اطلس کوانتوم

Quantum Coding Course

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About us

Quantum Atlas is an educational group which aims to educate people in various fields of quantum, from hardware to software and quantum machine learning.

www.quantumatlas.ir

QuantumSTEM

Quantum Atlas

Syllabus

Section 1	**Lecture 1**	Quantum Computation and Information (Theoretical lecture) – By Y. Mafi
	Lecture 2	Quantum Circuits (Coding lecture) – By A. Kookani
Section 2	**Lecture 3**	Quantum Simulation (Coding lecture) – By A. Kookani
	Lecture 4	IBMQ and Error Correction (Implementation and Theoretical lecture) – By Y. Mafi
Section 3	**Lecture 5**	Quantum Algorithm (Theoretical lecture) – By Y. Mafi
	Lecture 6	Quantum Algorithm Simulation (Coding lecture) – By A. Kookani

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01

Quantum Noise

Quantum Noise

What is Coherence Time?

- **Definition**: Coherence time refers to the time period during which a qubit maintains its quantum state without significant decoherence.
- **Significance**: It is a critical parameter for quantum computation, as it determines how long a qubit can reliably perform operations before losing its quantum properties.

Types of Coherence Times:

- **T_1 (Relaxation Time)**: Time for a qubit to lose energy and decay from its excited state $|1\rangle$ to the ground state $|0\rangle$.
- **T_2 (Dephasing Time)**: Time over which a qubit loses its phase information due to interactions with its environment.

Quantum Noise

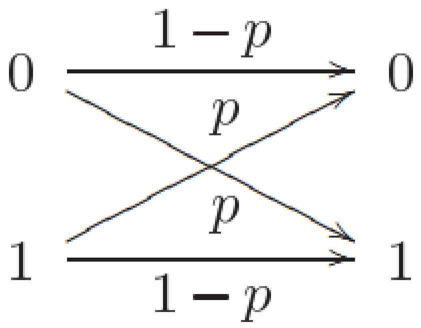
Coherence Time in Superconductive Qubits:

- **Typical Values**: Ranges from microseconds to milliseconds, depending on the qubit design and material.
- **Challenges**: Superconductive qubits are sensitive to environmental noise, leading to shorter coherence times.
- **Improvements**: Engineering techniques like better shielding, material purification, and advanced error correction methods help extend coherence time.

Quantum Noise

What is Quantum Noise?

- **Definition**: Quantum noise refers to the random fluctuations that affect the quantum state of a qubit, leading to errors in quantum computations.
- **Origin**: It arises from the interaction of qubits with their environment, causing decoherence and state transitions.



Quantum Noise

Sources of Quantum Noise:

- **Thermal Noise**: Caused by temperature fluctuations that affect the energy states of qubits.
- **Electromagnetic Noise**: Arises from ambient electromagnetic fields that can perturb the qubit's state.
- **1/f Noise**: A type of low-frequency noise, often due to defects or impurities in the qubit materials.

Quantum Noise in Superconductive Qubits:

- **Sensitivity**: Superconductive qubits are particularly sensitive to external noise because of their reliance on very low temperatures and precise electromagnetic conditions.
- **Decoherence**: Quantum noise is a major contributor to decoherence, shortening the coherence time of superconductive qubits.
- **Mitigation**: Techniques like cryogenic cooling, shielding from electromagnetic interference, and material engineering are used to reduce quantum noise.

Quantum Noise

Solutions to Quantum Noise in Superconductive Qubits:

1. Cryogenic Cooling

- **Description**: Maintaining qubits at ultra-low temperatures (millikelvin range) to minimize thermal noise.
- **Benefit**: Reduces thermal fluctuations, extending coherence time.

2. Electromagnetic Shielding

- **Description**: Isolating qubits from external electromagnetic fields using shielding materials.
- **Benefit**: Decreases electromagnetic interference, leading to lower noise levels.

3. Material Engineering

- **Description**: Using high-purity materials and refined fabrication techniques to reduce defects and impurities.
- **Benefit**: Minimizes 1/f noise, enhancing qubit stability.

Quantum Noise

4. Quantum Error Correction

- **Description**: Implementing algorithms that detect and correct errors caused by quantum noise.
- **Benefit**: Compensates for noise-induced errors, improving overall computation accuracy.

5. Advanced Circuit Designs

- **Description**: Designing qubits and circuits to be less sensitive to noise, such as through topological qubits or optimized control sequences.
- **Benefit**: Increases robustness against noise, enabling more reliable quantum operations.

Quantum Noise

Quantum Noise types:

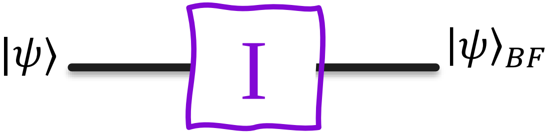
1. Bit-flip noise
2. Phase-flip noise
3. Amplitude-damping noise
4. Phase-damping noise
5. Etc.

Quantum Noise

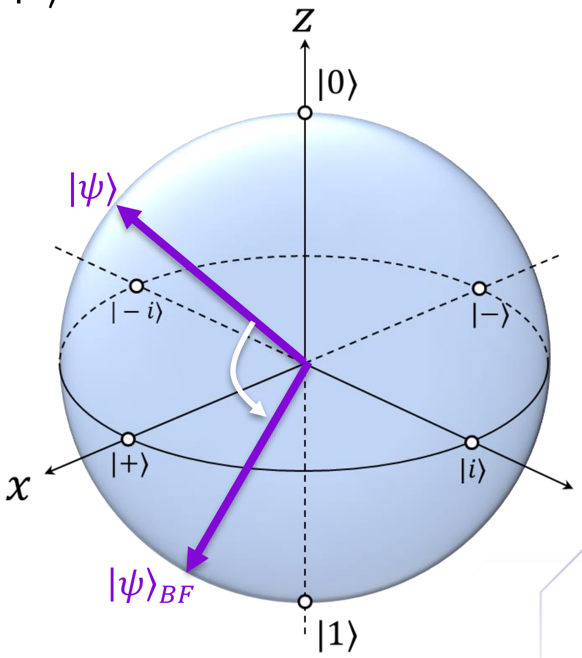
Bit-flip noise (BF): bit-flip noise changes a qubit's state from $|0\rangle$ to $|1\rangle$ or vice versa.

$$|0\rangle \xrightarrow{p} |1\rangle \quad \Rightarrow \quad |0\rangle \xrightarrow{BF} \sqrt{1-p}\,|0\rangle + \sqrt{p}\,|1\rangle$$

$$|1\rangle \xrightarrow{p} |0\rangle \quad \Rightarrow \quad |1\rangle \xrightarrow{BF} \sqrt{p}\,|0\rangle + \sqrt{1-p}\,|1\rangle$$



Noisy operation

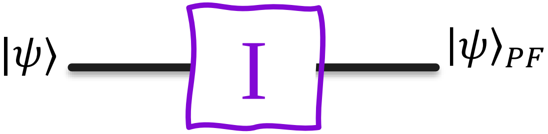


Quantum Noise

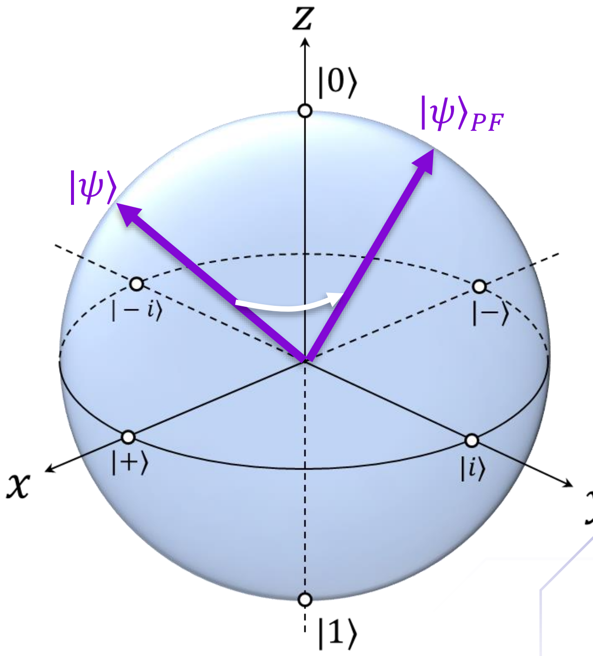
Phase-flip noise (PF): phase-flip noise alters the relative phase of a qubit's superposition state.

$$|0\rangle \xrightarrow{p} |0\rangle \quad \Rightarrow \quad |0\rangle \xrightarrow{PF} |0\rangle$$

$$|1\rangle \xrightarrow{p} -|1\rangle \quad \Rightarrow \quad |1\rangle \xrightarrow{PF} -\sqrt{p}|1\rangle + \sqrt{1-p}|1\rangle$$



Noisy operation



Quantum Noise

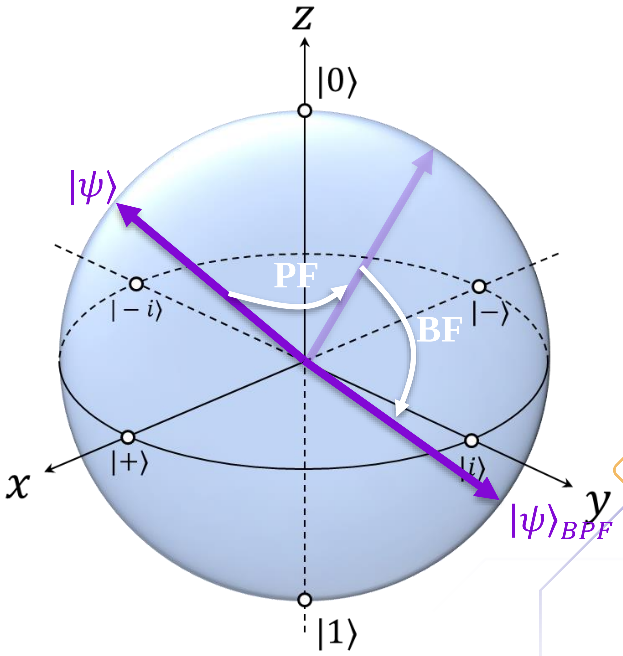
Bit- and phase-flip noise (BPF): Combination of two noises.

$$|0\rangle \xrightarrow{p} |1\rangle \qquad \qquad |0\rangle \xrightarrow{p} |0\rangle$$

$$|1\rangle \xrightarrow{p} |0\rangle \qquad \& \qquad |1\rangle \xrightarrow{p} -|1\rangle$$

$$|\psi\rangle \;—\; \boxed{\mathrm{I}} \;—\; |\psi\rangle_{BPF}$$

Noisy operation



Quantum Noise

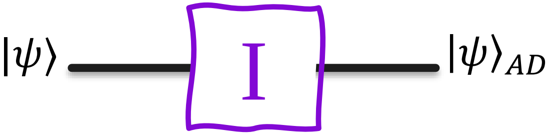
Amplitude-damping noise (AD): amplitude-damping noise results in the loss of energy, driving a qubit towards the $|0\rangle$ state.

$$|0\rangle \overset{p}{\rightarrow} |0\rangle$$

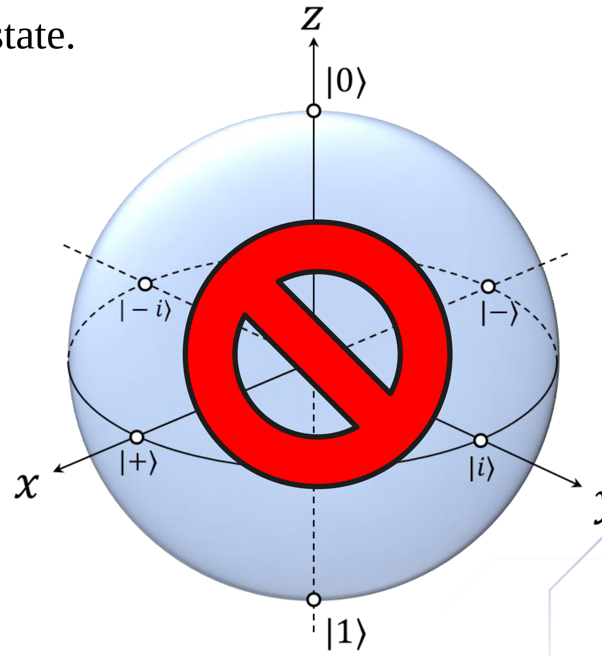
$$|1\rangle \overset{p}{\rightarrow} \sqrt{p}|0\rangle + \sqrt{1-p}|1\rangle$$

For example:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \overset{AD}{\rightarrow} |\psi\rangle_{AD} = \alpha|0\rangle + \beta\left(\sqrt{p}|0\rangle + \sqrt{1-p}|1\rangle\right)$$
$$= \left(\alpha + \beta\sqrt{p}\right)|0\rangle + \beta\sqrt{1-p}|1\rangle$$



Noisy operation



Quantum Noise

Phase-damping noise (PD): phase-damping noise causes a loss of coherence without changing the population of the states.

$$|0\rangle \xrightarrow{p} |0\rangle$$

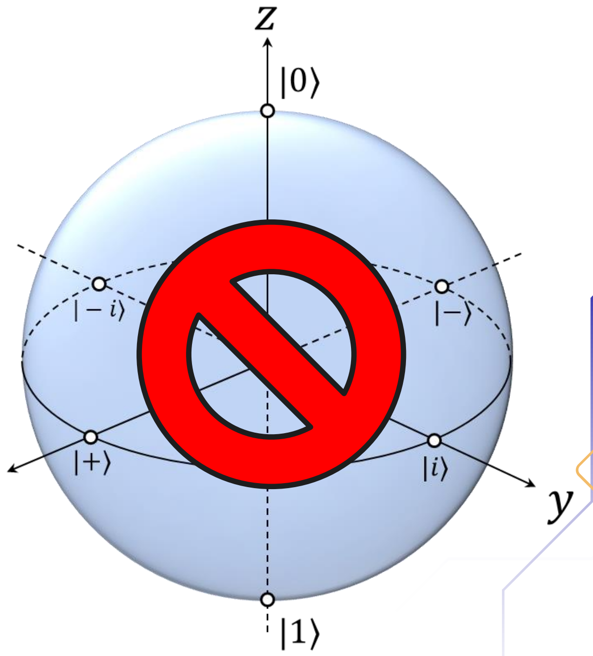
$$|1\rangle \xrightarrow{p} \text{decoherence}$$

$$|\psi\rangle = \alpha|0\rangle + e^{i\phi}\beta|1\rangle \rightarrow \rho = |\psi\rangle\langle\psi| = \begin{bmatrix} \alpha^2 & \alpha\beta e^{i\phi} \\ \alpha\beta e^{-i\phi} & \beta^2 \end{bmatrix}$$

$$\rightarrow \rho_{PD} = \begin{bmatrix} \alpha^2 & \alpha\beta e^{i\phi} \\ \alpha\beta e^{-i\phi} & \beta^2 \end{bmatrix}$$

Noisy operation

decrease the coherence of qubit

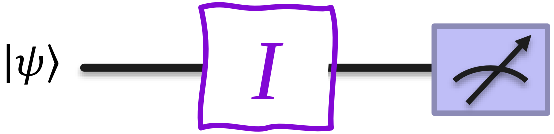


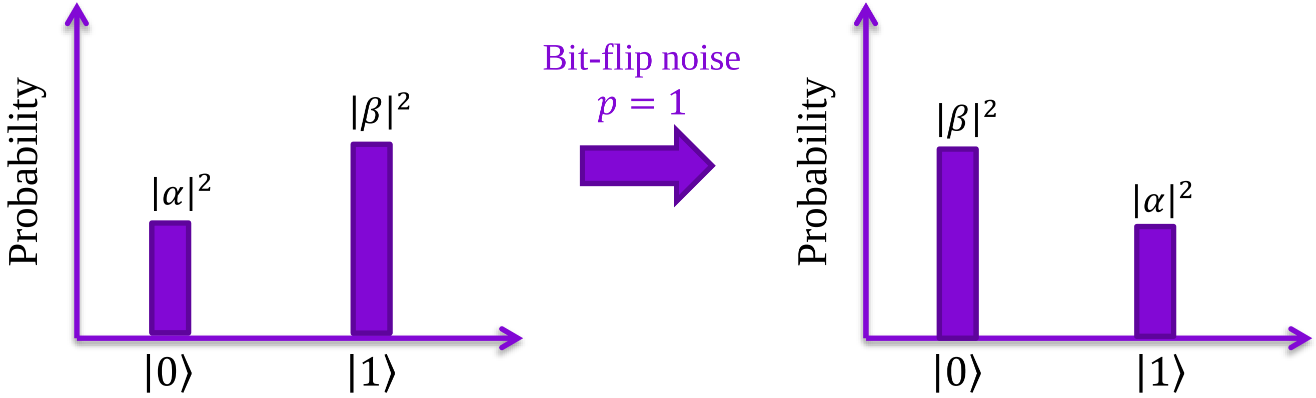
Quantum Noise

Assume single-qubit quantum state is $|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle \rightarrow |\alpha|^2 + |\beta|^2 = 1$

Normalization condition

Bit-flip noise



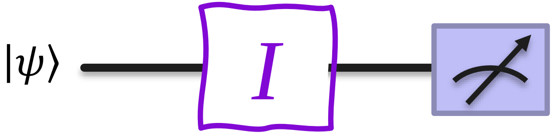


Quantum Noise

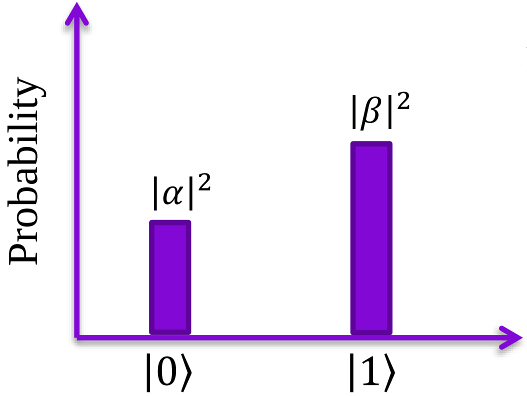
Assume single-qubit quantum state is $|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle \rightarrow |\alpha|^2 + |\beta e^{i\phi}|^2 = 1$

