Trapped-ion quantum computing

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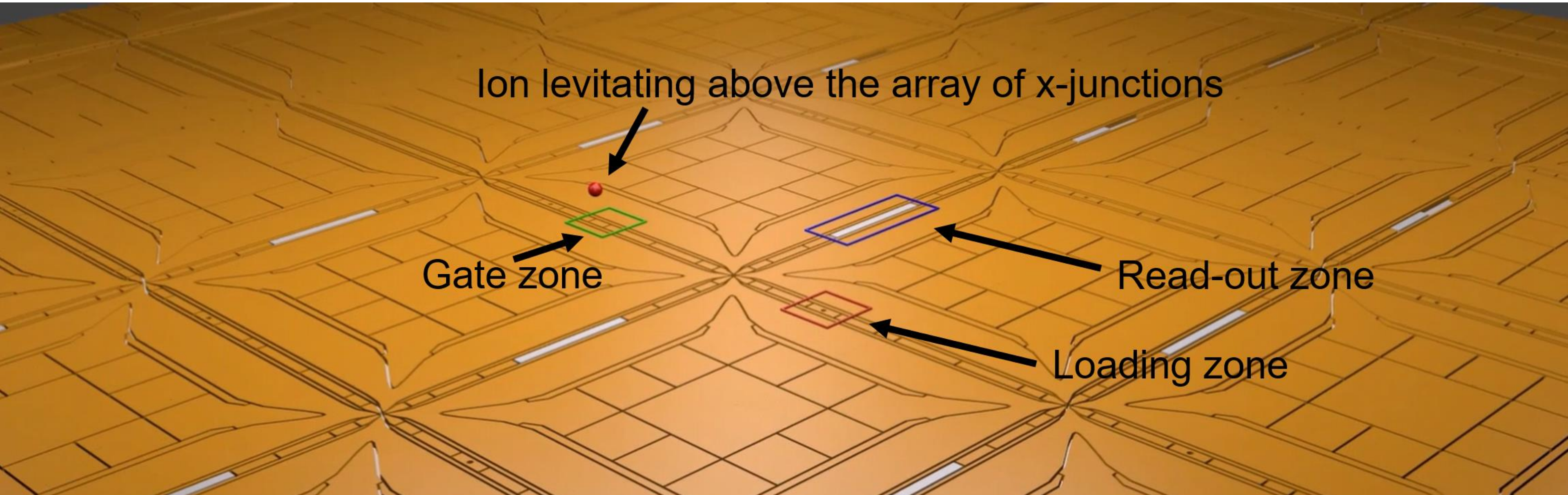
http://www.sussex.ac.uk/physics/iqt



Two computational regimes

- Noisy-Intermediate-Scale-Quantum devices (NISQ)
  - No error correction
  - Very limited applications
  - ~ 100 qubits
- Fault tolerant quantum computing
  - Error correction and all operations must have error below fault-tolerant threshold
  - Most applications in quantum computing
  - Millions or billions of qubits!

Current quantum computers operate with 10s - 100s of qubits

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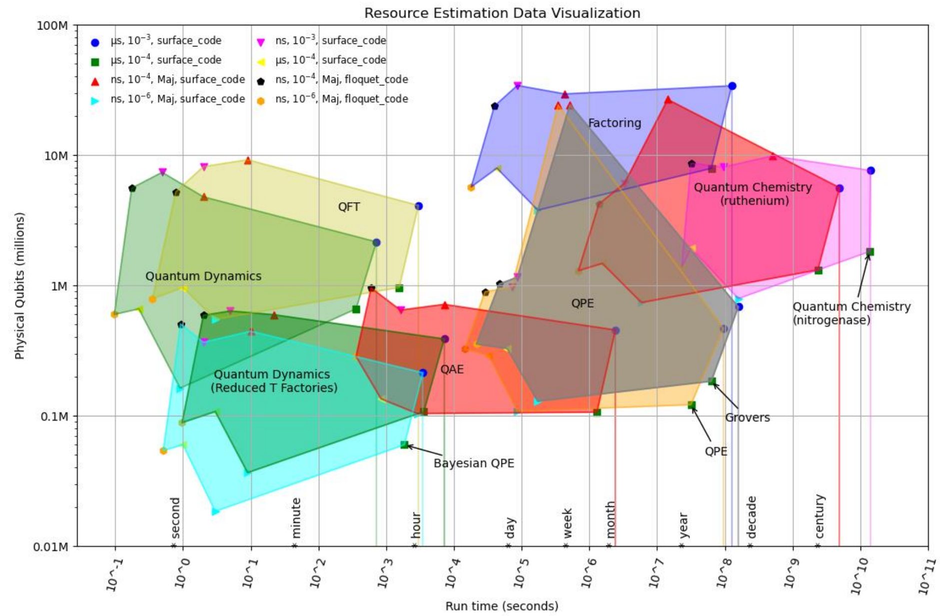
A look at applications

- Quantum Dynamics (2D Ising) is a simulation of a 2D transverse-field Ising model with 100 quantum spins, propagate for ten time steps using a fourth-order Trotter algorithm
- Quantum Dynamics (Reduced T factories) is the same use case as above with the number of T factories reduced to show the trade off of qubits needed and runtime
- Factoring calculates the pair of prime factors of a 2048 bit integer
- Quantum Chemistry (Ruthenium) calculates the energy of a ruthenium-based catalyst for carbon fixation
- Quantum Chemistry (Nitrogenase) demonstrates the application of quantum computing to explore reaction mechanisms in complex chemical systems, specifically focusing on biological nitrogen fixation in nitrogenase.
- Quantum Phase Estimation (SHO) utilized to analyze the energy spectrum of unitary oracles, focusing on estimating the phase (energy) of a particle confined in a simple harmonic oscillator trap. This method serves as a fundamental tool for dissecting basic systems in physics.
- Bayesian QPE is an example of a QPE applications in calculating an inner product between two 2-dimensional vectors and estimating the energy of a simple Hamiltonian while integrating Bayesian statistics in the phase estimation process.
- Iterative QPE is another example of a QPE application which represents the most basic application among the discussed cases, potentially explaining why its estimates are an order of magnitude lower.
- QFT demonstrates capabilities in solving problems in number theory and quantum physics, applying QFT to a uniformly prepared state ∣ + ⟩.
- Grover’s Search Algorithm designed to efficiently identify the unique input that leads to a specific output value in a black box function. It achieves this with a significantly higher probability and speed compared to classical search methods.
- Quantum Amplitude Estimation (QAE) utilizes advance quantum computing’s capacity to resolve complex computational problems by estimating amplitudes of a given quantum state with high precision.

Taken from:

The GQI Quantum Resource Estimator Playbook

https://quantumcomputingreport.com/



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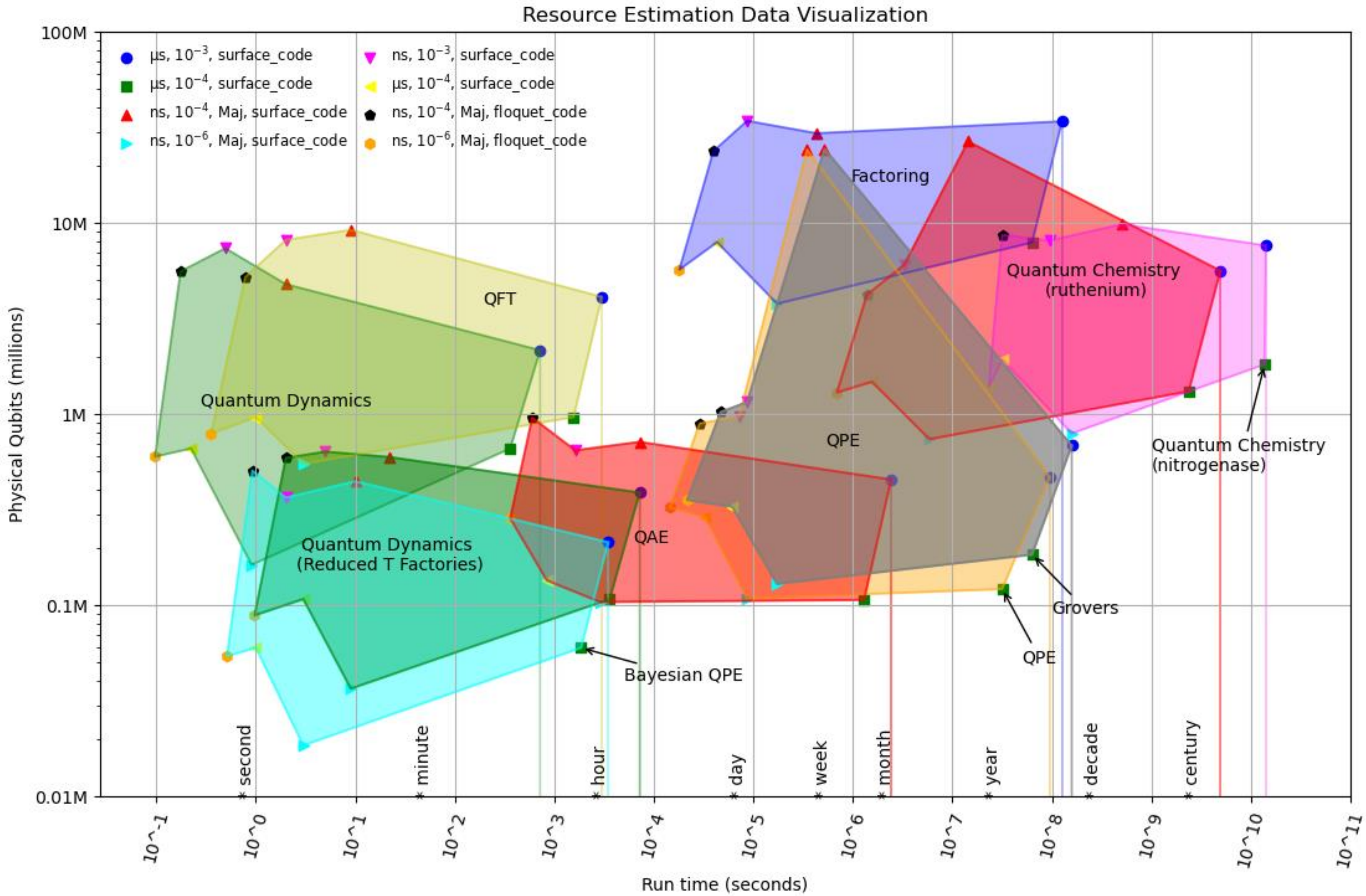
A look at applications



Taken from:
The GQI Quantum Resource Estimator Playbook
https://quantumcomputingreport.com/

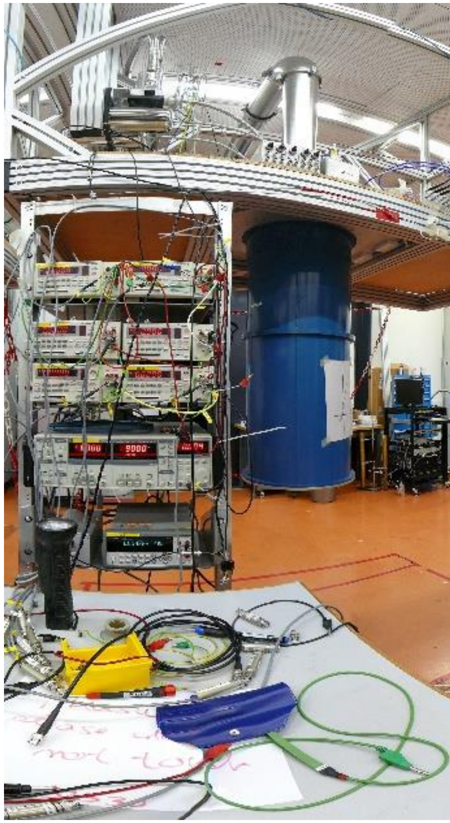
Why trapped ions?

