Quantum Hardware
- Part 2 and 3 -

2024/06/14

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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

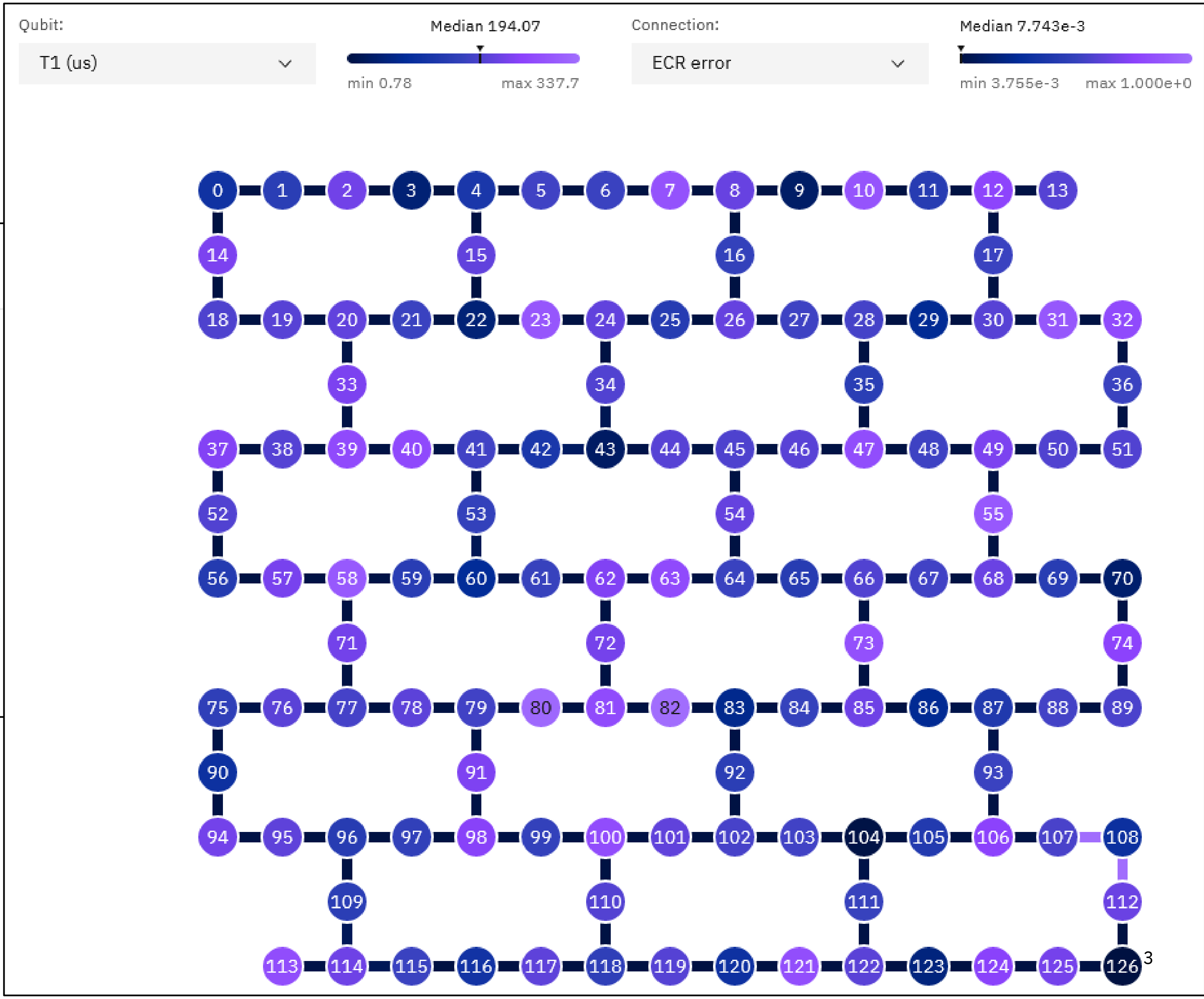
127
Qubits

2.4%
EPLG

5K
CLOPS

Status: ● Online
System region: us-east
Total pending jobs: 210 jobs
Processor type ⓘ: Eagle r3
Version: 2.1.28
Basis gates: ECR, ID, RZ, SX, X
Your instance usage: 0 jobs

Median ECR error: 7.653e-3
Median SX error: 2.340e-4
Median readout error: 1.080e-2
Median T1: 183.48 us
Median T2: 138.56 us



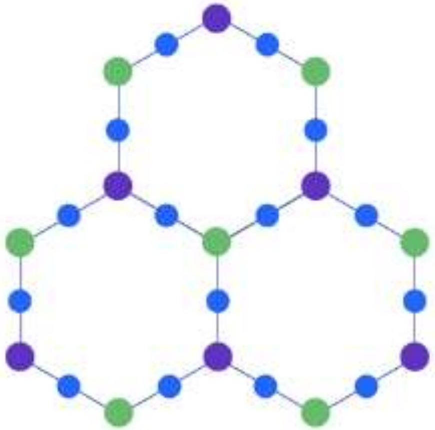
Qubit: T1 (us)

Connection: ECR error

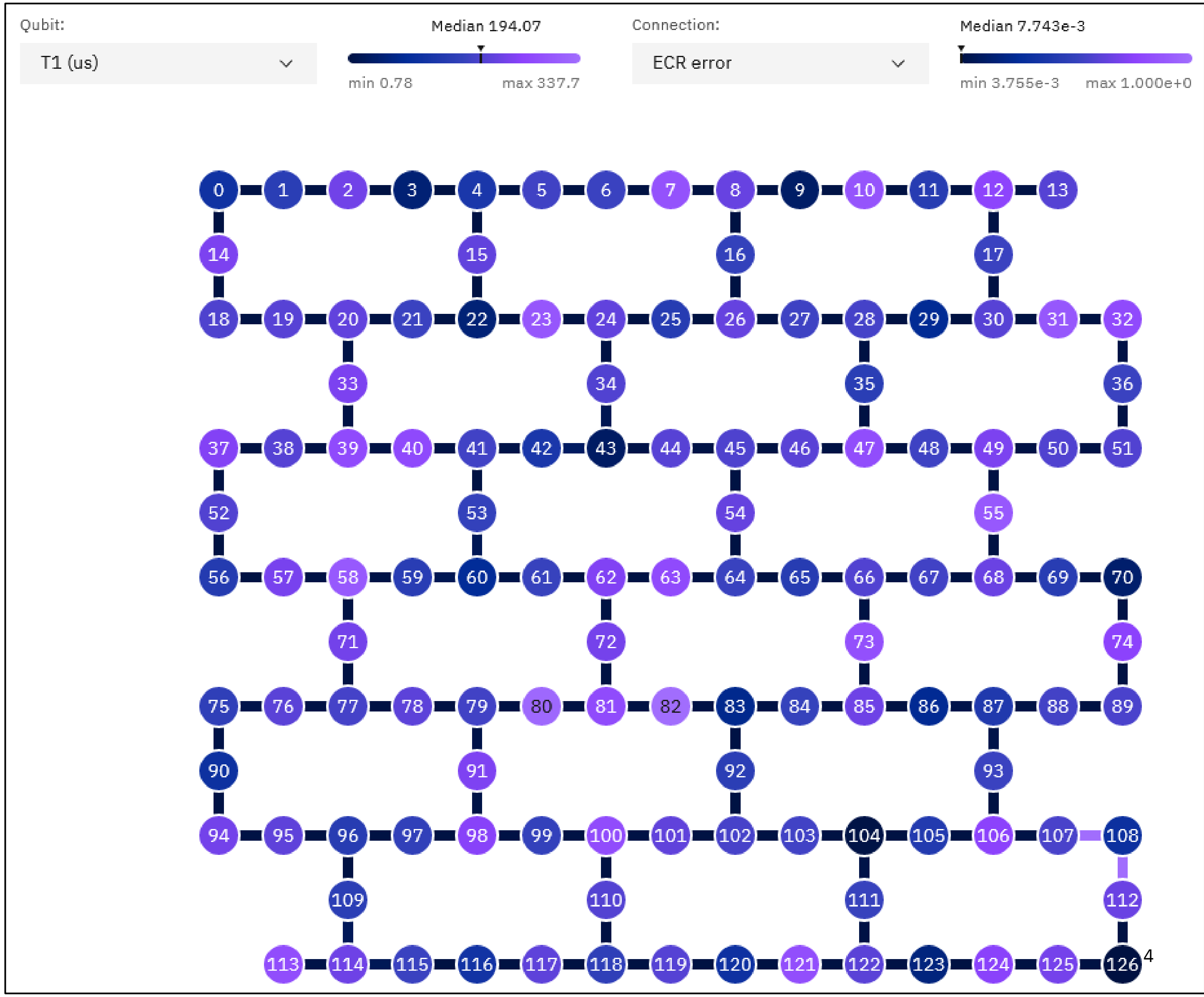
Device map – heavy-hex lattice

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



Qubit: T1 (us)

Median 194.07

min 0.78

max 337.7

Connection: ECR error

Median 7.743e-3

min 3.755e-3

max 1.000e+0

Cf. New error correction codes
High-threshold and low-overhead fault-tolerant quantum memory, Sergey Bravyi et al., 2023

Device map and calibration data

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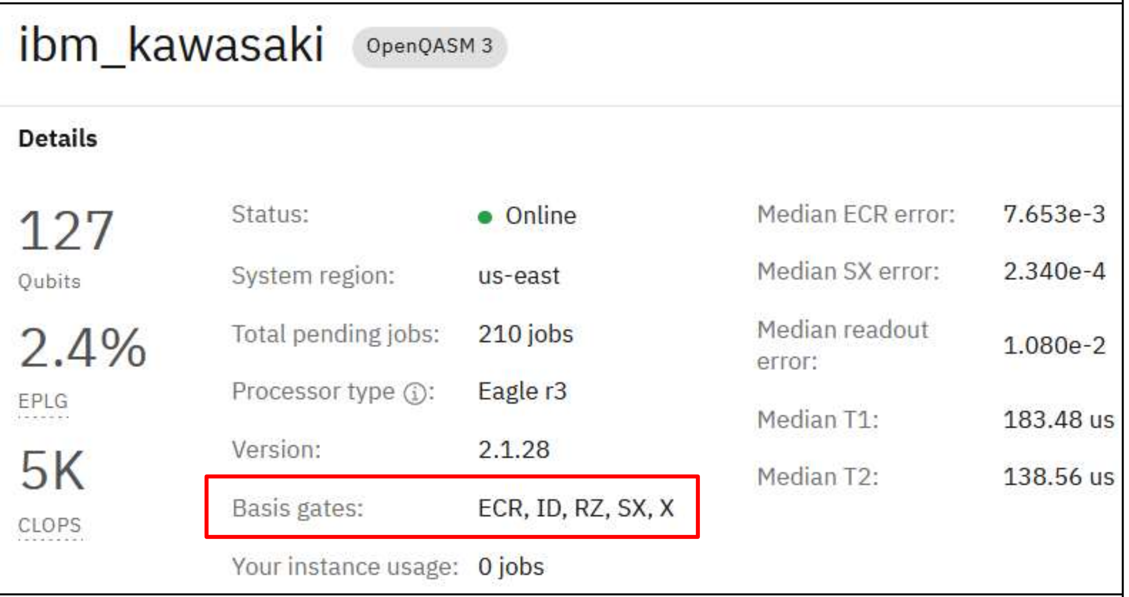