Normalization condition

Phase-flip noise

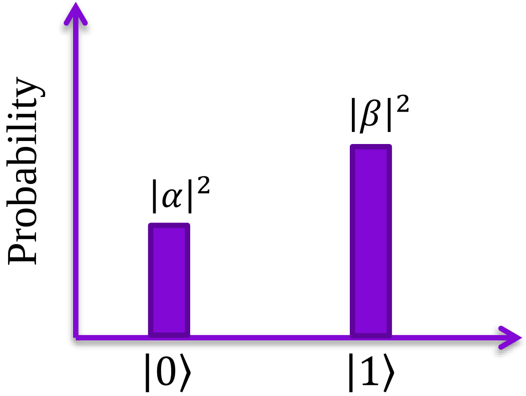


$$|\psi\rangle_{PF} = \alpha|0\rangle - \beta e^{i\phi}|1\rangle \rightarrow \begin{cases} P(|0\rangle) = |\alpha|^2 \\ P(|1\rangle) = |\beta e^{i\phi}|^2 = |\beta|^2 \end{cases}$$



Phase-flip noise

$p = 1$

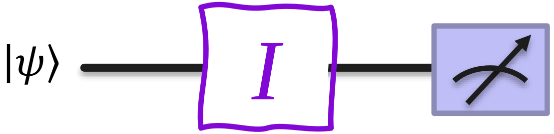


Quantum Noise

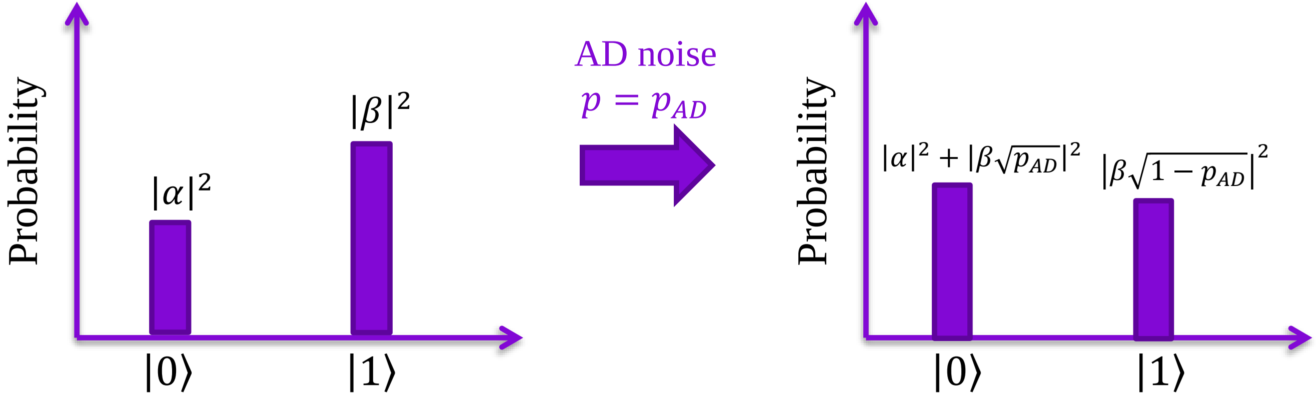
Assume single-qubit quantum state is $|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle \rightarrow |\alpha|^2 + |\beta e^{i\phi}|^2 = 1$

Normalization condition

Amplitude-damping noise



$$|\psi\rangle_{AD} = \alpha|0\rangle + \beta e^{i\phi}\left(\sqrt{p_{AD}}|0\rangle + \sqrt{1-p_{AD}}|1\rangle\right)$$

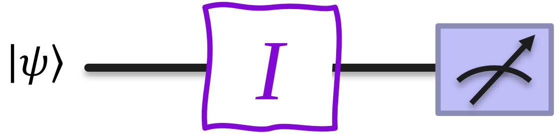


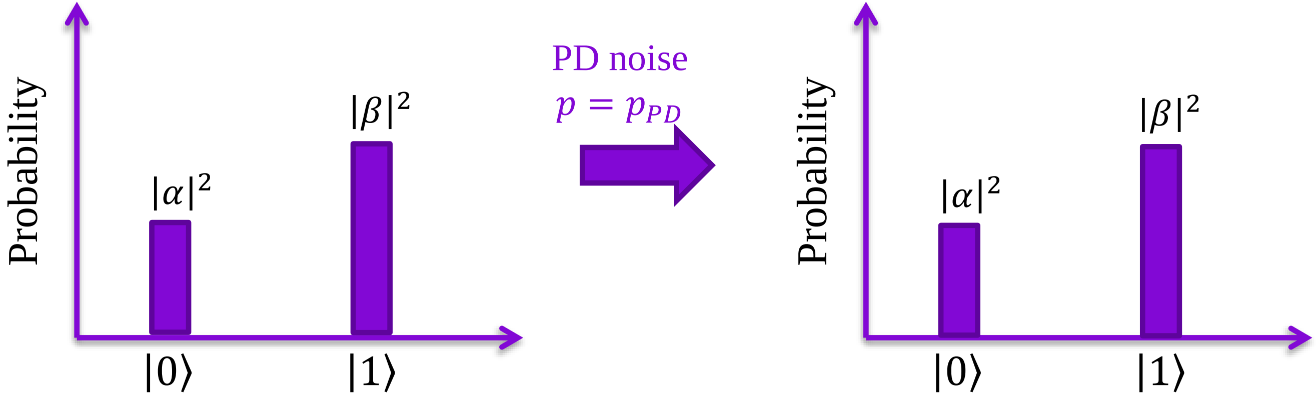
Quantum Noise

Assume single-qubit quantum state is $|\psi\rangle = \alpha|0\rangle + \beta e^{i\phi}|1\rangle \rightarrow |\alpha|^2 + |\beta e^{i\phi}|^2 = 1$

Normalization condition

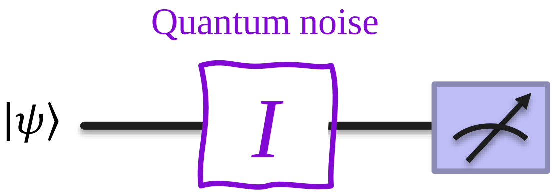
Phase-damping noise

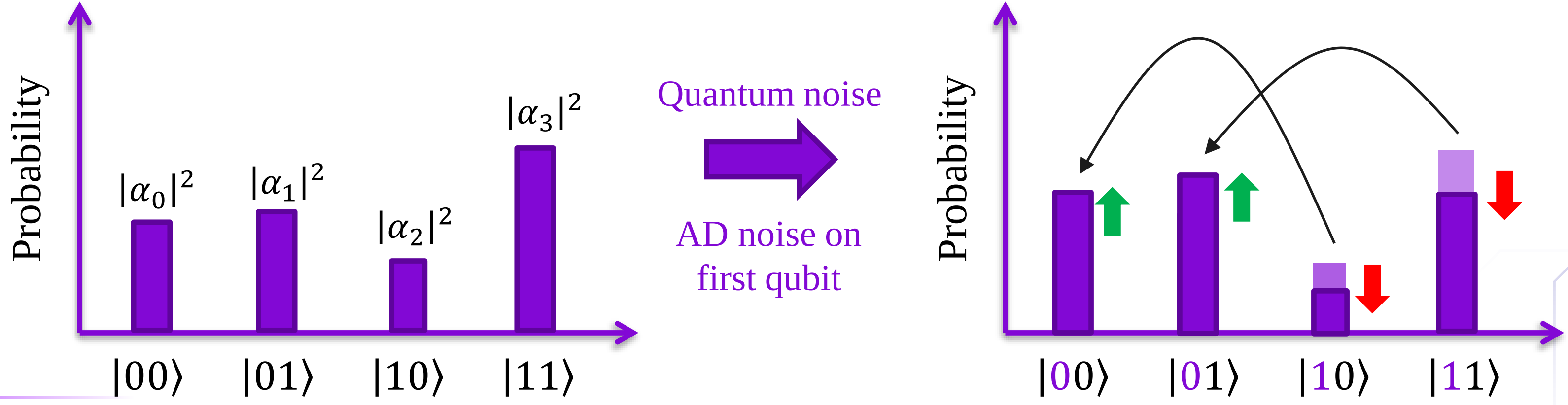




Quantum Noise

Assume two-qubit quantum state is $|\psi\rangle = \alpha_0|00\rangle + \alpha_1 e^{i\phi_1}|01\rangle + \alpha_2 e^{i\phi_2}|10\rangle + \alpha_3 e^{i\phi_3}|11\rangle$





02

Error correction

Error correction

Error Correction in Digital Circuits

Types of Errors:

- **Single-Bit Errors:** Occurs when only one bit in the data is altered.
- **Burst Errors:** Multiple consecutive bits are corrupted.
- **Random Errors:** Errors occurring sporadically throughout the data.

Error Detection Techniques:

- **Parity Check:** Adds a single bit to the data to make the number of 1s either even (even parity) or odd (odd parity).
- **Checksum:** Calculates a value based on the data, which is transmitted along with the data. The receiver recalculates and compares the checksum to detect errors.
- **Cyclic Redundancy Check (CRC):** A more robust technique using polynomial division to detect errors.

Error correction

Parity Check Example:

❖ You have a 4-bit data sequence: 1011.

- **Even Parity:**
  - Count the number of 1s in the data: 1011 has three 1s.
  - To make it even, add a parity bit of 1 (since adding 1 makes the total number of 1s even).
  - Transmitted Data: 10111.
- **Odd Parity:**
  - If odd parity is required, and the number of 1s is already odd, you add a parity bit of 0 to keep it odd.
  - Transmitted Data: 10110.

❖ At the Receiver End:

- The receiver checks the parity:
  - For even parity, if the total number of 1s is odd, an error is detected.
  - For odd parity, if the total number of 1s is even, an error is detected.

Error correction

Error Correction Techniques:

- **Hamming Code:** Corrects single-bit errors and detects two-bit errors by adding redundant bits to the data.
- **Reed-Solomon Code:** Used in CDs, DVDs, and QR codes, it can correct multiple random errors.
- **BCH Code:** Generalizes the Hamming code and can correct multiple errors in a block of data.
- **Turbo Codes and LDPC Codes:** Advanced methods used in modern communication systems like 4G and 5G for high-efficiency error correction.

Error correction

Hamming Code Example:

❖ You have a 4-bit data sequence: 1011.

- Step 1: Determine Parity Bit Positions
  - For a 4-bit data sequence, 3 parity bits (P1, P2, P4) are needed, replace indices are powers of 2.
- Step 2: Arrange the Data and Parity Bits
  - Data bits are placed in the remaining positions. _ _ 1 _ 0 1 1 (P1, P2, D3, P4, D5, D6, D7).
- Step 3: Calculate the Parity Bits
  - P1: Covers bits 1, 3, 5, 7: 1 _ 1 _ 0 1 : $P1 = 1 \oplus 1 \oplus 0 \oplus 1 = 1$.
  - P2: Covers bits 2, 3, 6, 7: _ 1 1 _ 0 1 : $P2 = 1 \oplus 1 \oplus 1 \oplus 1 = 0$.
  - P4: Covers bits 4, 5, 6, 7: _ _ 1 0 0 1 : $P4 = 0 \oplus 0 \oplus 1 \oplus 1 = 0$.

❖ Final Encoded Data with Parity Bits: P1 P2 D3 P4 D5 D6 D7 = 1 0 1 0 0 1 1.

❖ At the Receiver End:

- The receiver checks the parity bits.
- If any parity check fails, the position of the error can be determined by the combination of failed parity bits.
- For example, if parity bits P1 and P2 fail, the error is in the 3rd bit, as P1 = 1 and P2 = 2, giving 1 + 2 = 3.

Error correction

What is Quantum Error Correction?

- **Definition**: Quantum error correction (QEC) involves techniques to protect quantum information from errors due to quantum noise, decoherence, and other disturbances.
- **Challenge**: Unlike classical bits, qubits are susceptible to multiple types of errors (bit-flip, phase-flip) simultaneously, making error correction more complex.

Error correction

Quantum Error Correction in Superconductive Qubits

- **Error Susceptibility**: Superconductive qubits are prone to noise due to their sensitivity to environmental fluctuations, requiring robust error correction techniques.
- **QEC Codes**: Techniques like the Shor Code, **Steane Code**, and Surface Code are used to detect and correct errors in superconductive qubits.
- **Redundancy**: QEC encodes logical qubits into multiple physical qubits to detect and correct errors without directly measuring and disturbing the quantum state.

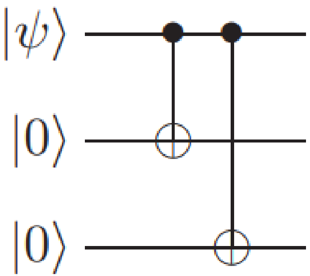
Error correction

The three qubit bit flip code:

We encode the single qubit state $\alpha|0\rangle + \beta|1\rangle$ in three qubits as $\alpha|000\rangle + \beta|111\rangle$.

Logic qubit state:

$$|0_L\rangle \equiv |000\rangle$$
$$|1_L\rangle \equiv |111\rangle$$



Error detection:

$M_0 = \|000\rangle\ or\ \|111\rangle$	no error
$M_1 = \|100\rangle\ or\ \|011\rangle$	bit-flip error on qubit one
$M_2 = \|010\rangle\ or\ \|101\rangle$	bit-flip error on qubit two
$M_3 = \|001\rangle\ or\ \|110\rangle$	bit-flip error on qubit three

Recovery: For example, if the error syndrome was 1, indicating a bit flip on the first qubit, then we flip that qubit again, recovering the original state $\alpha|000\rangle + \beta|111\rangle$ with perfect accuracy.

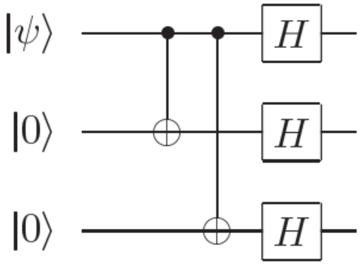
Error correction

The three qubit phase flip code:

We encode the single qubit state $\alpha|0\rangle + \beta|1\rangle$ in three qubits as $\alpha|{+}{+}{+}\rangle + \beta|{-}{-}{-}\rangle$.

Logic qubit state:

$$|0_L\rangle \equiv |{+}{+}{+}\rangle$$
$$|1_L\rangle \equiv |{-}{-}{-}\rangle$$



Error detection:

$M_0 = |{+}{+}{+}\rangle$ *or* $|{-}{-}{-}\rangle$ no error
$M_1 = |{-}{+}{+}\rangle$ *or* $|{+}{-}{-}\rangle$ bit-flip error on qubit one
$M_2 = |{+}{-}{+}\rangle$ *or* $|{-}{+}{-}\rangle$ bit-flip error on qubit two
$M_3 = |{+}{+}{-}\rangle$ *or* $|{-}{-}{+}\rangle$ bit-flip error on qubit three

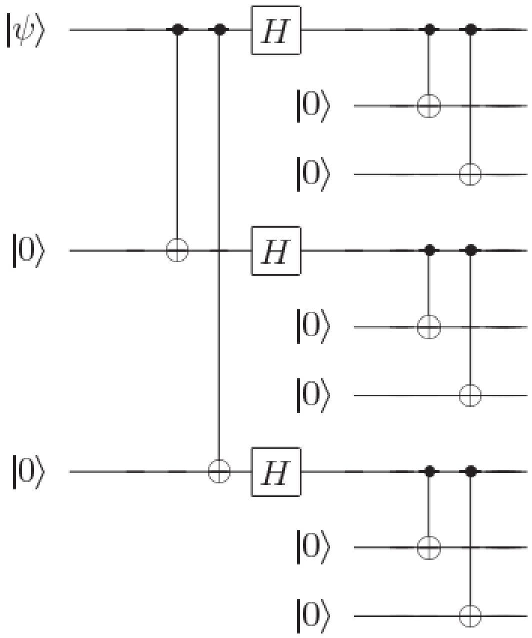
Recovery: For example, suppose we detected a flip in the sign of the first qubit from $|+\rangle$ to $|-\rangle$. Then we recover by applying $HXH = Z$ to the first qubit.

Error correction

The Shor code is a combination of the three qubit phase flip and bit flip codes.

$$|0\rangle \rightarrow |0_L\rangle \equiv \frac{(|000\rangle + |111\rangle)(|000\rangle + |111\rangle)(|000\rangle + |111\rangle)}{2\sqrt{2}}$$

$$|1\rangle \rightarrow |1_L\rangle \equiv \frac{(|000\rangle - |111\rangle)(|000\rangle - |111\rangle)(|000\rangle - |111\rangle)}{2\sqrt{2}} .$$



03

Coupling Map

Coupling Map

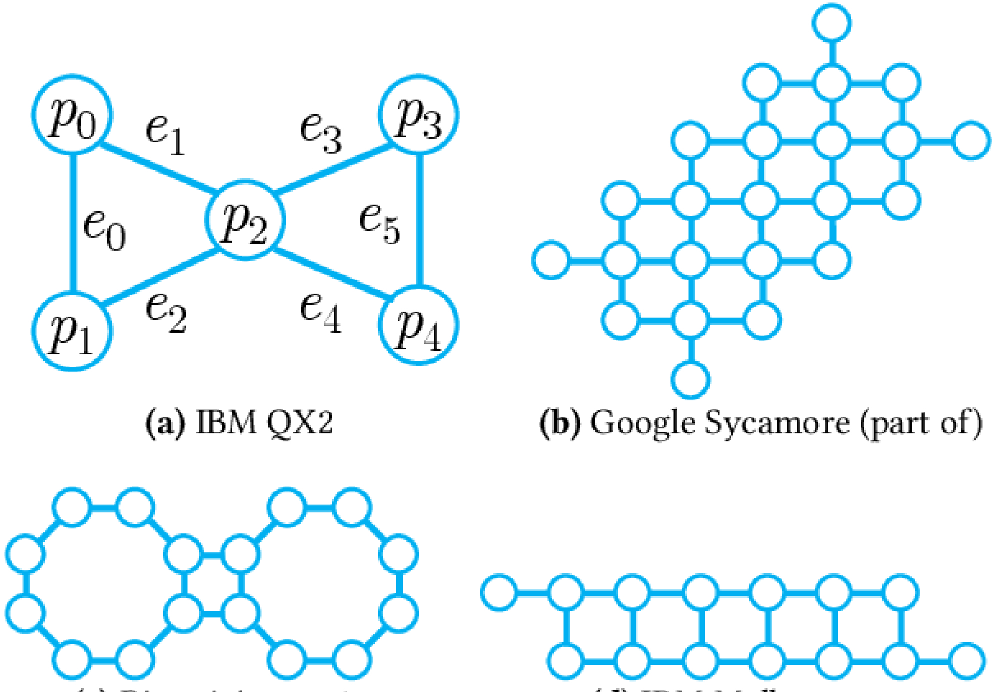
What is a Coupling Map?

