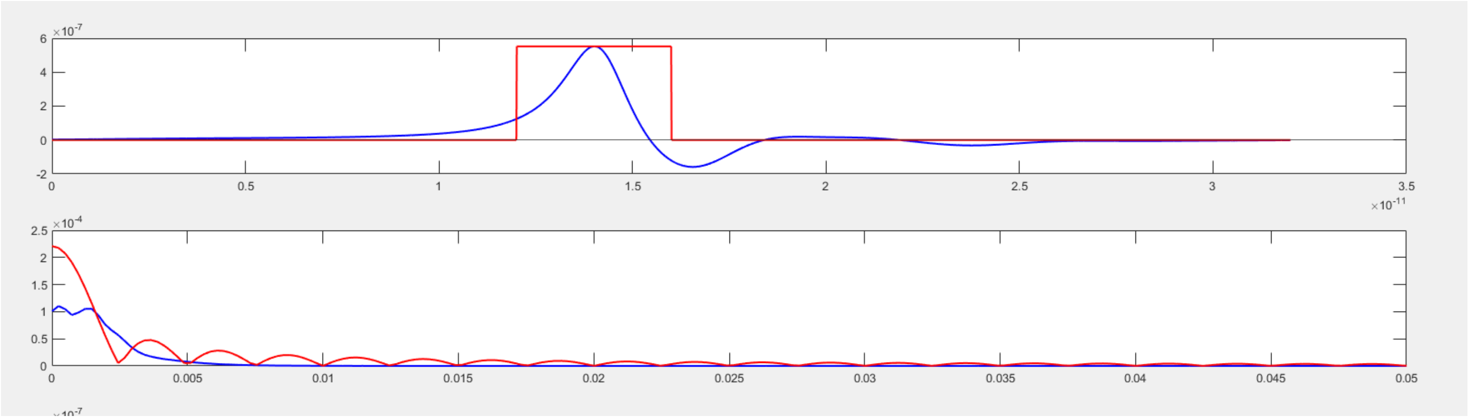
Connection scheme



Qubit pulse

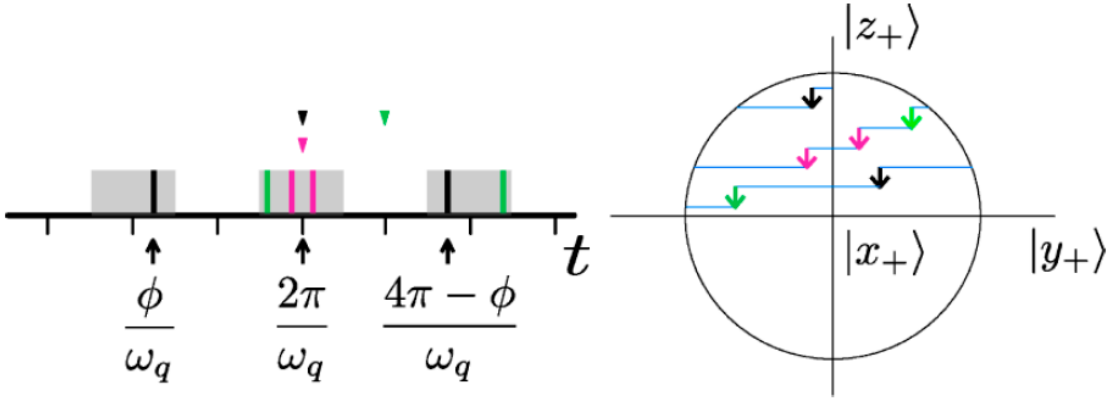


DC/SFQ-converter and rectangle pulse comparison



SCALLOP sequences

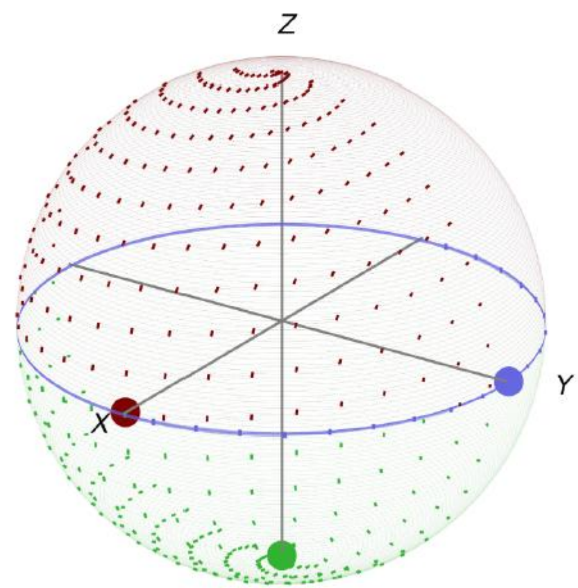
Main idea: Implementing pulses symmetrically with respect to the qubit