Lesson 9. Quantum Hardware

1. Opening

Here, you will discuss the positioning of this lecture and provide an outline of its content.
Additionally, as a foundation for learning about quantum computer hardware, you will explore an overview of the technologies used in quantum computing devices .

9. Quantum Hardware
- Part 1 -

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Course Schedule 2024

Date	Lecture Title	Lecturer	Date	Lecture Title	Lecturer
4/5	Invitation to the Utility Era	Tamiya Onodera	6/7	Classical Simulation (Clifford Circuit, Tensor Network)	Yoshiaki Kawase
4/19	Quantum Gates, Circuits, and Measurements	Kifumi Numata	6/14	Quantum Hardware	Masao Tokunari / Tamiya Onodera
4/26	Quantum Teleportation / Superdense Coding	Kifumi Numata	6/21	Quantum Circuit Optimization (Transpilation)	Toshinari Itoko
5/10	Quantum Algorithms: Grover Search	Atsushi Matsuo	6/28	Quantum Noise and Quantum Error Mitigation	Toshinari Itoko
5/15 (Wed)	Quantum Algorithms: Phase Estimation	Kento Ueda	7/5	Utility Scale Experiment I	Tamiya Onodera
5/24	Quantum Algorithms: Variational Quantum Algorithms (VQA)	Takashi Imamichi	7/12	Utility Scale Experiment II	Yukio Kawashima
5/30 (Thu)	Quantum Simulation (Ising model, Heisenberg, XY model), Time Evolution (Suzuki Trotter, QDrift)	Yukio Kawashima	7/19	Utility Scale Experiment III	Kifumi Numata / Tamiya Onodera/ Toshinari Itoko

Self introduction – Masao Tokunari

Staff Research Scientist, Quantum Hardware at IBM Research – Tokyo
- Quantum hardware components
- Quantum transduction
- Quantum system deployment

Expertise in optical experiments
- Doctor of Physics at the University of Tokyo
  - Gravitational wave detector technology
  - Kuroda-lab, ICRR (Institute for Cosmic Ray Research)
- Work experience in optical interconnects in IBM

Outline

Part 1: Superconducting qubits
- Physics of the superconducting qubits
- Qubit control
- Quantum non-demolition measurement
- Two-qubit gate

Part 2: Device map and calibration data
- Hands-on: extracting the device information

Part 3: Qubit scaling
- Modularity
- Microwave component development

Summary

IBM Quantum System One

Quantum computing technologies

Ions
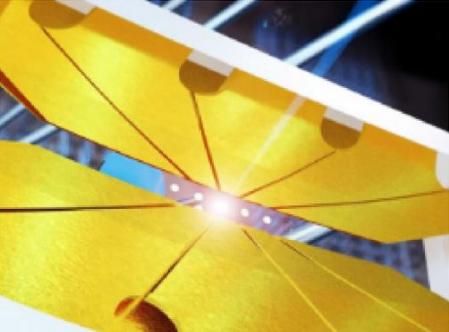
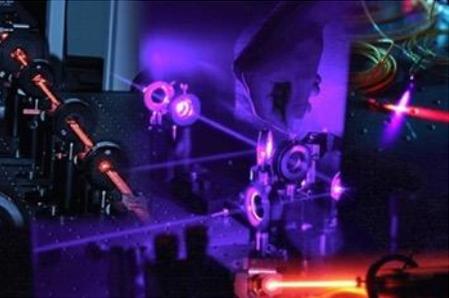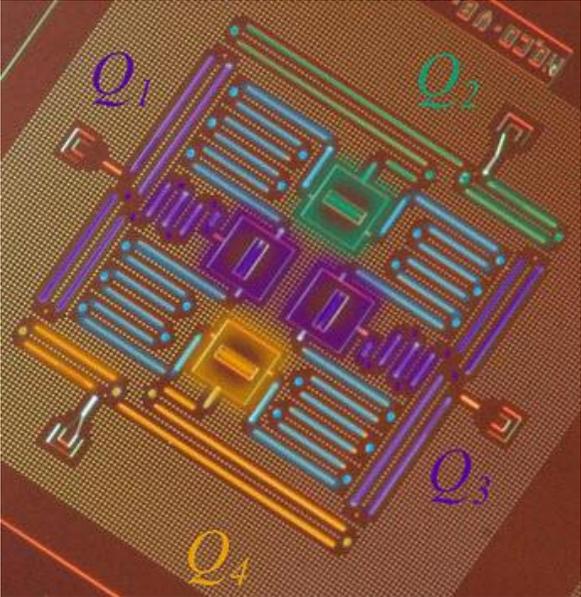Credit: N. M. Linke et al.,
University of Maryland, 2017

Photons

Image from the Centre for
Quantum Computation &
Communication Technology

Superconducting circuits

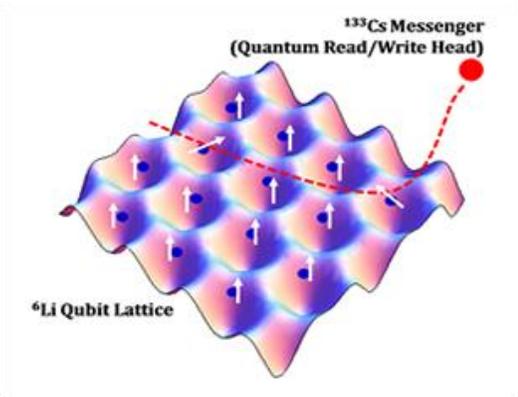Credit: A. D. Córcoles et al.,
IBM, 2015

Neutral atoms

Image from Cheng Group,
University of Chicago

Solid-state defects
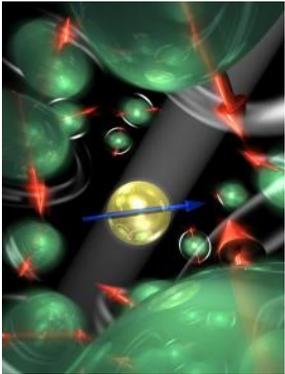(NV centers, phosphorous in Si)

Image from Hanson Group, Delft
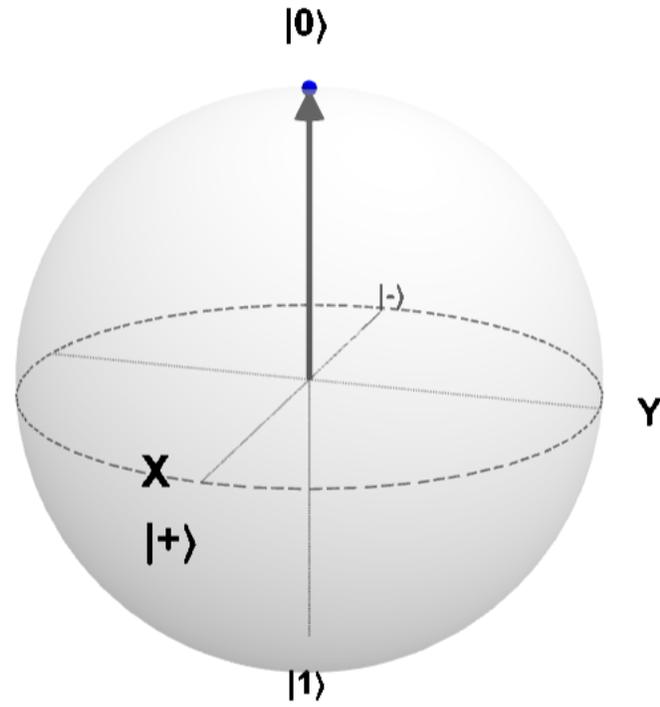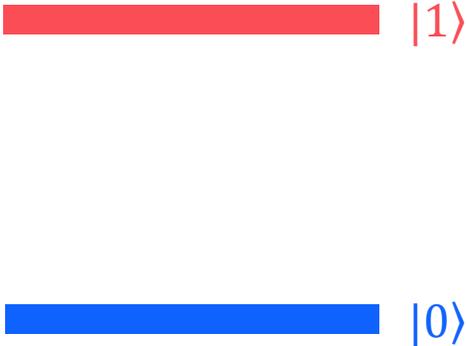
Qubit: idea

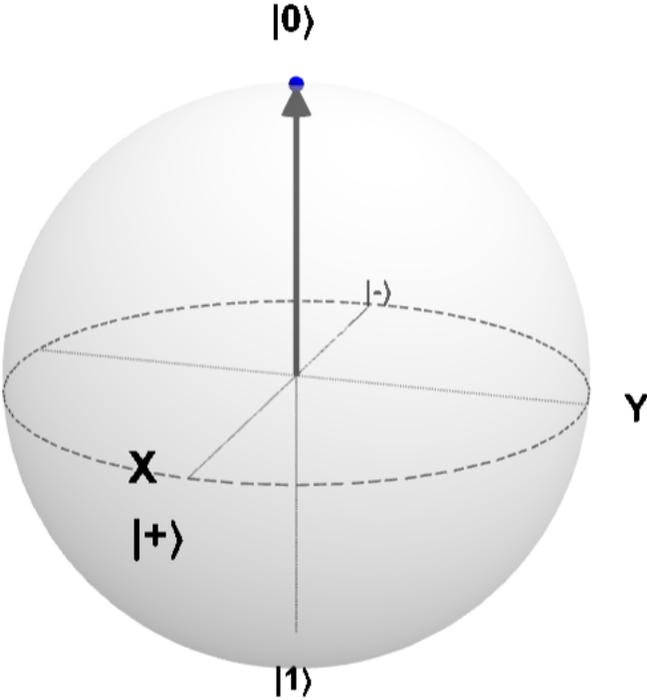Energy levels

Bloch sphere

$|1\rangle$

$|0\rangle$

Qubit: idea and reality

Energy levels

Bloch sphere

Real quantum computer

$|1\rangle$

$|0\rangle$

$|0\rangle$

$|-\rangle$

Y

X

$|+\rangle$

$|1\rangle$
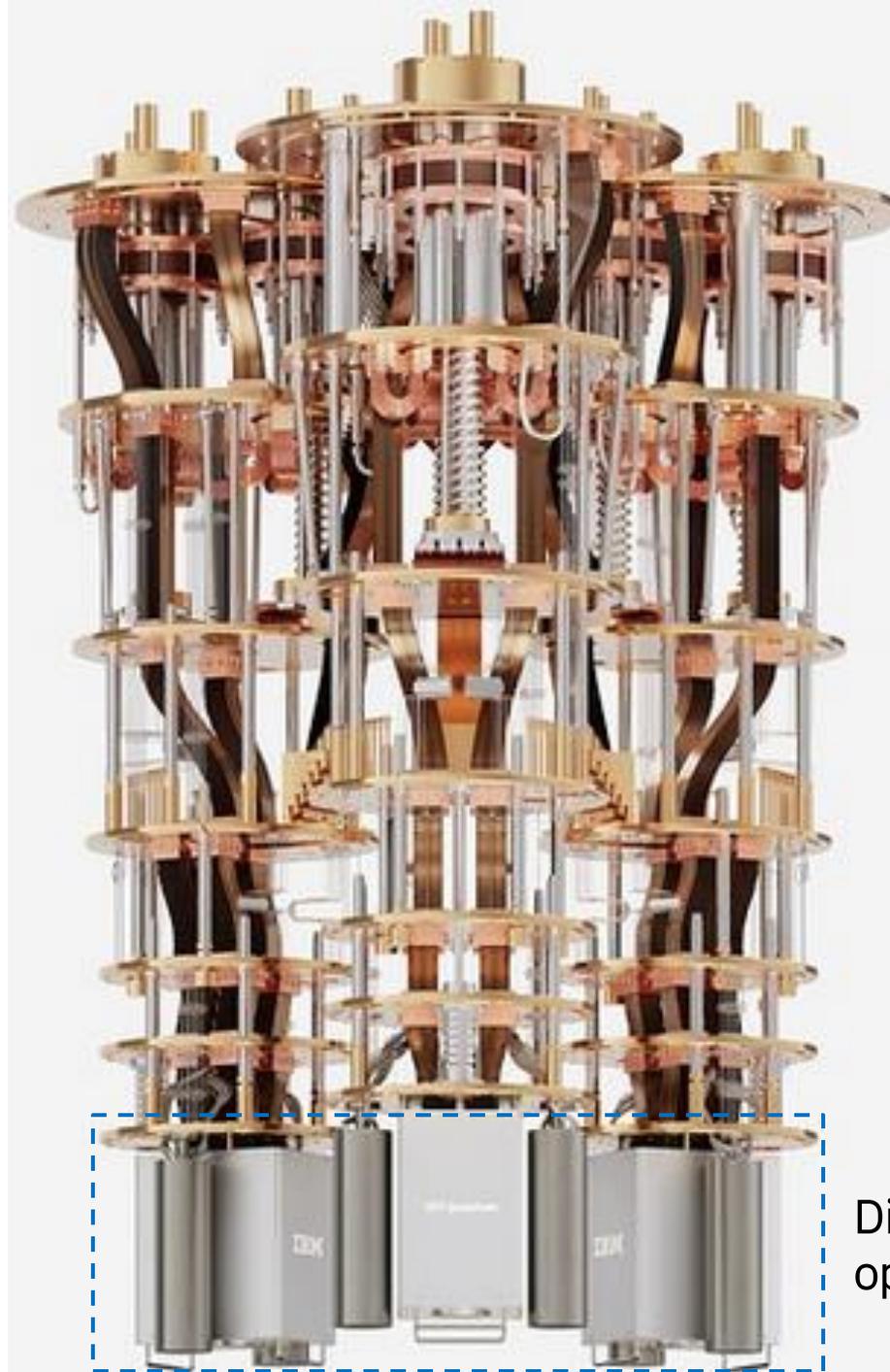
Dilution refrigerator operated at 10 mK

Lesson 9. Quantum Hardware

2. The physics of the superconducting of qubits

you will learn about the schemes through which quantum computers execute computations. In preparation for the next section, where you will study superconducting qubits—one of the most important components of quantum computers—, this section will first cover electromagnetic oscillators .

Qubit chip: superconducting circuits on Si chip

Readout resonator

Readout resonator
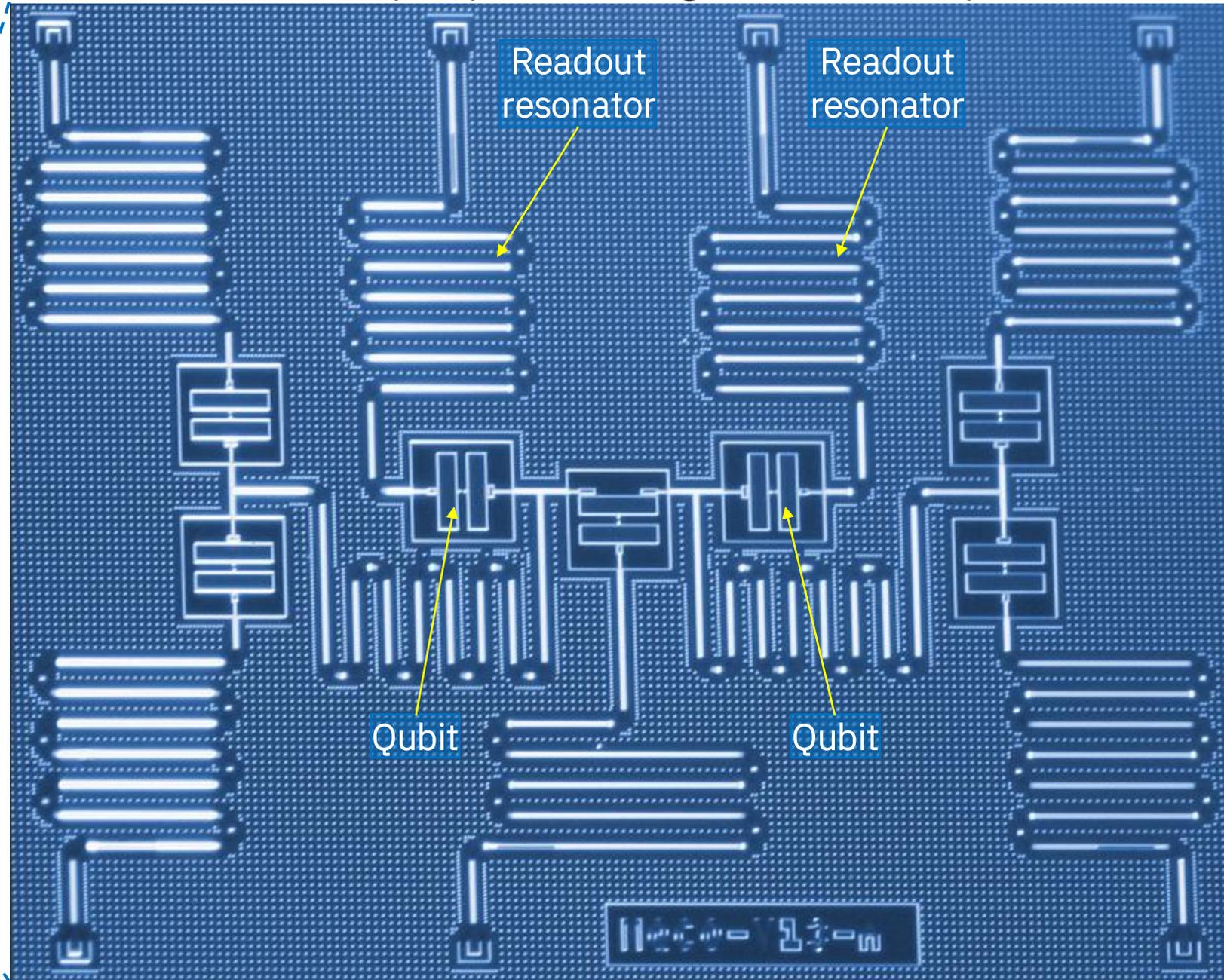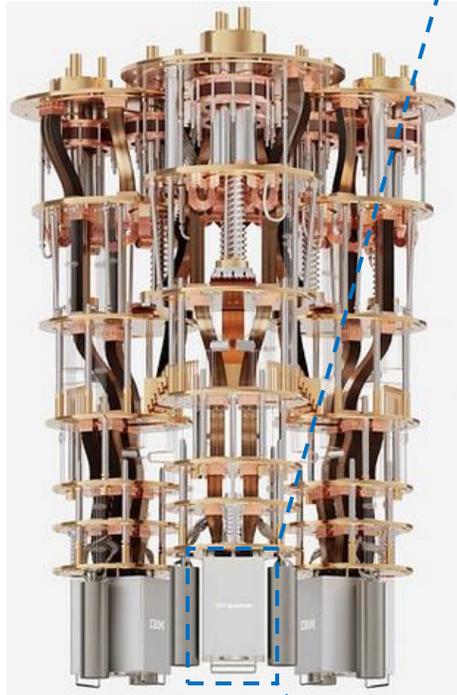
Qubit

