

☰ ShorRE.qs    ☰ Q# Estimates X    ⌂ ...

## Azure Quantum Resource Estimator

### ▼ Results

Run name	T factory fraction	Physical qubits	Runtime	rQOPS
<b>qubit_gate_ns_e3, surface_code</b>	<b>69.08 %</b>	<b>416,894</b>	<b>25 secs</b>	<b>32,794,118</b>
qubit_gate_ns_e4, surface_code	43.17 %	63,566	13 secs	61,944,445
qubit_maj_ns_e4, floquet_code	82.75 %	501,484	10 secs	82,592,593
qubit_maj_ns_e6, floquet_code	31.47 %	42,956	5 secs	148,666,667

### ▼ Space-time diagram

Created with Azure Quantum Resource Estimator

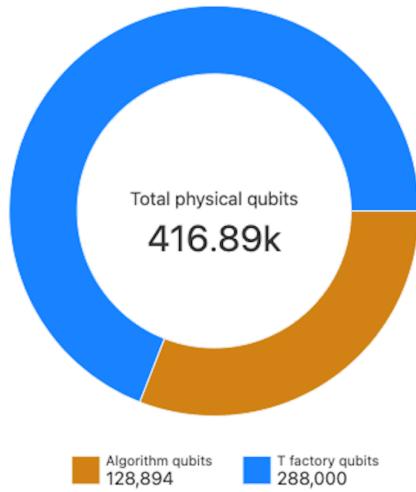
Physical qubits (logarithmic)

Runtime (logarithmic)

1 minute

25 secs, physical qubits: 416.89k, code distance: 17

## ▼ Space diagram



Physical resource estimates	
Total physical qubits	416,894
T factory parameters	
Physical T factory qubits	288,000
Resource estimation breakdown	
T factory copies	16
Physical qubits per T factory	18,000
Physical algorithmic qubits	128,894
Logical algorithmic qubits	223
Logical qubit parameters	
Physical qubits	578

## ▼ Resource Estimates

Show detailed rows

### ▼ Physical resource estimates

Runtime	25 secs	<u>Total runtime</u>
This is a runtime estimate for the execution time of the algorithm. In general, the execution time corresponds to the duration of one logical cycle (6,800 nanosecs) multiplied by the 3,631,576 logical cycles to run the algorithm. If however the duration of a single T factory (here: 83,200 nanosecs) is larger than the algorithm runtime, we extend the number of logical cycles artificially in order to exceed the runtime of a single T factory.		
rQOPS	32.79M	<u>Reliable quantum operations per second</u>
		The value is computed as the number of logical qubits after layout (223) (with a logical error rate of 1.37e-10) multiplied by the clock frequency (147,058.82), which is the number of logical cycles per second.
Physical qubits	416.89k	<u>Number of physical qubits</u>
		This value represents the total number of physical qubits, which is the sum of 128,894 physical qubits to implement the algorithm logic, and 288,000 physical qubits to execute the T factories that are responsible to produce the T states that are consumed by the algorithm.

### ▼ Resource estimates breakdown

Logical algorithmic qubits	223	<u>Number of logical qubits for the algorithm after layout</u>
Laying out the logical qubits in the presence of nearest-neighbor constraints requires additional logical qubits. In particular, to layout the $Q_{\text{alg}} = 97$ logical qubits in the input algorithm, we require in total $2 \cdot Q_{\text{alg}} + \lceil \sqrt{8 \cdot Q_{\text{alg}}} \rceil + 1 = 223$ logical qubits.		
Algorithmic depth	3.63M	<u>Number of logical cycles for the algorithm</u>
		To execute the algorithm using <i>Parallel Synthesis Sequential Pauli Computation</i> (PSSPC), operations are scheduled in terms of multi-qubit Pauli measurements, for which assume an execution time of one logical cycle. Based on the input algorithm, we require one multi-qubit measurement for the 105,840 single-qubit measurements, the 58 arbitrary single-qubit rotations, and the 1 T gates, three multi-qubit measurements for each of the 1,175,013 CCZ and 0 CCIX gates in the input program, as well as 11 multi-qubit measurements for each of the 58 non-Clifford layers in which there is at least one single-qubit rotation with an arbitrary angle rotation.
Logical depth	3.63M	<u>Number of logical cycles performed</u>
This number is usually equal to the logical depth of the algorithm, which is 3,631,576. However, in the case in which a single T factory is slower than the execution time of the algorithm, we adjust the logical cycle depth to exceed the T factory's execution time.		
Clock frequency	147.06k	<u>Number of logical cycles per second</u>
		This is the number of logical cycles that can be performed within one second. The logical cycle time is 7 microsecs.