frequency. By increasing the number of pulses on the qubit frequency, it is possible to reduce overall leakage.



$|x_+\rangle \longrightarrow |z_-\rangle$ (green)

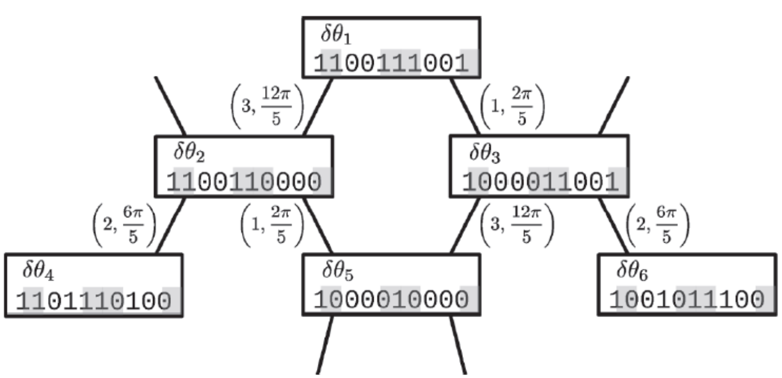
$|z_+\rangle \longrightarrow |x_+\rangle$ (red)

$|y_+\rangle \longrightarrow |y_+\rangle$ (blue)