Qubit

Qubit and readout resonator

Equivalent circuits
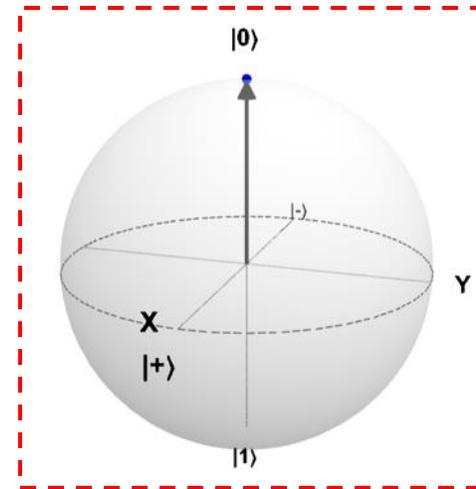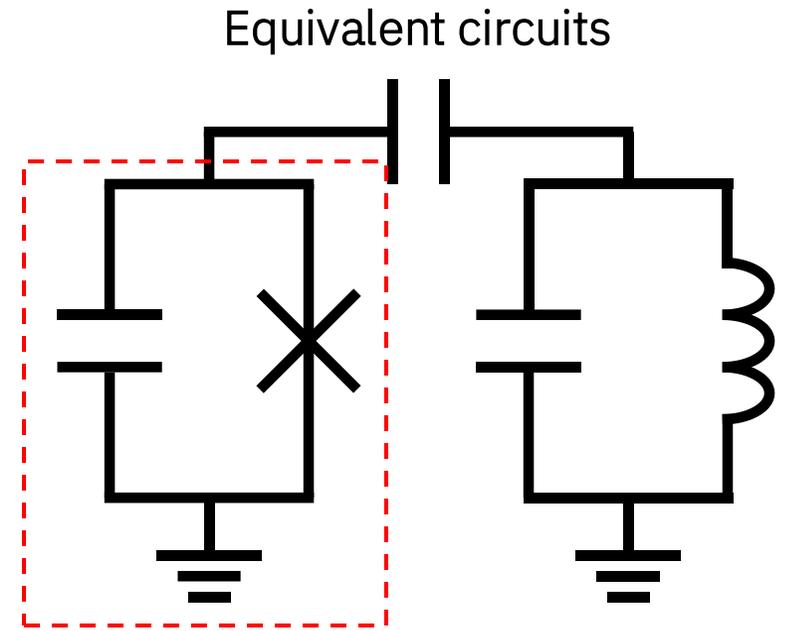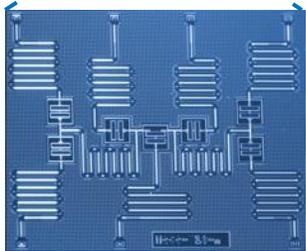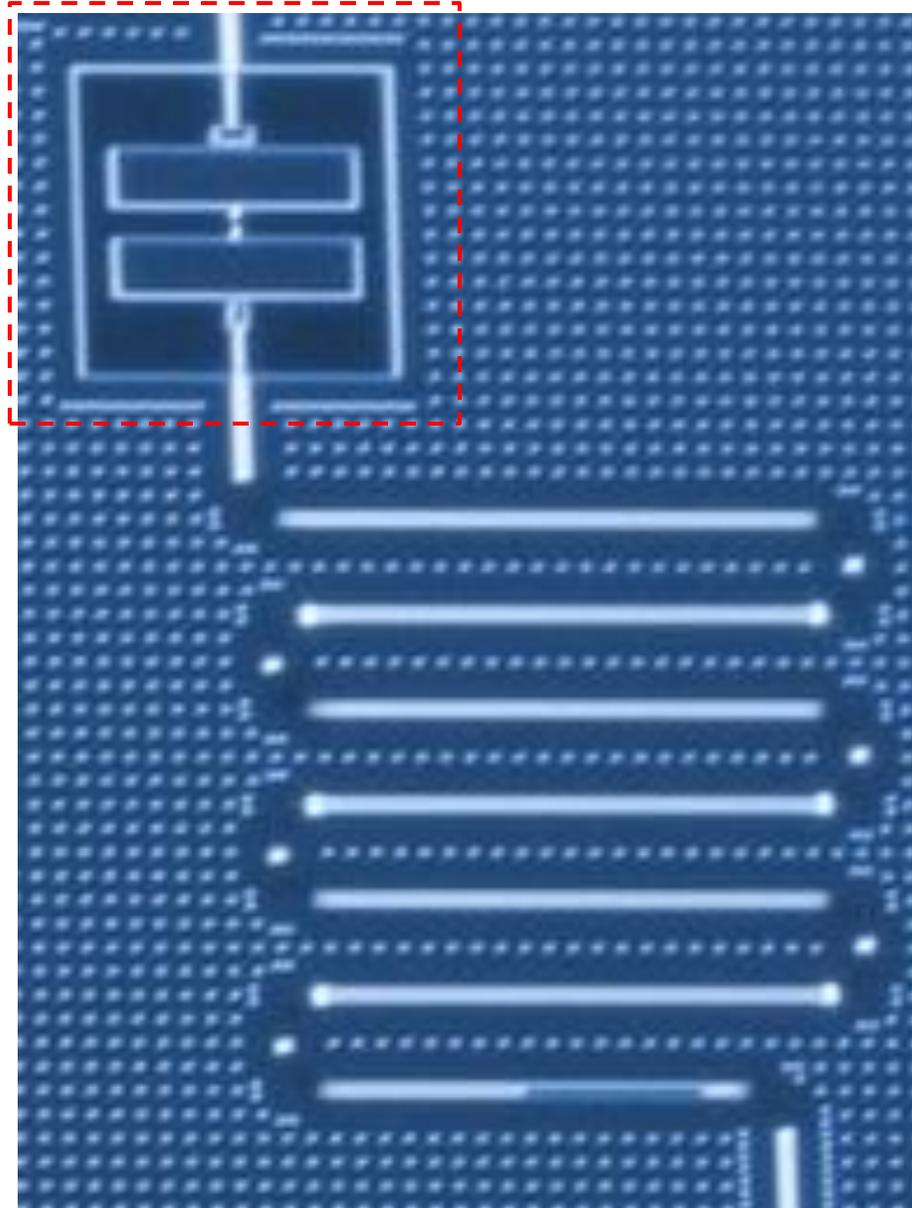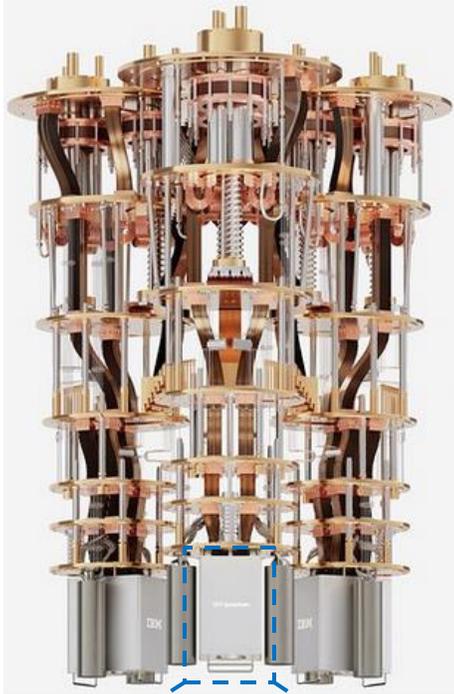
Quantum computation flow

Control
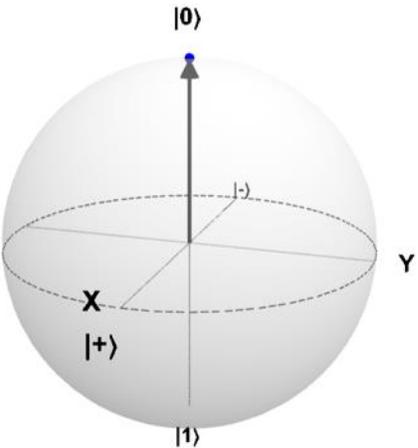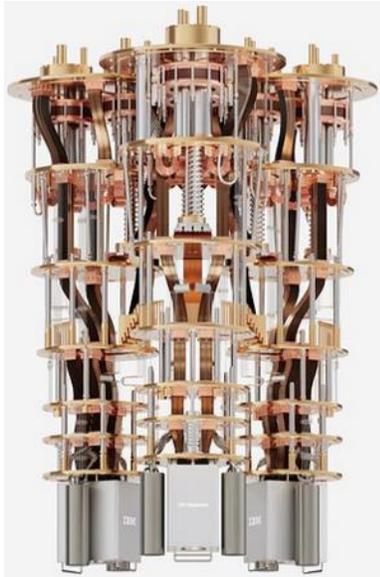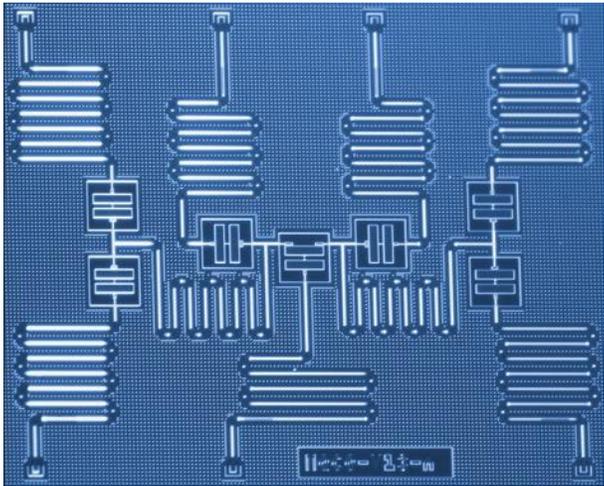
Readout

Schematic of superconducting quantum computer
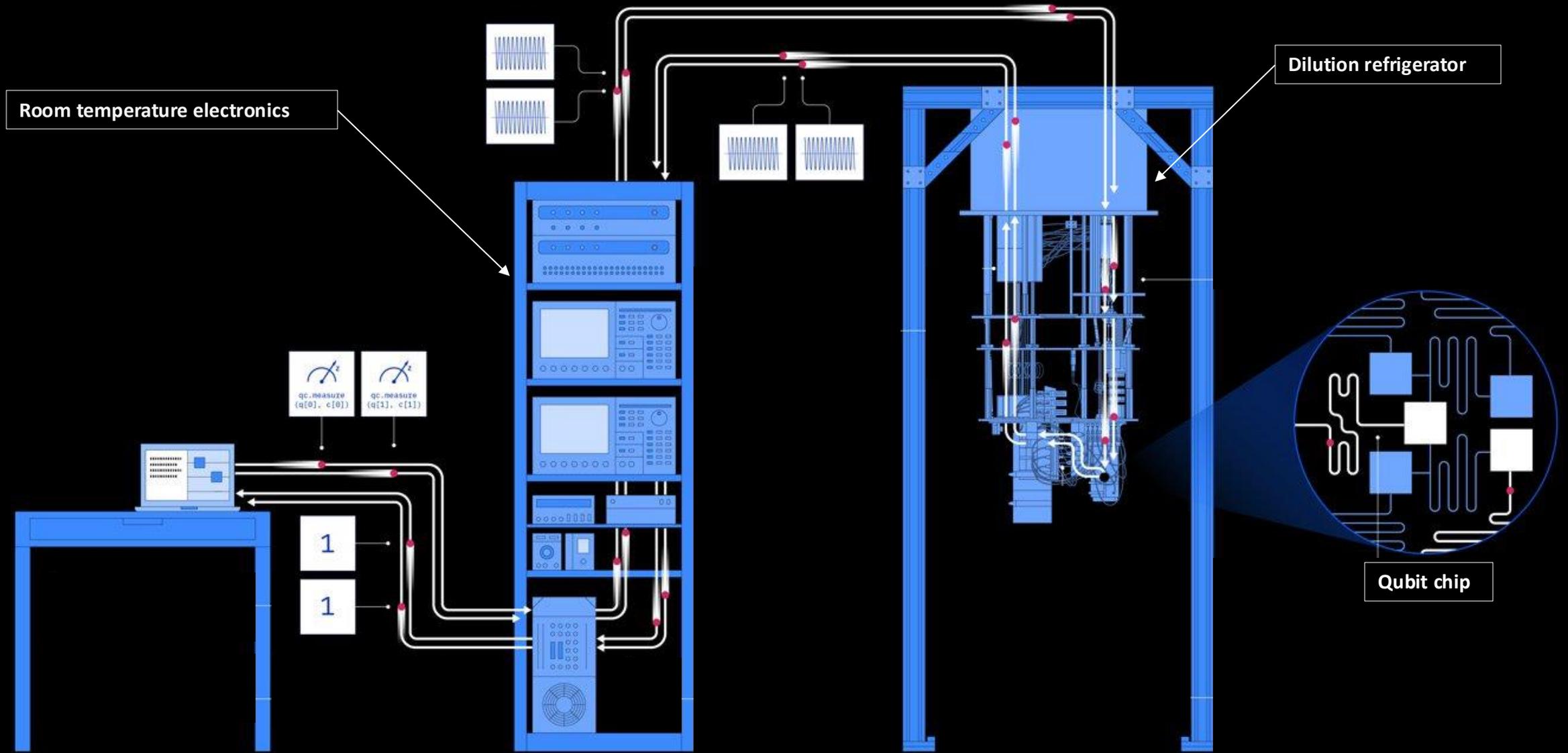
How do real qubits behave: Natural atoms

Electron potential-energy landscape

ω_{01} between $|0\rangle$ and $|1\rangle$

No level here

Quantization of energy

$|1\rangle$

$|0\rangle$

Radial distance from nucleus
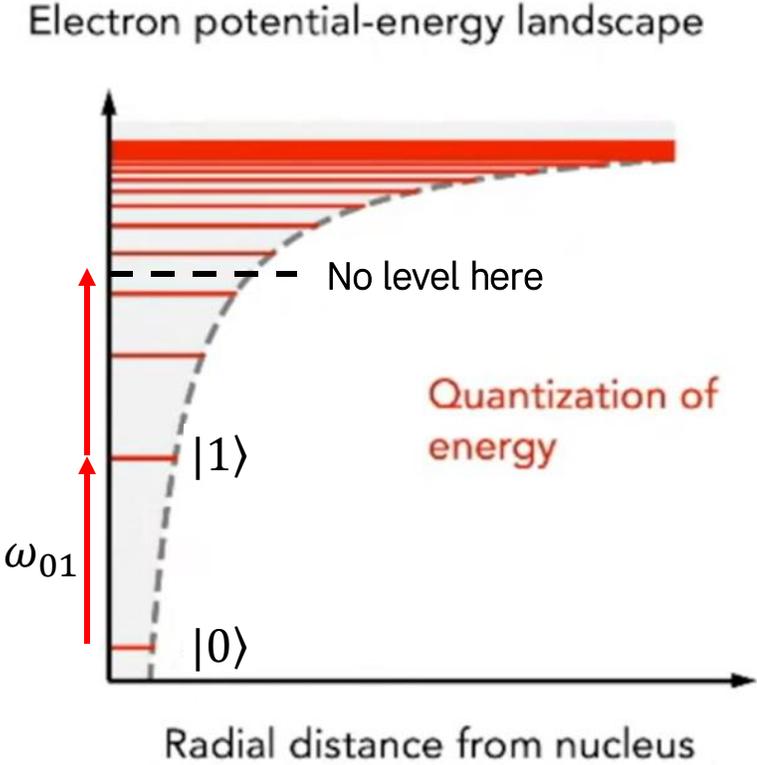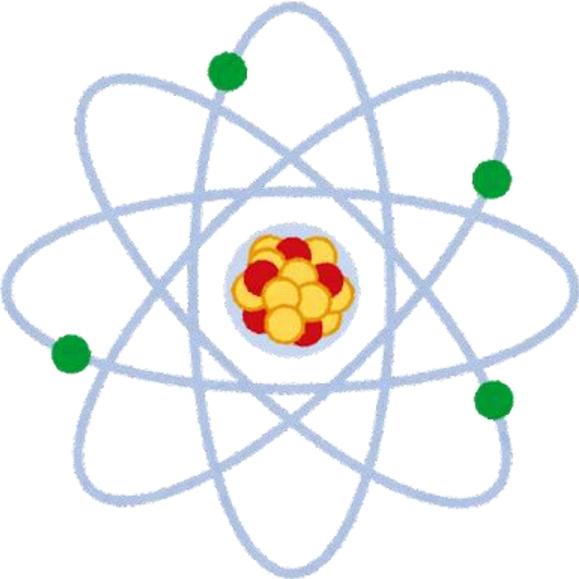
Image: Z. Minev, IBM, 2022

Qubit
- Multi energy levels
- Quantized (Discrete)
- Anharmonicity

Artificial atoms = superconducting qubits
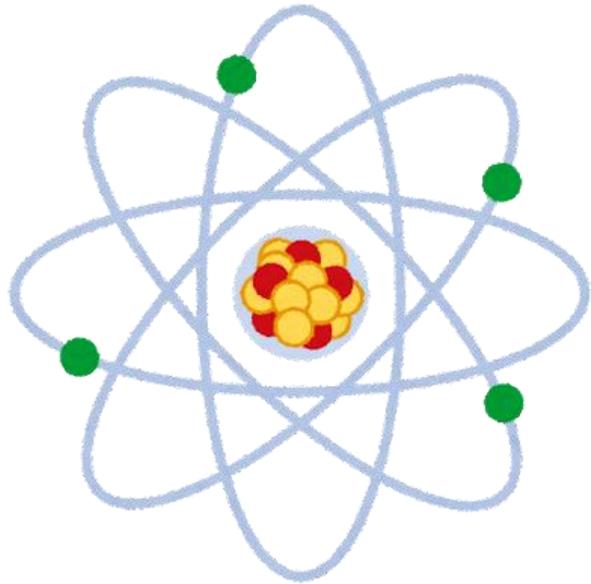
Natural atoms

Artificial atoms

Superconducting qubit

Substrate
Dielectric

Qubit pad
Metal

Qubit inductor
Non-Linear
e.g., Josephson Junction

Image: Z. Minev
https://youtu.be/eZJjQGu85Ps?si=LrAlGV4CZOa-qHY3

18
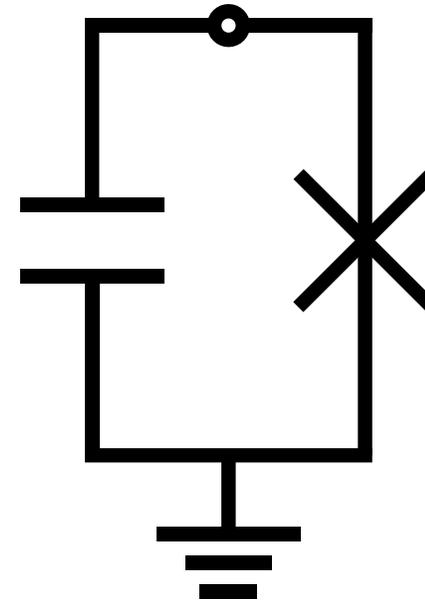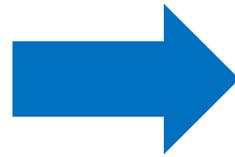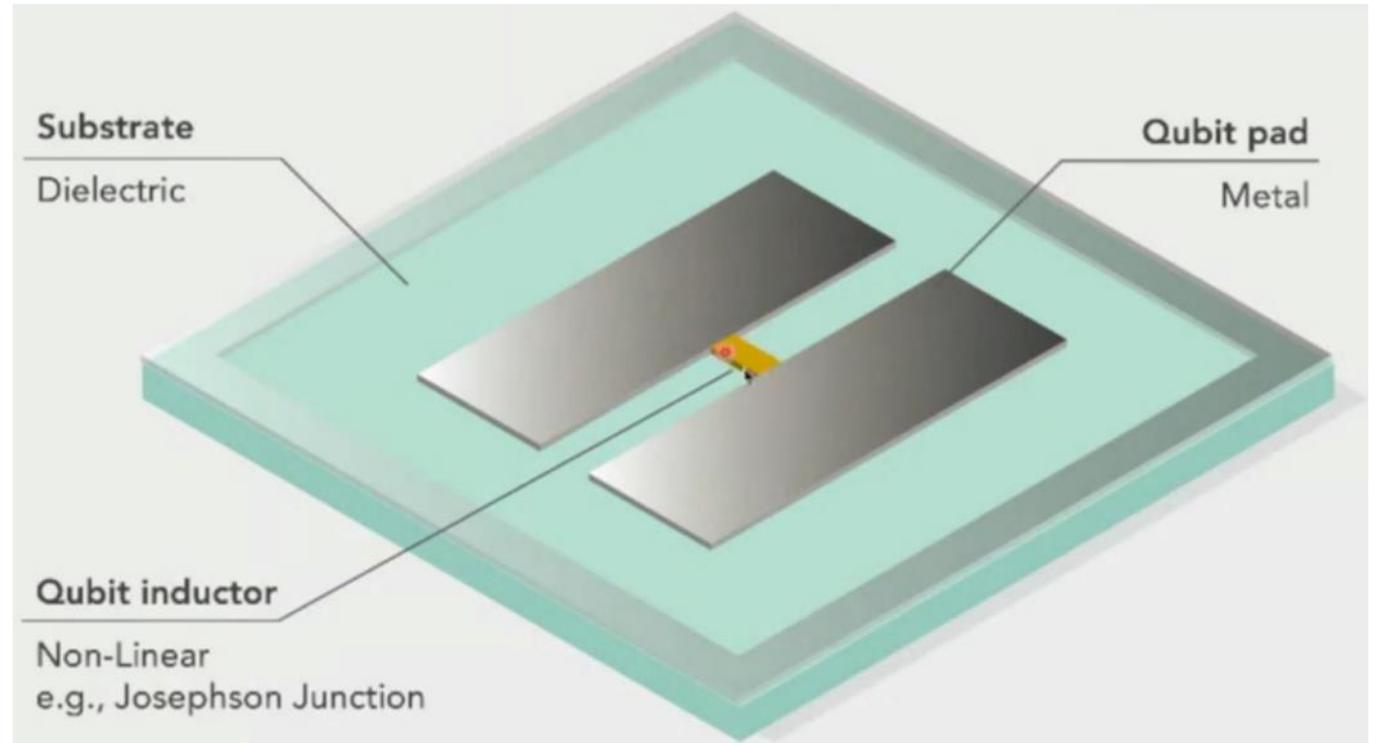
Electromagnetic oscillator
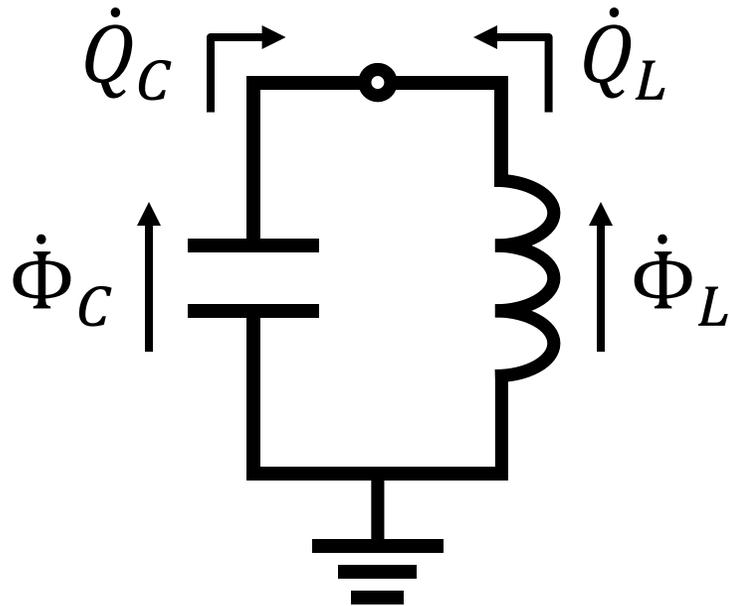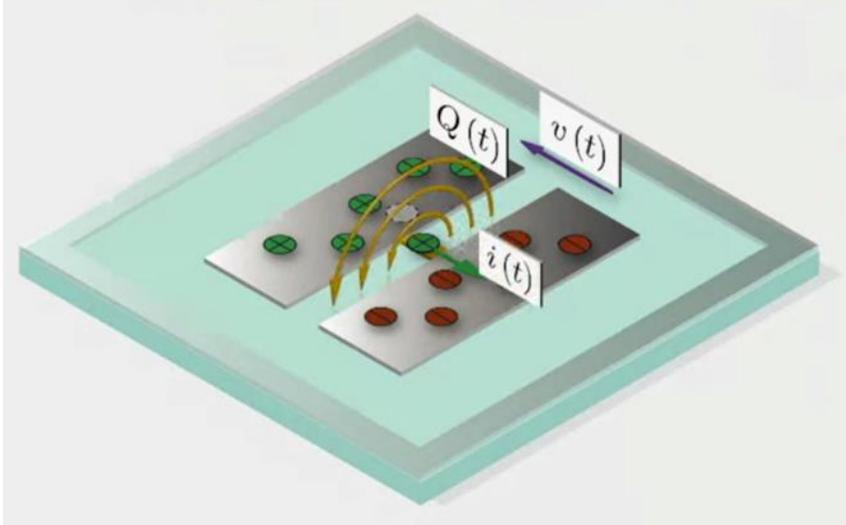
Universal relationships
$$\dot{Q} = I$$
$$\dot{\Phi} = V$$
Capacitance, Inductance relationships
$$Q = CV \left(= C\dot{\Phi} \right)$$
$$\Phi = LI \left(= L\dot{Q} \right)$$