Number of T states	4.70M	<b>Number of T states consumed by the algorithm</b>
		To execute the algorithm, we require one T state for each of the 1 T gates, four T states for each of the 1,176,013 CCZ and 0 CCIX gates, as well as 11 for each of the 58 single-qubit rotation gates with arbitrary angle rotation.
Number of T factories	16	<b>Number of T factories capable of producing the demanded 4,700,691 T states during the algorithm's runtime</b>
		The total number of T factories 16 that are executed in parallel is computed as $\left\lceil \frac{\text{T states} \cdot \text{T factory duration}}{\text{T states per T factory} \cdot \text{algorithm runtime}} \right\rceil = \left\lceil \frac{4,700,691 \cdot 83,200 \text{ ns}}{1 \cdot 24,694,716,800 \text{ ns}} \right\rceil$
Number of T factory invocations	293.79k	<b>Number of times all T factories are invoked</b>
		In order to prepare the 4,700,691 T states, the 16 copies of the T factory are repeatedly invoked 293,794 times.
Physical algorithmic qubits	128.89k	<b>Number of physical qubits for the algorithm after layout</b>
		The 128,894 are the product of the 223 logical qubits after layout and the 578 physical qubits that encode a single logical qubit.
Physical T factory qubits	288.00k	<b>Number of physical qubits for the T factories</b>
		Each T factory requires 18,000 physical qubits and we run 16 in parallel, therefore we need 288,000 = 18,000 · 16 qubits.
Required logical qubit error rate	1.37e-10	<b>The minimum logical qubit error rate required to run the algorithm within the error budget</b>
		The minimum logical qubit error rate is obtained by dividing the logical error probability 1.11e-1 by the product of 223 logical qubits and the total cycle count 3,631,576.
Required logical T state error rate	2.36e-8	<b>The minimum T state error rate required for distilled T states</b>
		The minimum T state error rate is obtained by dividing the T distillation error probability 1.11e-1 by the total number of T states 4,700,691.
Number of T states per rotation	11	<b>Number of T states to implement a rotation with an arbitrary angle</b>
		The number of T states to implement a rotation with an arbitrary angle is $[0.53 \log_2(58/0.111) + 5.3]$ [arXiv:2203.10064]. For simplicity, we use this formula for all single-qubit arbitrary angle rotations, and do not distinguish between best, worst, and average cases.

#### ▼ Logical qubit parameters

QEC scheme	surface_code	<b>Name of QEC scheme</b>
		You can load pre-defined QEC schemes by using the name <code>surface_code</code> or <code>floquet_code</code> . The latter only works with Majorana qubits.
Code distance	17	<b>Required code distance for error correction</b>
		The code distance is the smallest odd integer greater or equal to $\frac{2 \log(0.03/1.3706386635819607e-10)}{\log(0.01/0.001)} - 1$
Physical qubits	578	<b>Number of physical qubits per logical qubit</b>
		The number of physical qubits per logical qubit are evaluated using the formula $2 * \text{codeDistance} * \text{codeDistance}$ that can be user-specified.
Logical cycle time	7 microsecs	<b>Duration of a logical cycle in nanoseconds</b>
		The runtime of one logical cycle in nanoseconds is evaluated using the formula $(4 * \text{twoQubitGateTime} + 2 * \text{oneQubitMeasurementTime}) * \text{codeDistance}$ that can be user-specified.
Logical qubit error rate	3.00e-11	<b>Logical qubit error rate</b>
		The logical qubit error rate is computed as $0.03 \cdot \left(\frac{0.001}{0.01}\right)^{\frac{17+1}{2}}$
Crossing prefactor	0.03	<b>Crossing prefactor used in QEC scheme</b>
		The crossing prefactor is usually extracted numerically from simulations when fitting an exponential curve to model the relationship between logical and physical error rate.