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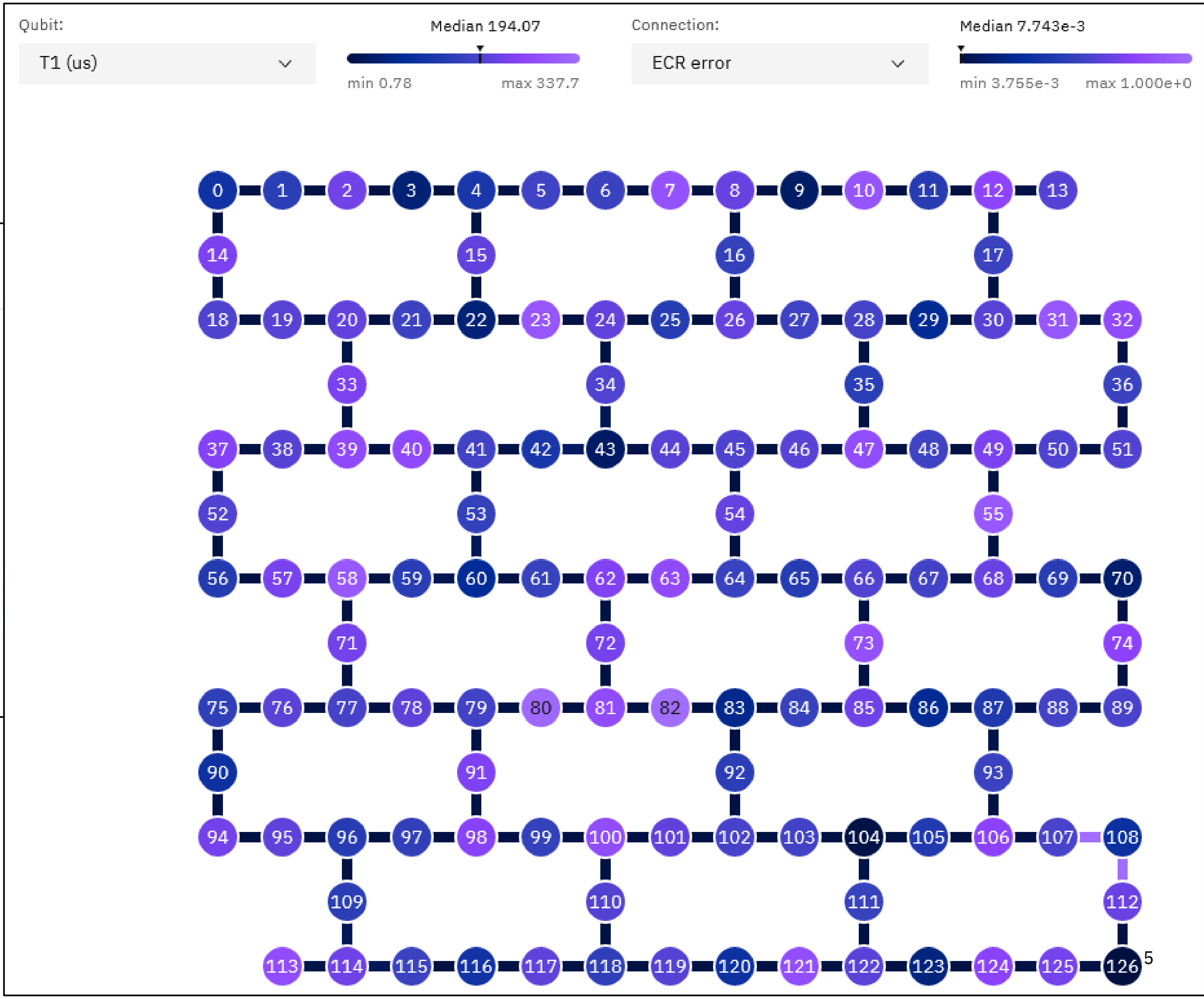

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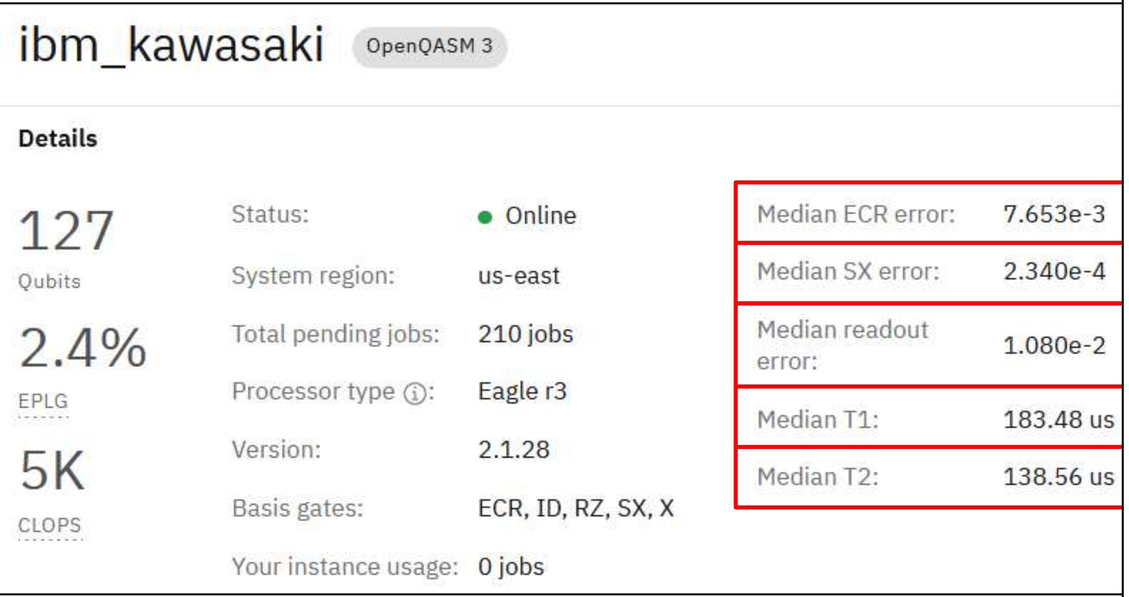
Basis gates

- 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



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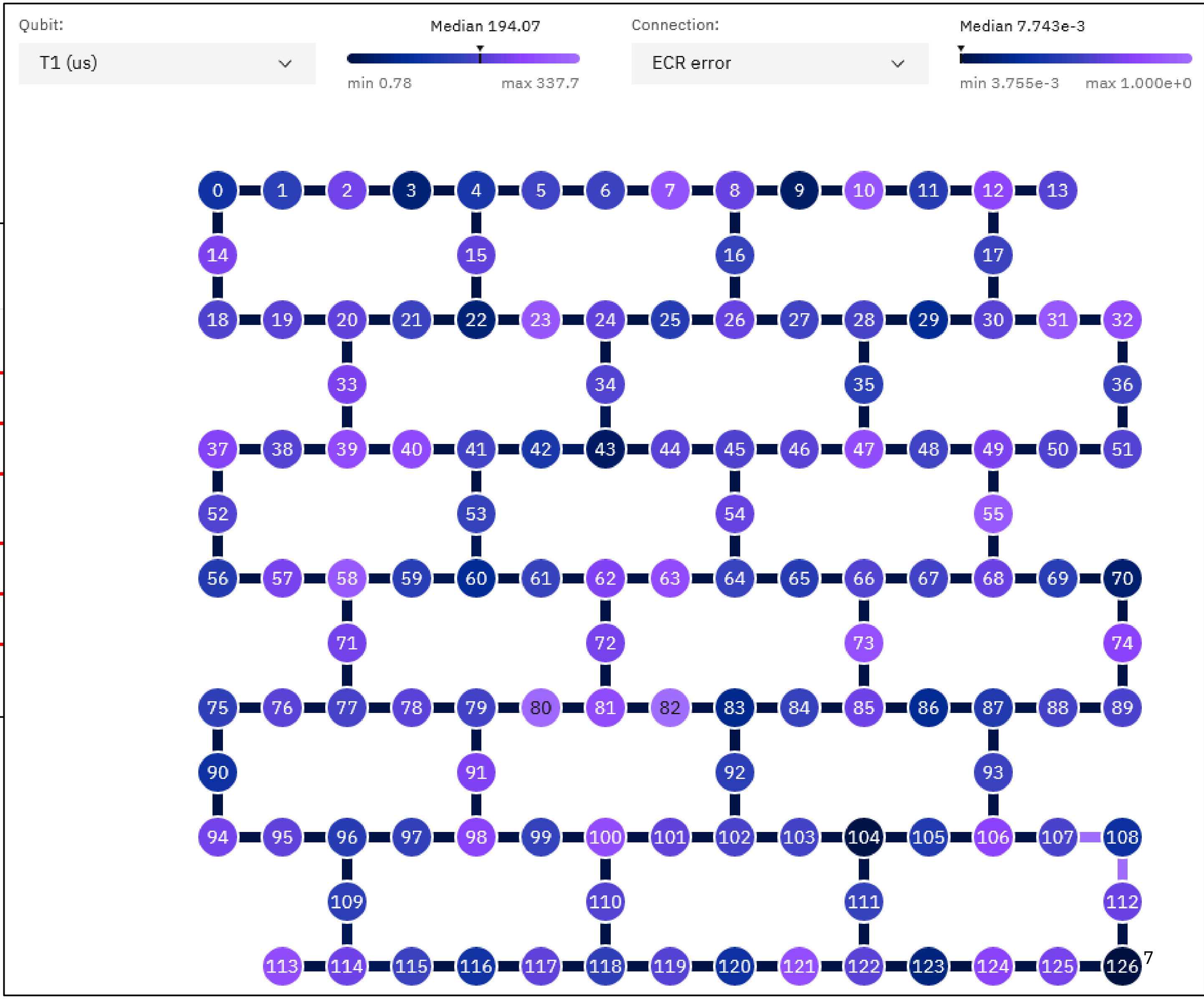