Kirchhoff's voltage law
$$\dot{\Phi}_C = \dot{\Phi}_L$$
$$\Rightarrow \Phi_C = \Phi_L \equiv \Phi$$
Kirchhoff's current law
$$\dot{Q}_C + \dot{Q}_L = 0$$
$$\Rightarrow C\ddot{\Phi}_C + \frac{\Phi_L}{L} = C\ddot{\Phi} + \frac{\Phi}{L} = 0$$
$$\Rightarrow \ddot{\Phi} = -\omega_0^2 \Phi, \omega_0 = \frac{1}{\sqrt{LC}}$$
$$\Rightarrow \Phi = \Phi_0 e^{-i\omega_0 t}$$
Harmonic oscillator of resonance frequency ω_0

Electromagnetic oscillator
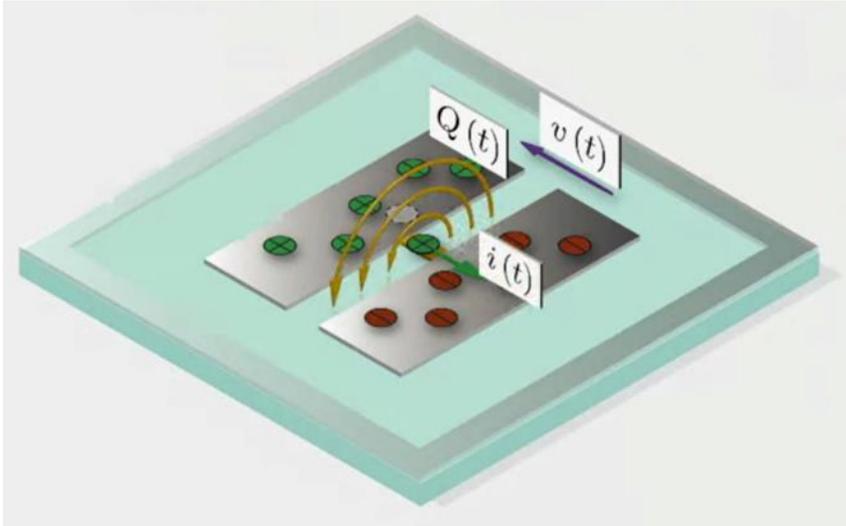
Consider an LC circuit with a linear inductor L. The following formula is derived from Kirchhoff's law.

$$C\ddot{\Phi} + \frac{\Phi}{L} = 0$$
$$\Phi = \Phi_0 e^{-i\omega_0 t}$$
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

In the LC circuit, magnetic flux Φ oscillates as a harmonic oscillator of resonance frequency ω_0
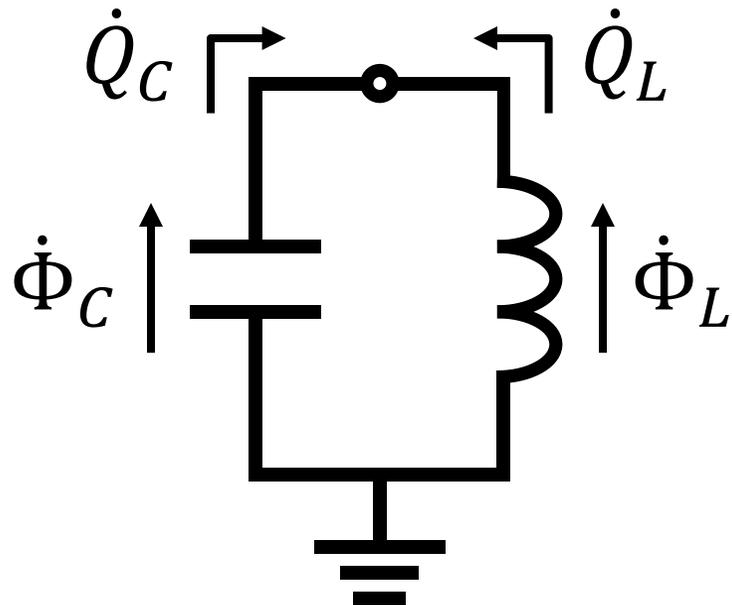
Analogy with a mechanical oscillator
Magnetic flux → Position: $\Phi \mapsto x$
Inductance → Spring constant: $\frac{1}{L} \mapsto k$
Capacitance → Mass: $C \mapsto m$
Voltage → Velocity: $\dot{\Phi}(=V) \mapsto v$
Charge → Momentum: $Q(=CV) \mapsto p(=mv)$
Equation of motion: $C\ddot{\Phi} + \frac{\Phi}{L} = 0 \mapsto F = ma$

$\dot{Q}_C$ $\dot{Q}_L$

$\dot{\Phi}_C$ $\dot{\Phi}_L$

$Q(t)$ $v(t)$ $i(t)$

Lagrangian and Hamiltonian
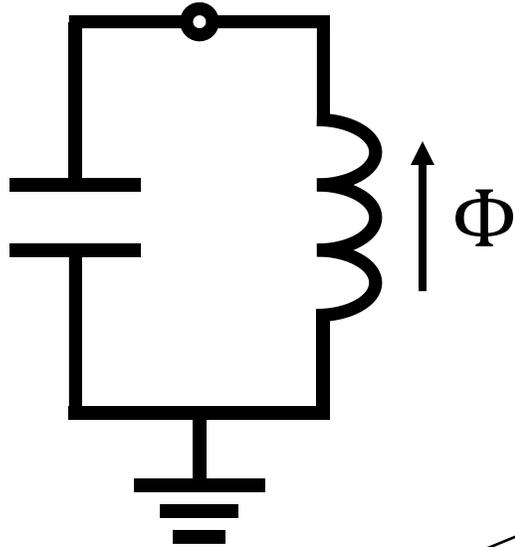
Lagrangian = Kinetic energy – Potential energy

$$\mathcal{L}(\Phi, \dot{\Phi}) = K_{cap}(\dot{\Phi}) - U_{ind}(\Phi)$$

$$= \frac{C\dot{\Phi}^2}{2} - \frac{\Phi^2}{2L} \qquad \longmapsto \frac{1}{2}mv^2 - \frac{1}{2}kx^2$$

Euler-Lagrange equation (= equation of motion)

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\Phi}}\right) - \frac{\partial \mathcal{L}}{\partial \Phi} = 0 \qquad \longmapsto F = ma$$

Canonically conjugate variable of Φ

$$\frac{\partial \mathcal{L}}{\partial \dot{\Phi}} = C\dot{\Phi} = Q$$

$$C\ddot{\Phi} + \frac{\Phi}{L} = 0$$

Legendre transformation: Lagrangian → Hamiltonian

$$\mathcal{H}(\Phi, Q) = Q\dot{\Phi} - \mathcal{L}(\Phi, \dot{\Phi}) = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

Kinetic energy + Potential energy

Canonical equation (= equation of motion)

$$\dot{\Phi} = \frac{\partial \mathcal{H}}{\partial Q} = \frac{Q}{C}, \qquad \dot{Q} = -\frac{\partial \mathcal{H}}{\partial \Phi} = -\frac{\Phi}{L}$$

$$U_{ind}(\Phi) = \frac{\Phi^2}{2L}$$

$$K_{cap}(Q) = \frac{Q^2}{2C}$$

Energy

Φ
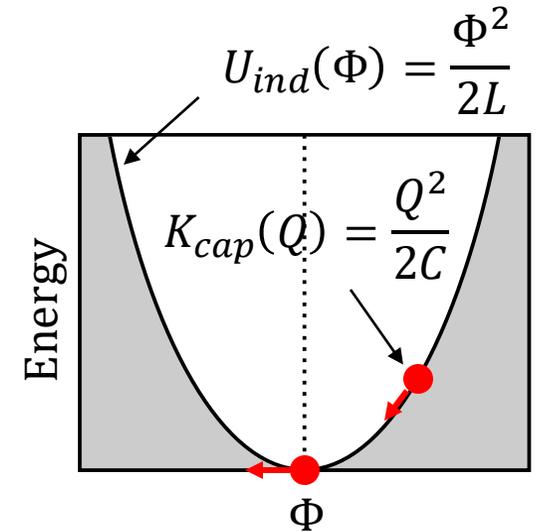
Hamiltonian dynamics and phase space

Hamiltonian is denoted using $\alpha(t)$ as follows

$$\mathcal{H} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L} = \frac{1}{2}\hbar\omega_0(\alpha^*\alpha + \alpha\alpha^*) = \hbar\omega_0\left(n + \frac{1}{2}\right)$$

$$\alpha(t) = \sqrt{1/2\hbar Z}[\Phi(t) + iZQ(t)] = \alpha(0)e^{-i\omega_0 t}$$

$$Z = \sqrt{L/C}$$

$\alpha(t)$ is a classical analog of bosonic ladder operator

Hamiltonian → Total energy

$\alpha(t)$: point in phase space

$$\mathcal{H}(\Phi, Q) = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

$$\begin{cases} \dot{\Phi} = \dfrac{\partial \mathcal{H}}{\partial Q} = \dfrac{Q}{C} \\[2mm] \dot{Q} = -\dfrac{\partial \mathcal{H}}{\partial \Phi} = -\dfrac{\Phi}{L} \end{cases}$$
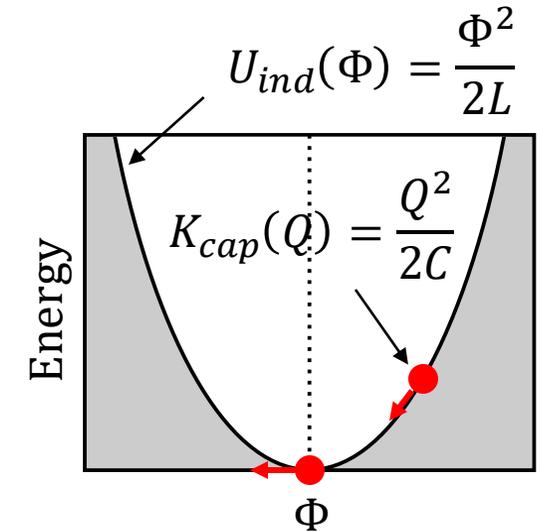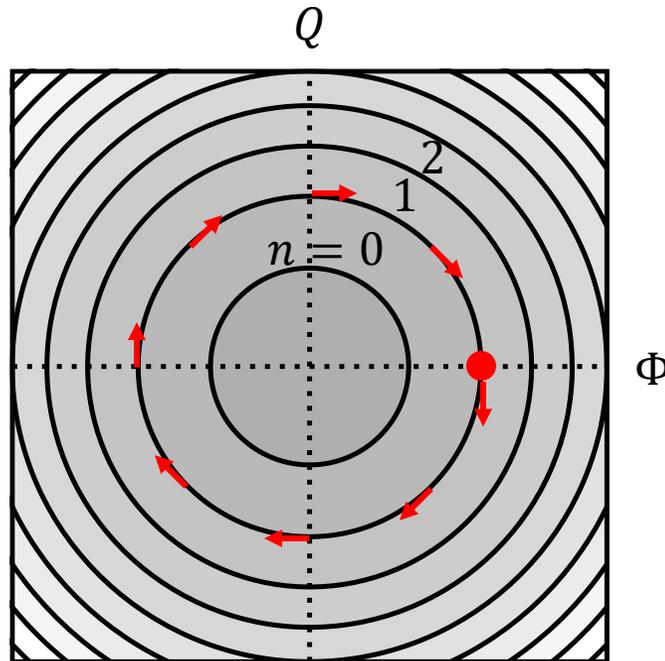
The classical and quantum oscillator

	Classical	Quantum

Hamiltonian

$$\Phi(t)$$
$$Q(t)$$
$$\mathcal{H} = \frac{\Phi^2}{2L} + \frac{Q^2}{2C}$$
$$= \frac{1}{2}\hbar\omega_0(\alpha^*\alpha + \alpha\alpha^*)$$

$$\widehat{\Phi}$$
$$\hat{Q}$$
$$\widehat{H} = \frac{\widehat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C}$$
$$= \frac{1}{2}\hbar\omega_0(\hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger)$$

Phase space

$$\alpha(t) = \sqrt{\frac{1}{2\hbar Z}}[\Phi(t) + iZQ(t)]$$
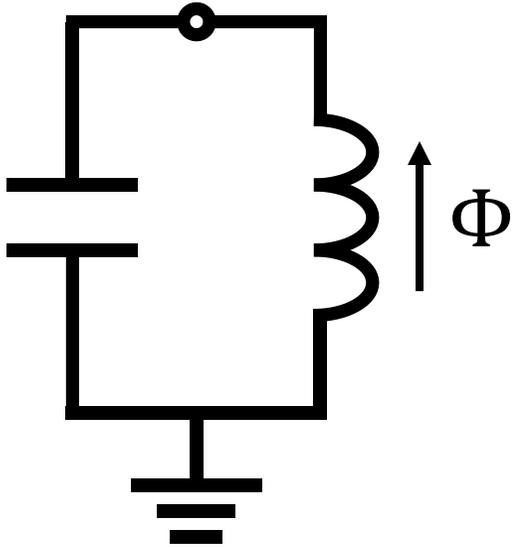$$\alpha(t) = \alpha(0)e^{-i\omega_0 t}$$
$$\Phi(t) = \sqrt{\frac{\hbar Z}{2}}(\alpha^*(t) + \alpha(t))$$
$$Q(t) = i\sqrt{\frac{\hbar}{2Z}}(\alpha^*(t) - \alpha(t))$$

$$\hat{a} = \sqrt{\frac{1}{2\hbar Z}}(\widehat{\Phi} + iZ\hat{Q})$$
$$\hat{a}(t) = \hat{a}(0)e^{-i\omega_0 t}$$
$$\widehat{\Phi} = \Phi_{zpf}(\hat{a}^\dagger + \hat{a})$$
$$\hat{Q} = iQ_{zpf}(\hat{a}^\dagger - \hat{a})$$

Zero-point fluctuation

$$\Phi_{zpf} = \sqrt{\frac{\hbar Z}{2}}$$
$$Q_{zpf} = \sqrt{\frac{\hbar}{2Z}}$$

Commutation

$$\{\alpha, \alpha^*\} = 1/i\hbar$$

$$[\hat{a}, \hat{a}^\dagger] = 1$$

Energy levels of the quantum harmonic oscillator

Energy levels and wavefunction

Hamiltonian (~Total energy) of the quantized LC circuit

$$\hat{H} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \frac{1}{2}\hbar\omega_0(\hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger) = \hbar\omega_0\left(\underline{\hat{a}^\dagger\hat{a}} + \frac{1}{2}\right)$$

$$\hat{a} = \sqrt{\frac{1}{2\hbar Z}}(\hat{\Phi} + iZ\hat{Q}), Z = \sqrt{L/C}$$

$\hat{N}$: photon number

Energy levels are equally spaced, so it cannot be used as a qubit!
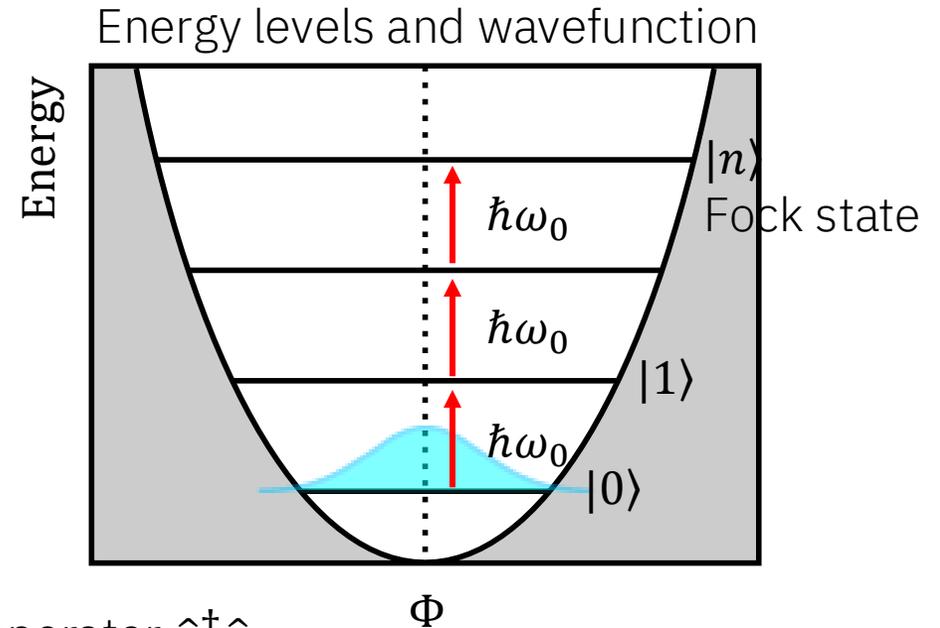
Annihilation operator $\hat{a}$

$\hat{a}|0\rangle = 0$

$\hat{a}|1\rangle = |0\rangle$

$\hat{a}|n\rangle = \sqrt{n}|n-1\rangle$

$$\hat{a} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & \sqrt{3} \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

Creation operator $\hat{a}^\dagger$

$\hat{a}^\dagger|0\rangle = |1\rangle$

$\hat{a}^\dagger|1\rangle = \sqrt{2}|2\rangle$

$\hat{a}^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$

$$\hat{a}^\dagger = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & \sqrt{2} & 0 & 0 \\ 0 & 0 & \sqrt{3} & \ddots \end{pmatrix}$$

Photon number operator $\hat{a}^\dagger\hat{a}$

$\hat{a}^\dagger\hat{a}|0\rangle = 0$

$\hat{a}^\dagger\hat{a}|1\rangle = |1\rangle$

$\hat{a}^\dagger\hat{a}|n\rangle = n|n\rangle$

$$\hat{a}^\dagger\hat{a} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

Readout resonator is the linear LC
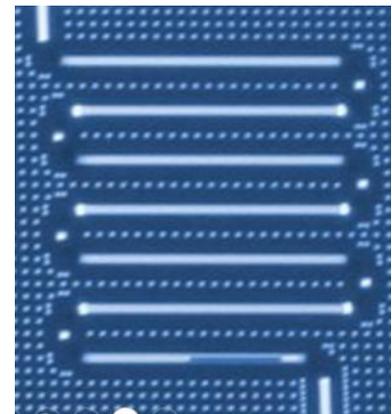
Lesson 9. Quantum Hardware

3. What is the Transmon Qubit?

Qubits are implemented as transmon qubits on quantum computers.
In this section, you will learn about the principles that enable the transmon qubit to function as a qubit and how it is controlled.

The transmon qubit as a non-linear oscillator

Transmon: transmission-line shunted plasma oscillation qubit
https://arxiv.org/pdf/cond-mat/0703002

Superconductor (e.g., Al)

Insulator (e.g., AlOx)

Cooper pair   tunneling
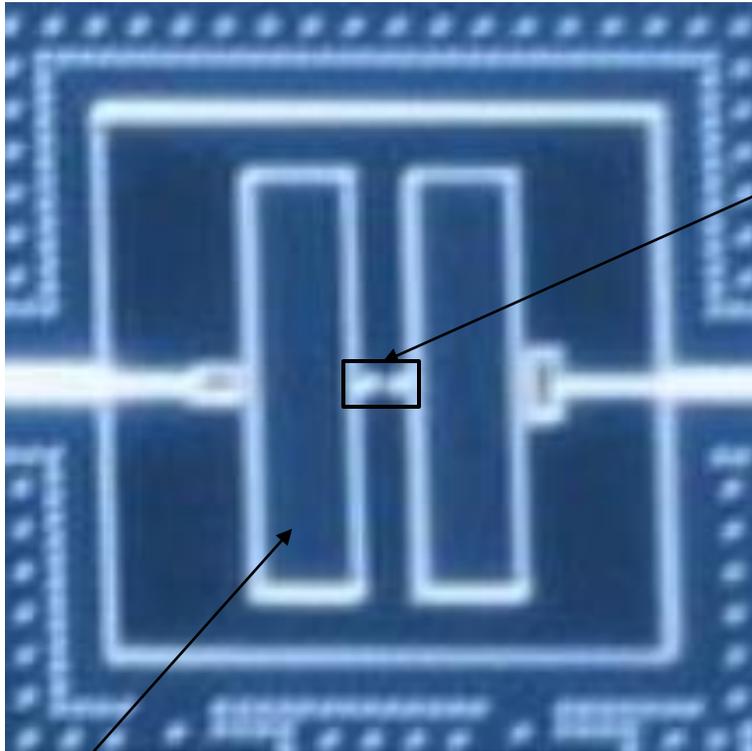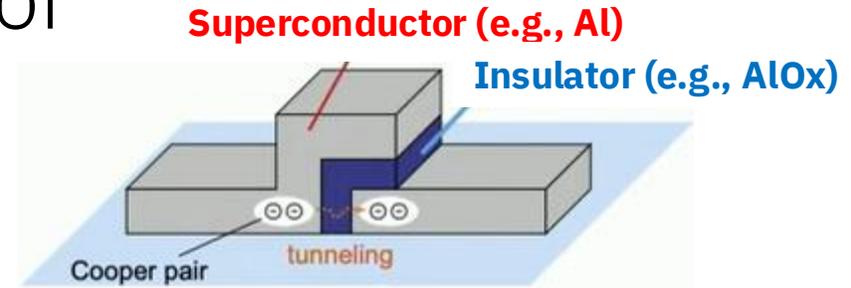
Nonlinear qubit inductor
e.g., Josephson junction

Josephson
junction

Linear L
$\Phi = LI$

$$U_{lin} = \frac{\Phi^2}{2L}$$
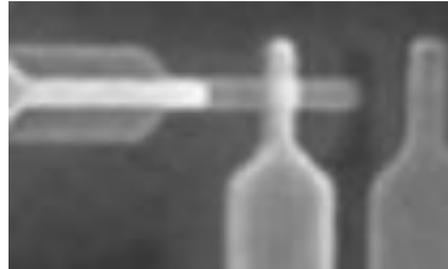
Qubit

Capacitor
Superconducting material (Nb, TiN, Ta, etc.)