Error correction threshold	0.01	<b>Error correction threshold used in QEC scheme</b>
Logical cycle time formula	$(4 * \text{twoQubitGateTime} + 2 * \text{oneQubitMeasurementTime}) * \text{codeDistance}$	<b>QEC scheme formula used to compute logical cycle time</b>  This is the formula that is used to compute the logical cycle time 6,800 ns.
Physical qubits formula	$2 * \text{codeDistance} * \text{codeDistance}$	<b>QEC scheme formula used to compute number of physical qubits per logical qubit</b>  This is the formula that is used to compute the number of physical qubits per logical qubits 578.

#### ▼ T factory parameters

Physical qubits	18.00k	<b>Number of physical qubits for a single T factory</b>
Runtime	83 microsecs	<b>Runtime of a single T factory</b>  The runtime of a single T factory is the accumulated runtime of executing each round in a T factory.
Number of output T states per run	1	<b>Number of output T states produced in a single run of T factory</b>  The T factory takes as input 270 noisy physical T states with an error rate of 0.001 and produces 1 T states with an error rate of 2.16e-8.
Number of input T states per run	270	<b>Number of physical input T states consumed in a single run of a T factory</b>  This value includes the physical input T states of all copies of the distillation unit in the first round.
Distillation rounds	2	<b>The number of distillation rounds</b>  This is the number of distillation rounds. In each round one or multiple copies of some distillation unit is executed.
Distillation units per round	18, 1	<b>The number of units in each round of distillation</b>  This is the number of copies for the distillation units per round.
Distillation units	15-to-1 space efficient, 15-to-1 RM prep	<b>The types of distillation units</b>  These are the types of distillation units that are executed in each round. The units can be either physical or logical, depending on what type of qubit they are operating. Space-efficient units require fewer qubits for the cost of longer runtime compared to Reed-Muller preparation units.
Distillation code distances	5, 13	<b>The code distance in each round of distillation</b>  This is the code distance used for the units in each round. If the code distance is 1, then the distillation unit operates on physical qubits instead of error-corrected logical qubits.
Number of physical qubits per round	18.00k, 10.48k	<b>The number of physical qubits used in each round of distillation</b>  The maximum number of physical qubits over all rounds is the number of physical qubits for the T factory, since qubits are reused by different rounds.
Runtime per round	26 microsecs, 57 microsecs	<b>The runtime of each distillation round</b>  The runtime of the T factory is the sum of the runtimes in all rounds.
Logical T state error rate	2.16e-8	<b>Logical T state error rate</b>  This is the logical T state error rate achieved by the T factory which is equal or smaller than the required error rate 2.36e-8.

#### ▼ Pre-layout logical resources

Logical qubits (pre-layout)	97	<b>Number of logical qubits in the input quantum program</b>
T gates	1	<b>Number of T gates in the input quantum program</b>  This includes all T gates and adjoint T gates, but not T gates used to implement rotation gates with arbitrary angle, CCZ gates, or CCIg gates.