- **Definition**: A coupling map represents the physical connections and interactions between qubits in a quantum processor.
- **Importance**: It determines which qubits can directly interact with each other, affecting how quantum gates are implemented across a qubit array.

Coupling Map in Superconductive Qubits

- **Topology**: Superconductive qubits are typically arranged in specific topologies (e.g., linear, lattice) where qubits are connected by coupling elements like resonators.
- **Interaction**: The coupling map outlines which qubits can exchange information directly, influencing the overall efficiency of quantum algorithms.
- **Constraints**: Limited connectivity in the coupling map may require additional gates (SWAP gates) to move qubit states, impacting computation time.

Coupling Map



(a) IBM QX2

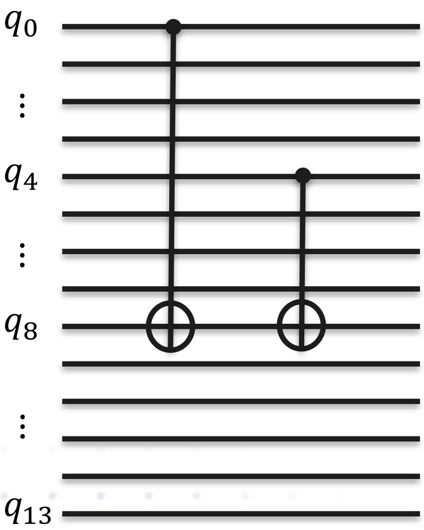
(b) Google Sycamore (part of)

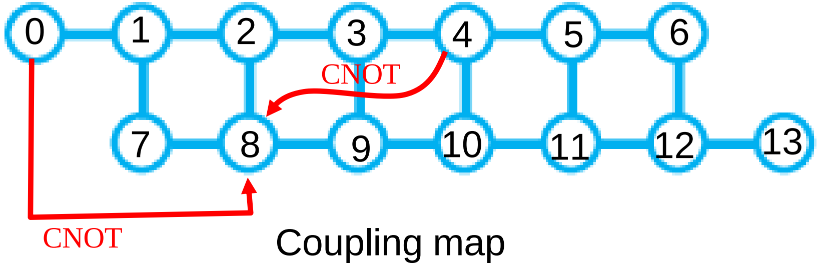
(c) Rigetti Aspen-4

(d) IBM Melbourne

Challenge 2

How can we implement the following circuit based on the coupling map? (only use CNOT gates)





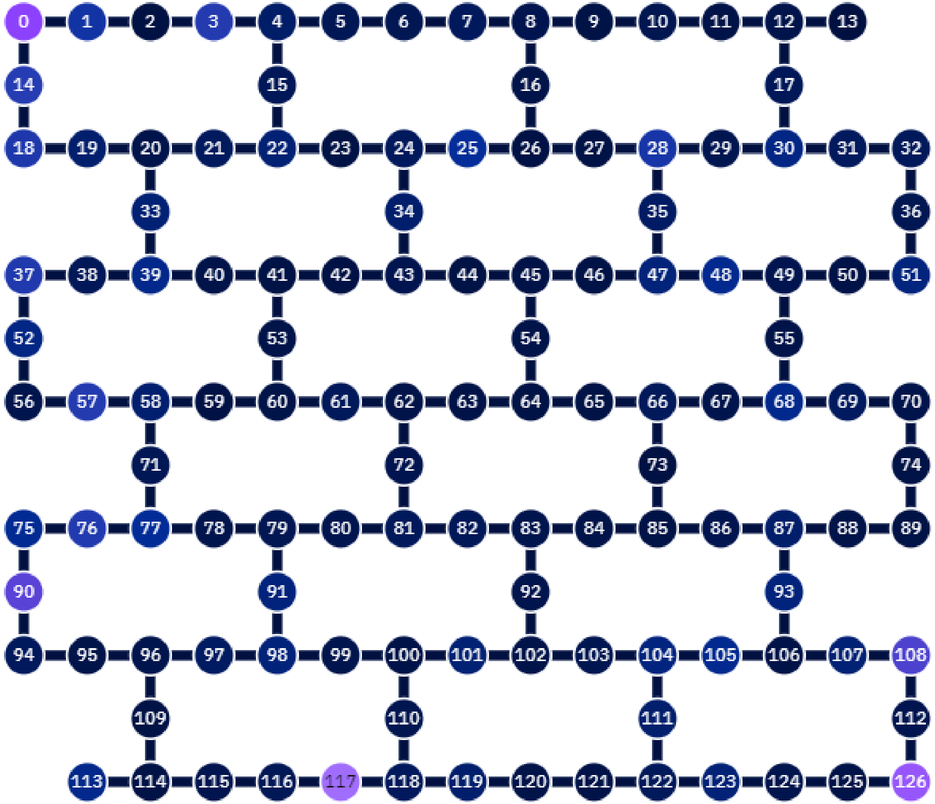
Coupling map

Coupling Map

IBMQ Parameters:

- T1 (µs)
- T2 (µs)
- Frequency (GHz)
- Anharmonicity (GHz)
- Readout Assignment Error
- Prob meas0 prep1
- Prob meas1 prep0
- Readout Length (ns)
- ID Error
- Z-Axis Rotation (rz) Error
- √X (sx) Error
- Pauli-X Error
- ECR Error
- Gate Time (ns)

IBMQ-Kyoto- 127 qubit (logic qubit)



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Coupling Map

❖ T_1 (µs) – Relaxing time:

- **Description**: T_1, or relaxation time, is the time it takes for a qubit to decay from its excited state (|1⟩) to its ground state (|0⟩).
- **Importance**: Longer T_1 times are desirable, as they indicate a qubit can retain its excited state for longer, reducing errors in quantum computations.

❖ T_2 (µs) – dephasing time:

- **Description**: T_2, or dephasing time, measures how long a qubit maintains its phase coherence. Longer It's the time over which the qubit's superposition state (a combination of |0⟩ and |1⟩) dephases due to interactions with its environment.
- **Importance**: T_2 times are crucial for maintaining the integrity of quantum superpositions and performing accurate quantum operations.

Coupling Map

❖ Frequency (GHz):

- **Description**: The operational frequency of a qubit, typically in the GHz range. It represents the energy difference between the qubit's ground state and excited state.
- **Importance**: The frequency determines how qubits interact and resonate with control pulses, influencing gate operations and qubit behavior.

❖ Anharmonicity (GHz):

- **Description**: A measure of how much the energy levels of a qubit deviate from being equally spaced. In superconducting qubits, this parameter is crucial for distinguishing between the qubit's logical states ($|0\rangle$ and $|1\rangle$) and higher energy states.
- **Importance**: Higher anharmonicity allows for better control of the qubit, reducing errors from transitions to unwanted states.

Coupling Map

❖ Readout Assignment Error:

- **Description**: The probability that a qubit's state is incorrectly measured. It's the error rate associated with the qubit's state being incorrectly assigned during readout.
- **Importance**: Lower readout assignment errors are essential for accurate measurement of quantum states, which is critical for reliable quantum computations.

❖ Prob meas0 prep1:

- **Description**: The probability that a qubit prepared in the $|1\rangle$ state is measured incorrectly as $|0\rangle$.
- **Importance**: This metric is a specific component of readout errors and impacts the accuracy of quantum measurement outcomes.

Coupling Map

❖ Prob meas1 prep0:

- **Description**: The probability that a qubit prepared in the |0⟩ state is measured incorrectly as |1⟩.
- **Importance**: Like Prob meas0 prep1, this parameter is critical for evaluating the accuracy of quantum measurements, particularly in error correction schemes.

❖ Readout Length (ns):

- **Description**: The duration of time it takes to perform a measurement on a qubit.
- **Importance**: Shorter readout lengths can reduce the overall operation time of quantum circuits, helping to minimize the impact of decoherence during measurements.

Coupling Map

- ID Error:
- **Description**: The error rate associated with the identity (I) gate, which ideally leaves the qubit's state unchanged.
- **Importance**: Even though an identity gate is a "do-nothing" operation, errors can still occur, and low ID errors are important for maintaining qubit integrity during idle periods.

- Z-Axis Rotation (rz) Error:
- **Description**: The error rate for a Z-axis rotation (rz) gate, which rotates the qubit around the Z-axis of the Bloch sphere.
- **Importance**: Low rz errors are crucial for precise phase control in quantum algorithms, especially in operations that rely on phase shifts.

Coupling Map

❖ √X (sx) Error:

- **Description**: The error rate for a √X gate, which performs a square root of the Pauli-X (X) gate, rotating the qubit state halfway from |0⟩ to |1⟩.
- **Importance**: The √X gate is commonly used in quantum algorithms, and low errors in this gate ensure more accurate qubit state manipulations.

❖ Pauli-X Error:

- **Description**: The error rate associated with the Pauli-X (X) gate, which flips the qubit state from |0⟩ to |1⟩ and vice versa.
- **Importance**: Low Pauli-X errors are essential for reliable qubit state flips, which are fundamental operations in quantum computing.

Coupling Map

❖ ECR Error:

- **Description**: The error rate for the Echoed Cross-Resonance (ECR) gate, which is a commonly used two-qubit gate in IBM quantum systems.
- **Importance**: The ECR gate is crucial for entangling qubits, and low error rates are important for maintaining the integrity of two-qubit operations, which are essential for most quantum algorithms.

❖ Gate Time (ns):

- **Description**: The time it takes to perform a specific quantum gate operation.
- **Importance**: Shorter gate times reduce the exposure to decoherence and noise, which can improve the overall fidelity of quantum operations.

Coupling Map

اطلس کوانتوم

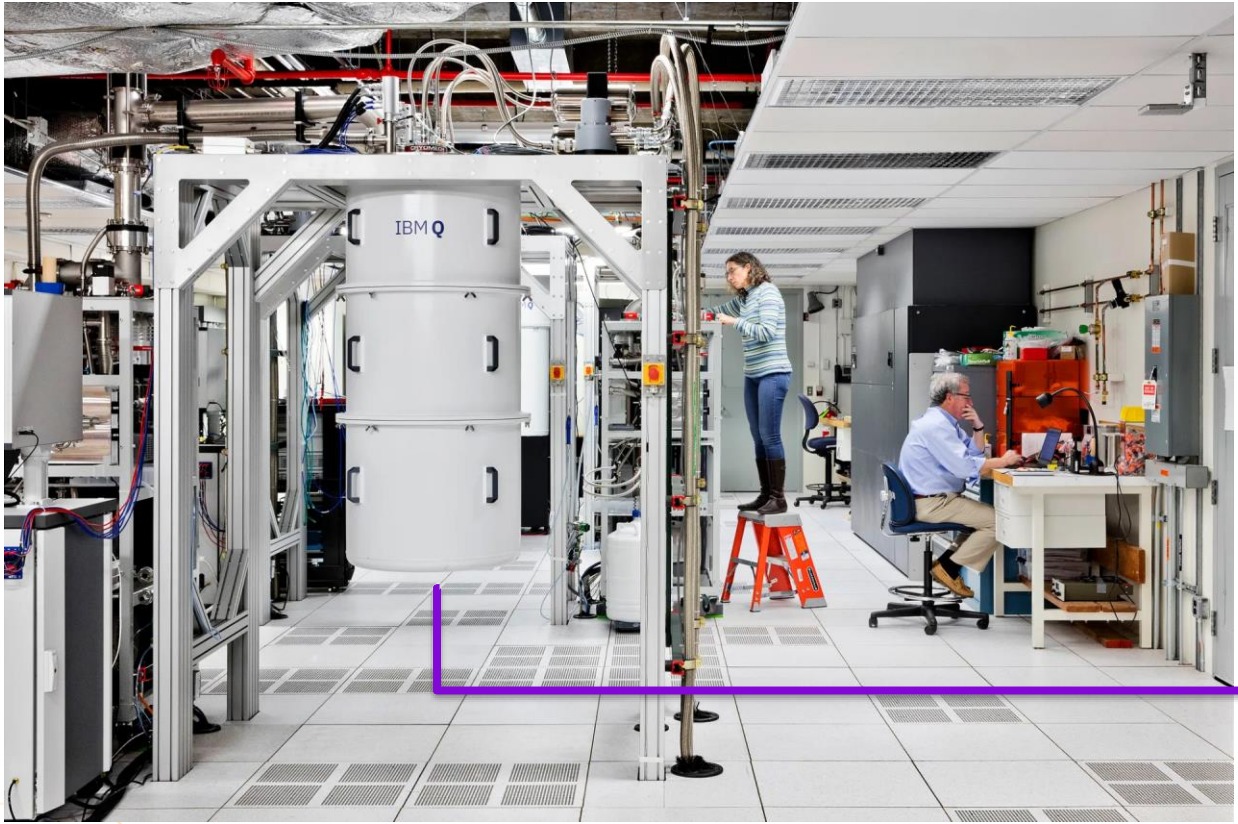
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Qubit	T1 (us)	T2 (us)	Frequency	Anharmor	Readout a	Prob meas0 p	Prob meas1 pre	Readout leng	ID error	Z-axis rotatio	âˆšx (sx) erroi	Pauli-X error	ECR error	Gate time (ns)	Operational
2	0	168.6064	18.33669	4.908524	-0.30803	0.2375	0.2628	0.2122	1400	0.0006255	0	0.000625504	0.000625504	0_14:0.01613164	0_14:660	TRUE
3	1	145.1158	130.2211	4.855718	0	0.1055	0.0842	0.1268	1400	0.00056889	0	0.00056889	0.00056889	1_2:0.010694311	1_2:660;1_0:660	TRUE
4	2	57.61654	36.06632	4.733157	-0.31092	0.0043	0.0048	0.0038	1400	0.00029821	0	0.000298211	0.000298211			TRUE
5	3	214.8084	47.68236	4.820081	-0.31055	0.1322	0.1024	0.162	1400	0.00046813	0	0.000468127	0.000468127	3_2:0.011534986	3_2:660	TRUE
6	4	245.8107	59.76318	4.854354	-0.31043	0.036667	0.023333333	0.05	1400	0.00024799	0	0.000247994	0.000247994	4_5:0.015414819	4_5:660;4_3:660	TRUE
7	5	35.68969	277.6362	4.727692	-0.3107	0.02	0.013333333	0.026666667	1400	0.00058605	0	0.000586046	0.000586046			TRUE
8	6	314.2023	297.1554	4.782687	-0.31015	0.018333	0.023333333	0.013333333	1400	0.00021366	0	0.000213657	0.000213657	6_5:0.018150457	6_5:660	TRUE
9	7	304.2644	146.0481	4.943912	-0.30798	0.0265	0.041	0.012	1400	0.00021921	0	0.000219205	0.000219205	7_6:0.007509108	7_6:660	TRUE
10	8	209.8465	106.7787	5.169272	-0.30532	0.014	0.007	0.021	1400	0.00023003	0	0.00023003	0.00023003	8_16:0.00957094	8_16:660;8_9:660;8_7:6	TRUE
11	9	312.8732	171.0547	4.935708	-0.30874	0.0063	0.007	0.0056	1400	0.00023164	0	0.000231635	0.000231635	9_10:0.00510809	9_10:660	TRUE
12	10	233.0737	55.55578	4.838635	-0.30966	0.0158	0.0162	0.0154	1400	0.00015617	0	0.000156166	0.000156166			TRUE
13	11	216.7796	254.8701	5.085454	-0.30508	0.0083	0.0094	0.0072	1400	0.00017863	0	0.000178632	0.000178632	11_10:0.0065817	11_10:660;11_12:660	TRUE
14	12	344.5276	133.3674	4.952372	-0.30811	0.011	0.0136	0.0084	1400	0.00078846	0	0.000788456	0.000788456	12_13:0.0058776	12_13:660	TRUE
15	13	276.7471	224.723	4.859094	-0.3086	0.003	0.004	0.002	1400	0.00013093	0	0.000130927	0.000130927			TRUE
16	14	163.6136	110.6744	4.941641	-0.30814	0.1356	0.1468	0.1244	1400	0.00094859	0	0.00094859	0.00094859			TRUE
17	15	251.4372	75.79088	4.965353	-0.30807	0.0225	0.0132	0.0318	1400	0.00018213	0	0.000182131	0.000182131	15_4:0.00573950	15_4:660	TRUE
18	16	177.4201	132.0287	4.989458	-0.30698	0.0098	0.0132	0.0064	1400	0.00032507	0	0.000325074	0.000325074	16_26:0.0056731	16_26:660	TRUE
19	17	271.48	184.0792	5.049796	-0.30572	0.0221	0.0302	0.014	1400	0.00026568	0	0.000265676	0.000265676	17_12:0.0061252	17_12:660;17_30:660	TRUE
20	18	293.1973	280.1017	4.840967	-0.30961	0.1226	0.1312	0.114	1400	0.00015759	0	0.000157594	0.000157594	18_14:0.0104632	18_14:660;18_19:660	TRUE
21	19	394.1418	51.59486	4.798659	-0.31048	0.042	0.047	0.037	1400	0.00135499	0	0.001354994	0.001354994	19_20:0.0137482	19_20:660	TRUE
22	20	296.6446	35.5345	4.731343	-0.31047	0.0111	0.0124	0.0098	1400	0.00032584	0	0.000325836	0.000325836			TRUE
23	21	252.9278	24.47747	4.832574	0	0.0279	0.019	0.0368	1400	0.00042617	0	0.000426172	0.000426172	21_20:0.0092756	21_20:660	TRUE

