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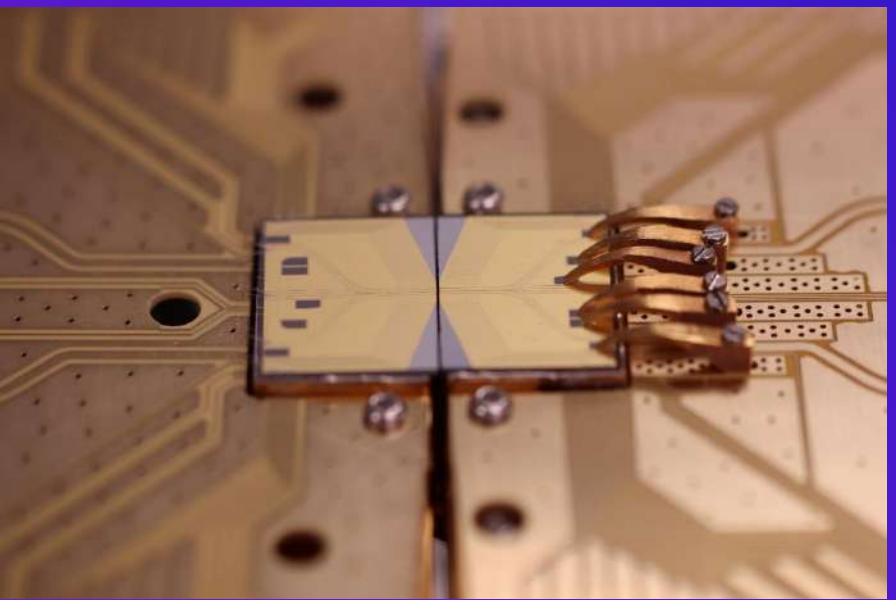
Developing modular microwave trapped-ion quantum computers for operation with millions of qubits



Winfried K. Hensinger

University of Sussex

Ion Quantum Technology Group

Sussex Centre for Quantum Technologies

Universal Quantum Ltd

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

http://www.sussex.ac.uk/scqt/

https://universalquantum.com/

Head of group:
Prof. Winfried Hensinger

Senior Scientist:
Prof. Sebastian Weidt

Group Administrator:
Emily Crozier

Electronics Engineer:
Andy Betts

Software Engineer:
Joe Swainston

PDRAs:
Dr Sam Hile
Dr Pedro Taylor-Burdett
Dr Martin Siegele
Dr Chris Knapp
Dr Sahra Kulmiya

PhD Students:
Gareth Hopkins
Scott Mason
Parsa Rahimi
Toby Maddock
James Urquhart
Mo Saleh
James Urquhart
Matthew Aylett
Rares Barcan
Thomas Clarke
Caleb Burhan
Sameer Yadav
Finn O'Dwyer
Damian Gimeno
Ru Morgan



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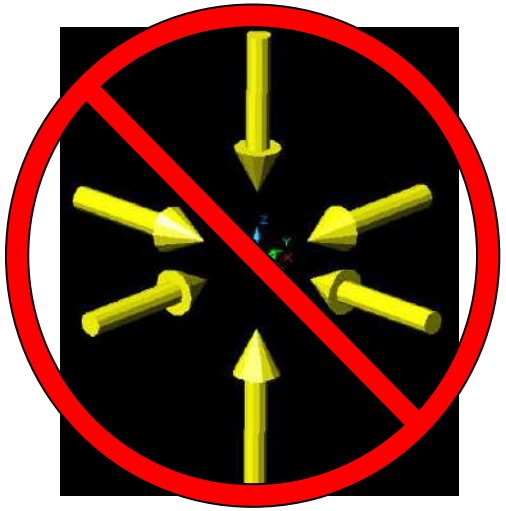
Two computational regimes

- 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
  - Hundred thousands or millions of qubits!

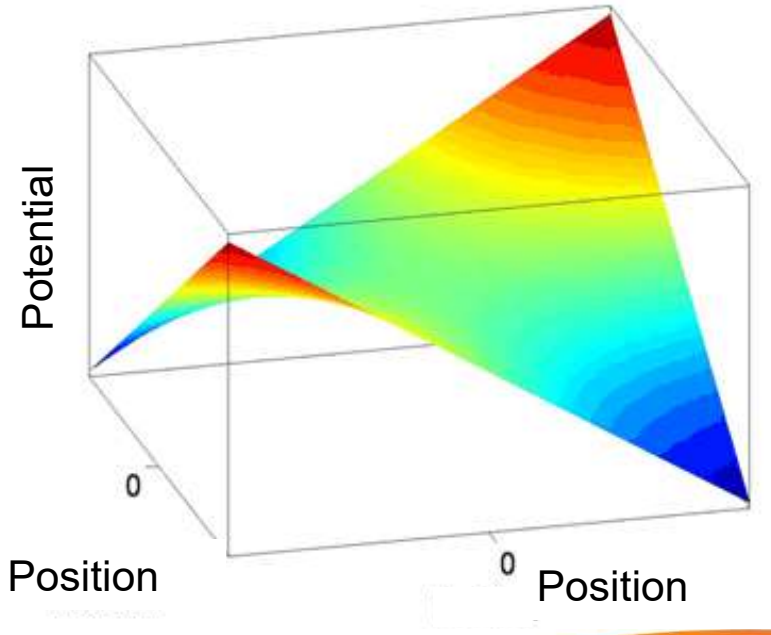
Current quantum computers have 100-1000 qubits

