PHYS-464
Fabrication and Losses of Quantum processors elements

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Outline

- What is a qubit? How can we make one?
- Defining a "good" qubit…
- Design qubits and readout circuits for quantum processors
- Chips fabrication in the cleanrooms
- Where are losses coming from?
- Few design guidelines to reduce losses in your chips

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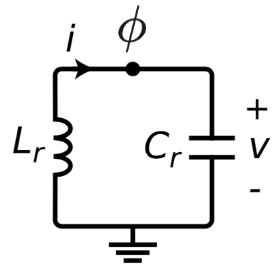
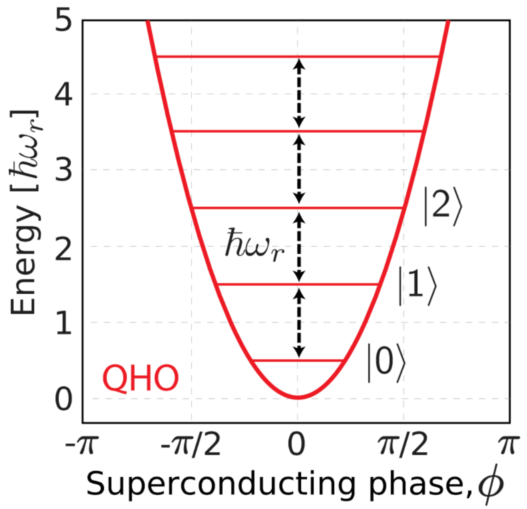
Transmon Qubit

- Transmons are currently the most commonly used superconducting qubits.

- Adding a nonlinear component (a Josephson Junction) to an harmonic oscillator, the same way we build transmons, it is possible to generate enough anharmonicity to generate unevenly spaced energy levels.

- This generates our “approximated” two-level system, which we will use as computational space.





P. Krantz et al., *A quantum engineer’s guide to superconducting qubits*, Appl. Phys. Rev. **6**, 021318 (2019)

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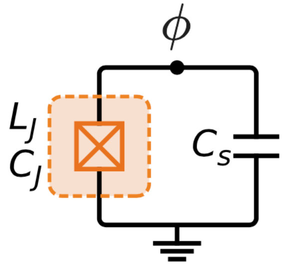

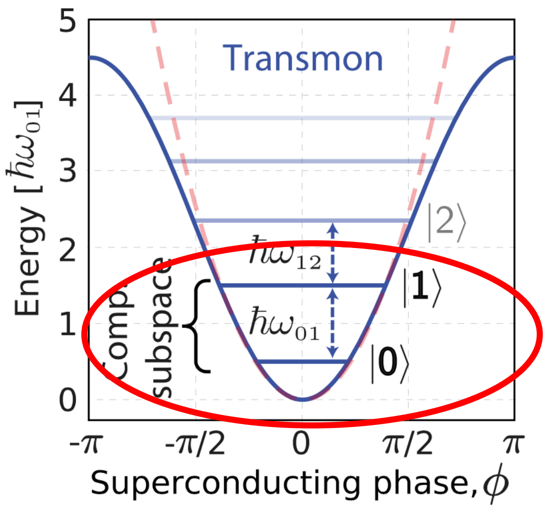

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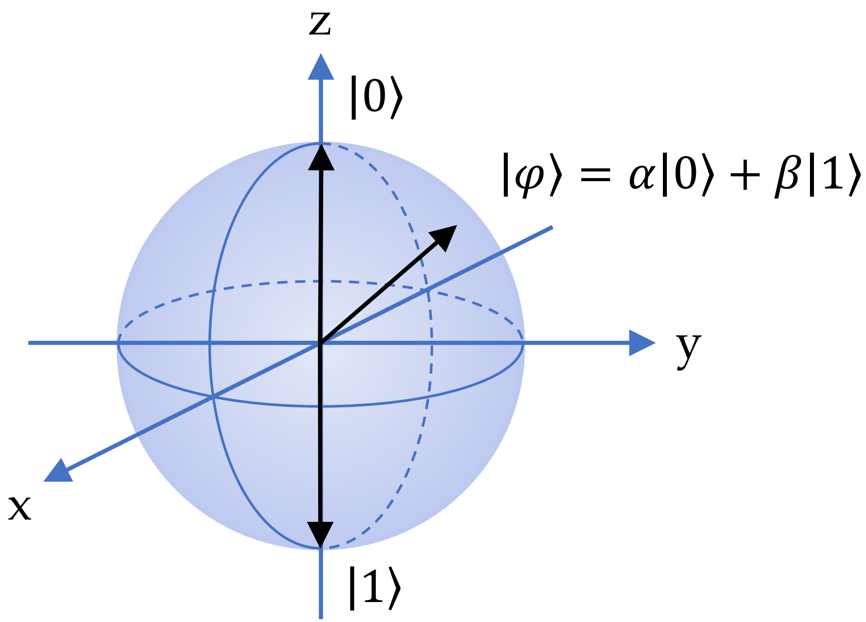
Qubit States and Bloch Sphere

- The state of a qubit is usually represented with the Bloch's sphere.
- The north and south poles of the qubit represent the states $|0\rangle$ and $|1\rangle$ respectively, also called as **ground** and **excited** states.
- The qubit state $|\varphi\rangle$ is generally the **superposition** of ground and excited states.
- Rotations along the x and y axes are performed via the so-called *drive* control line, rotations along the z axis via the *flux* control line.



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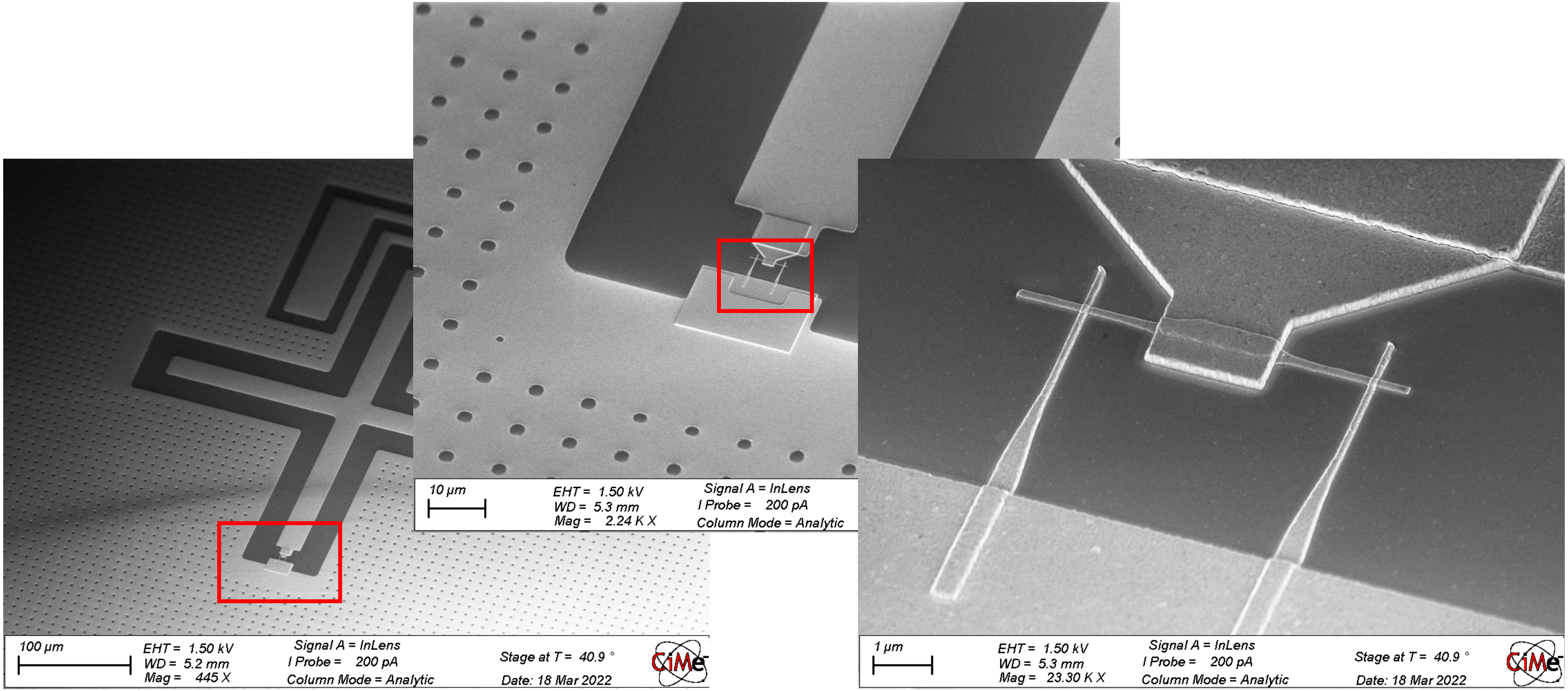
Transmons in EPFL



S. Frasca, *High-kinetic inductance superconducting technology for quantum applications*, PhD Thesis, EPFL, 2023

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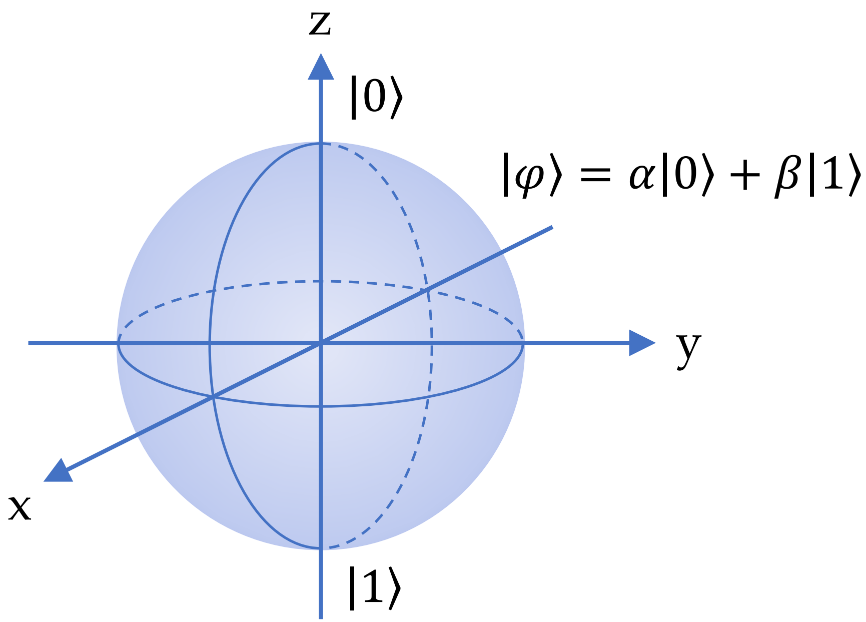
Energy loss and dephasing in qubits

- In simple terms, the quantum state in a qubit can be modified through two main perturbative effects, called **energy relaxation** and **pure dephasing**.

- Energy relaxation implies energy loss to the environment. It is usually visualized as a rotation along the x or y axes.

- Pure dephasing is due to mismatch between qubit resonant frequency and drive frequency. It is usually visualized as a rotation along the z axis.

- Decoherence is a process that implies both perturbation mechanisms and describes the loss of a superposition state.



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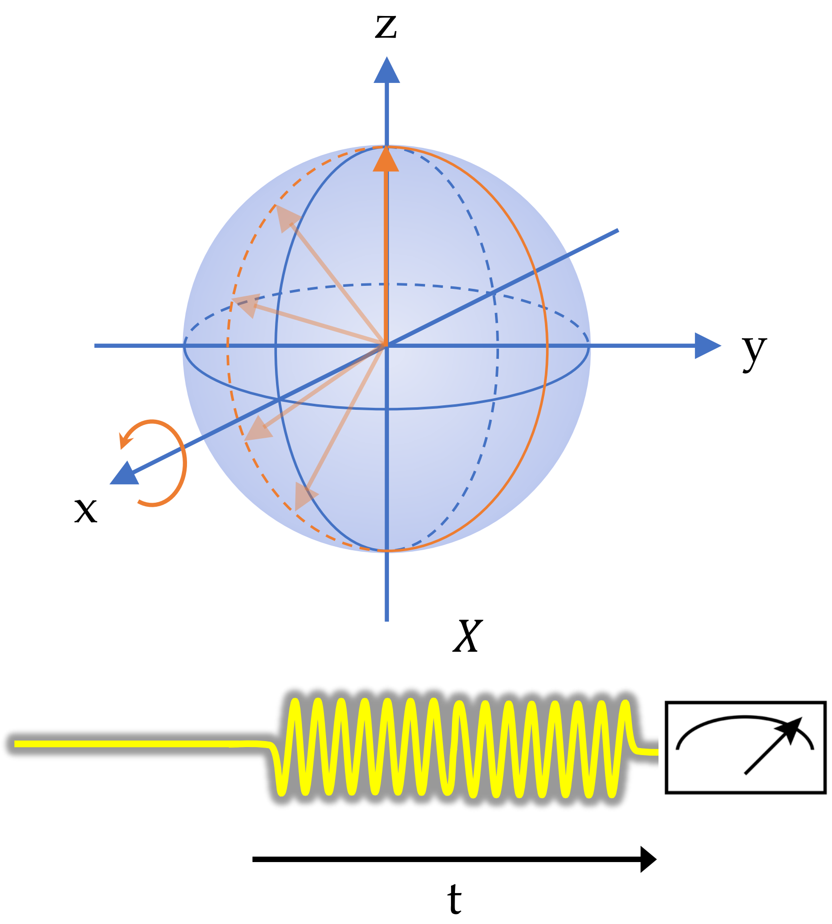
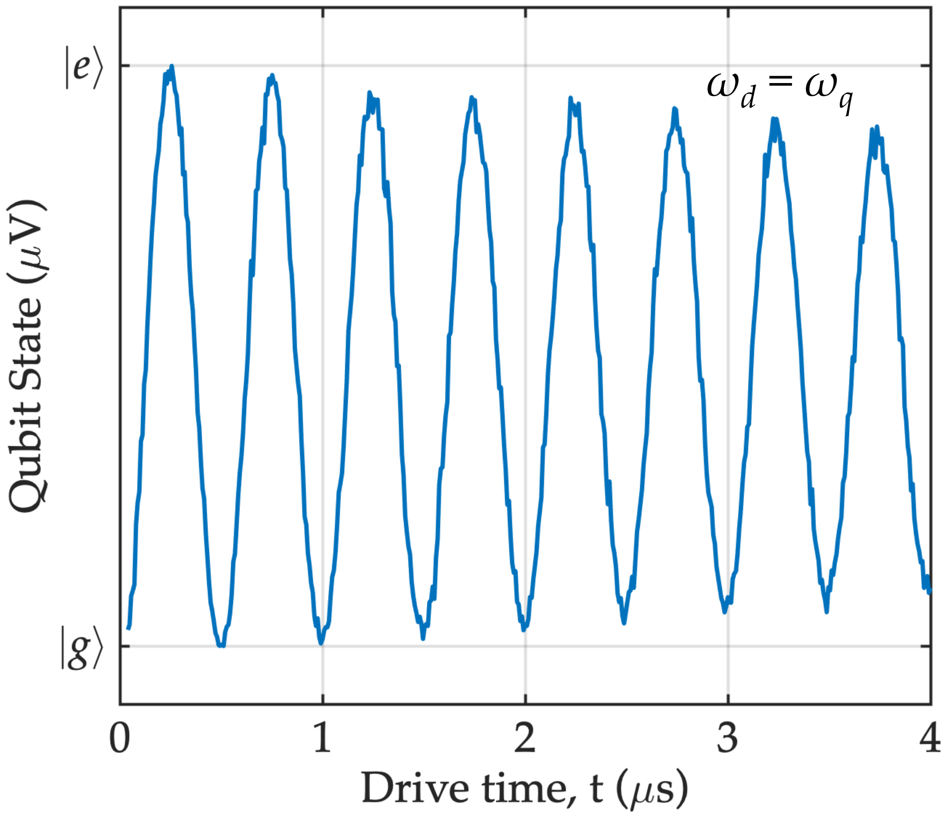
Rabi oscillation





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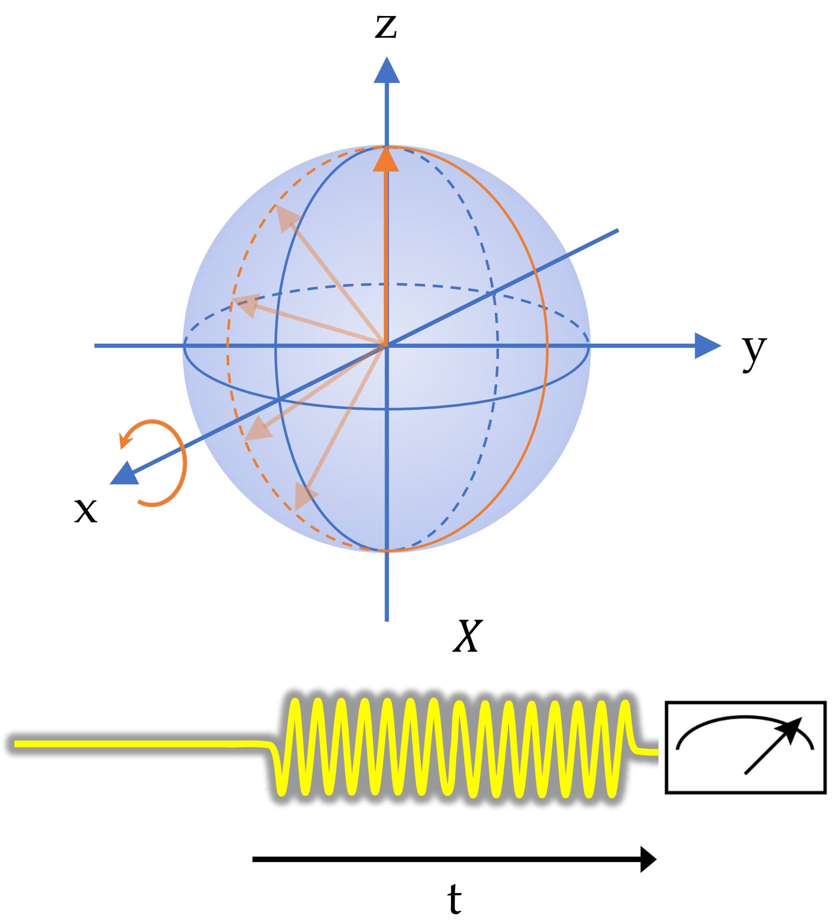