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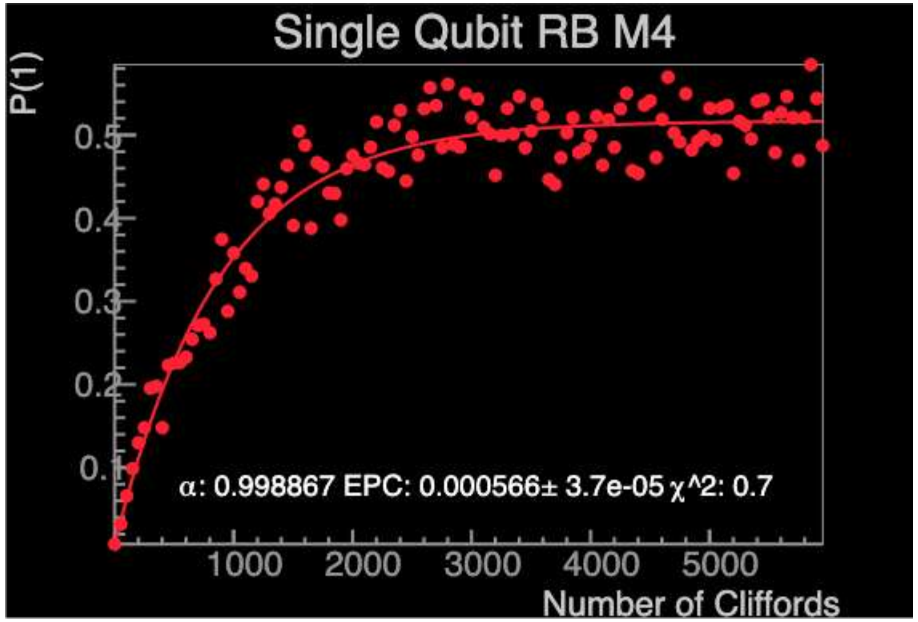
Gate error – Randomized benchmarking

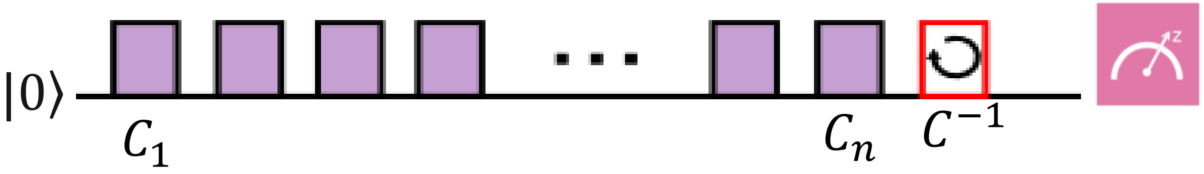


Randomized Benchmarking

- 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



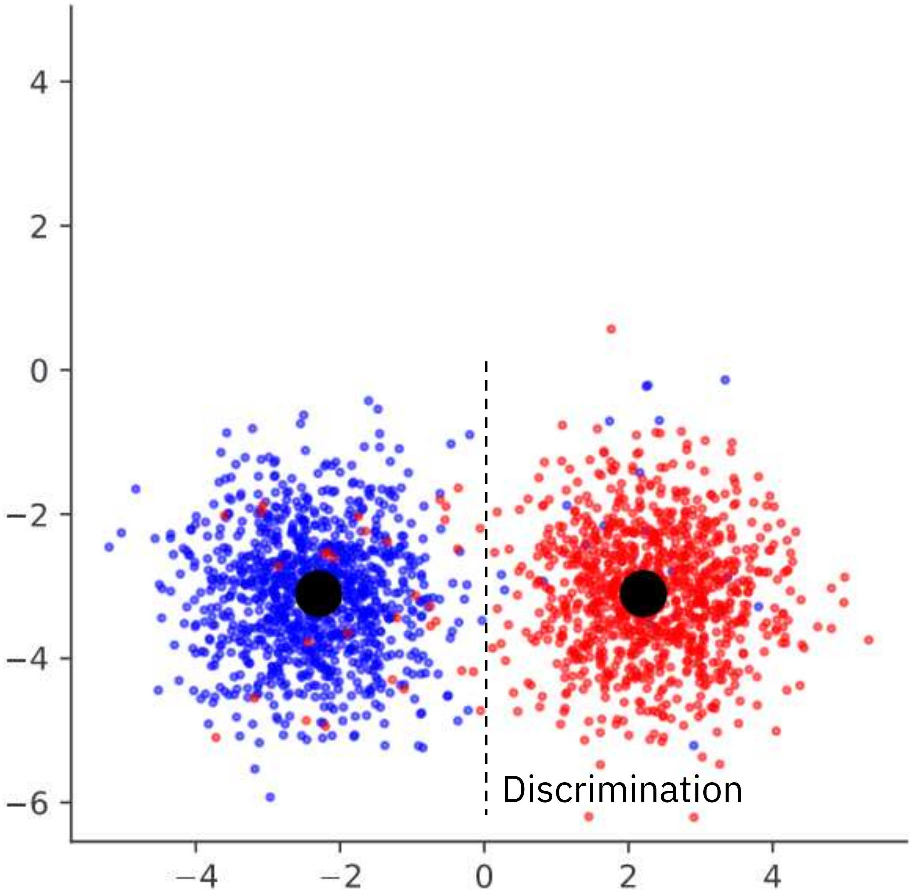
Magesan et al., PRL 106, 180504 (2011)

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

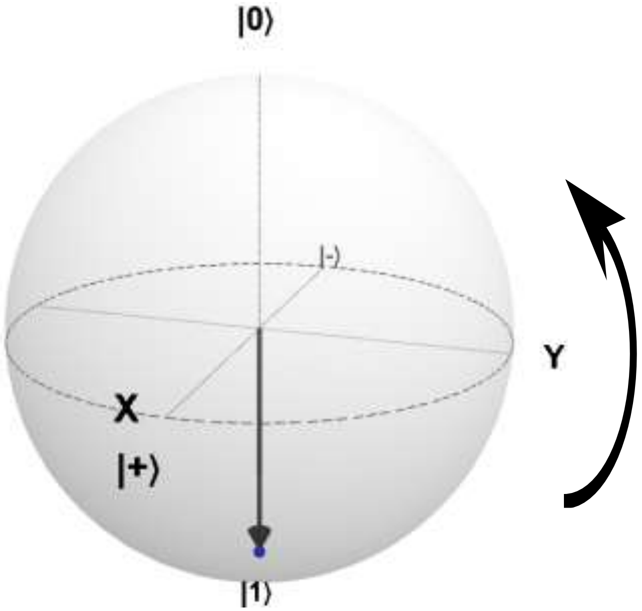


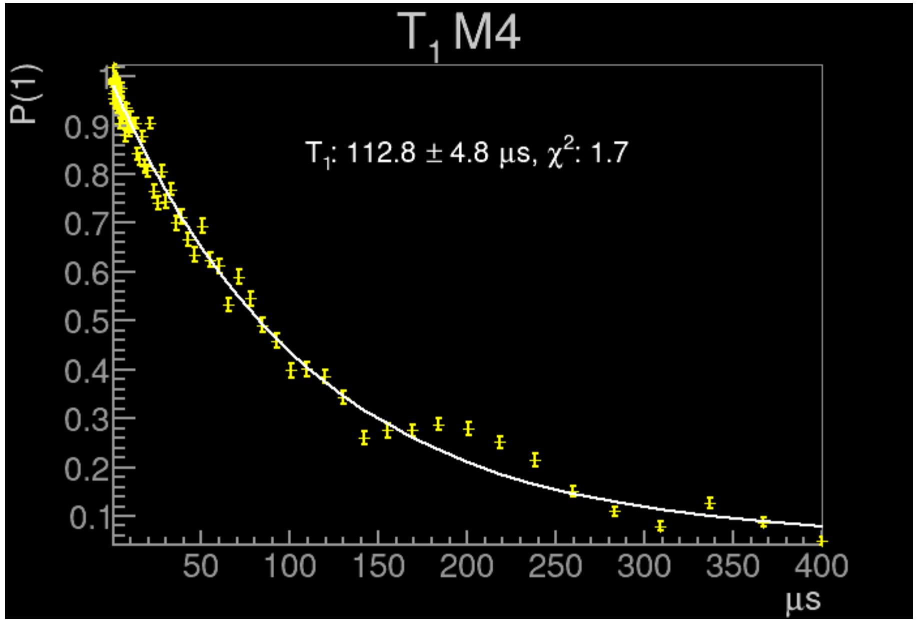
Relaxation time (T1): amplitude damping

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





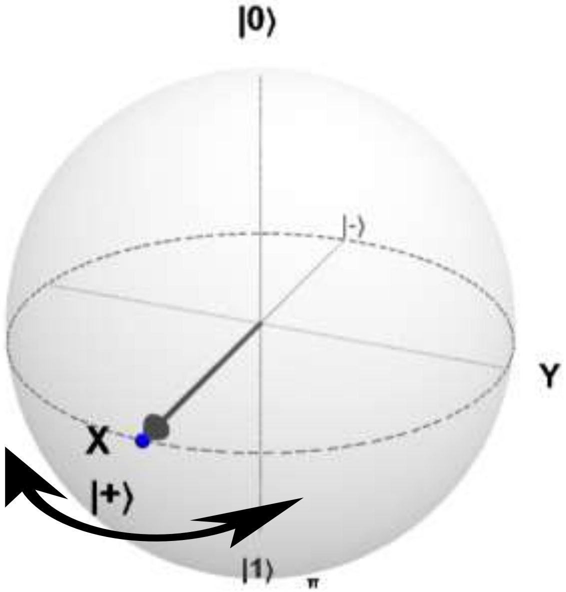
Decoherence time (T2): phase damping

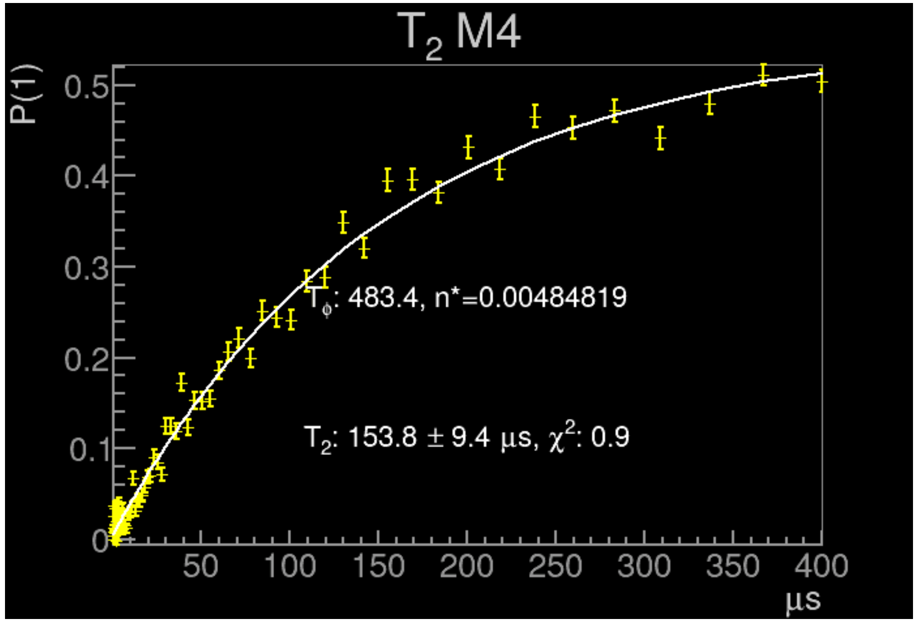
Fluctuations in energy levels due to thermal broadening or magnetic noise