Qubit Hamiltonian

$$\hat{H} = \frac{\hat{Q}^2}{2C} - E_J \cos\left(\frac{\hat{\Phi}}{\phi_0}\right)$$

Nonlinear potential
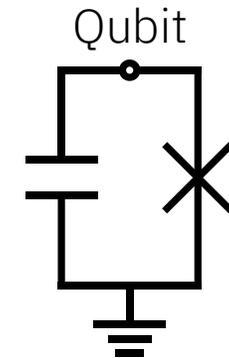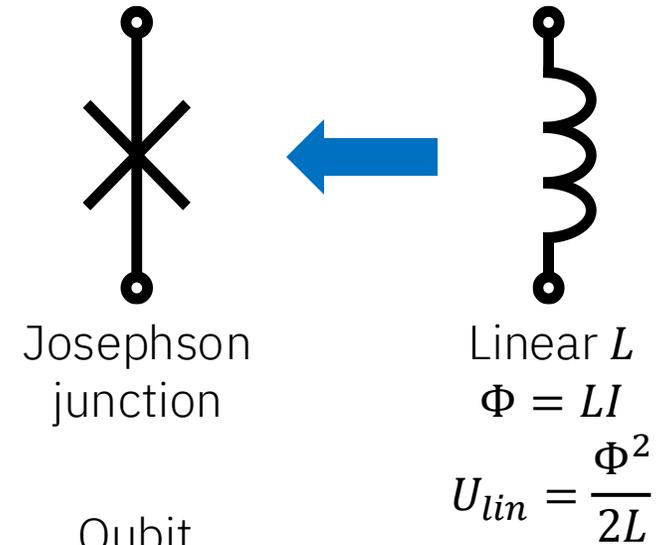
Hamiltonian of the transmon qubit

Hamiltonian of the transmon qubit

$$\hat{H}^{RWA} = \hbar\omega_q \hat{a}^\dagger \hat{a} - \frac{\hbar\alpha}{2}\hat{a}^{\dagger 2}\hat{a}^2 = \hbar\omega_q \hat{N} - \frac{\hbar\alpha}{2}\hat{N}(\hat{N}-1)$$

Linear   Nonlinear

where α is anharmonicity, so the energy levels are anharmonic.

$$U_{lin} = \frac{\widehat{\Phi}^2}{2L_J} \qquad U_J = -E_J \cos\left(\frac{\widehat{\Phi}}{\phi_0}\right)$$

$\omega_{12} = \omega_q - \alpha$

$\omega_{01} = \omega_q$
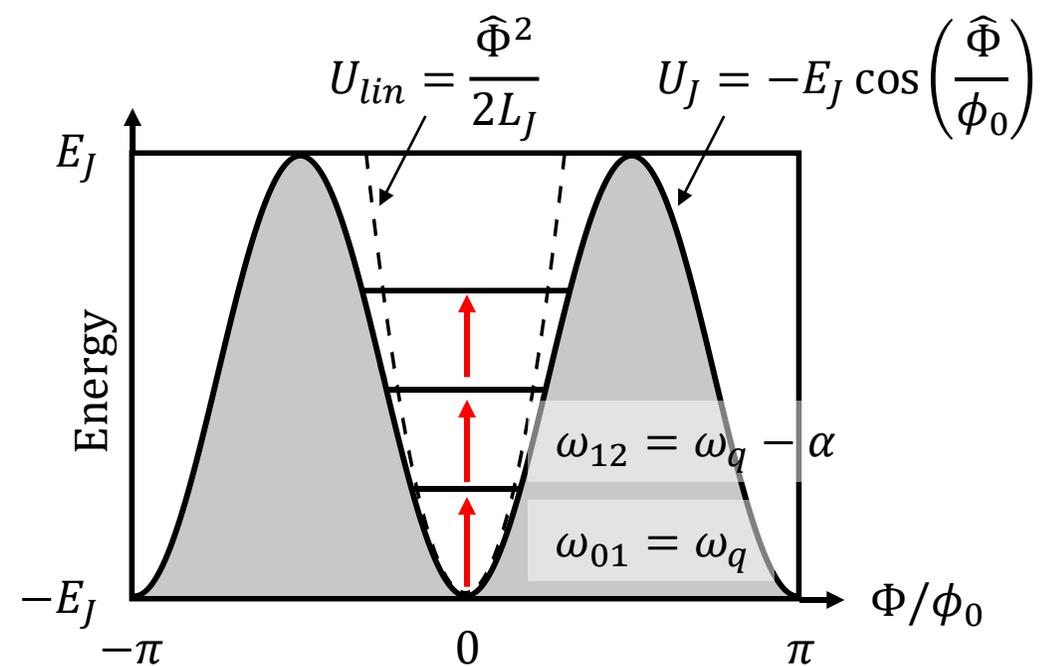
The qubit acts as a two-level system due to the anharmonicity!

Q. What is the frequency and the anharmonicity of the qubit of ibm_kawasaki?

Check out on the IBM quantum platform

https://quantum.ibm.com/

A. Qubit: Microwave frequency range

Qubit:
Frequency (GHz) ⌄   Median 5.24
min 4.904   max 5.584

Qubit:
Anharmonicity (GHz) ⌄   Median -0.30259
min -0.36561   max -0.2064
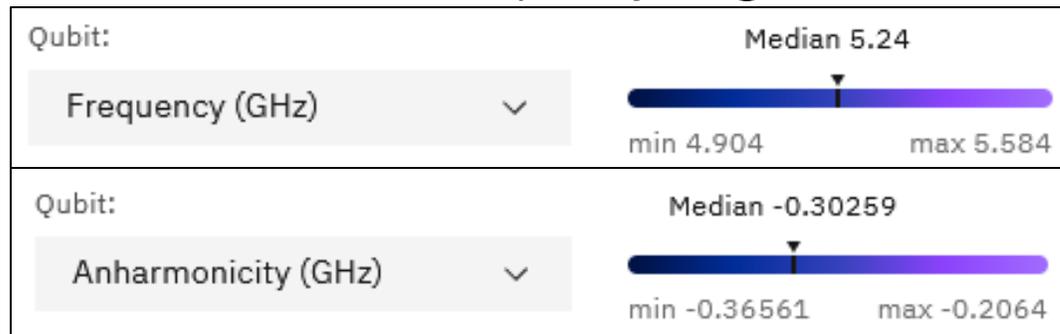
The qubit frequency corresponds to the following temperature

$$\omega_q \sim 5\ \text{GHz} \Leftrightarrow T_q \sim 0.25\ \text{K}\ (\hbar\omega_q = k_B T_q)$$

$\hbar\omega_q \gg k_B T$ must be satisfied for qubits not to be affected by thermal noise

⇒ Necessity of 10mK order refrigerator

Qubit transition spectrum

$$\hat{H}^{RWA} = \hbar\omega_q \hat{a}^\dagger \hat{a} - \frac{\hbar\alpha}{2}\hat{a}^{\dagger 2}\hat{a}^2 = \hbar\omega_q \hat{N} - \frac{\hbar\alpha}{2}\hat{N}(\hat{N}-1)$$

$L_J = 14 \text{ nH}$ $\qquad E_J = \frac{\phi_0^2}{L_J} = 12 \text{ GHz}$ $\qquad \omega_0 = \sqrt{\frac{1}{LC}} = 2\pi \times 5.3 \text{ GHz}$

$C_J = 65 \text{ fF}$ $\qquad E_C = \frac{e^2}{2C} = 0.3 \text{ GHz} \left(= \Delta_q = \alpha\right)$ $\qquad \frac{Q_{zpf}}{2e} \sim 1$

$$U_{lin} = \frac{\widehat{\Phi}^2}{2L_J} \qquad U_J = -E_J \cos\left(\frac{\widehat{\Phi}}{\phi_0}\right)$$

$\omega_{12} = \omega_q - \alpha = 4.7 \text{ GHz}$

$\omega_{01} = \omega_q = 5.0 \text{ GHz}$

$\omega_{nn+1} = \omega_q - n\alpha$

$\omega_{23} = \omega_q - 2\alpha$

$\omega_{12} = \omega_q - \alpha$

$\omega_{02}/2 = \omega_q - \alpha/2 \qquad \omega_{01} = \omega_q$

$|3\rangle$ $|2\rangle$ $|1\rangle$ $|0\rangle$

$\omega_{23} \qquad \omega_{12} \qquad \omega_{02}/2 \qquad \omega_{01} \qquad \omega$
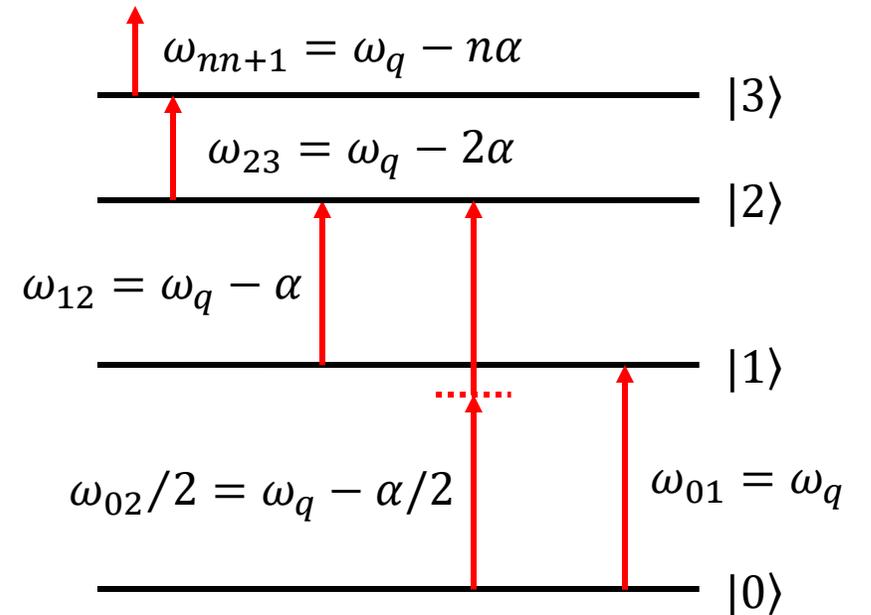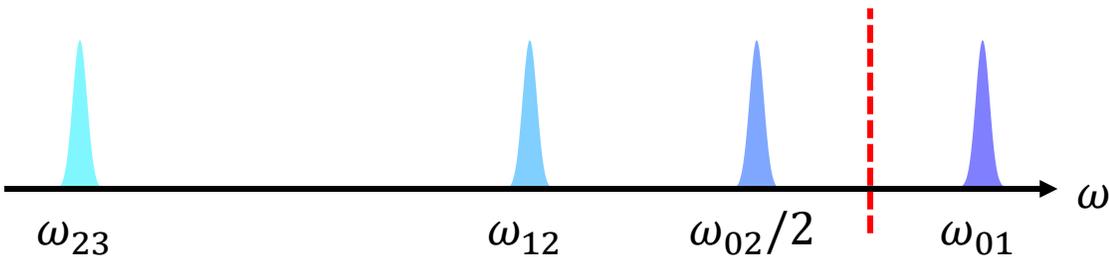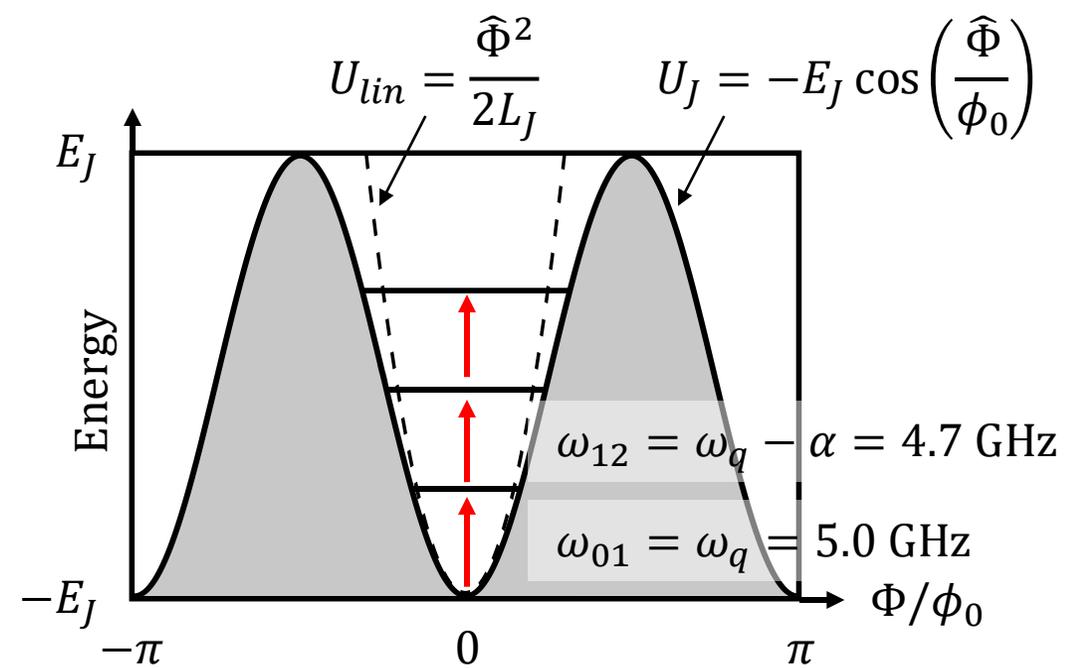
Restrict to qubit subspace

Fock number operator

$$\hat{a}^\dagger \hat{a} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

$$\widehat{N} - \frac{1}{2}\hat{I} \longmapsto -\frac{1}{2}\hat{Z}$$

Qubit Pauli Z operator

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Annihilation operator

$$\hat{a} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & \sqrt{3} \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

$$\hat{a} \longmapsto \hat{\sigma} = \frac{1}{2}(\hat{X} + i\hat{Y})$$

Qubit Pauli X and Y operators

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

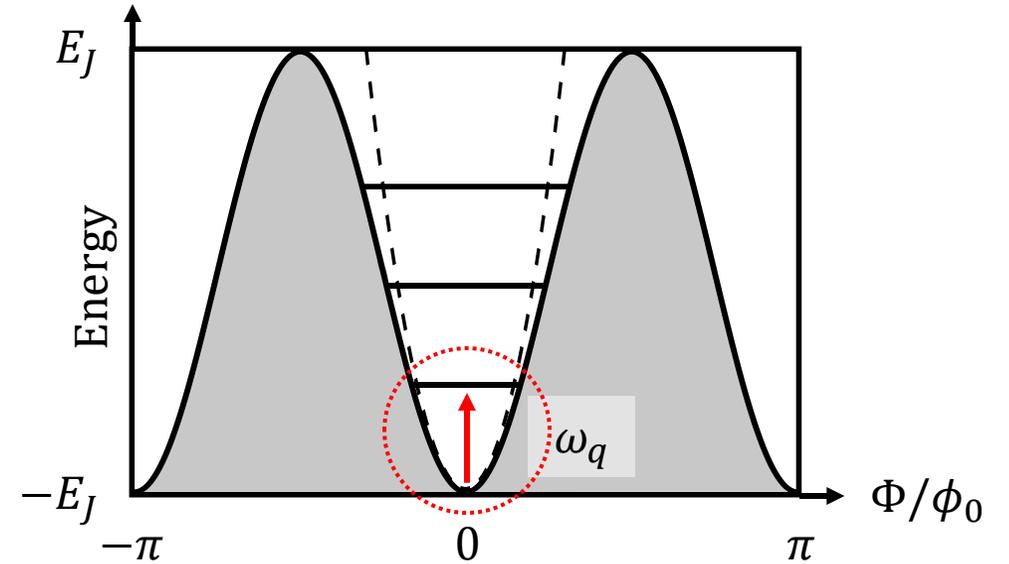Qubit Hamiltonian

$$\widehat{H}_{\text{qubit}} = -\frac{1}{2}\hbar\omega_q \hat{Z}$$

Qubit control

Qubit is controlled by microwave drive pulse

$$\hat{H}_{\text{drive}} = i\frac{\hbar}{2}\Omega(t)(\hat{\sigma}^\dagger - \hat{\sigma}) = \frac{\hbar}{2}\Omega(t)\hat{Y}$$

Drive pulse oscillates with ω_d

$$\Omega(t) = \Omega_0\sin(\omega_d t + \theta)$$
$$\hat{\sigma}(t) = \hat{\sigma}e^{-i\omega_d t}$$

$$\hat{H}_{\text{drive}}^{RWA} = -\frac{\hbar}{4}\Omega_0(\hat{\sigma}^\dagger e^{-i\theta} + \hat{\sigma}e^{i\theta})$$

Rabi rate $\Omega(t)$ and phase θ tune rotation speed and rotation axis, respectively

$$\hat{X} = \hat{\sigma}^\dagger + \hat{\sigma}$$
$$\hat{Y} = i(\hat{\sigma}^\dagger - \hat{\sigma})$$

Capacitive coupling $iQ(\hat{a}^\dagger - \hat{a})$

Input-output line (cable, waveguide, etc.)

$\Omega(t)$

Microwave drive pulse

$\omega_d = \omega_1$
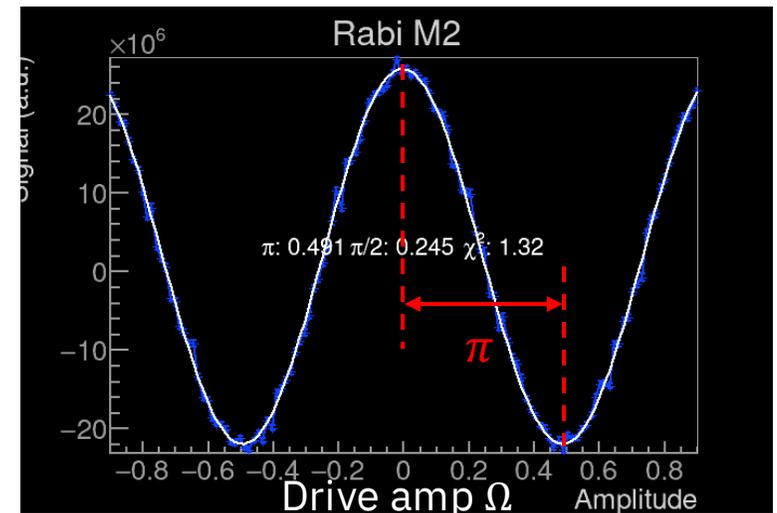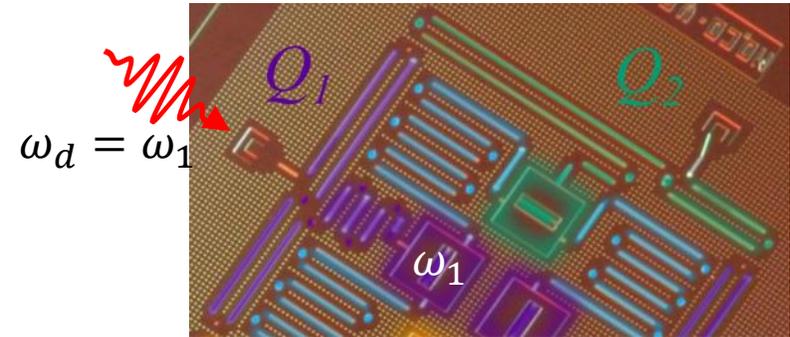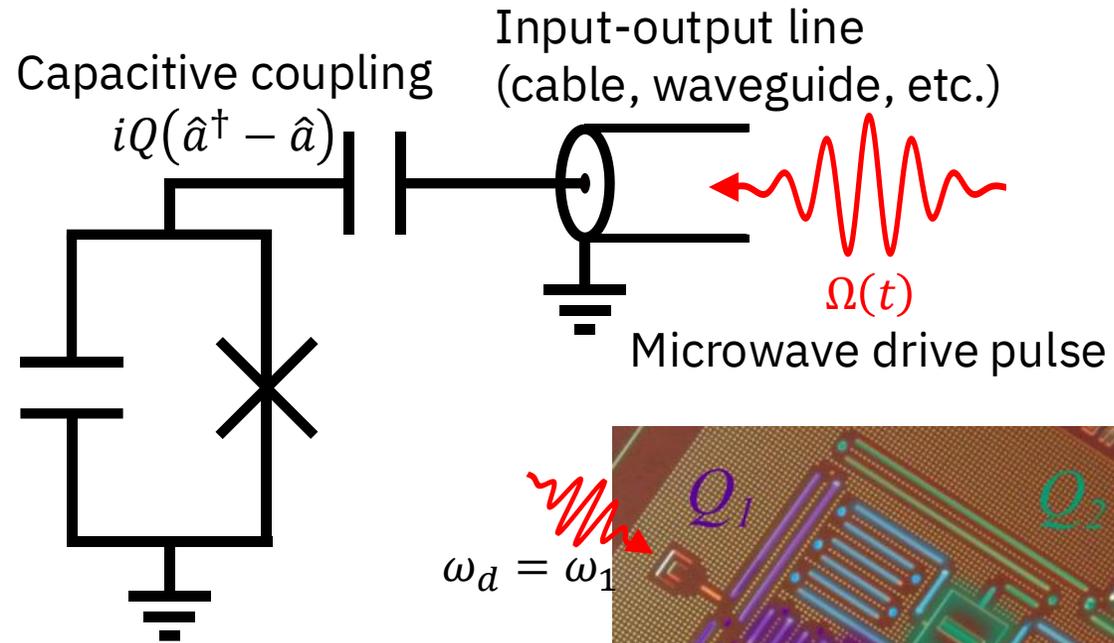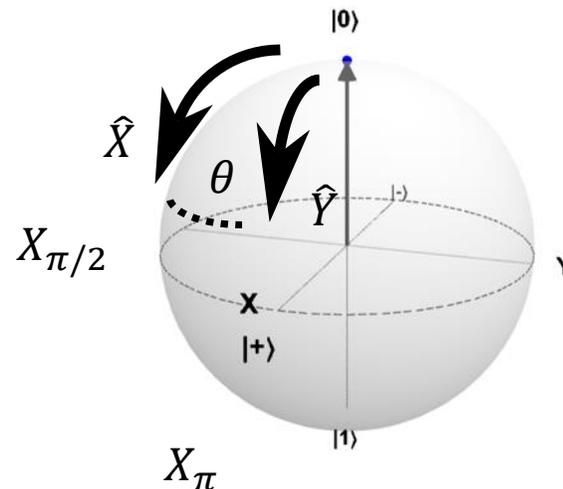
Lesson 9. Quantum Hardware

4. Qubit measurement on the hardware devices

There are two classes of measurements: demolition and non-demolition, such as dispersive measurement. In this section, you will learn about the mechanism of non-demolition dispersive measurement, which is extracted from the resonator.