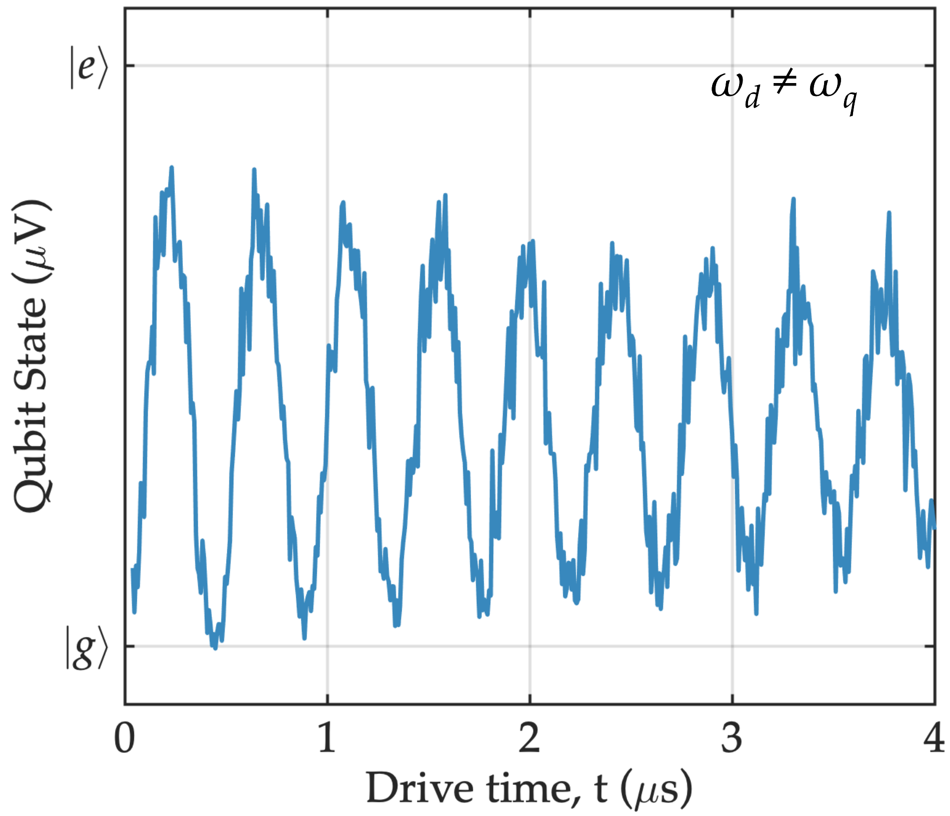

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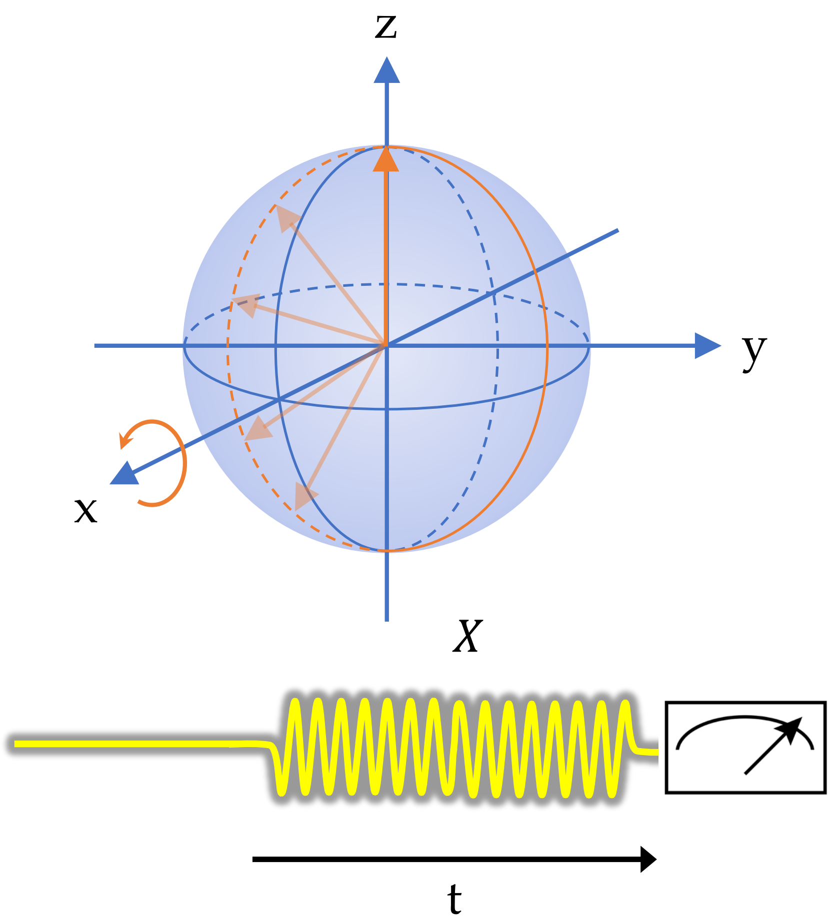

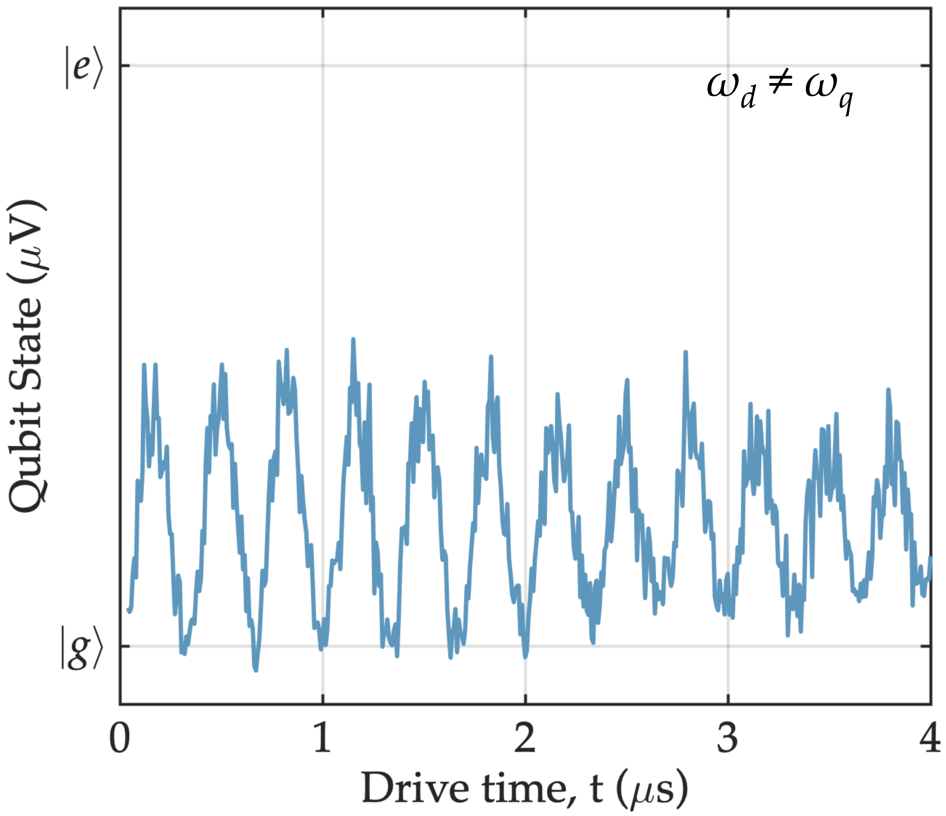

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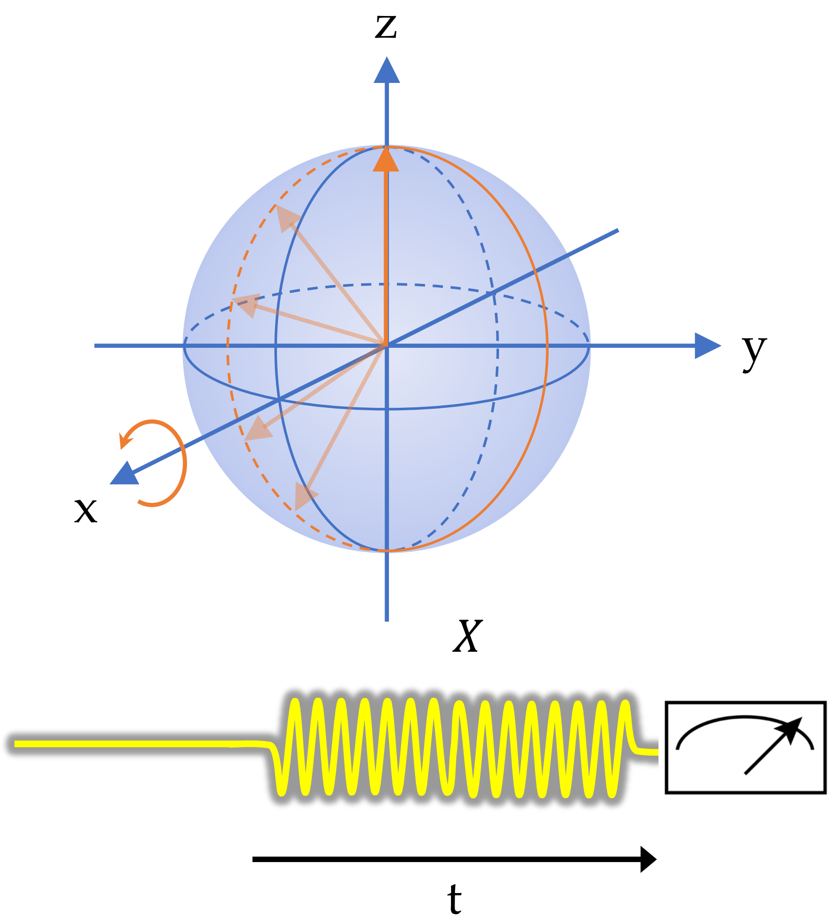

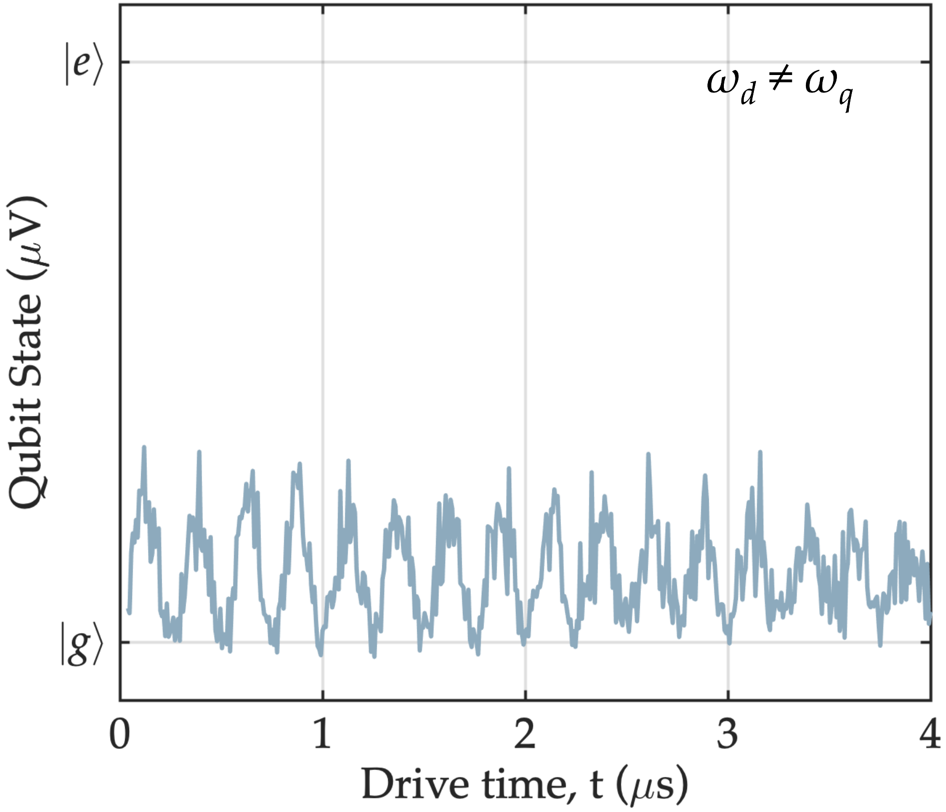

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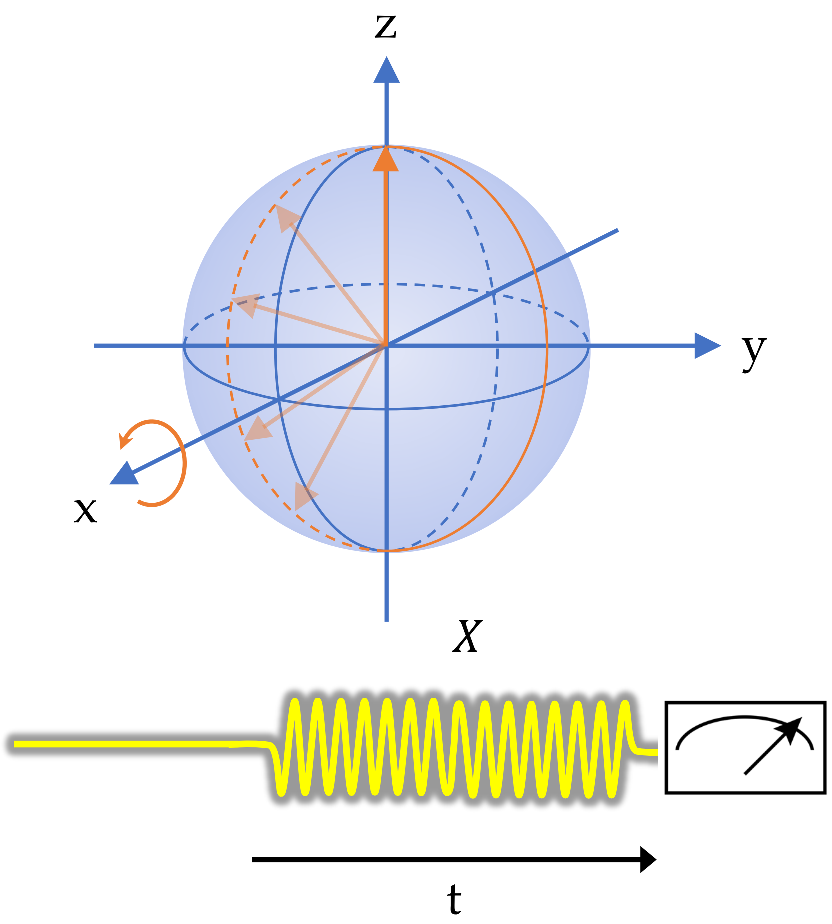