- 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

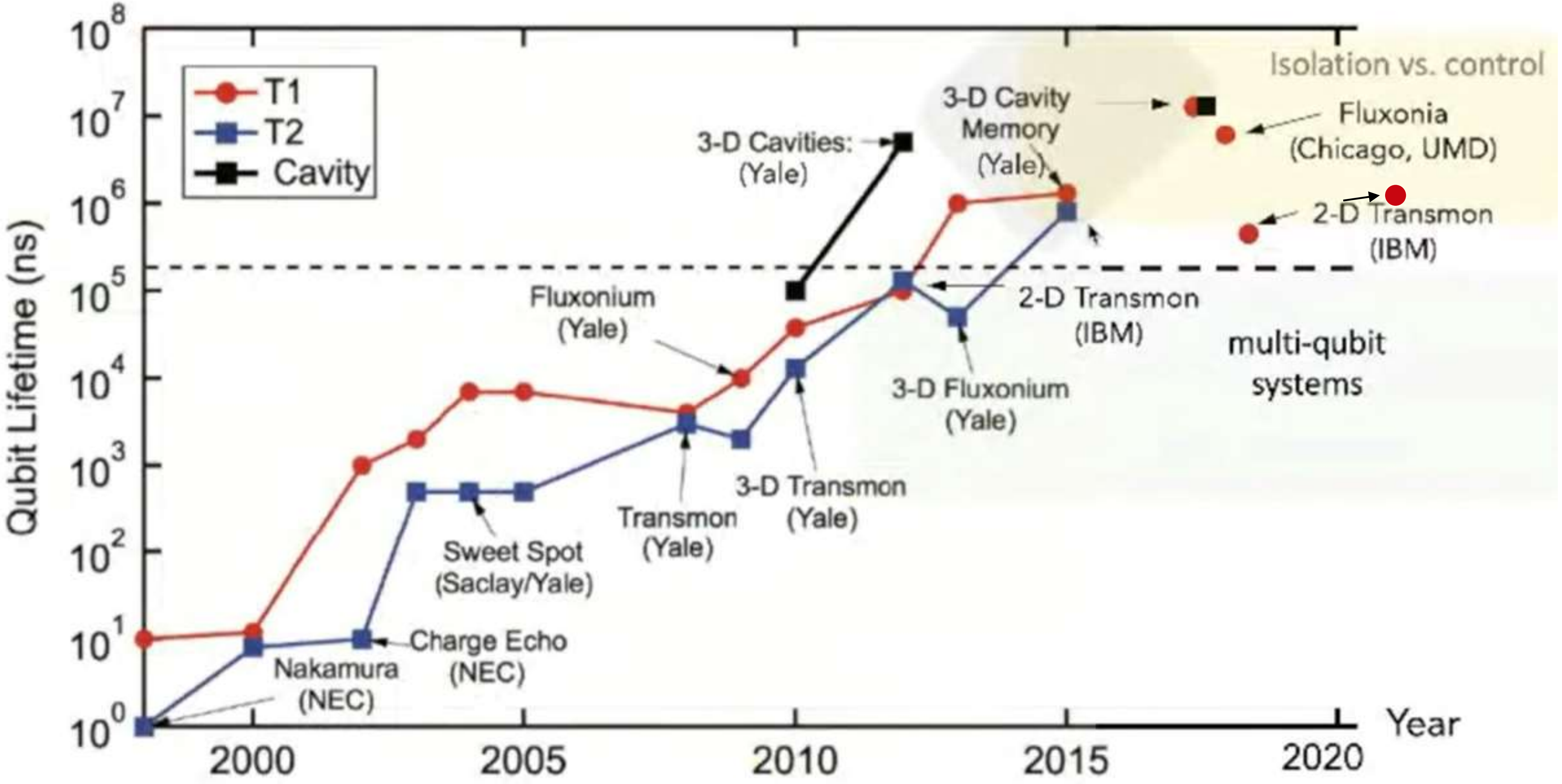


Image made by Devoret and Schoelkopf (2013), updated by Reagor (2015), and updated by Minev (2020), and updated

Hands-on

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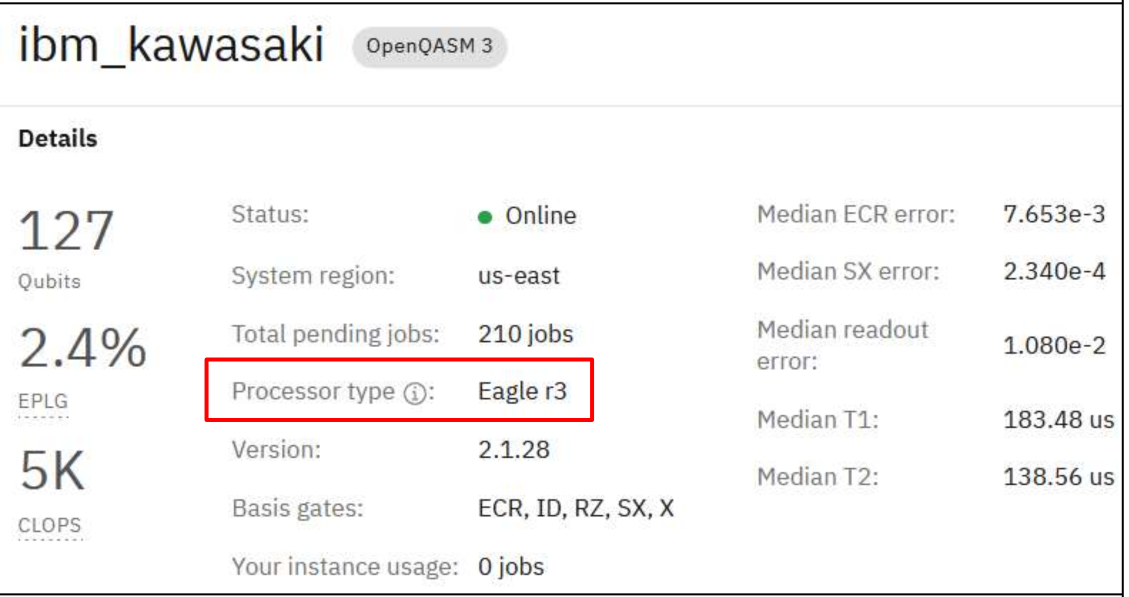
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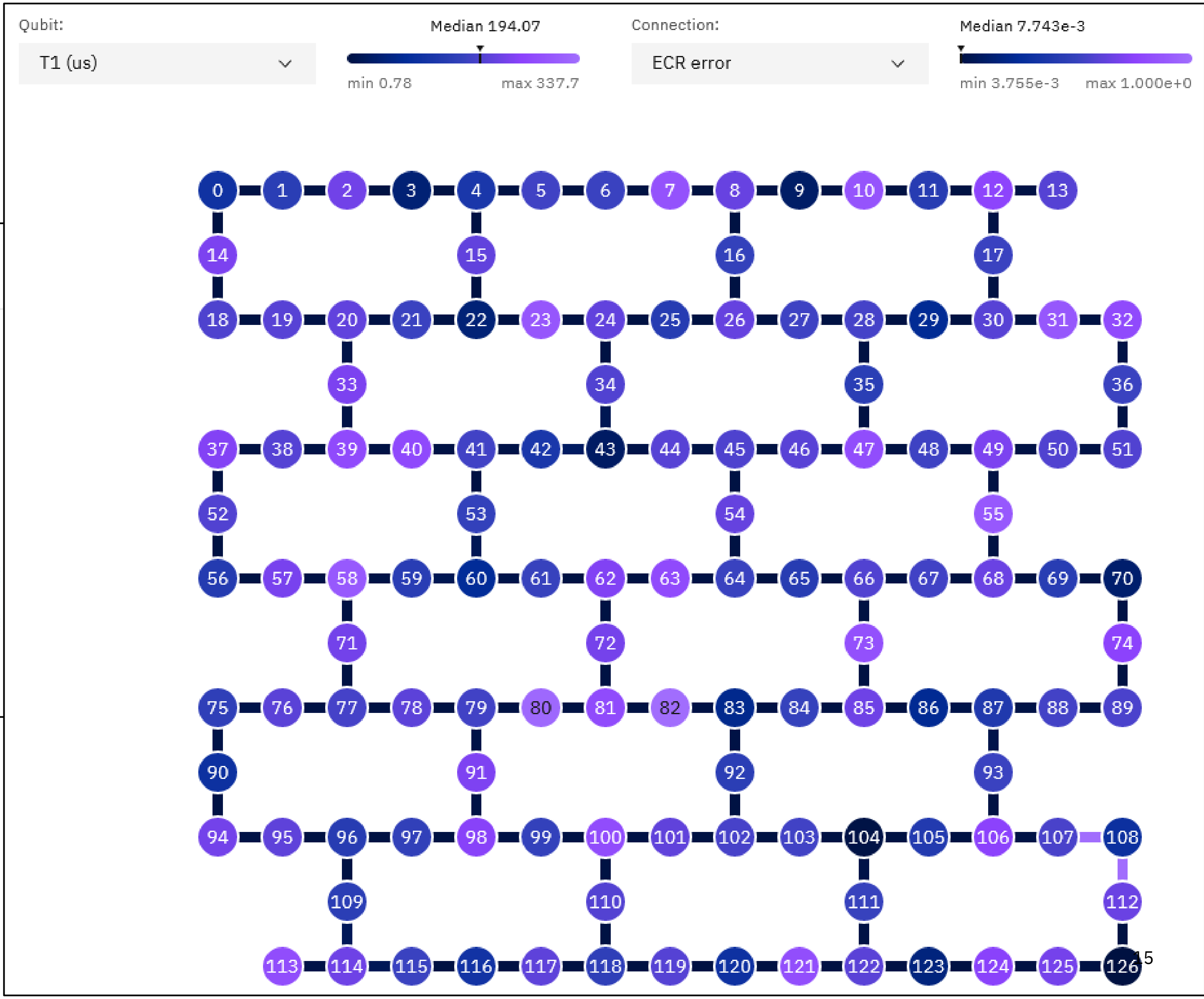
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2016
2017
2018
→ 2019

