IQM

WE BUILD QUANTUM COMPUTERS

Winter School

Superconducting quantum processor design with KQCircuits®

KQC

github.com/iqm-finland/KQCircuits

CI passing | DOI 10.5281/zenodo.4944796 | License GPLv3

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Schedule

Monday	Tuesday	Wednesday	Thursday	Friday
Caspar & Pavel	Alessandro	Alessandro	Niko & Eelis	Caspar
Introduction to QPU design Installing KQCircuits First look around	Introduction to designing Create a custom qubit element	Design a custom chip	Finite element simulations	Mask export Composite waveguides GUI

Workshop format

Introductions + hands-on exercises

- Follow along
- Ask for help if you are stuck

Questions?!

Ask questions any time!

- ✋ Raise hand (or just interrupt)
- Zoom chat
- Discord

🔴 Presentations are recorded

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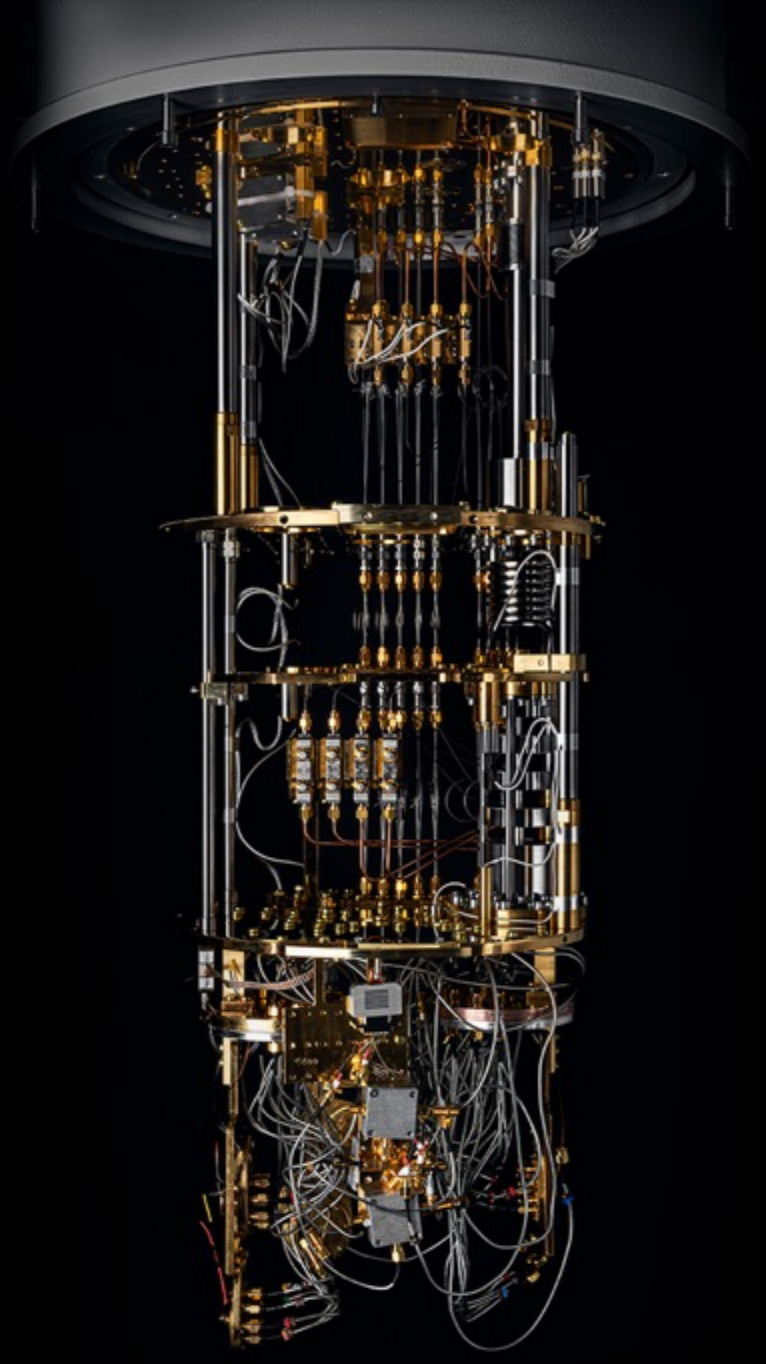
W E   B U I L D   Q U A N T U M   C O M P U T E R S