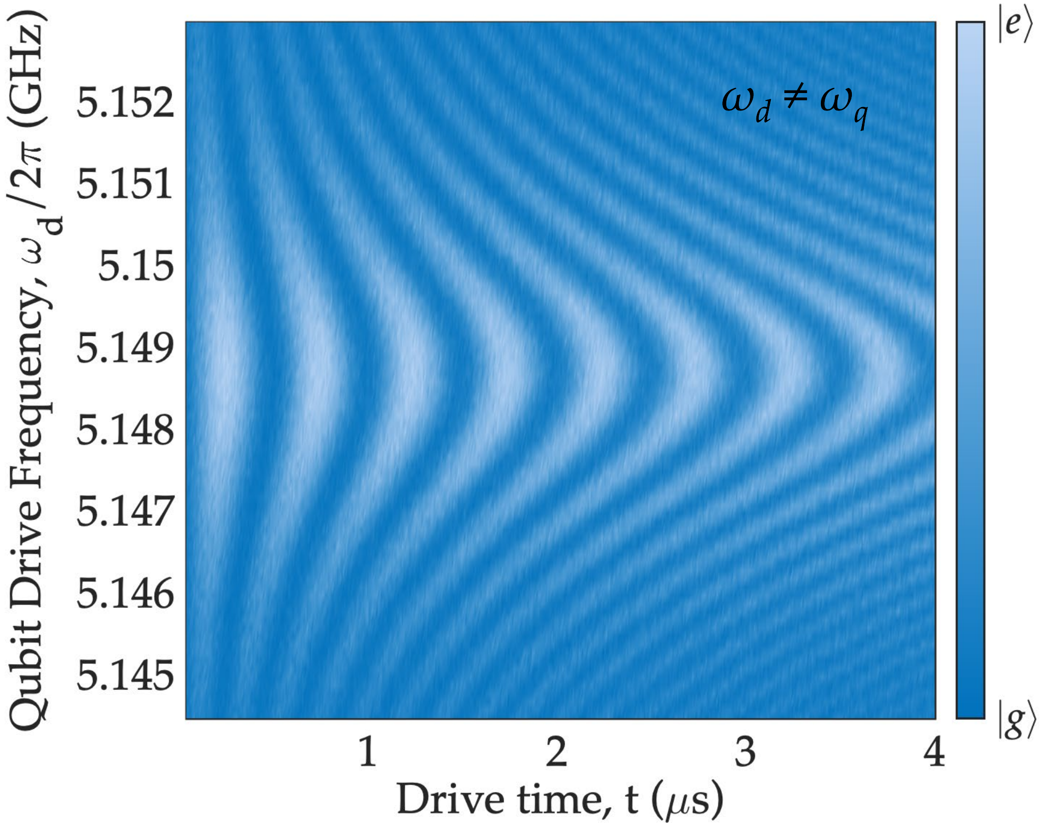

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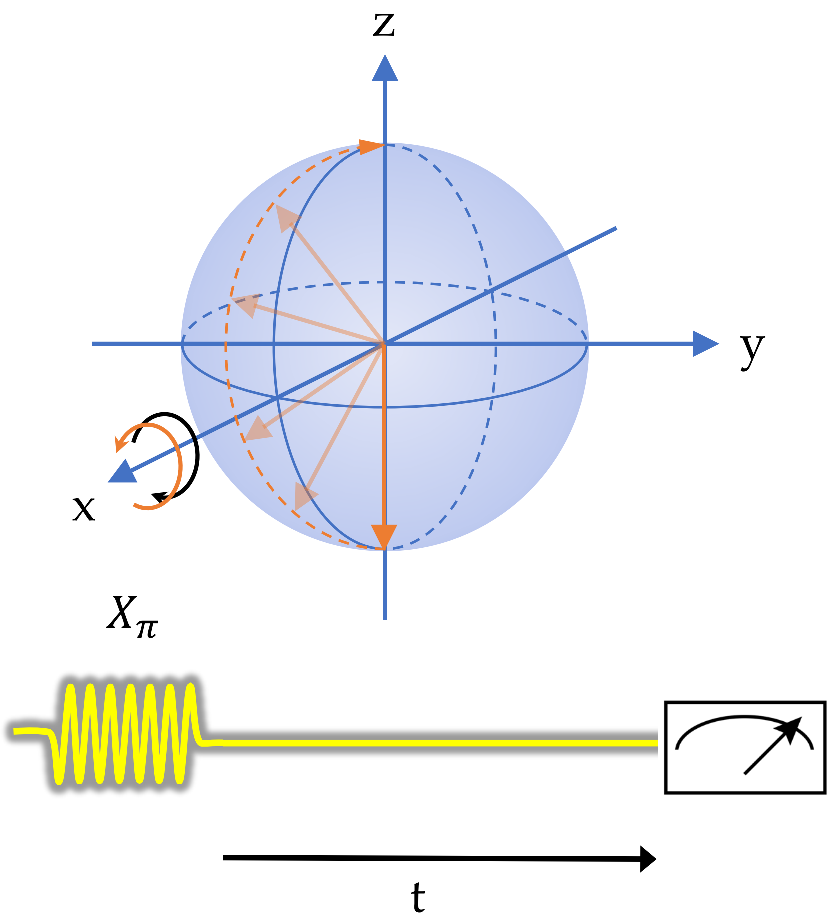
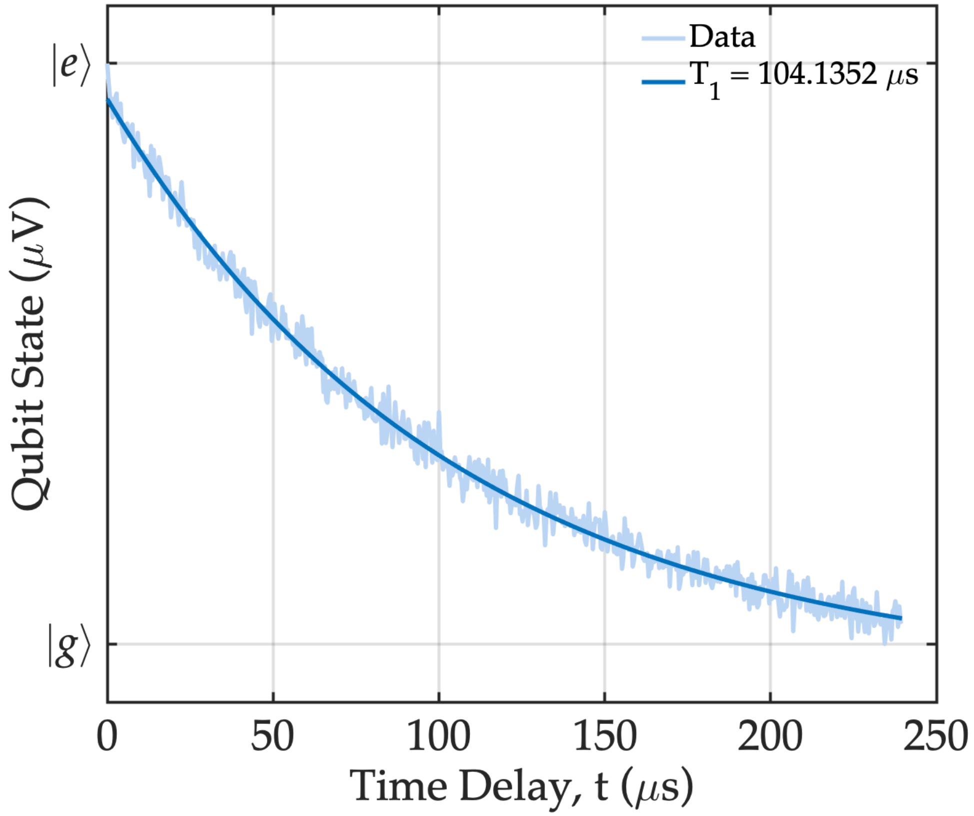
Relaxation Time, T_1





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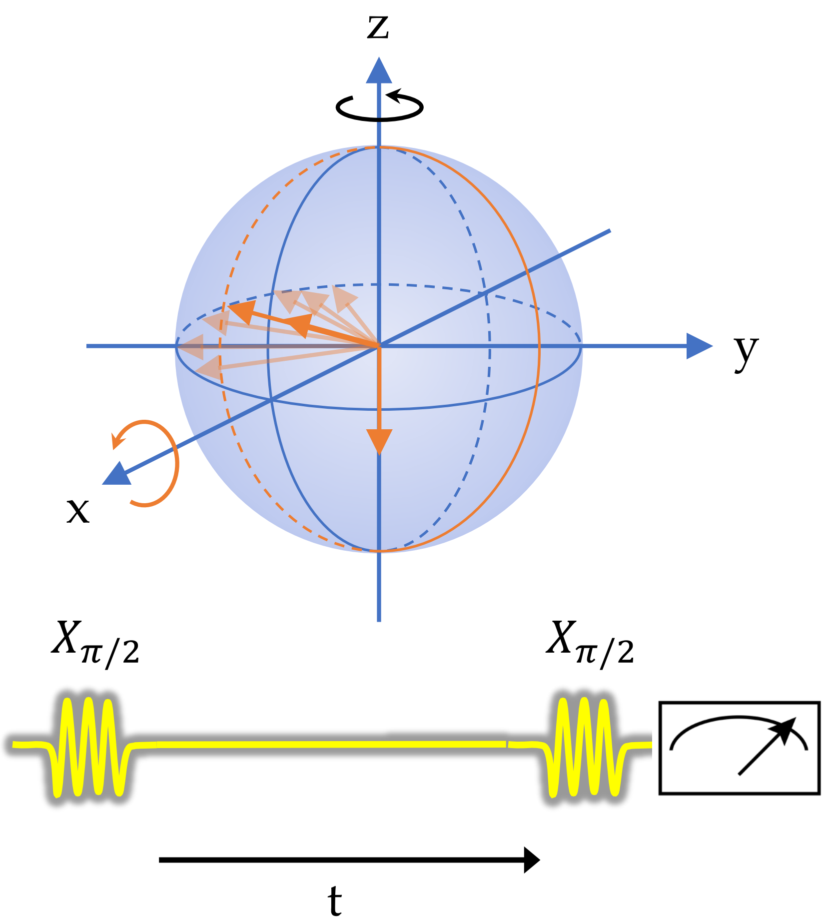
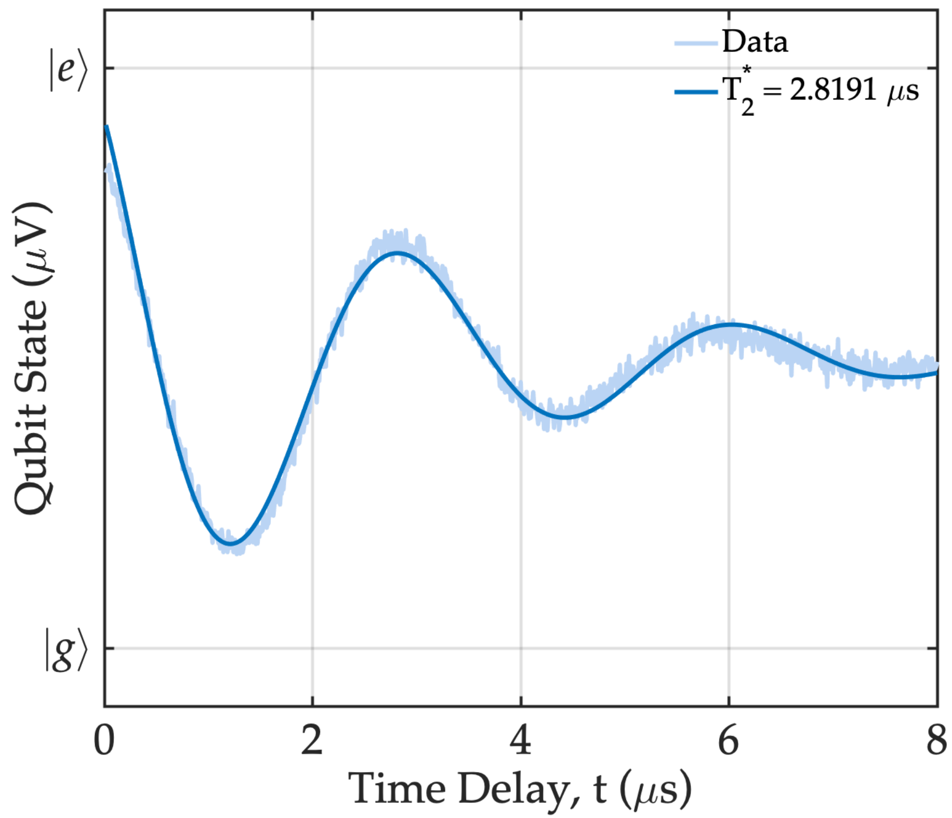
Ramsey Measurement, T_2^*





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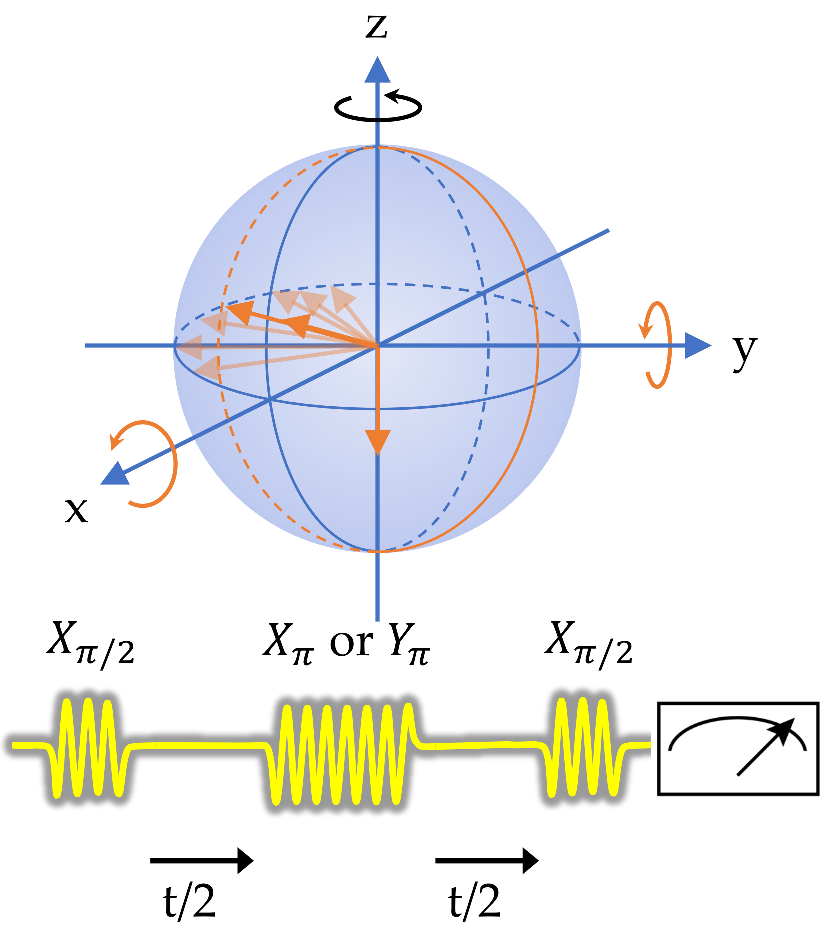
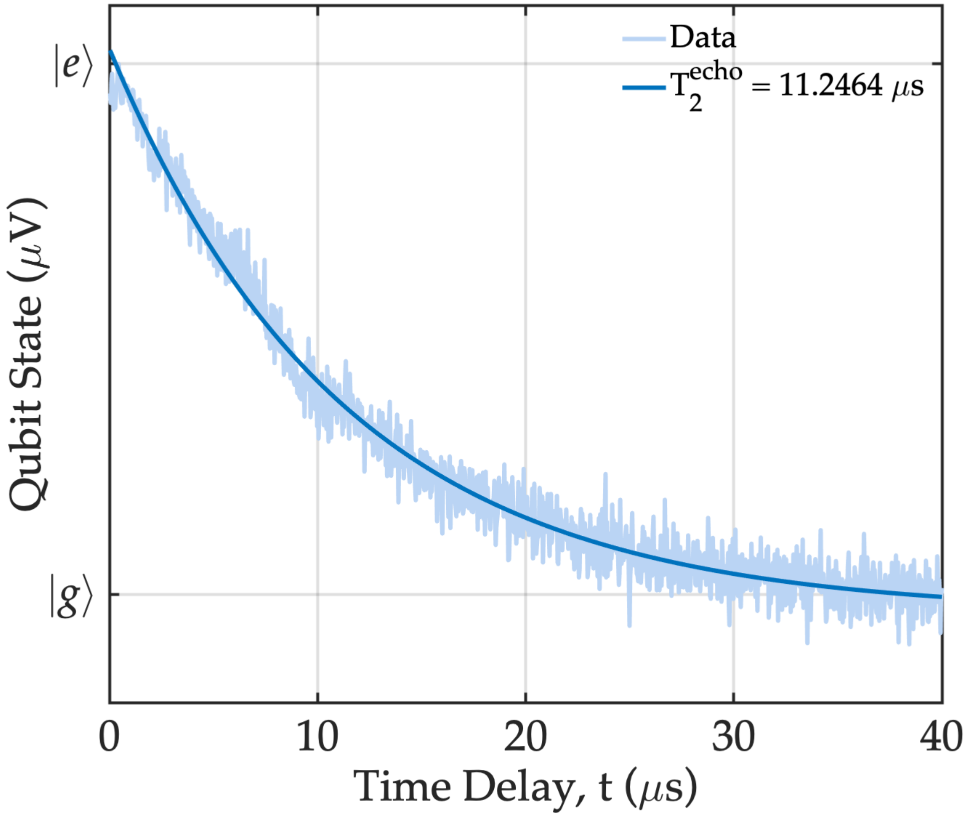
Spin Echo Measurement, T_{2e}





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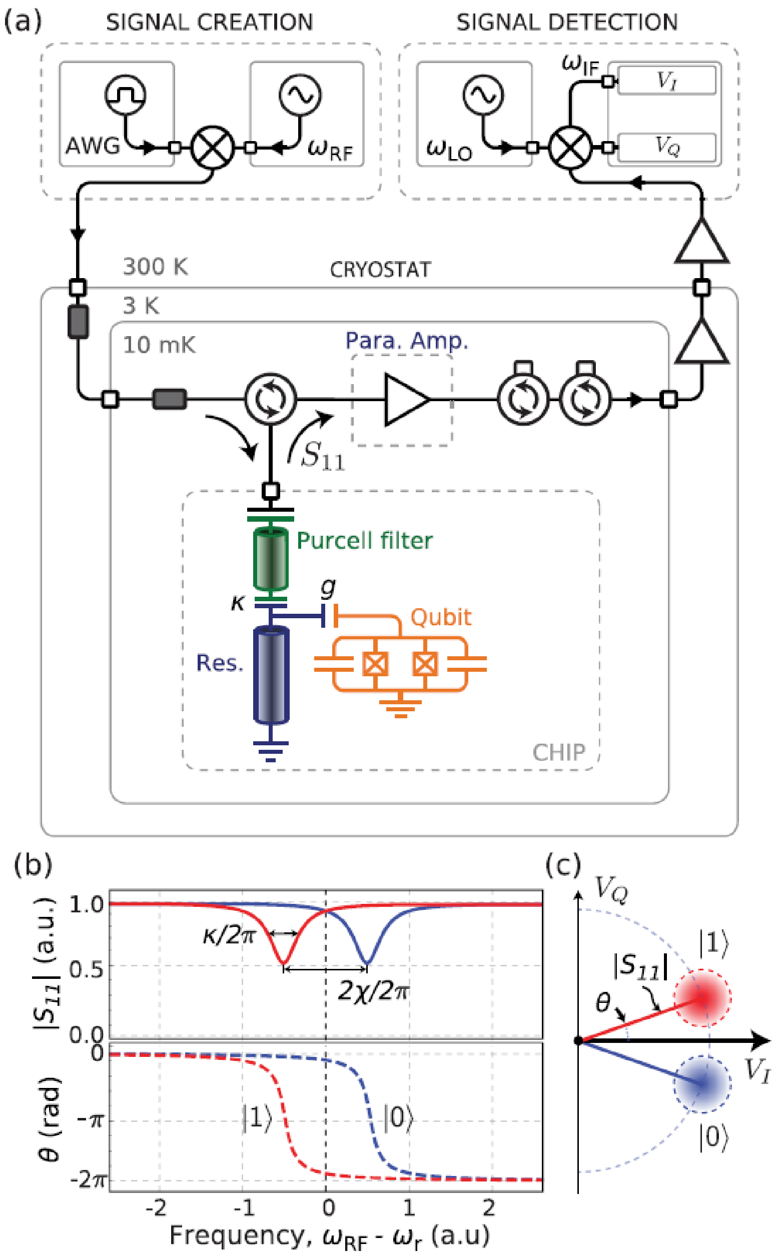
The idea of a non-destructive measurement

- In order to perform a non-destructive measurement of the qubit state, in circuit quantum electrodynamics (cQED) it is common to have a qubit interact non-destructively with a superconducting resonator.

