Quantum Benchmarking I

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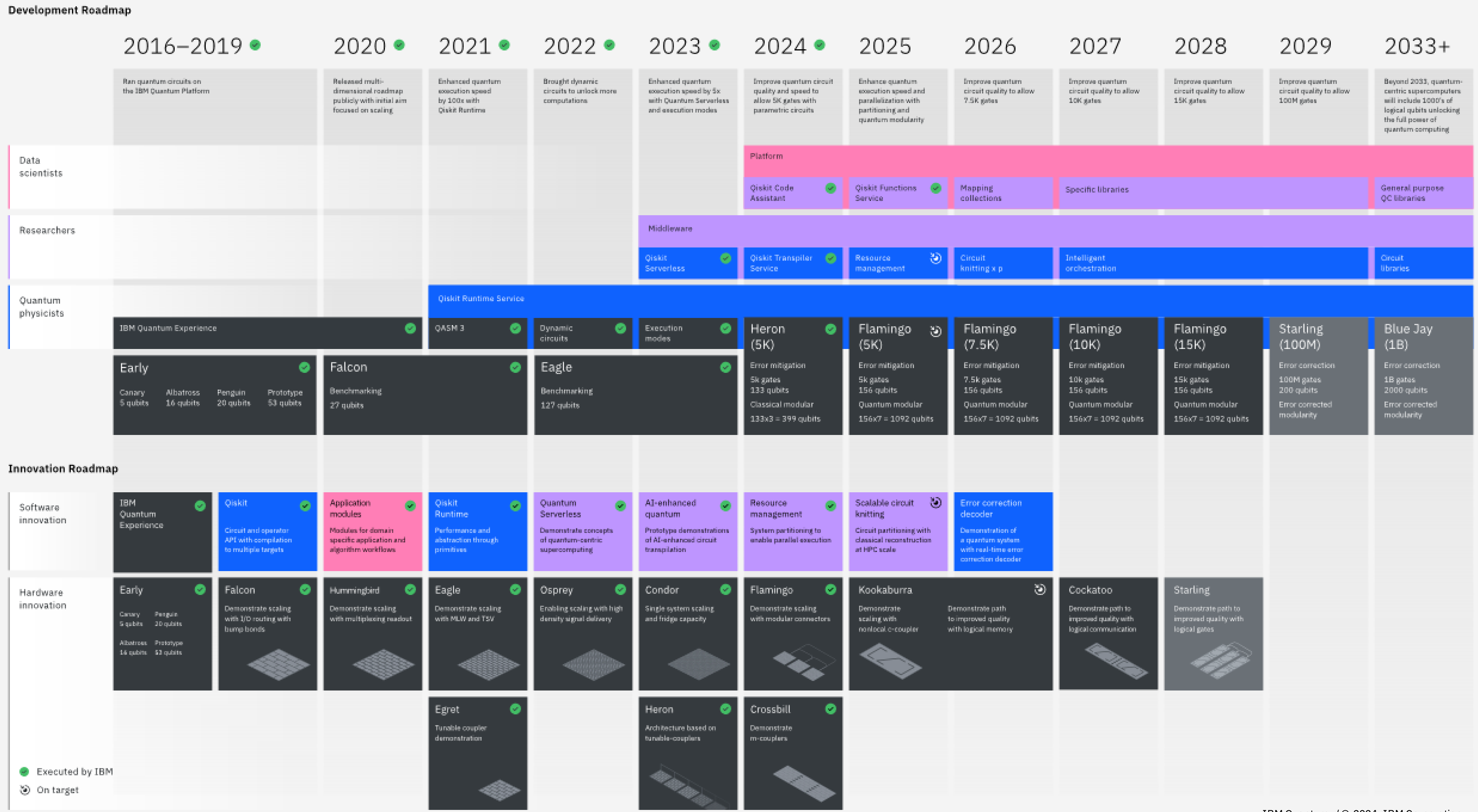
Outline

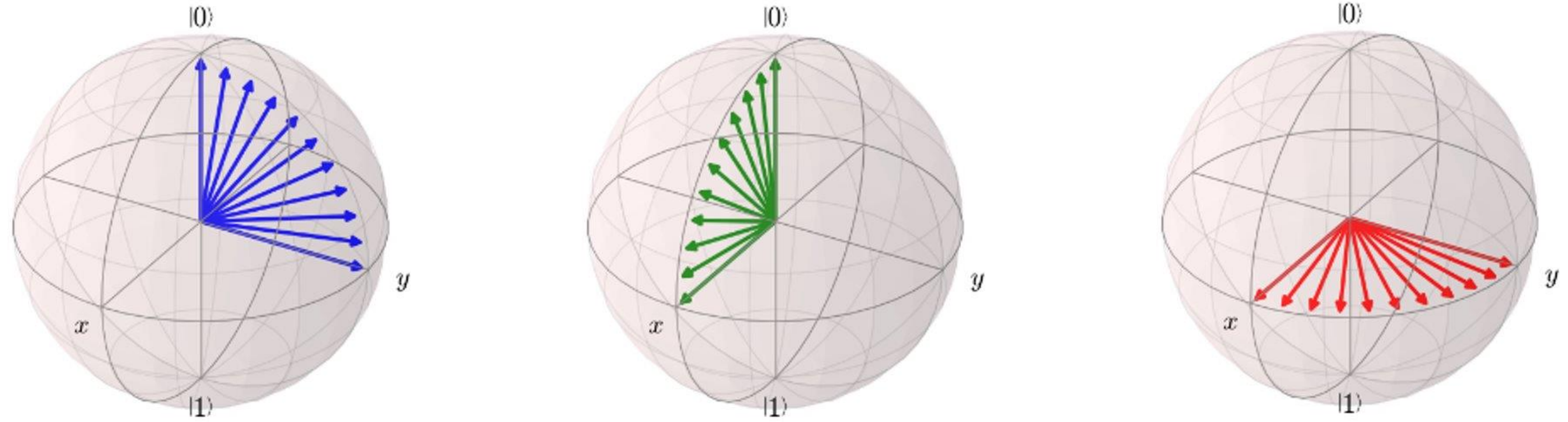
- Qubits, Quantum Gates, and Noise
- Benchmarking IBM Quantum Systems
- Device-Level Benchmarks
  - T1
  - T2
  - Readout Fidelity
- Subsystem-Level Benchmarks
  - Randomized Benchmarking
  - Quantum State Tomography
- Continued in Part 2…



