Qub-IT: Quantum sensing with transmon-based itinerant single-photon counter

Hervè Atsè Corti on behalf of the Qub-IT collaboration
INFN Florence, University of Pisa

Outline

- Qub-IT project introduction
- Quantum sensing
- Transmon qubit
- Design tech-stack
- First qubit designs
- First fabricated cQED blocks
- First fabricated JPA
- Conclusions

Qub-IT collaboration

INFN sections:

- Ferrara
- Florence
- Laboratorio Nazionale Frascati
- Milan
- Milan Bicocca
- Pisa
- Salerno
- TIFPA

Partners:

- CNR-INF
- FBK

Project started January 2022

Qub-IT goals

Goal:

- Itinerant photon detection
- Low dark count rate
- Surpass state-of-the-art detector efficiency

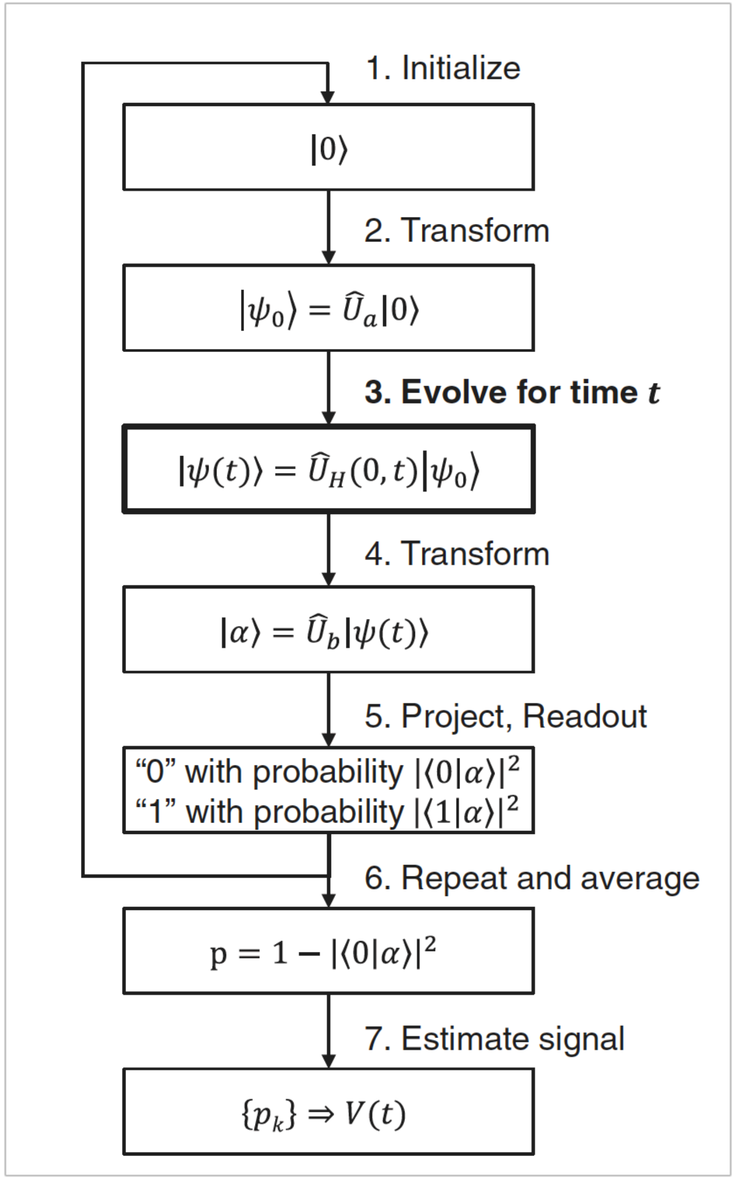
How?

- Quantum non destructive measurements
- Entangled qubits

$$\left|\psi(t)\right\rangle = \frac{1}{\sqrt{2}}\left|0..0\right\rangle + e^{-i\phi(t)}\left|1..1\right\rangle$$

Current deliverable (31/12/2022) - Design of 1 transmon qubit coupled to 1 resonator

How Ramsey quantum sensing works?

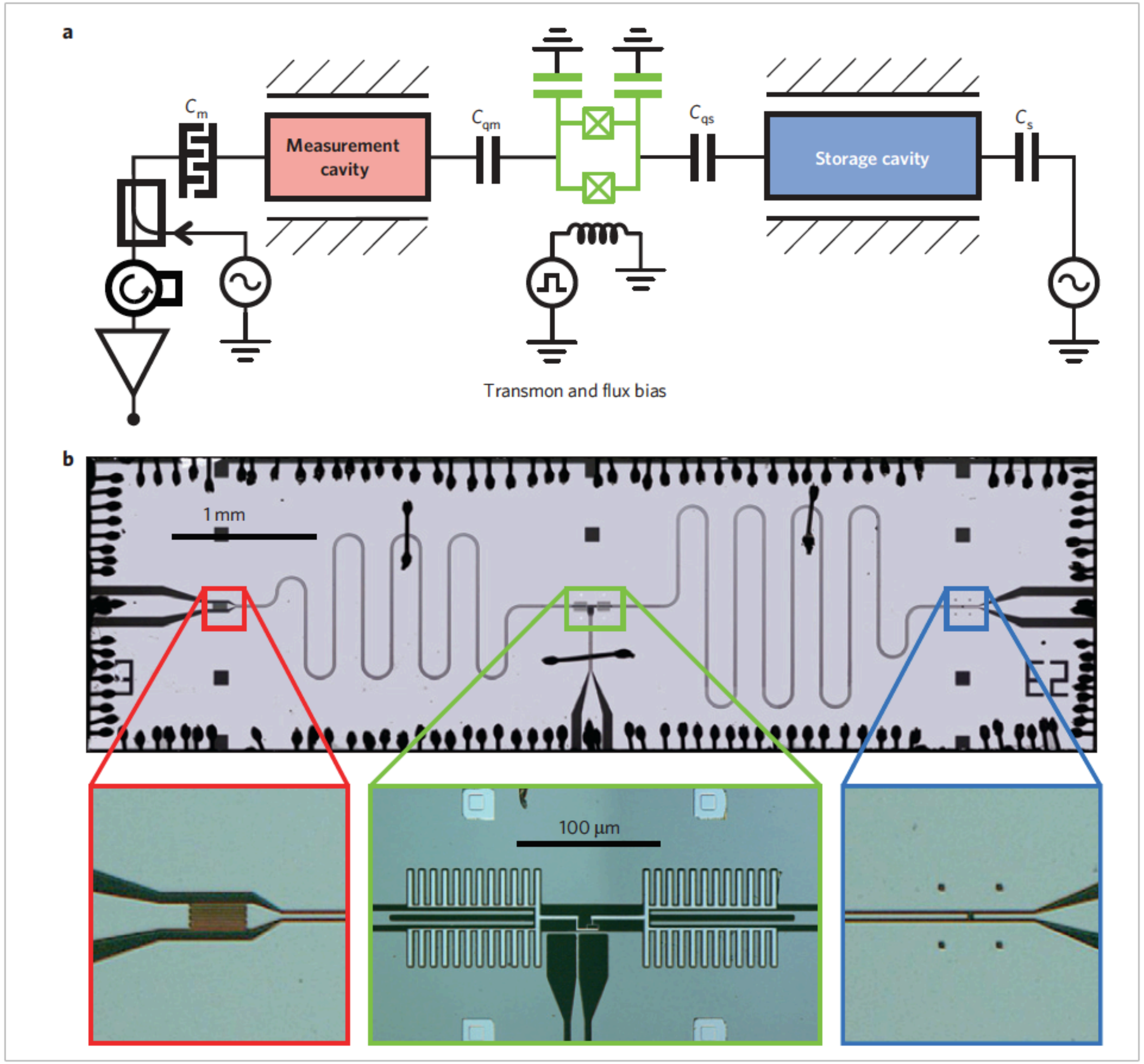


The qubit encodes into its state phase the history of the interaction with the surrounding environment.