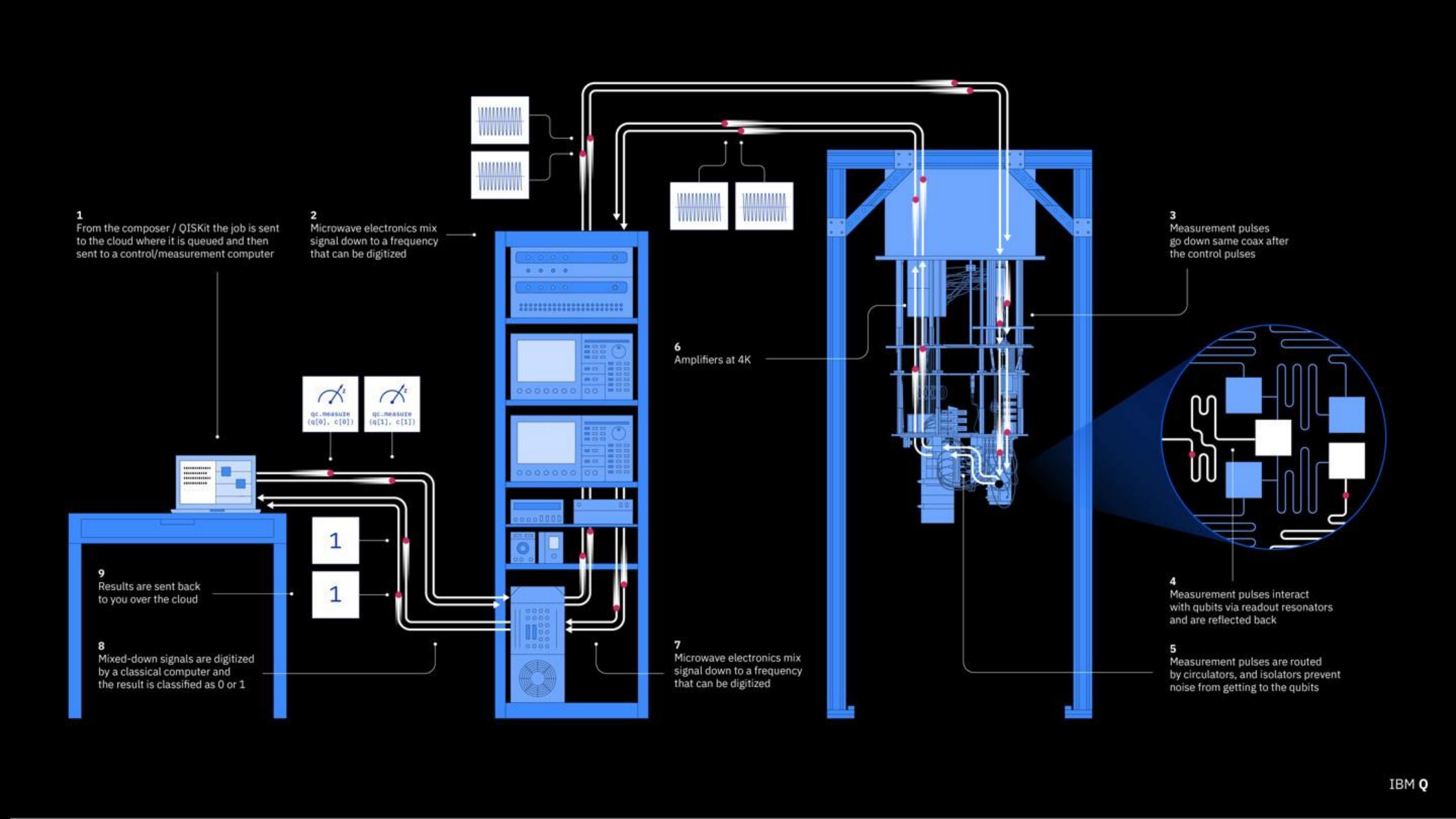
ibm_kyoto_calibrations_2024-08-

04

IBMQ Implementation

IBMQ Implementation

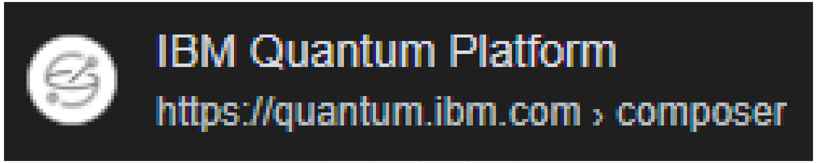



1
From the composer / QISKit the job is sent to the cloud where it is queued and then sent to a control/measurement computer
2
Microwave electronics mix signal down to a frequency that can be digitized
3
Measurement pulses go down same coax after the control pulses
4
Measurement pulses interact with qubits via readout resonators and are reflected back
5
Measurement pulses are routed by circulators, and isolators prevent noise from getting to the qubits
6
Amplifiers at 4K
7
Microwave electronics mix signal down to a frequency that can be digitized
8
Mixed-down signals are digitized by a classical computer and the result is classified as 0 or 1
9
Results are sent back to you over the cloud
qc.measure (q[0], c[0])
qc.measure (q[1], c[1])
1
1
IBM Q

IBMQ Implementation

What is IBM Quantum Composer?

- **Definition**: IBM Quantum Composer is a visual, drag-and-drop interface that allows users to design and execute quantum circuits on IBM's quantum computers.
- **Purpose**: It is designed for both beginners and experts to create, simulate, and run quantum circuits without needing to write code.

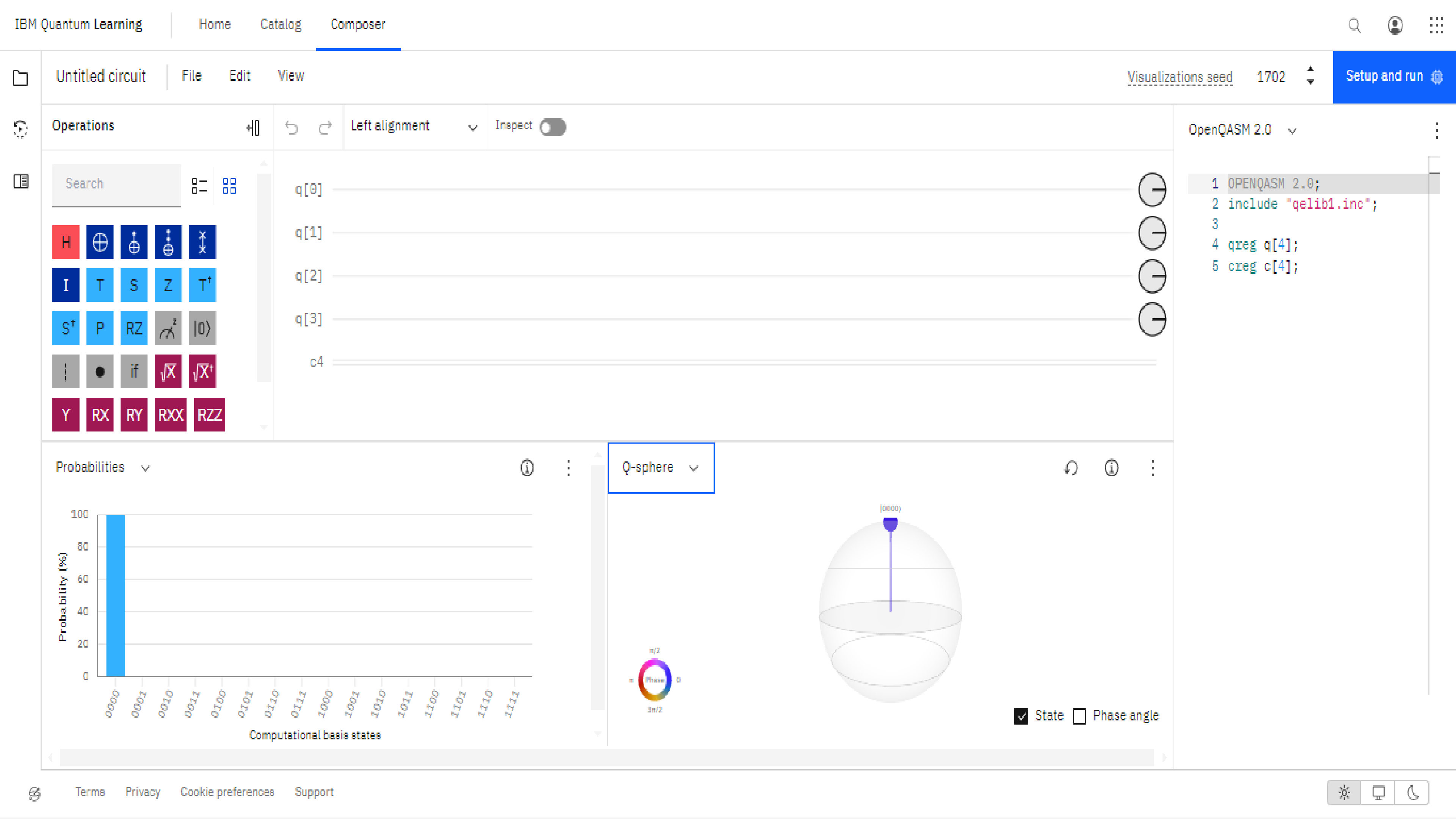


https://quantum.ibm.com/composer

IBMQ Implementation

Key Features:

- **Visual Circuit Design**: Users can construct quantum circuits by dragging and dropping quantum gates onto qubits, making it easy to visualize and build quantum algorithms.
- **Real-Time Simulation**: Quantum Composer offers the ability to simulate circuits in real-time, providing instant feedback on the circuit's behavior before running it on an actual quantum device.
- **Access to IBM Quantum Devices**: Circuits designed in Quantum Composer can be executed on IBM's cloud-accessible quantum computers, ranging from small to large-scale devices.
- **Quantum Assembly Language (QASM)**: For more advanced users, Quantum Composer provides access to the underlying QASM code, which can be edited directly for more precise control over the quantum circuit.


IBM Quantum Learning
Home
Catalog
Composer
Untitled circuit
File
Edit
View
Visualizations seed
1702
Setup and run
Operations
Left alignment
Inspect
OpenQASM 2.0
Search
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Z
T†
S†
P
RZ
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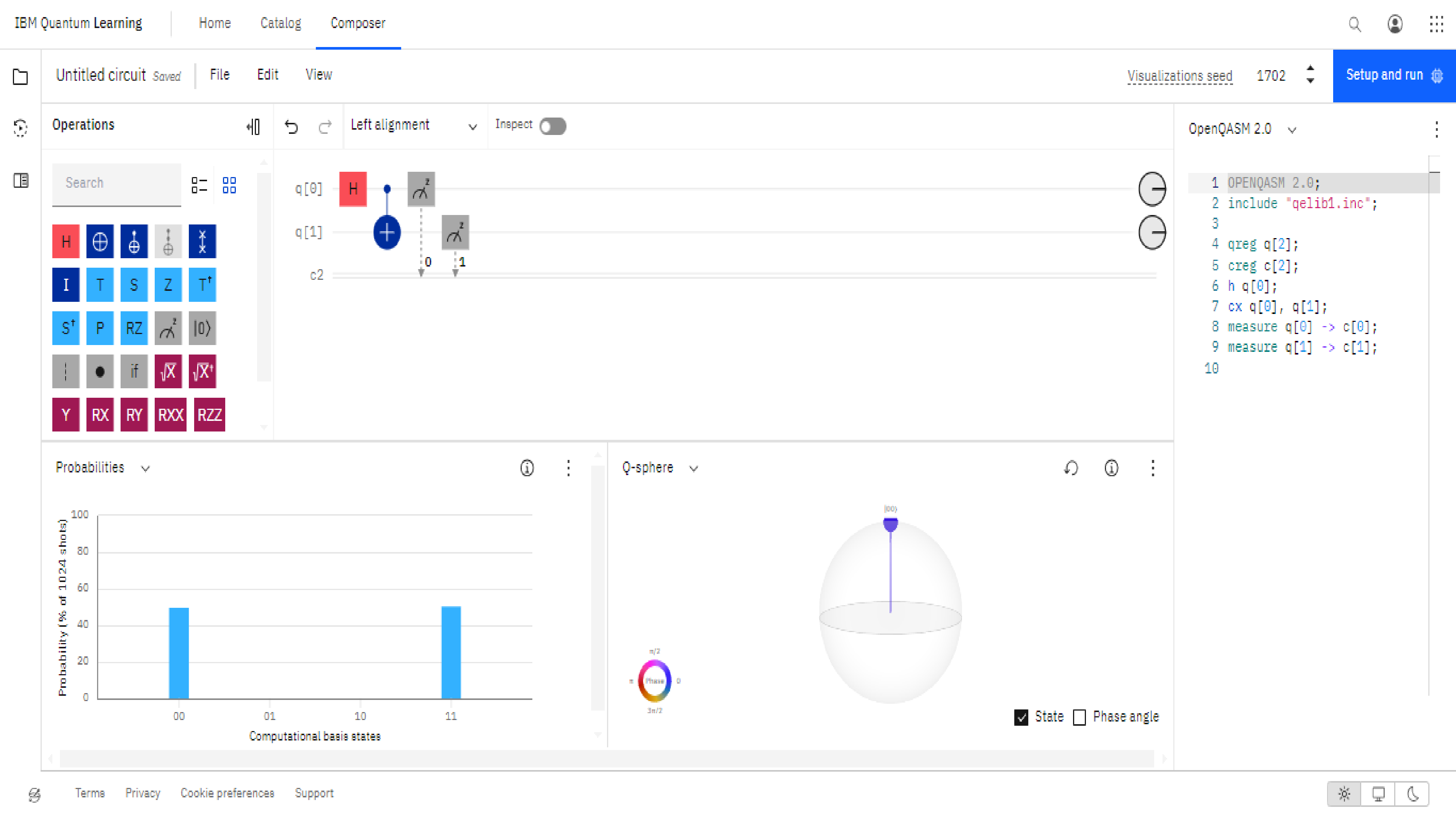
if
√X
√X†
Y
RX
RY
RXX
RZZ
q[0]
q[1]
q[2]
q[3]
c4
1 OPENQASM 2.0;
2 include "qelib1.inc";
3
4 qreg q[4];
5 creg c[4];
Probabilities
Q-sphere
100
80
60
40
20
0
Probability (%)
0000
0001
0010
0011
0100
0101
0110
0111
1000
1001
1010
1011
1100
1101
1110
1111
Computational basis states
State
Phase angle
Terms
Privacy
Cookie preferences
Support