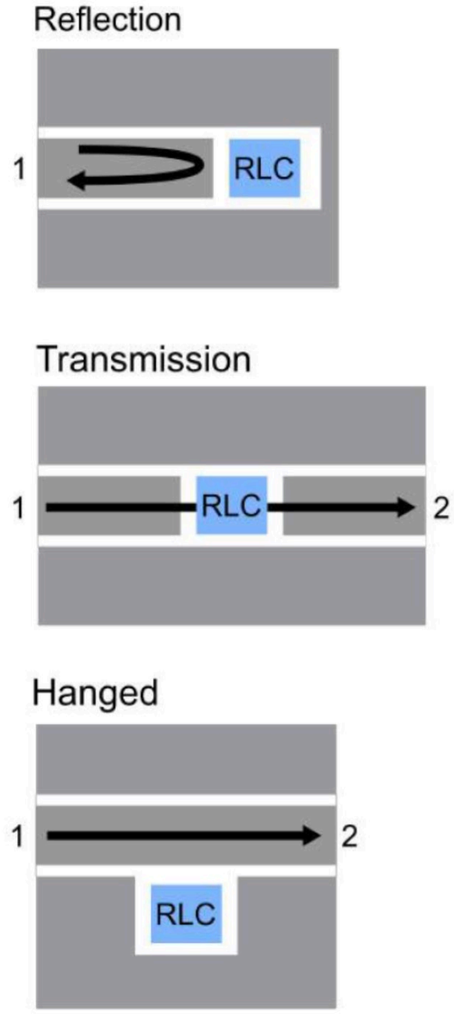
- By sensing the resonant frequency of the readout resonator, i.e. a resonator strongly coupled to the qubit, we can distinguish whether the qubit is in the ground or excited states, without actively measuring it.

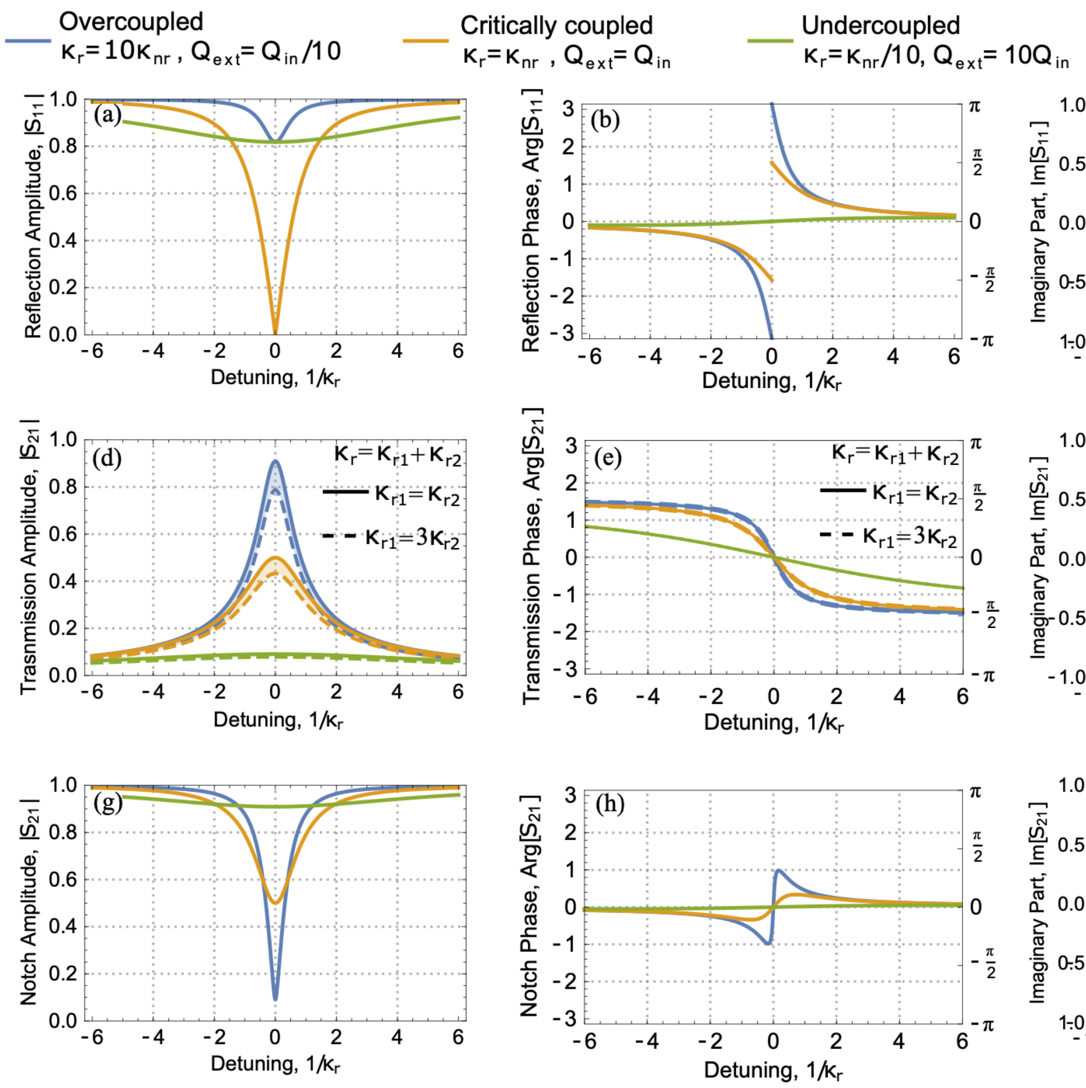
- This regime of non-distructive interaction is defined as **dispersion regime**.



P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. **6**, 021318 (2019)

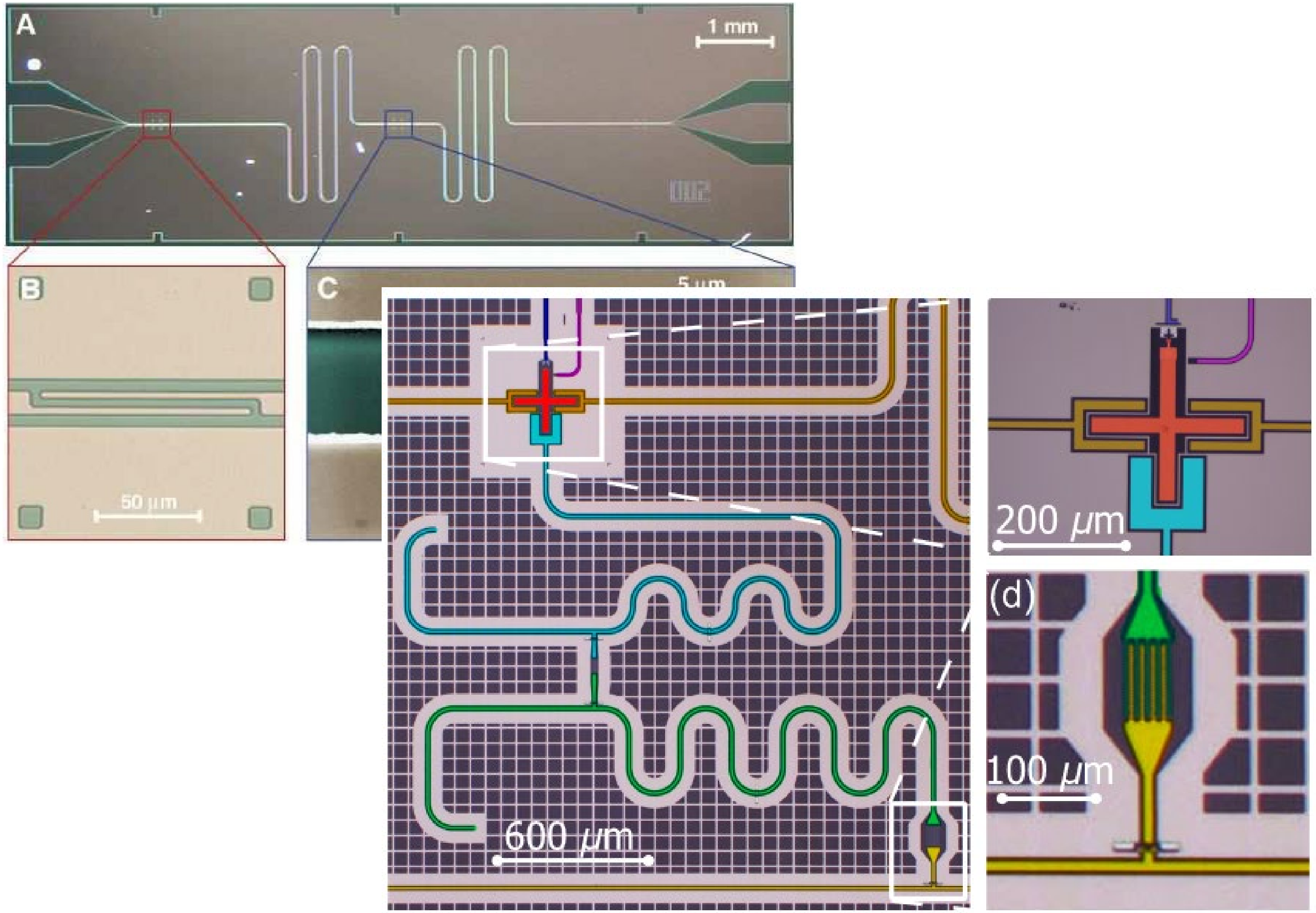
Readout strategies for resonating structures

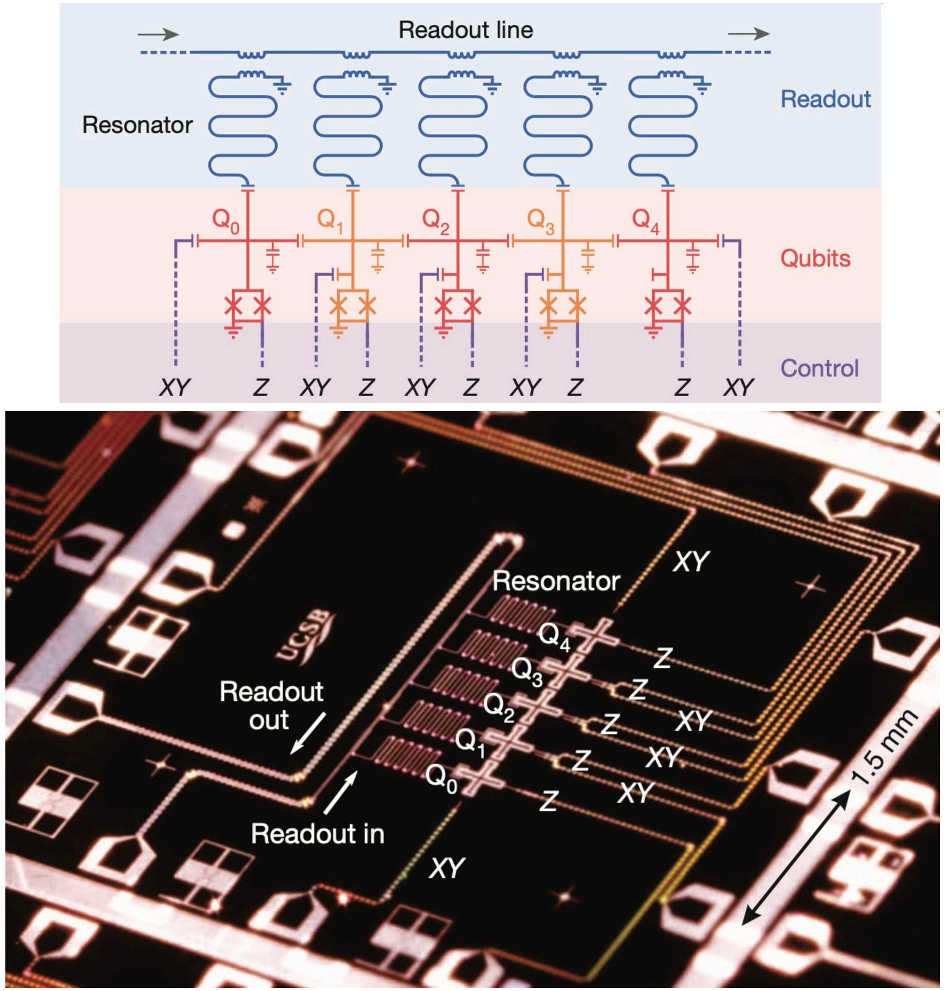




M. Scigliuzzo, *Effects of the environment on quantum systems*, PhD Thesis, Chalmers University, 2021

Qubits readout resonators





A. Wallraff et al., *Circuit quantum electrodynamics: coherent coupling of a single photon to a cooper pair box*, Nature **431**, 162 (2004)

J. Heinsoo et al., *rapid high-fidelity multiplexed readout of superconducting qubits*, Phys. Rev. Appl. **10**, 034040 (2018)

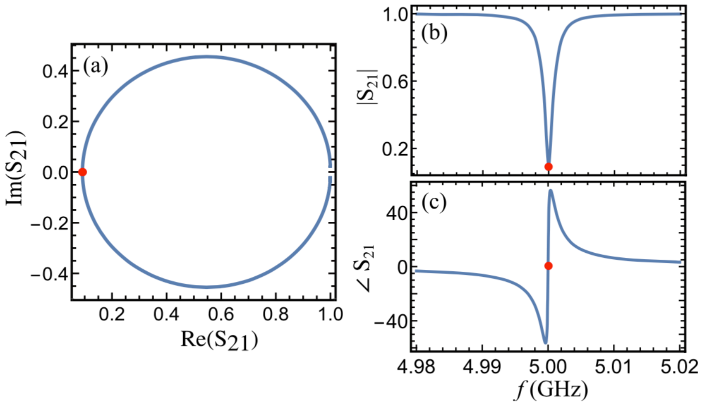
R. Barends et al., *Superconducting quantum circuits at the surface code threshold for fault tolerance*, Nature **508**, 7497 (2015)

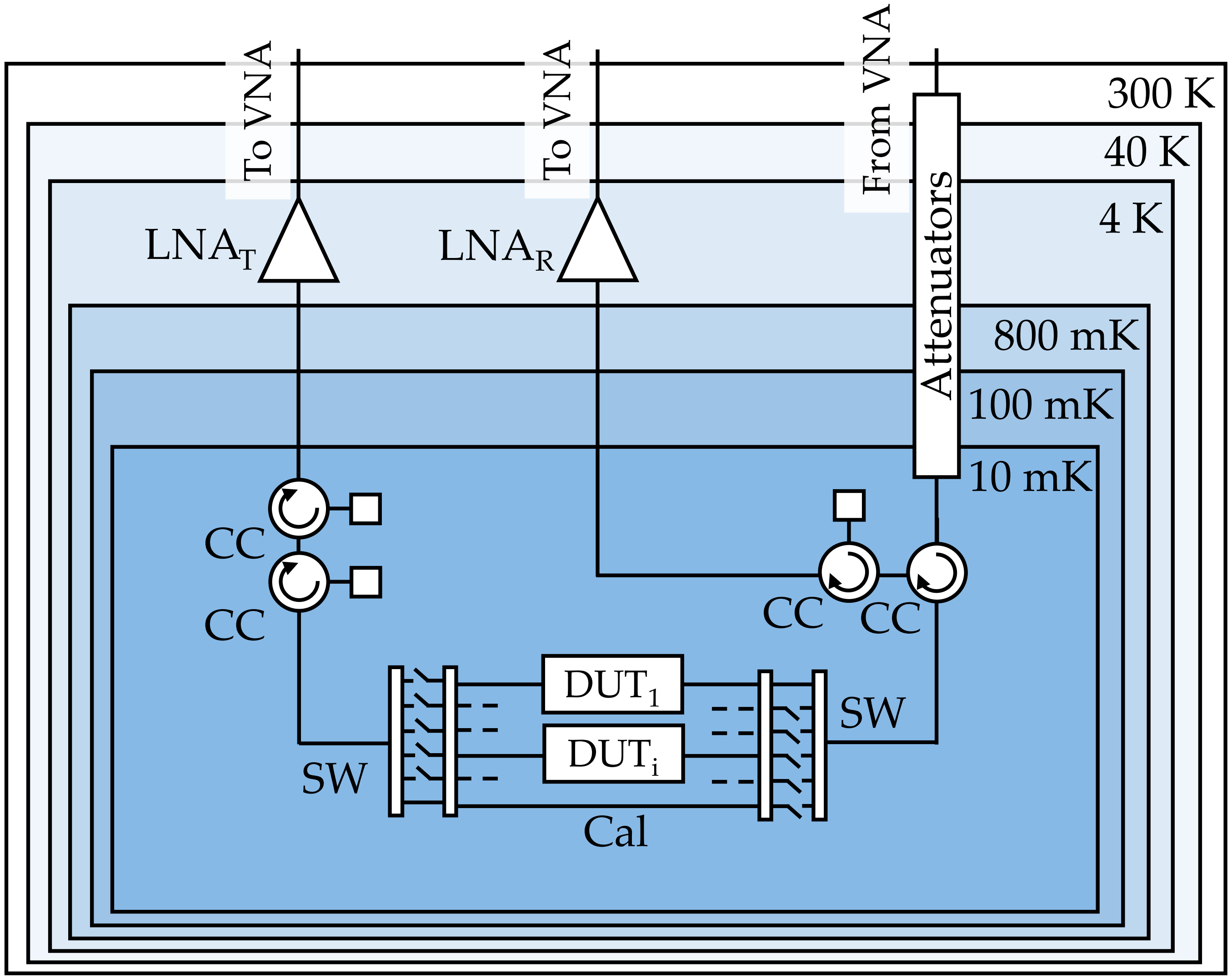
How to measure quality of superconducting resonators

- Classical setup for resonators' Quality Factors measurements.