Rotation gates	58	<b>Number of rotation gates in the input quantum program</b>
This is the number of all rotation gates. If an angle corresponds to a Pauli, Clifford, or T gate, it is not accounted for in this number.		
Rotation depth	58	<b>Depth of rotation gates in the input quantum program</b>
This is the number of all non-Clifford layers that include at least one single-qubit rotation gate with an arbitrary angle.		
CCZ gates	1.18M	<b>Number of CCZ-gates in the input quantum program</b>
This is the number of CCZ gates.		
CCIX gates	0	<b>Number of CCIX-gates in the input quantum program</b>
This is the number of CCIX gates, which applies $-iX$ controlled on two control qubits [1212_5069].		
Measurement operations	105.84k	<b>Number of single qubit measurements in the input quantum program</b>
This is the number of single qubit measurements in Pauli basis that are used in the input program. Note that all measurements are counted, however, the measurement result is determined randomly (with a fixed seed) to be 0 or 1 with a probability of 50%.		

#### ▼ Assumed error budget

Total error budget	3.33e-1	<b>Total error budget for the algorithm</b>
The total error budget sets the overall allowed error for the algorithm, i.e., the number of times it is allowed to fail. Its value must be between 0 and 1 and the default value is 0.001, which corresponds to 0.1%, and means that the algorithm is allowed to fail once in 1000 executions. This parameter is highly application specific. For example, if one is running Shor's algorithm for factoring integers, a large value for the error budget may be tolerated as one can check that the output are indeed the prime factors of the input. On the other hand, a much smaller error budget may be needed for an algorithm solving a problem with a solution which cannot be efficiently verified. This budget $\epsilon = \epsilon_{\text{log}} + \epsilon_{\text{dis}} + \epsilon_{\text{syn}}$ is uniformly distributed and applies to errors $\epsilon_{\text{log}}$ to implement logical qubits, an error budget $\epsilon_{\text{dis}}$ to produce T states through distillation, and an error budget $\epsilon_{\text{syn}}$ to synthesize rotation gates with arbitrary angles. Note that for distillation and rotation synthesis, the respective error budgets $\epsilon_{\text{dis}}$ and $\epsilon_{\text{syn}}$ are uniformly distributed among all T states and all rotation gates, respectively. If there are no rotation gates in the input algorithm, the error budget is uniformly distributed to logical errors and T state errors.		
Logical error probability	1.11e-1	<b>Probability of at least one logical error</b>
This is one third of the total error budget 3.33e-1 if the input algorithm contains rotation with gates with arbitrary angles, or one half of it, otherwise.		
T distillation error probability	1.11e-1	<b>Probability of at least one faulty T distillation</b>
This is one third of the total error budget 3.33e-1 if the input algorithm contains rotation with gates with arbitrary angles, or one half of it, otherwise.		
Rotation synthesis error probability	1.11e-1	<b>Probability of at least one failed rotation synthesis</b>
This is one third of the total error budget 3.33e-1.		

#### ▼ Physical qubit parameters

Qubit name	qubit_gate_ns_e3	<b>Some descriptive name for the qubit model</b>
You can load pre-defined qubit parameters by using the names <code>qubit_gate_ns_e3</code> , <code>qubit_gate_ns_e4</code> , <code>qubit_gate_us_e3</code> , <code>qubit_gate_us_e4</code> , <code>qubit_maj_ns_e4</code> , or <code>qubit_maj_ns_e6</code> . The names of these pre-defined qubit parameters indicate the instruction set (gate-based or Majorana), the operation speed (ns or $\mu$ s regime), as well as the fidelity (e.g., e3 for $10^{-3}$ gate error rates).		
Instruction set	GateBased	<b>Underlying qubit technology (gate-based or Majorana)</b>
When modeling the physical qubit abstractions, we distinguish between two different physical instruction sets that are used to operate the qubits. The physical instruction set can be either <i>gate-based</i> or <i>Majorana</i> . A gate-based instruction set provides single-qubit measurement, single-qubit gates (incl. T gates), and two-qubit gates. A Majorana instruction set provides a physical T gate, single-qubit measurement and two-qubit joint measurement operations.		
Single-qubit measurement time	100 ns	<b>Operation time for single-qubit measurement (<code>t_meas</code>) in ns</b>
This is the operation time in nanoseconds to perform a single-qubit measurement in the Pauli basis.		
Single-qubit gate time	50 ns	<b>Operation time for single-qubit gate (<code>t_gate</code>) in ns</b>
This is the operation time in nanoseconds to perform a single-qubit Clifford operation, e.g., Hadamard or Phase gates.		