IBM Quantum Learning
Home
Catalog
Composer
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View
Visualizations seed
1702
Setup and run
Operations
Left alignment
Inspect
OpenQASM 2.0
Search
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RZ
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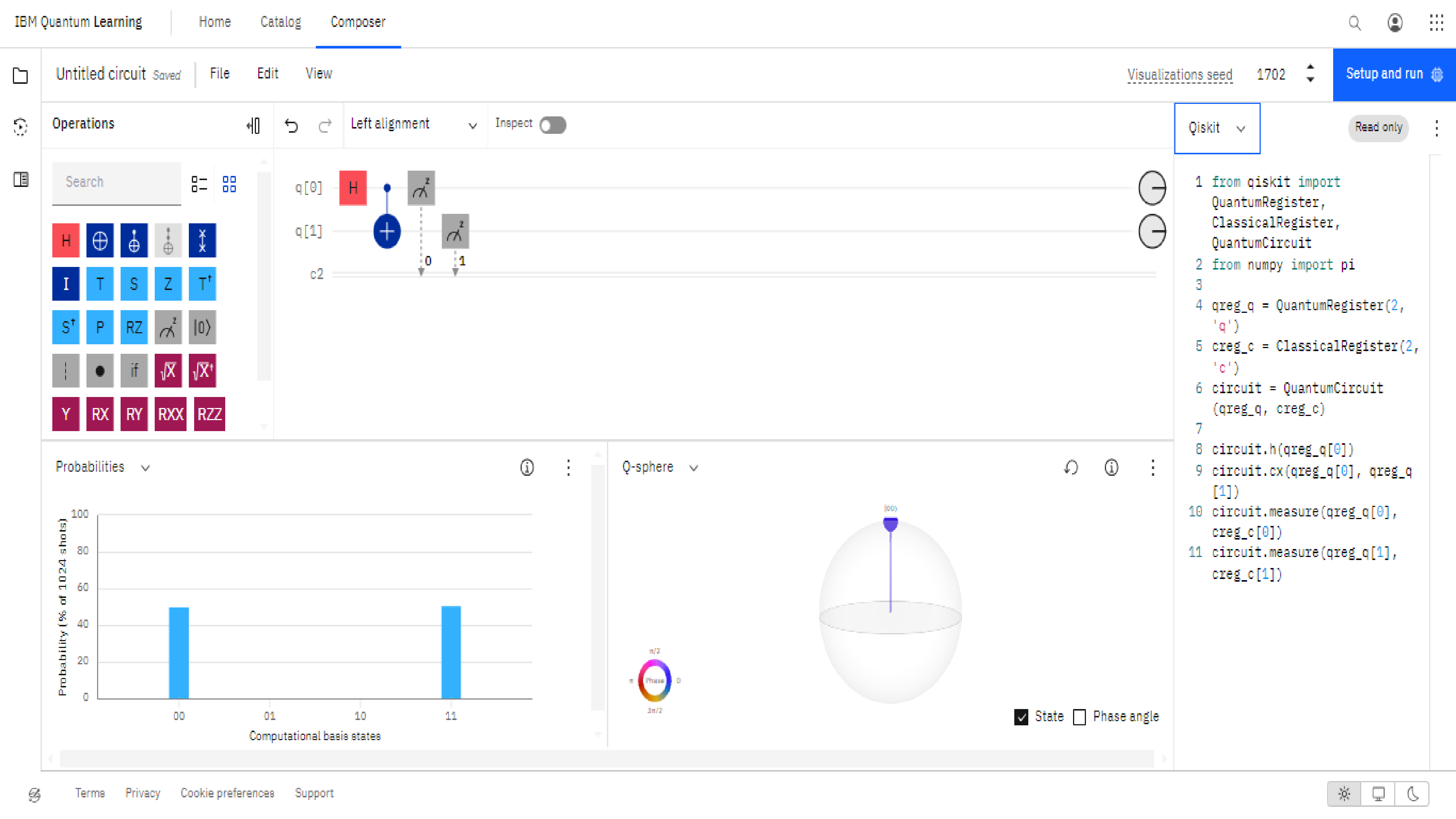
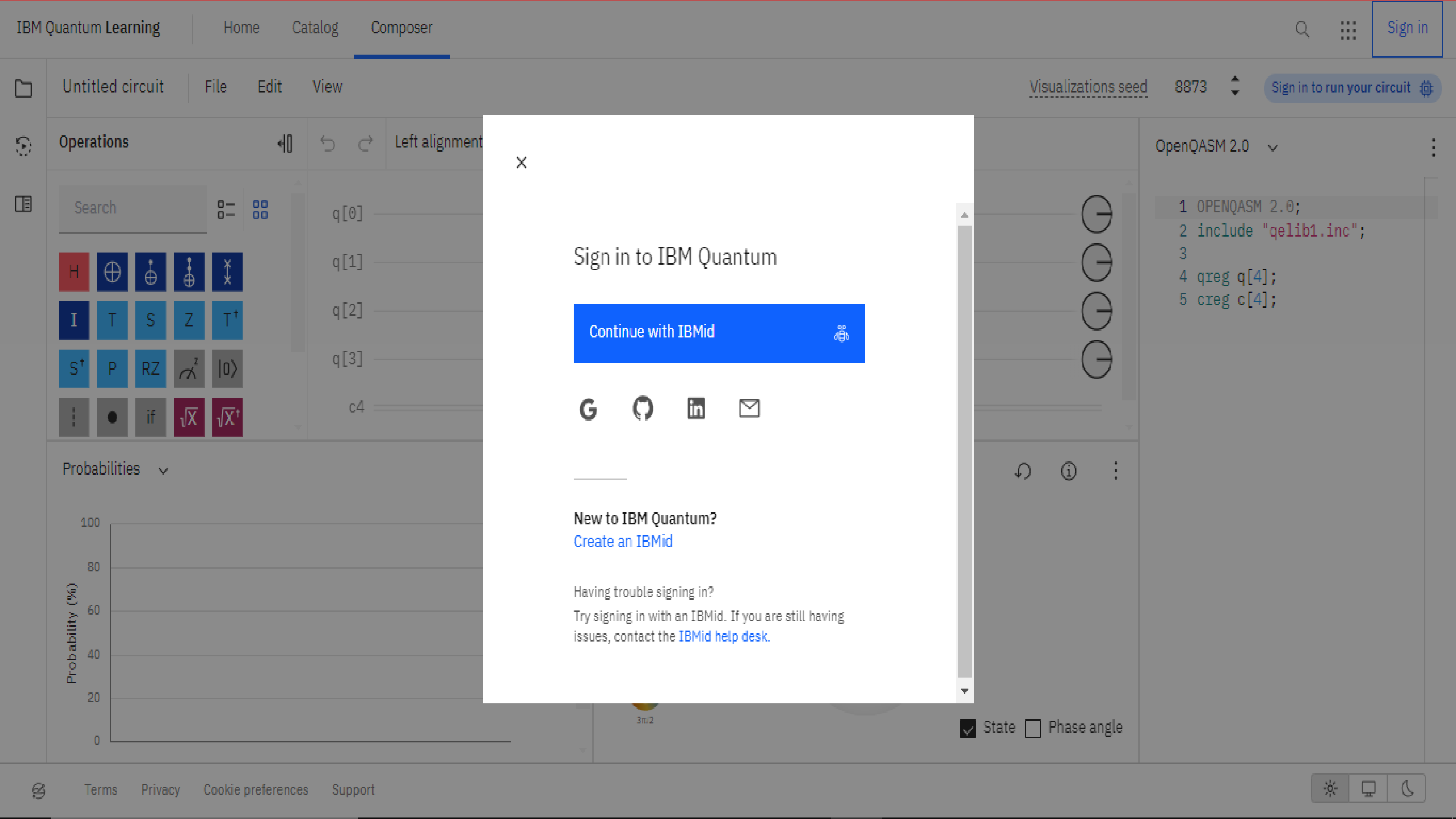
if
Y
RX
RY
RXX
RZZ
q[0]
q[1]
c2
0
1
OPENQASM 2.0;
include "qelib1.inc";
qreg q[2];
creg c[2];
h q[0];
cx q[0], q[1];
measure q[0] -> c[0];
measure q[1] -> c[1];
Probabilities
Probability (% of 1024 shots)
100
80
60
40
20
0
00
01
10
11
Computational basis states
Q-sphere
|00⟩
State
Phase angle
Terms
Privacy
Cookie preferences
Support


IBM Quantum Learning
Home
Catalog
Composer
Untitled circuit Saved
File
Edit
View
Visualizations seed
1702
Setup and run
Operations
Left alignment
Inspect
Qiskit
Read only
Search
q[0]
q[1]
c2
0
1
from qiskit import QuantumRegister, ClassicalRegister, QuantumCircuit
from numpy import pi
qreg_q = QuantumRegister(2, 'q')
creg_c = ClassicalRegister(2, 'c')
circuit = QuantumCircuit(qreg_q, creg_c)
circuit.h(qreg_q[0])
circuit.cx(qreg_q[0], qreg_q[1])
circuit.measure(qreg_q[0], creg_c[0])
circuit.measure(qreg_q[1], creg_c[1])
Probabilities
Probability (% of 1024 shots)
Computational basis states
00
01
10
11
Q-sphere
State
Phase angle
Terms
Privacy
Cookie preferences
Support


IBM Quantum Learning
Home
Catalog
Composer
Sign in
Untitled circuit
File
Edit
View
Visualizations seed
8873
Sign in to run your circuit
Operations
Left alignment
Search
H
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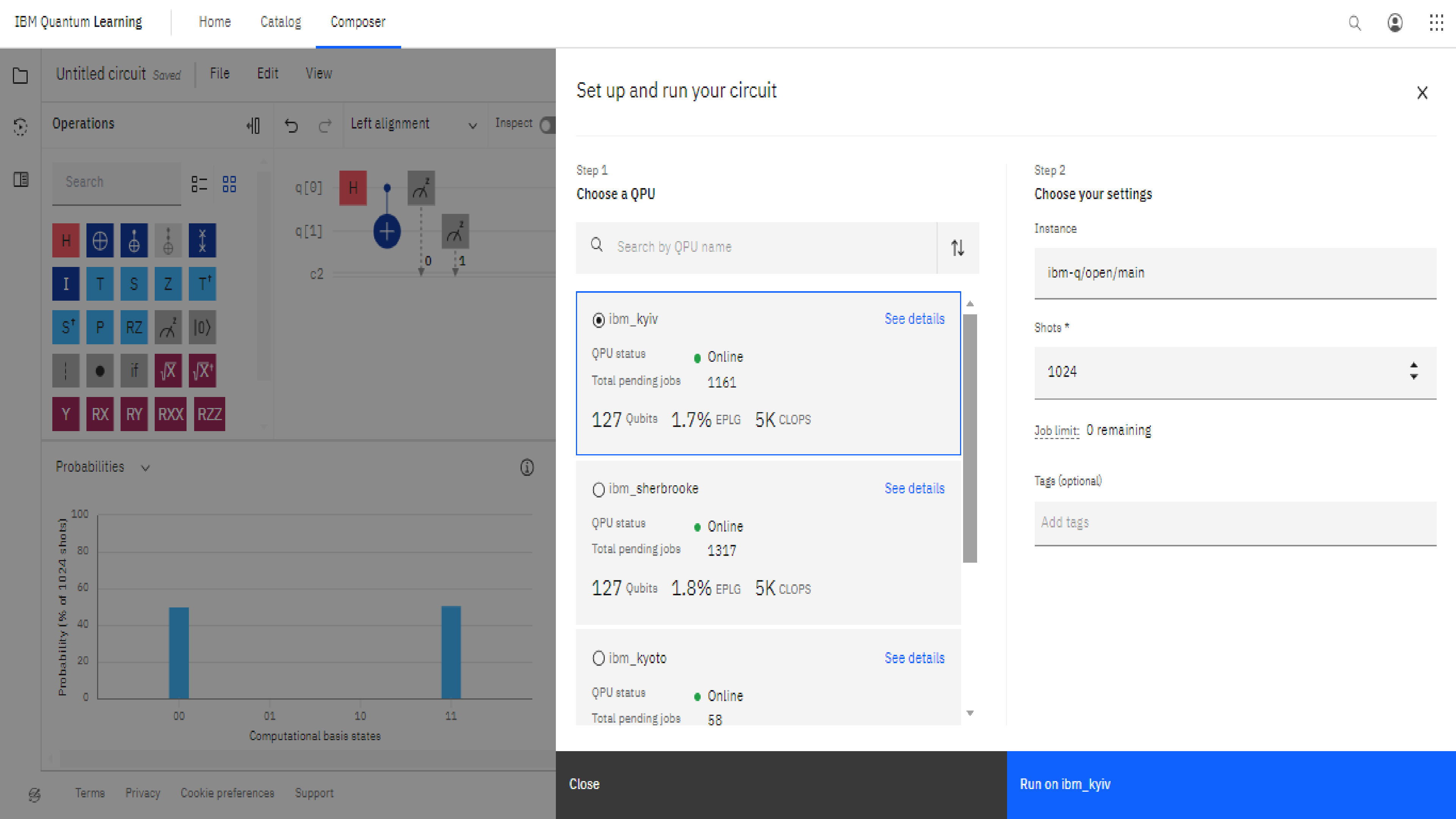
S
Z
RZ
P
if
q[0]
q[1]
q[2]
q[3]
c4
OpenQASM 2.0
1 OPENQASM 2.0;
2 include "qelib1.inc";
3
4 qreg q[4];
5 creg c[4];
Sign in to IBM Quantum
Continue with IBMid
New to IBM Quantum?
Create an IBMid
Having trouble signing in?
Try signing in with an IBMid. If you are still having issues, contact the IBMid help desk.
Probabilities
Probability (%)
100
80
60
40
20
0
State
Phase angle
Terms
Privacy
Cookie preferences
Support


IBM Quantum Learning
Home
Catalog
Composer
Untitled circuit Saved
File
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View
Operations
Left alignment
Inspect
Search
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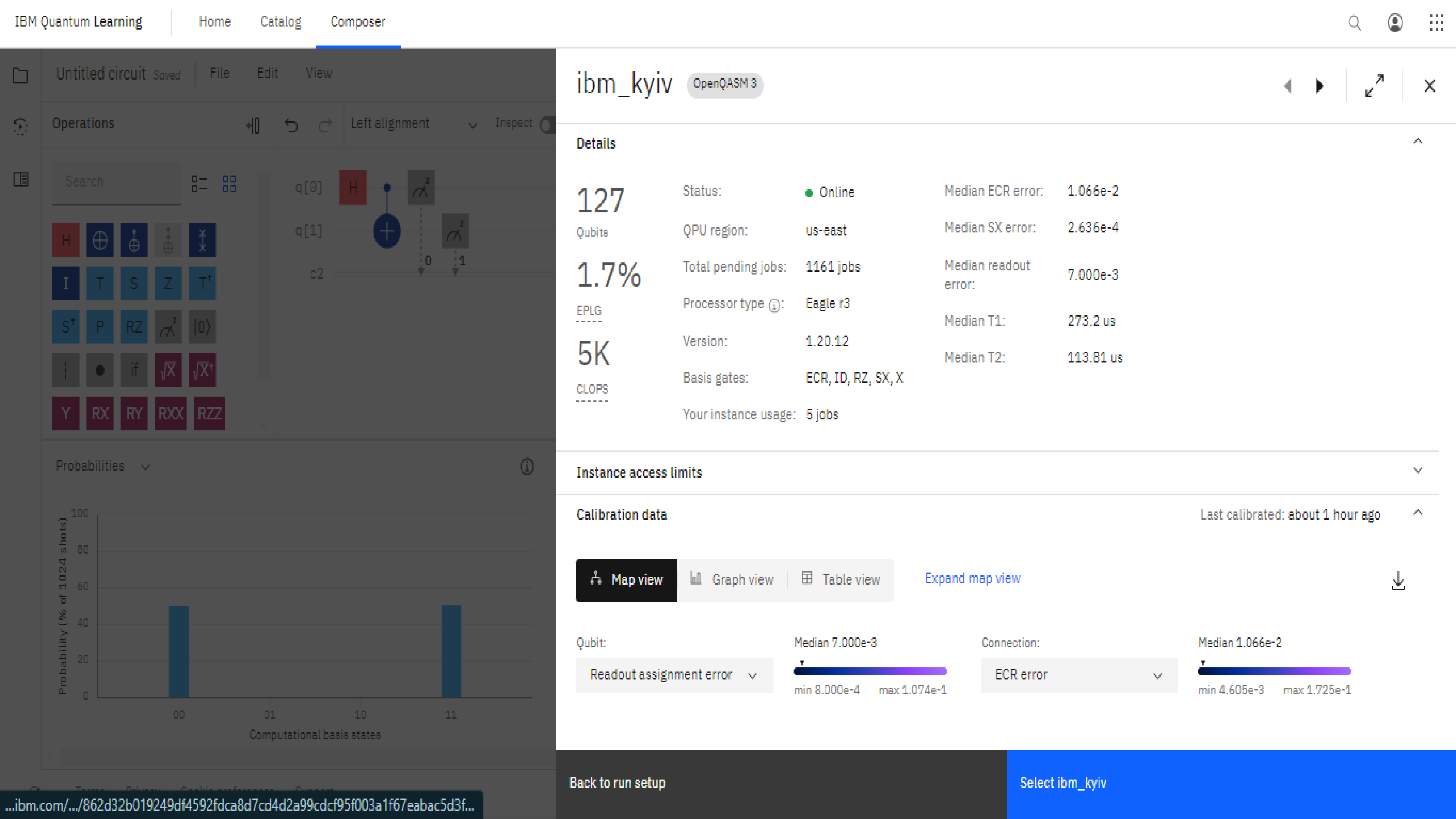
RZ
|0⟩
if
√X
√X†
Y
RX
RY
RXX
RZZ
q[0]
q[1]
c2
0
1
Probabilities
Probability (% of 1024 shots)
100
80
60
40
20
0
00
01
10
11
Computational basis states
Terms
Privacy
Cookie preferences
Support
Set up and run your circuit
Step 1
Choose a QPU
Search by QPU name
ibm_kyiv
See details
QPU status
Online
Total pending jobs
1161
127 Qubits 1.7% EPLG 5K CLOPS
ibm_sherbrooke
See details
QPU status
Online
Total pending jobs
1317
127 Qubits 1.8% EPLG 5K CLOPS
ibm_kyoto
See details
QPU status
Online
Total pending jobs
58
Step 2
Choose your settings
Instance
ibm-q/open/main
Shots *
1024
Job limit: 0 remaining
Tags (optional)
Add tags
Close
Run on ibm_kyiv