- Use of a VNA to estimate the scattering parameters from which one can extract the quality factors. For instance, for hanged-style resonators:

$$S_{21} = 1 - \frac{\kappa_e}{\kappa_e + \kappa_i} \frac{1}{1 + 2j(\omega - \omega_r)}$$





Transmon Qubits Characterization Design

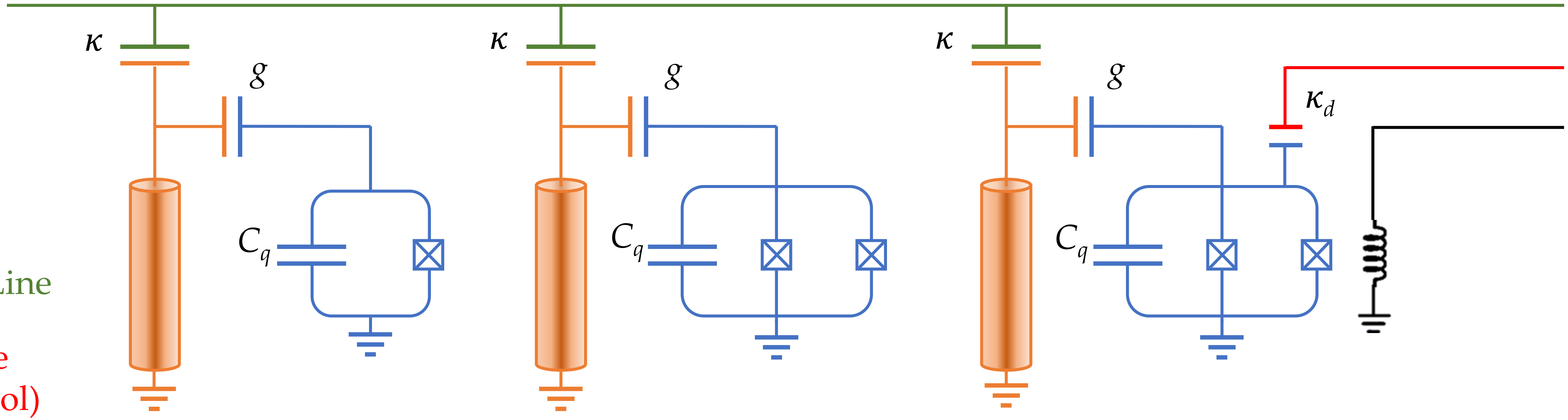
Resonator

Transmon

Readout Line

Drive Line
(XY Control)

Flux Line
(Z Control)



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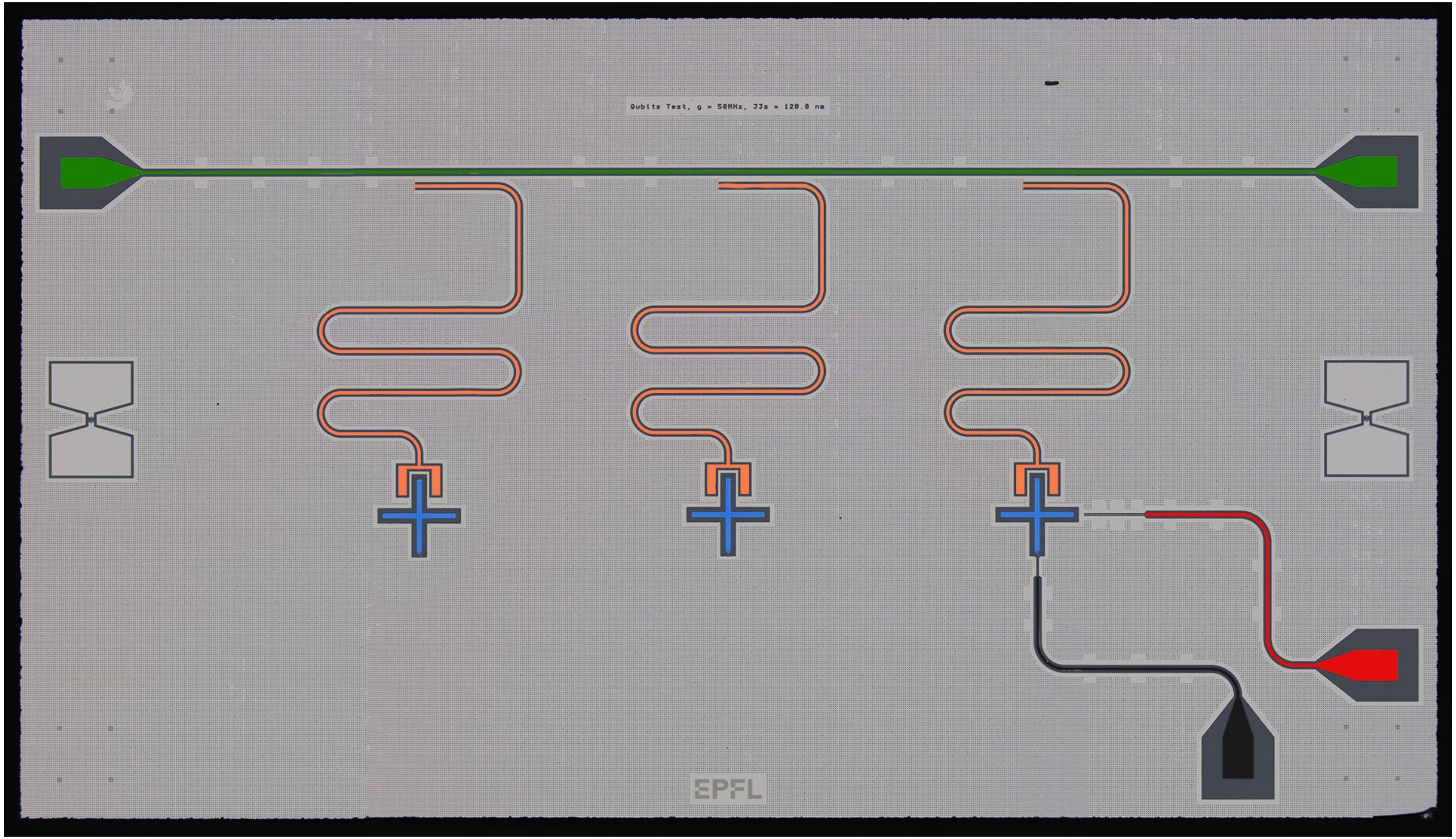

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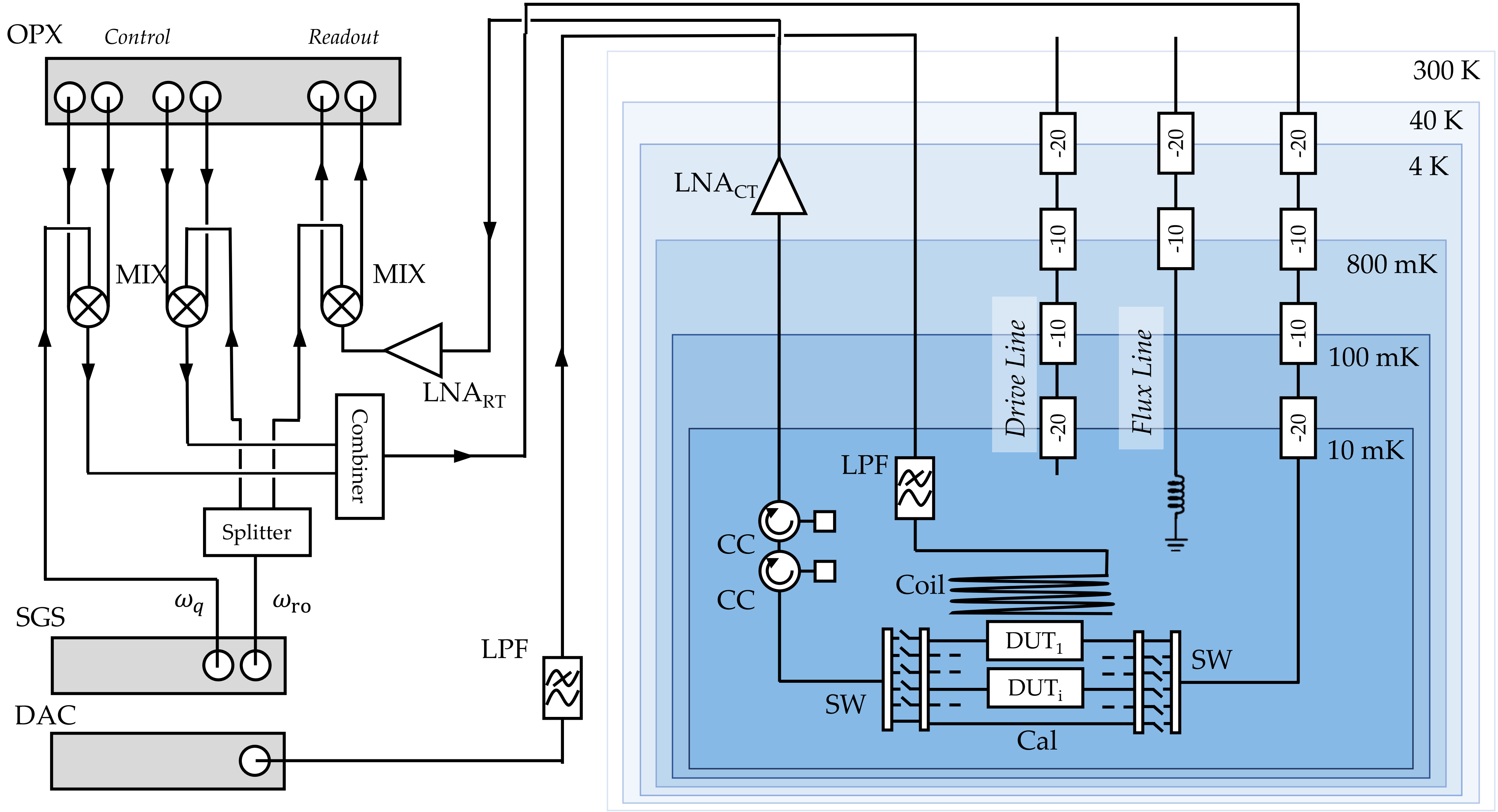
Setup to measure Qubits



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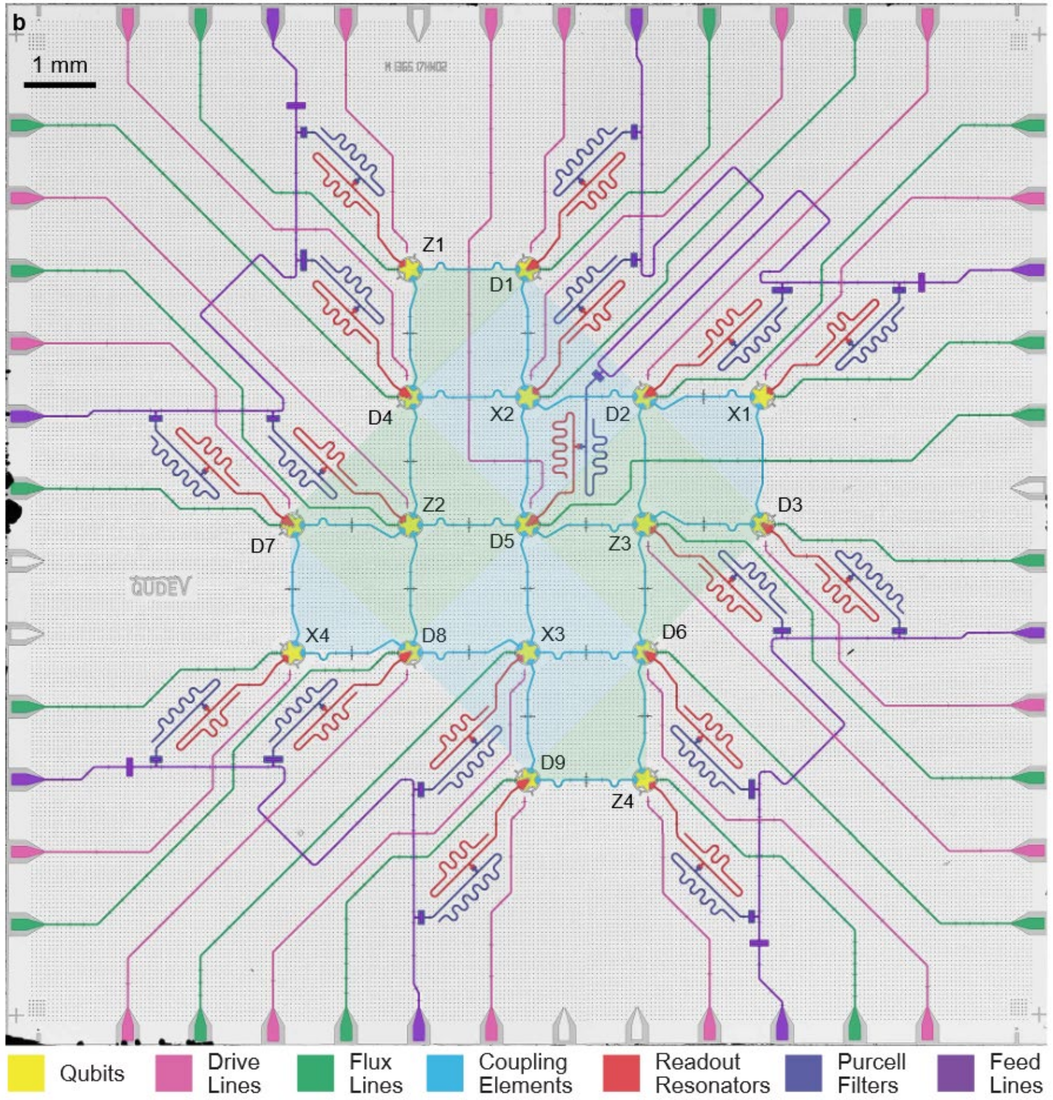
Fabrication steps involved in cQED devices

Fabrication steps involved to make qubits:

- Conventional Fabrication Techniques:
  - Thin films deposition or growth
  - Lithography (photo- or electron beam-)
  - Etching (chemical or physical)

- Unconventional Techniques:
  - Dolan bridge-like angled deposition
  - Manhattan-like angled deposition



S. Krinner et al., *Realizing Repeated Quantum Error Correction in a Distance-Three Surface Code*, Nature **605**, 669 (2022)

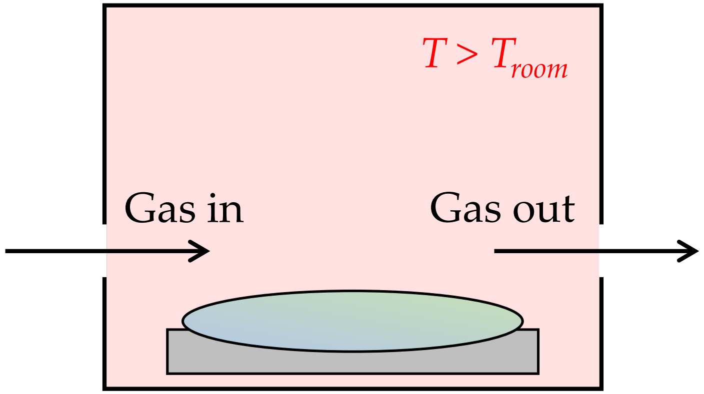
Thin film deposition or growth

- Divided in **chemical** and **physical** depositions.

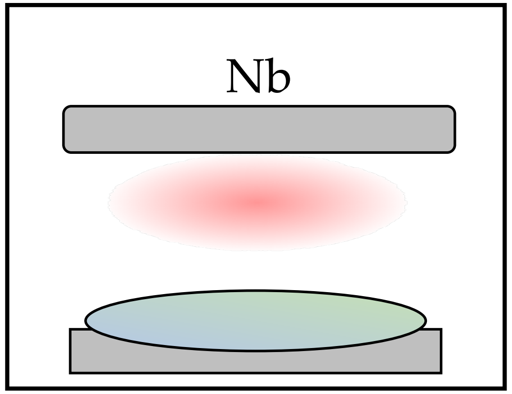
- The chemical vapor deposition (CVD) techniques require two reagents to react at the surface of the sample. It's a conformal deposition techniques but generally require high temperatures of operation.

- The physical vapor deposition (PVD) techniques simply let material deposit on the surface of the sample. Usually anisotropic, can be used for processes where deposition directionality matters.

CVD



PVD (sputtering)

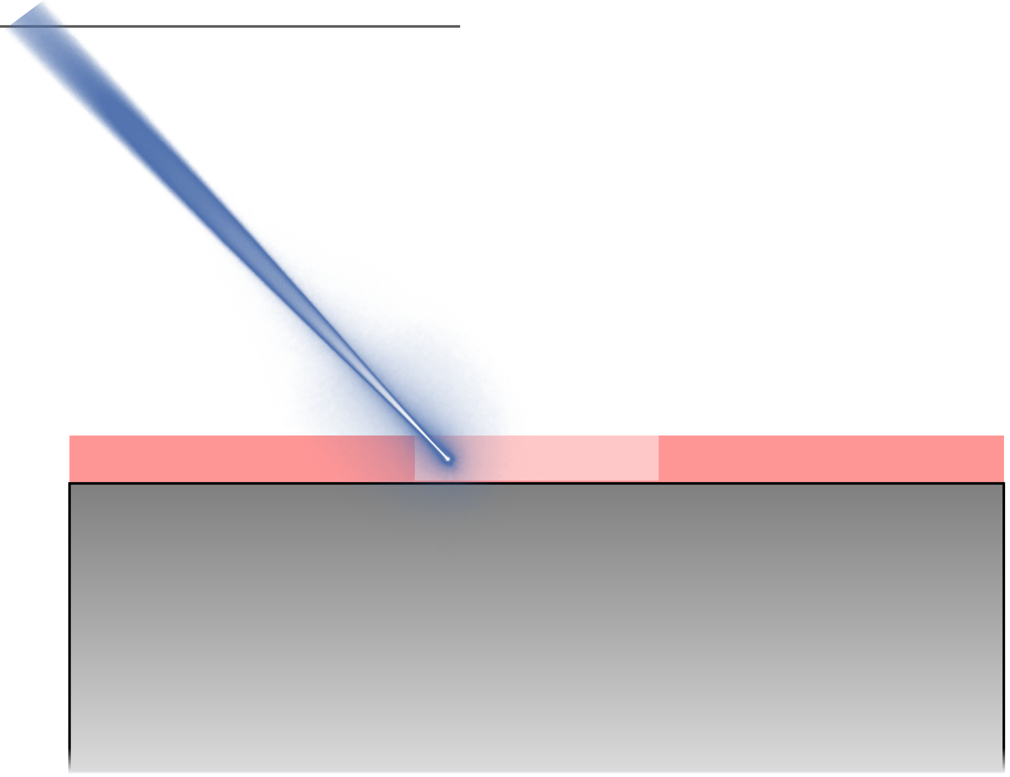


Lithography step

- Lithography is generally performed using either a laser or a beam of electrons to modify the chemical composition of a **lithography resist**, i.e. a polymer reactive to specific wavelengths or to electrons.