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\,|0\rangle + e^{-i\phi(t)}\,|1\rangle = \frac{1}{\sqrt{2}}\,|0\rangle + e^{-i\omega_0 t}\,|1\rangle \quad .$$

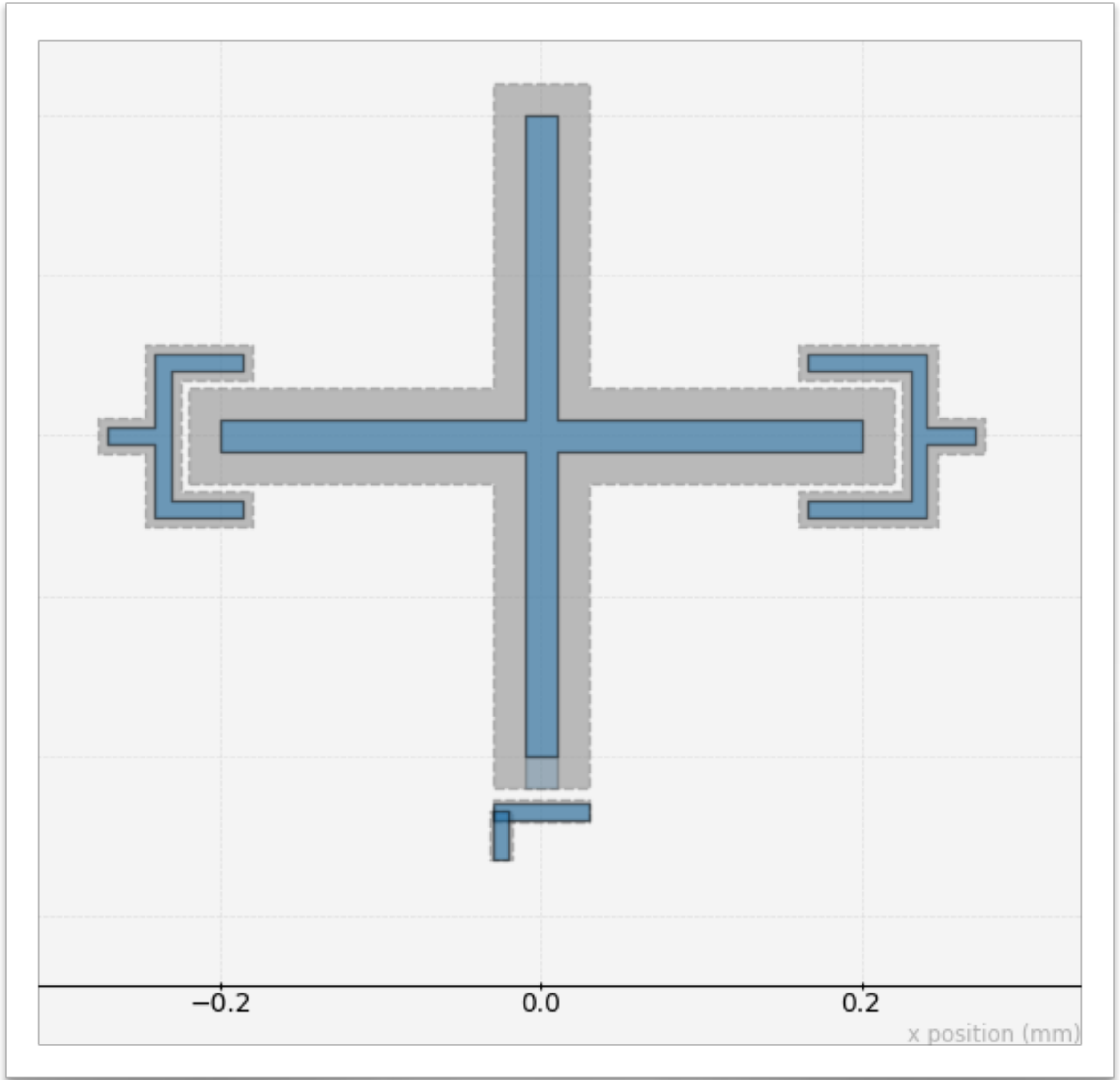
Degen et al.
Quantum Sensing

Qubit based single-photons counter



B. R. Johnson et al.
[Quantum Non-demolition Detection of Single Microwave Photons in a Circuit]

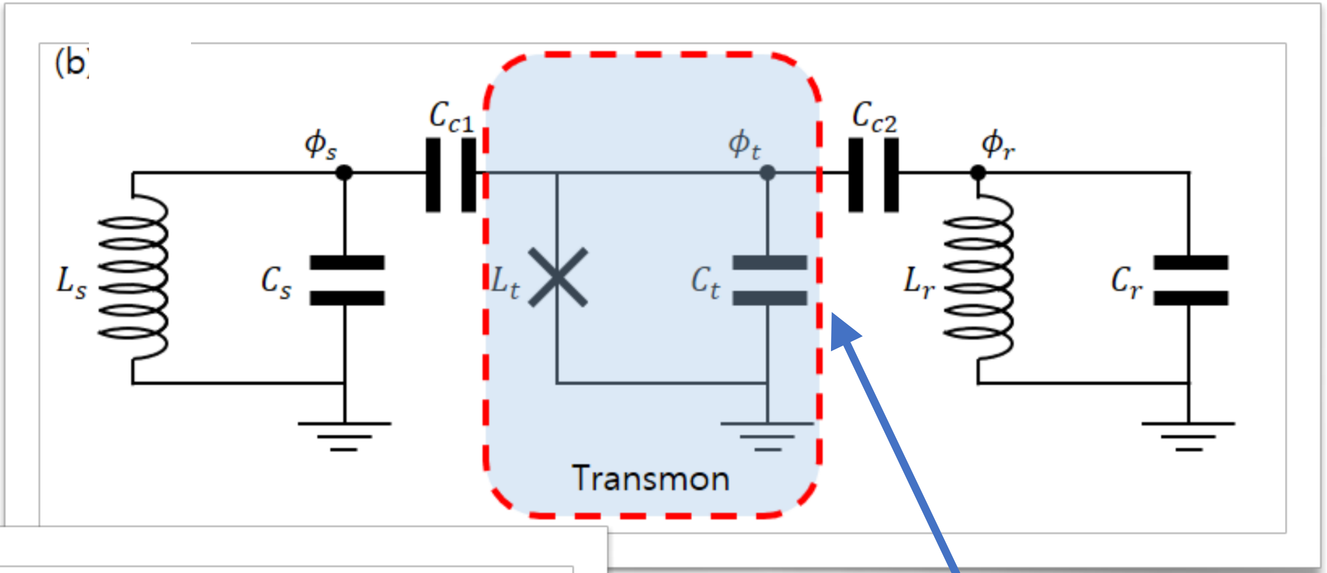
Transmon qubits

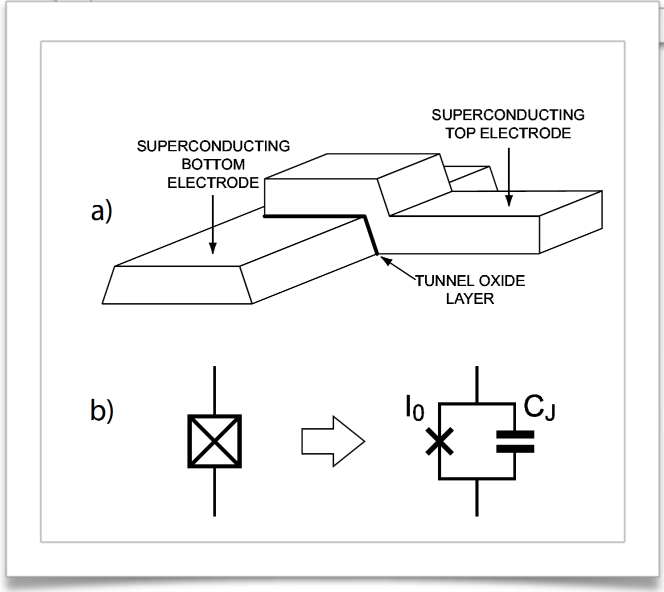


Main advantages:

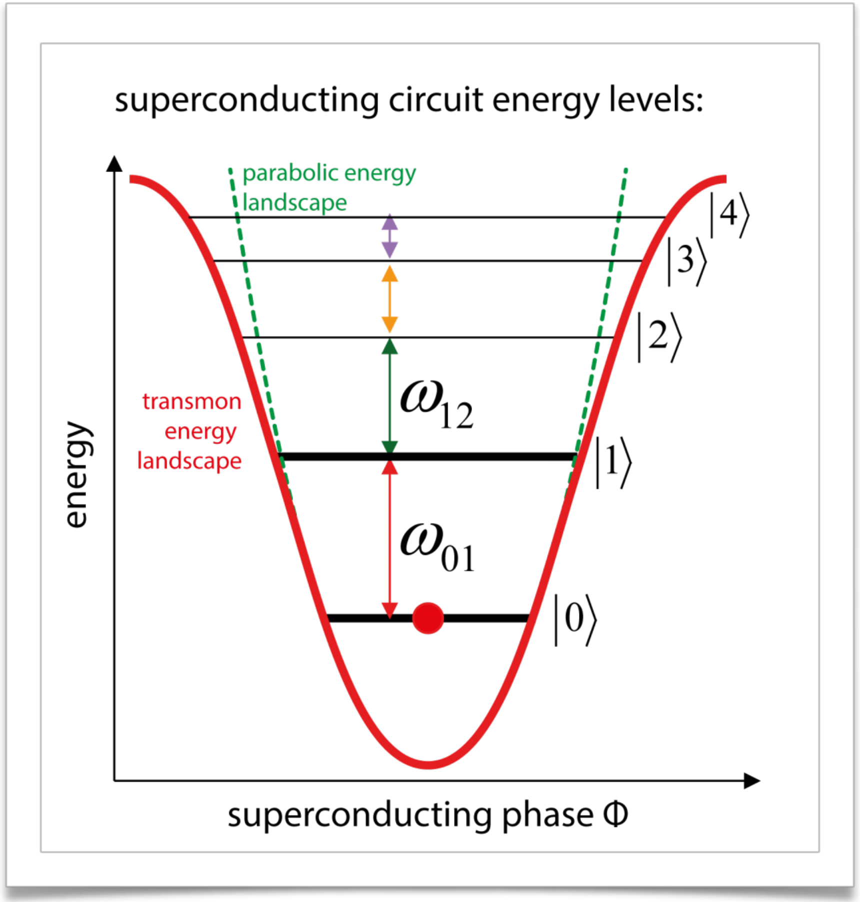
- high T_1 ($\sim 10 - 100\ \mu s$)
- high T_2 ($\sim T_1$)
- relatively easy to build
- controlled and measured via EM pulses

Transmon equivalent circuit





- C_t shunt capacitance reduces charge noise
- $C_t \gg Cj$
- $E_J \gg Ec$



M. H. Devoret et al.
Superconducting Qubits: A Short Review

Qiskit Metal

- Open-source quantum hardware design framework
- Python based
- Extensive use of Jupyter Notebook
- Parasitic extraction through Ansys Q3D
- EM simulation through Ansys HFSS

Qiskit Metal installer
https://github.com/Qiskit/qiskit-metal

Qiskit Metal documentation
https://qiskit.org/documentation/metal/