2016
2017
2018
2019
→ 2020

2016

2017

2018

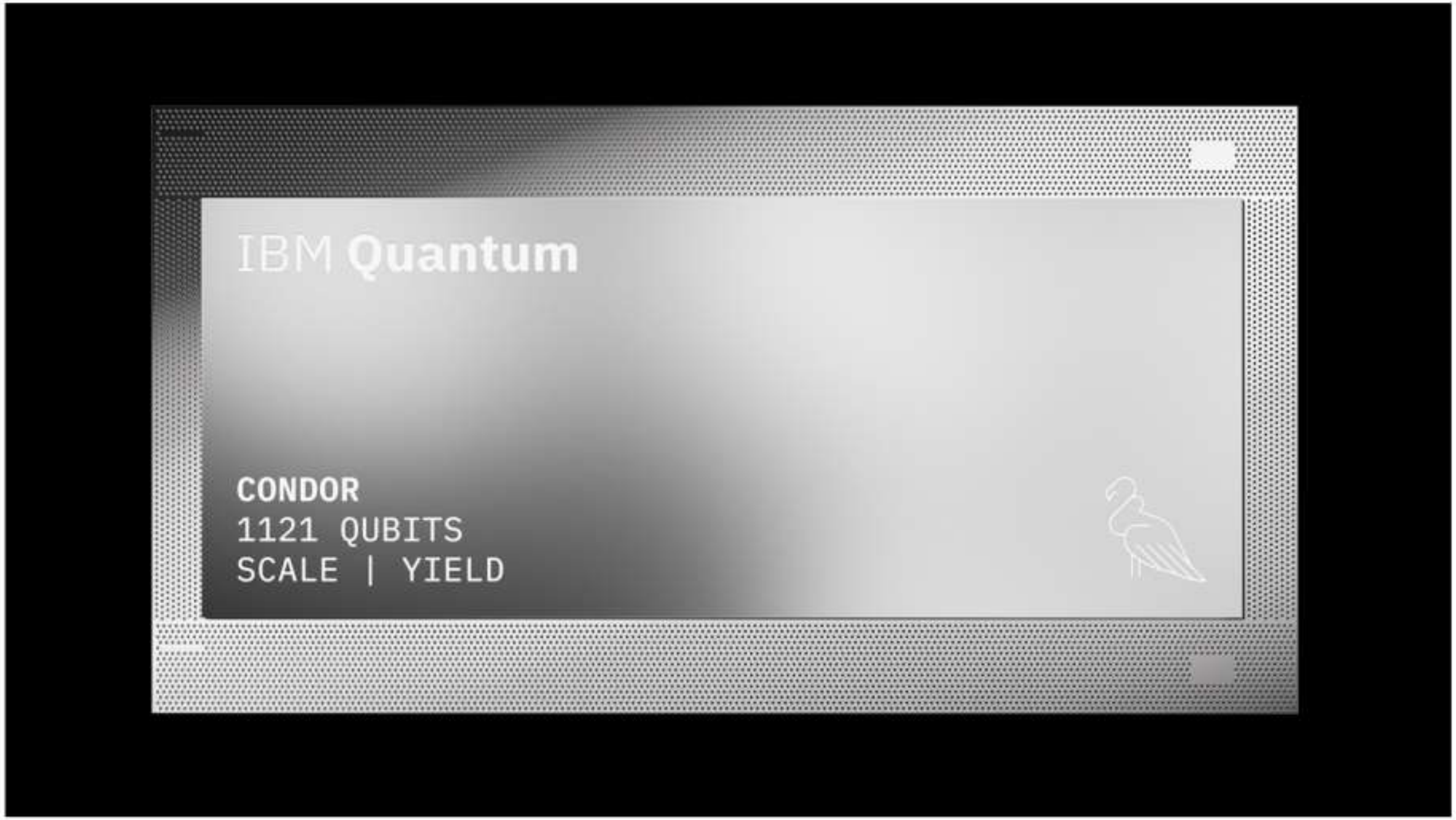
2019

2020

→ 2021

2016
2017
2018
2019
2020
2021
→ 2022

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

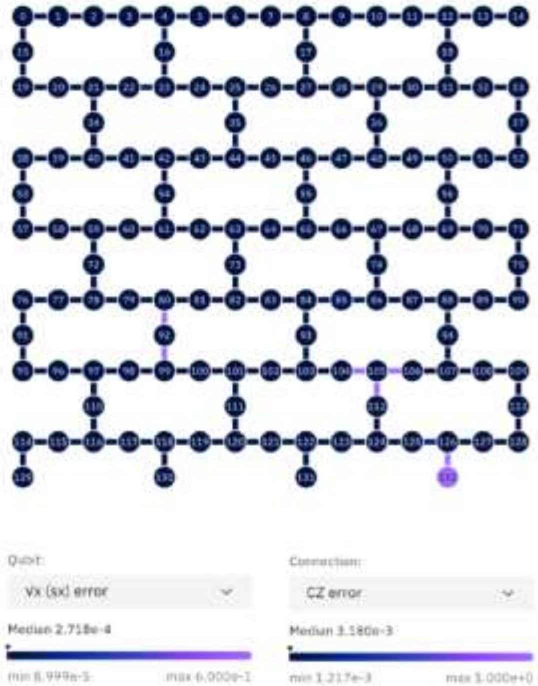
Introducing

Heron

133 qubit systems

Tunable coupler architecture

ibm_montecarlo

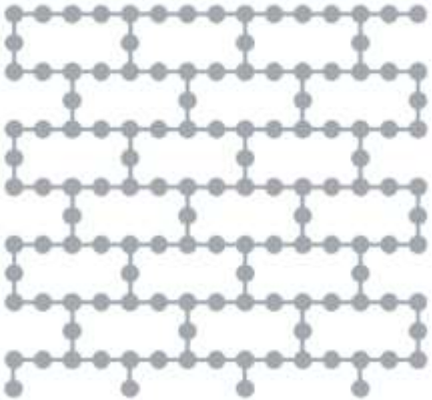


Median 2.718e-4
min 8.999e-5
max 6.000e-1

Median 3.180e-3
min 1.217e-3
max 1.000e+0

	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



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

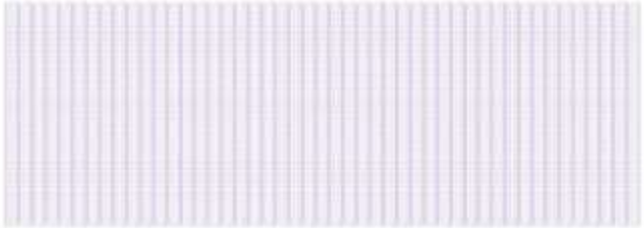
100 qubit circuit

Heron R1

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

9300 gates *(estimate)*

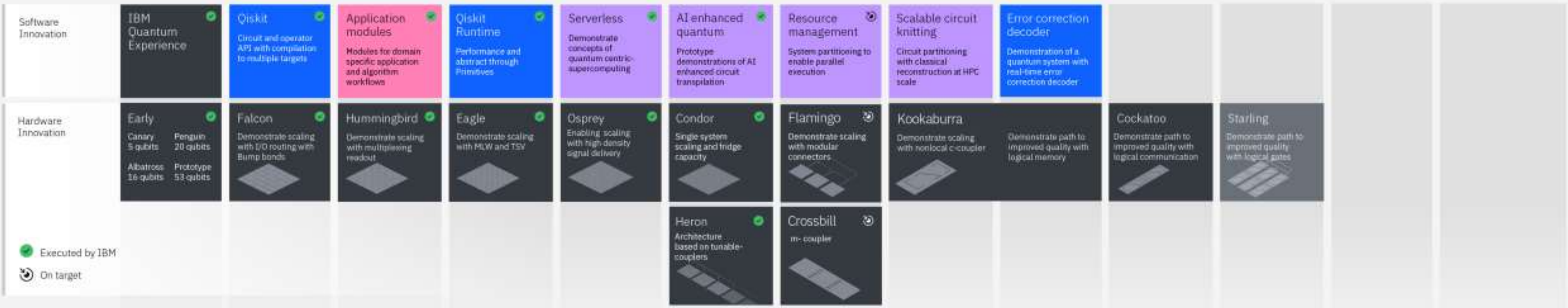
100 qubit circuit



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) ◎ Error Mitigation 5k gatos 133 qubits Classical modular 133x3 = 399 qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (10K) Error Mitigation 10k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (15K) Error Mitigation 15k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Starling (100M) Error correction 100M gates 200 qubits Error corrected modularity	Blue Jay (1B) Error correction 1B gates 2000 qubits Error corrected modularity
	Early ✓ Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon ✓ Benchmarking 27 qubits		Eagle ✓ Benchmarking 127 qubits								