Development Roadmap
2016–2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2033+
Ran quantum circuits on the IBM Quantum Platform
Released multi-dimensional roadmap publicly with initial aim focused on scaling
Enhanced quantum execution speed by 100x with Qiskit Runtime
Brought dynamic circuits to unlock more computations
Enhanced quantum execution speed by 5x with Quantum Serverless and execution modes
Improve quantum circuit quality and speed to allow 5K gates with parametric circuits
Enhance quantum execution speed and parallelization with partitioning and quantum modularity
Improve quantum circuit quality to allow 7.5K gates
Improve quantum circuit quality to allow 10K gates
Improve quantum circuit quality to allow 15K gates
Improve 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 scientists
Platform
Qiskit Code Assistant
Qiskit Functions Service
Mapping collections
Specific libraries
General purpose QC libraries
Researchers
Middleware
Qiskit Serverless
Qiskit Transpiler Service
Resource management
Circuit knitting x p
Intelligent orchestration
Circuit libraries
Quantum physicists
Qiskit Runtime Service
IBM Quantum Experience
QASM 3
Dynamic circuits
Execution modes
Heron (5K)
Error mitigation
5k gates
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 abstraction through primitives
Quantum 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
Egret
Tunable coupler demonstration
Heron
Architecture based on tunable-couplers
Crossbill
Demonstrate m-couplers
Executed by IBM
On target

Qubits and Quantum Gates

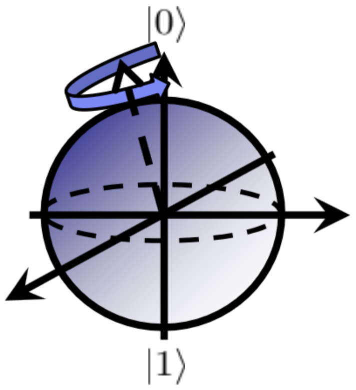
- Qubits
  - State described by $|\Psi\rangle = c_0|0\rangle + c_1|1\rangle$
  - State represented by Bloch vector on the Bloch sphere $|\Psi\rangle = \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$
- Gates
  - Unitary operations that rotate the statevector around the Bloch sphere
  - Ideal gates preserve the length of the vector and rotate it by a precise amount



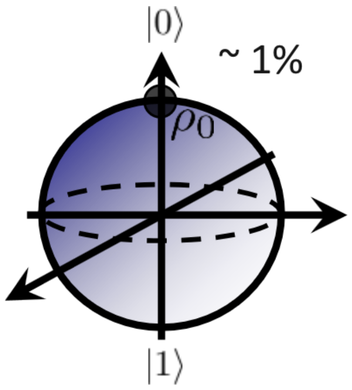
IBM **Quantum**

Quantum Noise

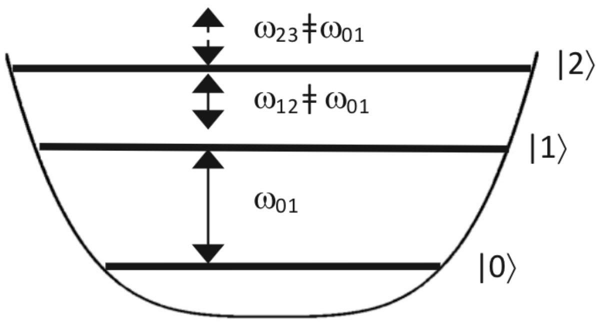
Angle/axis



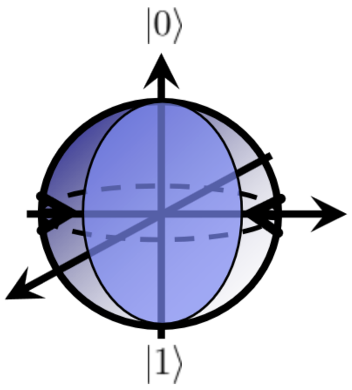
Preparation



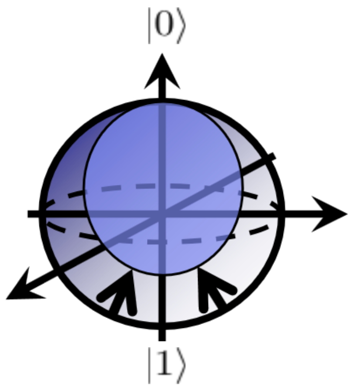
Leakage



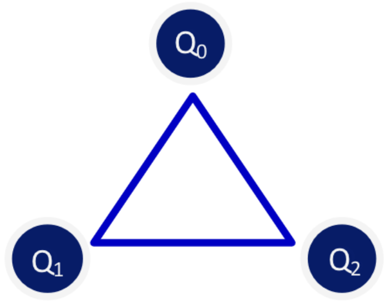
Dephasing



Damping



Crosstalk



Quantum Noise

- **Quantum operations** are described by completely positive, trace-preserving (CPTP) maps. These can be represented using operator-sum representation.

$$E(\rho) = \sum_k E_k \rho E_k^\dagger \quad where \ \sum_k E_k^\dagger E_k = 1$$

- Noise can cause this rotation to deviate from the ideal rotation.
  - Over/under-rotations
  - Change in magnitude of vector

Quantum Noise

Bit, Phase, and Bit-Phase Flip Noise:

- Represented by Pauli X, Z, and Y errors.
- These flips **reflect the Bloch vector** across the **X**, **Z**, or **Y** axis planes.

Depolarizing Noise:

- Replaces the quantum state with the maximally mixed state with some probability:
- $\rho \mapsto (1-p)\rho + (p/3)(X\rho X + Y\rho Y + Z\rho Z)$
- Shrinks the Bloch vector toward the **origin uniformly**.