Energy Participation Ratio (EPR)

Qiskit Metal uses the EPR (p_{mj}) method to define the anharmonicity, the total dispersive shift and the Lamb shift of qubit and resonator modes.

number of JJ → J

$$\chi_{mn} = \sum_{1}^{J} \frac{\hbar\omega_m\omega_n}{4E_j} p_{mj} p_{nj}$$

$$\alpha_m = \frac{\chi_{mm}}{2}$$

$$\Delta_m = \frac{1}{2}\sum_{n=1}^{N} \chi_{mn}$$

Energy Participation Ratio (EPR)

The EPR (p_{mj}) of a eigenmode m corresponds to the fraction of the total inductive energy stored in the part that accounts for the linear response of the j-th Josephson junction when only that mode is excited.

$$\hat{\mathscr{E}}_j = \hat{\mathscr{E}}_{j,lin} + \hat{\mathscr{E}}_{j,nl} \qquad p_{mj} = \frac{\overline{\langle \hat{\mathscr{E}}_{j,lin} \rangle}}{\overline{\langle \hat{\mathscr{E}}_{ind} \rangle}} = \frac{E_j \phi_{mj}^2}{\frac{\hbar\omega_m}{2}}$$

Z. K. Minev et al.
Energy-participation quantization of Josephson circuits

Qiskit Metal feedback

Strengths

- good design workflow
- classical and quantum simulations
- framework structure
- customisable
- open-source
- great community and helpful developers