How to trap an ion



An ion is a charged atom
→ need electric field minimum to trap it

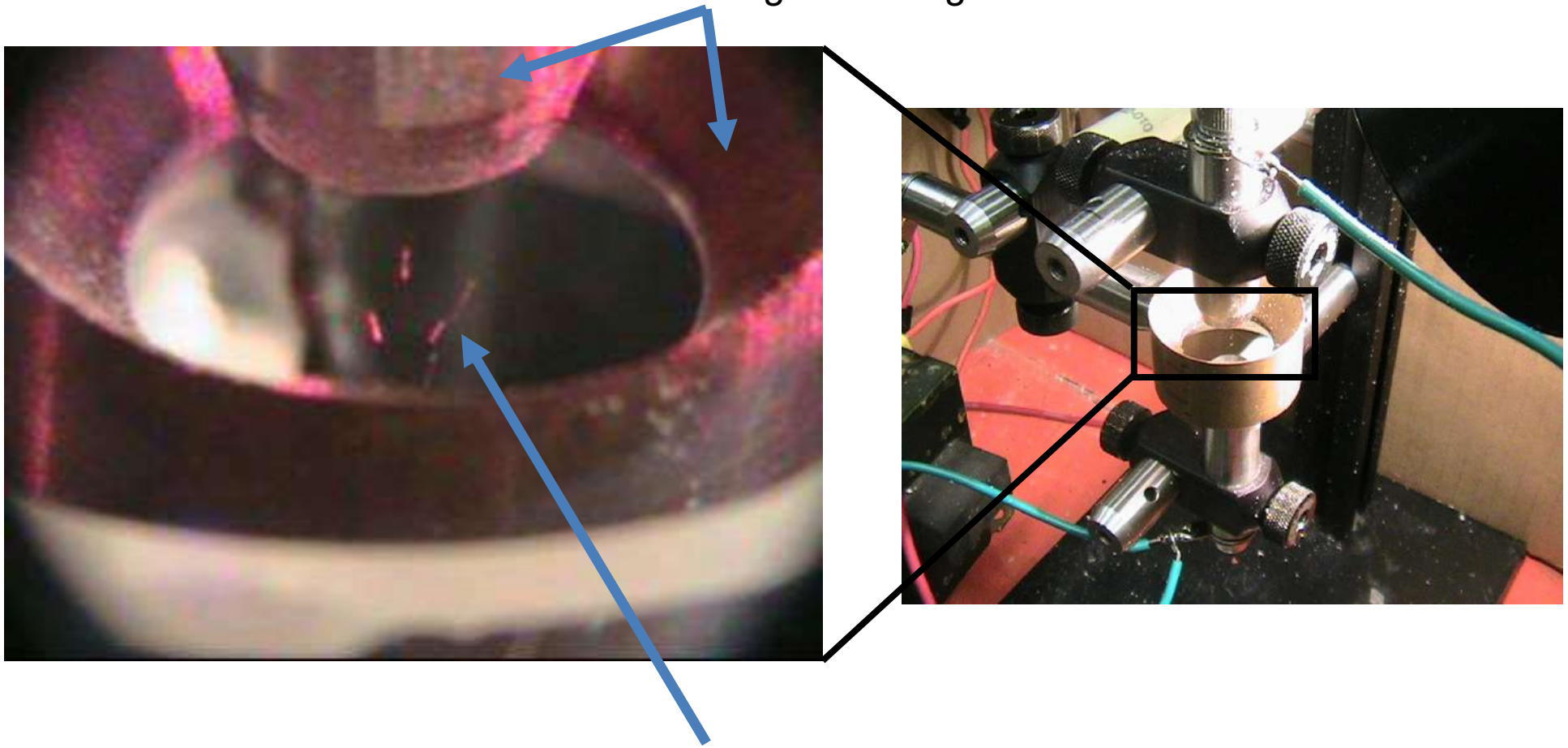
$$\nabla \cdot E = 0$$





Charged particle trap

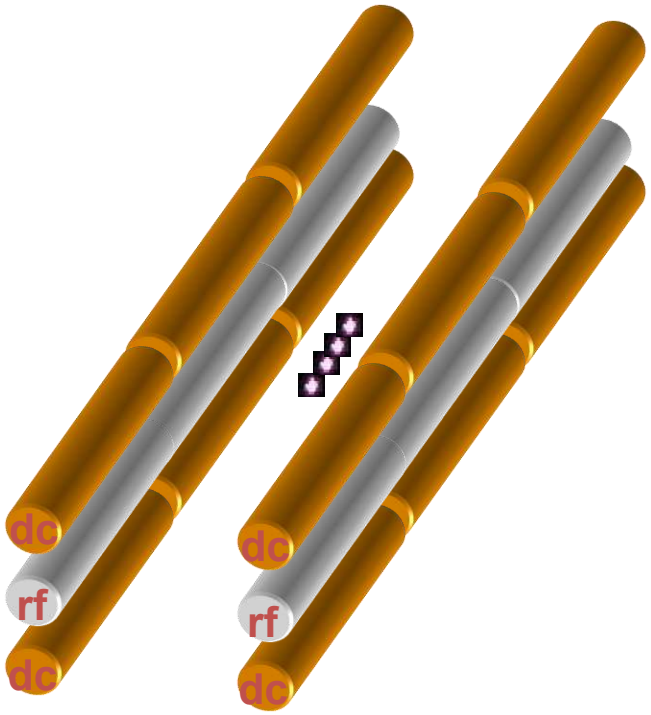
Electrodes emitting oscillating electric field