Quantum Noise

Amplitude Damping Noise:

- Models **energy relaxation** (e.g., spontaneous emission).
- Causes $|1\rangle \rightarrow |0\rangle$ transitions.
- Bloch vector decays toward the **south pole** of the sphere.

Phase Damping (Dephasing) Noise:

- Models loss of quantum coherence without energy loss.
- Shrinks the **transverse (X, Y) components** of the Bloch vector.
- Bloch vector decays toward the **Z-axis** (classical mixture of $|0\rangle$ and $|1\rangle$).

Quantum Noise

Type	**Details**
Decoherence	• Arises from interaction with environment • T1 (**Relaxation**): Excited state decays to ground • T2 (**Dephasing**): Phase information is lost without energy loss. • Appears as **shrinking of the Bloch vector** toward the center.
Gate Miscalibration (Coherent Errors)	• Gate implements a unitary that deviates from the ideal. • Systematic **over- or under-rotations** due to imperfect control pulses.
State Preparation and Measurement (SPAM) Errors	• **State Preparation**: Incorrect initialization • **Measurement**: Bit-flip errors during readout
Crosstalk	• Unintended interactions between qubits. • Correlated errors between qubits
Leakage and Non-Markovianity	• Qubit escapes the 2-level subspace (e.g., to higher energy levels). • Errors that depend on history or temporal correlations, not captured by simple noise channels.

Why is Characterizing Noise Important?

- Noise limits performance of quantum algorithms.
- Noise is hardware-specific and needs to be empirically characterized.
- Accurate noise models enable:
  - Error mitigation on near-term devices (e.g., zero-noise extrapolation).
  - Simulation of realistic devices for algorithm validation.
  - Optimized qubit layout selection

Benchmarking IBM Quantum Systems

Qubit:

T1 (us)

- T1 (us)
- T2 (us)
- Readout assignment error
- Prob meas0 prep1
- Prob meas1 prep0

Median 149.25

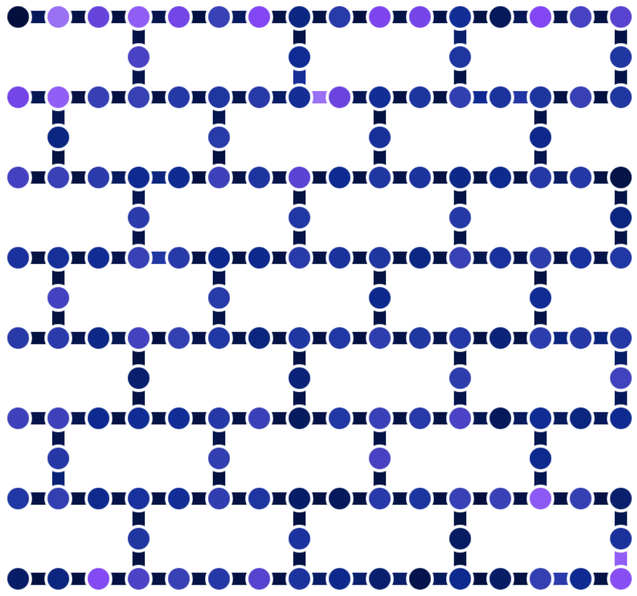
min 58.63 max 303.42

Connection:

CZ error

Median 4.204e-3

min 1.748e-3 max 1.262e-1



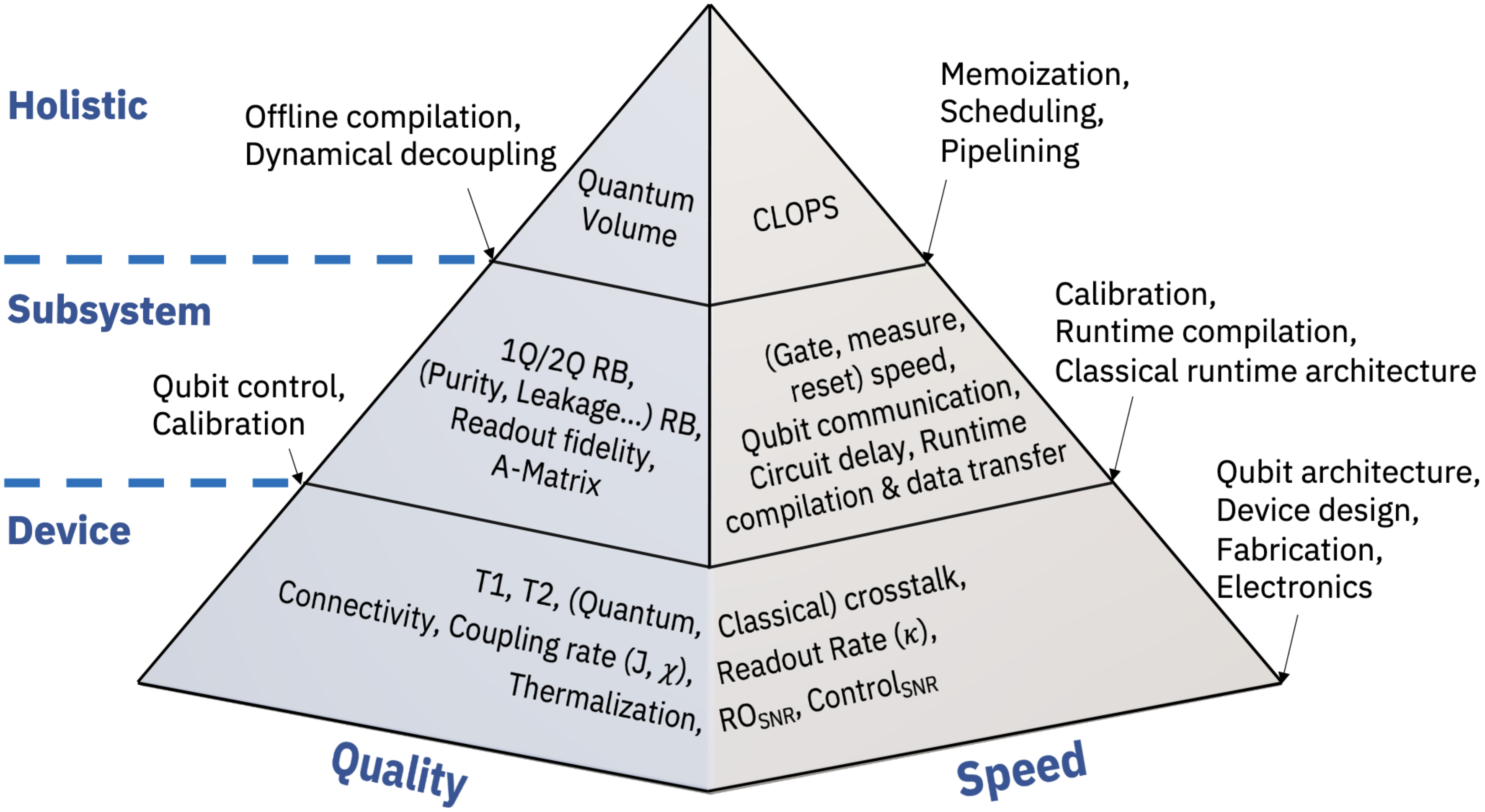
ibm_fez

Details

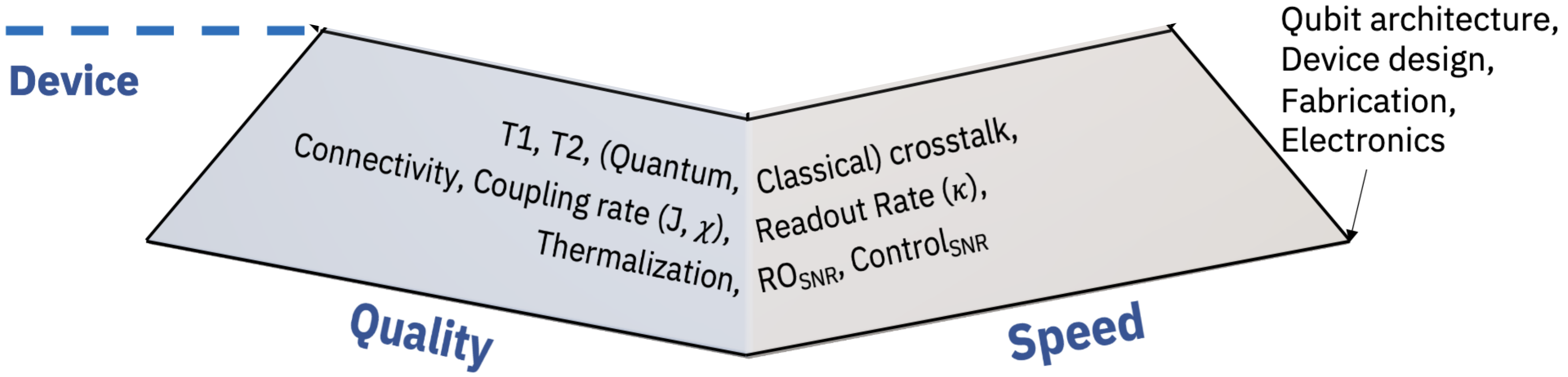
Qubits	2Q error (best)	2Q error (layered)	CLOPS
156	1.75e-3	5.28e-3	195K

Status: Online	Region: us-east	Processor type ⓘ: Heron r2	Version: 1.2.19
Total pending workloads: 1333 jobs	Your instance usage: 0 jobs	Basis gates: CZ, ID, RX, RZ, RZZ, SX, X	Median CZ error: 4.204e-3
Median SX error: 2.504e-4	Median readout error: 8.423e-3	Median T1: 149.25 us	Median T2: 98.15 us

Types of Benchmarks



Device-Level Benchmarks



T1 (Energy Relaxation)

Goal:

- Measure how quickly an excited qubit relaxes to the ground state.

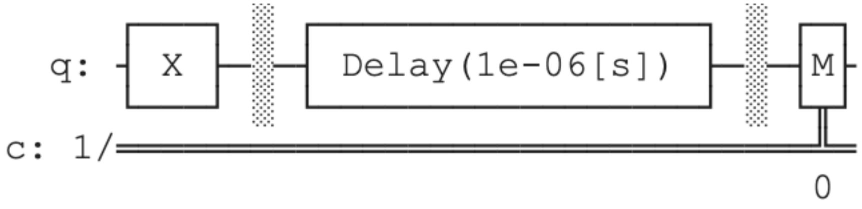
Protocol:

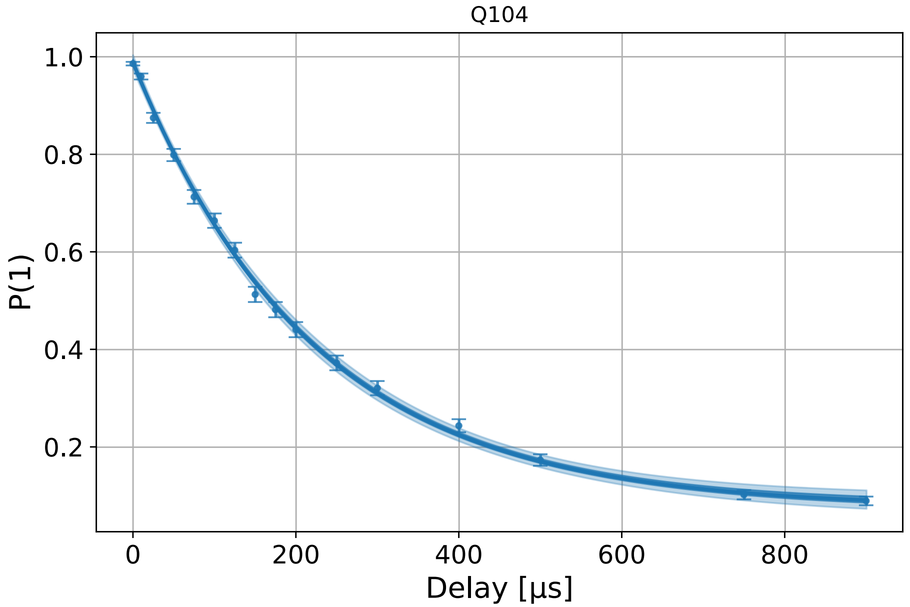
1. **Prepare** the qubit in the excited state $|1\rangle$ using an X gate.
2. **Wait** for a delay time t.
3. **Measure** in the computational basis.