Weaknesses

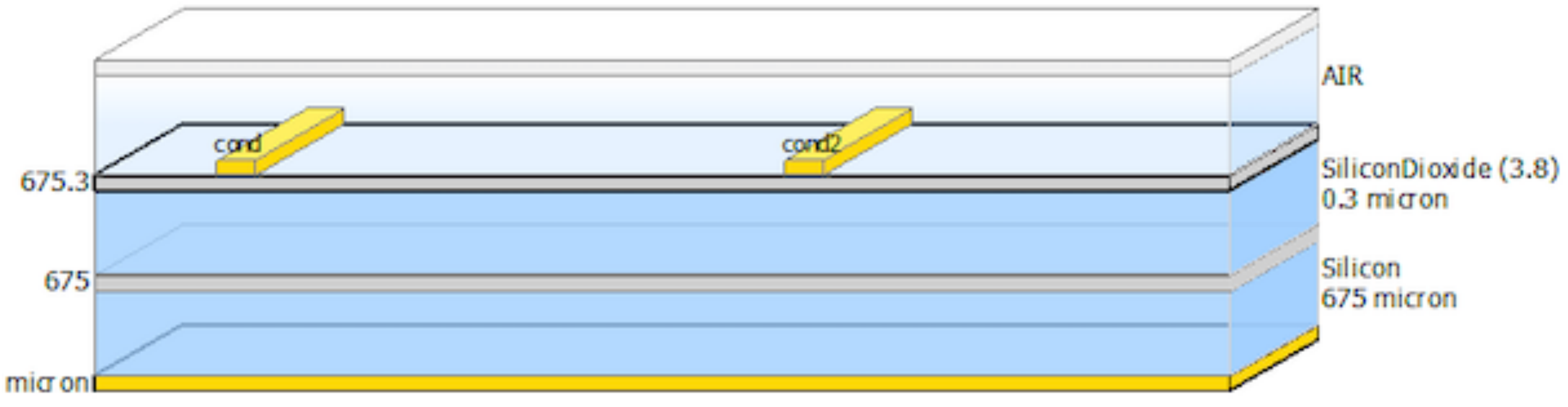
- GUI not mature
- requires Python knowledge
- severe bugs
- unstable code-base
- lack of documentation
- can’t design Josephson junctions

Qiskit-metal tips

- Can be installed and updated via Git or Pip
- Dedicated Slack channel
- Default HFSS mesh settings often lead to lengthy simulations
- Some qubit types are bugged (e.g. xmon)
- Needs some hack to simulate complex substrates
- Updates may break your code

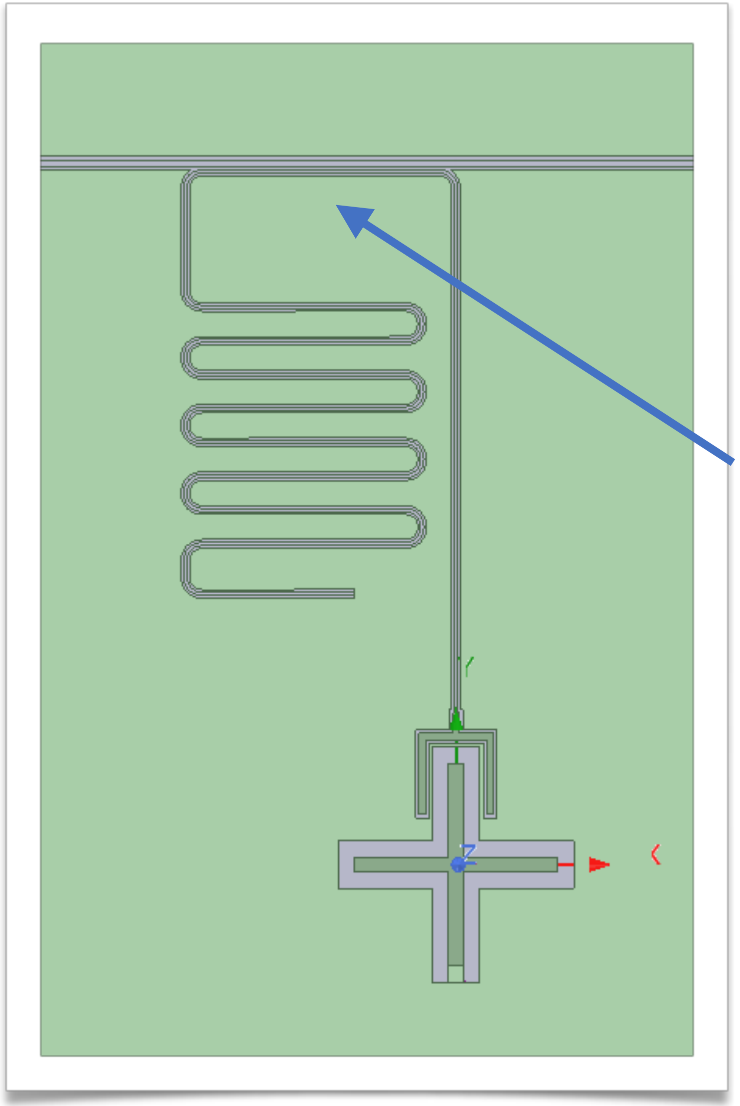
Chip structure

- Coplanar structure (2D)
- Area = 1 cm * 1 cm
- Silicon-based substrate
- Aluminum superconductor



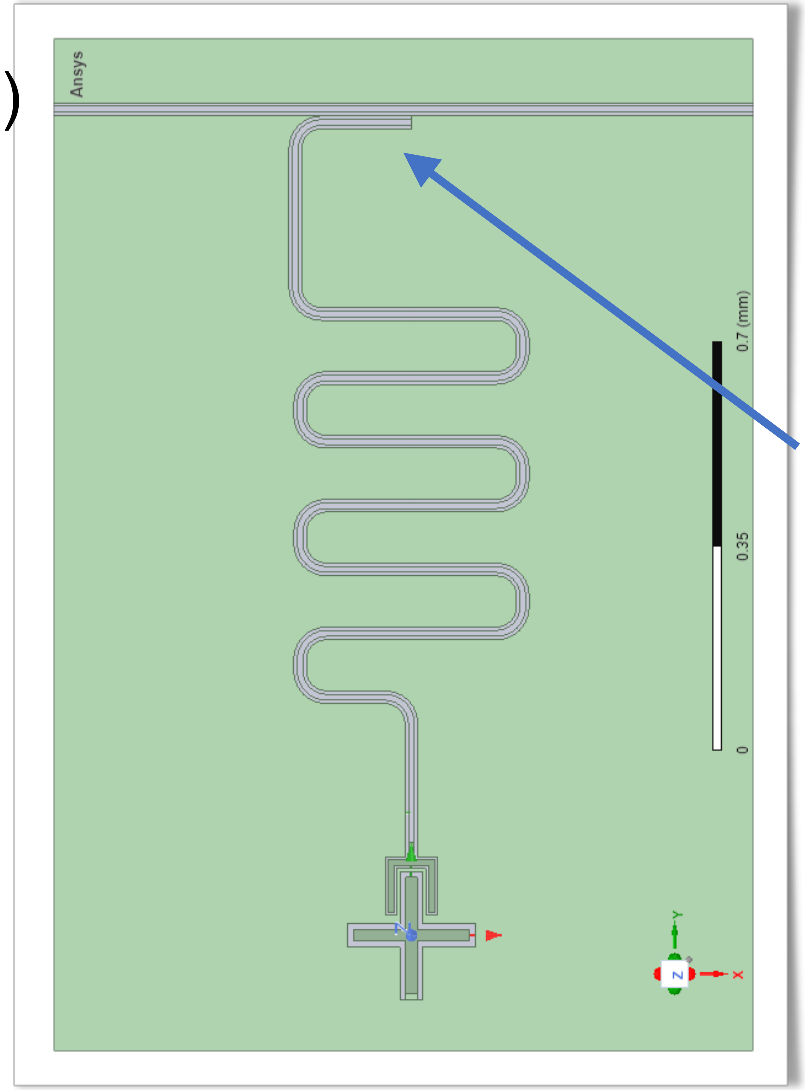
Qubit-resonator designs

1)