Trapped ions:

- Works at room temperature or mild cooling to liquid Nitrogen temperature
- Lots of cooling power available at that temperature (100s of Watts), therefore there is a straight path to scale to large qubit numbers
- Correlated errors are small amplitude so can be error corrected

Superconducting qubits:

- -273°C (milli-Kelivin) requires a dilution refrigerator
- Very little cooling power available at that temperature (~mW)
- Large amplitude correlated errors (due to cosmic rays)

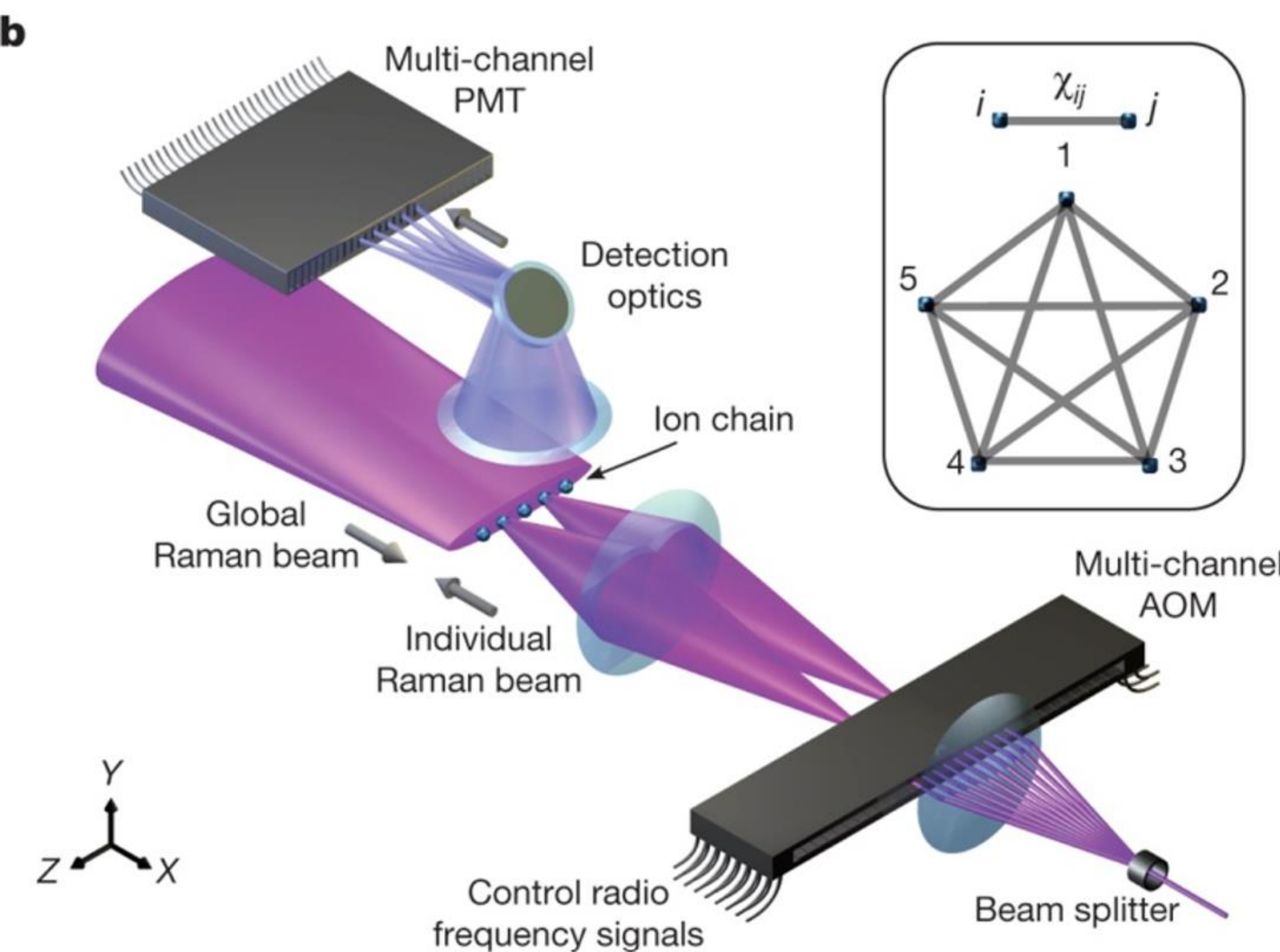


Dilution refrigerator in Andreas Wallraff's superconducting qubit laboratory at ETH Zurich

Trapped ion quantum computing architectures

Ion registers addressed by multiple laser beams architecture

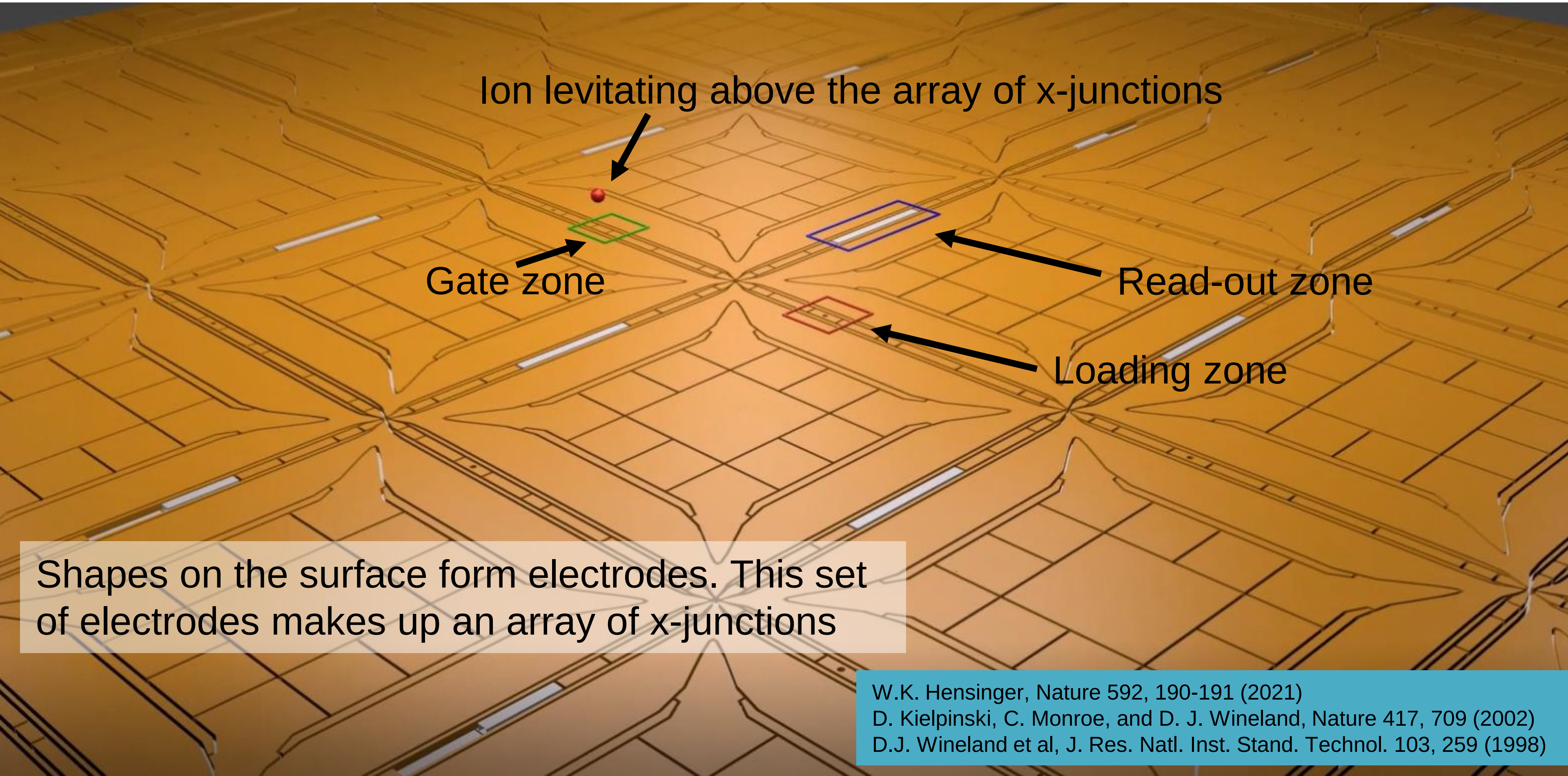
S Debnath *et al. Nature* **536,** 63–66 (2016)



- Technology used by IonQ
- A stationary chain of ions addressed by laser beams
- Modules connected via photonic interconnects
- Effective qubit size is dominated by vacuum system size, meaning scaling to large qubit numbers will results in very large quantum comuters
- Photonic interconnects have only effective coupling rates of ~1 1/s after the required distillation process

Shuttling based ion trap quantum computing architecture (QCCD)

- Ions levitate above an array of electrodes.
- Ions move as voltages are varied on the electrodes
- Quantum computation is carried out by moving ions between ‘processor zones, memory zones and readout zones

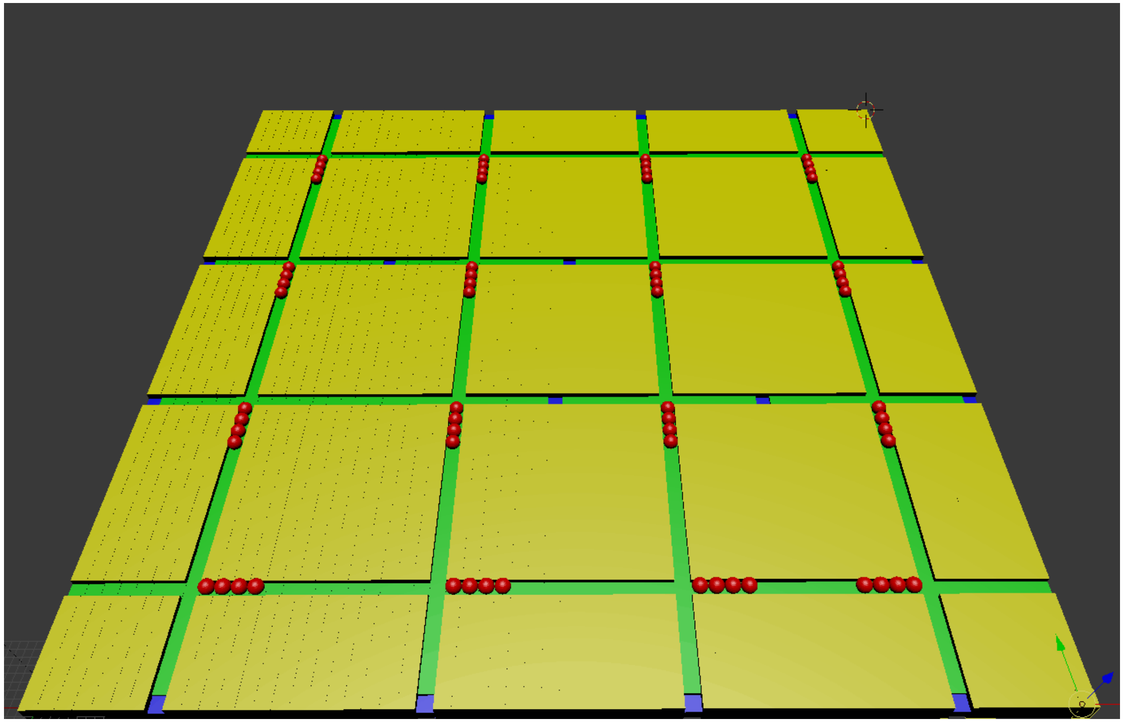


Shapes on the surface form electrodes. This set of electrodes makes up an array of x-junctions

W.K. Hensinger, Nature 592, 190-191 (2021)
D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002)
D.J. Wineland et al, J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998)

Routing problem for a large scale quantum computer

- Addressing traffic jams using optimized ion routing
- Unidirectional lanes reduce total shuttling time