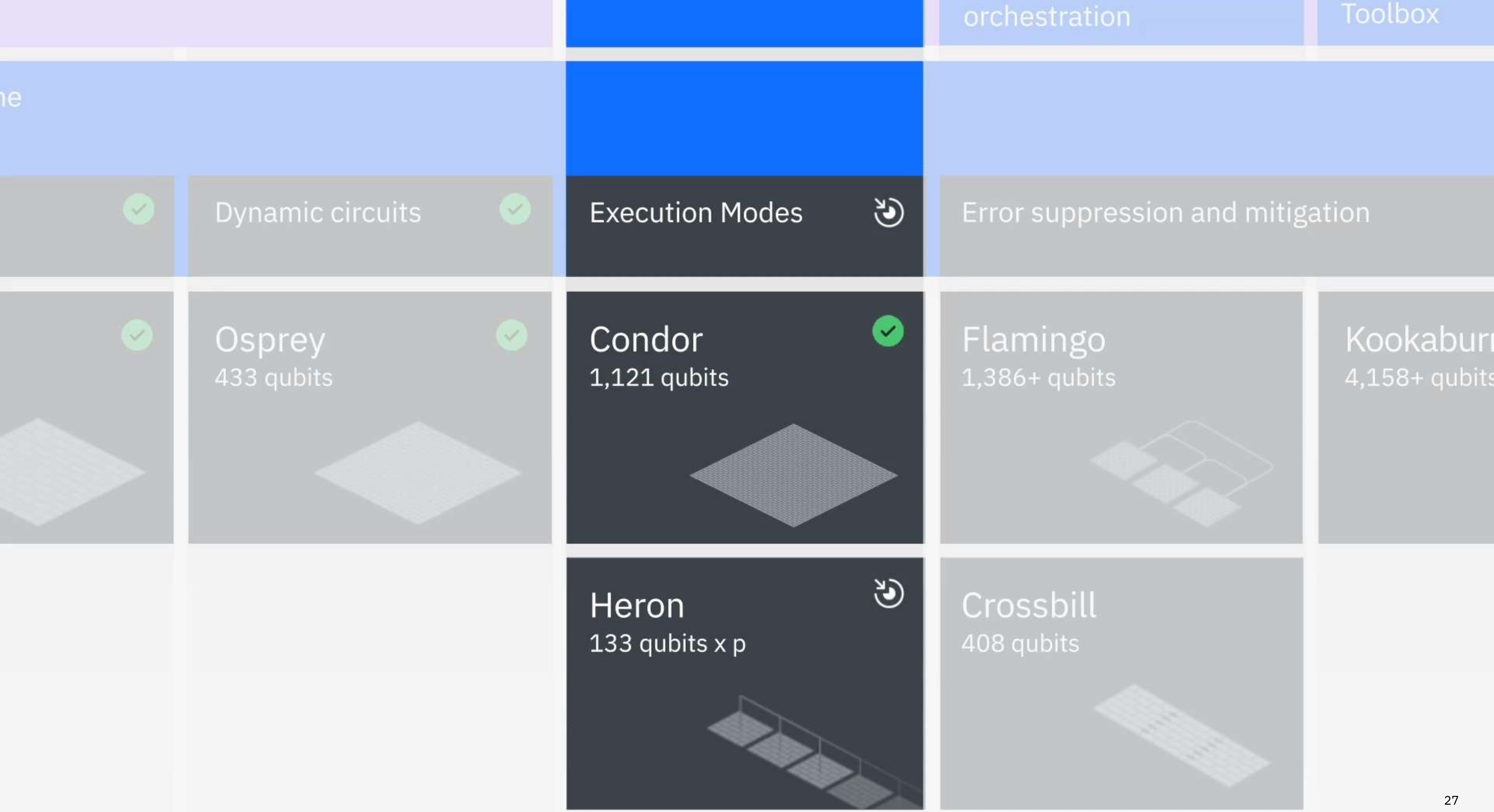
Innovation Roadmap



Software Innovation	IBM Quantum Experience ✓	Qiskit ✓ Circuit and operator API with compilation to multiple targets	Application modules ✓ Modules for domain specific application and algorithm workflows	Qiskit Runtime ✓ Performance and abstract through Primitives	Serverless ✓ Demonstrate concepts of quantum centric-supercomputing	AI enhanced quantum ✓ Prototype demonstrations of AI enhanced circuit transpilation	Resource management ◎ System partitioning to enable parallel execution	Scalable circuit knitting Circuit partitioning with classical reconstruction at HPC scale	Error correction decoder Demonstration of a quantum system with real-time error correction decoder				
Hardware Innovation	Early ✓ Canary 5 qubits Penguin 20 qubits Albatross 16 qubits Prototype 53 qubits	Falcon ✓ Demonstrate scaling with I/O routing with Bump bonds	Hummingbird ✓ Demonstrate scaling with multiplexing readout	Eagle ✓ Demonstrate scaling with MLW and TSV	Osprey ✓ Enabling scaling with high density signal delivery	Condor ✓ Single system scaling and fridge capacity	Flamingo ◎ Demonstrate scaling with modular connectors	Kookaburra Demonstrate scaling with nonlocal c-coupler	Demonstrate path to improved quality with logical memory	Cockatoo Demonstrate path to improved quality with logical communication	Starling Demonstrate path to improved quality with logical gates		
						Heron ✓ Architecture based on tunable-couplers	Crossbill ◎ m- coupler						

✓ Executed by IBM

◎ On target



orchestration

Toolbox

ne

✓

Dynamic circuits ✓

Execution Modes

Error suppression and mitigation

✓

Osprey ✓
433 qubits

Condor ✓
1,121 qubits

Flamingo
1,386+ qubits

Kookabur
4,158+ qubit

Heron
133 qubits x p

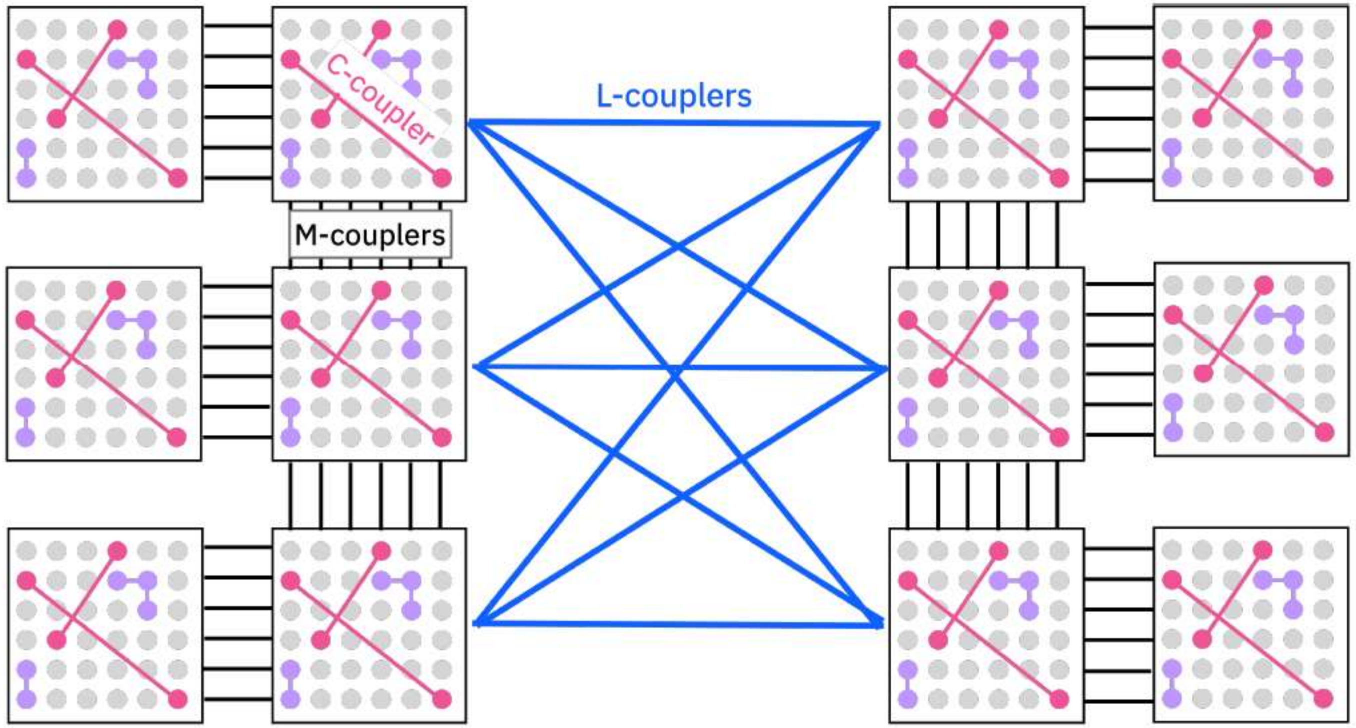
Crossbill
408 qubits

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

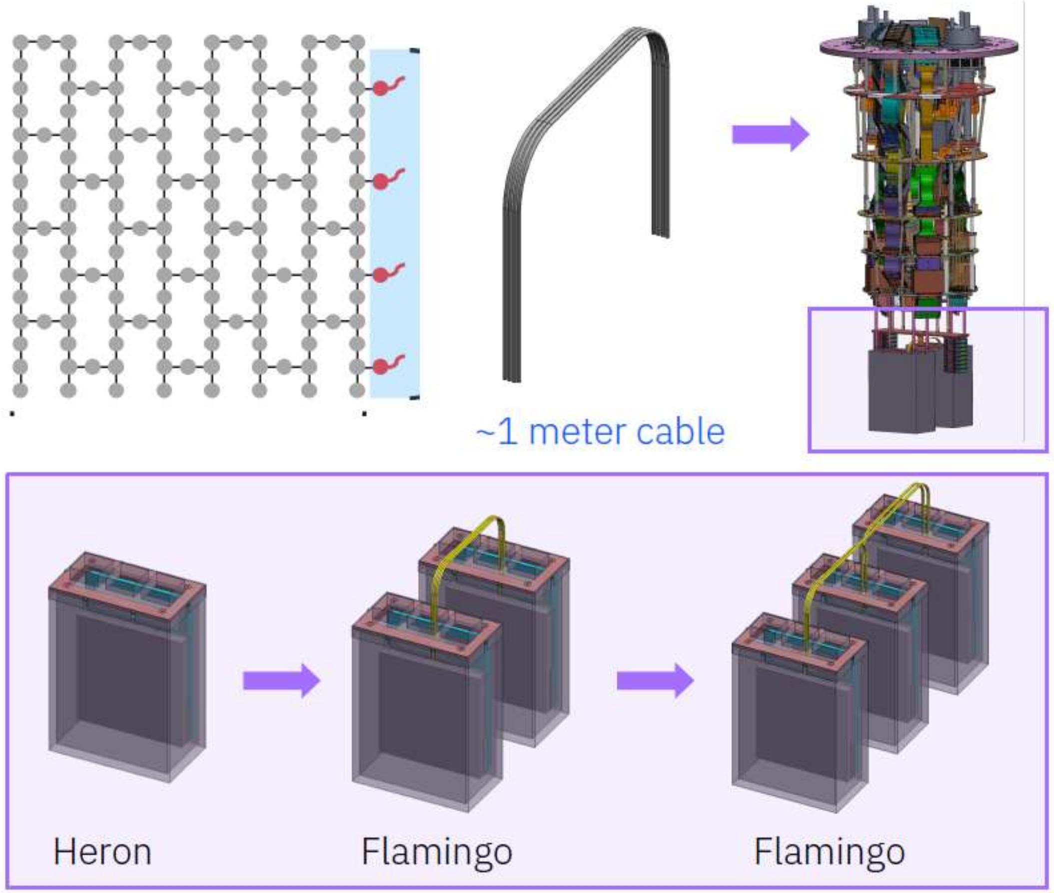
M-coupler enables joining multiple short-range chip-to-chip connections