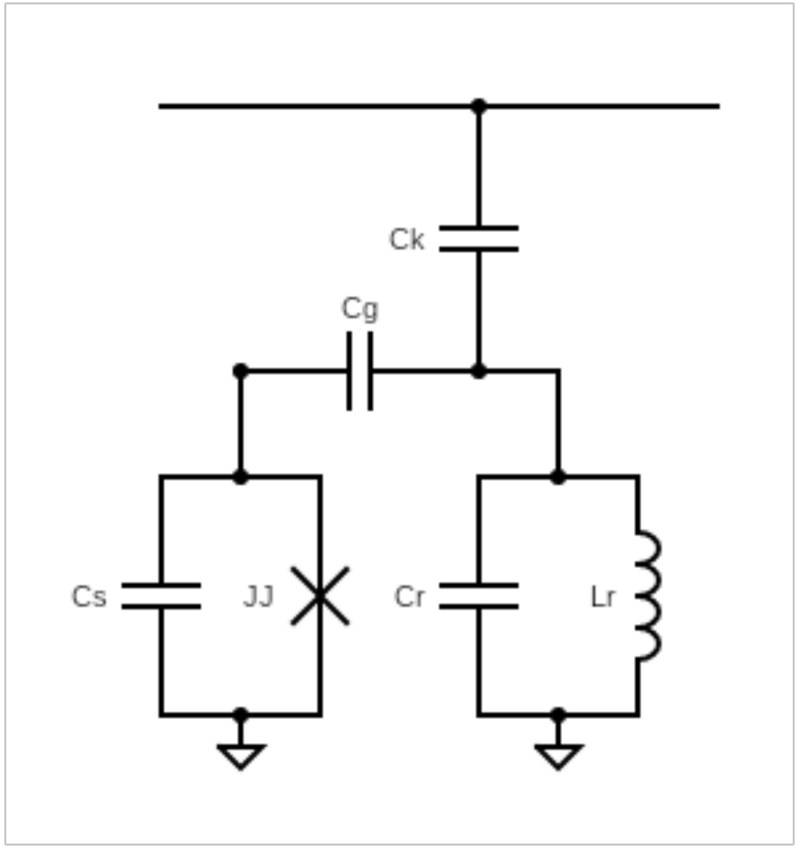
Capacitive coupling

2)

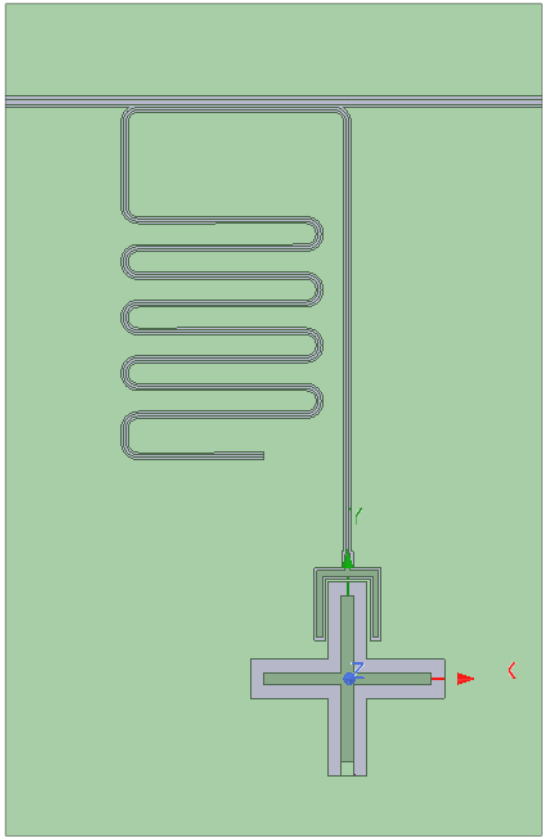


Inductive coupling

Capacitive design



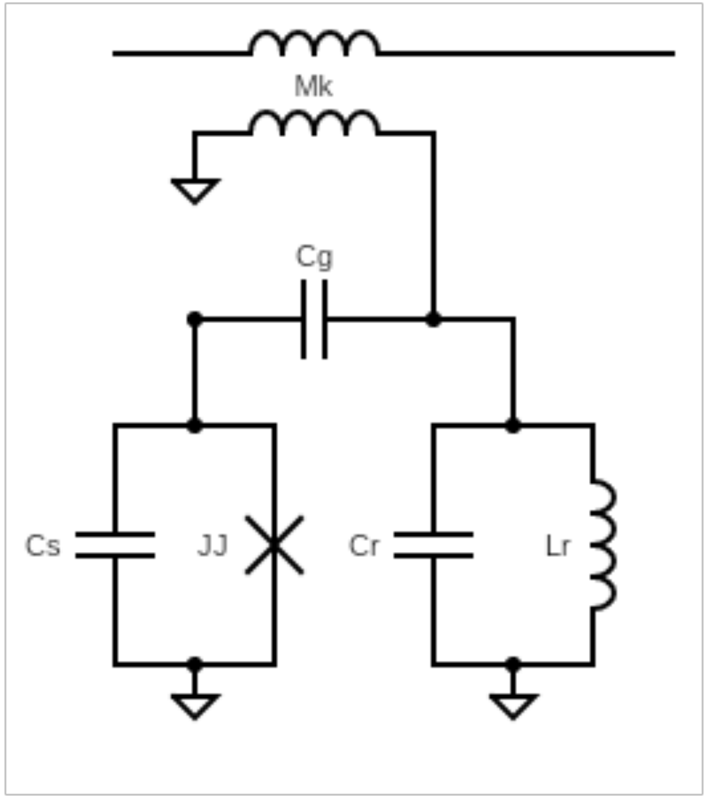
C_S = 69.72 fF
L_J = 10 nH
C_r = 375.08 fF
L_r = 1.80 nH
C_g = 3.09 fF
C_k = 16.53 fF
E_J/E_C = 61.61



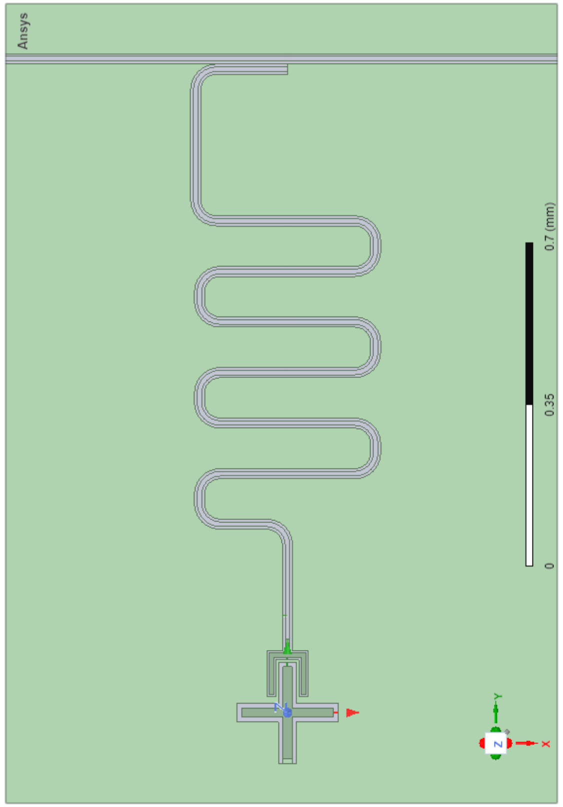
Note: C_r and L_r calculated using D. M. Pozar [Microwave Engineering]