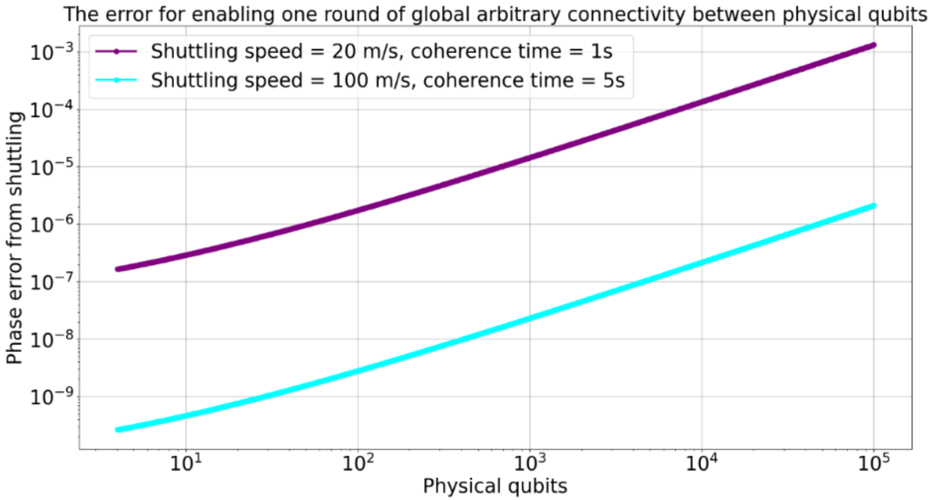


Efficient Qubit Routing for a Globally Connected Trapped Ion Quantum Computer
M. Webber, S. Herbert, S. Weidt and W.K. Hensinger, Advanced Quantum Technologies 3, 2000027 (2020)

Error for enabling one round of global connectivity

- High state fidelity shuttling has been demonstrated with shuttling speeds of 22m/s [Phys. Rev. Lett 120, 010501 (2018)], furthermore, speeds of 80m/s have also been achieved [Phys. Rev. Lett. 109, 080501(2012)].
- So how many shuttling operations are required for enabling all to all connectivity (i.e. N qubits performing randomly paired N/2 two qubit gates), given routing and congestion?
- In our investigation into routing algorithms [Webber et al. AVS Quantum Science 4.1 (2022): 013801] we found that the total time to enable all to all connectivity, τ, scales with qubit number, N, as approximately

$$\tau = 1.3\sqrt{N} + 2$$



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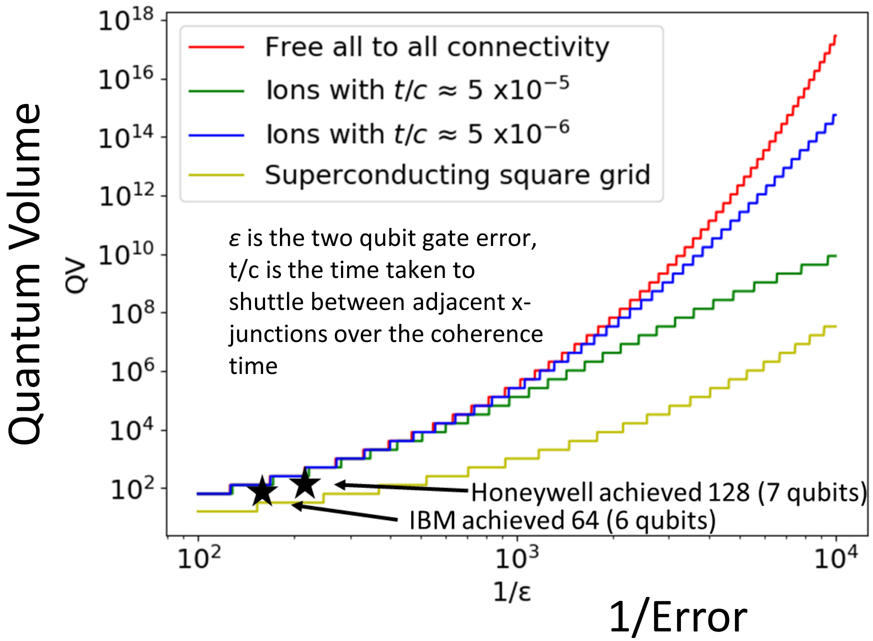
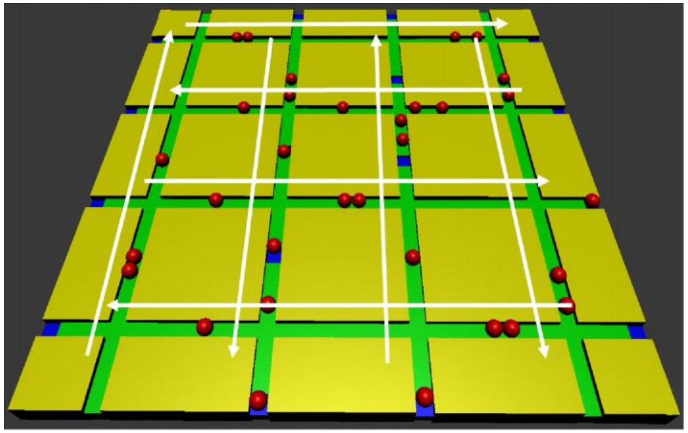
Connectivity and quantum volume





- An efficient ion routing algorithm has been created along with an appropriate error model, which can be used to estimate the achievable circuit depth and quantum volume as a function of experimental parameters.
- Connectivity plays a role in determining the power of a quantum computer
- Shuttling is nearly as good as free all to all connectivity or the ideal photonic interconnect approach, however, far easier to engineer
- Connectivity is a good reason why trapped ion quantum computing may be inherently superior in computational power to solid state approaches that require swap gates to shuttle qubits

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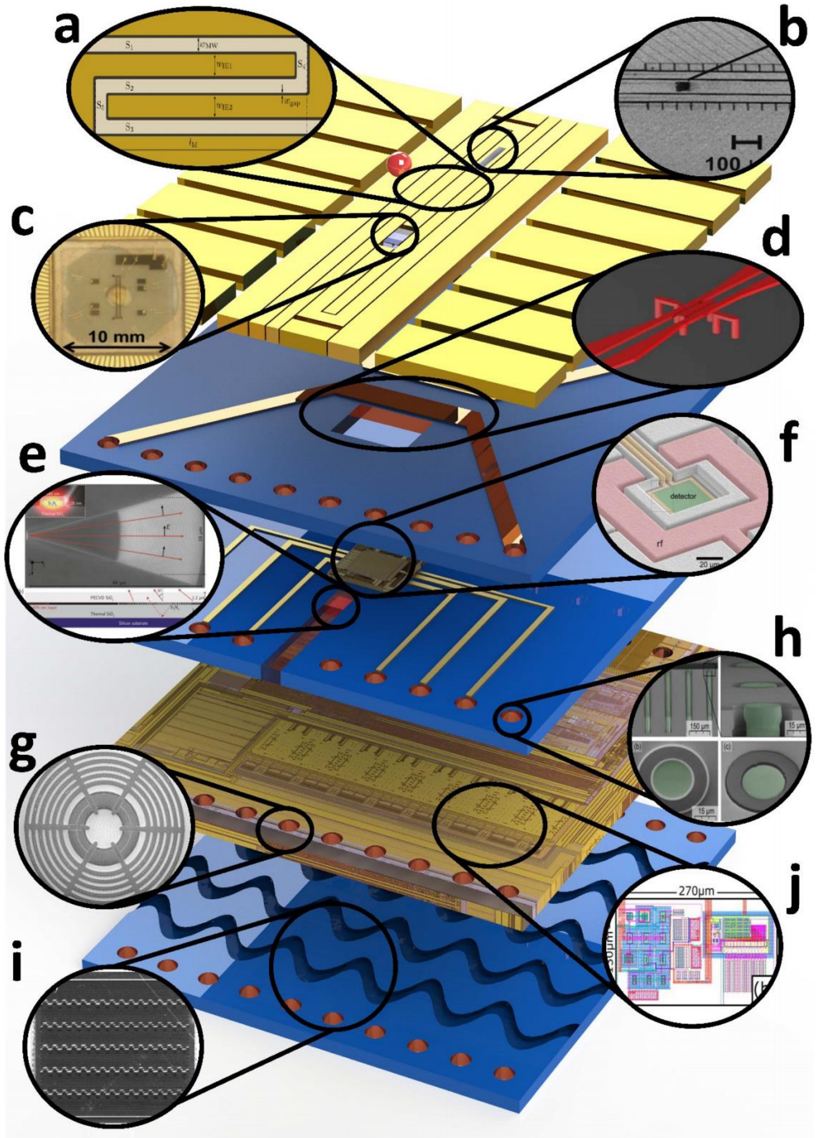
The hardware platform for a transport-based ion trap quantum computer

Advanced on chip technology

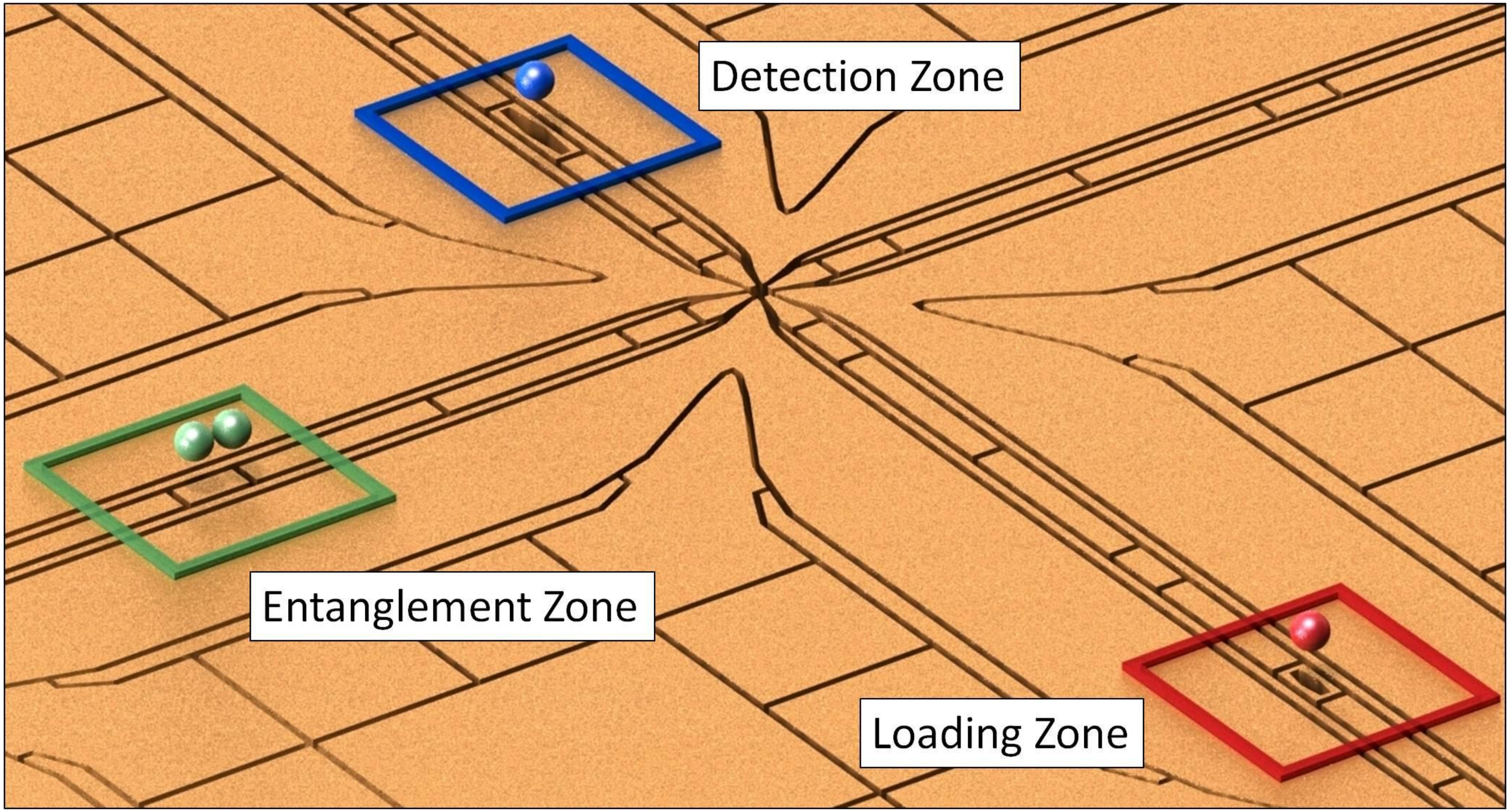


(a) Oscillating gradient CCWs [128] **(b)** Backside loading [69] **(c)** Transparent ITO electrode [98] **(d)** Static gradient CCWs [17] **(e)** Si_3N_4 grating for individual optical addressing [138] **(f)** Integrated photon detector [24] **(g)** Trench capacitors [69] **(h)** Through Silicon Vias (TSVs) [93] **(i)** Integrated electronics [25] **(j)** Microchannel cooling [161].