SCALLOP sequences pair selection (m,ϕ).
Elements are corresponding to the times

$\frac{\varphi}{\omega_q}$ and $\frac{2\pi m-\varphi}{\omega_q}$

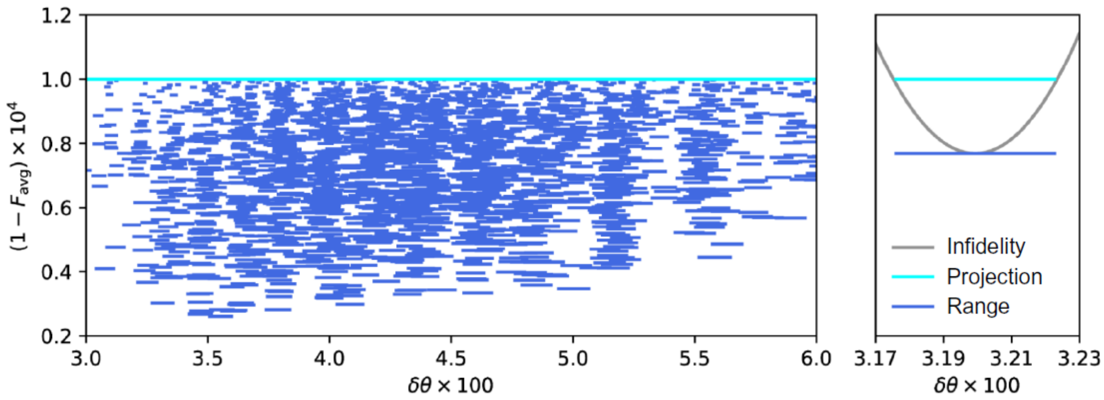


K. Li, Phys. Rev. Applied 12, 014044

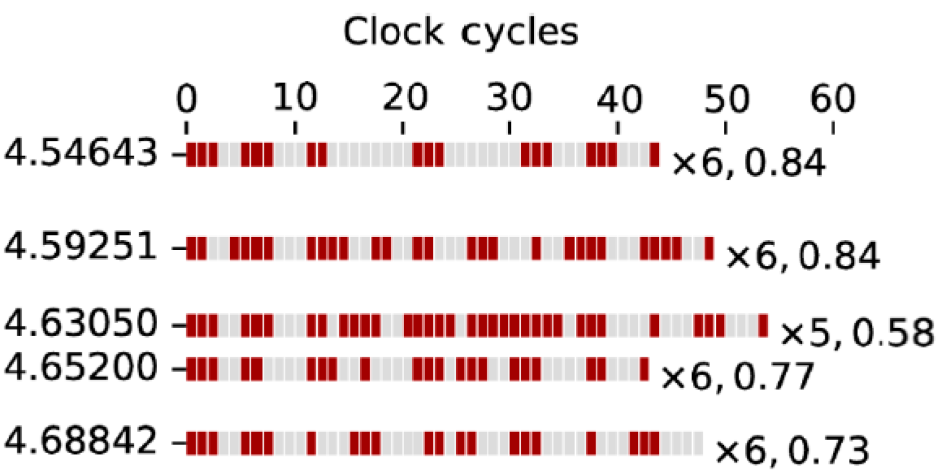
SCALLOP sequence selection

Selection parameters:
- Qubit frequency
- Qubit anharmonicity
- One pulse rotation
- Clock frequency
- Number of cycles

Angles and leakage values for different SCALLOP sequences



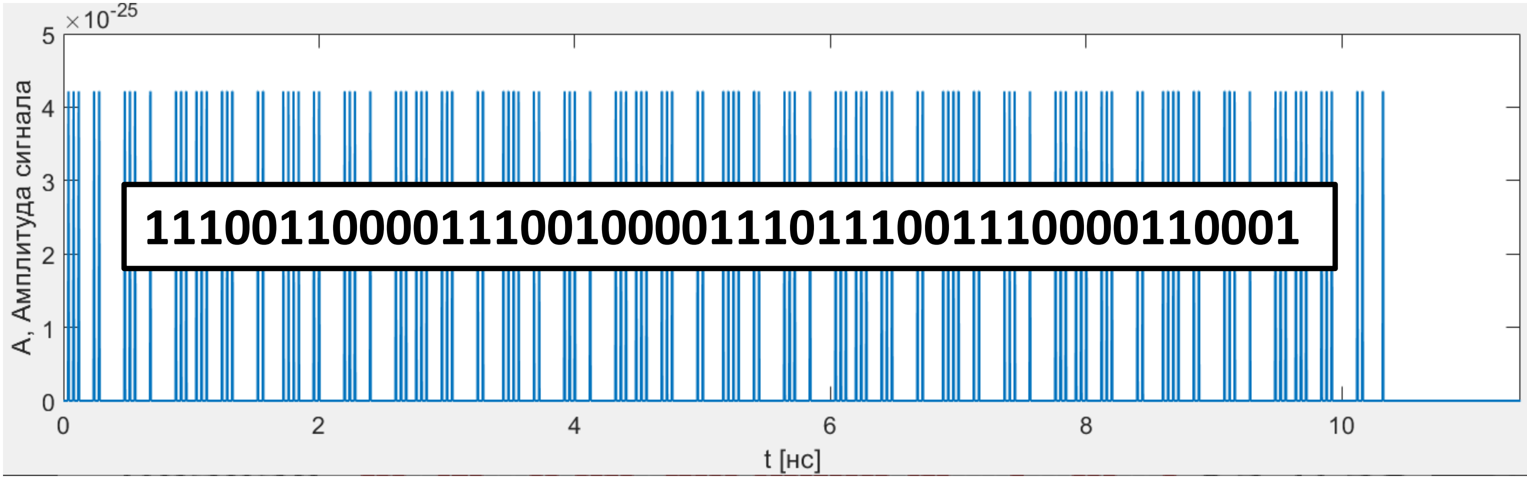
Examples of the SCALLOP sequences for the different qubit frequencies with the corresponding number of cycles