Introduction to superconducting quantum processor design



Caspar Ockeloen-Korppi
Team leader, Design and Simulation team

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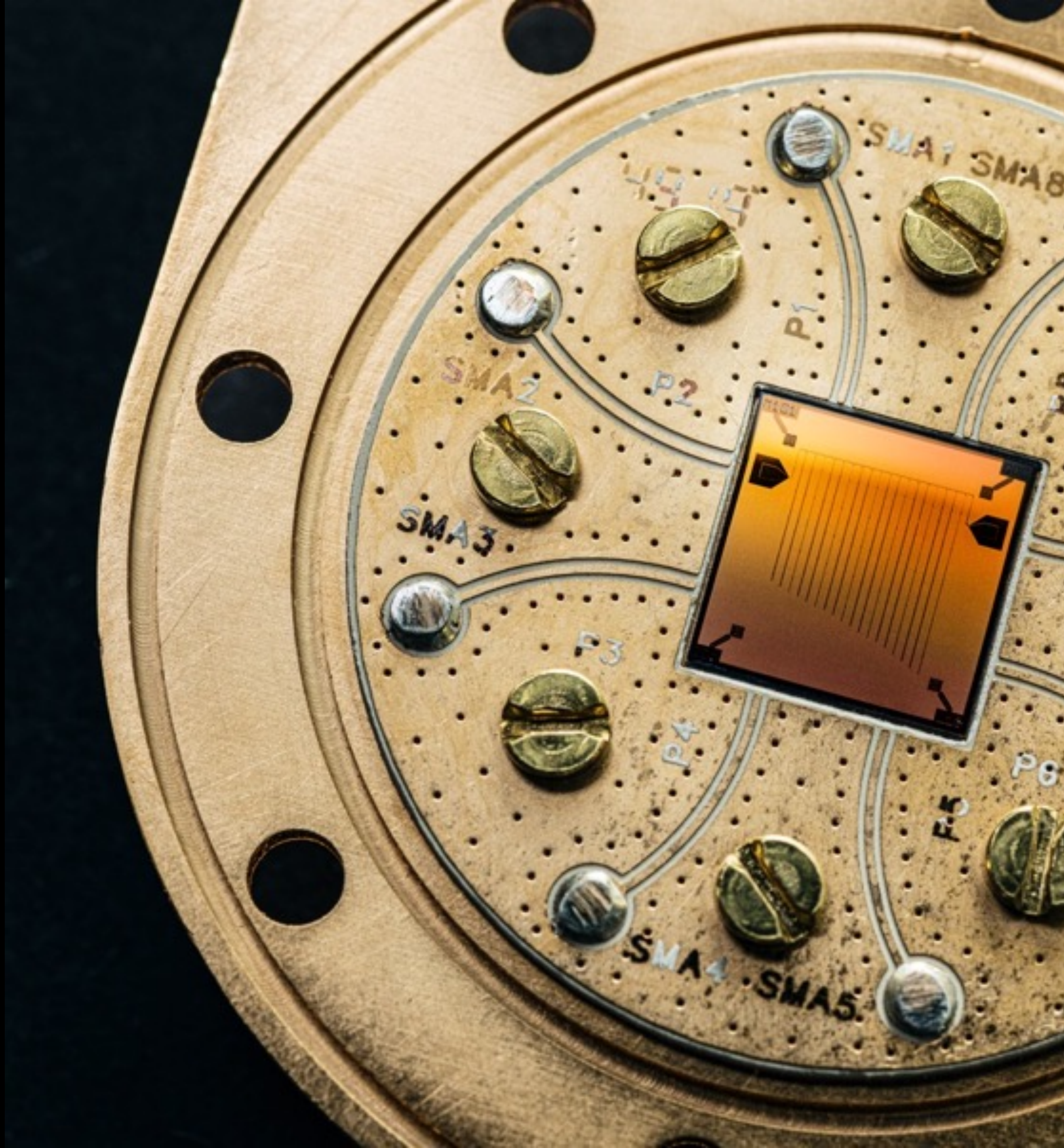
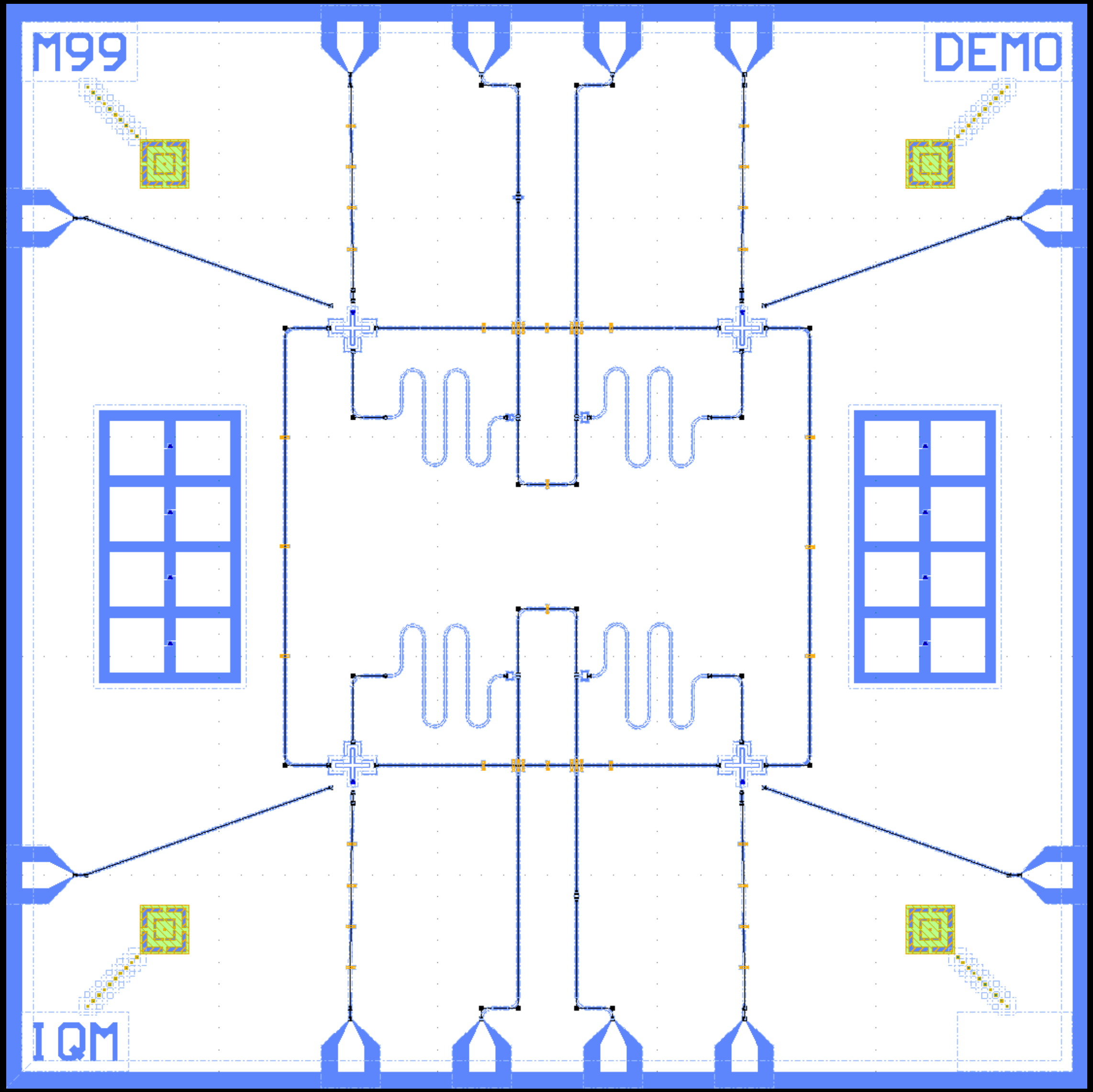
Outline