Repeat for multiple delay times t, collect probabilities P1(t)

Fitting model:

- $P1(t) = Ae^{-\frac{t}{T1}} + B$





T1 = 220 ± 5.83 μs
reduced-χ^2 = 0.9559

Data taken from ibm_marrakesh

T2 (Dephasing)

Goal:

- Measure how quickly phase coherence decays (dephasing).
- **Hahn/Spin echo** – cancels noise to isolate faster dephasing.

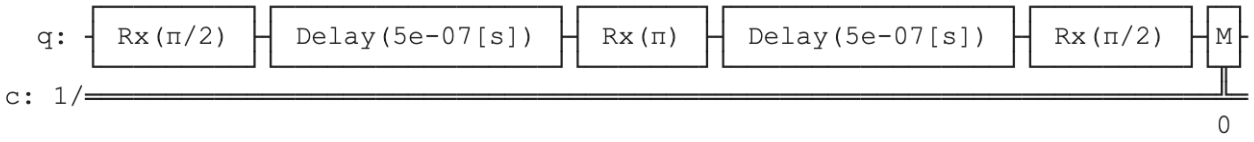
Protocol:

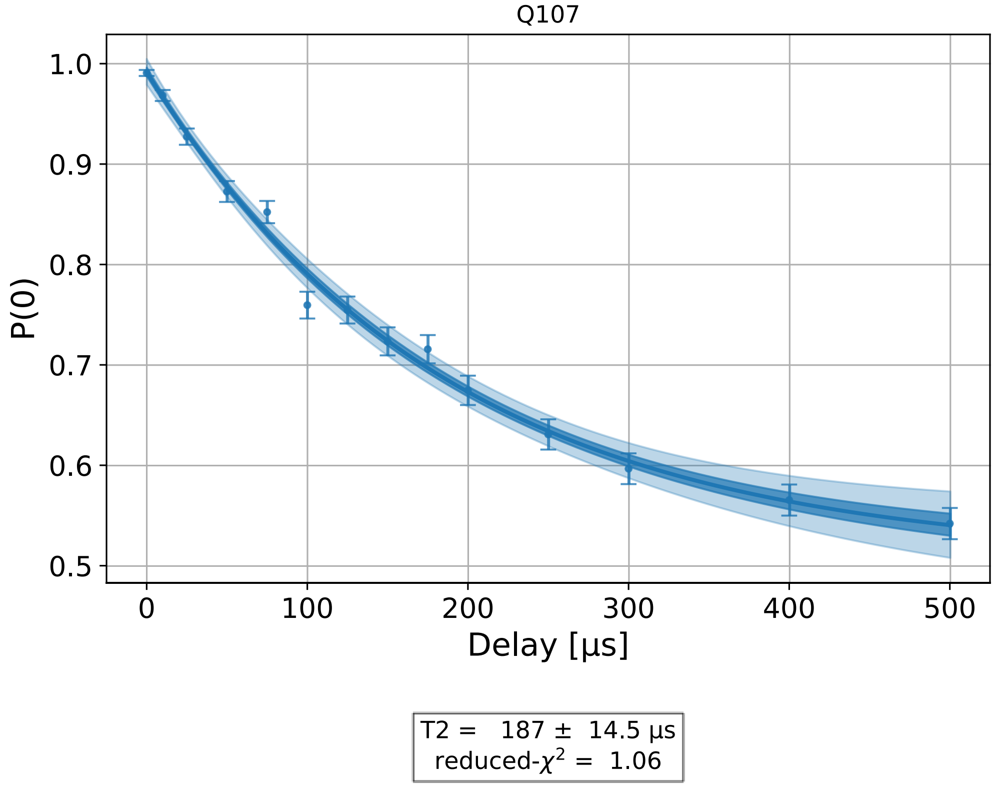
1. **Prepare** the qubit by applying a $\frac{\pi}{2}$ gate
2. **Repeat echo sequence** delay-pi-delay N times
3. **Apply** $\frac{\pi}{2}$ gate
4. **Measure** in the computational basis.

Repeat for multiple delay times t, collect probabilities P0(t)

Fitting model:

- $P0(t) = Ae^{-\frac{t}{T2}} + B$





Data taken from ibm_marrakesh

Readout Errors

Goal:

- Estimate the probability of misidentifying measurement outcomes of a known state.

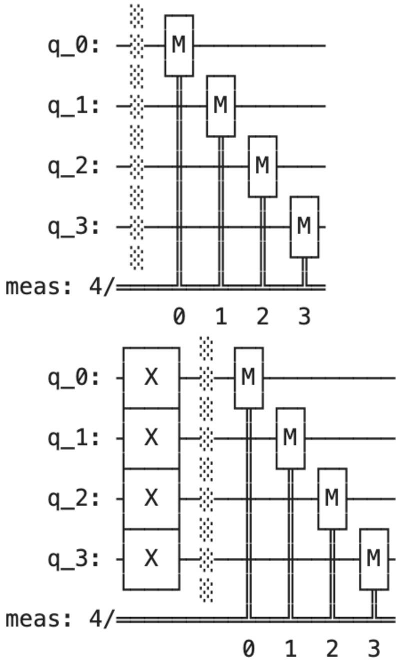
Protocol:

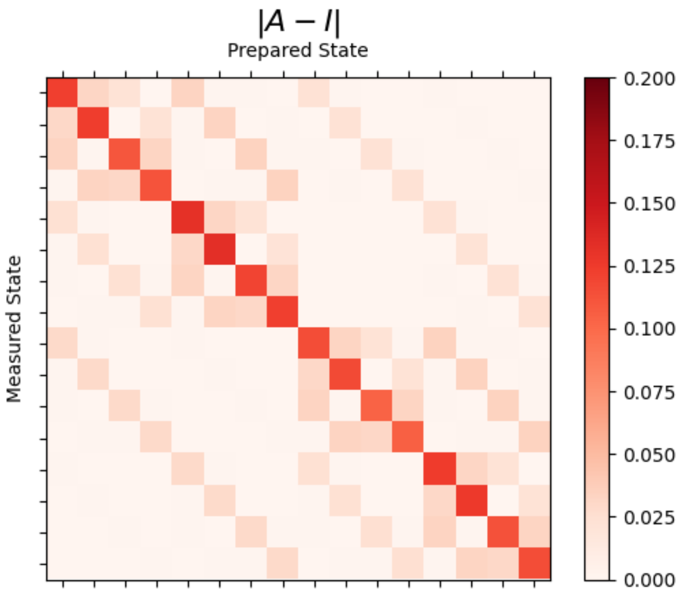
1. **Prepare** the qubits in all possible bitstring combinations
2. **Measure** in the computational basis.