Two-qubit gate time	50 ns	<b>Operation time for two-qubit gate in ns</b>
		This is the operation time in nanoseconds to perform a two-qubit Clifford operation, e.g., a CNOT or CZ gate.
T gate time	50 ns	<b>Operation time for a T gate</b>
		This is the operation time in nanoseconds to execute a T gate.
Single-qubit measurement error rate	0.001	<b>Error rate for single-qubit measurement</b>
		This is the probability in which a single-qubit measurement in the Pauli basis may fail.
Single-qubit error rate	0.001	<b>Error rate for single-qubit Clifford gate (p)</b>
		This is the probability in which a single-qubit Clifford operation, e.g., Hadamard or Phase gates, may fail.
Two-qubit error rate	0.001	<b>Error rate for two-qubit Clifford gate</b>
		This is the probability in which a two-qubit Clifford operation, e.g., CNOT or CZ gates, may fail.
T gate error rate	0.001	<b>Error rate to prepare single-qubit T state or apply a T gate (<math>p_{-T}</math>)</b>
		This is the probability in which executing a single T gate may fail.

### ▼ Constraints

Logical depth factor	constraint not set	<b>Factor the initial number of logical cycles is multiplied by</b>
		This is the factor takes into account a potential overhead to the initial number of logical cycles.
Maximum number of T factories	constraint not set	<b>The maximum number of T factories can be utilized during the algorithm's runtime</b>
		This is the maximum number of T factories used for producing the demanded T states, which can be created and executed by the algorithm in parallel.
Maximum runtime duration	constraint not set	<b>The maximum runtime duration allowed for the algorithm runtime</b>
		This is the maximum time allowed to the algorithm. If specified, the estimator targets to minimize the number of physical qubits consumed by the algorithm for runtimes under the maximum allowed.
Maximum number of physical qubits	constraint not set	<b>The maximum number of physical qubits allowed for utilization to the algorithm</b>
		This is the maximum number of physical qubits available to the algorithm. If specified, the estimator targets to minimize the runtime of the algorithm with number of physical qubits consumed not exceeding this maximum.

### ▼ Assumptions

- More details on the following lists of assumptions can be found in the paper [Accessing requirements for scaling quantum computers and their applications](#).
- Uniform independent physical noise.** We assume that the noise on physical qubits and physical qubit operations is the standard circuit noise model. In particular we assume error events at different space-time locations are independent and that error rates are uniform across the system in time and space.
- Efficient classical computation.** We assume that classical overhead (compilation, control, feedback, readout, decoding, etc.) does not dominate the overall cost of implementing the full quantum algorithm.
- Extraction circuits for planar quantum ISA.** We assume that stabilizer extraction circuits with similar depth and error correction performance to those for standard surface and Hastings-Haah code patches can be constructed to implement all operations of the planar quantum ISA (instruction set architecture).
- Uniform independent logical noise.** We assume that the error rate of a logical operation is approximately equal to its space-time volume (the number of tiles multiplied by the number of logical time steps) multiplied by the error rate of a logical qubit in a standard one-tile patch in one logical time step.
- Negligible Clifford costs for synthesis.** We assume that the space overhead for synthesis and space and time overhead for transport of magic states within magic state factories and to synthesis qubits are all negligible.
- Smooth magic state consumption rate.** We assume that the rate of T state consumption throughout the compiled algorithm is almost constant, or can be made almost constant without significantly increasing the number of logical time steps for the algorithm.