Extending Heron platform through modular coupling

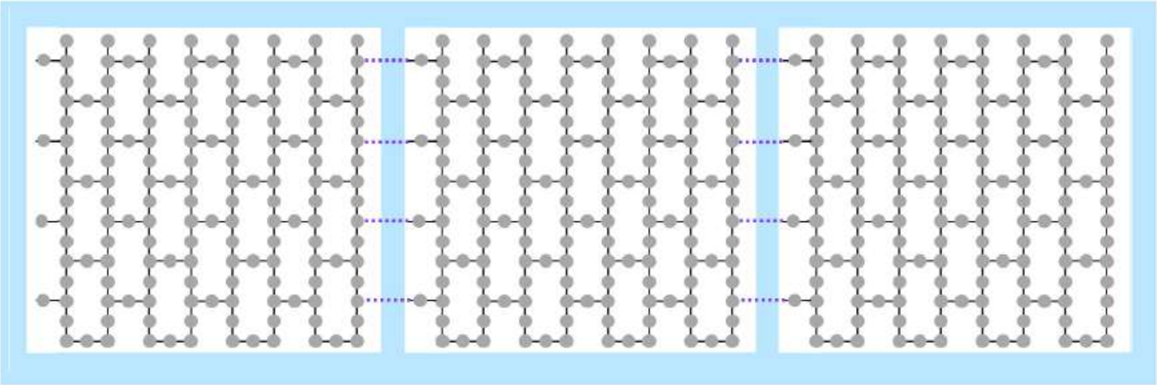
Flamingo

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

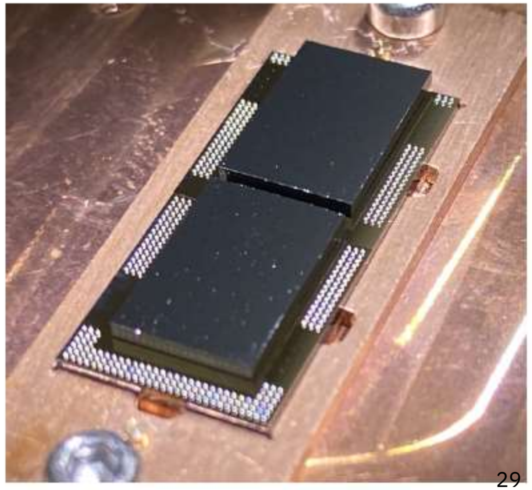


Crossbill

Heron platform + *m-coupler bus* + *m-coupler packaging*



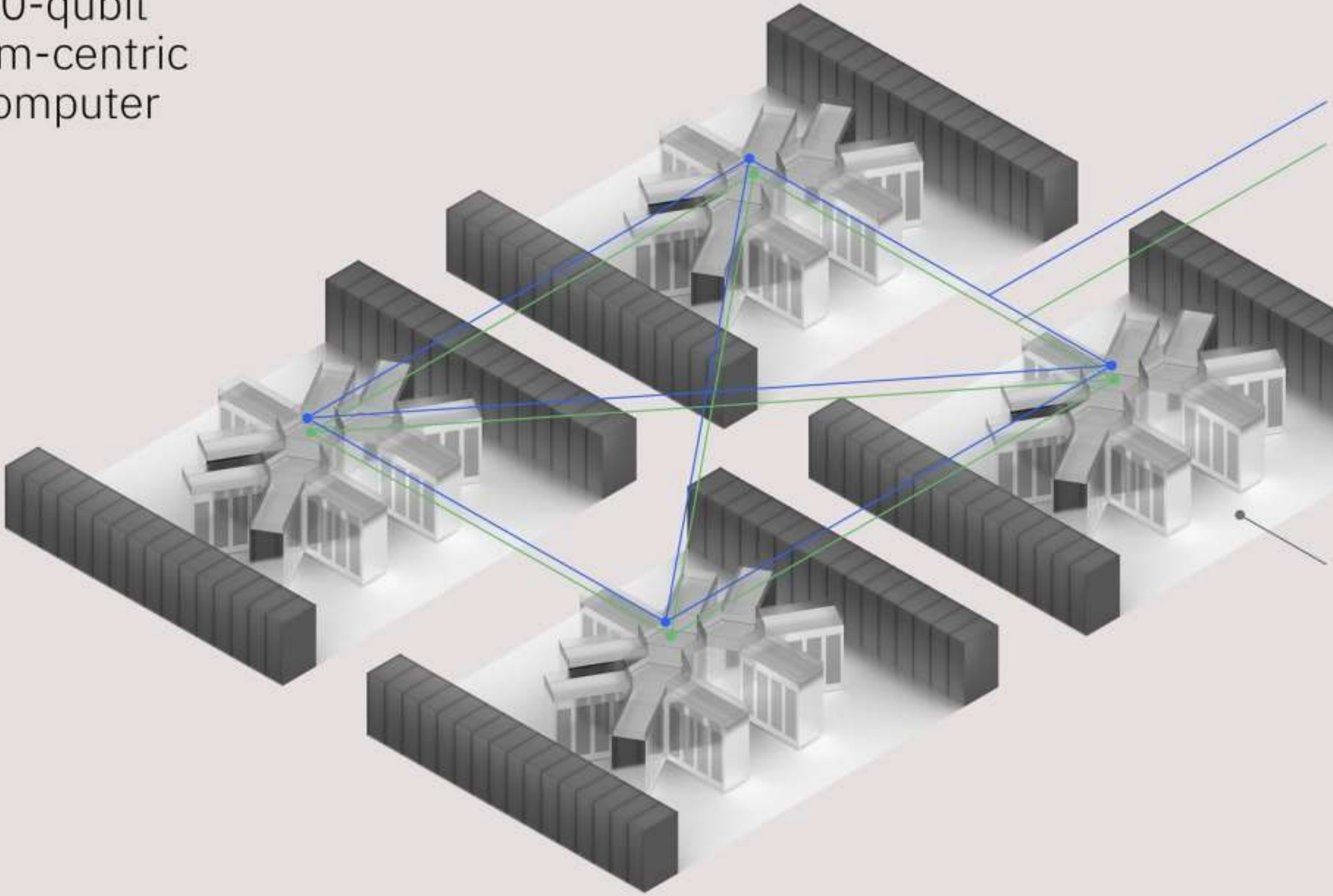
Qubit chiplets within
a multi-chip module



100,000-qubit quantum-centric supercomputer

—

2033



Classical connections

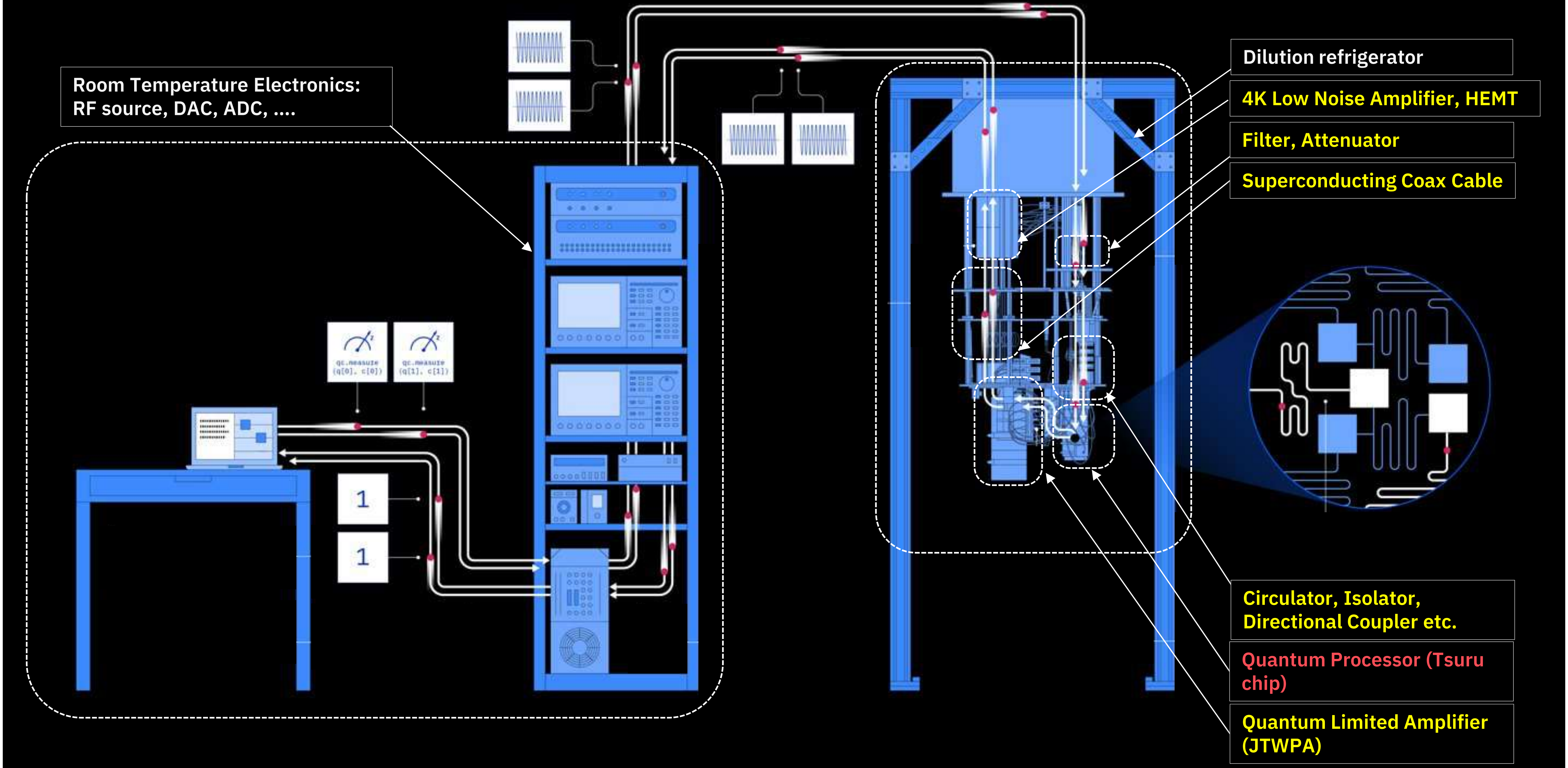
Quantum connections
Transducers to
optical interconnects

IBM Quantum System Two
25,000-qubit cluster

IBM **Quantum**

Schematic of superconducting quantum computer

IBM **Quantum**



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

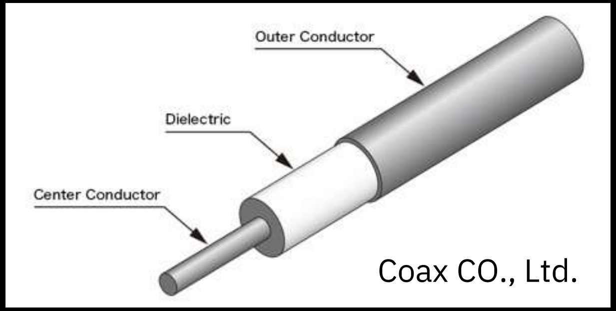
Google

N. Masluk et al., 2023 CEC/ICMC

Microwave components innovation is also crucial for further qubit scaling!