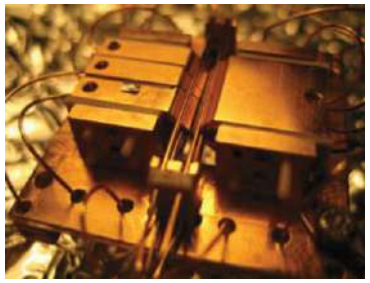


Dust particles that have been rubbed to attract a charge

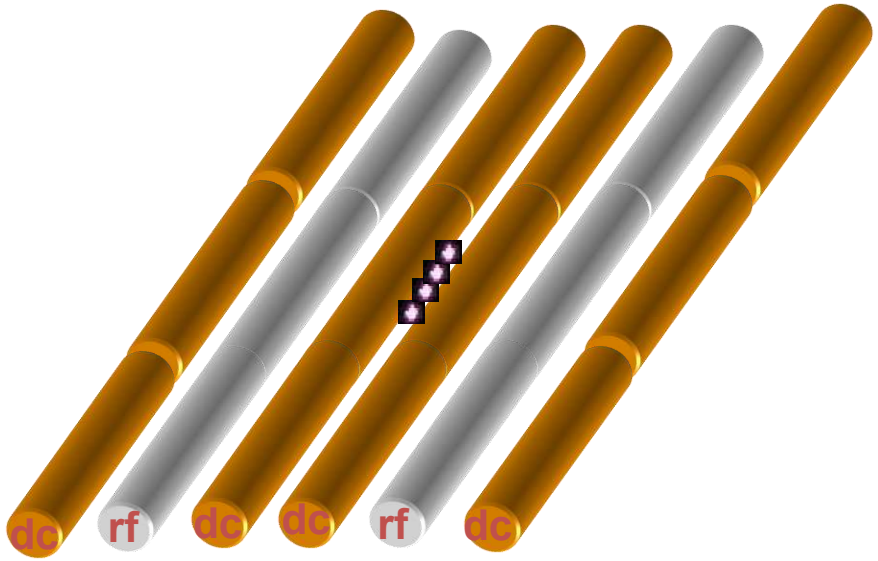
Ion trap technologies

Symmetric trap:
Trap electrodes surround the ion.

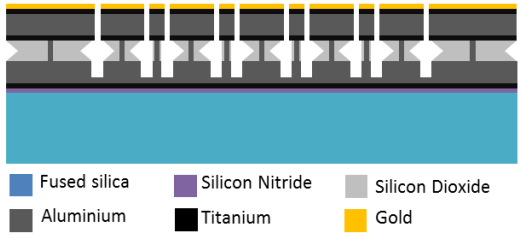


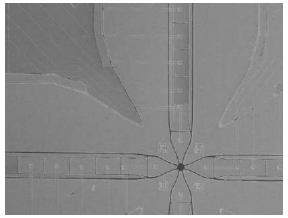


Assymetric or surface trap;
Trap electrodes reside in a single plane and the ion pathway is above that plane