Engineering of Microfabricated Ion Traps and Integration of Advanced On-Chip Features, Zak David Romaszko, Seokjun Hong, Martin Siegele, Reuben Kahan Puddy, Foni Raphaël Lebrun-Gallagher, Sebastian Weidt and Winfried Karl Hensinger, Nature Review Physics 2, 285-299 (2020)

Scalable Microwave based Architecture

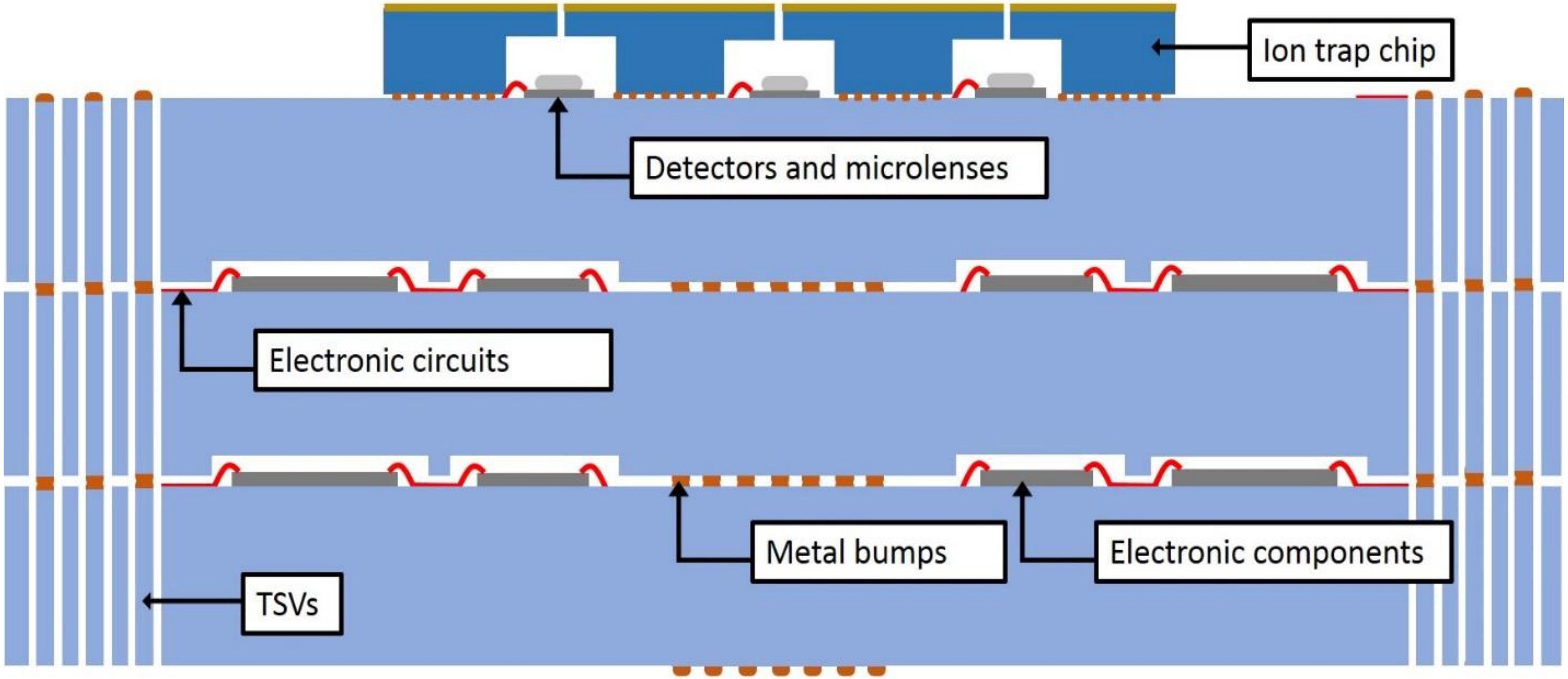
- X-Junctions



Blueprint for a microwave trapped ion quantum computer, B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich, and W.K. Hensinger, Science Advances 3, e1601540 (2017)

Blueprint for scalable ion trap quantum computer

- Multi-wafer Packaging, incorporating control electronics and optical detectors
- Die and wafer bonding techniques



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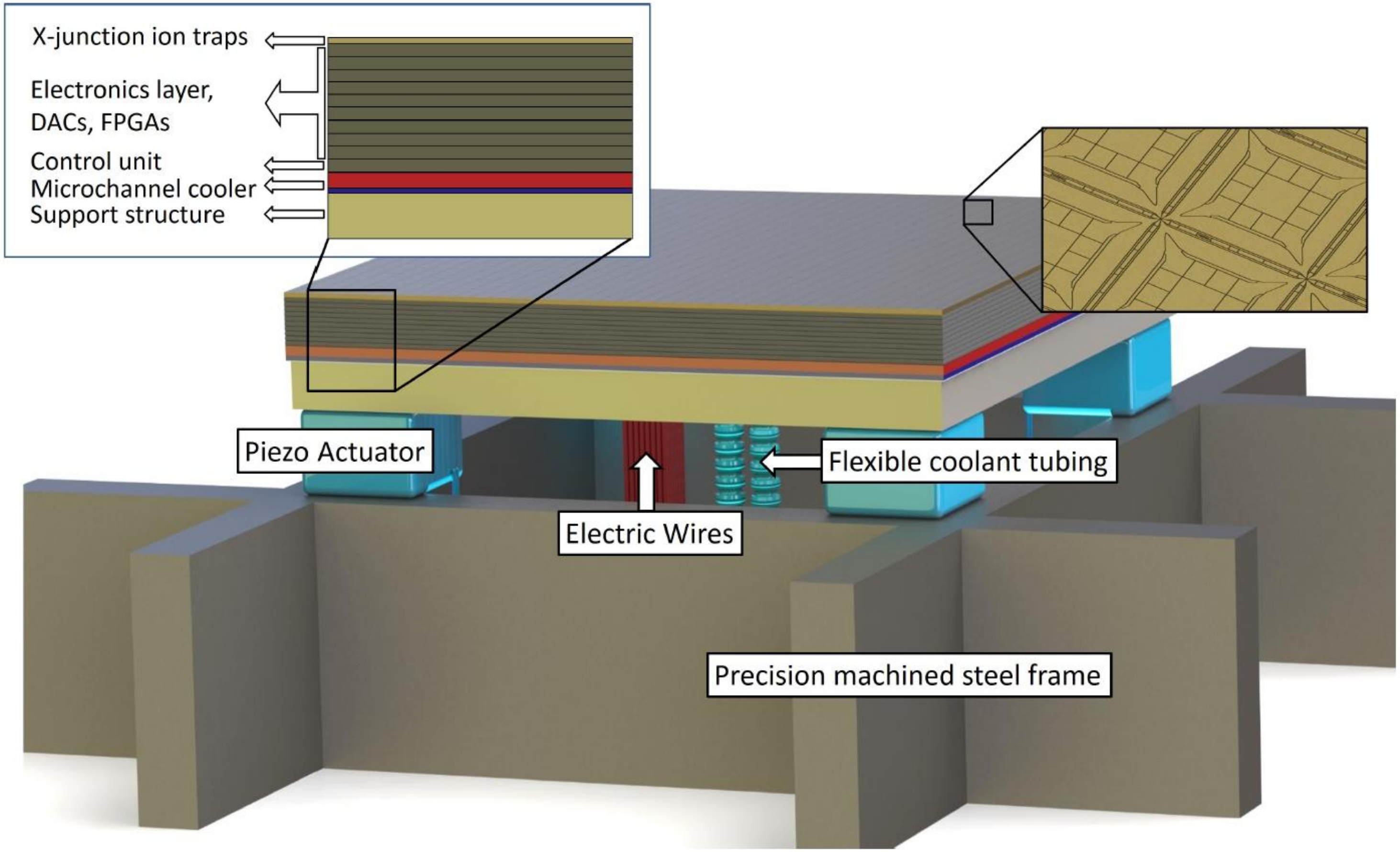
Quantum computing modules



Electronic quantum computing module produced via silicon foundry microfabrication

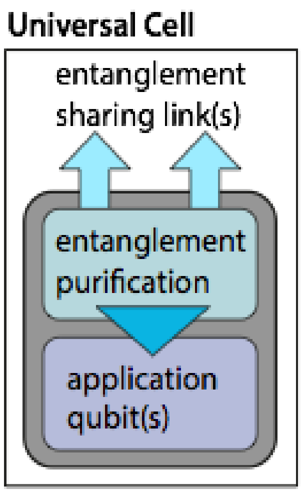
Blueprint for a microwave trapped ion quantum computer, B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich, and W.K. Hensinger, Science Advances 3, e1601540 (2017)

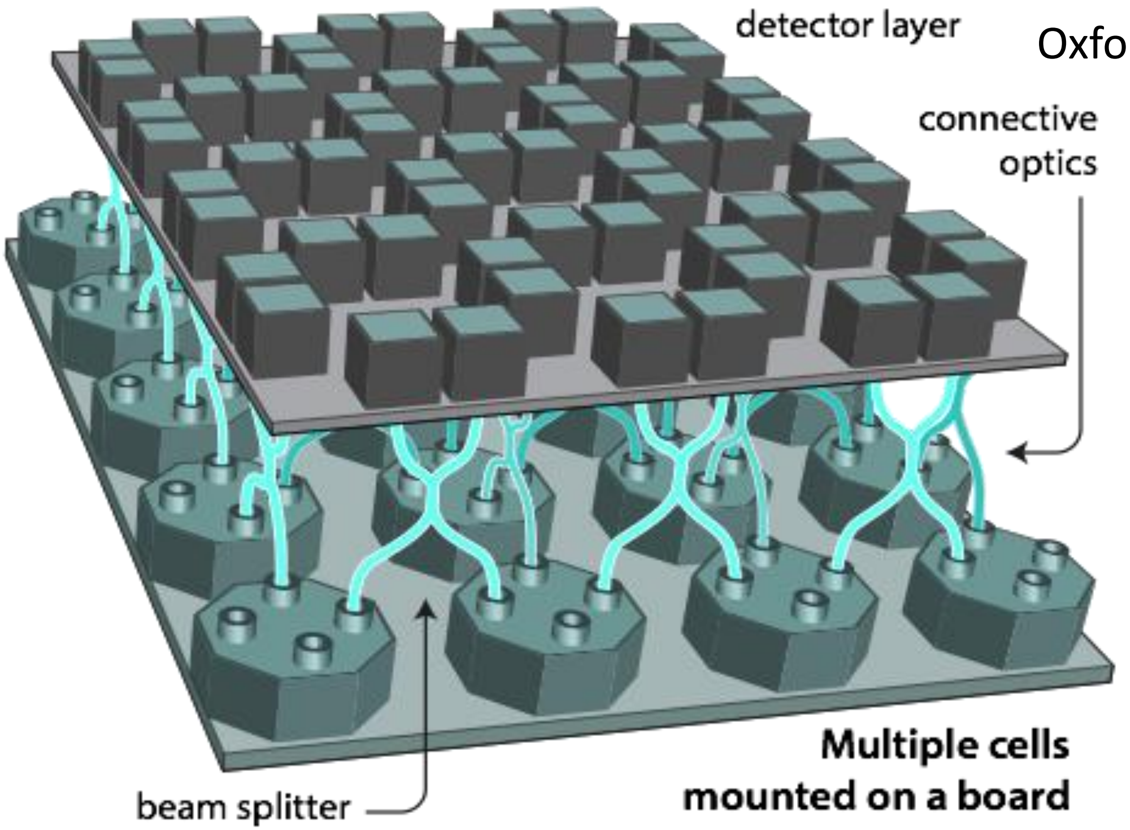
How to make trapped ion quantum computers modular?