Qubit measurement – two classes of measurements

Demolition
e.g., photon absorption

Non-demolition
e.g., dispersive measurement (QND)

Ref. Zlatko Minev, Qiskit global summer school in 2020
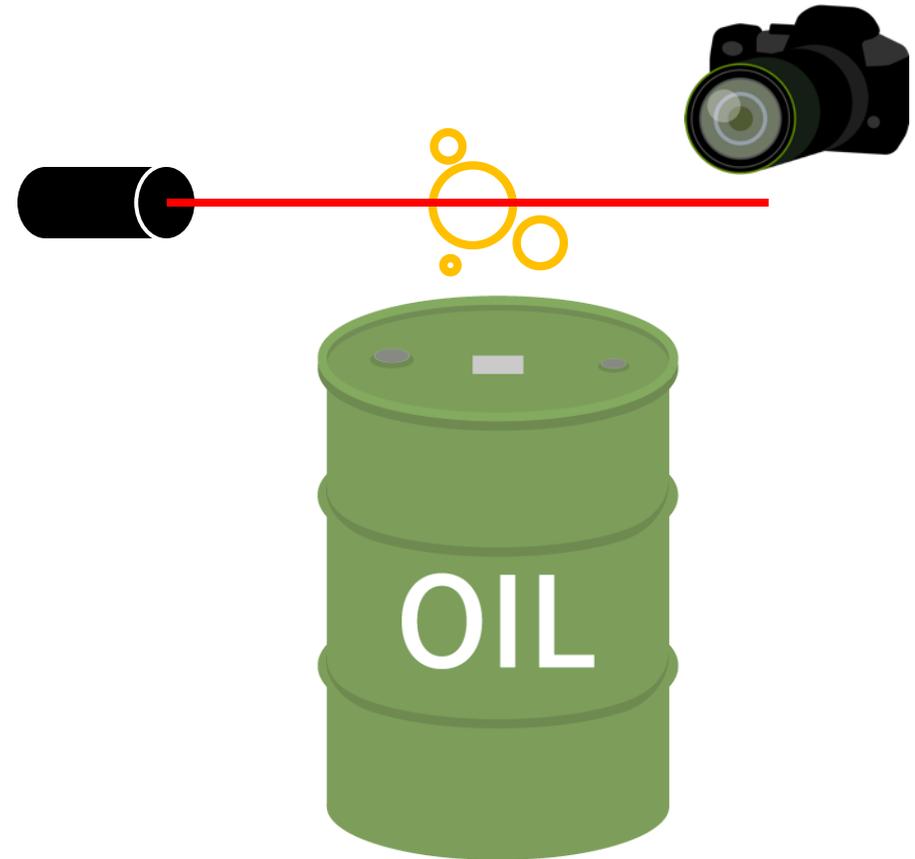
Circuit Quantum Electrodynamics dispersive measurement

Direct measurement
- Demolition
- Qubit energy leak out
- Noise come in

cQED dispersive measurement
Isolate qubit through resonator
- Non-demolition: extracted from resonator
- Not leak out qubit energy
- Isolate noise

Input-output line

Qubit

Qubit

Readout resonator: Linear LC circuit
(e.g., coplanar waveguide)

Si

Dispersive measurement

Qubit

Resonator

$$\hat{H} = \frac{\hat{Q}^2}{2C} - E_J \cos\left(\frac{\hat{\Phi}}{\phi_0}\right)$$

$$\omega_q \sim 5 \text{ GHz}$$

$\hat{Z}$

$\hat{a}$

$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L_J}$$

$$\omega_r \sim 7 \text{ GHz}$$

Qubit in $|1\rangle$ $|0\rangle$

Amplitude

2χ

Probe

$\omega_r - \chi$ $\omega_r + \chi$

Frequency

Phase
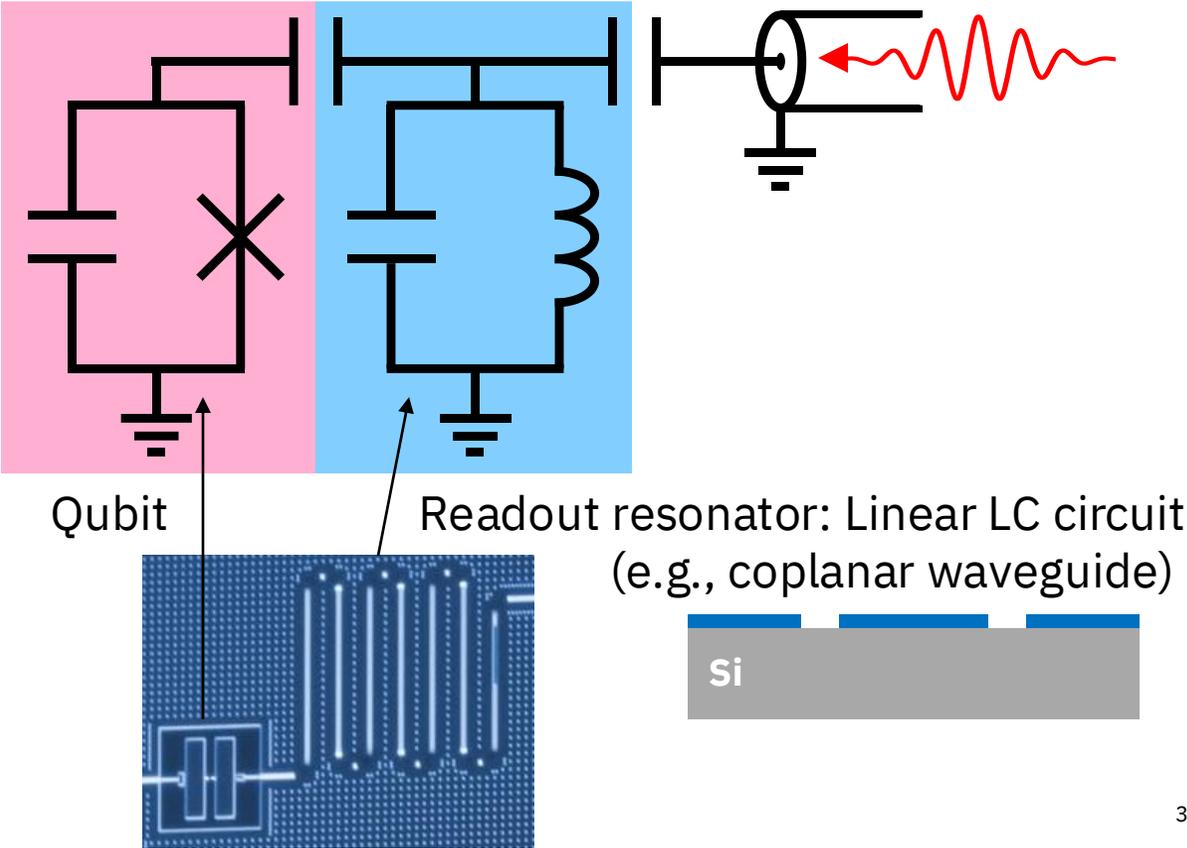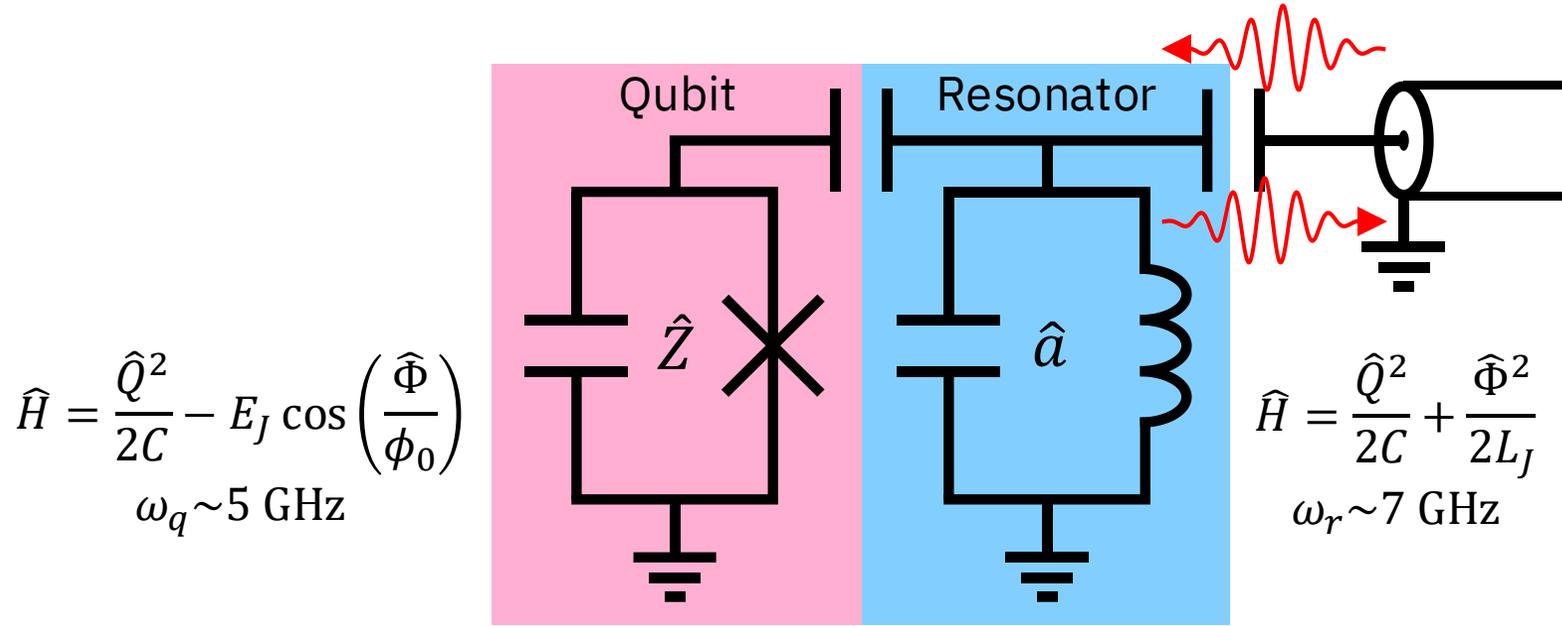
$|0\rangle, |1\rangle$ plot on IQ plane

Hamiltonian including qubit – resonator interaction

$$\hat{H}_{\text{eff}} = -\frac{1}{2}\hbar(\omega_q - \chi)\hat{Z} + \hbar(\underline{\omega_r + \chi\hat{Z}})\hat{a}^\dagger\hat{a}$$
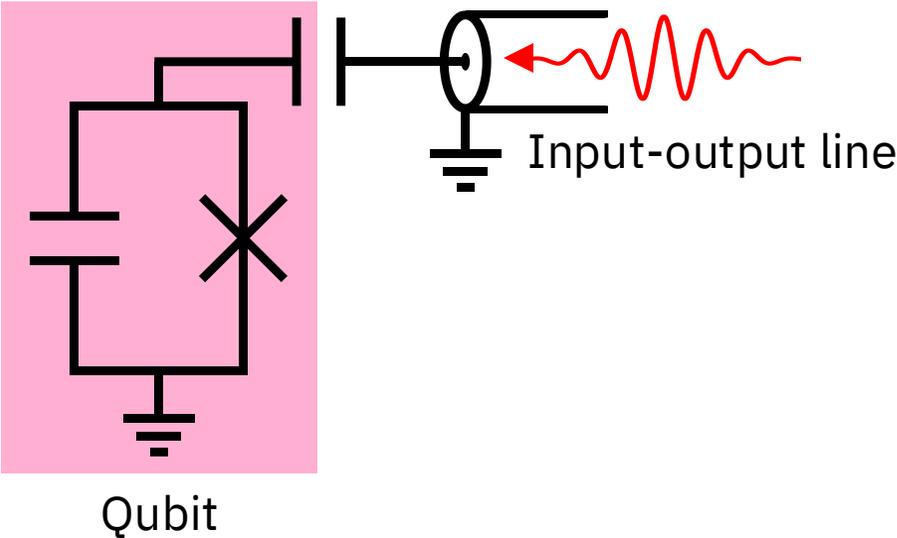
Resonator frequency is dispersive shifted depending on qubit state

Ref. Qiskit Textbook 6.4 Circuit Quantum Electrodynamics
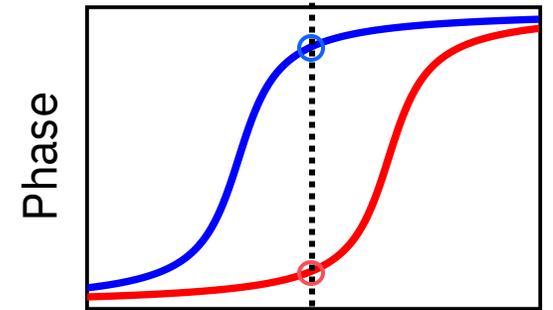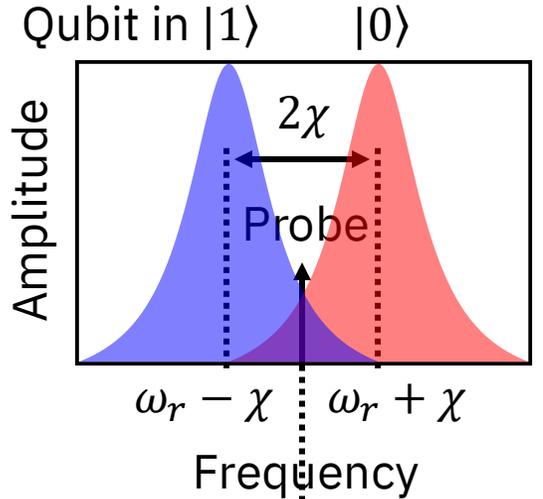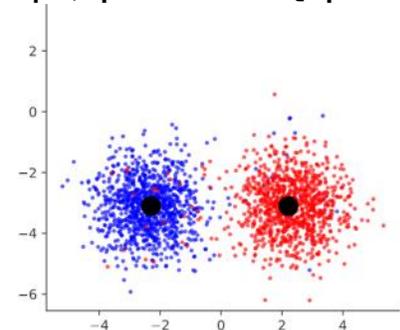
Lesson 9. Quantum Hardware

5. Two-qubit Gate -Cross Resonance Gate-

The Cross Resonance Gate, which serves as the basis for the CNOT gate, is implemented as the Echoed Cross Resonance (ECR) gate in hardware to mitigate dephasing. In this section, you will learn how the Cross Resonance Gate is realized in hardware.

Two-qubit gate – Cross resonance gate

ω_2, Q_1, Q_2, ω_1

- Cross resonance gate: basis of CNOT

Driving control qubit 1 with microwave at resonance frequency ω_2 of target qubit 2

$$\widetilde{H}_{\text{eff}}^{\text{CR}} = -\frac{\widetilde{\omega}_1 - \widetilde{\omega}_2}{2}\hat{Z}_1 + \frac{\Omega(t)}{2}\left(\hat{X}_2 - \frac{J}{2\Delta_{12}}\hat{Z}_1\hat{X}_2\right)$$

The entanglement is generated by the ZX interaction.

The max entanglement is reached, when qubit 1 is a 0/1 superposition, and CR gate of $\pi/2$ rotation is applied.

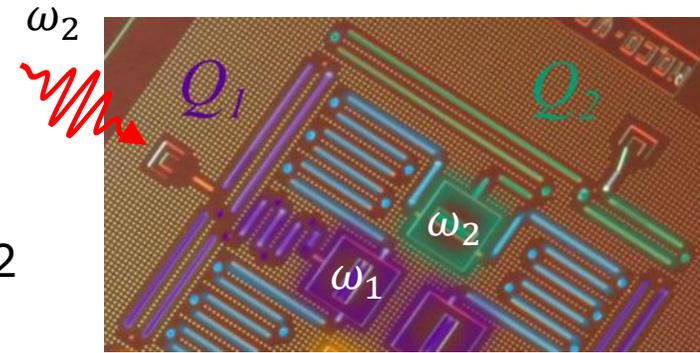$$ZX_{\pi/2} = \exp\{-i(\pi/4)ZX\} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -i & 0 & 0 \\ -i & 1 & 0 & 0 \\ 0 & 0 & 1 & i \\ 0 & 0 & i & 1 \end{pmatrix}$$

The direction of x-rotation is opposite depending on the state of control qubit

Control qubit 1   Target qubit 2

$\frac{|0\rangle - i|1\rangle}{\sqrt{2}}$

$|0\rangle$

$|1\rangle$
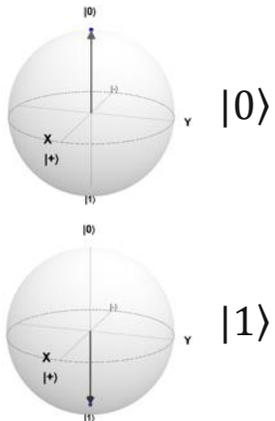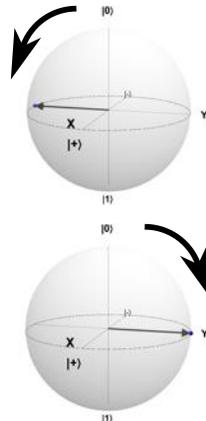
$\frac{|0\rangle + i|1\rangle}{\sqrt{2}}$

Echoed Cross Resonance (ECR) gate for removing dephasing

$CR_{\pi/4}$ X_π ω_2

ω_2 ω_1 $-CR_{\pi/4}$

https://javafxpert.github.io/grok-bloch/

36
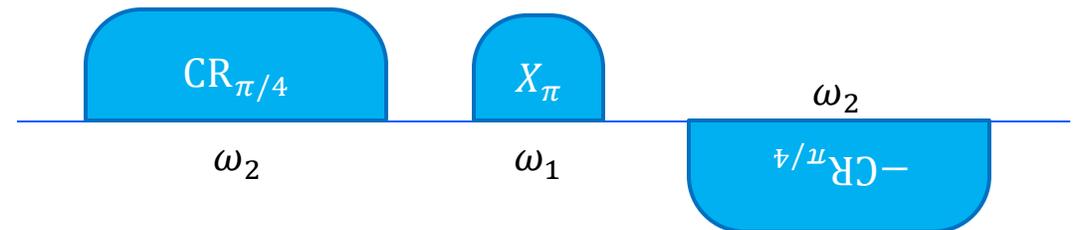
Lesson 9. Quantum Hardware

6. Device map and calibration data

In this section, you will learn about the meanings of various characteristic values in hardware, preparing for the subsequent hands-on sessions.