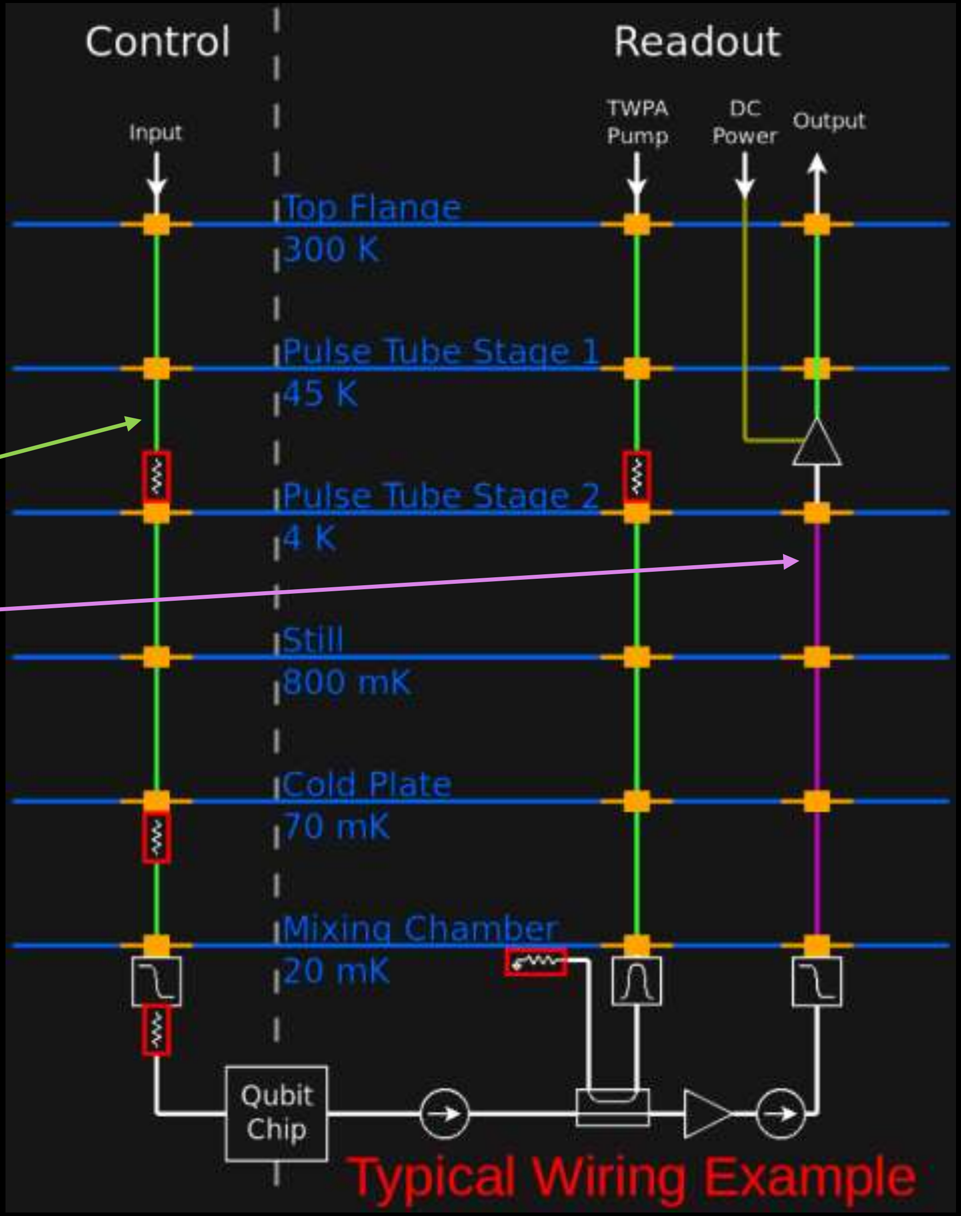
Components required for cryogenic microwave measurements

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



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

N. Masluk et al., 2023 CEC/ICMC

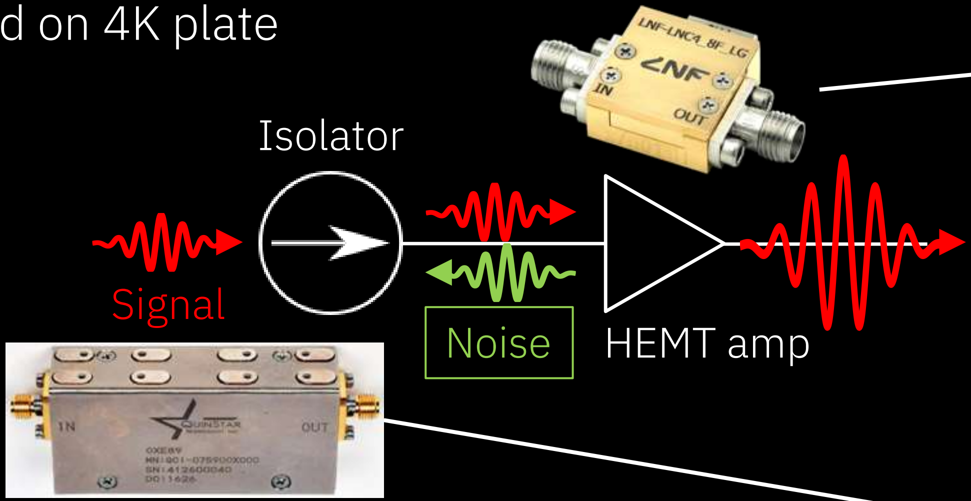
Components required for cryogenic microwave measurements

QLA (Quantum Limited Amplifier)

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

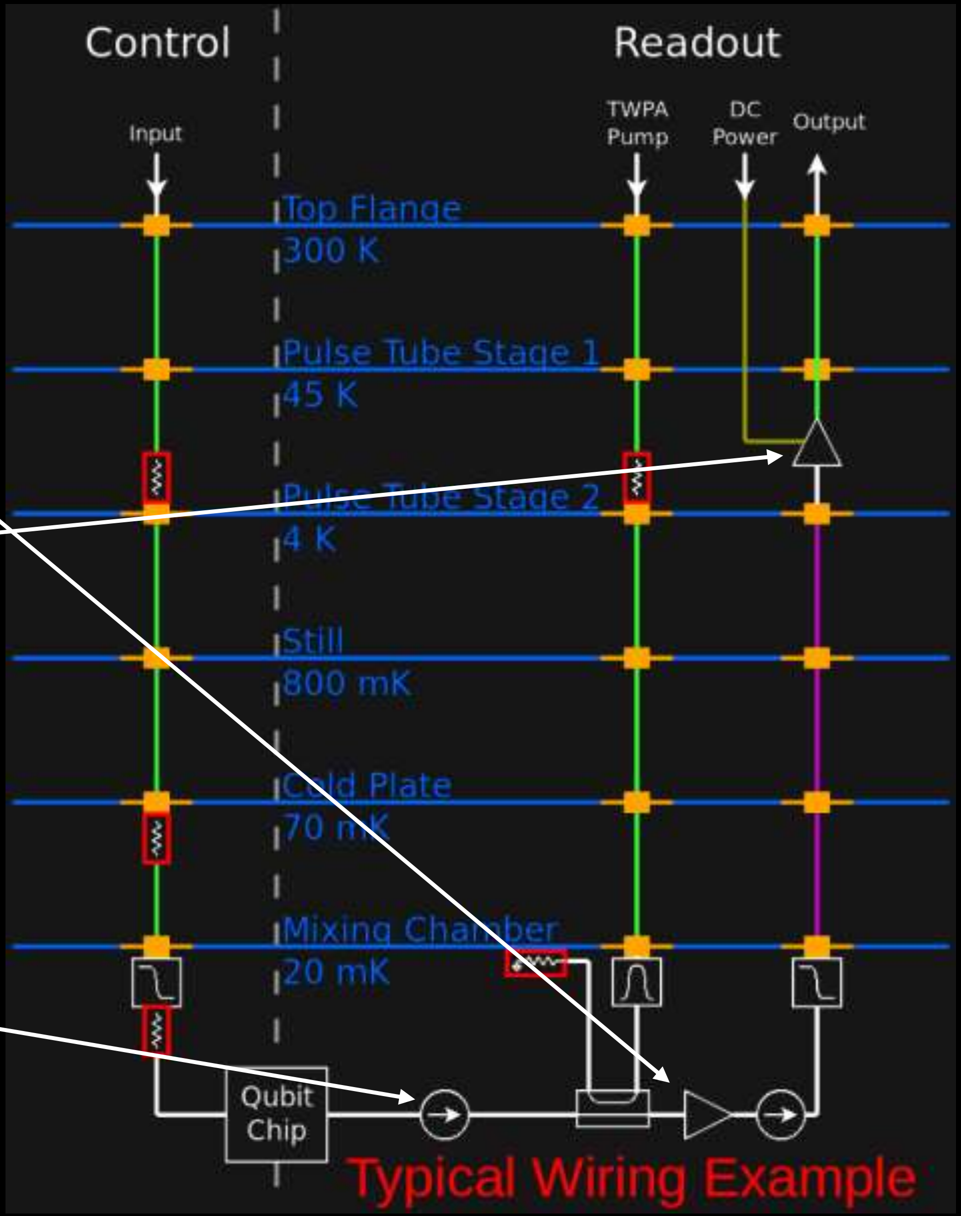
LNA (Low Noise Amplifier), HEMT

- III-V semiconductor amplifiers (e.g. InP, GaAs, etc.)
- Placed on 4K plate



Isolators

- Microwave irreciprocal directional device using magnetism
- Thermal noise isolation



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

- Zlatko Minev, Superconducting Qubits I: Quantizing a Harmonic Oscillator, Josephson Junctions, Presented at the Qiskit global summer school (2020). https://youtu.be/eZJjQGu85Ps?si=LrAlGV4CZOa-qHY3
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Thank you