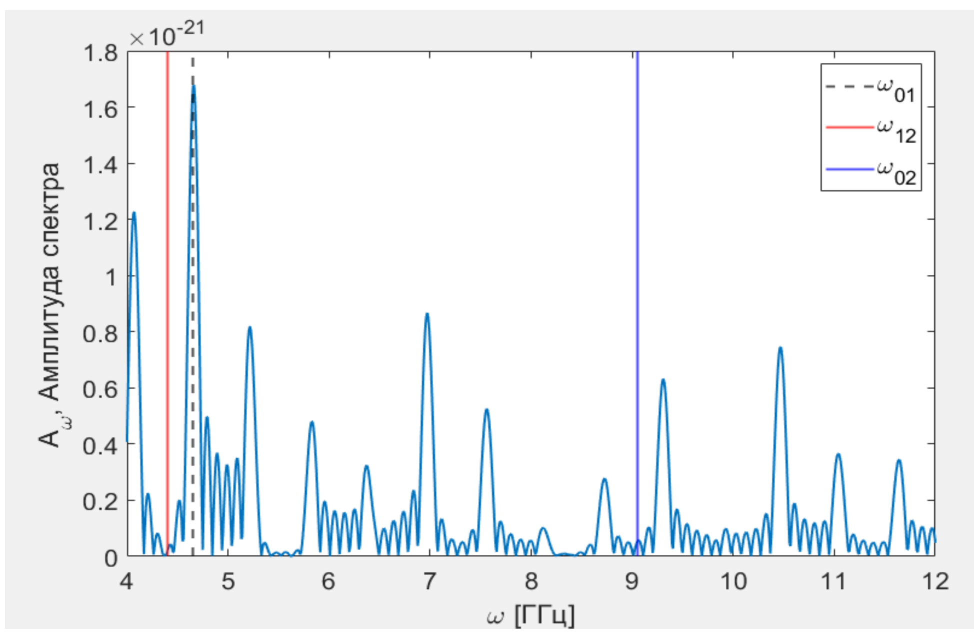
K. Li, Phys. Rev. Applied 12, 014044

Implementing π/2 rotation using SFQ technique

Number of cycles $N_c = 6$, implementing $Y_{\pi/2}$

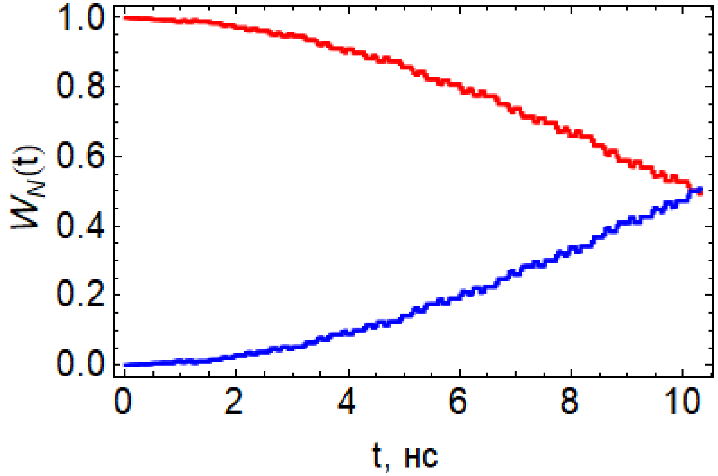


Fourier spectrum

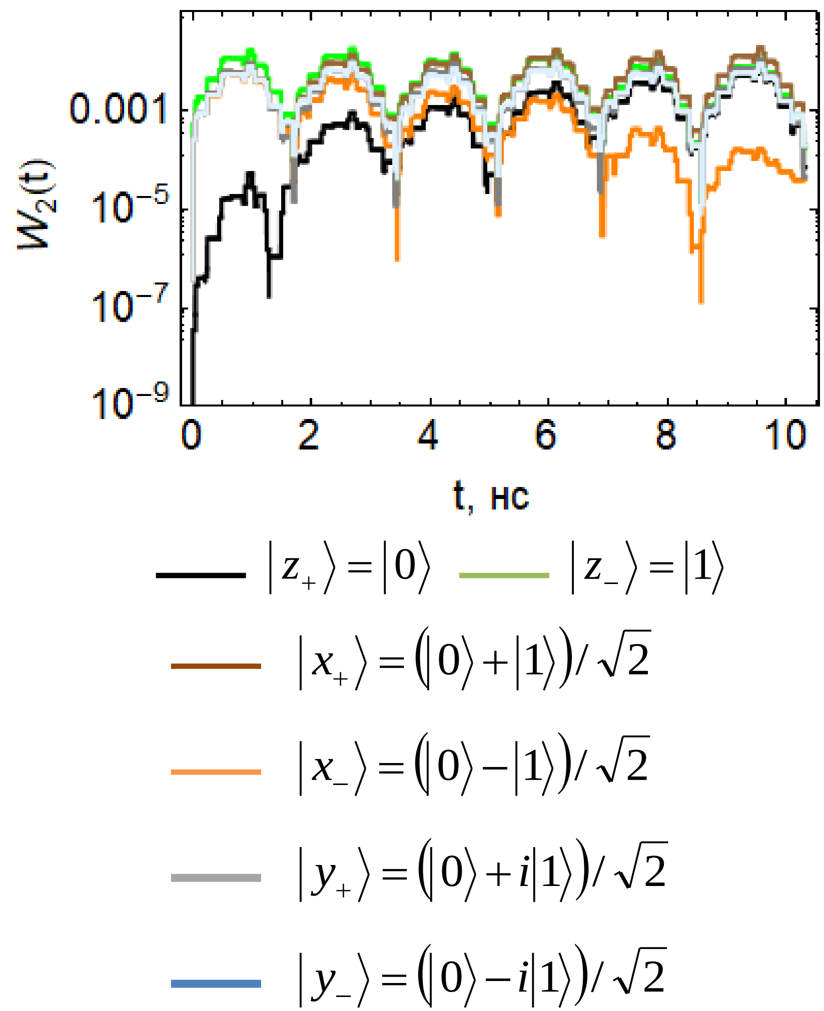


Implementing π/2 rotation using SFQ technique

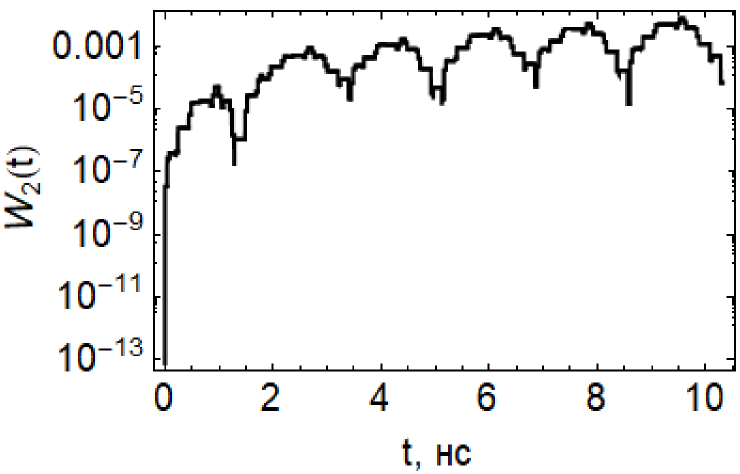
Qubit state population



Leakage (W_2) with different initial



Leakage



Average leakage $1 - \langle F \rangle = 6.03 * 10^{-5}$

Consclusions

- Quantum gates should be implemented as fast as possible because of the external noise coming from the environment, control lines and qubit itself

- Analogue control schemes using HF-devices are able to control already existing quantum processors but their usage is limited

- Using superconducting control schemes can solve this problems

- Using digital control schemes makes control more flexible and helps to reduces the undesirable leakage to higher qubit states