Repeat for statistics

Error model:

- $M = \begin{matrix} P(0|0) & P(0|1) \\ P(1|0) & P(1|1) \end{matrix}$
- $P(i|j) = \Pr(meas\ i\ |\ prep\ j)$

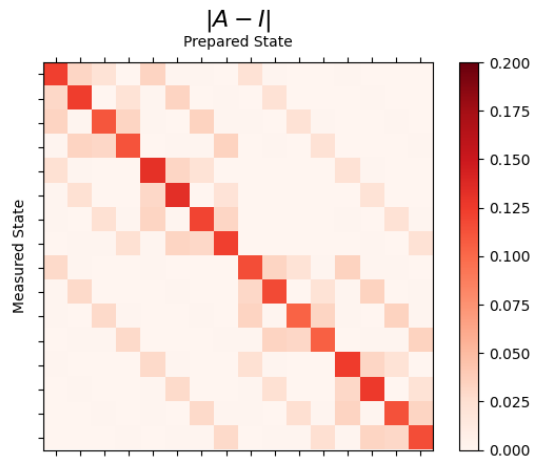


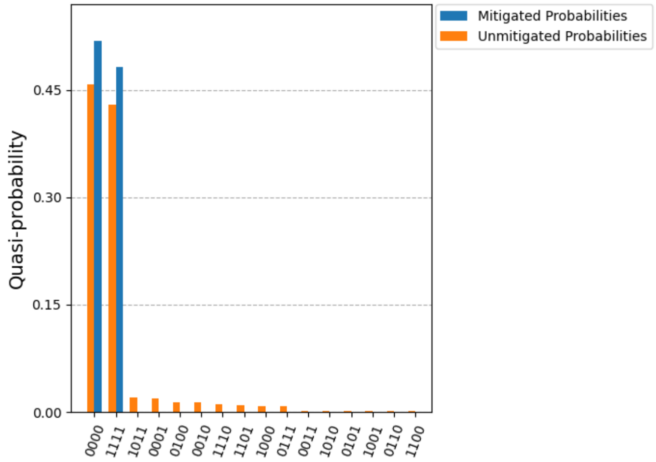


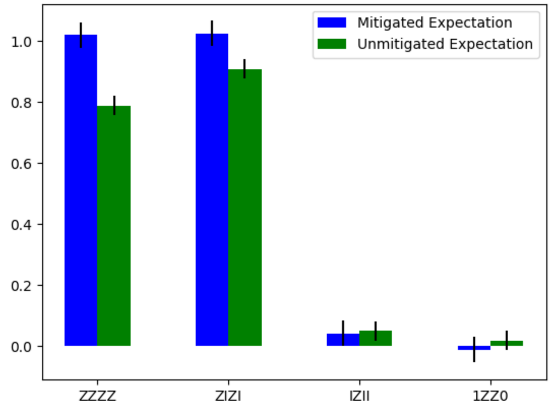
Readout Error Mitigation

- Once the error matrix is measured, it can be used to mitigate readout errors.

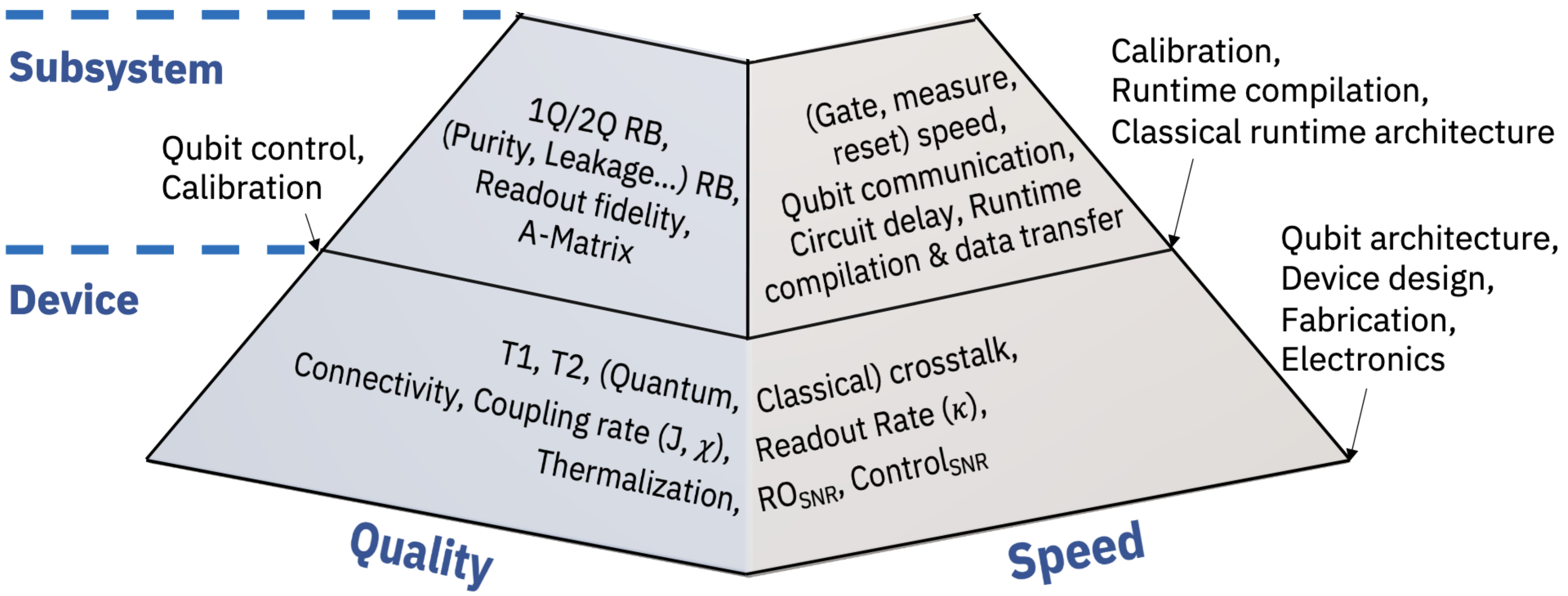
- Matrix inversion
  - Let $p_{noisy} = Mp_{true}$
  - Estimate $p_{true} = M^{-1}p_{noisy}$
- Quasiprobability inversion
  - Mitigation is usually performed locally per qubit, using tensor products of small (1- or 2-qubit) confusion matrices. Local noise assumptions allow building a scalable estimator.
  - Each measurement outcome is sampled with weights that may be negative or >1, but average to the correct result.