東京大学
THE UNIVERSITY OF TOKYO

9. Quantum Hardware
- Part 2 and 3 -

2024/06/14

Masao Tokunari

IBM Research – Tokyo
tokunari@jp.ibm.com

Outline

Part 1: Superconducting qubits
- Physics of the superconducting qubits
- Qubit control
- Quantum non-demolition measurement
- Qubit demonstration: qubit spectroscopy
- Two-qubit gate

Part 2: Device map and calibration data
- Hands-on: extracting the device information

Part 3: Qubit scaling
- Modularity
- Microwave component development

Summary

Device map and calibration data

https://quantum.ibm.com/services/resources

ibm_kawasaki OpenQASM 3

Details

127 Qubits

2.4% EPLG

5K CLOPS

Status:	● Online	Median ECR error:	7.653e-3
System region:	us-east	Median SX error:	2.340e-4
Total pending jobs:	210 jobs	Median readout error:	1.080e-2
Processor type ⓘ:	Eagle r3		
Version:	2.1.28	Median T1:	183.48 us
Basis gates:	ECR, ID, RZ, SX, X	Median T2:	138.56 us
Your instance usage:	0 jobs		

Device map – heavy-hex lattice

Heavy hexagonal code
- For quantum error correction
- Low connectivity (up to 3 neighbor qubits) to avoid frequency collision
- Modest fault tolerant threshold

https://www.ibm.com/quantum/blog/heavy-hex-lattice

Device map and calibration data

https://quantum.ibm.com/services/resources

Basis gates

- ECR: Echoed Cross Resonance, $ECR = XI_\pi \cdot ZX_{\pi/2} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & i \\ 0 & 0 & i & 1 \\ 1 & -i & 0 & 0 \\ -i & 1 & 0 & 0 \end{pmatrix}$

- ID: Identity, $I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

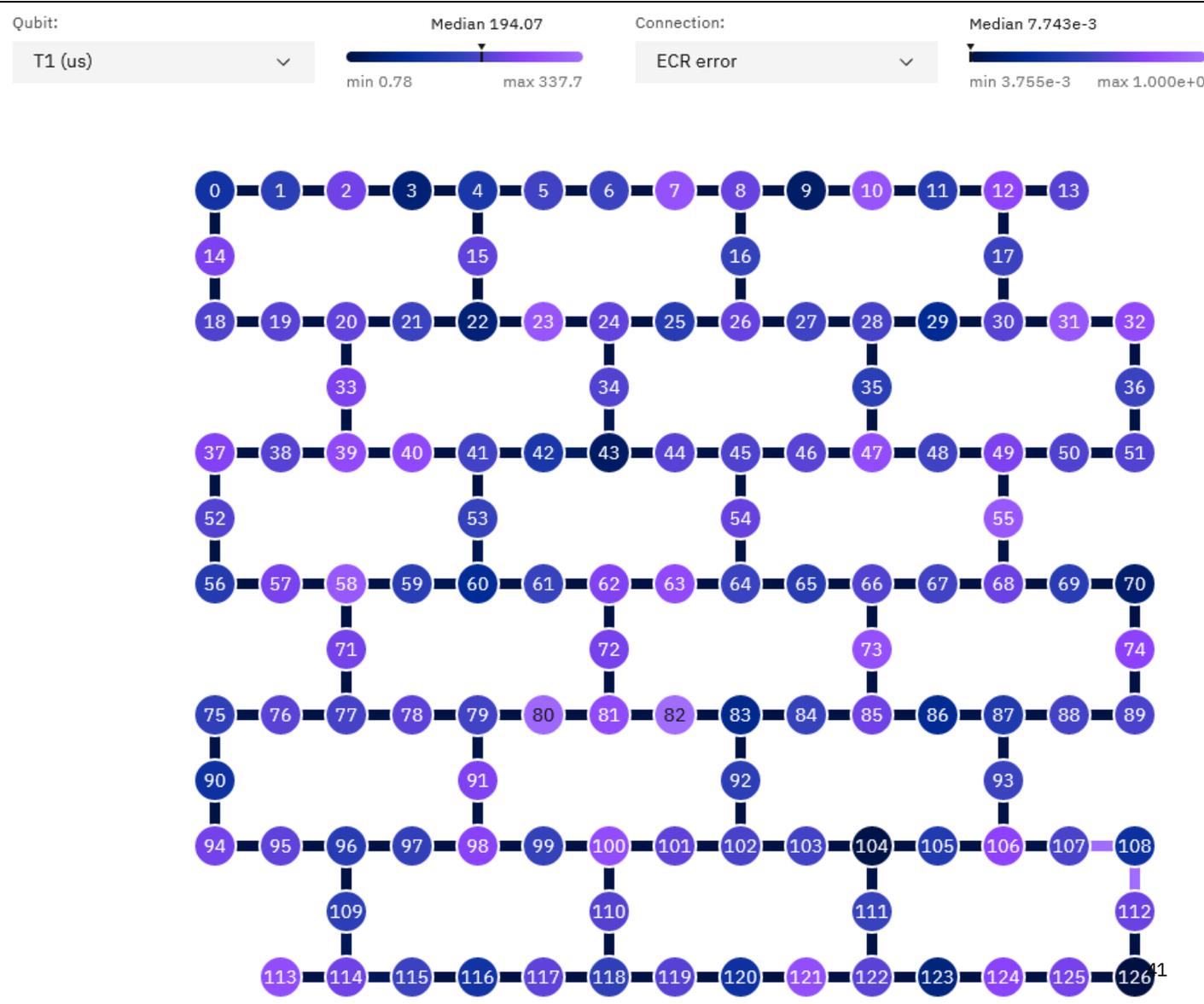- RZ: single-qubit rotation about Z-axis, $RZ(\theta) = \begin{pmatrix} e^{-i\frac{\theta}{2}} & 0 \\ 0 & e^{i\frac{\theta}{2}} \end{pmatrix}$

  Implemented virtually in hardware via frame changes.

- X: single-qubit pauli X gate, bit-flip, $X_\pi = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

- SX: sqrt X gate, $\sqrt{X}, X_{\pi/2} = \frac{1}{2} \begin{pmatrix} 1+i & 1-i \\ 1-i & 1+i \end{pmatrix}$

Device map and calibration data

https://quantum.ibm.com/services/resources

ibm_kawasaki OpenQASM 3

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2.4% EPLG

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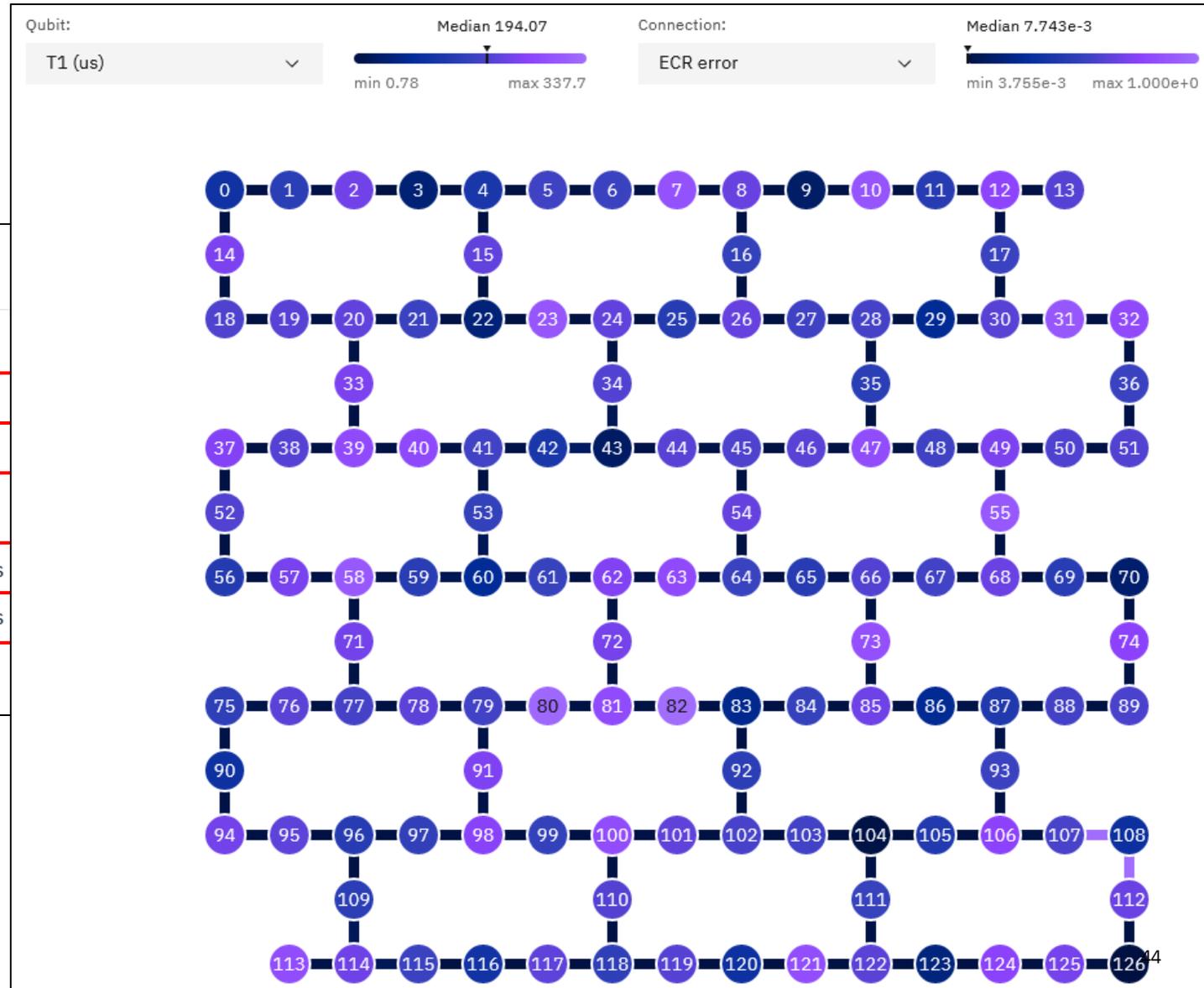
Gate error – Randomized benchmarking

Randomized Benchmarking
- Technique for characterizing gate errors
- Perform a random series of Clifford gates and undo
- Single qubit RB → 1Q gate error, SX error
- Two qubit RB → ECR error

Pulse sequence: N random Cliffords - inverse Clifford – measure
- Ci is a random gate sampled from a finite Clifford gate set
- C-1 is performed to make the total sequence equal to identity
- Measure the probabilities to get back to the ground state at the end of the sequence
- Vary sequence length, fit the fidelity decay to an exponential curve to report Error Per Clifford

Single Qubit RB M4

α: 0.998867 EPC: 0.000566± 3.7e-05 χ^2: 0.7

$|0\rangle$ C_1 ... C_n C^{-1}

45

Magesan et al., PRL 106, 180504 (2011)
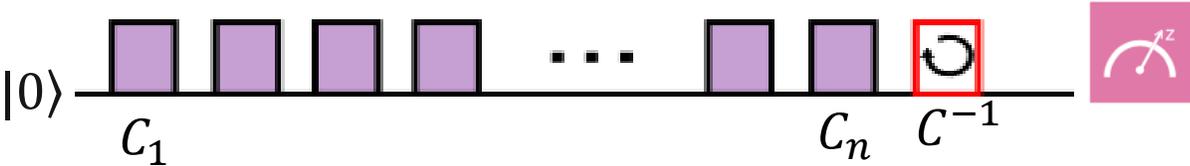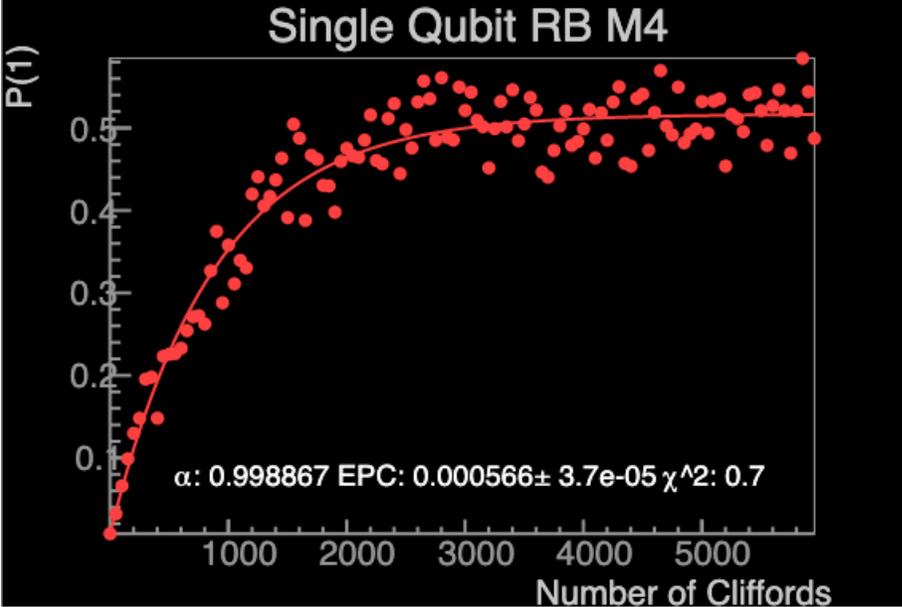
Readout error

Pulse sequence
- I - measure (blue)
- X_π - measure (red)
- Plot on IQ plane and discriminate 0/1

It is difficult to separate readout error and state preparation error

Discrimination
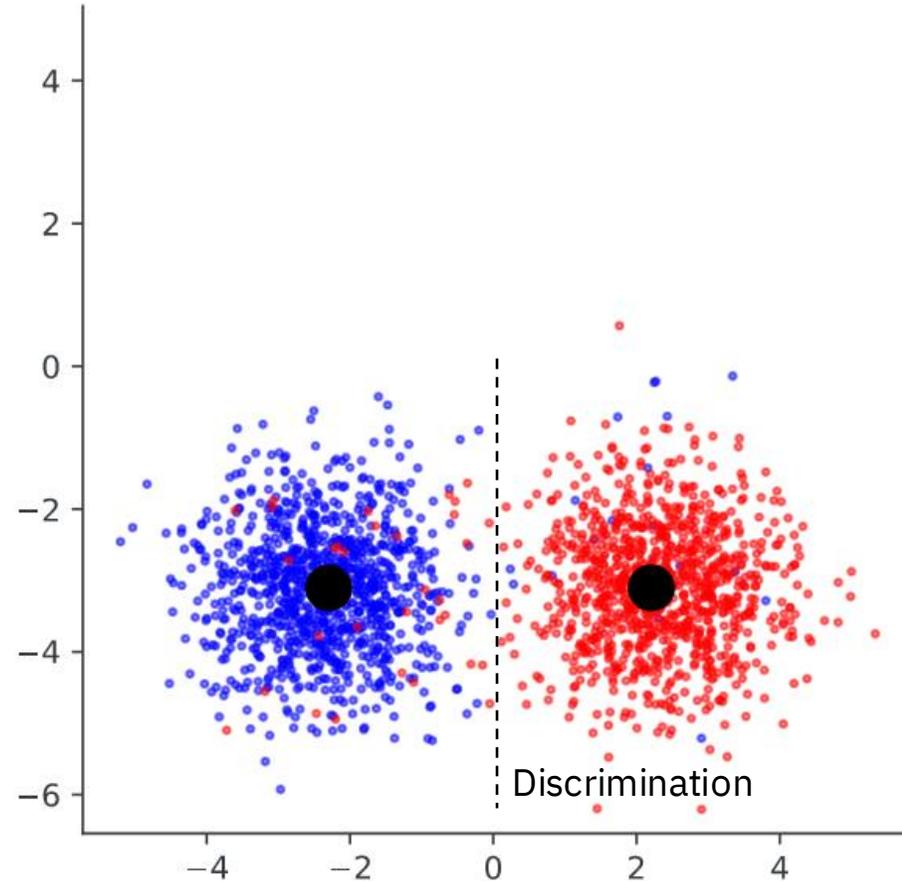
Relaxation time (T1): amplitude damping

Energy decay from the excited state $|1\rangle$ to the ground state $|0\rangle$
- Spontaneous emission due to electromagnetic environment
- Coupling to two-level systems (TLSs) or any other channel
- Superconductor phenomena: quasiparticles and vortices

- Energy relaxation is characterized by the timescale T1
- The probability of a relaxation error is given by $1 - e^{-t/T_1}$
- Pulse sequence : X_π - (vary delay) - measure
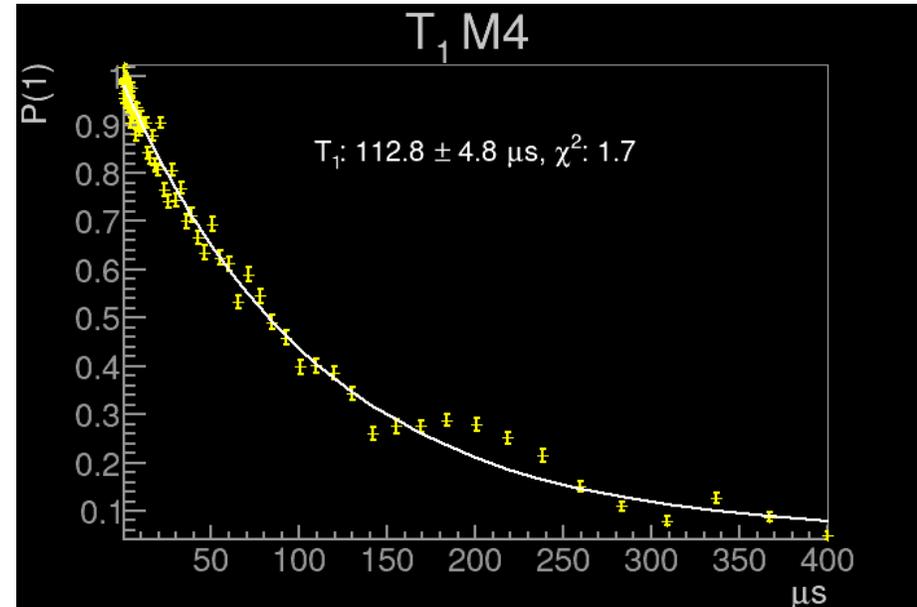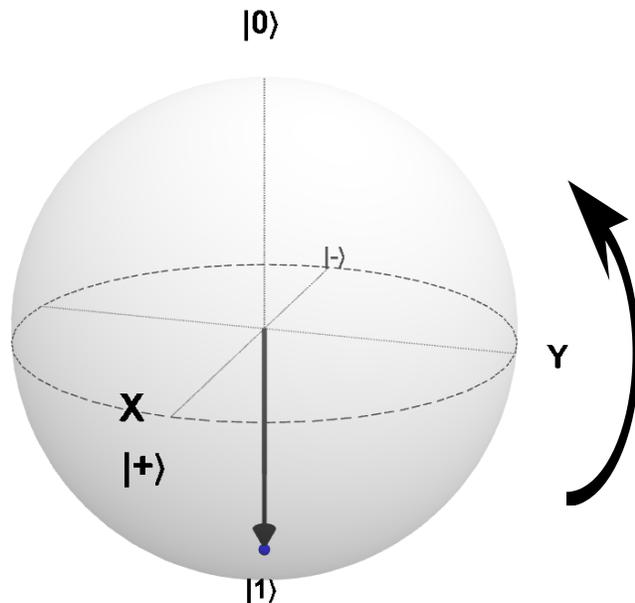
Decoherence time (T2): phase damping

Fluctuations in energy levels due to thermal broadening or magnetic noise
- Superposition states become classical, and a coherent state lose its phase information
- Ultimately limited by qubit relaxation (T_1), even with dephasing (T_ϕ) improvements

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

- Decoherence is characterized by the timescale T2
- The probability of a relaxation error is given by $1 - e^{-t/T_2}$
- Pulse sequence : $X_{\pi/2}$ - (vary delay) - X_π - (vary delay) - $X_{\pi/2}$ - measure
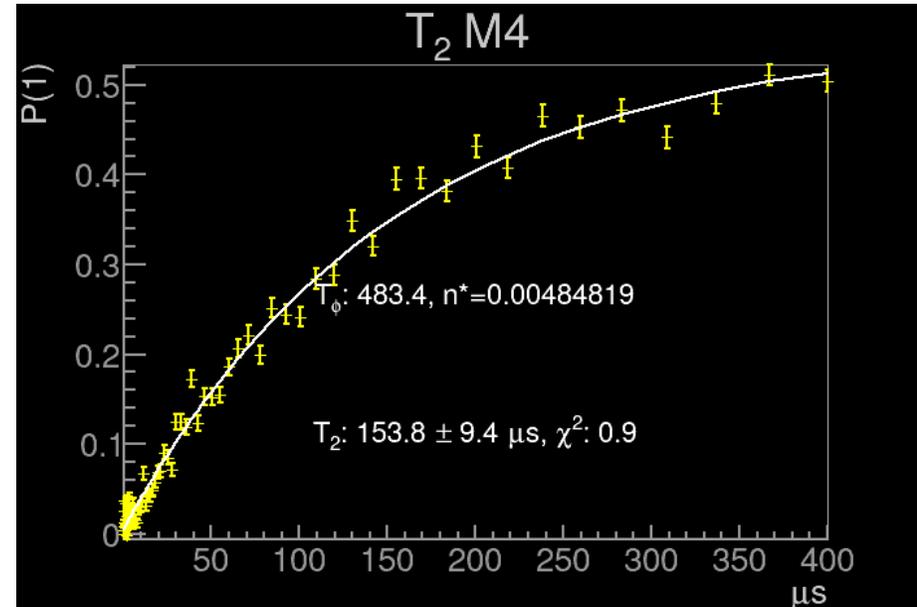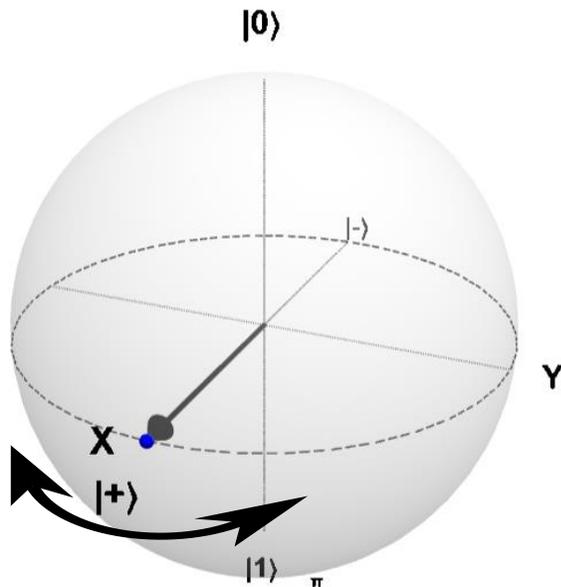
Coherence in superconducting circuits
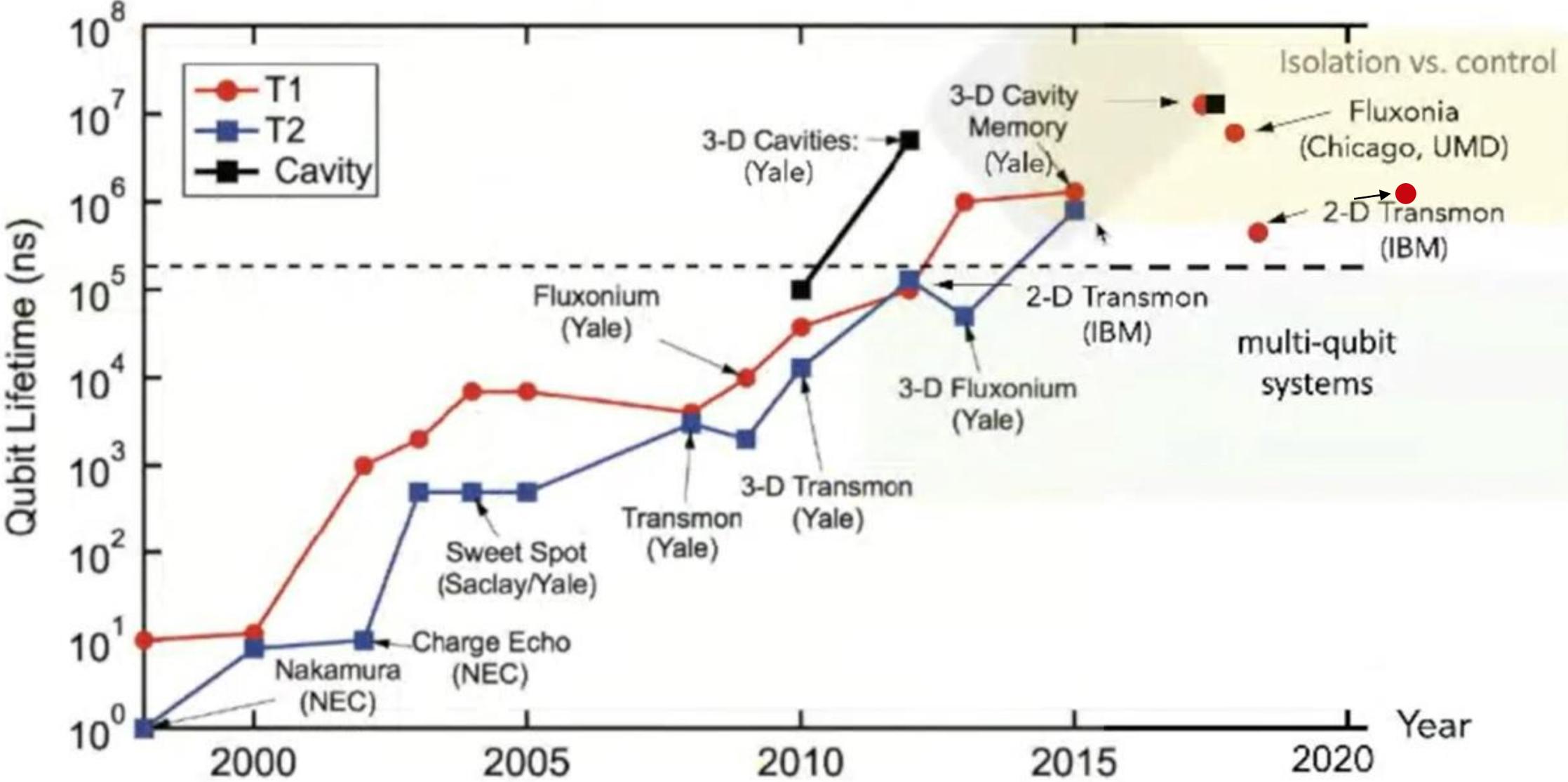
Image made by Devoret and Schoelkopf (2013), updated by Reagor (2015), and updated by Minev (2020), and updated

Lesson 9. Quantum Hardware

11. Qubit Scaling

IBM Quantum has achieved qubit scaling through various technologies. Additionally, modular coupling has been proposed for future scaling.
In this section, you will learn about the evolution of these approaches and the technological roadmap for the future .

