Introduction

This document lists values for SquidASM parameters to emulate ion trap systems. These values are listed for two scenarios: Current state of the art and optimistic estimate of what may be possible in QIA SGA2.

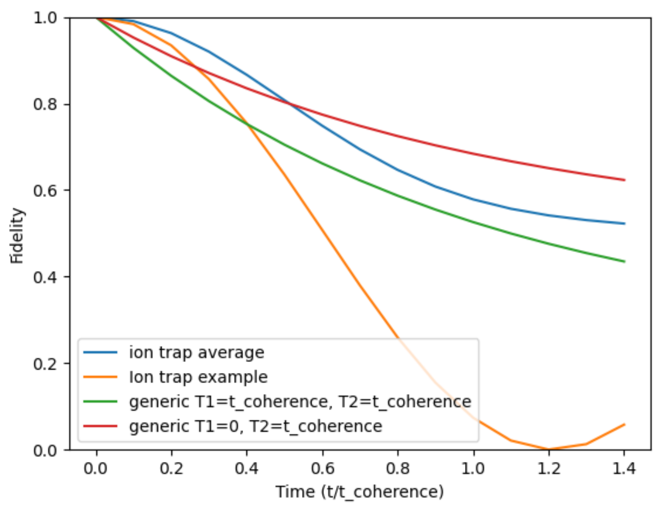
For both current state of the art and optimistic scenarios, the fidelity and success probability are reported in two scenarios: almost-whole detection window and truncated detection window. The truncation of the detection window enhances fidelity but comes at the cost of a substantially reduced entanglement rate.

Where possible references or the calculation are provided for the values listed, but many values have been obtained via internal QIA communication.

Model limitations

Currently, the trapped-ion model is not implemented in SquidASM, requiring the use of the generic qdevice model instead. However, this substitution does not account for several unique aspects of trapped-ion systems:

1. **Topology**: The trapped-ion system has a linear topology, whereas the generic qdevice assumes a fully connected topology, allowing any qubit to interact directly with any other qubit. This discrepancy overlooks the noise and delay introduced by rearranging qubits to enable interactions in a trapped-ion setup.
2. **Gate Set**: The trapped-ion system employs a single two-qubit gate, the Mølmer–Sørensen (MS) gate, while the generic qdevice includes the CNOT and CPHASE gates. Although these gates can be decomposed into the MS gate combined with single-qubit rotations in a trapped-ion system, this decomposition—and the associated noise and delays—are not modelled in SquidASM.
3. **Decoherence model**: The main contributor to decoherence in a trapped-ion system is collective Gaussian dephasing. The generic qdevice uses a T1T2 decoherence model. The graph below compares the different decoherence profiles.



SquidASM values – current

The table below presents current state of the art parameter values. These values have never been realised in a single ion trap system.

Notably the entanglement generation probability assumes double click protocol and a frequency conversion to telecom, but these two have not been combined before. To obtain a value an estimate is made of this probability. See the subsection link calculations for more information.

Parameter	Value	Reference
num_qubits	2	
single_qubit_gate_depolar_prob	0.02	Conversion of 0.99 fidelity from: Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 6
single_qubit_gate_time	12 us	Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 6
two_qubit_gate_depolar_prob	0.067	Conversion of 0.95 fidelity from: Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 6
two_qubit_gate_time	107 us	Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 6
T1, T2	62 ms	https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.130.213601 (Telecom-Wavelength Quantum Repeater Node Based on a Trapped-Ion Processor) A unpublished 4s coherence time has been obtained in lab, but this is without entanglement generation occurring on a different ion at the same time.
init_time	65 us	Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 4
measure_time	2 ms	Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 5
t_cycle (d=50km)	2.05 ms	250 us travel time 2x25km at 200,000 km/s in fiber + 1.8 ms overhead per photon Reference 1.8 ms: http://dx.doi.org/10.1103/PhysRevLett.130.050803 (total experiment time (7 hours) divided by the total number of attempts (13,656,928))
Almost-whole detection window		
fidelity	0.59	Phys. Rev. Lett. 130, 213601 (2023)
prob_success (d=50km)	$4.96 \cdot 10^{-4}$	Derived quantity, see subsection link calculations
Truncated detection window		
fidelity	0.88	Phys. Rev. Lett. 130, 213601 (2023)
prob_success (d=50km)	$6 \cdot 10^{-5}$	Derived quantity, see subsection link calculations

SquidASM values - Optimistic

The table below presents optimistic estimates for parameter values that the QIA could potentially achieve by the conclusion of SGA2.