- After *exposure* with the writing machine, the polymer is then developed in a chemical whose purpose is to remove selectively only the exposed (positive resist) or not exposed (negative resist) portion of the resist.

- Different resists have different resolutions, dosages (the amount of light/electrons required to “open” them) and resistance to different etchants.



Example of positive resist exposure and development

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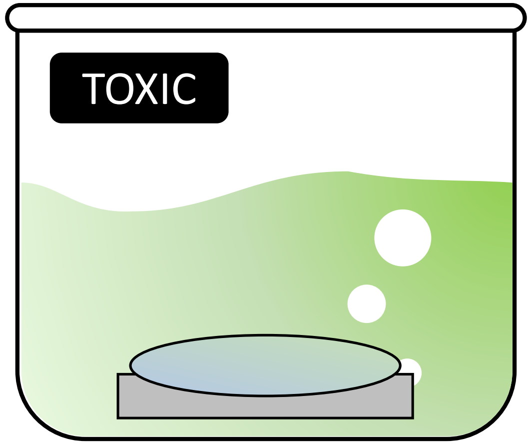
Example of positive resist exposure and development

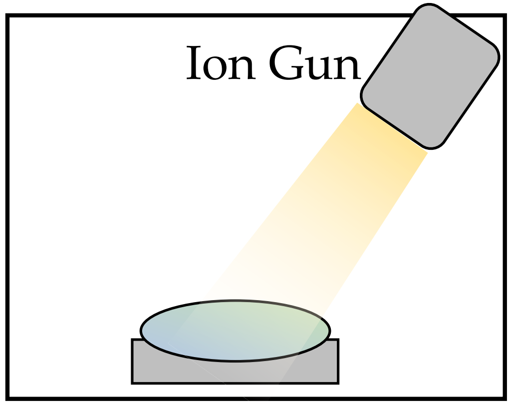
Etching

- Etching is the complementary process of the deposition, where material is not added but removed.
- It is usually performed via **chemical** etching (either an etchant bath or via plasma etching) which can be very isotropic, or through **physical** bombardment (ion gun etching and similar) which on the contrary is usually extremely directional.
- Chemical etching gives most times (when performed correctly) the best contrast between what we want to remove and what we don't.

Chemical Etching

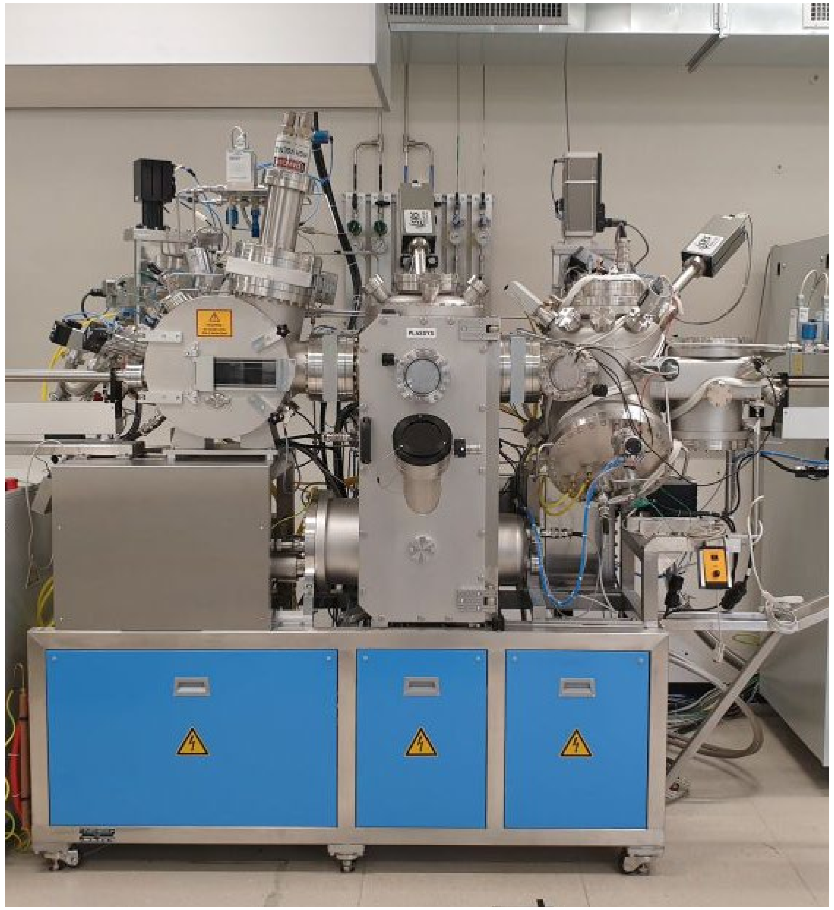


Physical Etching



Josephson junctions deposition

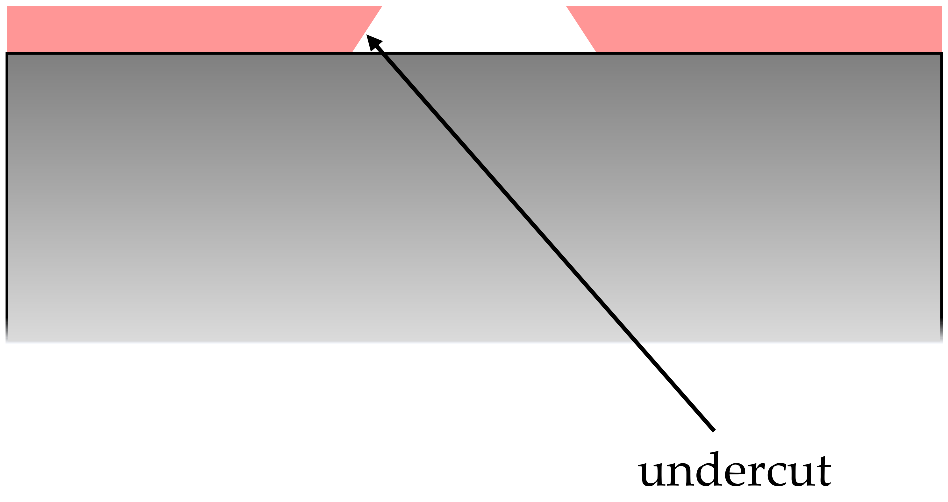
- As the most critical parameter of Josephson junctions is the control of the oxidation layer between the two superconductors, both electrodes and the oxidation need to happen in vacuum.
- This need lead to the technique used for Josephson junction depositions, which exploits the directionality of PVD (in the particular case, of metal evaporation) and sample tilt and rotation control, the so-called angled evaporation.
- There are two conventional techniques that exploit angled evaporations: the Dolan bridge technique and the Manhattan technique.



Three-chambers angled evaporator in CMi

Lift-off

- Before going through the two techniques, it is important to first explain the concept of liftoff.
- Liftoff is a patterning technique that avoids the use of etching. Indeed, by depositing specific type (or multiple layers) of resist, which form an undercut after development, it is possible to pattern first the substrate and then deposit only in the patterned area.
- After deposition, the material in excess deposited on top of the resist is *lifted off* and removed, leaving only the patterned feature covered by the deposited material.



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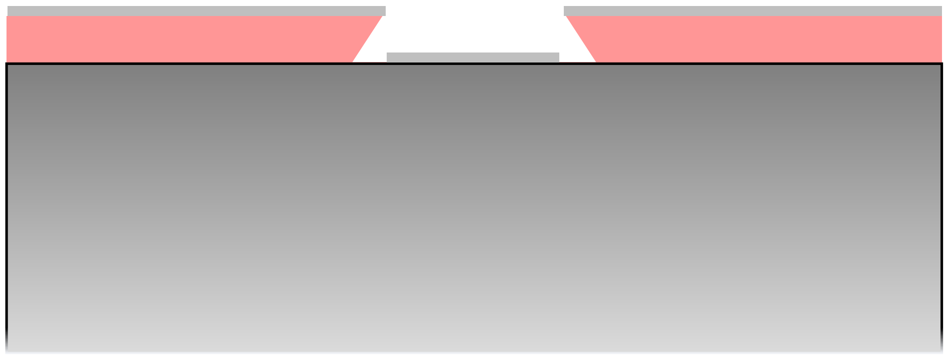

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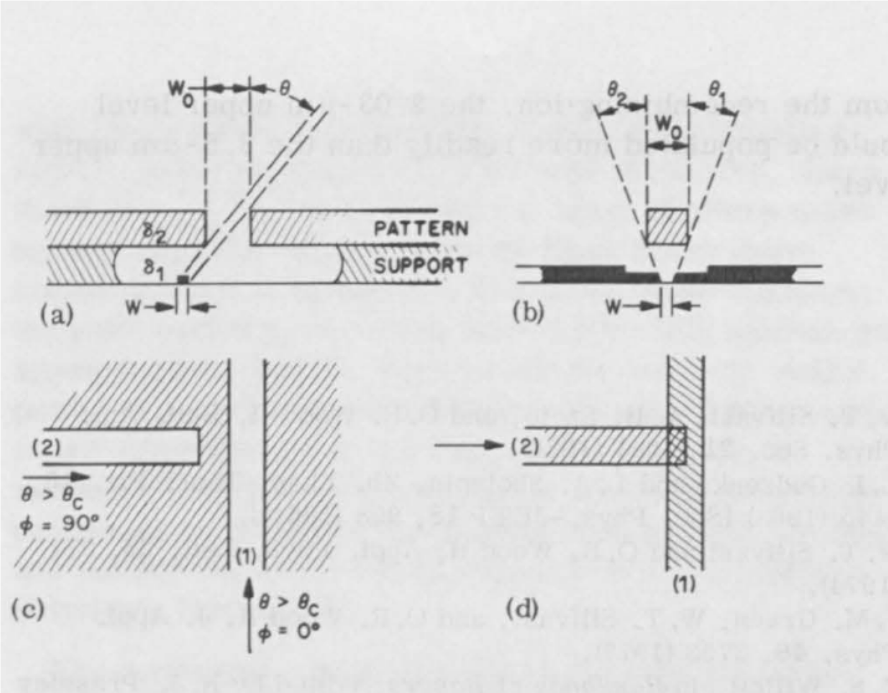
Dolan bridge technique

- Dolan bridge technique is used generally with a bilayer of resists (the top more robust to the etching of the developer) to generate floating resist structures, i.e. the bridges.
- Using angled evaporation, it is possible to deposit the first electrode, oxidize in a controlled environment, and then deposit the second electrode, all without breaking the vacuum.
- The principal drawback of this technique is that generally creates unwanted large junctions where the electrodes lie.



W. Yu-Lin et al., *Fabrication of Al/AlOx/Al Josephson junctions and superconducting quantum circuits by shadow evaporation and a dynamic oxidation process*, Chin. Phys. B **22**, 060309 (2013)
G. J. Dolan, *Offset masks for lift-off photoprocessing*, Appl. Phys. Lett. **31**, 337 (1977)

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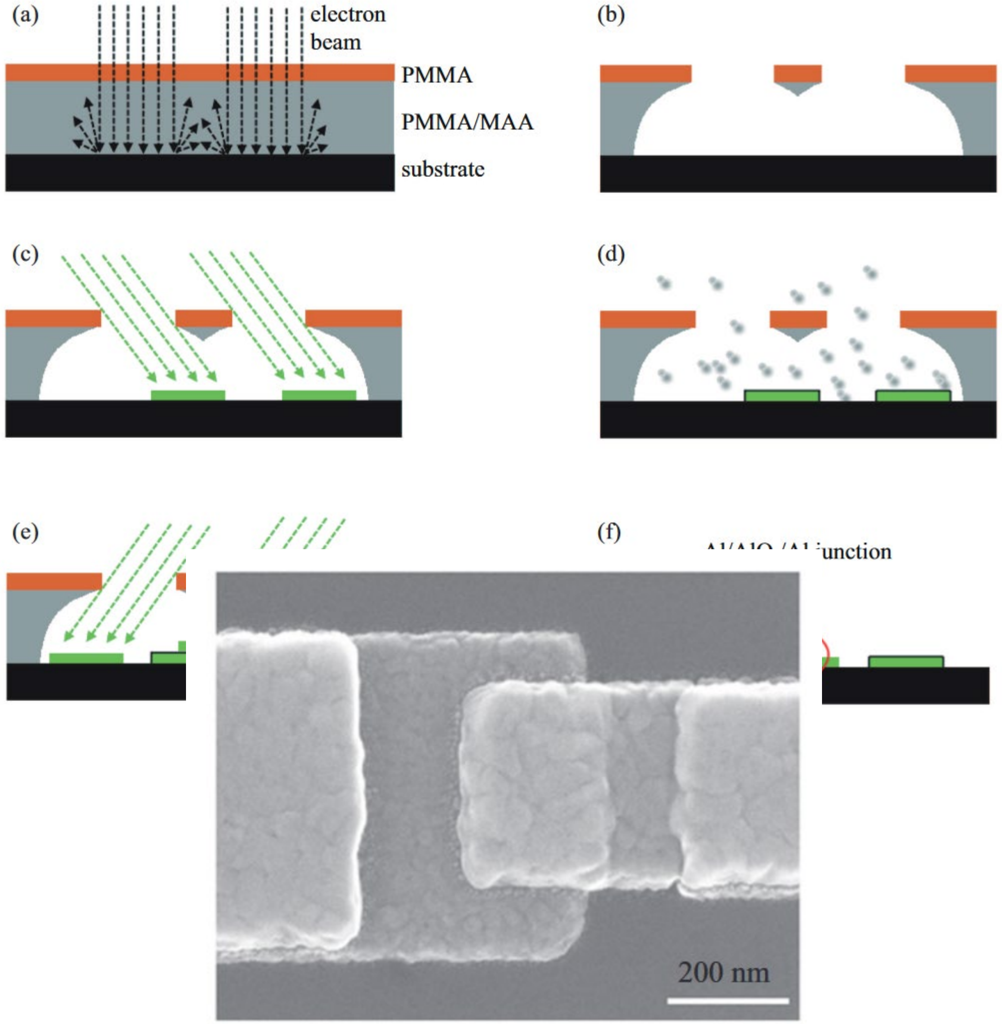

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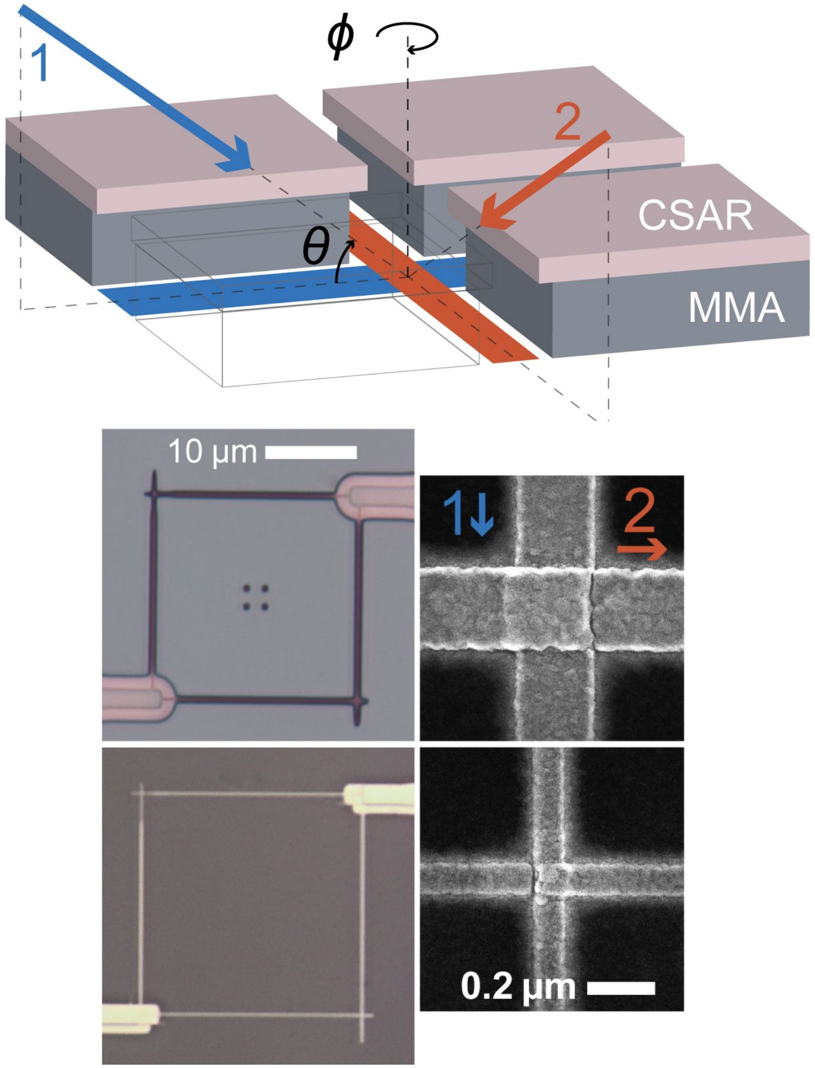
Manhattan technique

- Manhattan technique allows for the same advantages of the Dolan bridge but without the need of floating structures, i.e. the bridges, making it more robust during processing.