Outline

Device map and calibration data

ibm_kawasaki · OpenQASM 3

Details

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2.4% EPLG

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Basis gates:	ECR, ID, RZ, SX, X	Median T2:	138.56 us
Your instance usage:	0 jobs		

56

2016
2017
2018

→ 2019

2016
2017
2018
2019

→ 2020

IBM Quantum

HUMMINGBIRD
65 QUBITS
MULTIPLEXING

2016
2017
2018
2019
2020

→ 2021

2016
2017
2018
2019
2020
2021

→ 2022

IBM **Quantum**

OSPREY
433 QUBITS
SIGNAL DENSITY

2016
2017
2018
2019
2020
2021
2022

→ 2023

Condor

Pushing the limits of scale & yield

1,121

Superconducting qubits

50%

Increase in qubit density

1 mile +

Of flex cabling

Condor unblocked the road to scaling.

We now need to focus on gate depth and quality

2016
2017
2018
2019
2020
2021
2022

→ 2023

IBM Quantum
IBM Quantum

HERON
133 QUBITS
TUNABLE-COUPLER
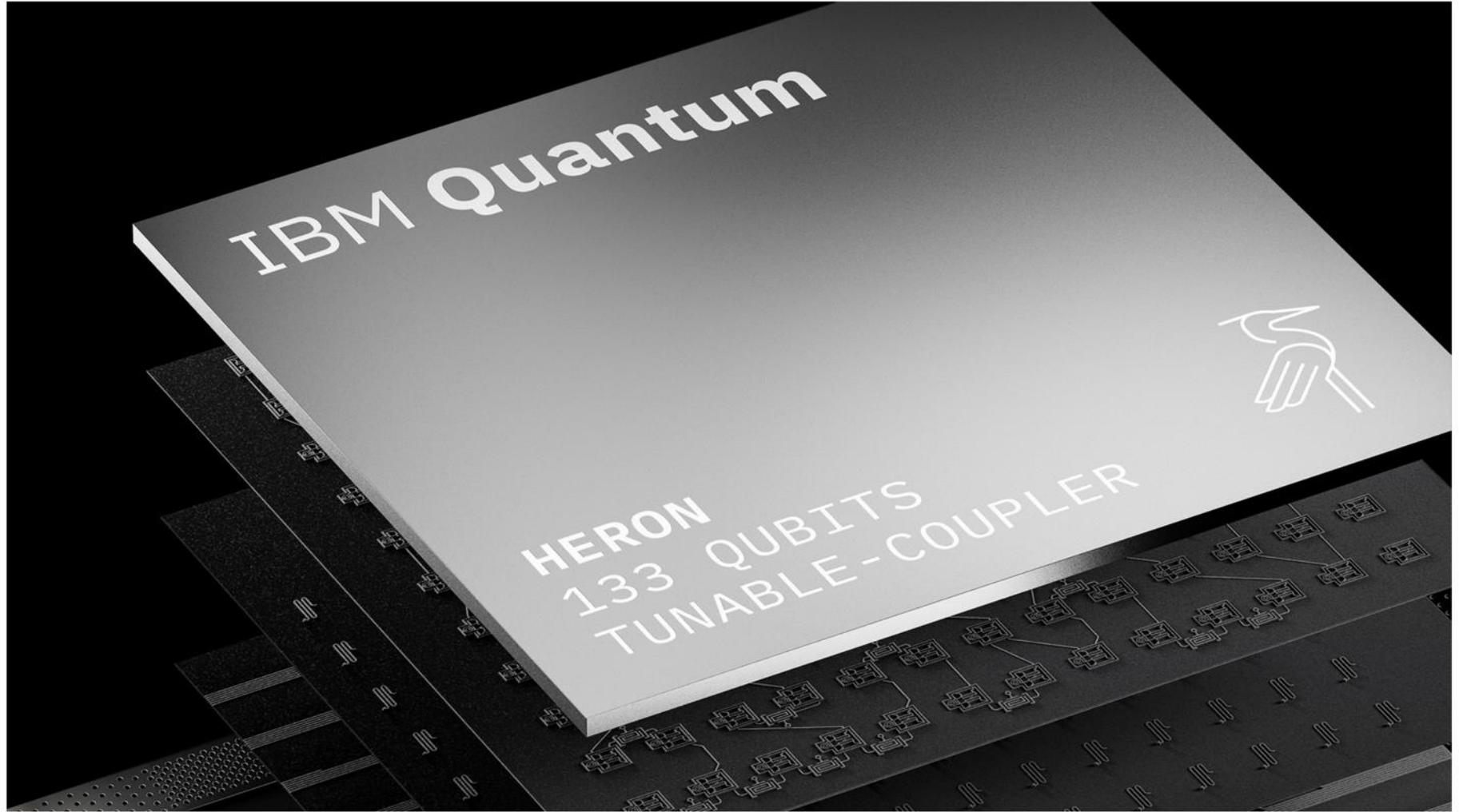
Heron

133 qubit systems

Tunable coupler architecture

ibm_montecarlo
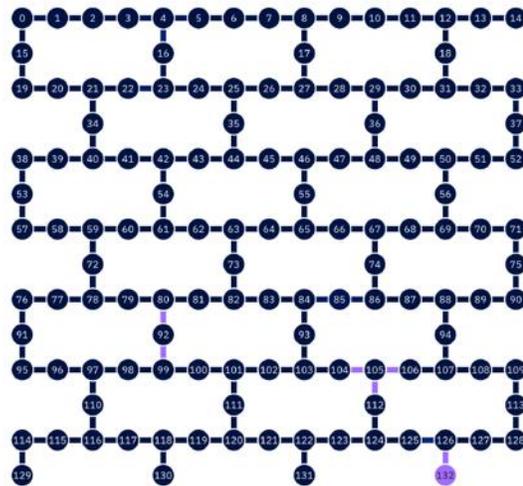
	ibm_sherbrooke Eagle	ibm_montecarlo (Heron)
Gate Error (best system)	0.6-0.7%	0.3% - Best ~ 0.1%
Crosstalk	High (qubit-qubit collisions)	Almost zero!
Gate time	500-600ns	90-100ns
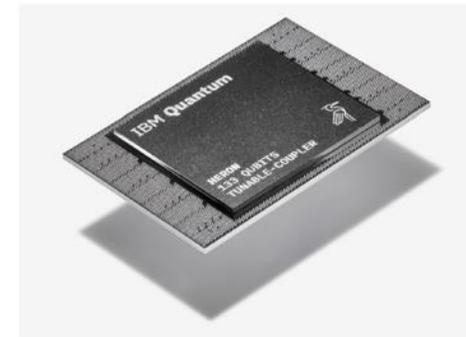
Tunable Coupler architecture - Performance

IBM Quantum

HERON
133 QUBITS
TUNABLE-COUPLER
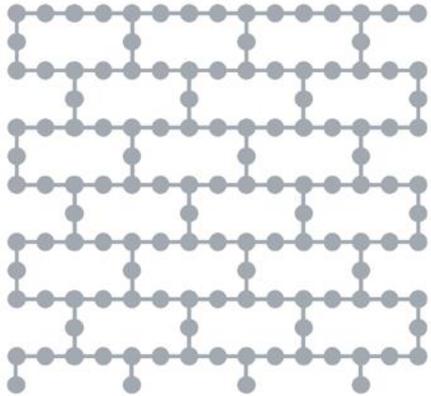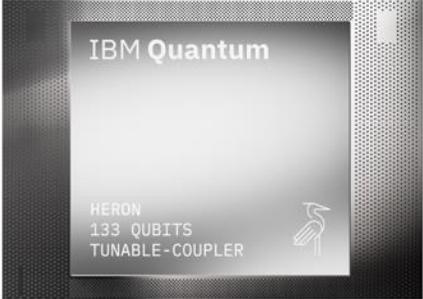
A major milestone in system performance:

A clear runway to our goal of 5K gates and beyond

Eagle R3

Mean T1 = 269 us
Mean ECR gate time = **537 ns**

2772 gates

100 qubit circuit

Heron R1

Mean T1 = 174 us
Mean CZ gate time = **96 ns**

9300 gates *(estimate)*

100 qubit circuit

Development Roadmap

2016–2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024	2025	2026	2027	2028	2029	2033+
Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing

Data Scientist

Platform

| Code assistant ⏱ | Functions | Mapping Collection | Specific Libraries | General purpose QC libraries |

Researchers

Middleware

| Quantum Serverless ✓ | Transpiler Service ⏱ | Resource Management | Circuit Knitting x P | Intelligent Orchestration | Circuit libraries |

Quantum Physicist

Qiskit Runtime

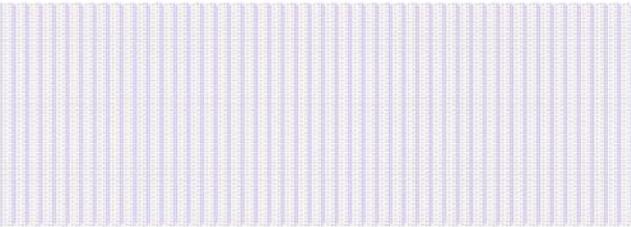| IBM Quantum Experience ✓ | QASM3 ✓ | Dynamic circuits ✓ | Execution Modes ✓ | Heron (5K) ⏱ | Flamingo (5K) | Flamingo (7.5K) | Flamingo (10K) | Flamingo (15K) | Starling (100M) | Blue Jay (1B) |

Heron (5K)	Flamingo (5K)	Flamingo (7.5K)	Flamingo (10K)	Flamingo (15K)	Starling (100M)	Blue Jay (1B)
Error Mitigation	Error Mitigation	Error Mitigation	Error Mitigation	Error Mitigation	Error correction	Error correction
5k gates	5k gates	7.5k gates	10k gates	15k gates	100M gates	1B gates
133 qubits	156 qubits	156 qubits	156 qubits	156 qubits	200 qubits	2000 qubits
Classical modular	Quantum modular	Quantum modular	Quantum modular	Quantum modular	Error corrected modularity	Error corrected modularity
133x3 = 399 qubits	156x7 = 1092 qubits	156x7 = 1092 qubits	156x7 = 1092 qubits	156x7 = 1092 qubits		

Early ✓	Falcon ✓	Eagle ✓
Canary 5 qubits / Albatross 16 qubits / Penguin 20 qubits / Prototype 53 qubits	Benchmarking 27 qubits	Benchmarking 127 qubits

Innovation Roadmap

Software Innovation

IBM Quantum Experience ✓	Qiskit ✓	Application modules ✓	Qiskit Runtime ✓	Serverless ✓	AI enhanced quantum ✓	Resource management ⏱	Scalable circuit knitting ⏱	Error correction decoder ⏱
	Circuit and operator API with compilation to multiple targets	Modules for domain specific application and algorithm workflows	Performance and abstract through Primitives	Demonstrate concepts of quantum centric-supercomputing	Prototype demonstrations of AI enhanced circuit transpilation	System partitioning to enable parallel execution	Circuit partitioning with classical reconstruction at HPC scale	Demonstration of a quantum system with real-time error correction decoder

Hardware Innovation

Early ✓	Falcon ✓	Hummingbird ✓	Eagle ✓	Osprey ✓	Condor ✓	Flamingo ⏱	Kookaburra		Cockatoo	Starling
Canary 5 qubits / Penguin 20 qubits / Albatross 16 qubits / Prototype 53 qubits	Demonstrate scaling with I/O routing with Bump bonds	Demonstrate scaling with multiplexing readout	Demonstrate scaling with MLW and TSV	Enabling scaling with high density signal delivery	Single system scaling and fridge capacity	Demonstrate scaling with modular connectors	Demonstrate scaling with nonlocal c-coupler	Demonstrate path to improved quality with logical memory	Demonstrate path to improved quality with logical communication	Demonstrate path to improved quality with logical gates

Heron ✓	Crossbill ⏱
Architecture based on tunable-couplers	m- coupler

✓ Executed by IBM
⏱ On target

ne

Dynamic circuits ✓

Execution Modes ↺

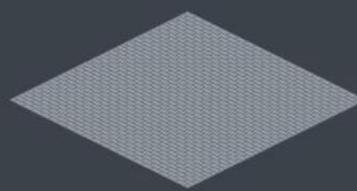Error suppression and mitigation

Osprey ✓
433 qubits

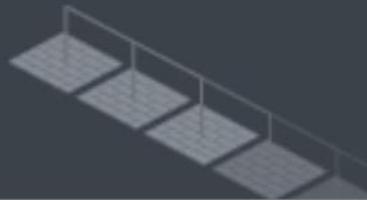Condor ✓
1,121 qubits

Flamingo
1,386+ qubits

Kookaburr
4,158+ qubits

Heron ↺
133 qubits x p
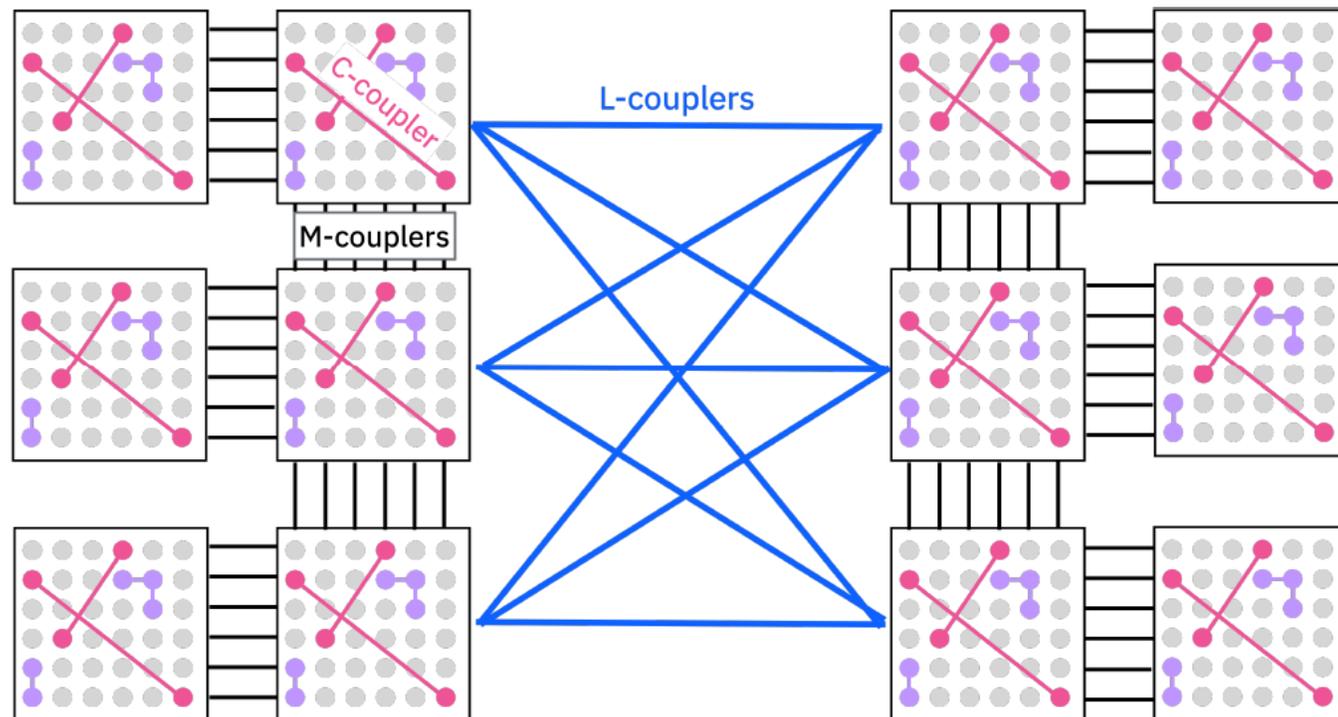
Crossbill
408 qubits

New error correction codes
and system modularity

C-coupler enables long-range
on-chip connections for high-rate
LDPC codes

L-coupler enables joining
multiple logical memories to
create large-scale systems

M-coupler enables joining multiple
short-range chip-to-chip connections

Extending Heron platform through modular coupling

Flamingo

Heron platform + *l-coupler* gate + *l-coupler* cable

~1 meter cable

Heron   Flamingo   Flamingo
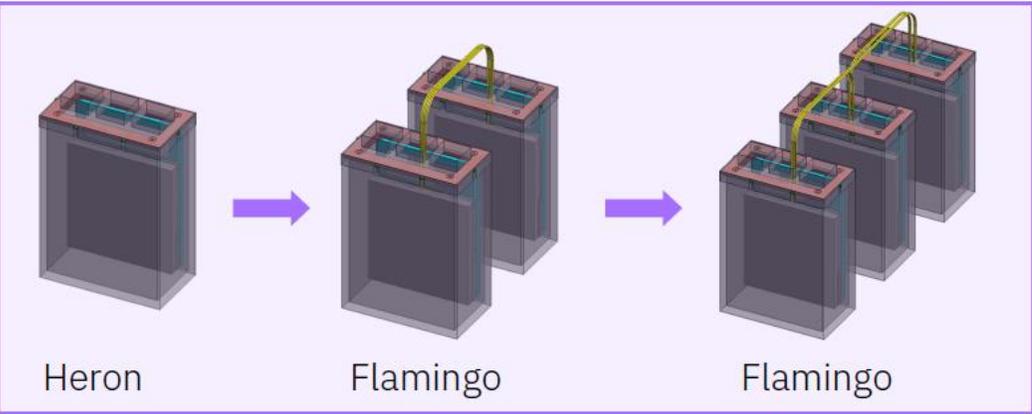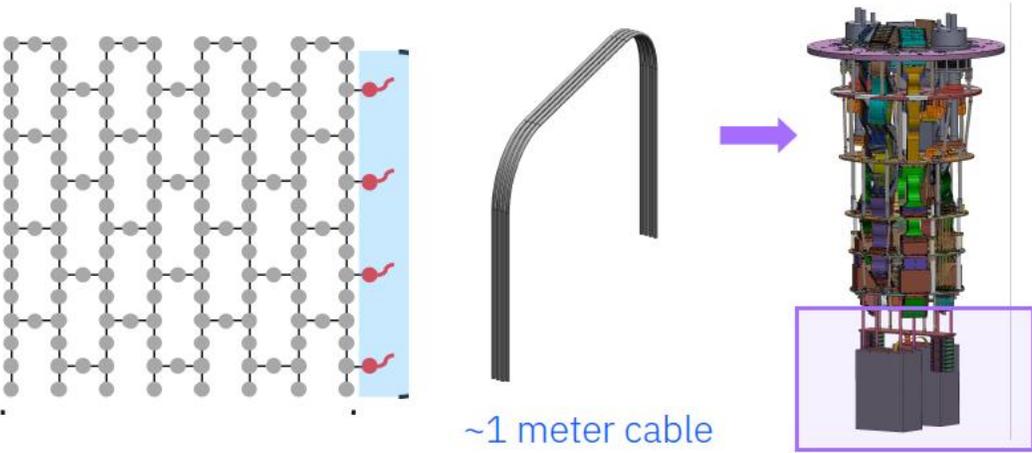
Crossbill