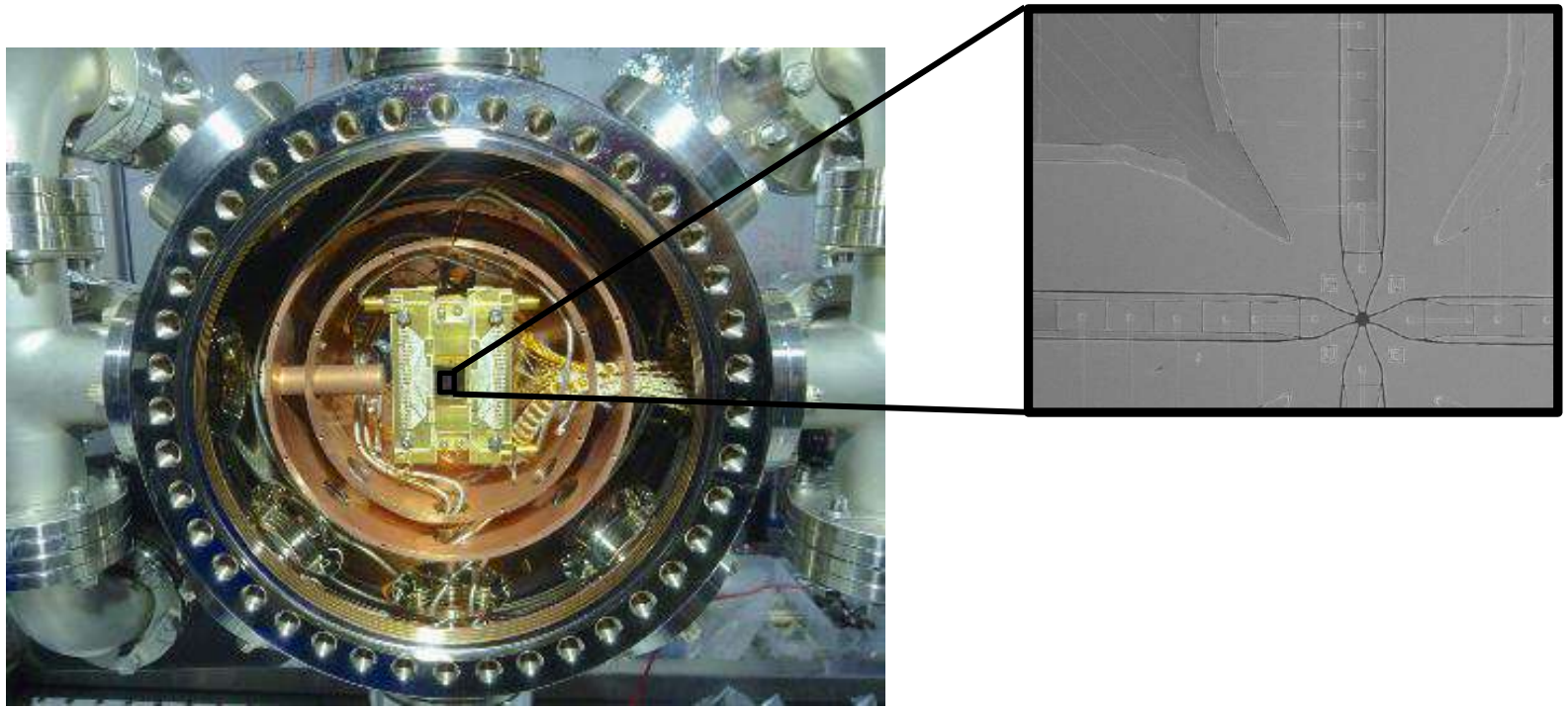


Scalability





Quantum computer microchip



Microchip developed at the University of Sussex

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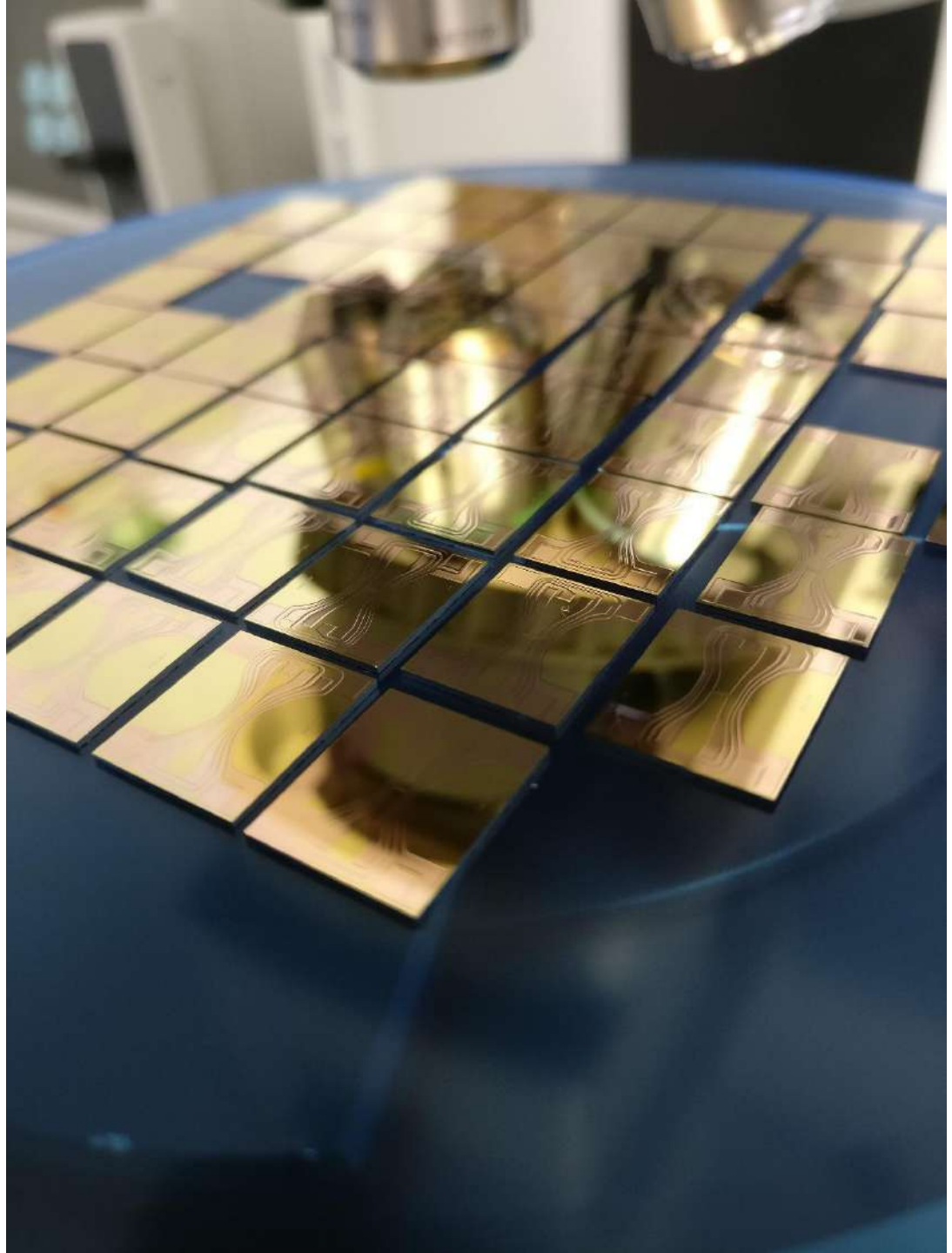
Microfabricated ion traps