Parameter	Value	Reference
num_qubits	20	
single_qubit_gate_depolar_prob	0.004	Conversion of 0.998 fidelity from: PRX Quantum 2, 020343 (2021), page 18
single_qubit_gate_time	15 us	PRX Quantum 2, 020343 (2021), page 18
two_qubit_gate_depolar_prob	0.004	Conversion of 0.997 fidelity from: PRX Quantum 2, 020343 (2021), page 18
two_qubit_gate_time	200 us	PRX Quantum 2, 020343 (2021), page 18
T1, T2	10 s	Internal QIA communication
init_time	65 us	Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 4
measure_time	2 ms	Phys. Rev. Lett. 130, 213601 (2023), supplemental material, page 5
t_cycle (d=50km)	450 us	250 us travel time 2x25km at 200,000 km/s in fiber + 200 us overhead per photon Reference 200 us: Internal QIA communication
Almost-whole detection window		
fidelity	0.80	Internal QIA communication
prob_success (d=50km)	$6.56 \cdot 10^{-3}$	Derived quantity, see subsection link calculations
Truncated detection window		
fidelity	0.95	Internal QIA communication
prob_success (d=50km)	$1.31 \cdot 10^{-3}$	Derived quantity, see subsection link calculations

Link calculations

Probability of success per cycle

The probability of success for a single entanglement attempt is given by:

$$p = \frac{p_a p_b}{2}$$

where p_a and p_b are the probabilities of photons arriving at the detector from nodes *a* and *b*, respectively. The factor of $\frac{1}{2}$ accounts for only half of the double-click patterns on the detector indicating successful entanglement.

The probability of photons arriving is calculated as:

$$p_a = p_b = q_m 10^{-0.02\frac{d}{2}}$$

where:

- q_m is the combined probability of generating ion-photon entanglement, successful frequency conversion to the telecom wavelength, and detector efficiency.
- *d* represents the distance between nodes, while the exponential term accounts for fibre losses at a rate of 0.2 dB per km.

Substituting for p_a and p_b, the overall probability is expressed as:

$$p = \frac{q_m^2}{2} 10^{-0.02d}$$

Link calculation parameters - current

Parameter	Value	Reference
t_cycle	2.05 ms	250 us travel time 2x25km at 200,000 km/s in fiber + 1.8 ms overhead per photon Reference 1.8 ms: http://dx.doi.org/10.1103/PhysRevLett.130.050803 (total experiment time (7 hours) divided by the total number of attempts (13,656,928))
Ion-photon entanglement generation	0.531	Computed by dividing 0,462/ 0.87, where 0.87 is the detector efficiency at ion wavelength and 0.462 the ion-photon entanglement generation efficiency multiplied by detector efficiency. Computation numbers reference: https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.2.020331 (Interface between Trapped-Ion Qubits and Traveling Photons with Close-to-Optimal Efficiency)
Frequency conversion	0,25	https://www.nature.com/articles/s41534-019-0186-3 (Light-matter entanglement over 50 km of optical fibre)
detector efficiency	0.75	Internal QIA communication Note: this is a detector at telecom wavelength
q_m	0.0996	Ion-photon entanglement generation probability * Frequency conversion * Detector efficiency

Almost-whole detection window		
p (50km)	$4.96 \cdot 10^{-4}$	
Entanglement rate	0.243 s^{-1}	1/t_cycle * *p*
Truncated detection window		
Detection window truncation factor	0.12	(3.5 per minute)/(0.49 per second) 3.5 per minute rate with detection window truncation 0.49 per second without detection window truncation Phys. Rev. Lett. 130, 050803 (2023)
p (50km)	$6 \cdot 10^{-5}$	Base probability * detection window truncation factor
Entanglement rate	0.029 s^{-1}	1/t_cycle * *p*

Link calculation parameters - optimistic

Parameter	Value	Reference
t_cycle	450 us	250 us travel time 2x25km at 200,000 km/s in fiber + 200 us overhead per photon Reference 200 us: Internal QIA communication
Ion-photon entanglement generation	0,575	Computed by dividing 0,5 / 0.87, where 0.87 is the detector efficiency at ion wavelength and 0.5 the ion-photon entanglement generation efficiency multiplied by detector efficiency. Computation numbers reference: Internal QIA communication
Frequency conversion	0,7	Internal QIA communication
detector efficiency	0.9	Internal QIA communication Note: this is a detector at telecom wavelength
q_m	0.362	Ion-photon entanglement generation probability * Frequency conversion * Detector efficiency
Almost-whole detection window		
p (50km)	$6.56 \cdot 10^{-3}$	
Entanglement rate	14.6 s^{-1}	1/t_cycle * *p*
Truncated detection window		
Detection window truncation factor	0.2	Internal QIA communication
p (50km)	$1.31 \cdot 10^{-3}$	Base probability * detection window truncation factor
Entanglement rate	2.92 s^{-1}	1/t_cycle * *p*