Heron platform + *m-coupler bus* + *m-coupler packaging*
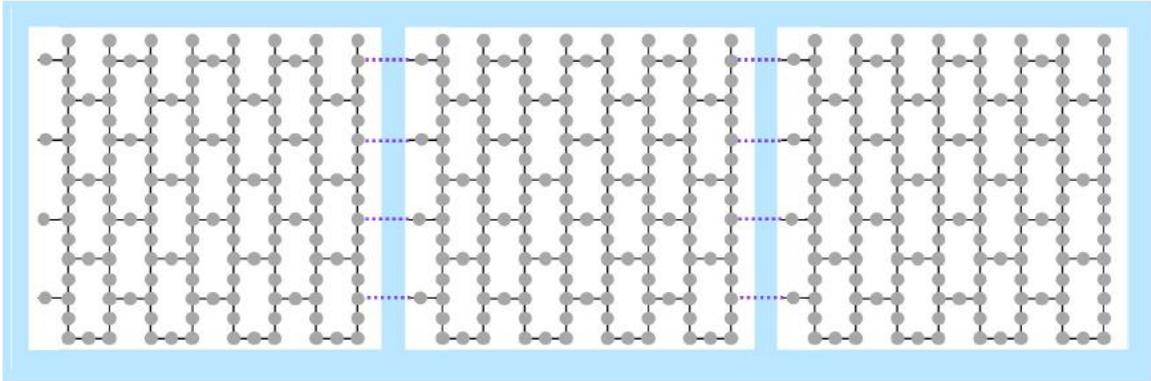
Qubit chiplets within
a multi-chip module
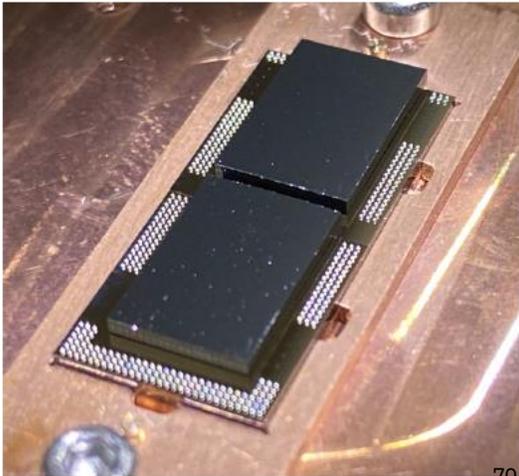
100,000-qubit quantum-centric supercomputer

—

2033

Classical connections

Quantum connections
Transducers to
optical interconnects

IBM Quantum System Two
25,000-qubit cluster
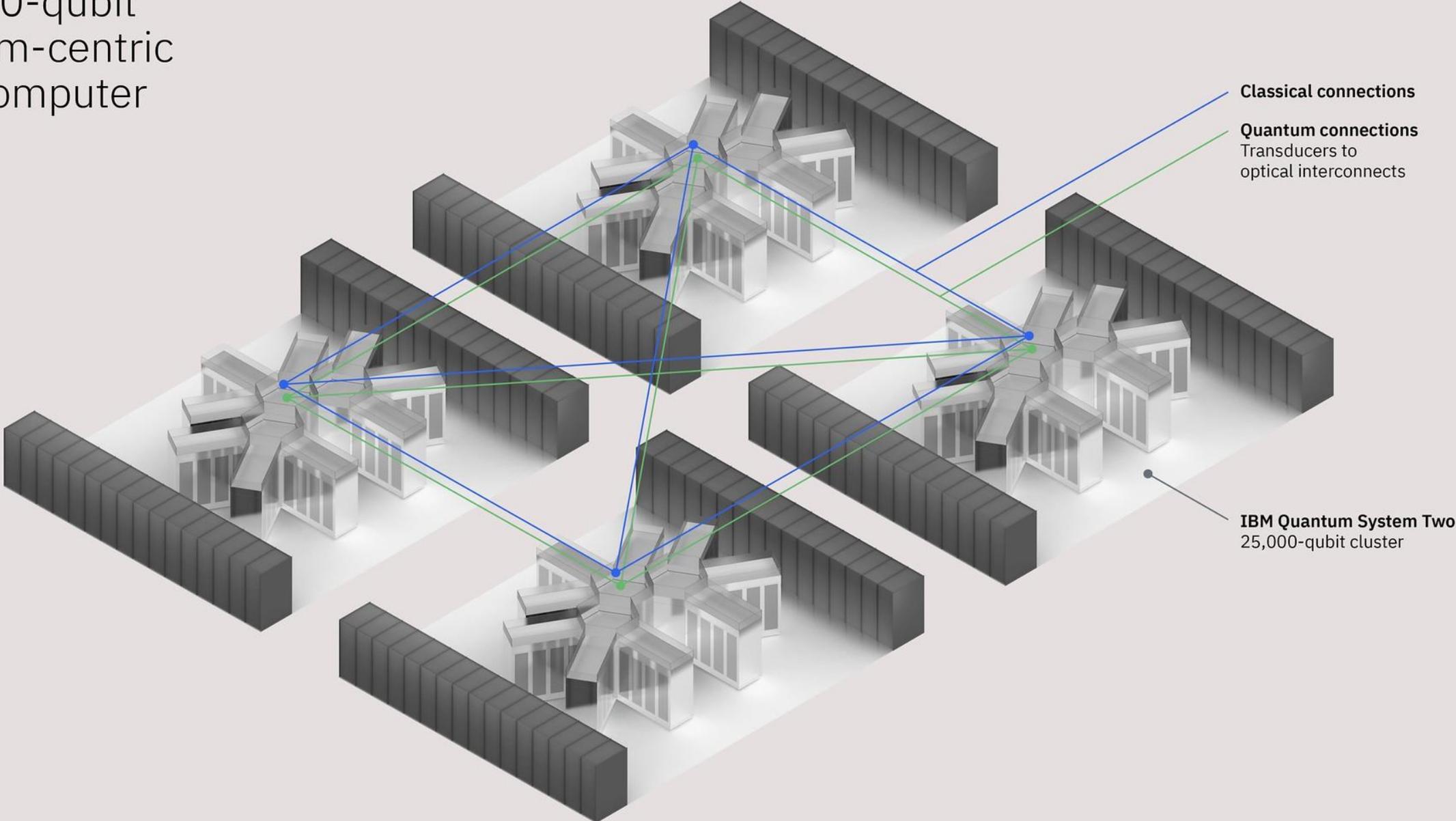
Lesson 9. Quantum Hardware

12. Development of other components

In addition to qubit scaling, achieving large-scale practical use of quantum computers requires technological innovations in other hardware components.
In this section, you will explore the technologies used in several components and the innovations needed for their advancement.

Schematic of superconducting quantum computer

Room Temperature Electronics:
RF source, DAC, ADC, ….

Dilution refrigerator

4K Low Noise Amplifier, HEMT

Filter, Attenuator

Superconducting Coax Cable

Circulator, Isolator, Directional Coupler etc.

Quantum Processor (Tsuru chip)

Quantum Limited Amplifier (JTWPA)
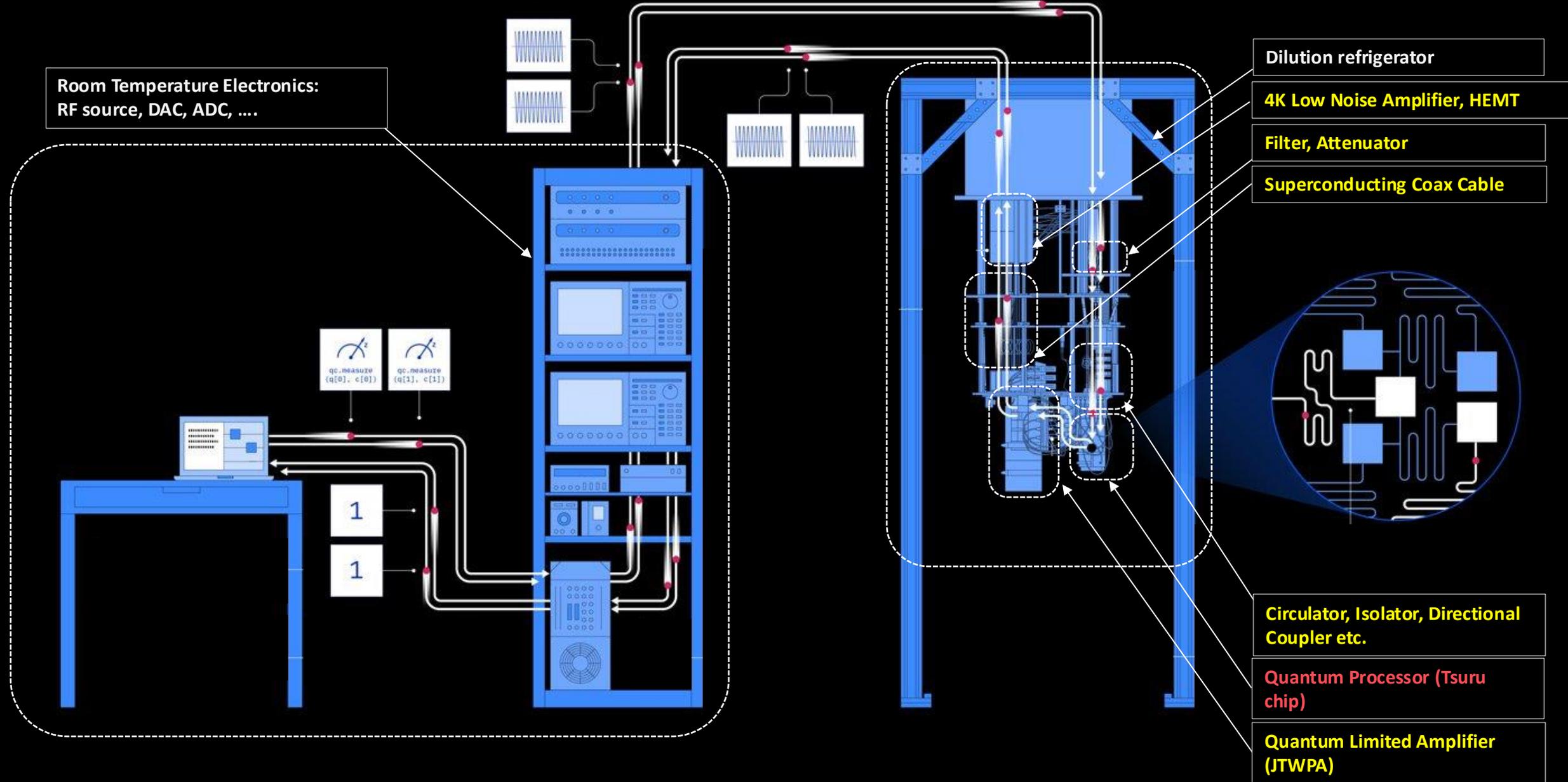
Quantum systems using coaxial cable wiring (and SMA connectors)

IBM

Google

N. Masluk et al., 2023 CEC/ICMC

Microwave components innovation is also crucial for further qubit scaling!

Components required for cryogenic microwave measurements

Wiring for microwave input/output
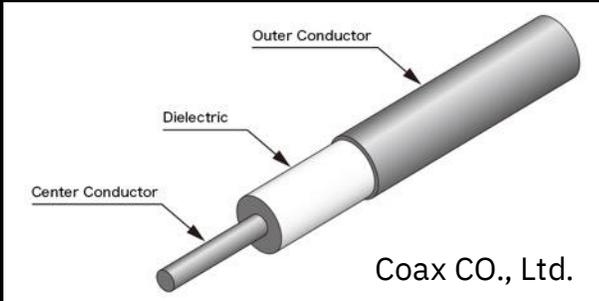- Low thermal conductivity
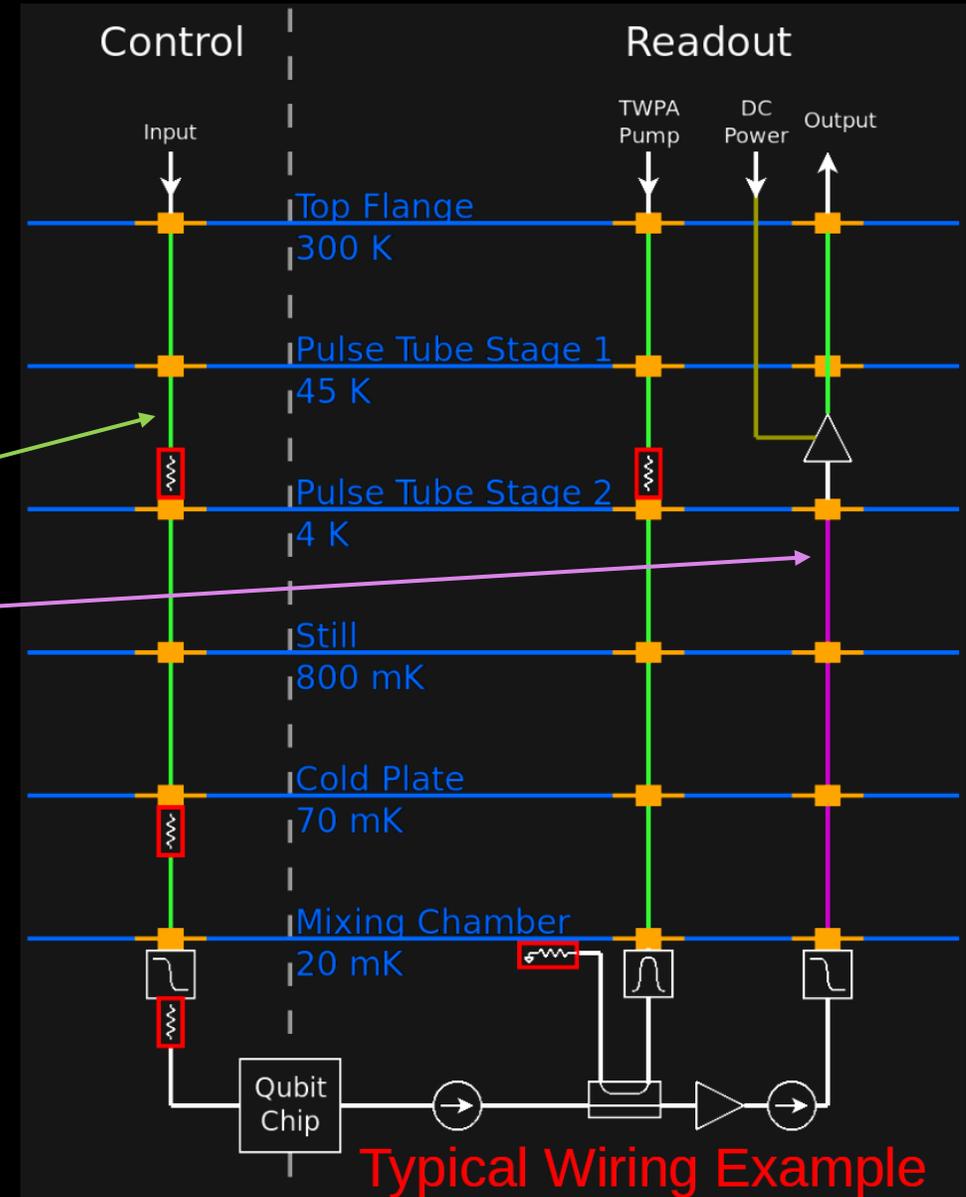- Low loss (for readout line)

Coax CO., Ltd.

Normal conducting coax
for control (e.g. CuNi)

Superconducting coax
for readout (e.g. NbTi)

Development of higher density
flex wiring is ongoing for more
qubit scaling

Typical Wiring Example
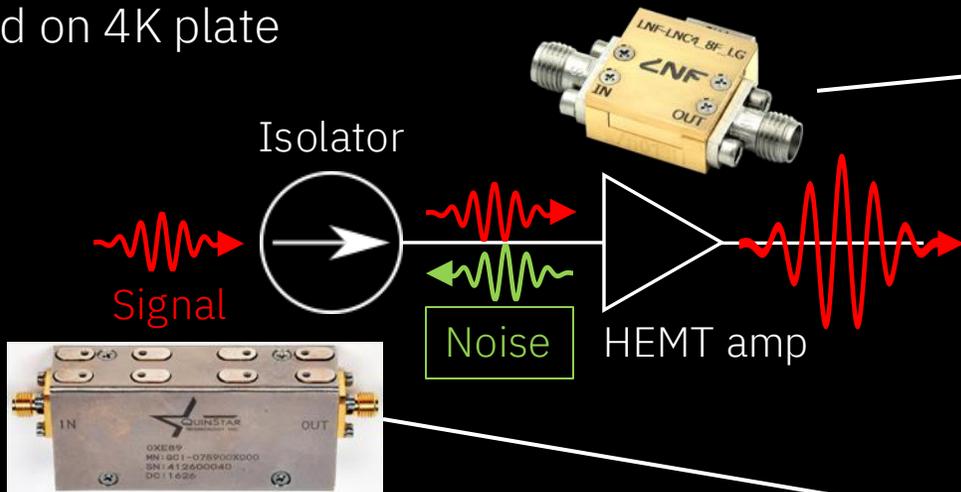
N. Masluk et al., 2023 CEC/ICMC

Components required for cryogenic microwave measurements

QLA (Quantum Limited Amplifier)
- Superconducting amplifiers (e.g. TWPA, JPC)
- Utilize nonlinearity of Josephson junctions

LNA (Low Noise Amplifier), HEMT
- III-V semiconductor amplifiers (e.g. InP, GaAs, etc.)
- Placed on 4K plate

Isolator

Signal

Noise   HEMT amp

Isolators
- Microwave irreciprocal directional device using magnetism
- Thermal noise isolation

Control   Readout

Input

TWPA Pump   DC Power   Output

Top Flange
300 K

Pulse Tube Stage 1
45 K

Pulse Tube Stage 2
4 K

Still
800 mK

Cold Plate
70 mK

Mixing Chamber
20 mK

Qubit Chip

Typical Wiring Example
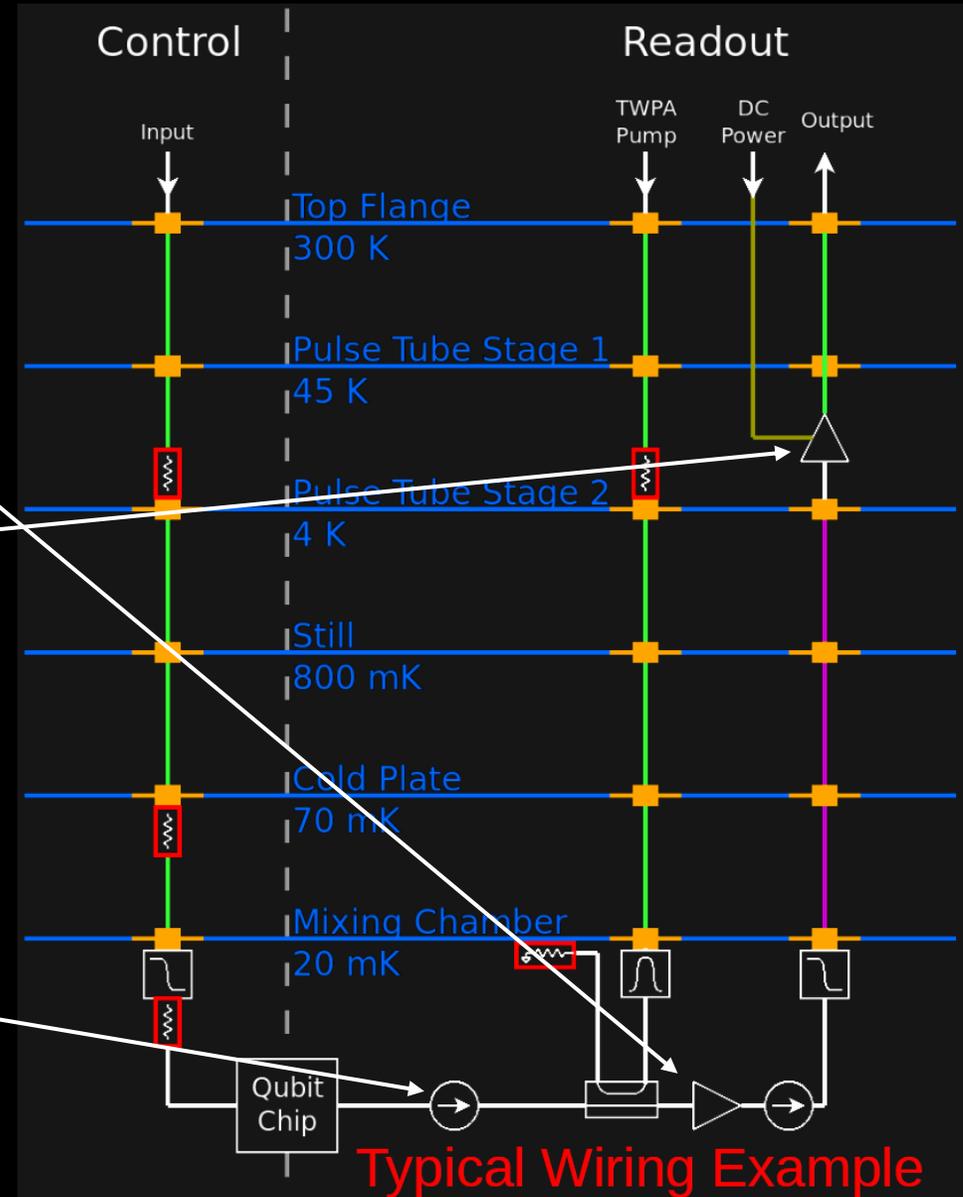
Quantum Hardware Test Center

- Key microwave component development for a robust supply chain
- Established at the University of Tokyo in 2022
- Testbed with IBM qubits

Summary

- Superconducting qubits are non-linear LC oscillators
- Qubit is controlled and measured by microwave drive pulse
- Qubit measurement is done by quantum non-demolition measurement
- Review of the ibm_kawasaki device map and calibration data
- Qubit scaling is done with modularity
- Development of cryogenic microwave components are also crucial for scaling

References

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- Nick Masluk, Cryogenic infrastructure for 400 qubits and beyond, Presented at the CEC/ICMC (2023).

Thank you