- QPU design process
- What is KQCircuits
- Some QPU elements
    - Transmon qubit
    - Waveguide resonator
    - Coupling



Superconducting Quantum processing unit

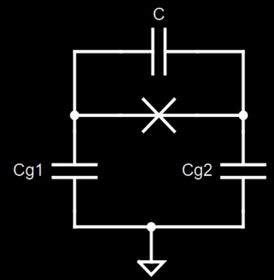
- Slab of Si covered by metal film
- Geometry etched to the film
- Consists of elements
  - Qubits
  - Couplers
  - Readout resonators
  - Drivelines and fluxlines
  - Probelines



QPU design process

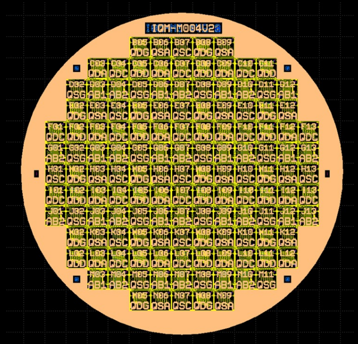
$H(\omega, g)$

Hamiltonian

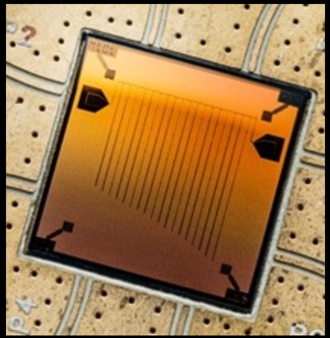


Circuit

Geometry
KQC



Mask Layout
KQC



Fabrication

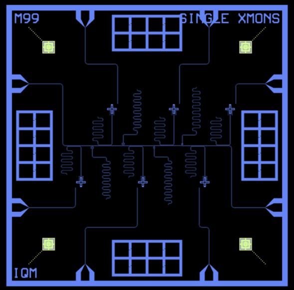
Element library
Components FEM
(enabled by KQC)

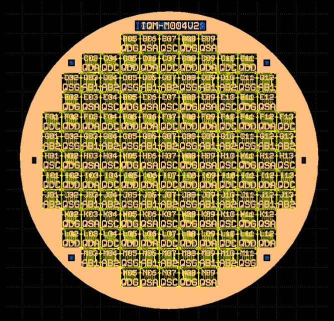
Validation
Netlist, DRC, Full FEM
(enabled by KQC)

What is KQCircuits?

- An open-source framework for designing superconducting circuit geometry
- Libraries of standard, usable Elements and Chips
- Focus on parametrized design enables large scale and reusable designs
- Integrates with finite element simulation tools
- Tools for quality control: design rules, netlist export, FEM simulations

What is KQCircuits?

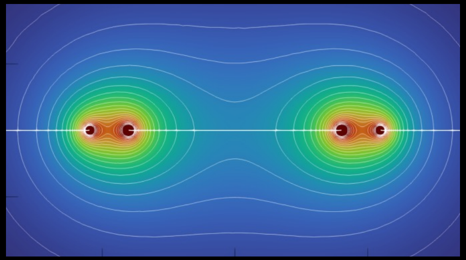




Parametrized Elements

Example Chips

Mask Layout generation



Export to Finite Element simulations
Ansys (HFSS, Q3D)
Sonnet
Elmer (open source)

Validation tools
Netlist export
Design rule check

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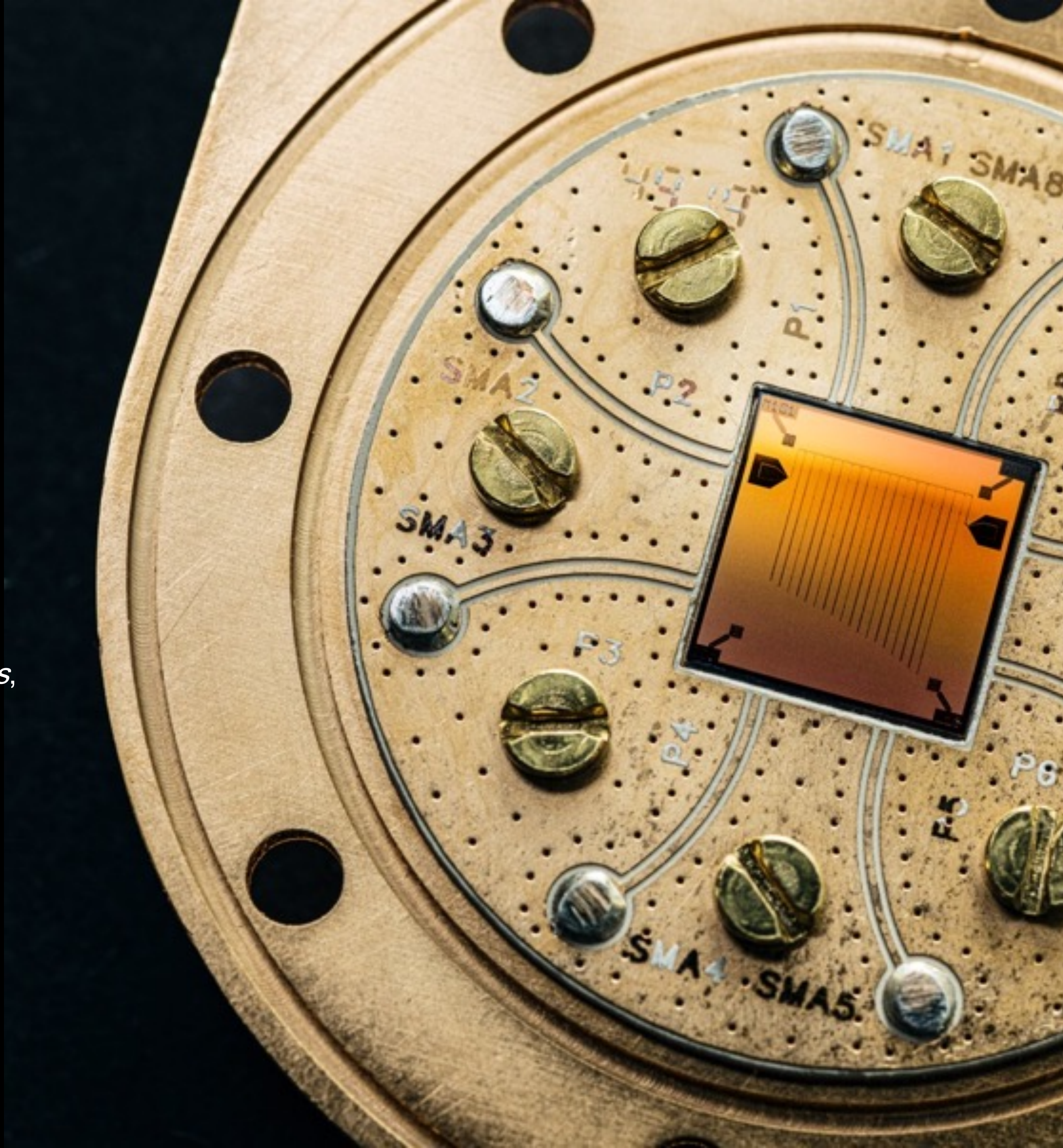
QPU Elements