Overview papers:

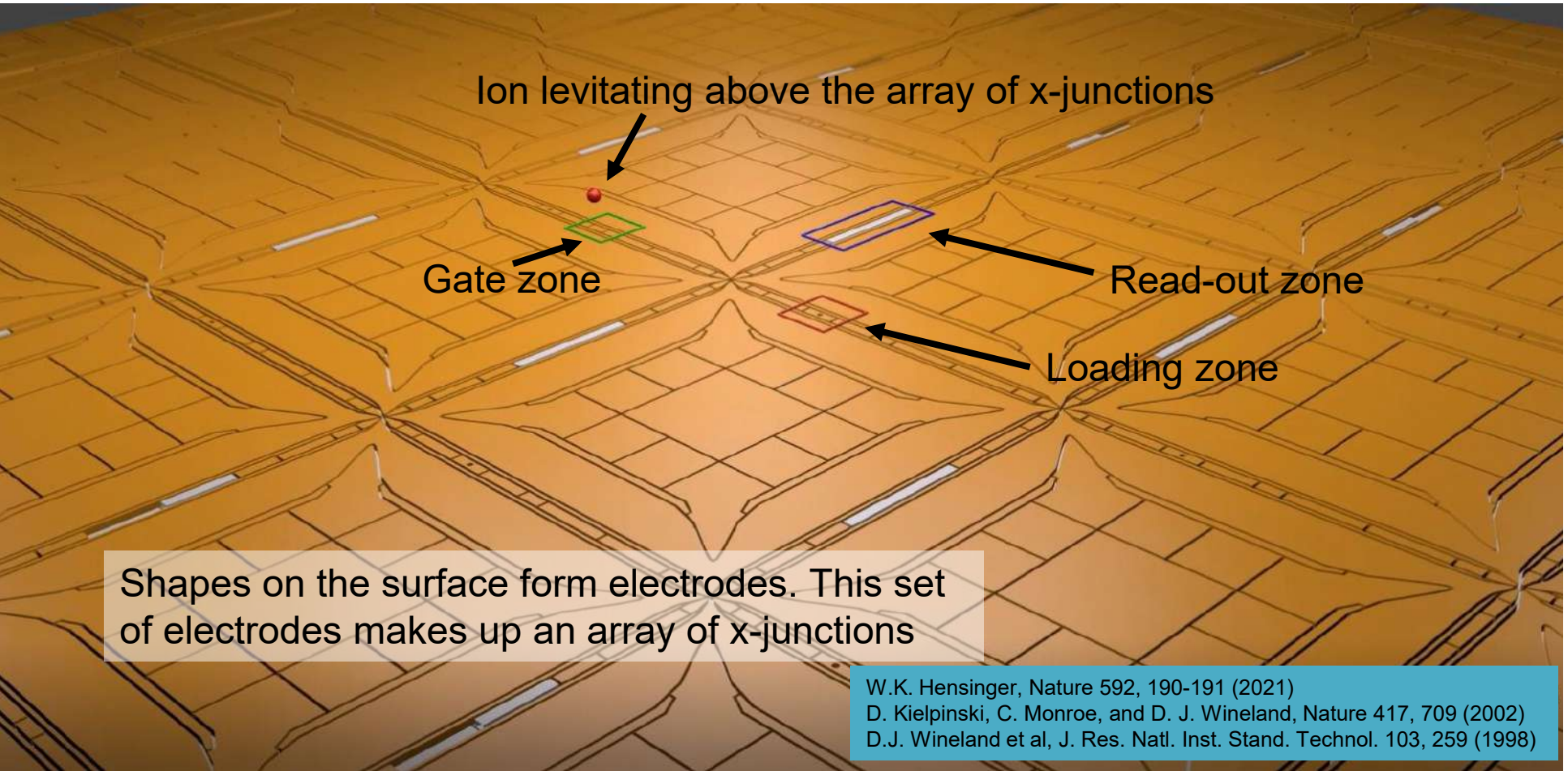
- Engineering of Microfabricated Ion Traps and Integration of Advanced On-Chip Features, Zak David Romaszko, Seokjun Hong, Martin Siegele, Reuben Kahan Puddy, Foni Raphaël Lebrun-Gallagher, Sebastian Weidt and Winfried Karl Hensinger, Nature Review Physics 2, 285-299 (2020)

- Microfabricated Ion Traps, Marcus D. Hughes, Bjoern Lekitsch, Jiddu A. Broersma and Winfried K. Hensinger, Contemporary Physics 52, 505 (2011)