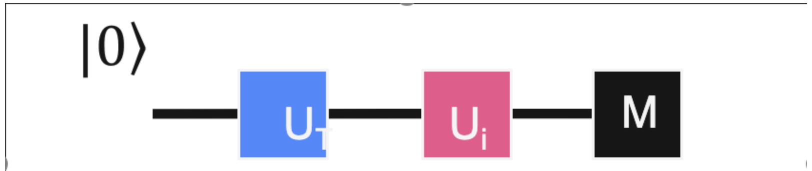
Subsystem-Level Benchmarks



Quantum State Tomography

Goal:

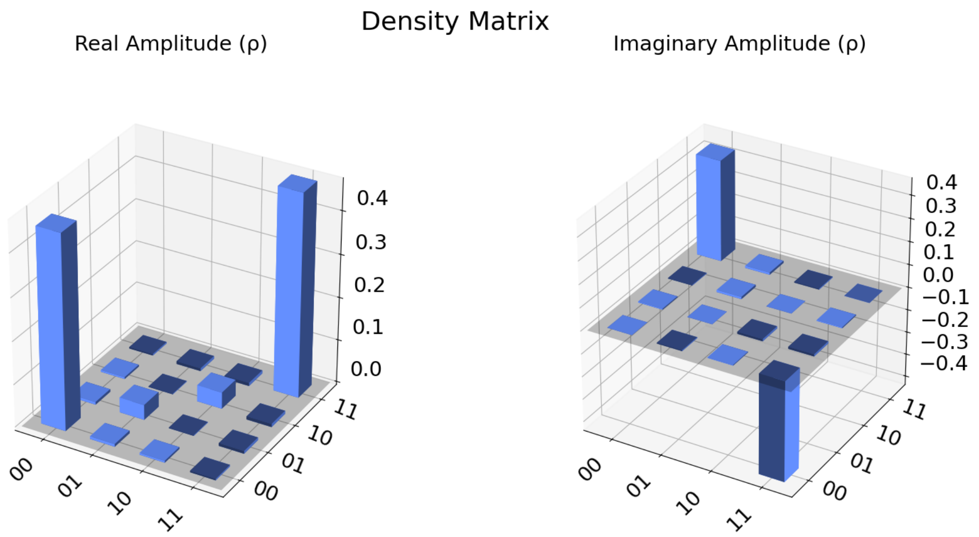
- Reconstruct the density matrix of a quantum state by preparing the state many times and measuring them in a complete basis.



$$U_i \in \{I, X_\pi, X_{\pm\pi/2}, Y_{\pm\pi/2}\}$$

Protocol:

1. **Prepare** the qubits in the state of interest.
2. **Measure** the state using a complete set of basis states (e.g. X, Y, Z)



Expensive: Exponentially large number of basis states to measure in as number of qubits grows.

Quantum Process Tomography

- **Goal**: Reconstruct a quantum operation from its effect on a complete set of inputs
- **Method**:
  - Prepare a **complete set of input states**
  - Apply the process circuit
  - Perform **quantum state tomography** on the output.

Reconstruct the process.

$$U_i \in \{I, X_\pi, X_{\pm\pi/2}, Y_{\pm\pi/2}\}$$

Randomized Benchmarking

Goal:

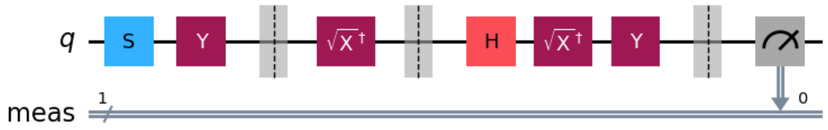
- Quantify the average error rate of quantum gates

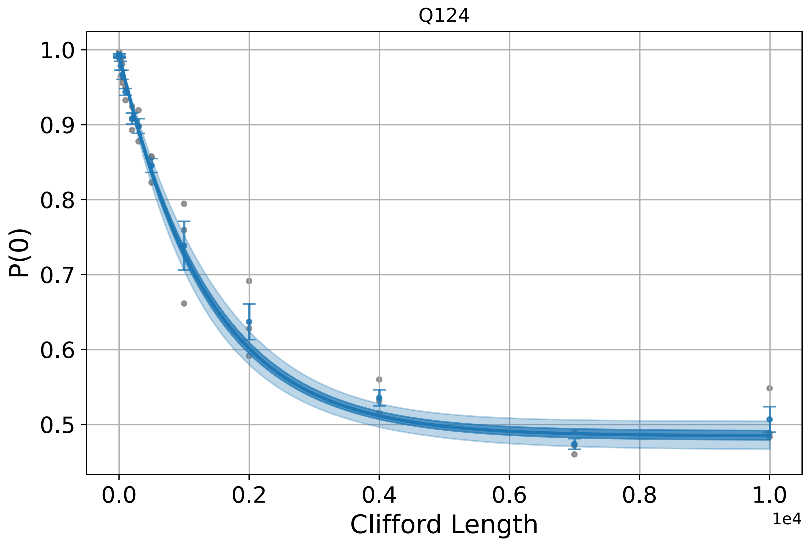
Protocol:

1. Generate a sequence of m random Clifford gates.
2. Append an **inversion gate** that ideally returns the qubit to the zero state. This inversion gate is classically easy to compute due to properties of the Clifford gates.
3. Measure.
4. Repeat for multiple sequence lengths, and average over many random sequences.