From Hamiltonian to circuit

Further reading:

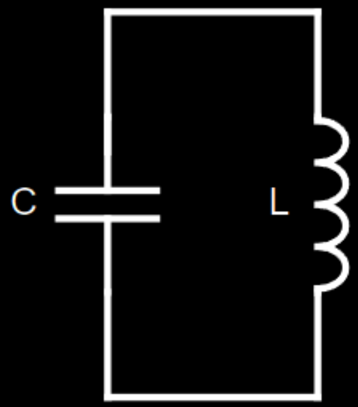
P Krantz et al, *A quantum engineer's guide to superconducting qubits*, Applied Physics Reviews **6**, 021318 (2019)

J. Koch et al, *Charge insensitive qubit design derived from the Cooper pair box,* Phys. Rev. A 76, 042319 (2007)



LC resonator

$$H_r = 4E_C n^2 + \frac{1}{2}E_L \phi^2$$



Resonance frequency:

$$\hbar\omega_r = \sqrt{8\,E_L E_C}$$

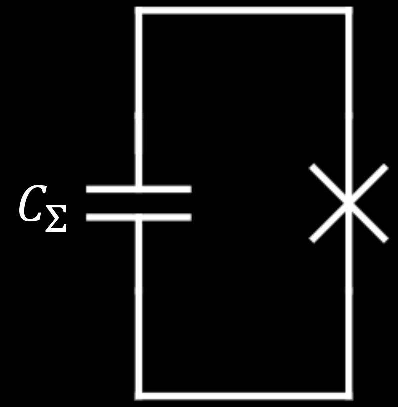
$$E_C = \frac{e^2}{2C}, \quad E_L = \frac{1}{L}\left(\frac{\Phi_0}{2\pi}\right)^2$$

$$\omega_r = 1/\sqrt{LC}$$

P Krantz et al, *A quantum engineer's guide to superconducting qubits*, Applied Physics Reviews **6**, 021318 (2019)

Transmon qubit

$$H_q = 4E_C n^2 - E_J \cos(\phi)$$



Qubit frequency: $\hbar\omega_q^{0\to1} \approx \sqrt{8\,E_J E_C} - E_C$

Anharmonicity: $\alpha = \omega_q^{1\to2} - \omega_q^{0\to1} \approx -E_C/\hbar$

Transmon regime: $E_J/E_C \geq 50$

$$E_C = \frac{e^2}{2C_\Sigma}, \quad E_J = \frac{I_C \Phi_0}{2\pi}$$

P Krantz et al, *A quantum engineer's guide to superconducting qubits*, Applied Physics Reviews **6**, 021318 (2019)