R. Barends
[Coherent Josephson qubit suitable for scalable quantum integrated circuits]

Inductive design



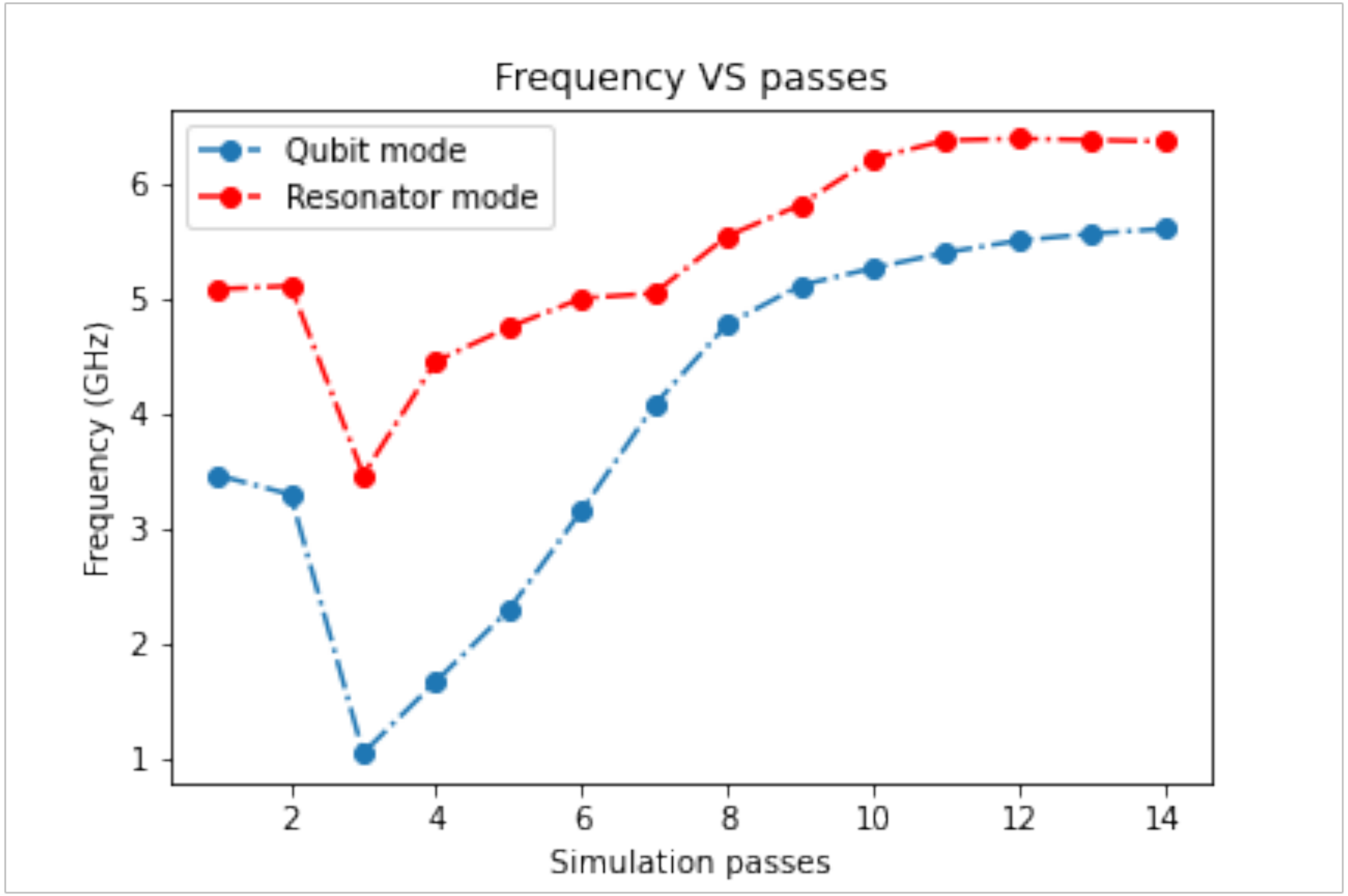
C_S = 56.41 fF
L_J = 8.00 nH
C_r = 301.35 fF
L_r = 1.22 nH
C_g = 3.14 fF
M_k = 15.08 pH
E_J/E_C = 62.81



Note: all calculation was done substituting $C_k = M_K / Z_0^2$
https://arxiv.org/pdf/1305.4249.pdf

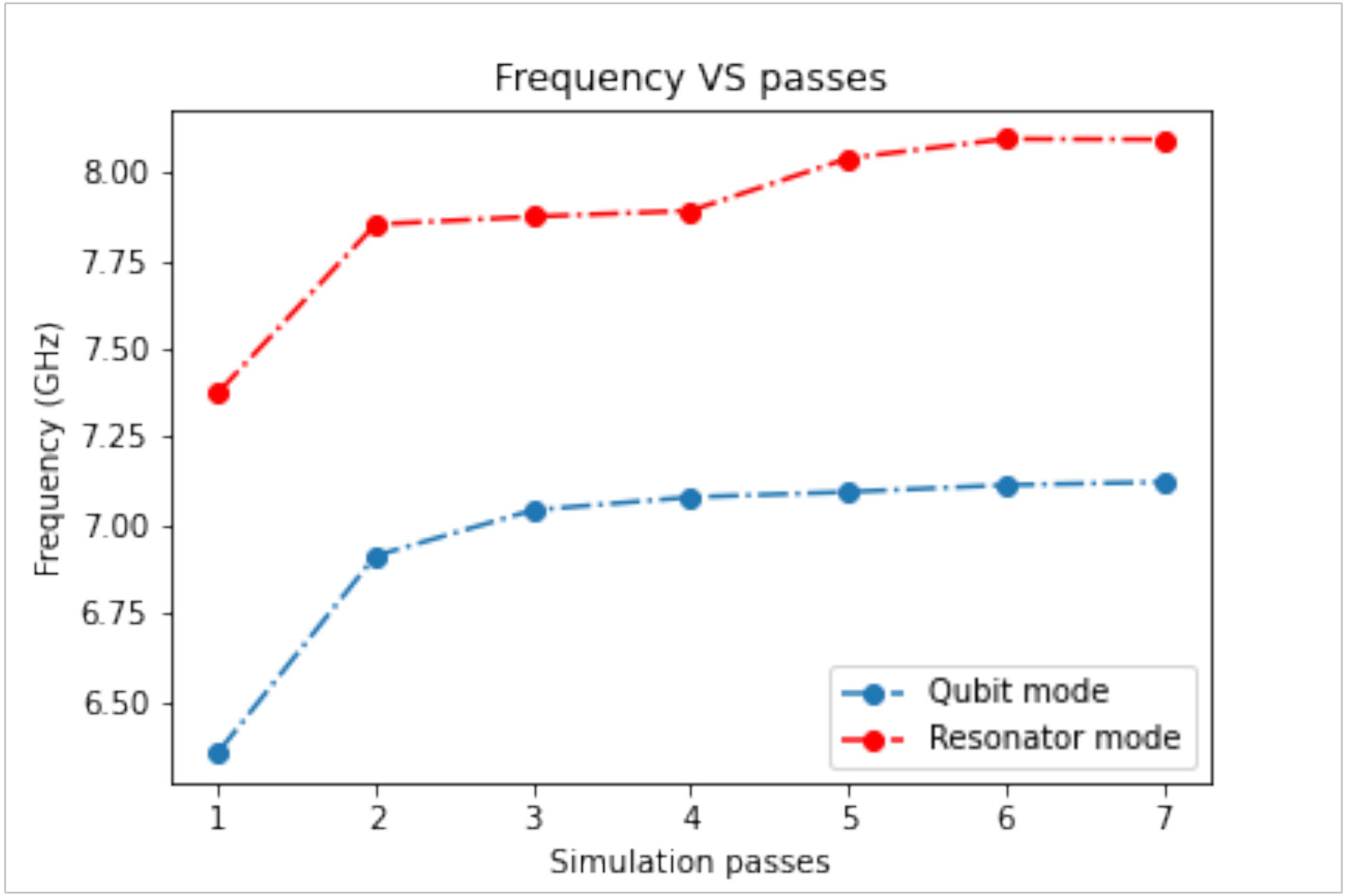
J. J. Burnett
Decoherence benchmarking of superconducting qubits