IBM Quantum Learning
Home
Catalog
Composer
Untitled circuit Saved
File
Edit
View
Operations
Left alignment
Inspect
Search
q[0]
q[1]
c2
0
1
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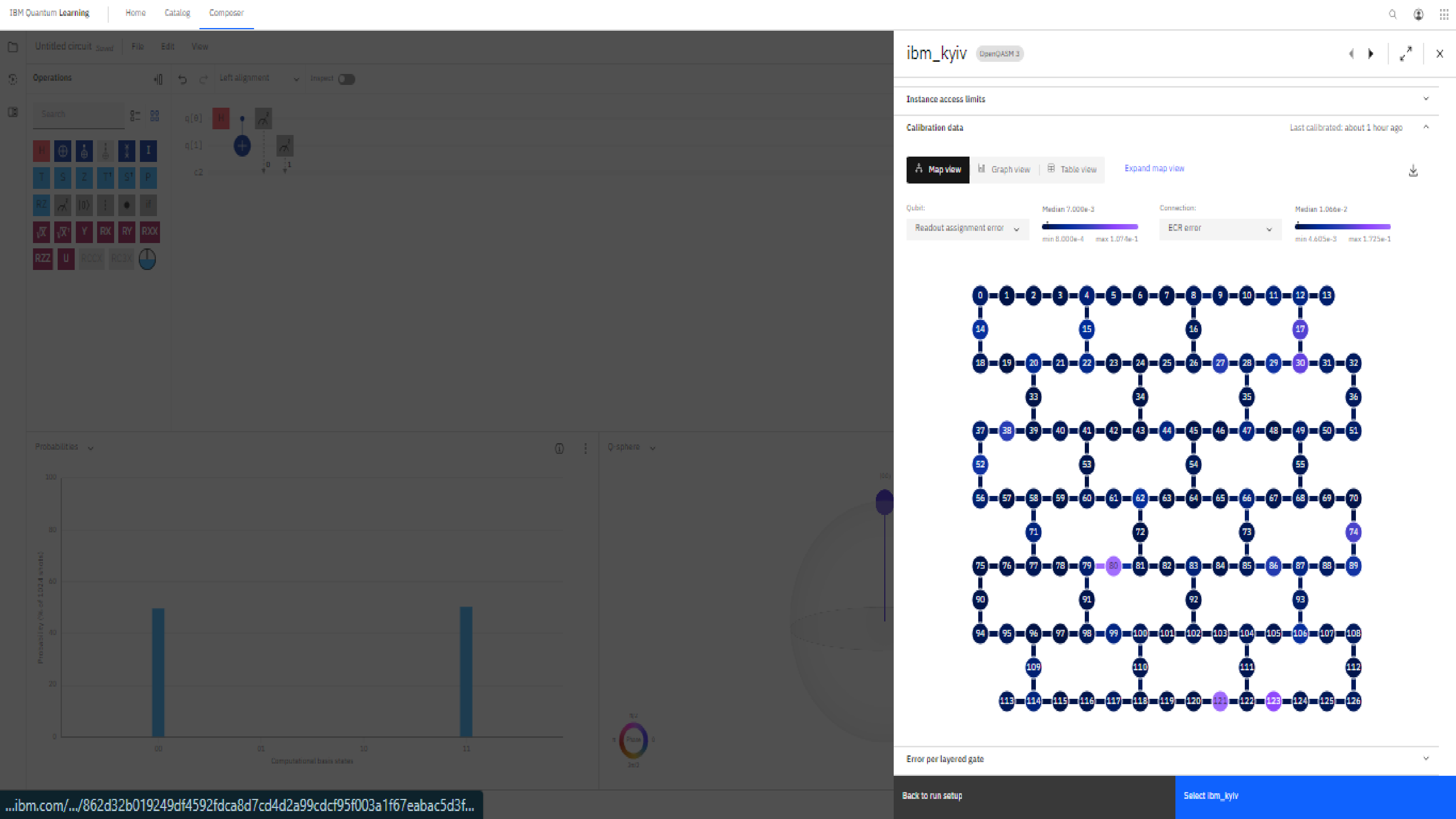
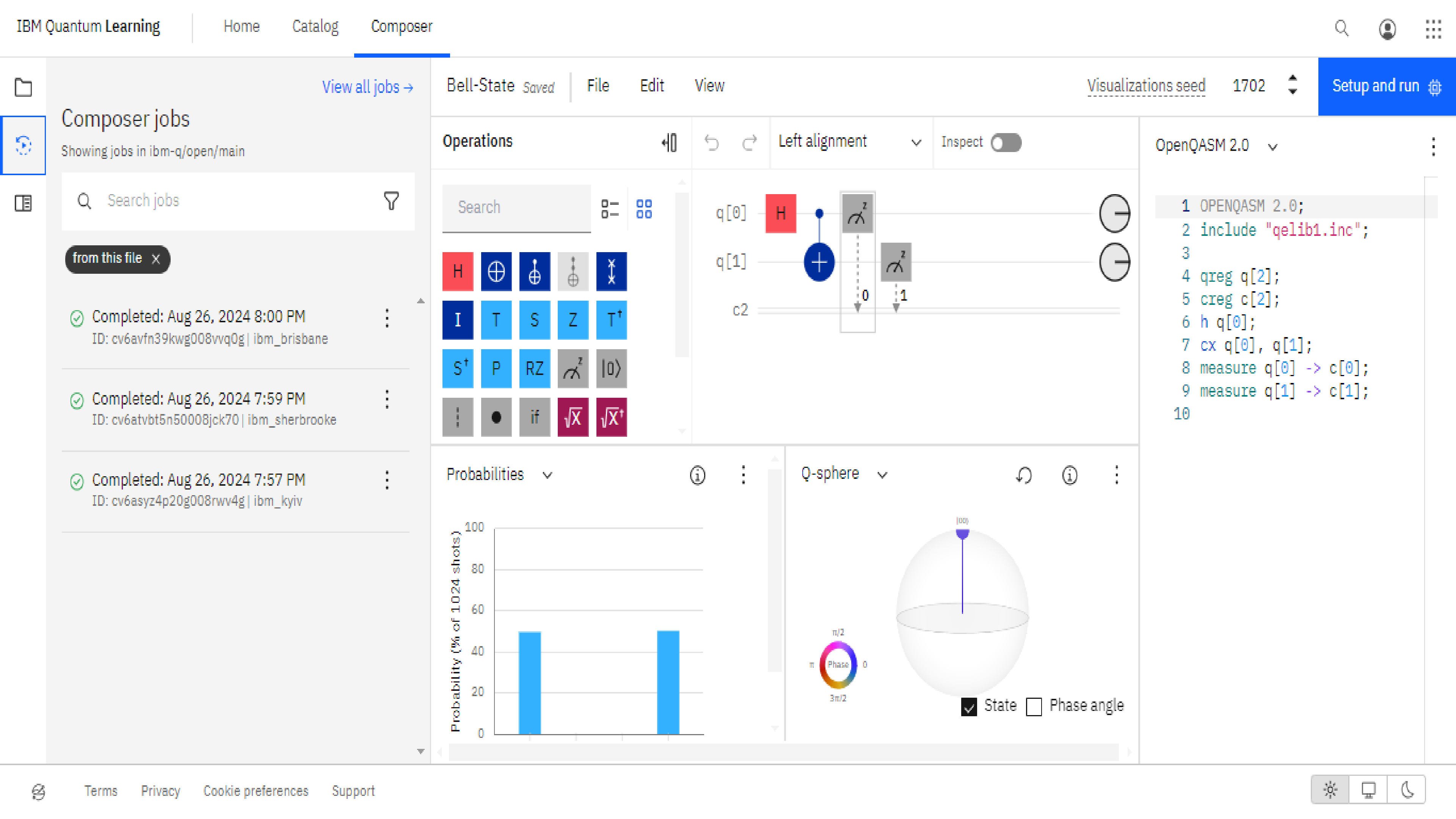
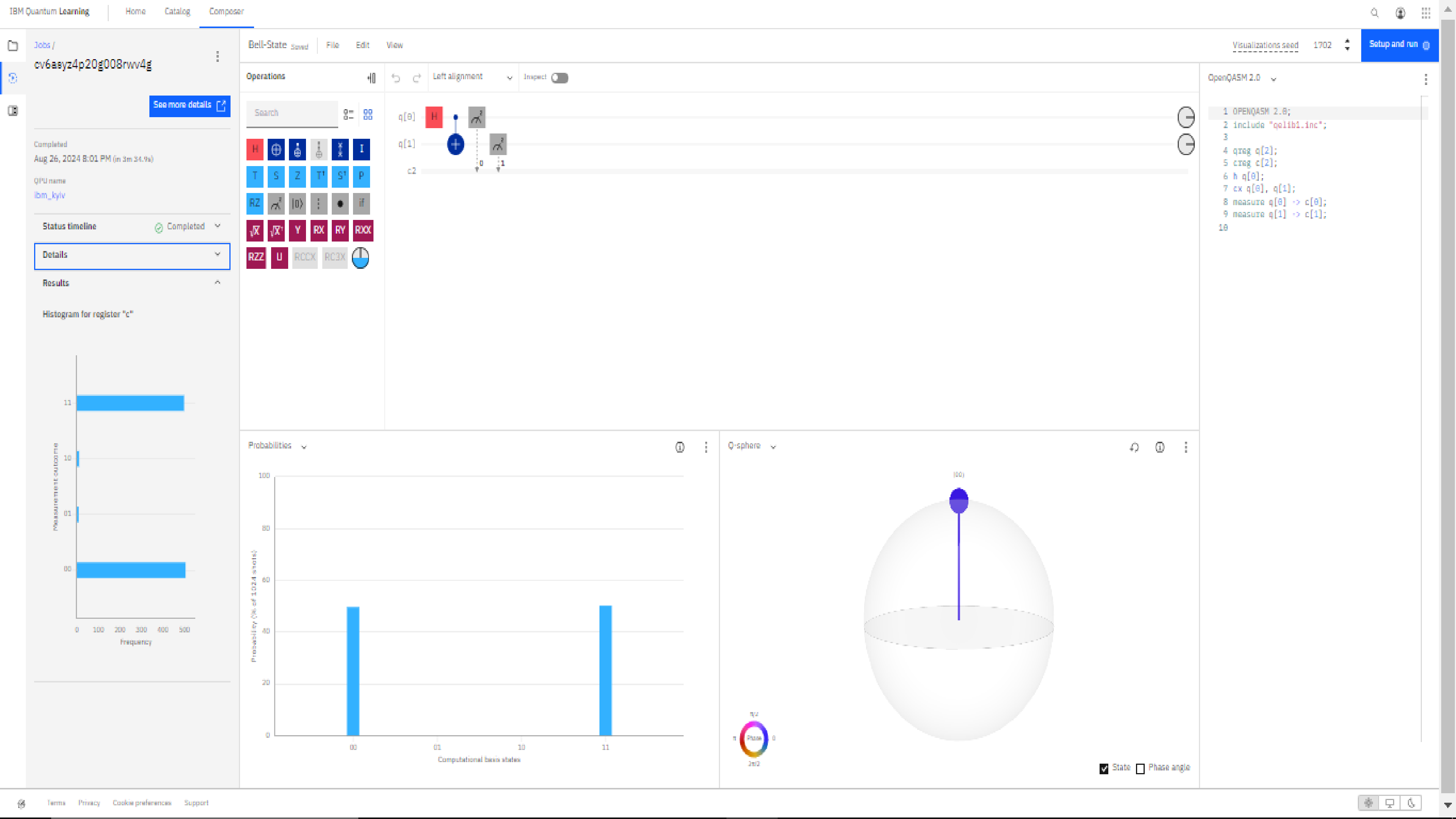
T
S
Z
RZ
|0⟩
if
√X
Y
RX
RY
RXX
RZZ
Probabilities
Probability (% of 1024 shots)
100
80
60
40
20
0
00
01
10
11
Computational basis states
ibm_kyiv
OpenQASM 3
Details
127
Qubits
1.7%
EPLG
5K
CLOPS
Status: Online
QPU region: us-east
Total pending jobs: 1161 jobs
Processor type: Eagle r3
Version: 1.20.12
Basis gates: ECR, ID, RZ, SX, X
Your instance usage: 5 jobs
Median ECR error: 1.066e-2
Median SX error: 2.636e-4
Median readout error: 7.000e-3
Median T1: 273.2 us
Median T2: 113.81 us
Instance access limits
Calibration data
Last calibrated: about 1 hour ago
Map view
Graph view
Table view
Expand map view
Qubit:
Readout assignment error
Median 7.000e-3
min 8.000e-4
max 1.074e-1
Connection:
ECR error
Median 1.066e-2
min 4.605e-3
max 1.725e-1
Back to run setup
Select ibm_kyiv
...ibm.com/.../862d32b019249df4592fdca8d7cd4d2a99cdcf95f003a1f67eabac5d3f...


IBM Quantum Learning
Home
Catalog
Composer
Untitled circuit
File
Edit
View
Operations
Left alignment
Inspect
Probabilities
Q-sphere
Computational basis states
ibm_kyiv
OpenQASM 3
Instance access limits
Calibration data
Last calibrated: about 1 hour ago
Map view
Graph view
Table view
Expand map view
Qubit:
Readout assignment error
Median 7.000e-3
min 8.000e-4
max 1.074e-1
Connection:
ECR error
Median 1.066e-2
min 4.605e-3
max 1.725e-1
Error per layered gate
Back to run setup
Select ibm_kyiv
...ibm.com/.../862d32b019249df4592fdca8d7cd4d2a99cdcf95f003a1f67eabac5d3f...


IBM Quantum Learning
Home
Catalog
Composer
View all jobs →
Composer jobs
Showing jobs in ibm-q/open/main
Search jobs
from this file
Completed: Aug 26, 2024 8:00 PM
ID: cv6avfn39kwg008vvq0g | ibm_brisbane
Completed: Aug 26, 2024 7:59 PM
ID: cv6atvbt5n50008jck70 | ibm_sherbrooke
Completed: Aug 26, 2024 7:57 PM
ID: cv6asyz4p20g008rwv4g | ibm_kyiv
Bell-State Saved
File
Edit
View
Visualizations seed
1702
Setup and run
Operations
Left alignment
Inspect
Search
H
I
T
S
Z
P
RZ
if
q[0]
q[1]
c2
0
1
OpenQASM 2.0
OPENQASM 2.0;
include "qelib1.inc";
qreg q[2];
creg c[2];
h q[0];
cx q[0], q[1];
measure q[0] -> c[0];
measure q[1] -> c[1];
Probabilities
Probability (% of 1024 shots)
100
80
60
40
20
0
Q-sphere
π/2
π
0
3π/2
Phase
State
Phase angle
Terms
Privacy
Cookie preferences
Support


IBM Quantum Learning
Home
Catalog
Composer
Jobs /
cv6asyz4p20g008rwv4g
See more details
Completed
Aug 26, 2024 8:01 PM
QPU name
ibm_kyiv
Status timeline
Completed
Details
Results
Histogram for register "c"
Frequency
Bell-State
File
Edit
View
Visualizations seed
1702
Setup and run
Operations
Left alignment
Inspect
Search
q[0]
q[1]
c2
OpenQASM 2.0
1 OPENQASM 2.0;
2 include "qelib1.inc";
4 qreg q[2];
5 creg c[2];
6 h q[0];
7 cx q[0], q[1];
8 measure q[0] -> c[0];
9 measure q[1] -> c[1];
Probabilities
Computational basis states
Q-sphere
State
Phase angle
Terms
Privacy
Cookie preferences
Support

All workloads /

cv6asyz4p20g008rwv4g

Edit Tags

Details

Mode: Job

QPU name: ibm_kyiv

Instance: ibm-q/open/main

Sent from: Bell-State

Program: sampler

# of PUBs: 1

Status details

Status

Completed

Usage stats

Actual usage

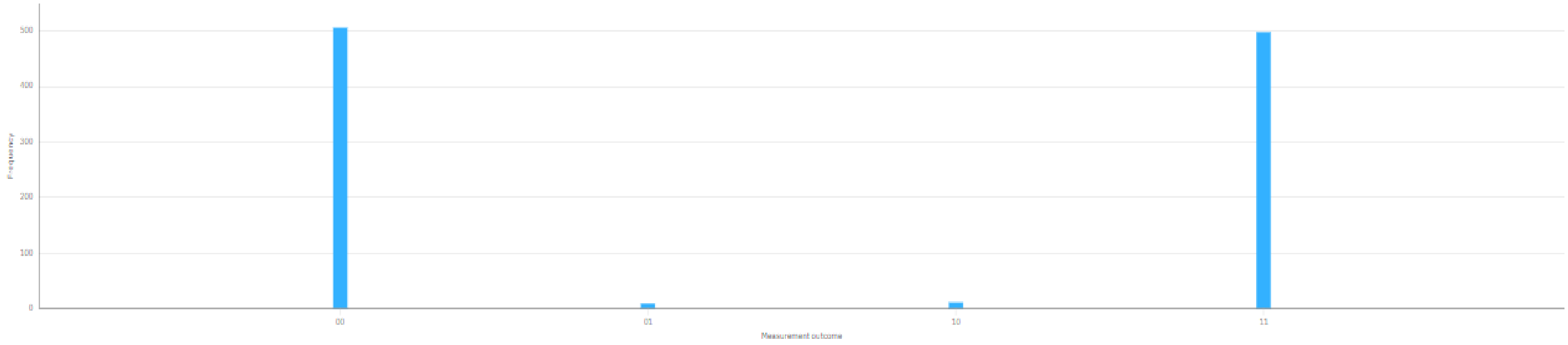
2s

Status timeline

- Created: Aug 26, 2024 7:57 PM
- Pending: 1m 11.6s
- In progress: Aug 26, 2024 7:58 PM
  Qiskit runtime usage: 2s
- Completed: Aug 26, 2024 8:01 PM

Total completion time: 3m 34.9s

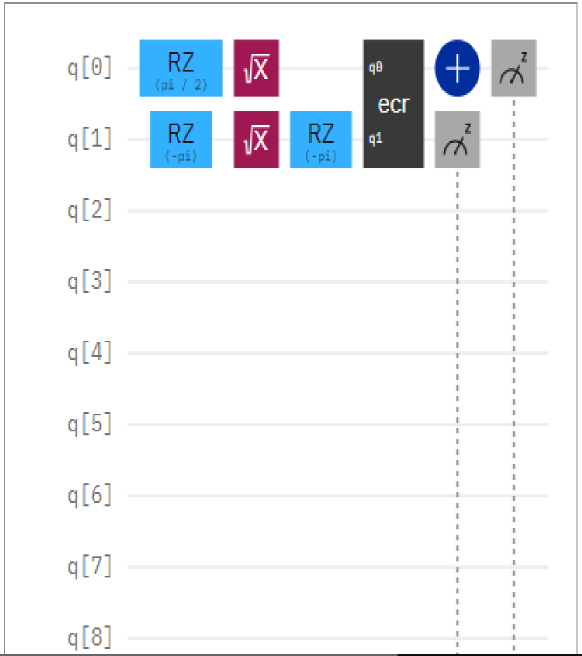
Histogram for register "c"

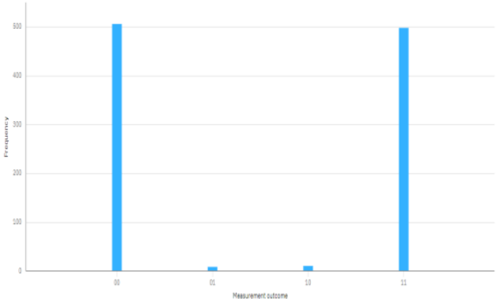


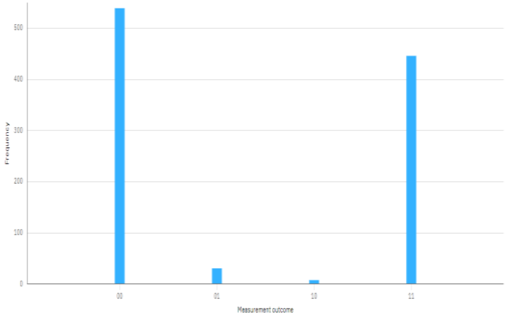
Circuit

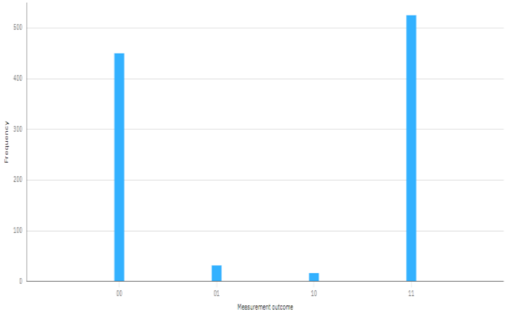
Circuit

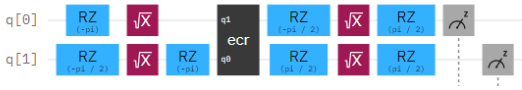
Diagram | Qasm | Qiskit

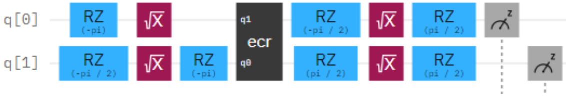












ibm_kyiv OpenQASM 3

Details

127 Qubits

1.7% EPLG

5K CLOPS

Status: Online
QPU region: us-east
Total pending jobs: 1006 jobs
Processor type: Eagle r3
Version: 1.20.12
Basis gates: ECR, ID, RZ, SX, X
Your instance usage: 0 jobs