Option 1: Connect modules using light particles (photons)

Optically linked array of quantum computing modules…

Oxford 20:20 engine





Pioneered by Chris Monroe's group
Current record: 250 1/s at 94% fidelity (Monroe group), meaning a few 1/s after distillation

- ➢ Challenging to build a practical device

Option 2: Use electric fields to connect modules

- Simpler engineering

- High connection speeds between modules are readily achievable (four order of magnitude faster than optical interconnects!)

- Allows for variable connectivity

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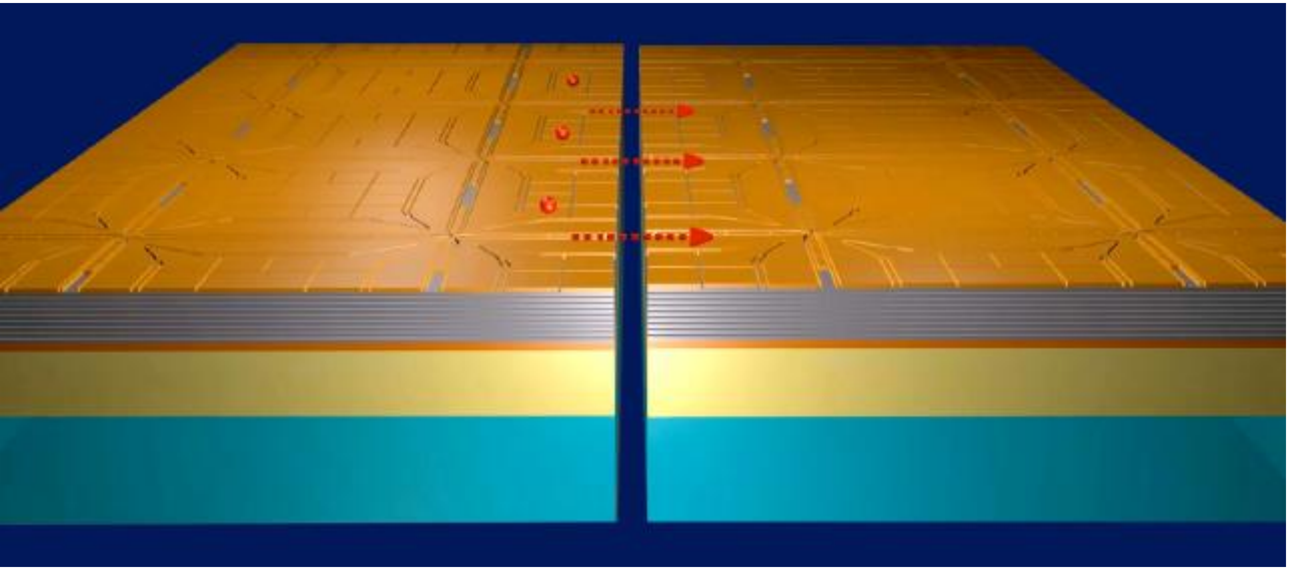
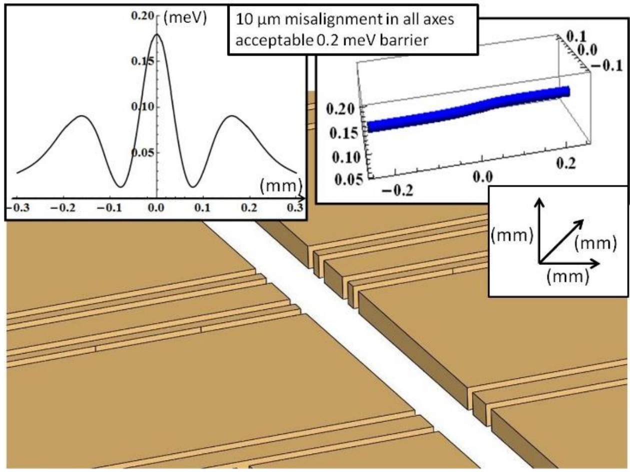
Modularity:
Connecting modules with electric fields





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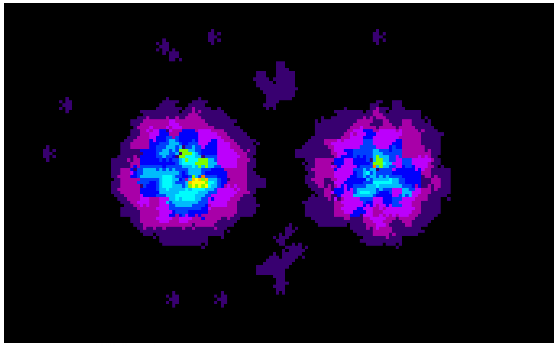
How to make two qubit gates?

In order to make a quantum gate, make use of motional state of the ions as data bus



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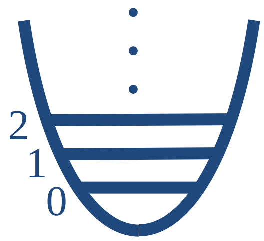
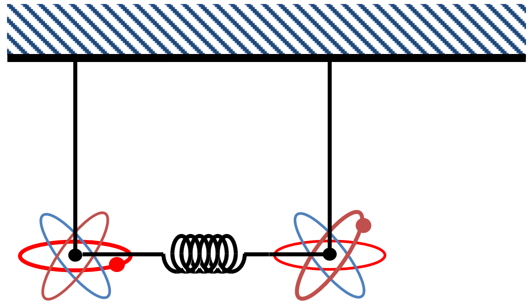
Another Qubit:
The quantized motion of a single mode of oscillation



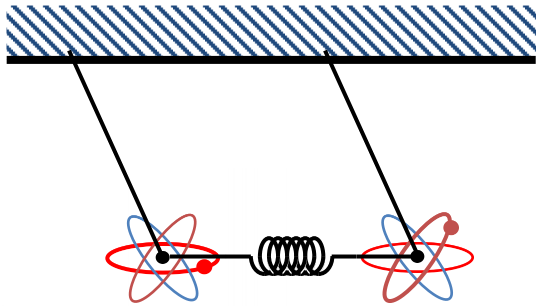
- harmonic motion of a collective single mode described by quantum states $|n\rangle_m = |0\rangle_m, |1\rangle_m, |2\rangle_m, \ldots$, where $E = \hbar\omega(n+½)$
  PHONONS: FORMALLY EQUIVALENT TO PHOTONS

- motional "data-bus" quantum bit spans $|n\rangle_m = |0\rangle_m$ and $|1\rangle_m$

logical $|0\rangle_m$



logical $|1\rangle_m$

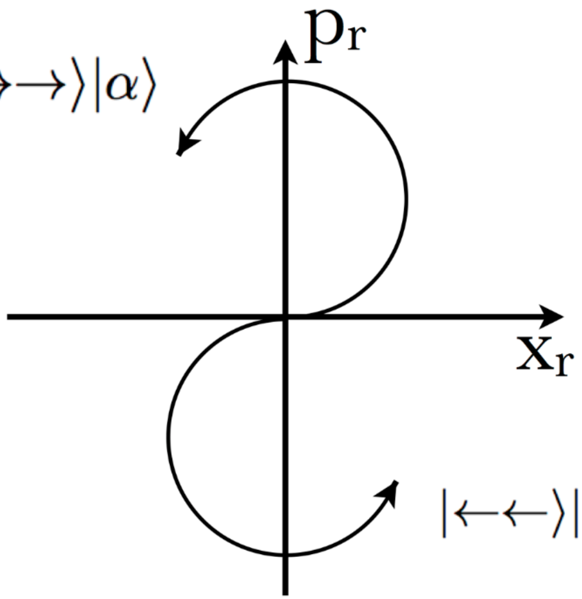


So the gate works like that:

1. Initialize internal state of ion 1
2. Map internal state of ion 1 on motional state of both ions
3. Map motional state of both ions on internal state of ion 2 in such a way that it represents desired gate

The quantum state is only encoded in the internal state of the ions after the gate, not the motional state!

Entanglement using the Molmer Sorensen gate



$$|\leftarrow\leftarrow\rangle \rightarrow i|\leftarrow\leftarrow\rangle$$

$$|\leftarrow\rightarrow\rangle \rightarrow |\leftarrow\rightarrow\rangle$$

$$|\rightarrow\leftarrow\rangle \rightarrow |\rightarrow\leftarrow\rangle$$

$$|\rightarrow\rightarrow\rangle \rightarrow i|\rightarrow\rightarrow\rangle$$

$$|\rightarrow\rangle = |0'\rangle + |D\rangle$$

$$|\leftarrow\rangle = |0'\rangle - |D\rangle$$

There are two different types of gates

- Gates using Raman beams
  - Sensitive to Laser amplitude and phase fluctuations
  - Requires two overlapping laser beams
  - Gate speed typically faster than microwave gates
  - Ultimate achievable fidelity limited by spontaneous emission
  - The number of laser beams required scales with the number of qubits

- Gates using global microwave fields
  - Gates executed by applying static voltages to a microchip
  - Gate speed slower than laser gates
  - Number of radiation fields is independent of the number of qubits
  - World-record gate fidelity already demonstrated

Delivery of Laser beams for gate execution?