Capacitive design simulation



	EPR results	Calculated values
$\omega_{01}/2\pi$	5.37 GHz	5.63 GHz
$\omega_r/2\pi$	6.37 GHz	6.13 GHz
α	-264 MHz	-265 MHZ
$\chi/2\pi$	-1.43 MHz	-2.23 MHz

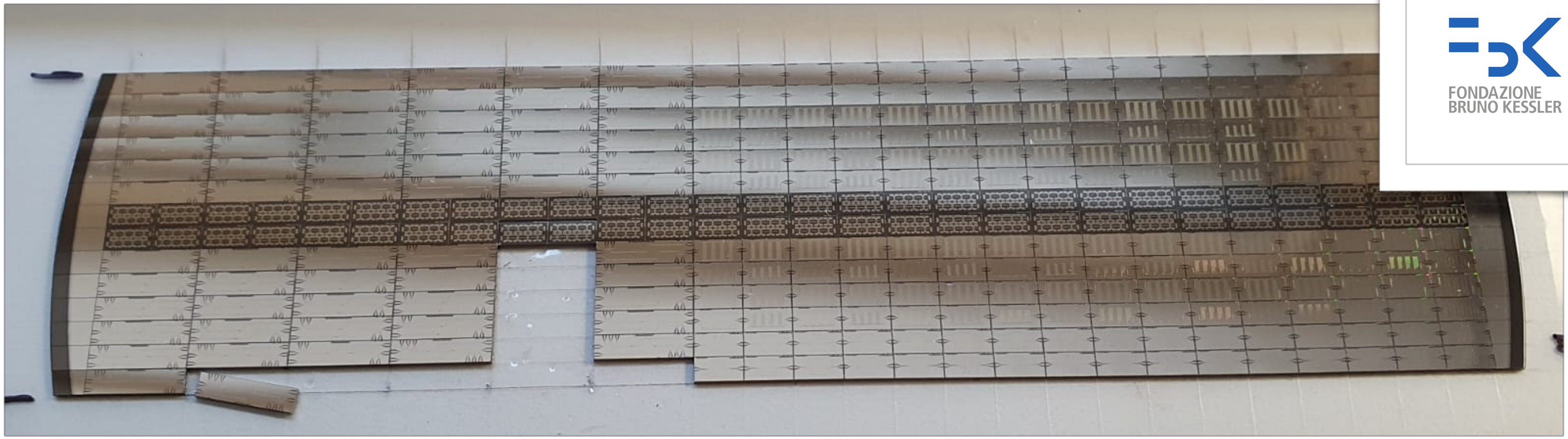
Inductive design simulation



	EPR results	Calculated values
$\omega_{01}/2\pi$	6.81 GHz	6.97 GHz
$\omega_r/2\pi$	8.09 GHz	8.04 GHz
α	-343 MHz	-325 MHz
$\chi/2\pi$	-1.38 MHz	-1.69 MHz

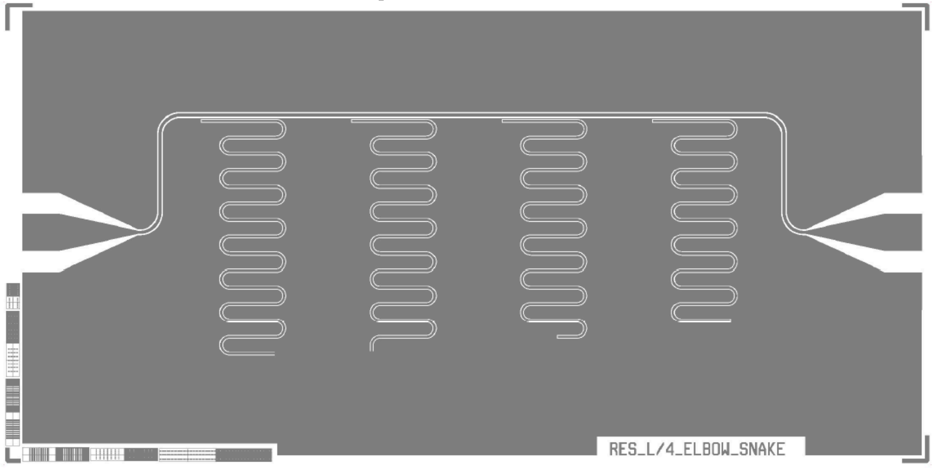
cQED building blocks

Inspired by Goppl et al. Coplanar Waveguide Resonators for Circuit Quantum Electrodynamics, we designed several resonators with different values and types of coupling capacitors.