An ion trap quantum computer

- 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

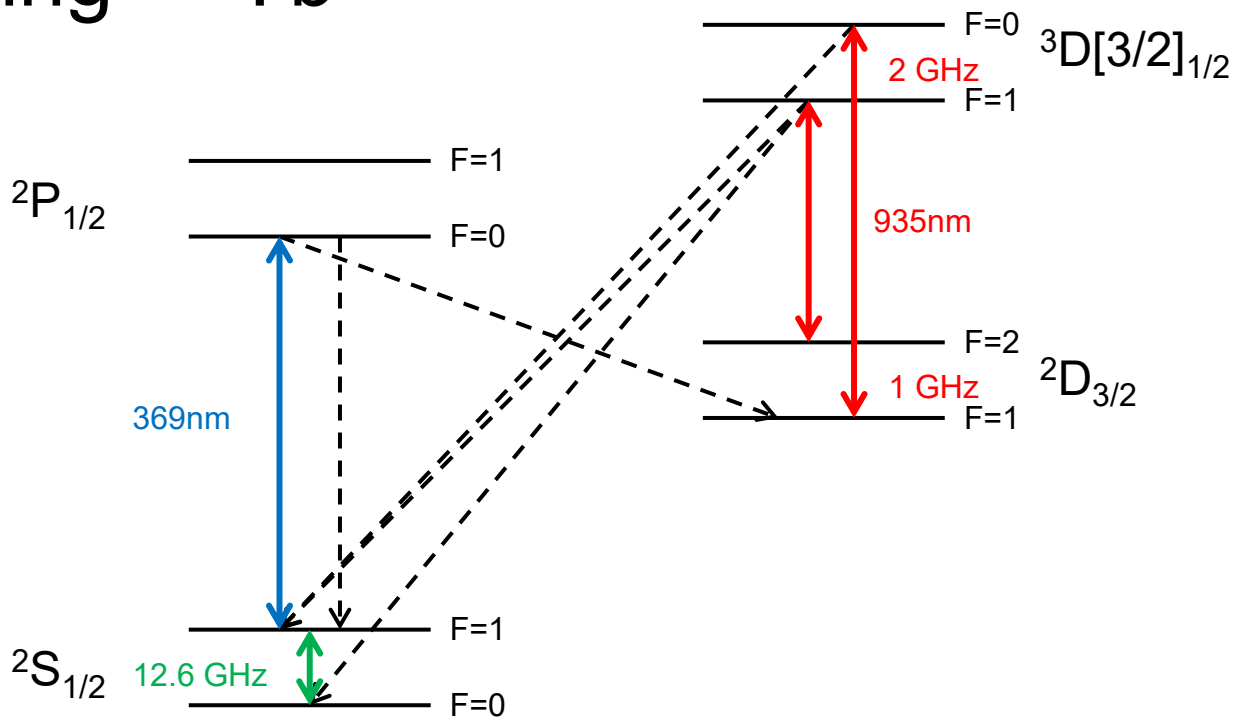


Shapes on the surface form electrodes. This set of electrodes makes up an array of x-junctions

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)

Yb ions

- Cooling $^{171}Yb^{+}$

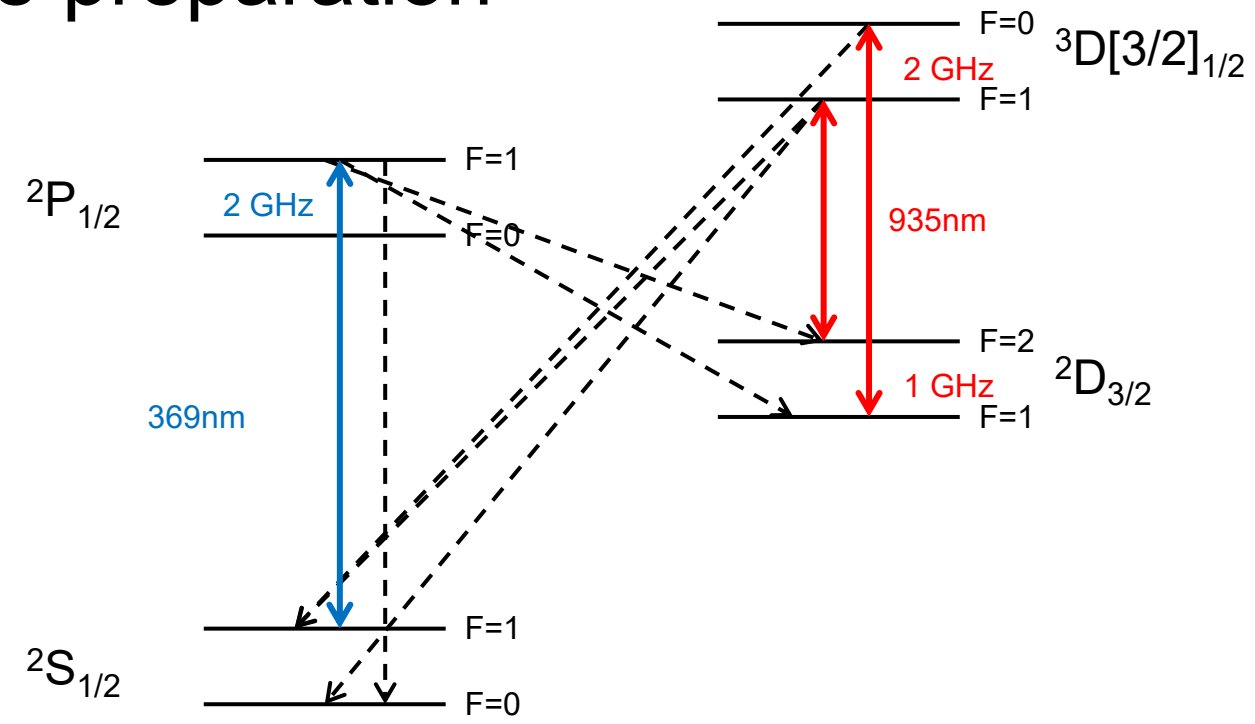


Key parts:

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

Yb ions

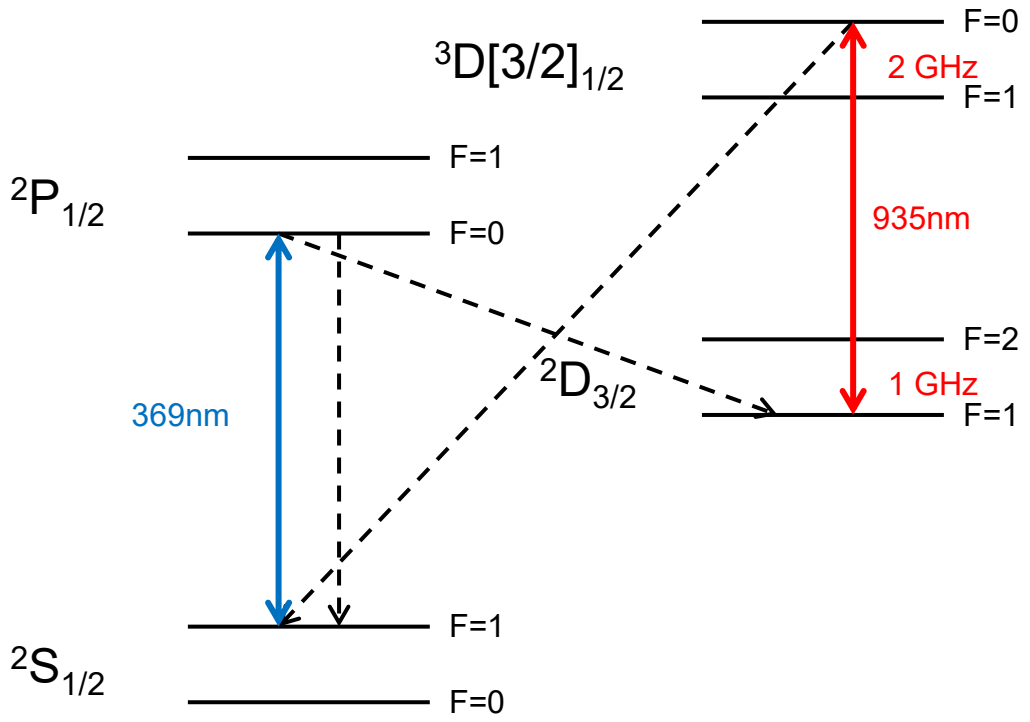
- State preparation



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