Median ECR error: 1.142e-2
Median SX error: 2.695e-4
Median readout error: 6.700e-3
Median T1: 269.55 us
Median T2: 119.44 us

ibm_sherbrooke OpenQASM 3

Details

127 Qubits

2.3% EPLG

5K CLOPS

Status: Online
QPU region: us-east
Total pending jobs: 2080 jobs
Processor type: Eagle r3
Version: 1.5.13
Basis gates: ECR, ID, RZ, SX, X
Your instance usage: 0 jobs

Median ECR error: 8.121e-3
Median SX error: 2.366e-4
Median readout error: 1.240e-2
Median T1: 287.31 us
Median T2: 193.33 us

ibm_brisbane OpenQASM 3

Details

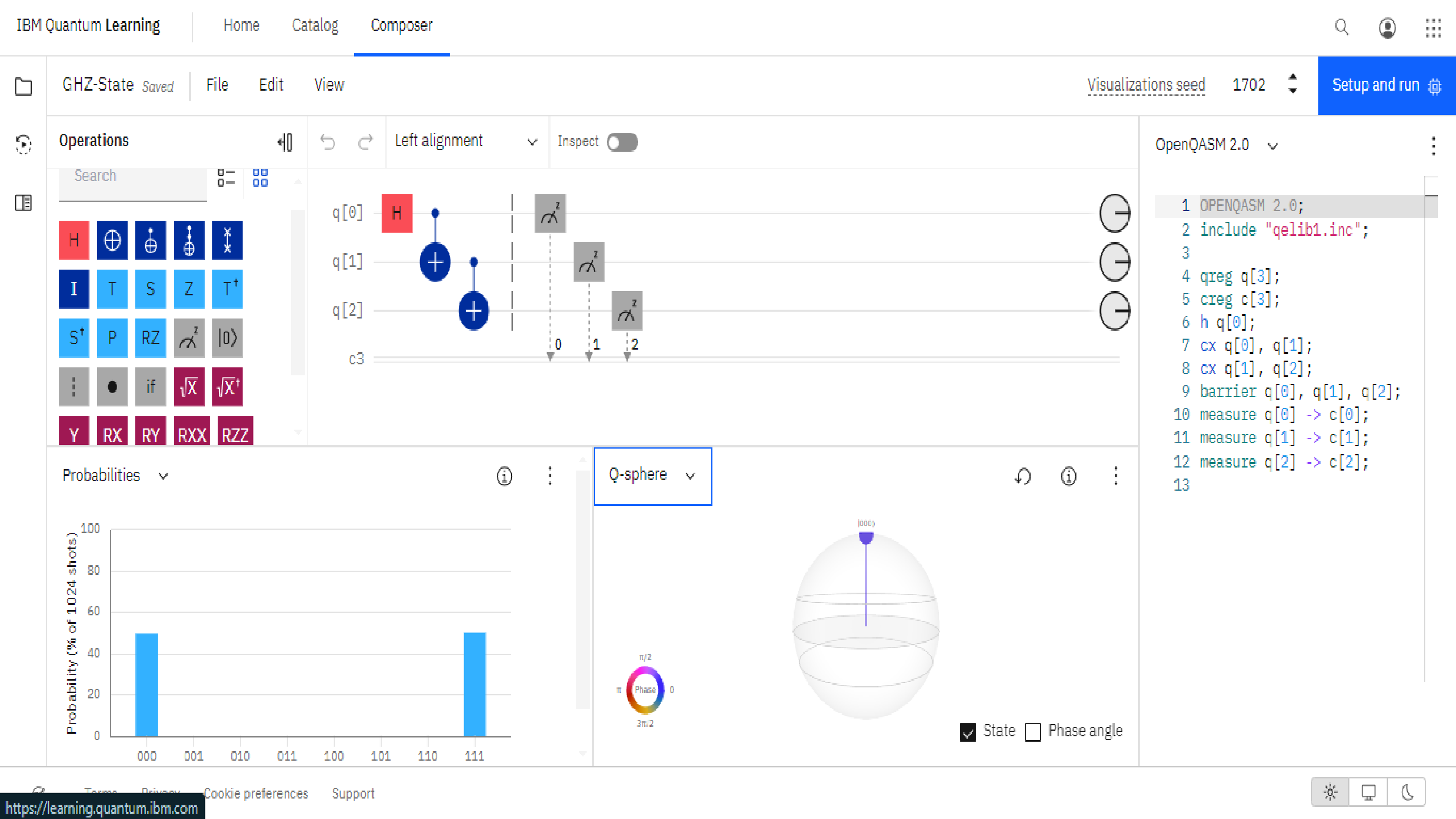
127 Qubits

4.2% EPLG

5K CLOPS

Status: Online
QPU region: us-east
Total pending jobs: 61 jobs
Processor type: Eagle r3
Version: 1.1.33
Basis gates: ECR, ID, RZ, SX, X
Your instance usage: 0 jobs

Median ECR error: 7.589e-3
Median SX error: 2.377e-4
Median readout error: 1.420e-2
Median T1: 227.09 us
Median T2: 134.42 us


IBM Quantum Learning
Home
Catalog
Composer
GHZ-State Saved
File
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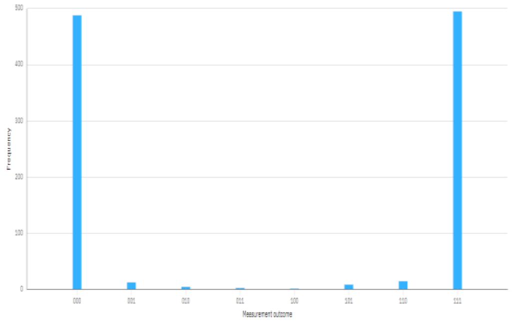
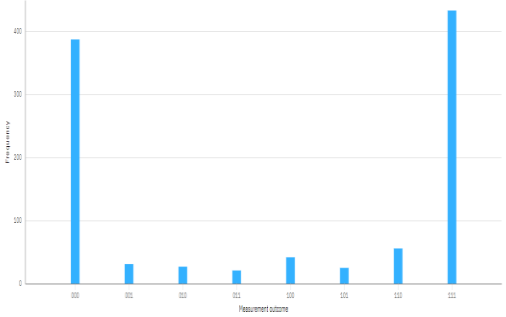
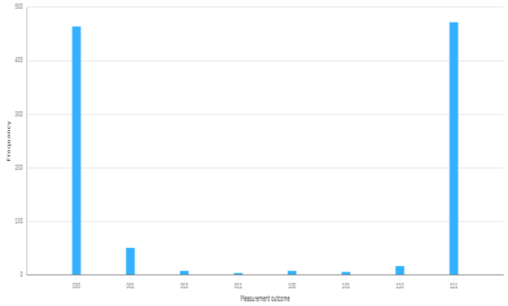
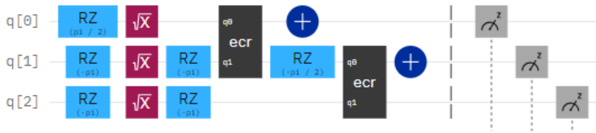
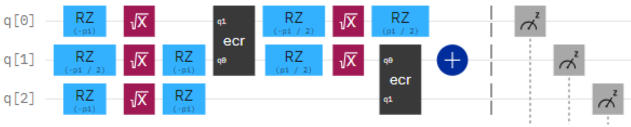
View
Visualizations seed
1702
Setup and run
Operations
Search
Left alignment
Inspect
q[0]
q[1]
q[2]
c3
H
0
1
2
OpenQASM 2.0
1 OPENQASM 2.0;
2 include "qelib1.inc";
3
4 qreg q[3];
5 creg c[3];
6 h q[0];
7 cx q[0], q[1];
8 cx q[1], q[2];
9 barrier q[0], q[1], q[2];
10 measure q[0] -> c[0];
11 measure q[1] -> c[1];
12 measure q[2] -> c[2];
13
Probabilities
Probability (% of 1024 shots)
100
80
60
40
20
0
000
001
010
011
100
101
110
111
Q-sphere
|000⟩
π/2
π
Phase
0
3π/2
State
Phase angle
Cookie preferences
Support
https://learning.quantum.ibm.com

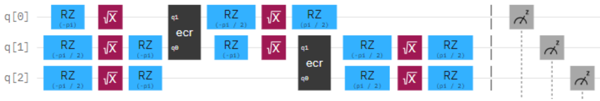












ibm_kyiv OpenQASM 3

Details

127 Qubits

1.7% EPLG

5K CLOPS

Status:	Online
QPU region:	us-east
Total pending jobs:	1006 jobs
Processor type:	Eagle r3
Version:	1.20.12
Basis gates:	ECR, ID, RZ, SX, X
Your instance usage:	0 jobs
Median ECR error:	1.142e-2
Median SX error:	2.695e-4
Median readout error:	6.700e-3
Median T1:	269.55 us
Median T2:	119.44 us

ibm_kyoto OpenQASM 3

Details

127 Qubits

3.2% EPLG

5K CLOPS

Status:	Online
QPU region:	us-east
Total pending jobs:	2 jobs
Processor type:	Eagle r3
Version:	1.2.40
Basis gates:	ECR, ID, RZ, SX, X
Your instance usage:	0 jobs
Median ECR error:	1.069e-2
Median SX error:	3.326e-4
Median readout error:	1.810e-2
Median T1:	215.91 us
Median T2:	87.55 us

ibm_brisbane OpenQASM 3

Details

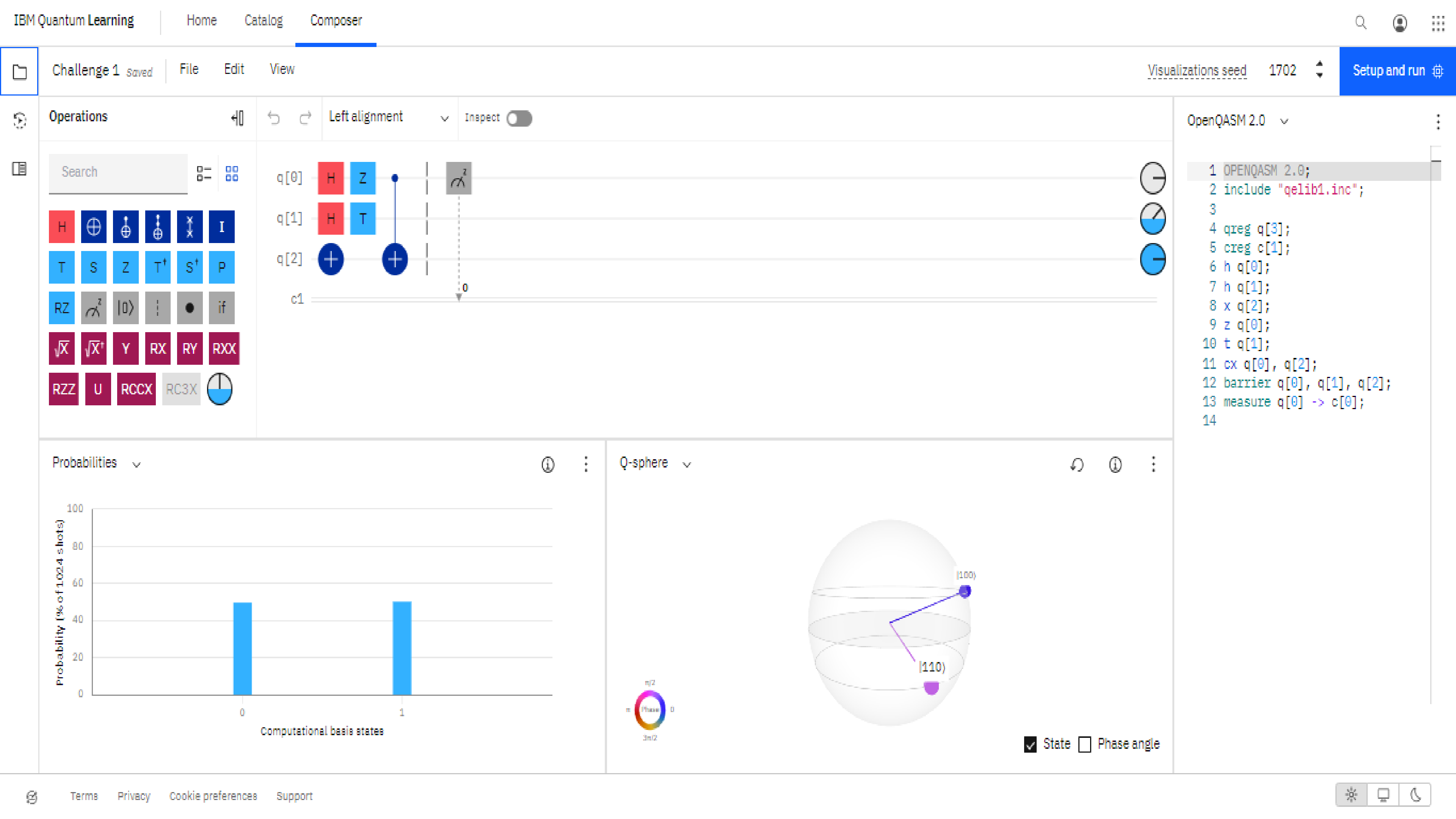
127 Qubits

4.2% EPLG

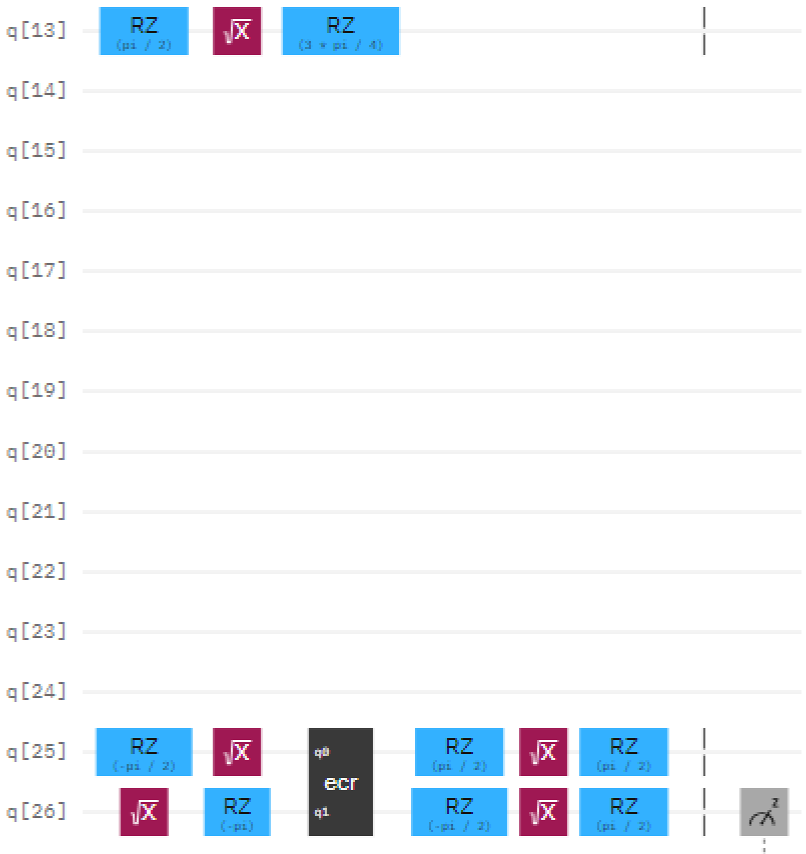
5K CLOPS

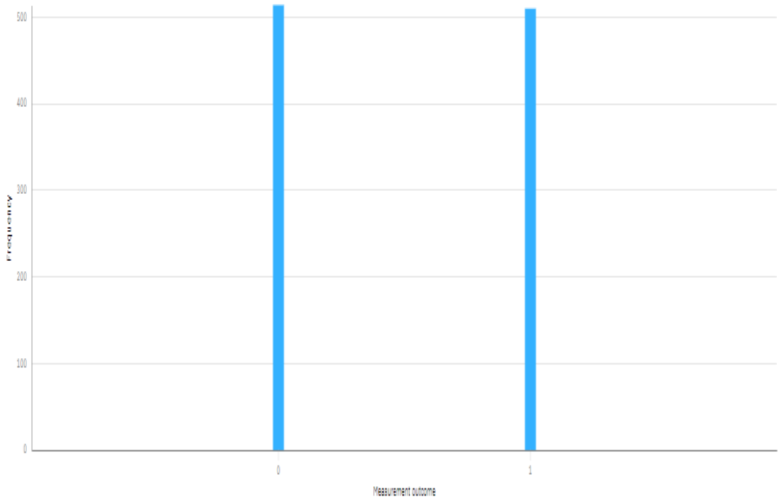
Status:	Online
QPU region:	us-east
Total pending jobs:	61 jobs
Processor type:	Eagle r3
Version:	1.1.33
Basis gates:	ECR, ID, RZ, SX, X
Your instance usage:	0 jobs
Median ECR error:	7.589e-3
Median SX error:	2.377e-4
Median readout error:	1.420e-2
Median T1:	227.09 us
Median T2:	134.42 us