Transmon qubit

$$H_q = 4E_C n^2 - E_J \cos(\phi)$$

Qubit frequency: $\hbar\omega_q^{0\to1} \approx \sqrt{8\,E_J E_C} - E_C$

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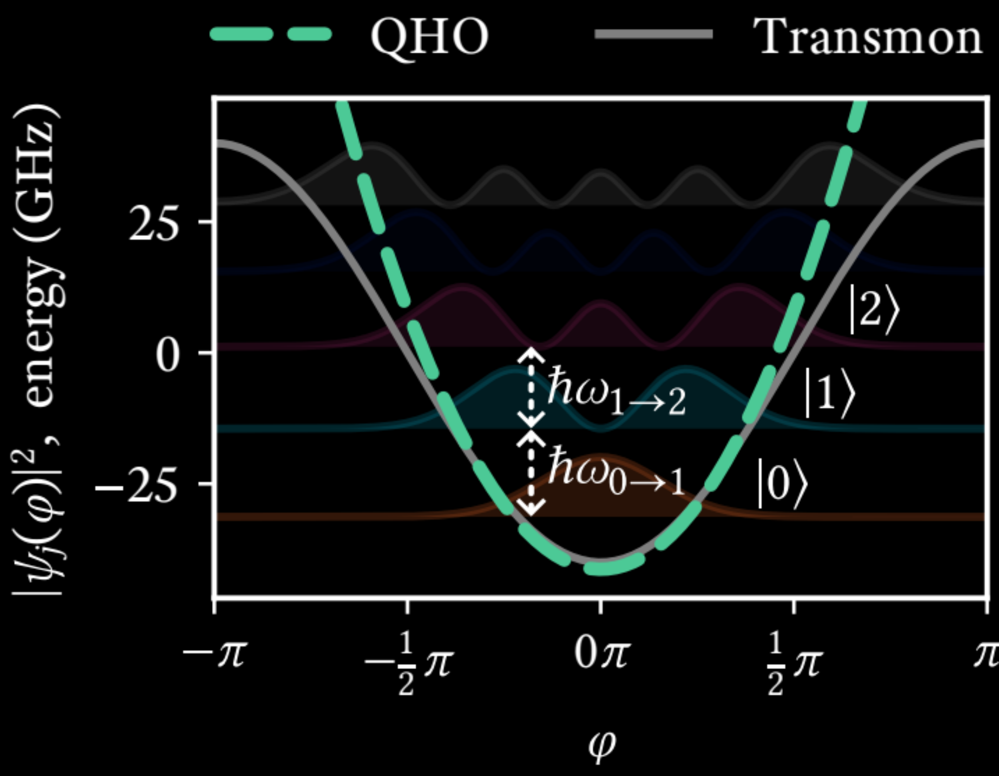
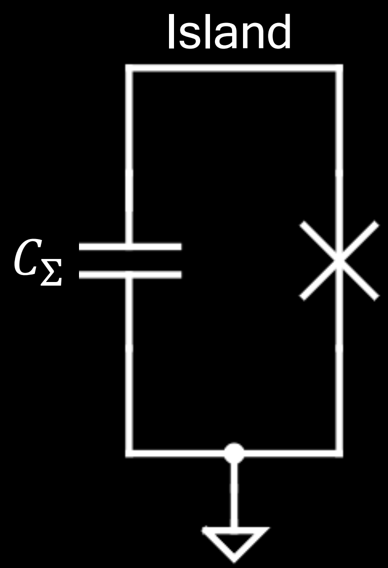
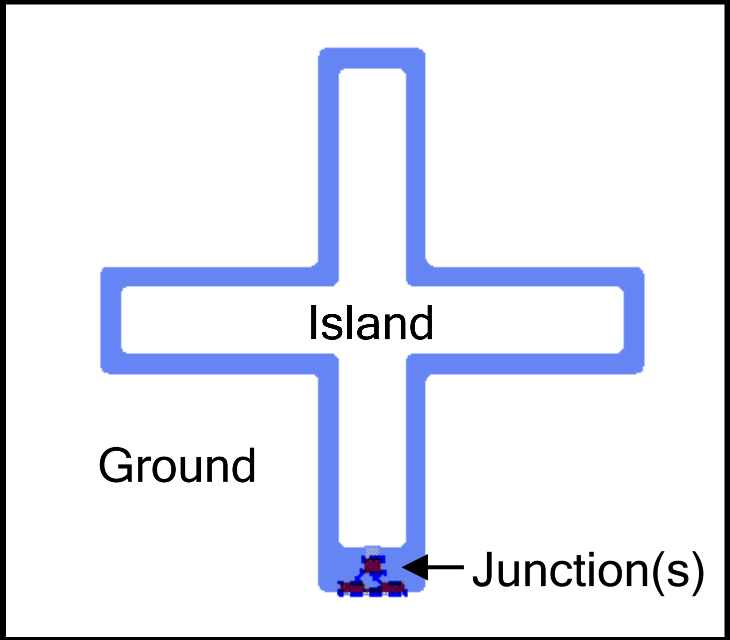