- As main drawback, generally Manhattan-style Josephson junctions require a subsequent patching step to connect the two electrodes to the metallic leads.

- Recently, a three-angles evaporation technique has been developed so that the patching step can be integrated within the deposition process.

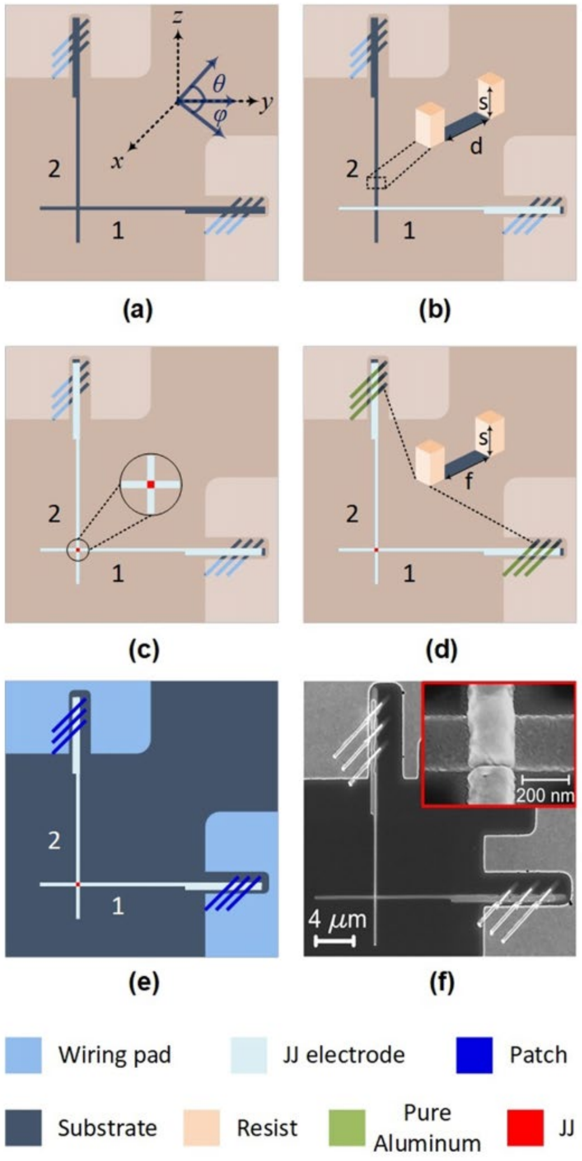


https://aqt.lbl.gov/josephson-junction-optimization-2/

A. Osman et al., *Simplified Josephson-junction fabrication process for reproducibly high-performance superconducting qubits*, Appl. Phys. Lett. **118**, 064002 (2021)

Manhattan technique

- Manhattan technique allows for the same advantages of the Dolan bridge but without the need of floating structures, i.e. the bridges, making it more robust during processing.
- As main drawback, generally Manhattan-style Josephson junctions require a subsequent patching step to connect the two electrodes to the metallic leads.
- Recently, a three-angles evaporation technique has been developed so that the patching step can be integrated within the deposition process.



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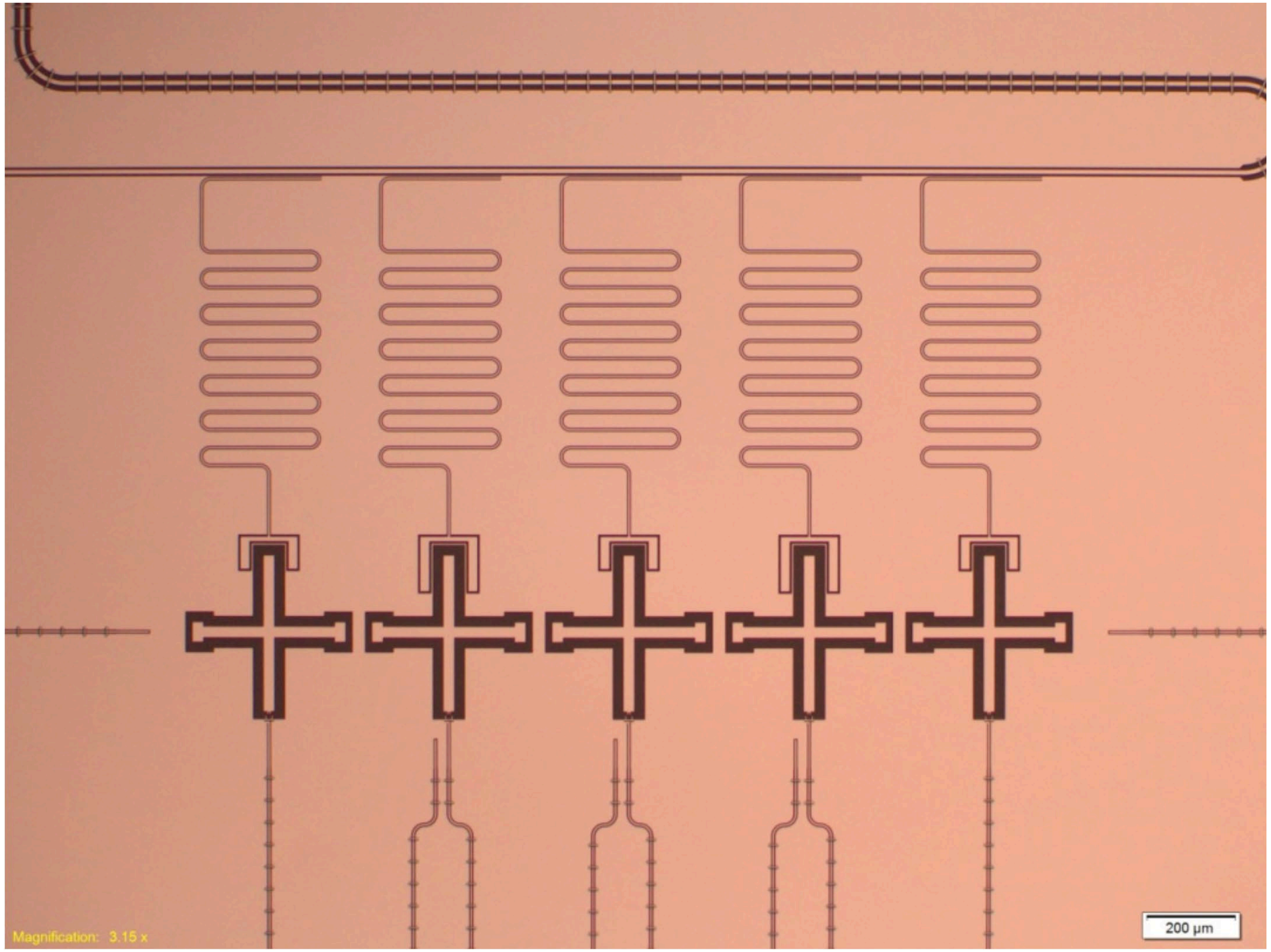
Device fabrication of a quantum processor

- MBE grown-Al on Sapphire
- Control wiring lithography and etching (photolitho + RIE Cl_2-based)
- Airbridges fabrication with SiO_2 layer (not suspended)
- Capacitor lithography and etching
- JJ deposition with angled evaporation (Manhattan) and patching step



R. Barends et al., *Superconducting quantum circuits at the surface code threshold for fault tolerance*, Nature **508**, 7497 (2015)

Outline

- What is a qubit? How can we make one?
- Defining a "good" qubit…
- Design qubits and readout circuits for quantum processors
- Chips fabrication in the cleanrooms
- Where are losses coming from?
- Few design guidelines to reduce losses in your chips

Losses generation

- Losses arise from:

$$\frac{1}{Q_i} = \tan\delta \simeq \delta,$$

  - Two-Level Systems (TLS)
  - Quasi particle creation
  - Vortex crossing loss
  - Radiative loss
  - Parasitic mode loss
  - Noise

TABLE I. Summary of resonator loss mechanisms and their properties. L or C denotes whether the loss is associated with capacitive or inductive resonator components. Columns 3–6 denote positive (+), negative (–), no (No), or unknown (blank) correlation between each loss type and the experimental parameter. Yes indicates that a correlation exists. TLS: two-level system loss. qp-IR: quasiparticle loss due to stray infrared light. qp-μw: quasiparticle loss due to microwave-induced pair-breaking. par. modes: parasitic modes. Geometry refers to the conductor/gap widths of the CPW and IDC for TLS and radiation losses, and the conductor width of the inductor for vortex loss.

Loss type	L or C	Power	Temperature	Frequency	Geometry
TLS	C	–	–	+	–
qp-thermal	L	No	+	+	
qp-IR	L	No	No		
qp-μw	L	+	+	+	
Vortex	L	No	+	+	+
Radiation	L, C	No	No	+	+
par. modes	L, C	No	No	Yes	

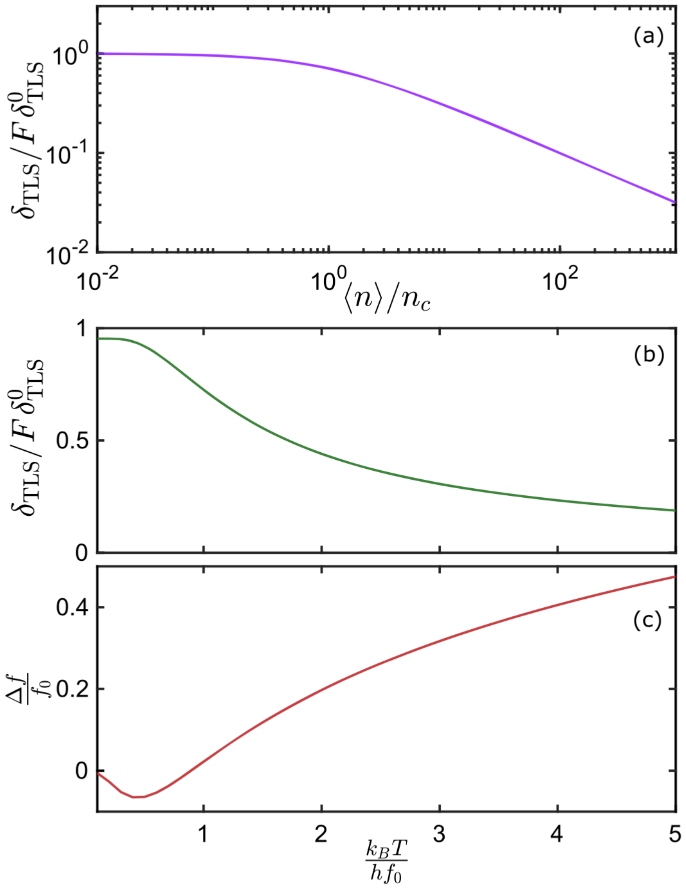
C. R. H. McRae et al., *Material loss measurements using superconducting microwave resonators*, Rev. Sci. Instrum. **91**, 0.1101 (2020)

TLS Losses

- Amorphous solids exhibit very different thermal, acoustic, and dielectric properties from crystalline solids at low temperatures, which can be modeled by the two-level system (TLS).

- A TLS can be excited by absorbing a photon (from a resonator or qubit) and relaxes by emitting a phonon into the bath, causing resonator loss and qubit decoherence.

- According to the TLS model, the TLS induces a power-dependent and temperature-dependent resonator loss δ_{TLS} and temperature-dependent resonance fractional frequency shift $\Delta f / f_0$



$$\delta_{TLS} = F\delta^0_{TLS}\frac{\tanh\left(\frac{\hbar\omega}{2k_BT}\right)}{\sqrt{1+\frac{\langle n\rangle}{n_c}}},$$

$$\frac{\Delta f}{f_0} = \frac{F\delta^0_{TLS}}{\pi}\left[\mathrm{Re}\left(\Psi\left(\frac{1}{2}+\frac{1}{2\pi i}\frac{\hbar\omega}{kT}\right)\right)-\log\frac{\hbar\omega}{2\pi kT}\right],$$

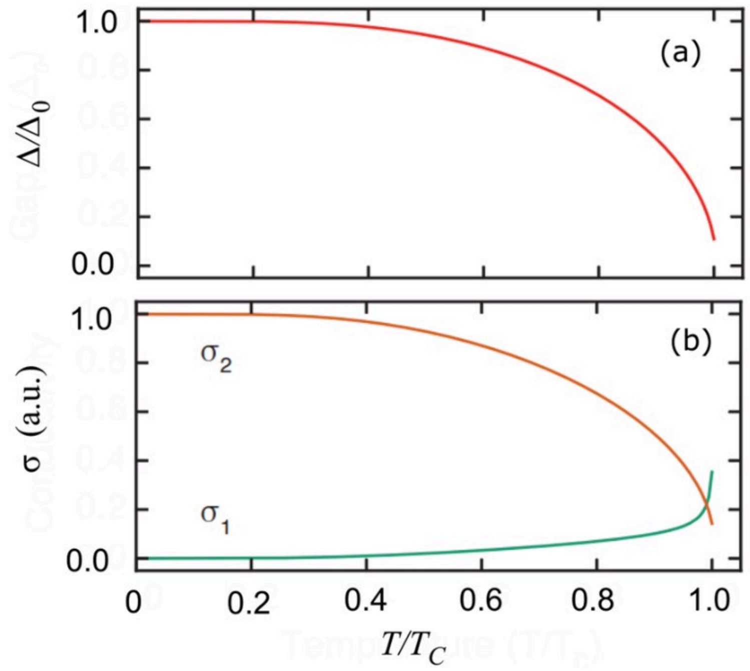
C. R. H. McRae et al., *Material loss measurements using superconducting microwave resonators*, Rev. Sci. Instrum. **91**, 0.1101 (2020)

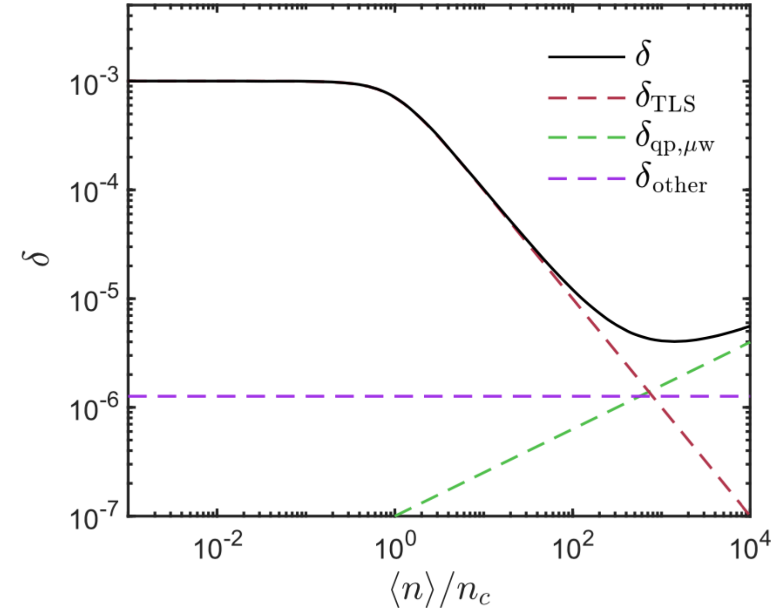
Quasi-particles Losses

- Quasiparticle density has the effect of reducing the superconducting energy gap Δ. This changes both R_S and λ. The change in surface impedance has the effect of shifting the frequency down and reducing the quality factor according to:

$$\frac{1}{Q} + 2i\frac{\delta f}{f} = \frac{\alpha}{\omega\mu\lambda}(R_S + i\delta X_S).$$

- Quasiparticles are generated by **thermal effects**, **IR or ionizing radiation** (like in SNSPDs or MKIDs), or by a too strong microwave excitation of the resonating superconductor.