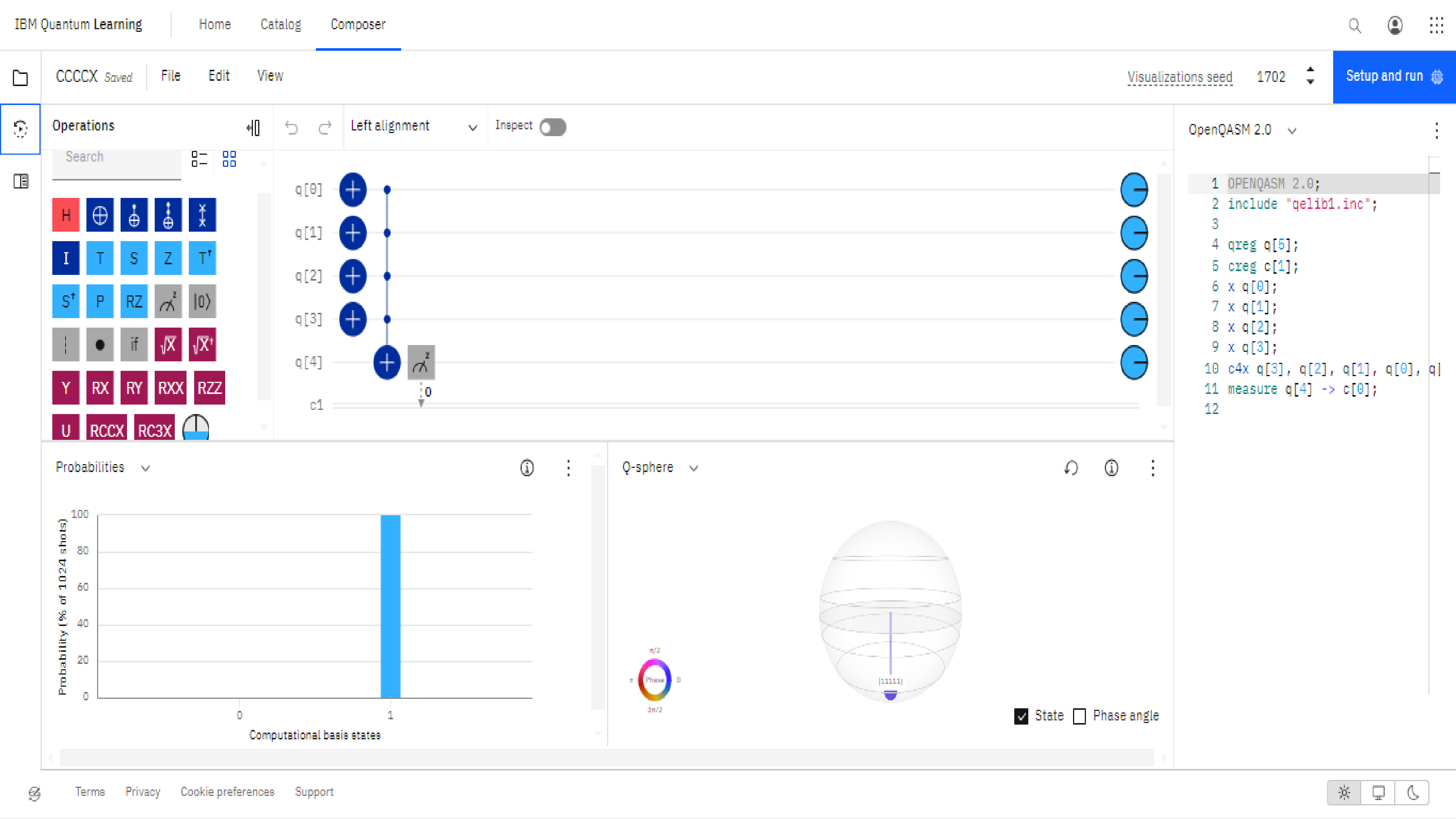
اطلس کوانتوم


IBM Quantum Learning
Home
Catalog
Composer
Challenge 1 Saved
File
Edit
View
Visualizations seed
1702
Setup and run
Operations
Search
Left alignment
Inspect
OpenQASM 2.0
H
I
T
S
Z
P
RZ
if
Y
RX
RY
RXX
RZZ
U
RCCX
RC3X
q[0]
q[1]
q[2]
c1
OPENQASM 2.0;
include "qelib1.inc";
qreg q[3];
creg c[1];
h q[0];
h q[1];
x q[2];
z q[0];
t q[1];
cx q[0], q[2];
barrier q[0], q[1], q[2];
measure q[0] -> c[0];
Probabilities
Probability (% of 1024 shots)
Computational basis states
Q-sphere
|100⟩
|110⟩
State
Phase angle
Terms
Privacy
Cookie preferences
Support

ibm_kyoto


q[13]
q[14]
q[15]
q[16]
q[17]
q[18]
q[19]
q[20]
q[21]
q[22]
q[23]
q[24]
q[25]
q[26]
RZ
√X
ecr
q0
q1




IBM Quantum Learning
Home
Catalog
Composer
CCCCX Saved
File
Edit
View
Visualizations seed
1702
Setup and run
Operations
Search
Left alignment
Inspect
H
I
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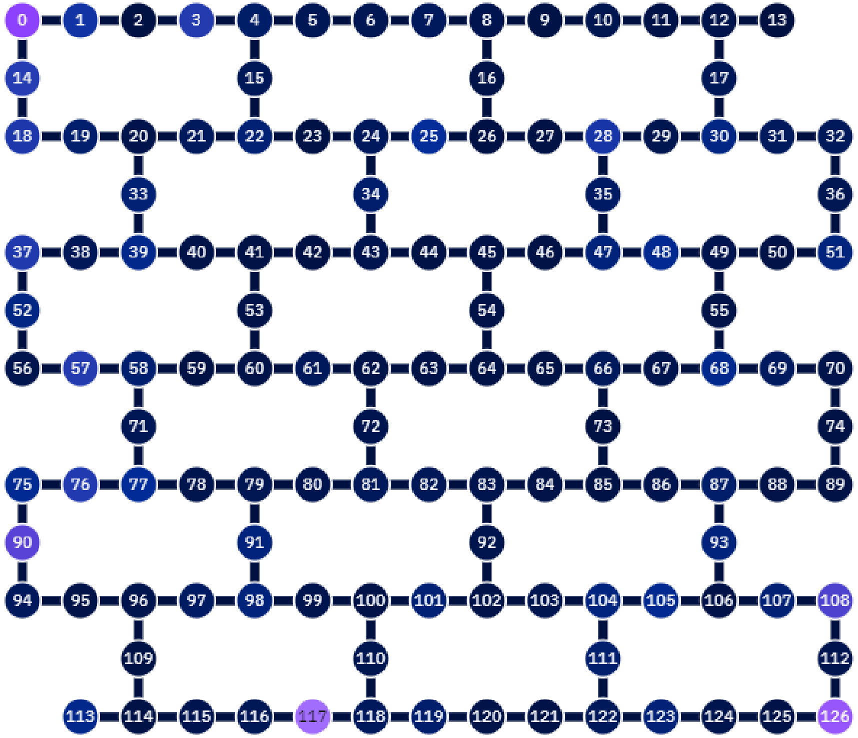
S
Z
S†
P
RZ
|0⟩
if
√X
√X†
Y
RX
RY
RXX
RZZ
U
RCCX
RC3X
q[0]
q[1]
q[2]
q[3]
q[4]
c1
0
OpenQASM 2.0
OPENQASM 2.0;
include "qelib1.inc";
qreg q[5];
creg c[1];
x q[0];
x q[1];
x q[2];
x q[3];
c4x q[3], q[2], q[1], q[0], q[
measure q[4] -> c[0];
Probabilities
Probability (% of 1024 shots)
100
80
60
40
20
0
0
1
Computational basis states
Q-sphere
|11111⟩
State
Phase angle
Terms
Privacy
Cookie preferences
Support

اطلس کوانتوم



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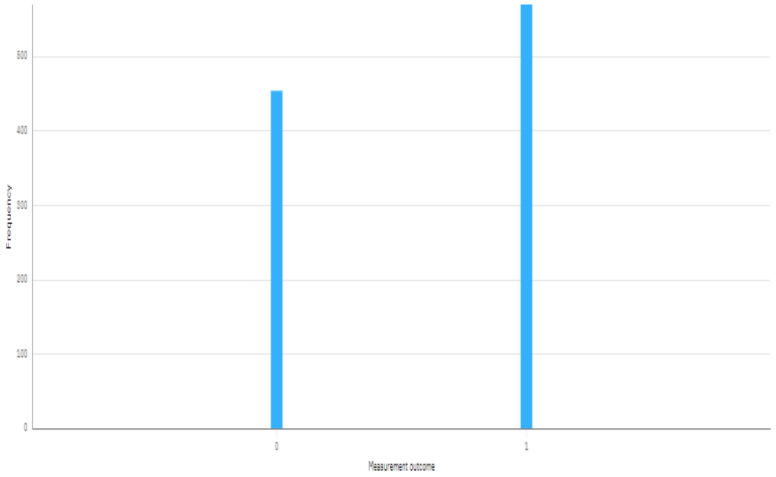
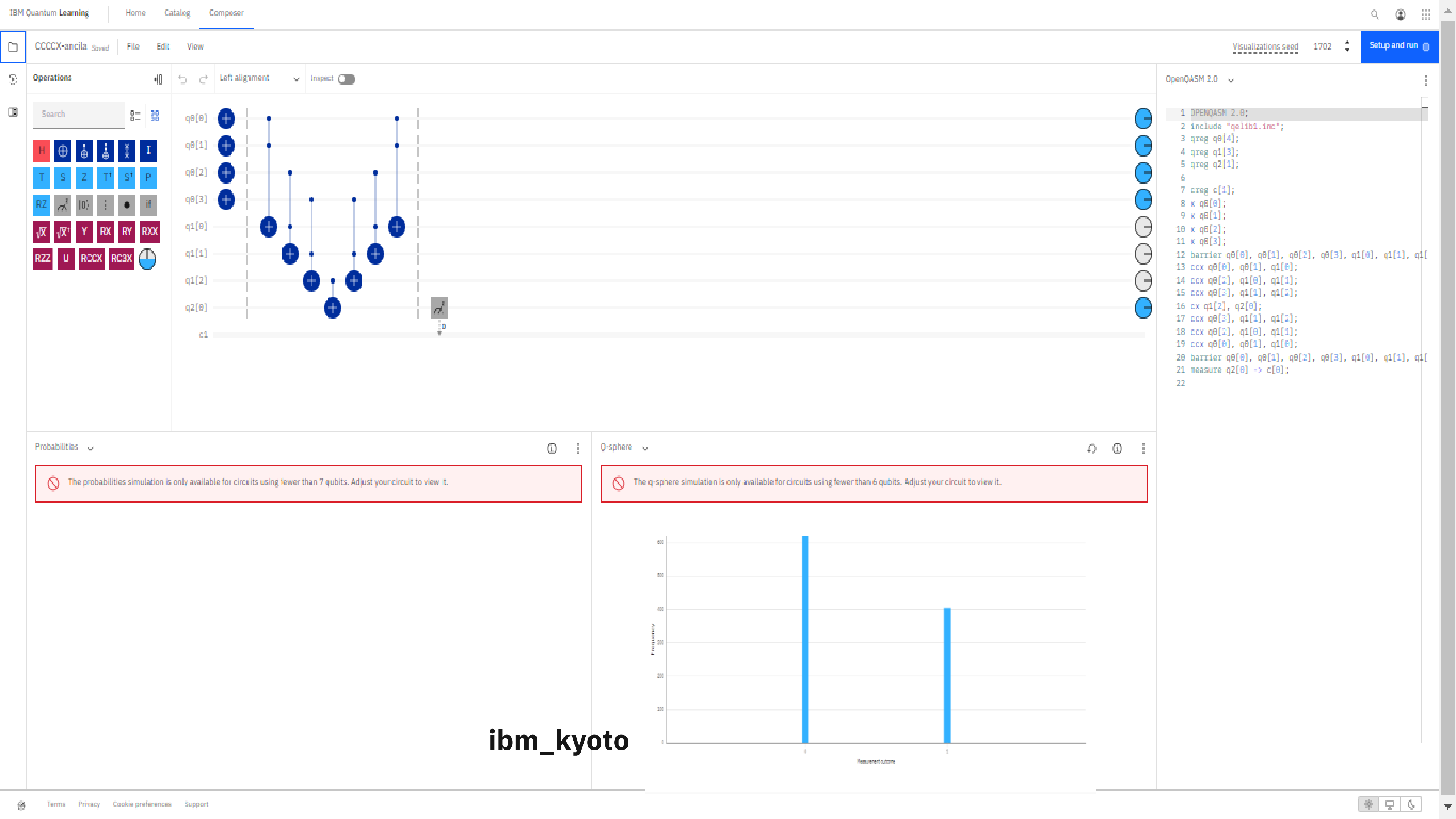
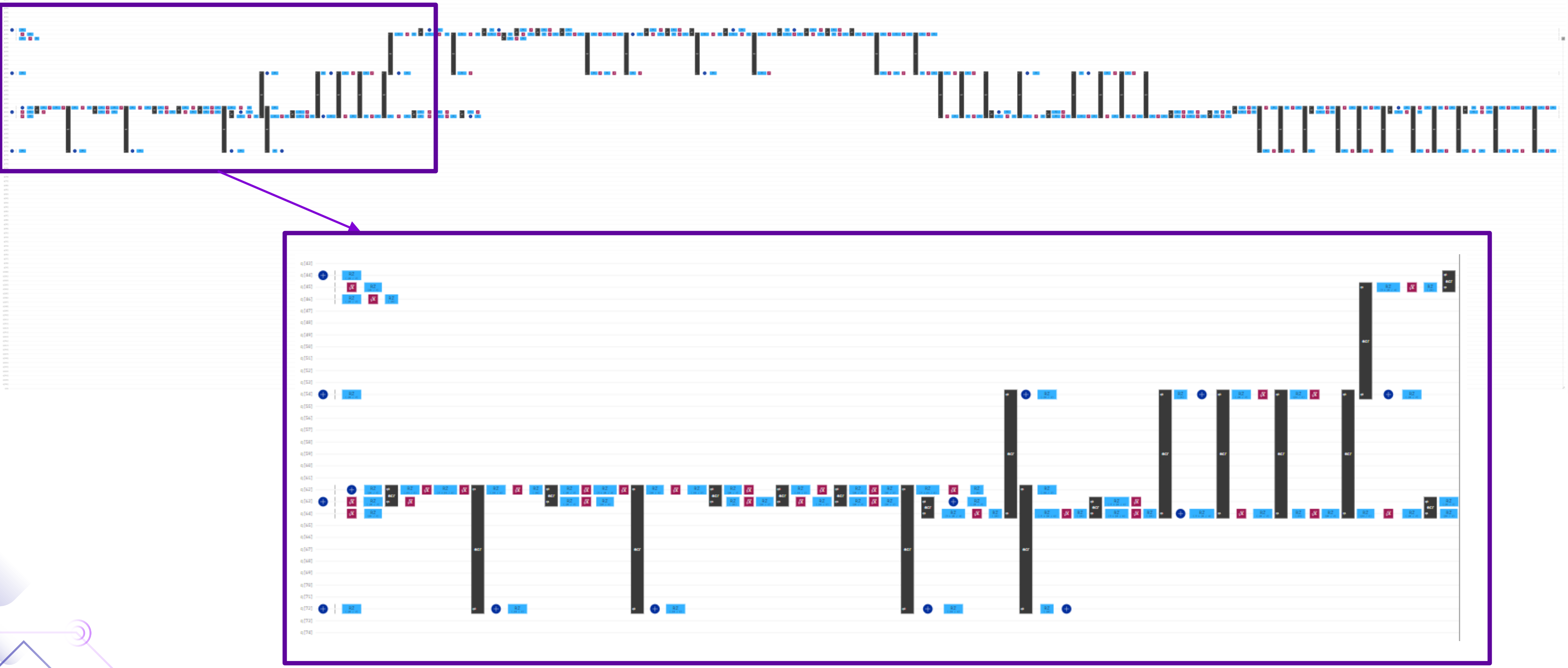


q[34]
q[35]
q[36]
q[37]
q[38]
q[39]
q[40]
q[41]
q[42]
q[43]
q[44]
q[45]
q[46]
RZ
√X
ecr


IBM Quantum Learning
Home
Catalog
Composer
CCCCX-ancila Saved
File
Edit
View
Visualizations seed
1702
Setup and run
Operations
Left alignment
Inspect
Search
q0[0]
q0[1]
q0[2]
q0[3]
q1[0]
q1[1]
q1[2]
q2[0]
c1
OpenQASM 2.0
OPENQASM 2.0;
include "qelib1.inc";
qreg q0[4];
qreg q1[3];
qreg q2[1];
creg c[1];
x q0[0];
x q0[1];
x q0[2];
x q0[3];
barrier q0[0], q0[1], q0[2], q0[3], q1[0], q1[1], q1[
ccx q0[0], q0[1], q1[0];
ccx q0[2], q1[0], q1[1];
ccx q0[3], q1[1], q1[2];
cx q1[2], q2[0];
ccx q0[3], q1[1], q1[2];
ccx q0[2], q1[0], q1[1];
ccx q0[0], q0[1], q1[0];
barrier q0[0], q0[1], q0[2], q0[3], q1[0], q1[1], q1[
measure q2[0] -> c[0];
Probabilities
The probabilities simulation is only available for circuits using fewer than 7 qubits. Adjust your circuit to view it.
Q-sphere
The q-sphere simulation is only available for circuits using fewer than 6 qubits. Adjust your circuit to view it.
Frequency
Measurement outcome
0
1
Terms
Privacy
Cookie preferences
Support

ibm_kyoto



Coding time ;)

اطلس کوانتوم