P Krantz et al, *A quantum engineer's guide to superconducting qubits*, Applied Physics Reviews **6**, 021318 (2019)

Single-island Transmon





Qubit-resonator coupling

Jaynes-Cummings Hamiltonian (two-level qubit):

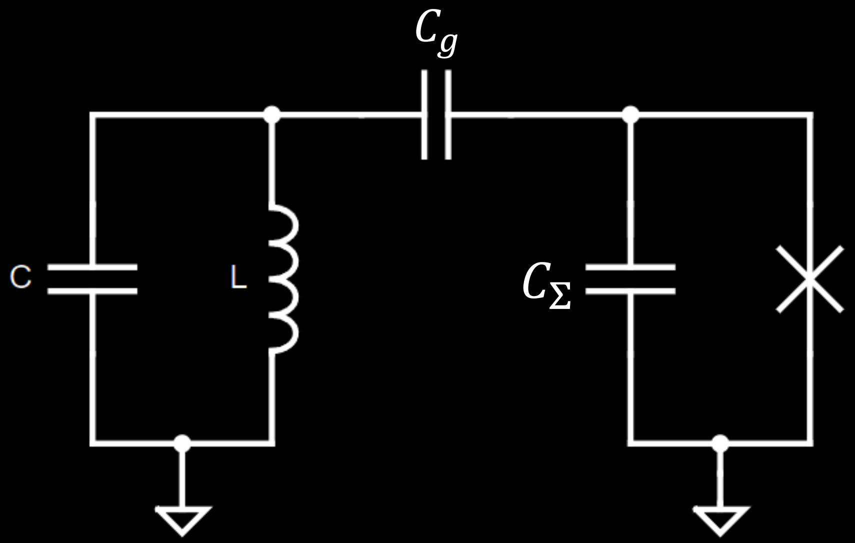
$$H_{JC} = \omega_r \left(a^\dagger a + \frac{1}{2}\right) + \frac{1}{2}\omega_q \sigma_z + g\left(\sigma_+ a + \sigma_- a^\dagger\right)$$

Weak capacitive coupling $C_g \ll C_\Sigma$, Transmon limit:

$$\hbar g = \frac{C_g}{C_\Sigma}\sqrt{2} e V_{rms}^0 \left(\frac{E_J}{8E_C}\right)^{\frac{1}{4}}$$

LC Resonator vacuum voltage fluctuations:

$$V_{rms}^0 = \sqrt{\frac{\hbar Z_0}{2}\omega_r}, \qquad Z_0 = \sqrt{L/C}$$

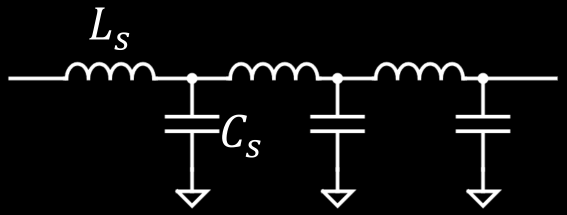


J. Koch et al, Phys. Rev. A 76, 042319 (2007)

Waveguide resonator

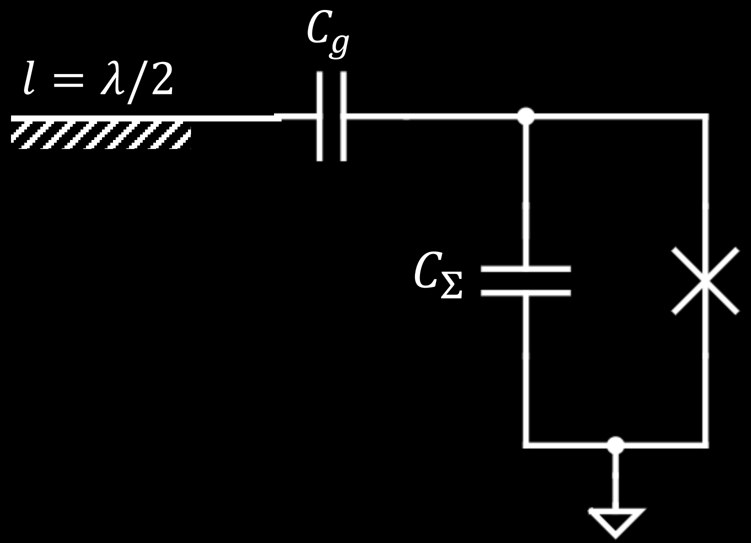
Transmission line characterized by L_s and C_s per unit length:

$$Z_0 = \sqrt{L_s/C_s}$$
$$c_{\text{eff}} = 1/\sqrt{L_s\, C_s}$$
$$\epsilon_{\text{eff}} = L_s C_s c^2$$

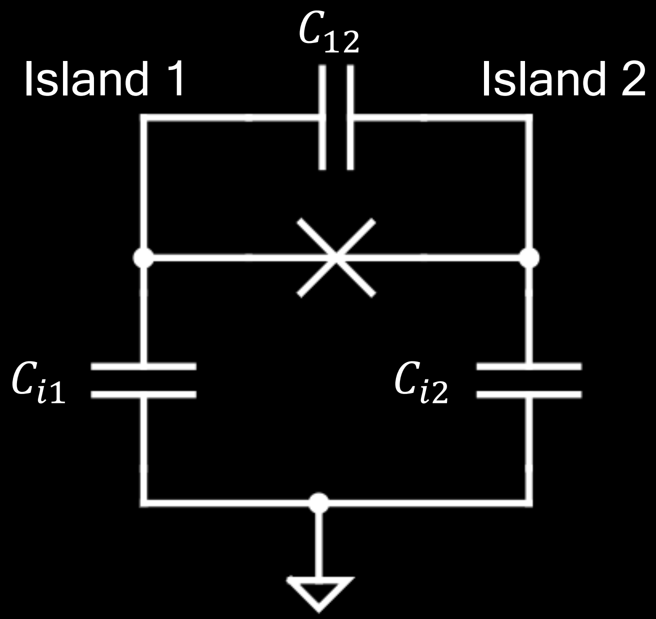


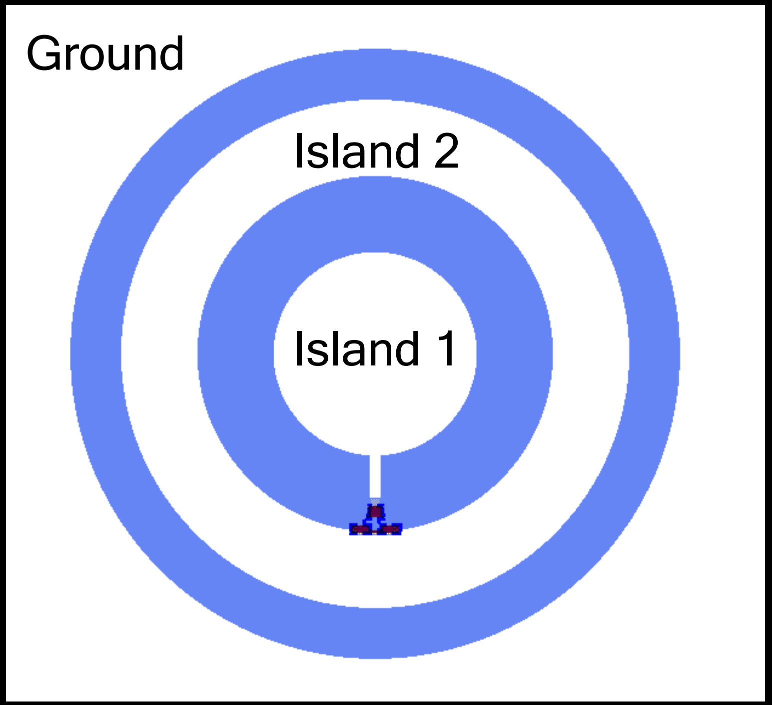
$\lambda/2$ resonator vacuum voltage fluctuations:

$$V_{rms}^0 = \sqrt{\frac{2}{\pi}}\sqrt{\frac{\hbar Z_0}{2}}\,\omega_r,$$



Two-island Transmon





C_Σ is the total capacitance across the junction:

$$C_\Sigma = C_{12} + \left(\frac{1}{C_{i1}} + \frac{1}{C_{i2}}\right)^{-1}$$

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