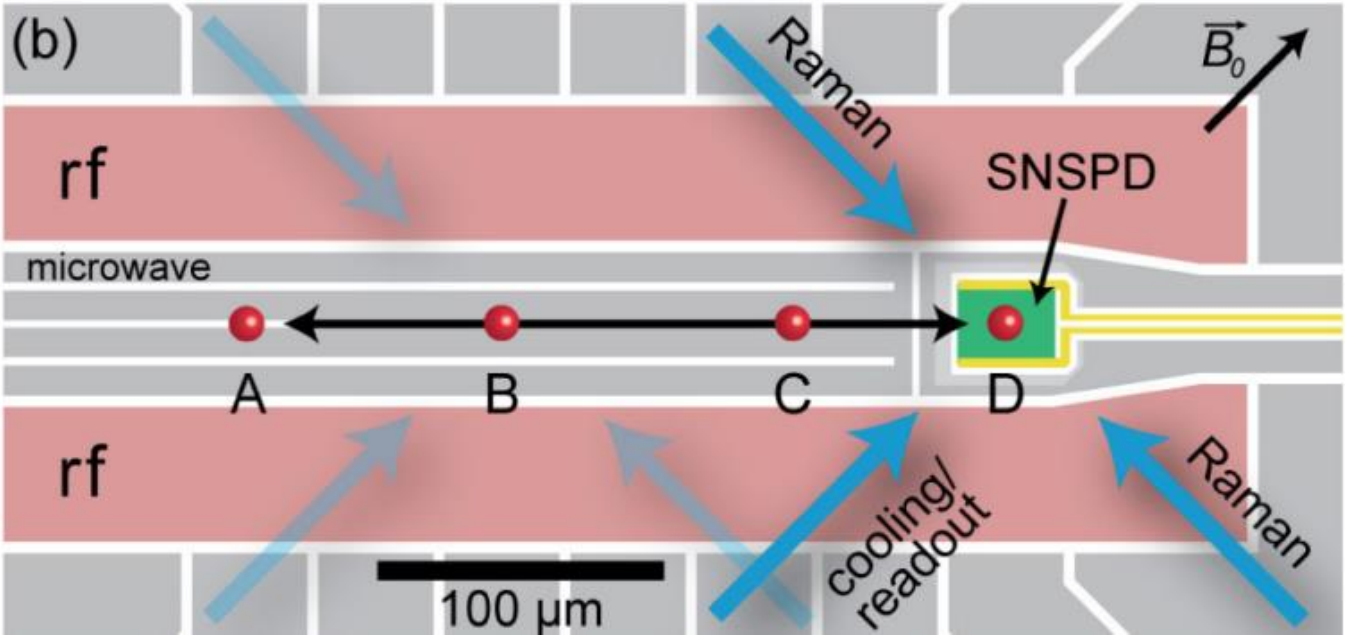


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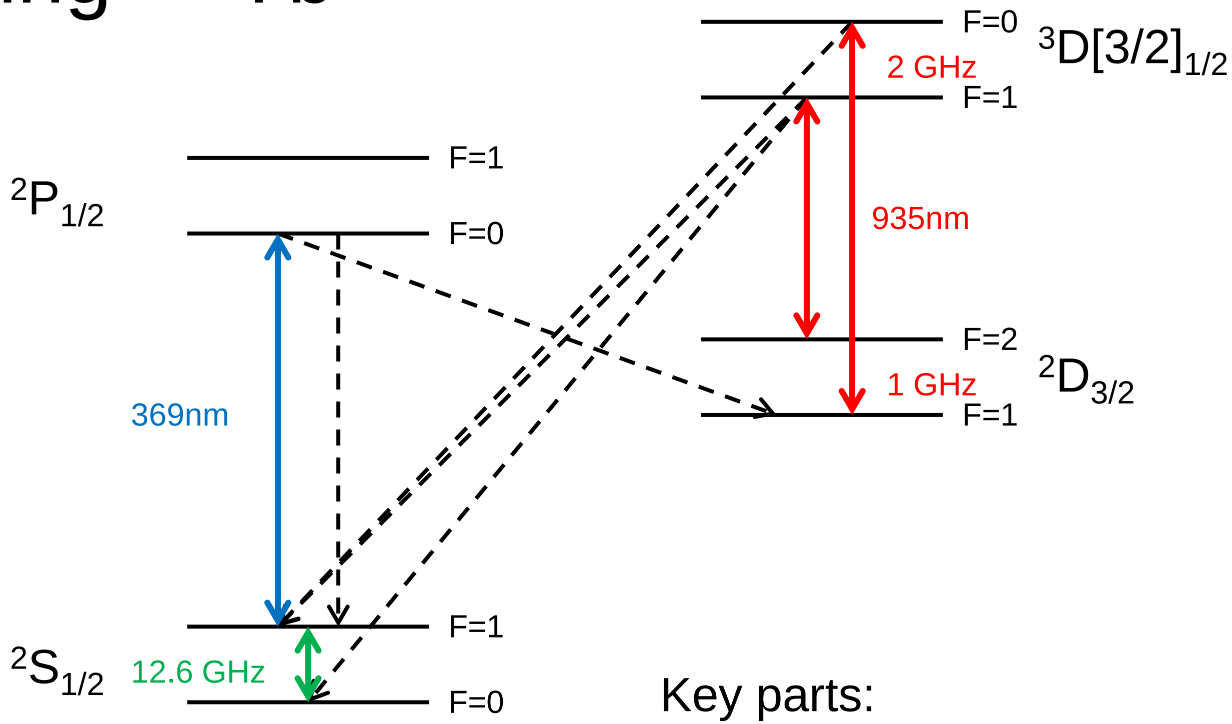
Image taken from:
State Readout of a Trapped Ion Qubit Using a Trap-Integrated Superconducting Photon Detector, S. L. Todaro, V. B. Verma, K. C. McCormick, D. T. C. Allcock, R. P. Mirin, D. J. Wineland, S. W. Nam, A. C. Wilson, D. Leibfried, and D. H. Slichter Phys. Rev. Lett. **126**, 010501 (2021)

How to cool, state prepare and detect the quantum state

Yb ions

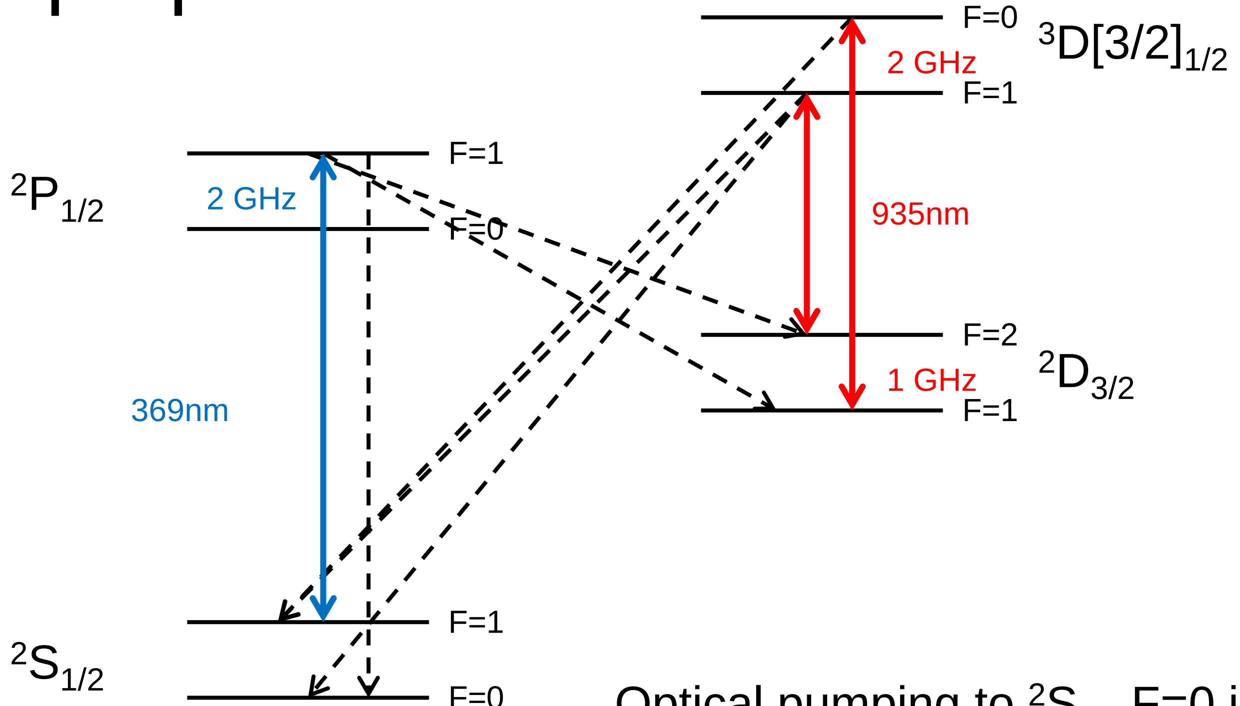
- Cooling $^{171}Yb^+$



Key parts:
- Closed cycle of transitions
- Red detuning making use of Doppler effect to slow down atoms

Yb ions

- State preparation

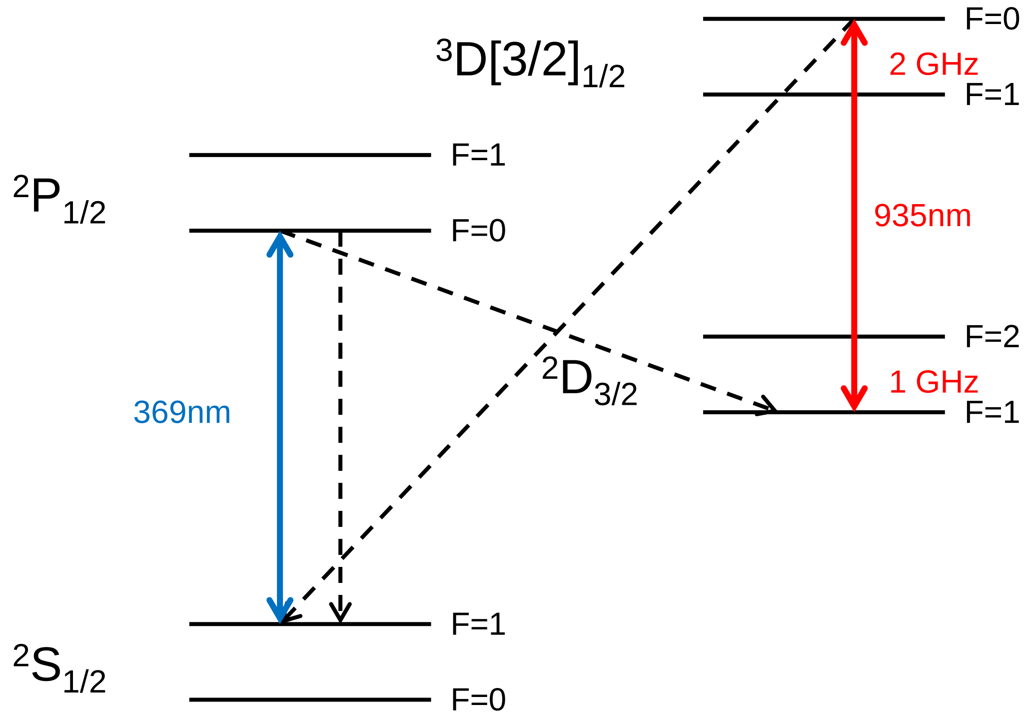


Optical pumping to $^2S_{1/2}$ F=0 in ~ 20 μs

Can the ion end up in any other state?
Compare cooling and state preparation?