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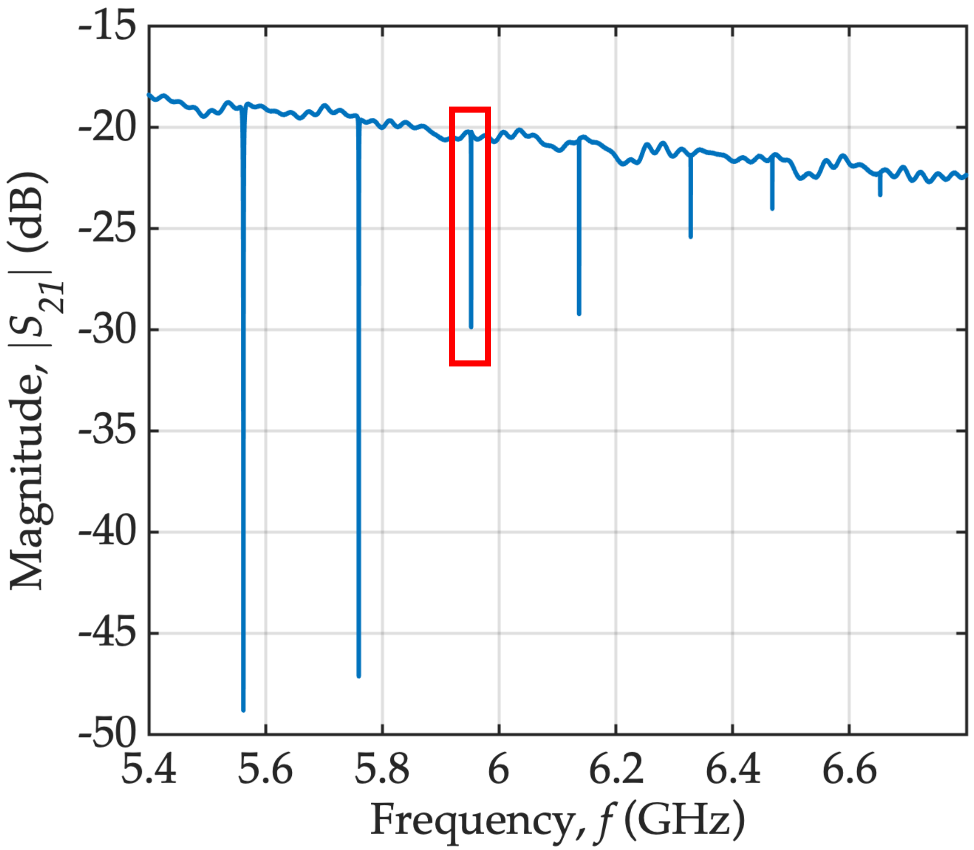
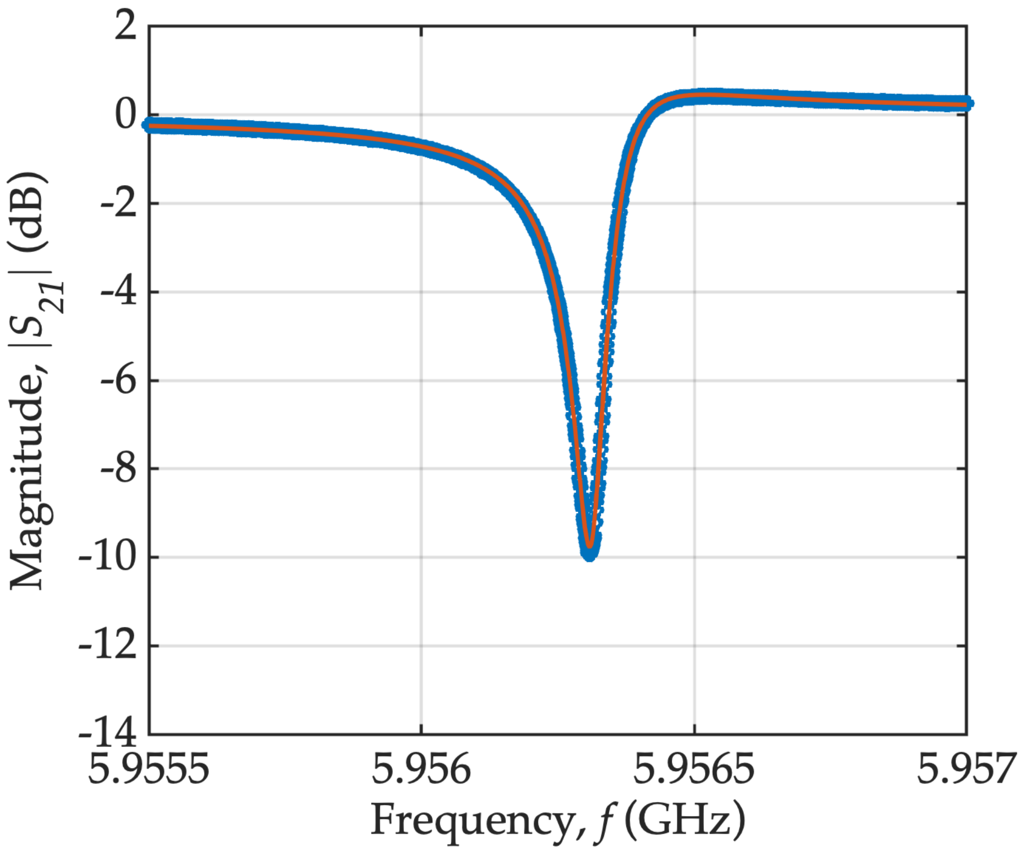
Fitting superconducting resonators

$$S_{21} = 1 - \frac{\kappa_e}{\kappa_e + \kappa_i} \frac{1}{1 + 2j(\omega - \omega_r)}$$





TLS and Quasiparticles combined effects

TLS Losses

Quasi-particles

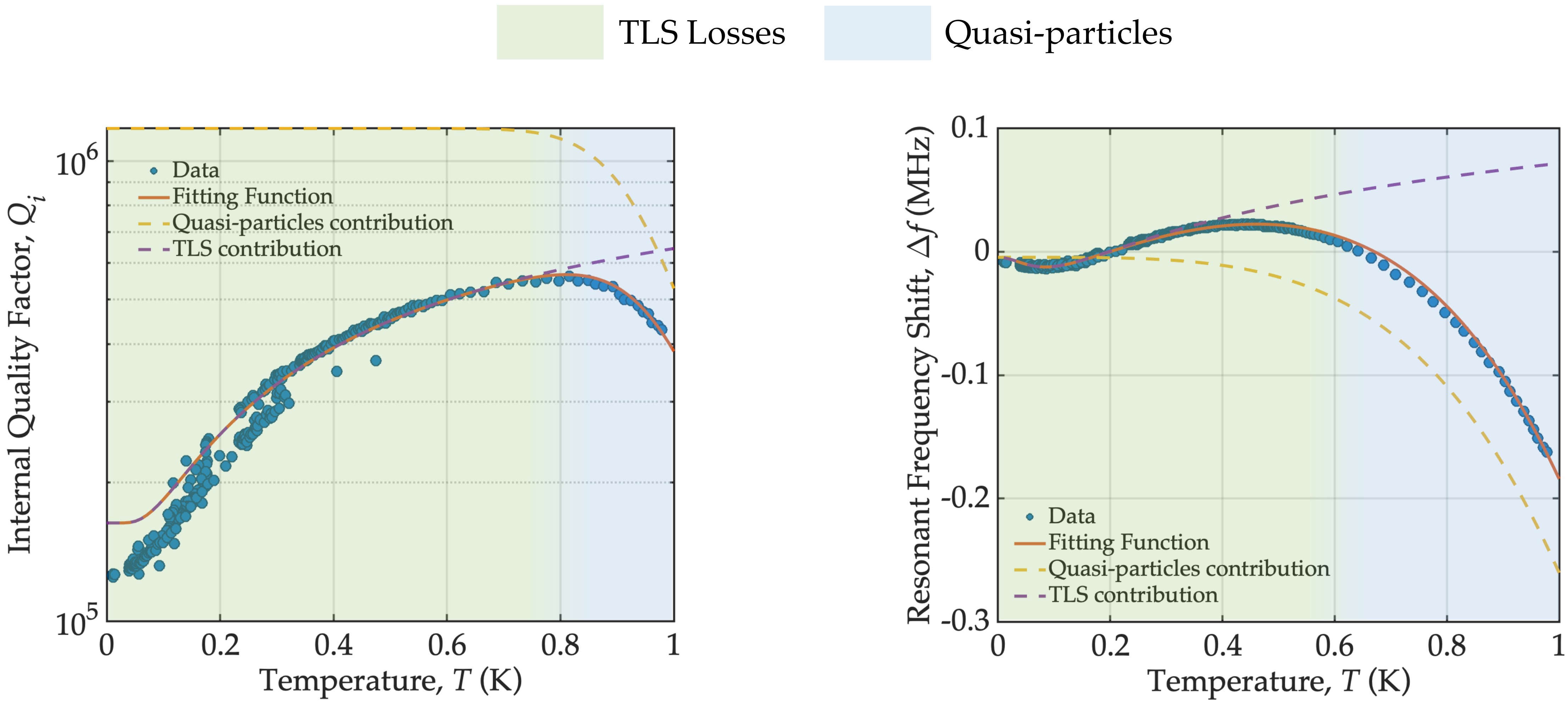
- **Two-level system** fluctuators (TLS) and **quasi-particles** population cause the reduction of the internal quality factor Q_i and the drift of resonant frequency f. They can be estimated in function of temperature T and average resonator photon number n_{ph}

$$\frac{1}{Q_i} = \delta_0 + F\delta^0_{\mathrm{TLS}} \frac{\tanh(\hbar\omega_0/2k_B T)}{(1 + \langle n_{\mathrm{ph}} \rangle / n_c)^\beta} + \frac{\alpha}{\pi}\sqrt{\frac{2\Delta}{hf_r}}\frac{n_{\mathrm{qp}}(T)}{n_s(0)\Delta}$$

$$\frac{\Delta f}{f_r} = \frac{F\delta^0_{\mathrm{TLS}}}{\pi}\left(\mathrm{Re}\left\{\Psi\left(\frac{1}{2} + \frac{hf_r}{2i\pi k_B T}\right)\right\} - \ln\frac{hf_r}{2\pi k_B T}\right) - \alpha\frac{\Delta L_{\mathrm{k}}}{L_{\mathrm{k}}}$$

S. Frasca et al., *High-kinetic inductance NbN films for high-quality compact superconducting resonators*, preprint on ArXiv (2023)

How do these terms affect Q_i and f in resonators



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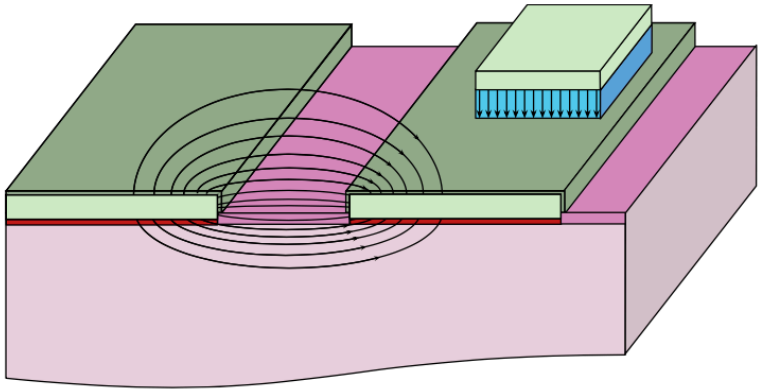
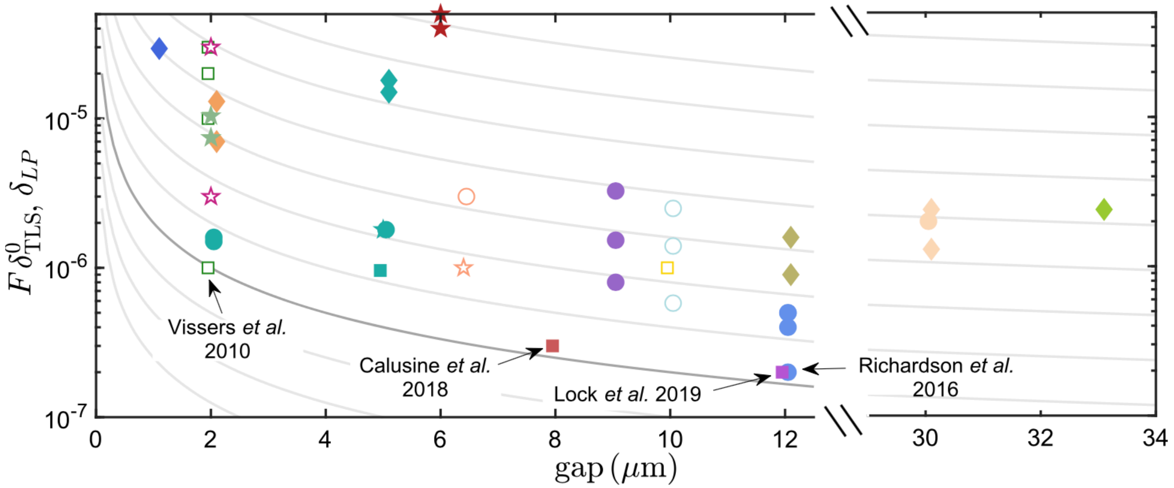
Engineering a solution... – Design Perspective



- On the design perspective, there are a few things that we should be careful about:
  - Form factor: CPW or IDC
  - Resonator coupling: κ_e, κ_i
  - Filling Factor: The resonator-induced intrinsic TLS loss F δ^0_{TLS} depends on both the intrinsic TLS loss, δ^0_{TLS}, of the material *and* what fraction of the capacitive energy is stored in the material of interest, its **dielectric participation ratio** or filling factor F

$$\langle n \rangle = \frac{\langle E_{int} \rangle}{\hbar\omega_0} = \frac{2}{\hbar\omega_0^2}\frac{Z_0}{Z_r}\frac{Q^2}{Q_c}P_{app},$$



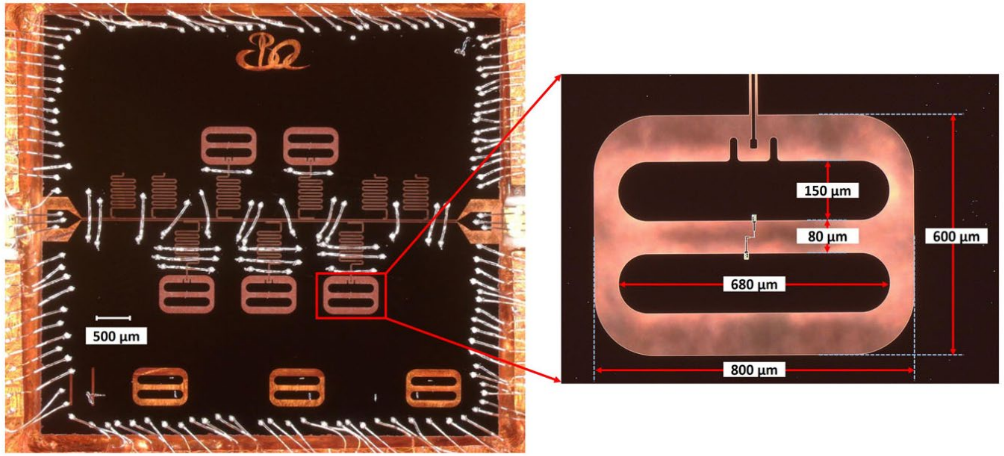
C. R. H. McRae et al., *Material loss measurements using superconducting microwave resonators*, Rev. Sci. Instrum. **91**, 0.1101 (2020)

Engineering a solution… – Materials Perspective

- Materials play a big role in qubits and resonators lifetime characteristics.
  - Good quality of substrate
  - Good quality superconductors (Ta and Nb have shown several advantages over Al, for instance)
  - Interfaces between resonator's capacitors and substrate
  - Careful of contamination during the fabrication
  - Oxidation and ageing

Table 1. Parameters of different qubits of eight chips.

Chips	Frequencies of Q_1–Q_5 (GHz)	T_1 (μs) of Q_1–Q_5
Nb-1	5.253/ 5.203/ 5.214/5.202 /5.515	26.5 /24.9 /21.6/ 26.5/ 19.2
Nb-2[a]	3.91/3.894/ 3.894	29.8/ 29.2/ 33.1
Al-1	4.562 /4.542/ 4.523 / 4.546 /4.549	92.6/78.8/ 21.2 /58.3/ 43.6
Al-2[a]	4.364 /4.339 /4.181/ 4.299	35.3/ 25.8 /107.8 /63.6
Ta-1[c]	4.450/ 4.559/ 4.412/ 4.418 /4.502	158.3/109.2/136.3/120.9/ 131.2
Ta-2[c]	4.688/ 4.659/ 4.608/ 4.681/ 4.735	359[d]/ 158/ 102.7 / 347 /158
Ta-3[a,c]	4.294/4.304/ 4.264/ 4.422	341[d]/225/372/ 337
Ta-4[c]	3.894/3.913/3.918 3.864/3.890	329.1[d]/476/401 / 312.8/316.8



C. Wang et al., *Towards practical quantum computers: transmon qubit with a lifetime approaching 0.5 milliseconds*, npj Quantum Information **8**, 3 (2022)

Engineering a solution… – Experimental Perspective

- In order to improve the losses, one can work on the setup to make it more efficient and robust.

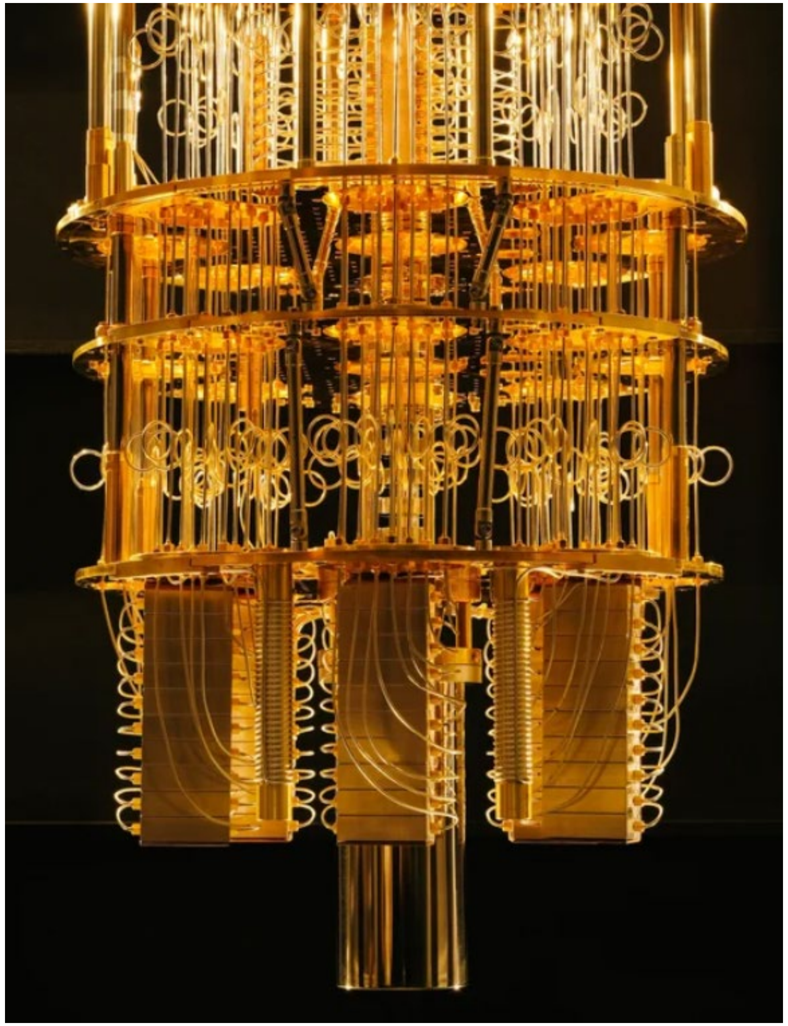
  - Use of proper low-loss coaxial cables and microwave components (NbTi for low losses, etc..)

  - Impedance matching and calibration

  - Proper fitting

  - Thermalization

  - Vortex loss mitigation and magnetic noise



IBM Q cryostat, Yorktown Heights, New York

Thank you

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