Error model:

- $F(m) = Ap^m + B$
- $r = \frac{1-p}{2}$





alpha = 0.9993 ± 3.7106e-05
EPC = 3.6813e-04 ± 1.8553e-05
EPG_rz = 0.0000e+00 ± 0.0000e+00
EPG_sx = 4.5342e-04 ± 2.2851e-05
EPG_x = 4.5342e-04 ± 2.2851e-05
reduced-χ^2 = 2.739

Data taken from ibm_marrakesh

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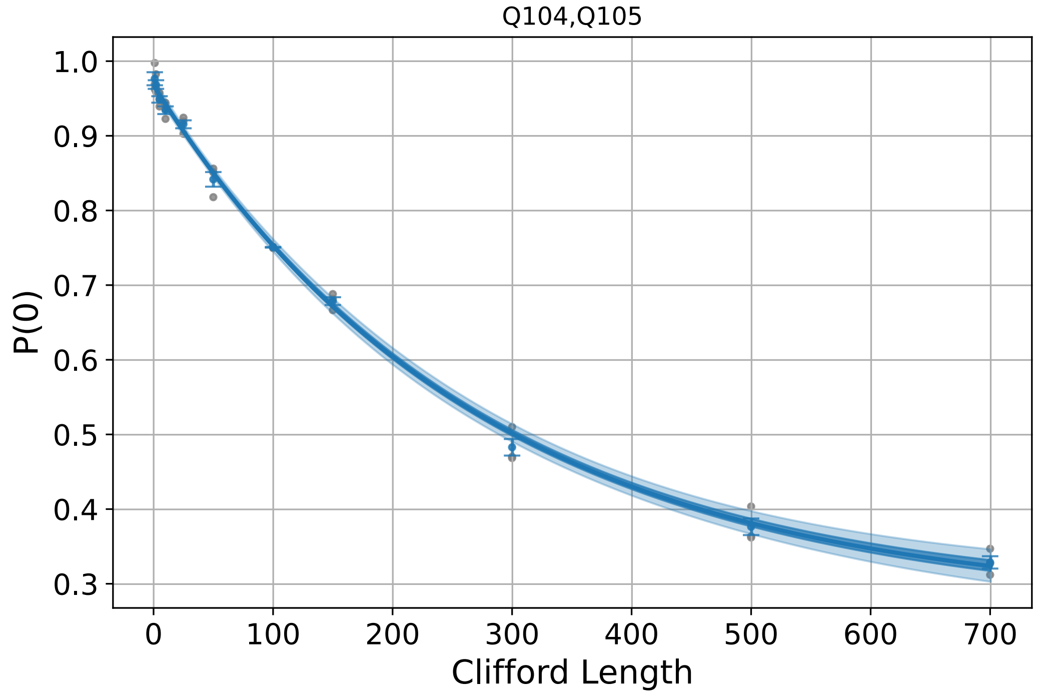
2Q Randomized Benchmarking

- Identical process to the 1Q experiment, except now the 2-qubit Clifford group is used
- Additional consideration: the EPC value obtained by the experiment indicates a depolarization which is a composition of underlying error channels for 2Q gates and 1Q gates in each qubit.
- In principle, RB scales to arbitrary n-qubit gate sets.
- However, the size of the Clifford group quickly scales with the number of qubits!



alpha = 0.9963 ± 1.2629e-04
EPC = 0.002762 ± 9.4719e-05
EPG_cz = 0.002068 ± 7.0925e-05
reduced-χ^2 = 2.054

Data taken from ibm_marrakesh

More Randomized Benchmarking

- **Simultaneous RB** *(arXiv:1204.6308)*: Benchmarks multiple qubits at once to reveal **crosstalk** or **inter-qubit interference** effects during gate execution.
- **Direct RB** *(arXiv:1807.07975):* Avoids compiling gates into Cliffords by directly benchmarking native gate sets, providing more **hardware-relevant error rates**.
- **Interleaved RB** *(arXiv:1203.4550)*: Estimates the error of a **specific gate** by interleaving it with random Cliffords and comparing the decay to standard RB.
- **Mirror RB** *(arXiv:2207.07272, arXiv:2112.09853)*: Uses **palindromic (mirror) sequences** with no final inversion gate; isolates gate errors while canceling coherent over/under-rotations.
- **BIRB – Bare Inversion Randomized Benchmarking** *(arXiv:2309.05147)*: Removes the need for computing the inverse Clifford by **replacing it with a known bare gate**, simplifying implementation.
- **Correlated RB** *(arXiv:2003.02354)*: Detects and quantifies **spatial or temporal correlations** in gate errors, beyond what standard RB captures.
- **Leakage RB** *(arXiv:1412.4126, arXiv:1704.03081)*: Extends RB to detect **leakage outside the computational subspace**, critical for systems with higher excited states (e.g., transmons).
- **Coherence RB / Unitarity RB** *(arXiv:1604.03076, arXiv:1503.07865, arXiv:1504.06597)*: Measures the **unitarity** of noise to distinguish **coherent** from **incoherent** errors, offering deeper insight into error sources.

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Experiment Manuals

- T1: https://qiskit-community.github.io/qiskit-experiments/manuals/characterization/t1.html
- T2: https://qiskit-community.github.io/qiskit-experiments/manuals/characterization/t2hahn.html
- Readout Errors: https://qiskit-community.github.io/qiskit-experiments/manuals/measurement/readout_mitigation.html
- Quantum State Tomography: https://qiskit-community.github.io/qiskit-experiments/manuals/verification/state_tomography.html
- Randomized Benchmarking: https://qiskit-community.github.io/qiskit-experiments/manuals/verification/randomized_benchmarking.html