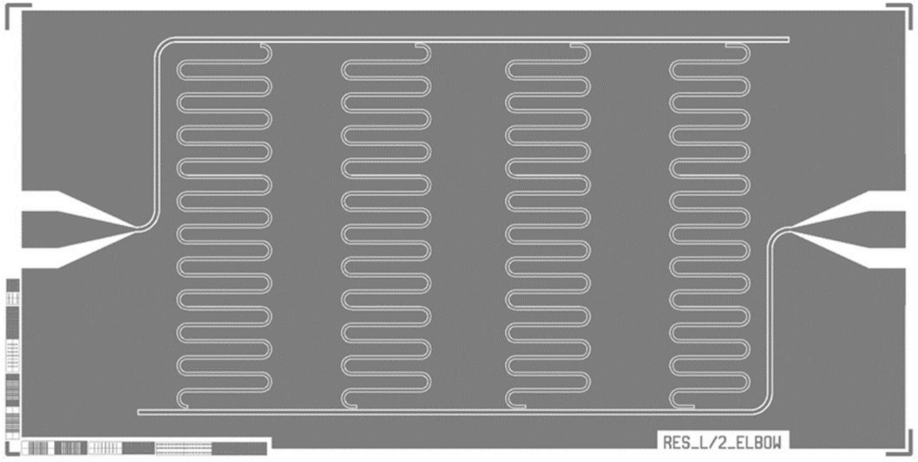


cQED building blocks

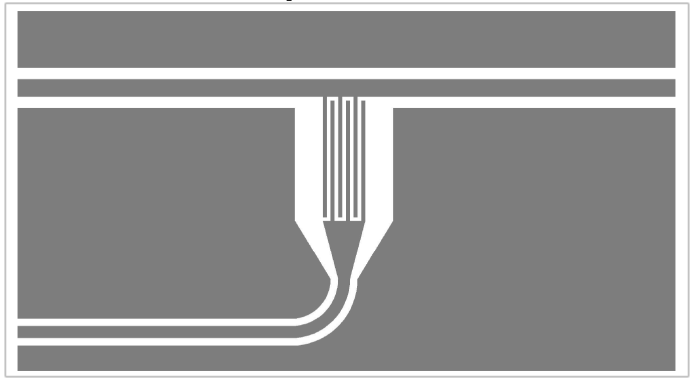
λ/4 "absorption" resonators



λ/2 "transmission" resonators

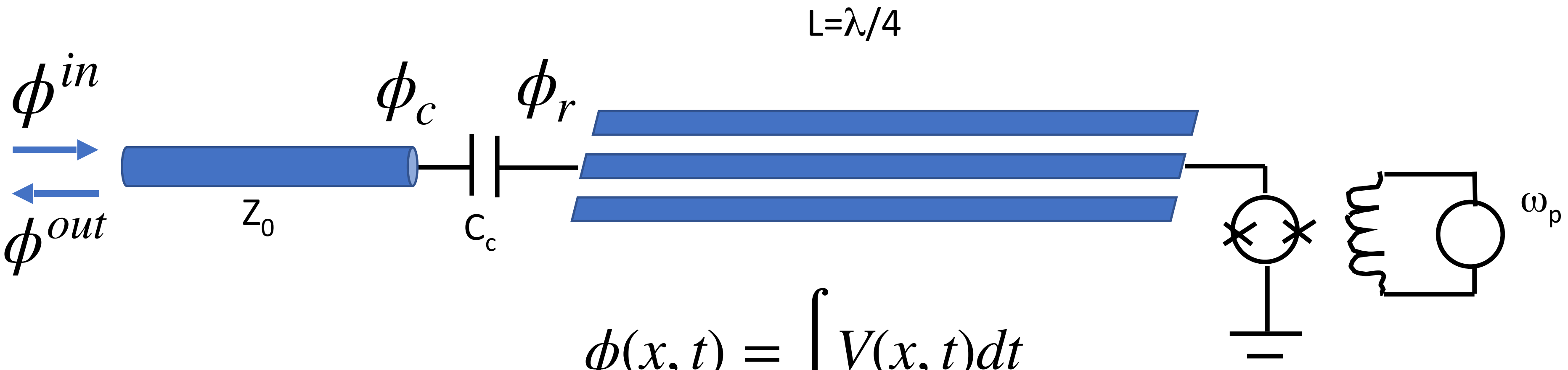


Capacitors



Flux Josephson Parametric amplifier (JPA)

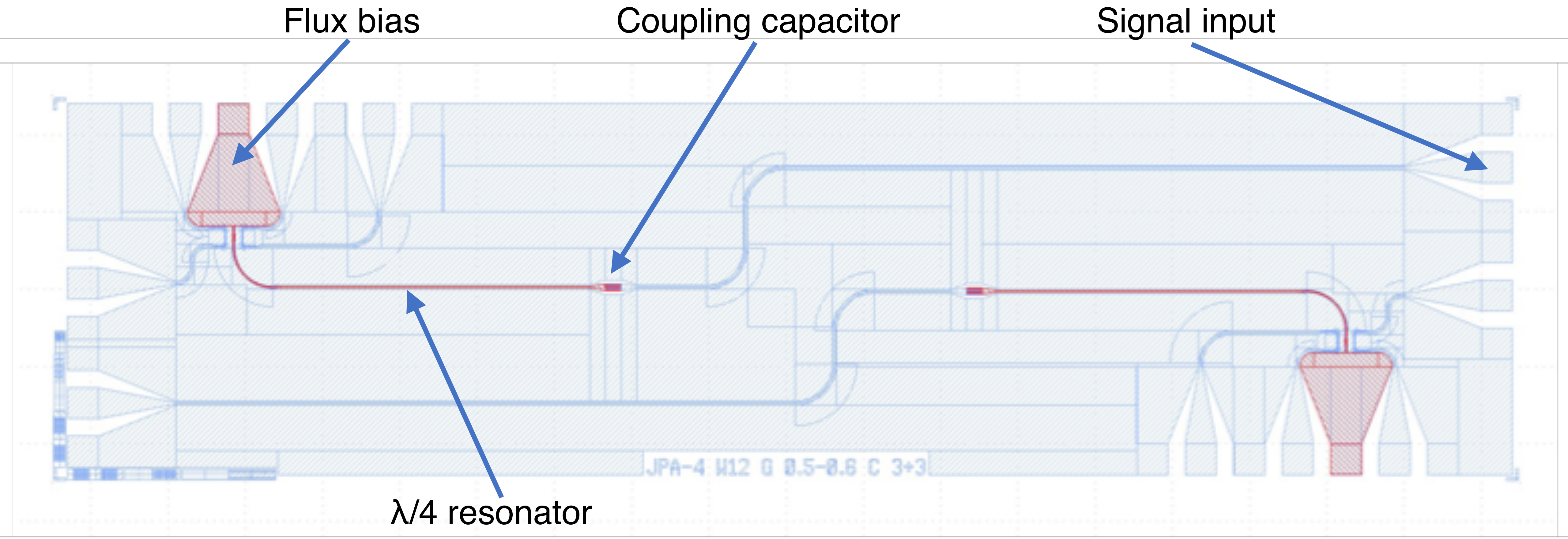
We designed simulated and fabricated Flux JPAs at 8.5 and 5 GHz



$$\phi(x,t) = \int V(x,t)dt$$

The chips are now under test and will be used for qubit readout and for dark matter (axions) experiments

Flux Josephson Parametric amplifier (JPA)



Flux Josephson Parametric amplifier (JPA)

FONDAZIONE BRUNO KESSLER

Next steps

TODO:

- JPA, resonators and coupling capacitances test and characterisation
- fabrication of qubit-resonator test-chip (FBK)
- simulation vs hardware comparison (to test Qiskit Metal)

Contact info

Thanks for your attention!

Contact: herve.corti@phd.unipi.it

Qub-IT website: https://web.infn.it/qub-it/

Qub-IT agenda: https://agenda.infn.it/category/1635/