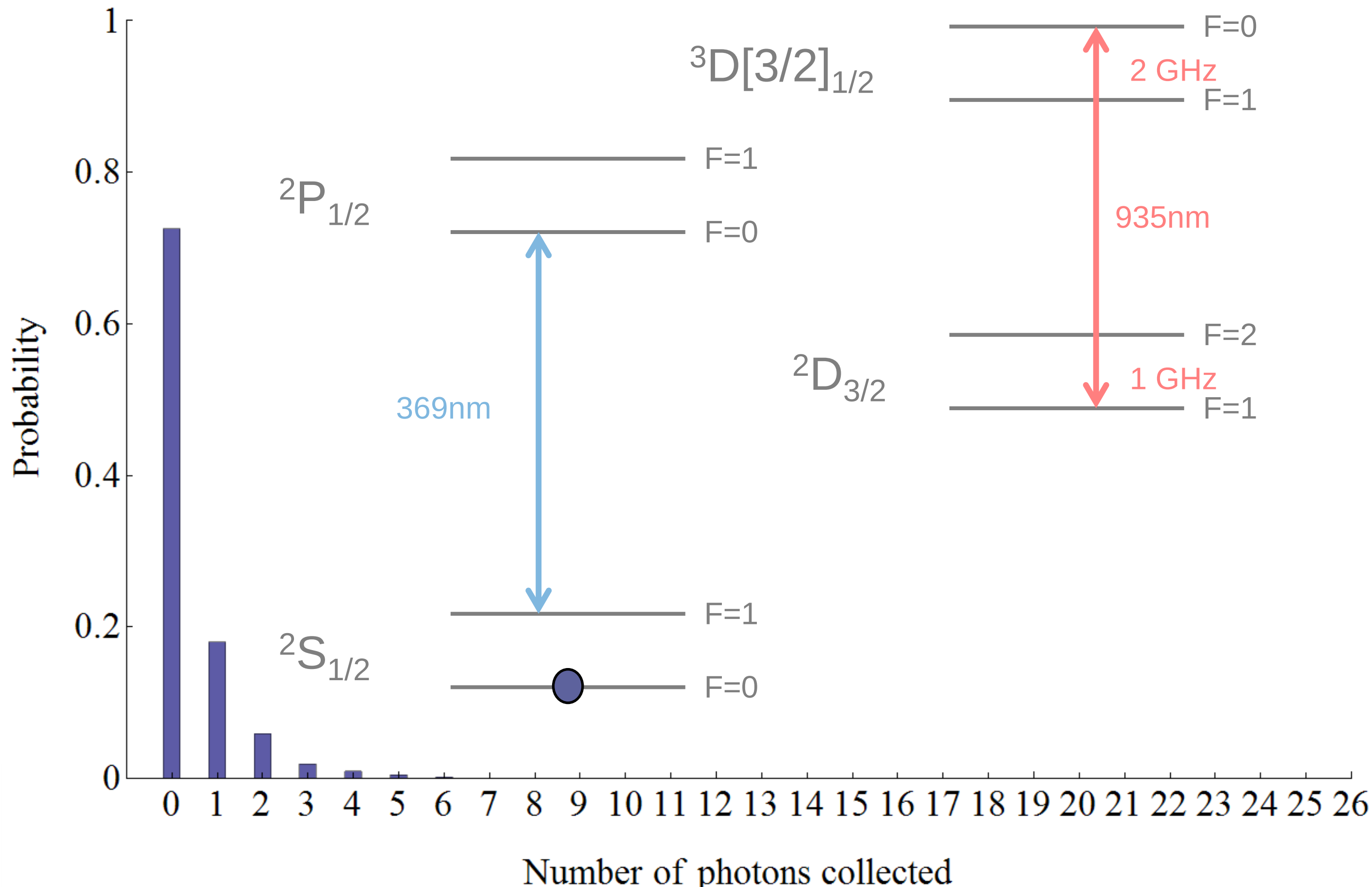
Yb ions

- State detection



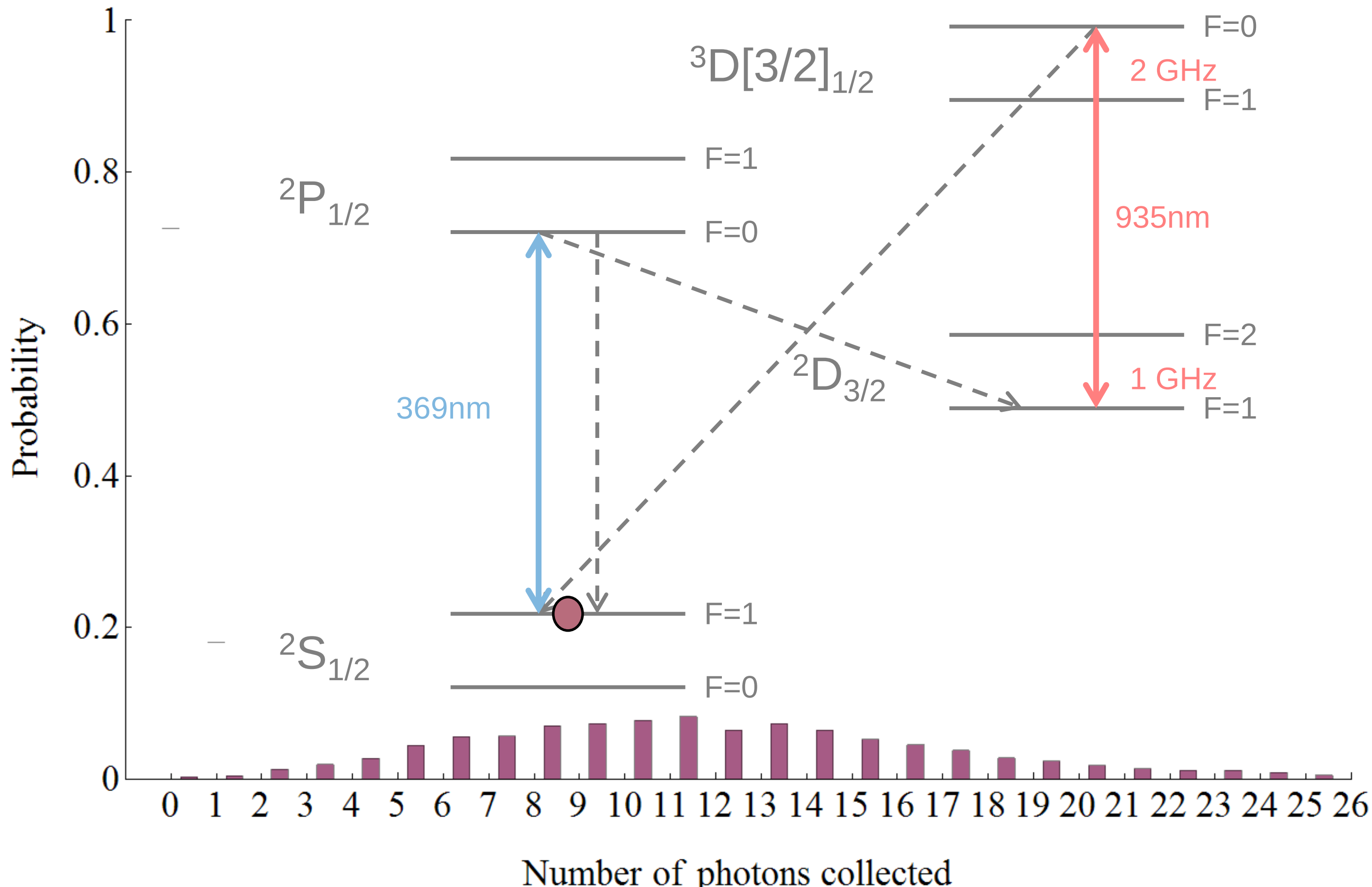
Yb ions

- State detection



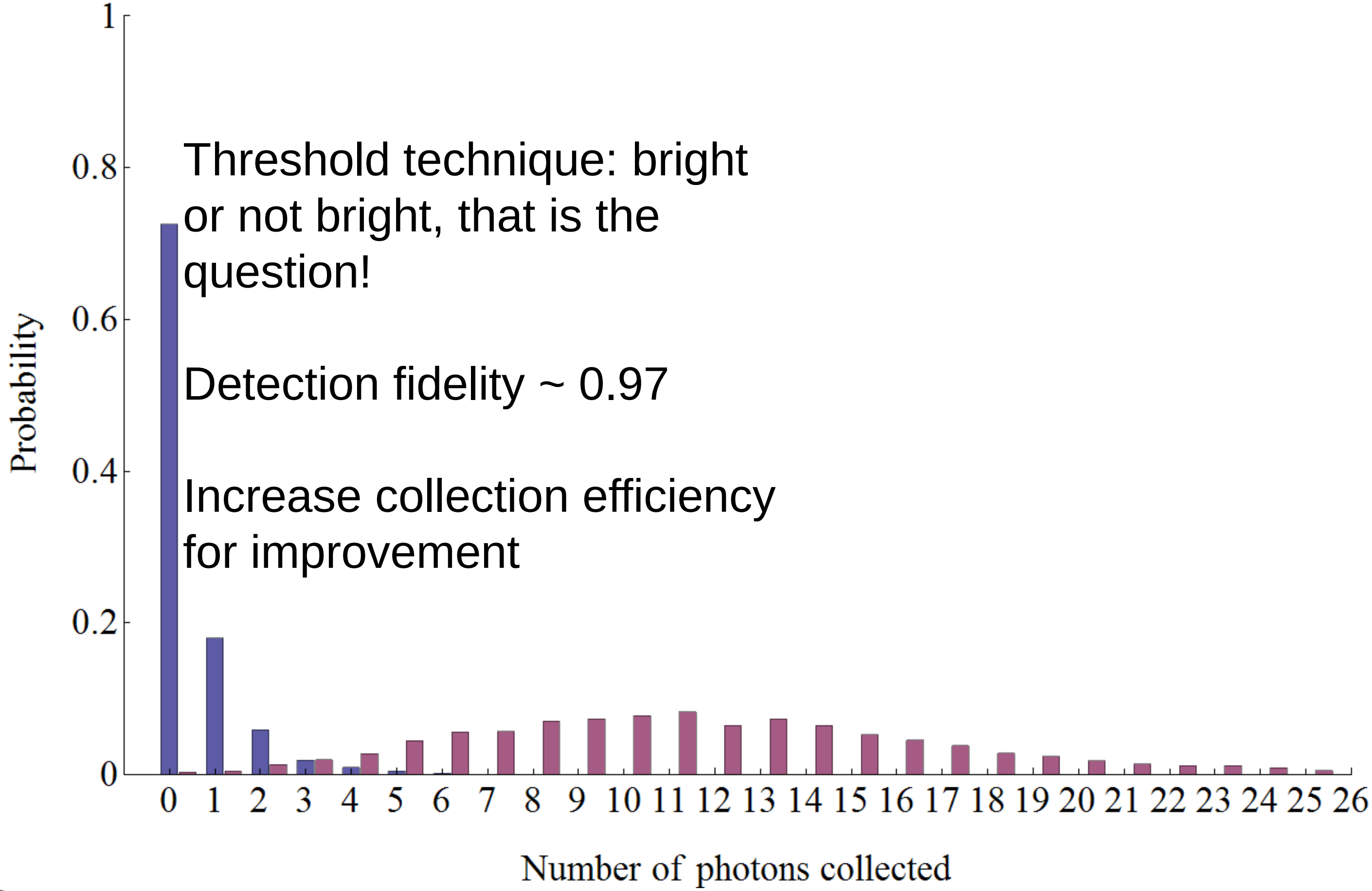
Yb ions

- State detection



Yb ions

- State detection



Threshold technique: bright or not bright, that is the question!

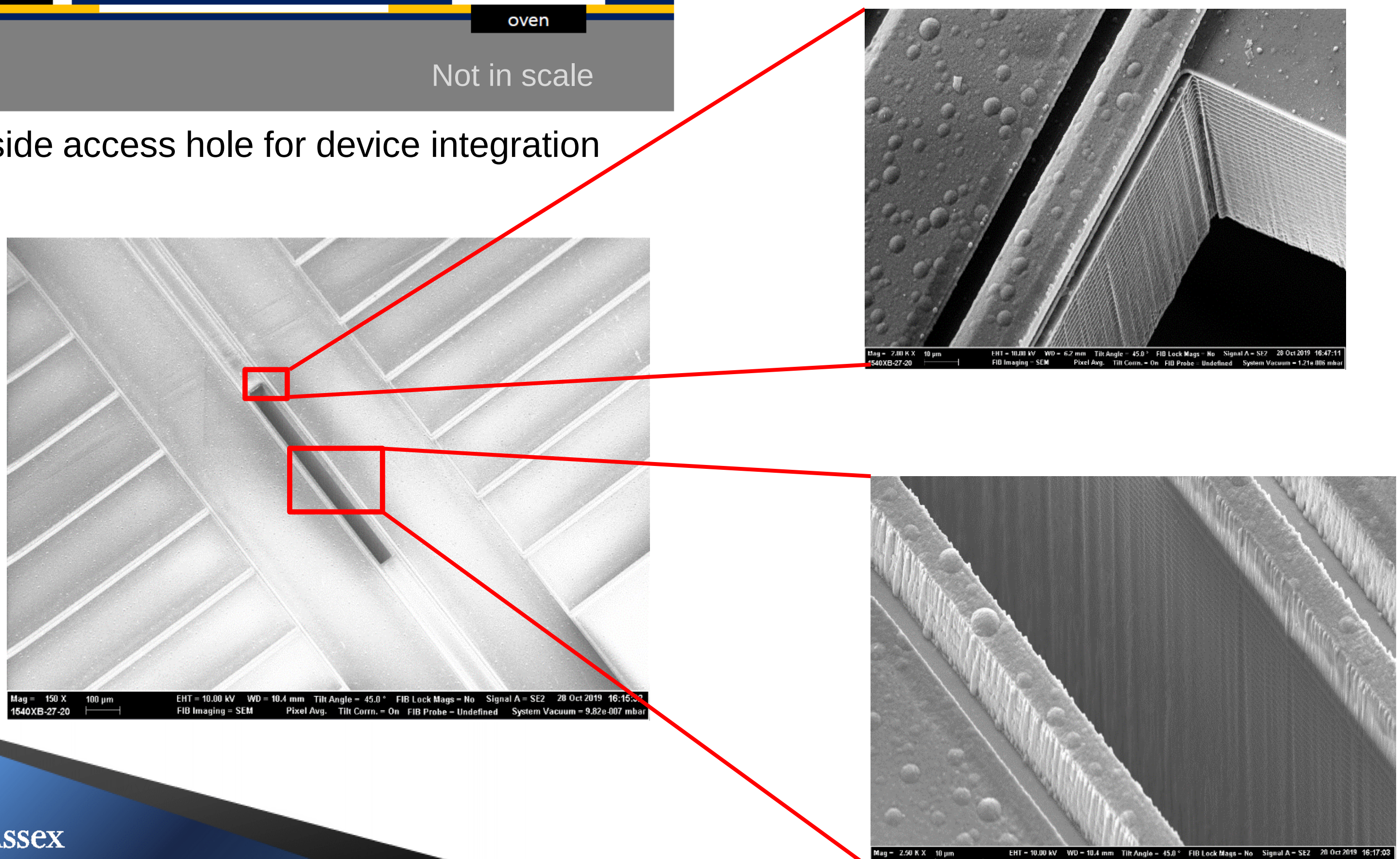
Detection fidelity ~ 0.97

Increase collection efficiency for improvement

Integration of detectors and ovens

Backside access hole for device integration

Fabricated by IQT Sussex



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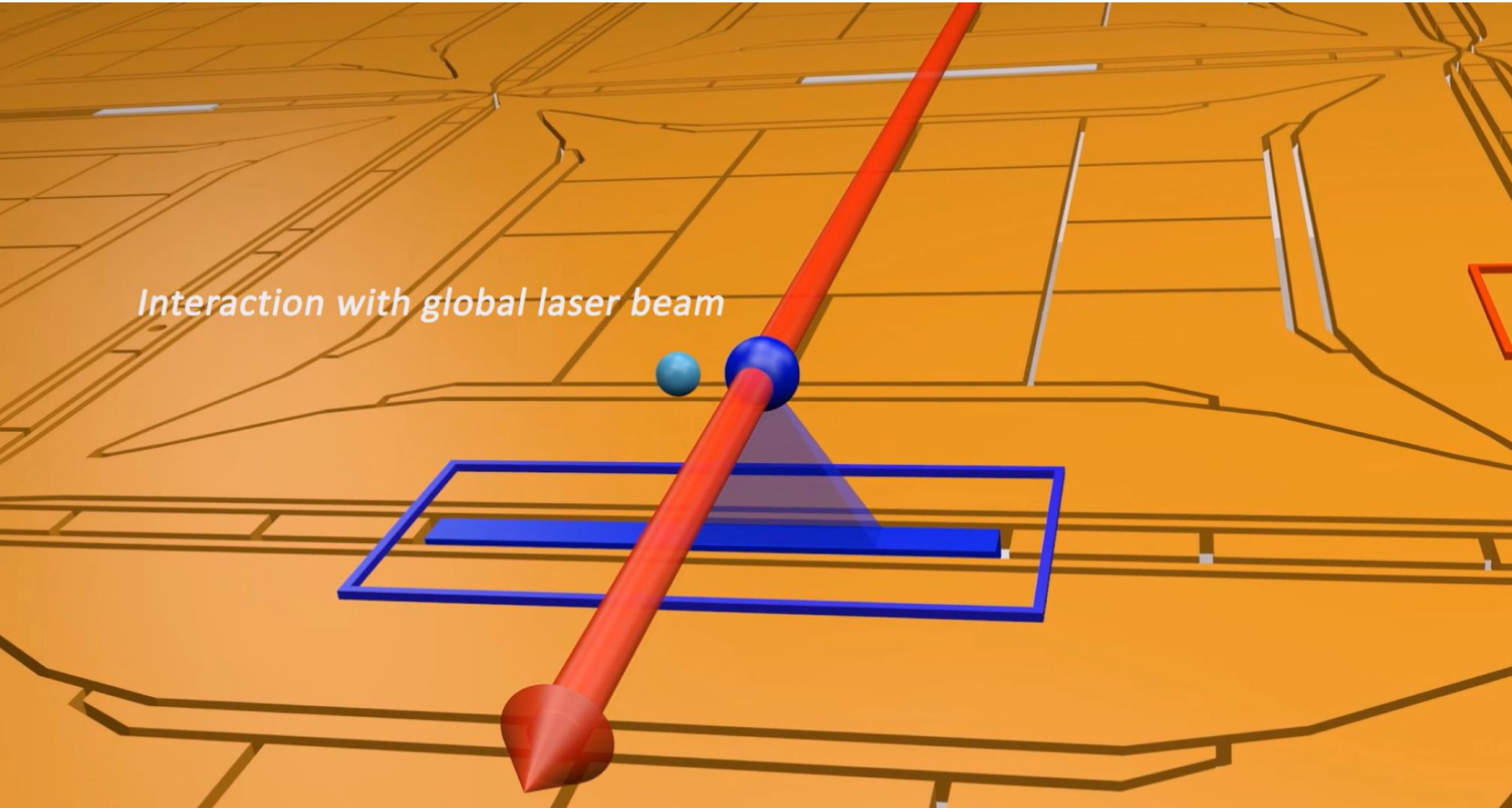
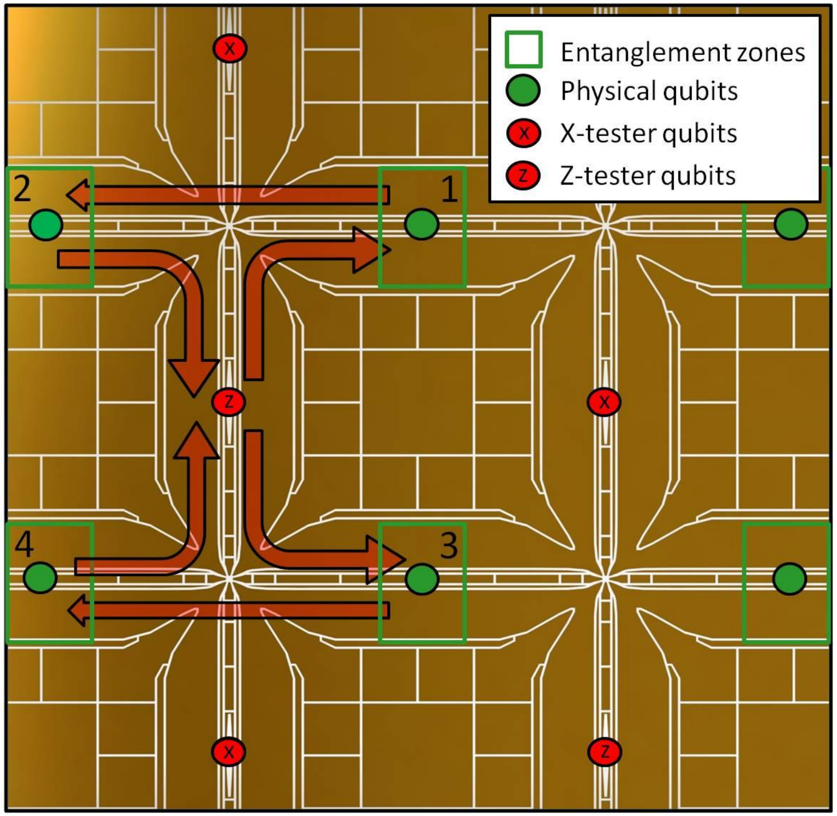
Delivery of laser beams for detection, cooling, repumping and photoionisation?



How to correct for errors – quantum error correction

Using the surface code in a transport-based quantum computer



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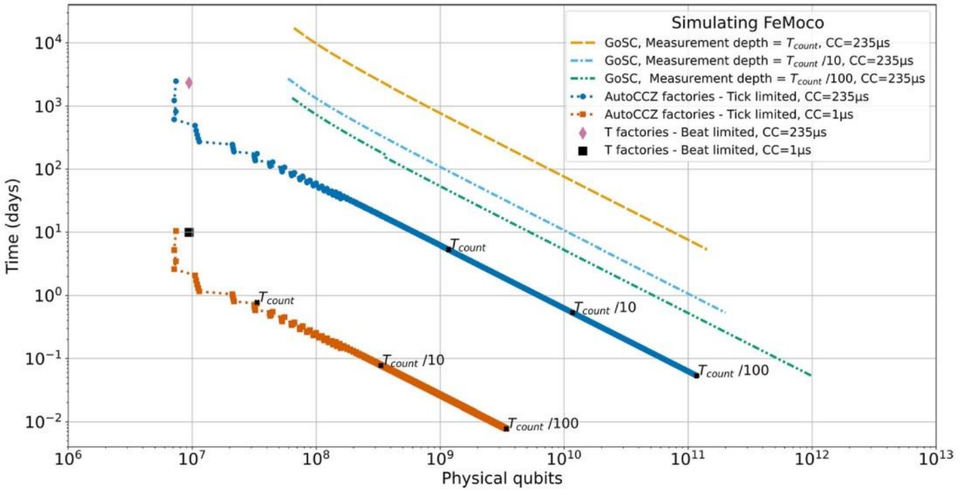
The Impact of Hardware Specifications on Reaching Quantum Advantage in the Fault Tolerant Regime

- We have determined how a quantum computer could break the encryption of Bitcoin and simulate the FeMo-co molecule, a crucial molecule for Nitrogen fixation.
- We show that it is possible to compensate for slower clock cycle times by using more qubits.
- Four years ago, we estimated that a trapped ion quantum computer would need a billion physical qubits to break RSA encryption equating to a size 100m^2. With innovations across the board, the size of such a quantum computer would now just need to be 2.5m^2

Time to simulate the FeMo-co molecule depends on the number of qubits available



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The Impact of Hardware Specifications on Reaching Quantum Advantage in the Fault Tolerant Regime
Mark Webber, Vincent Elfving, Sebastian Weidt and Winfried K. Hensinger, AVS Quantum Sci. 4, 013801 (2022)

How many qubits – the choice of code

- Surface code
  - Very well established code known to work well.
  - To enable high value industry applications where quantum computers may need to compute for extended periods, a ratio of physical to logical qubits of 1000:1 will be required.
  - Transversal gates enabled by the connectivity of the ion trap platform will reduce the overall required qubit count.

- qLDPC and other codes
  - A new generation of codes that promises but smaller ratio of physical to logical qubits.
  - These codes require enhanced connectivity that is natural to the ion trap hardware platform.
  - While it is known how to use this code to protect logical qubits as a memory, nobody has yet developed a way how to do logical operations with such codes.
  - While these codes look very interesting showing a lot of potential, more work is required in order to demonstrate their practical usability.

Technology integration

While trapped-ion quantum computing is more advanced than most other hardware platforms and there are no hard physics barriers that need to be overcome, I would identify

- integration of all demonstrated achievements into a single device that illustrates the capability of scaling to utility scale

as the biggest challenge towards realizing a utility scale machine.

As such I believe the following questions should be addressed:

- How can you demonstrate with a smaller machine that integration is successful?
- Does the technology in the demonstrator work at the million-qubit scale or is there a significant change of technology required when going towards bigger machines?
- How significant is such change of technology?
- What engineering problems remain to be solved?
- What risks remain (e.g. anticipated use of a particular error correction code).

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Summary

- Trapped ions are a tremendously mature platform to build practical quantum computers.
- The transport-based ion trap architecture is capable of giving rise to quantum computing systems with millions of qubits.
- The enhanced connectivity of trapped ion devices implies much smaller resource requirements to enable quantum advantage for important quantum computing applications.
- At small scale, transport-based trapped ion quantum computers have already demonstrated key specifications for fault-tolerant operation to execute important industry applications.
- It's important to understand how and if the chosen architecture can perform at the million-qubit scale and what technology innovations would be required to give rise to operation at that scale.

More information:
Research group: http://www.sussex.ac.uk/physics/iqt
Research centre: http://www.sussex.ac.uk/scqt/
Email: w.k.hensinger@sussex.ac.uk