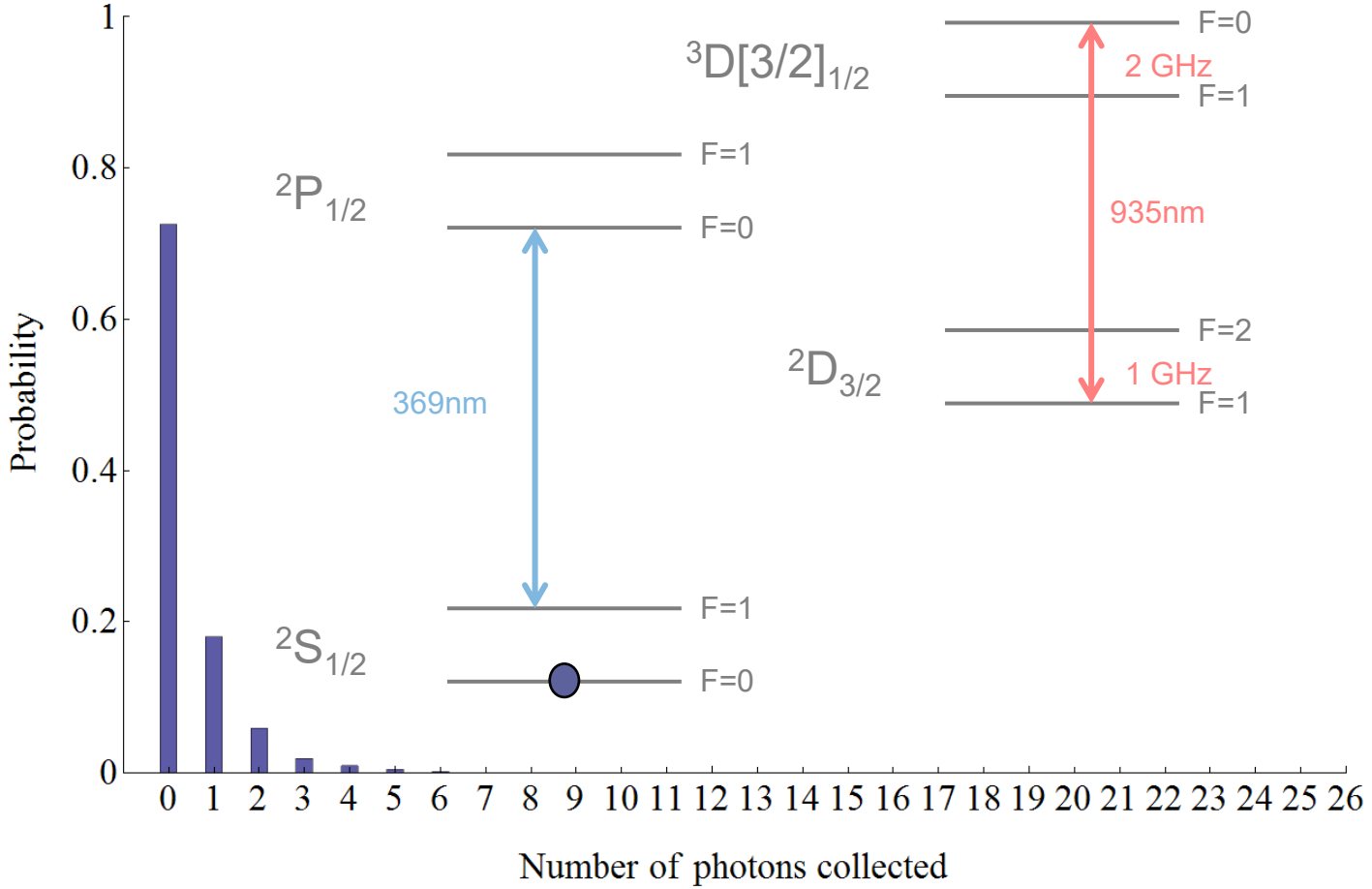
Yb ions

- State detection



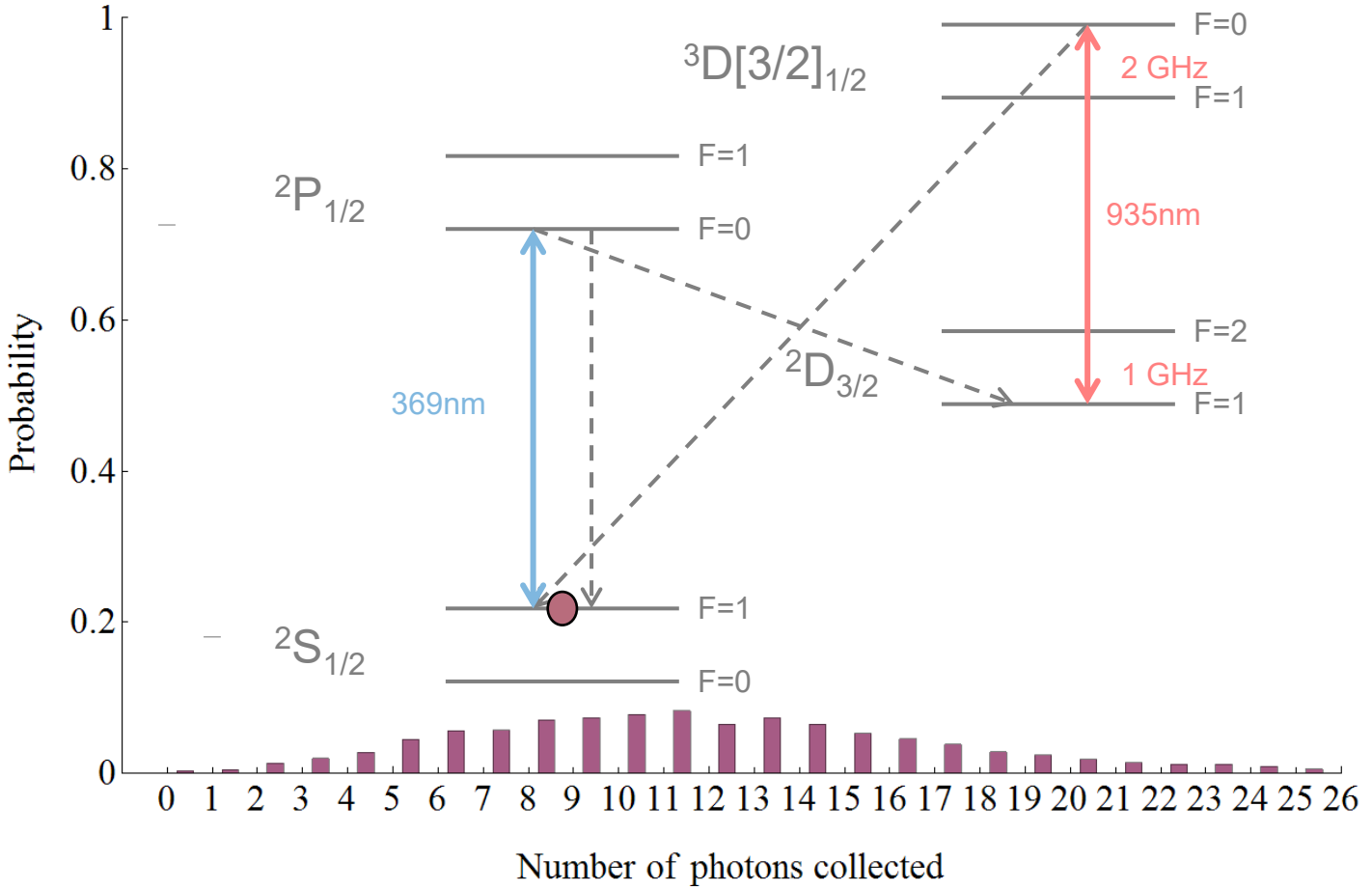
Yb ions

- State detection



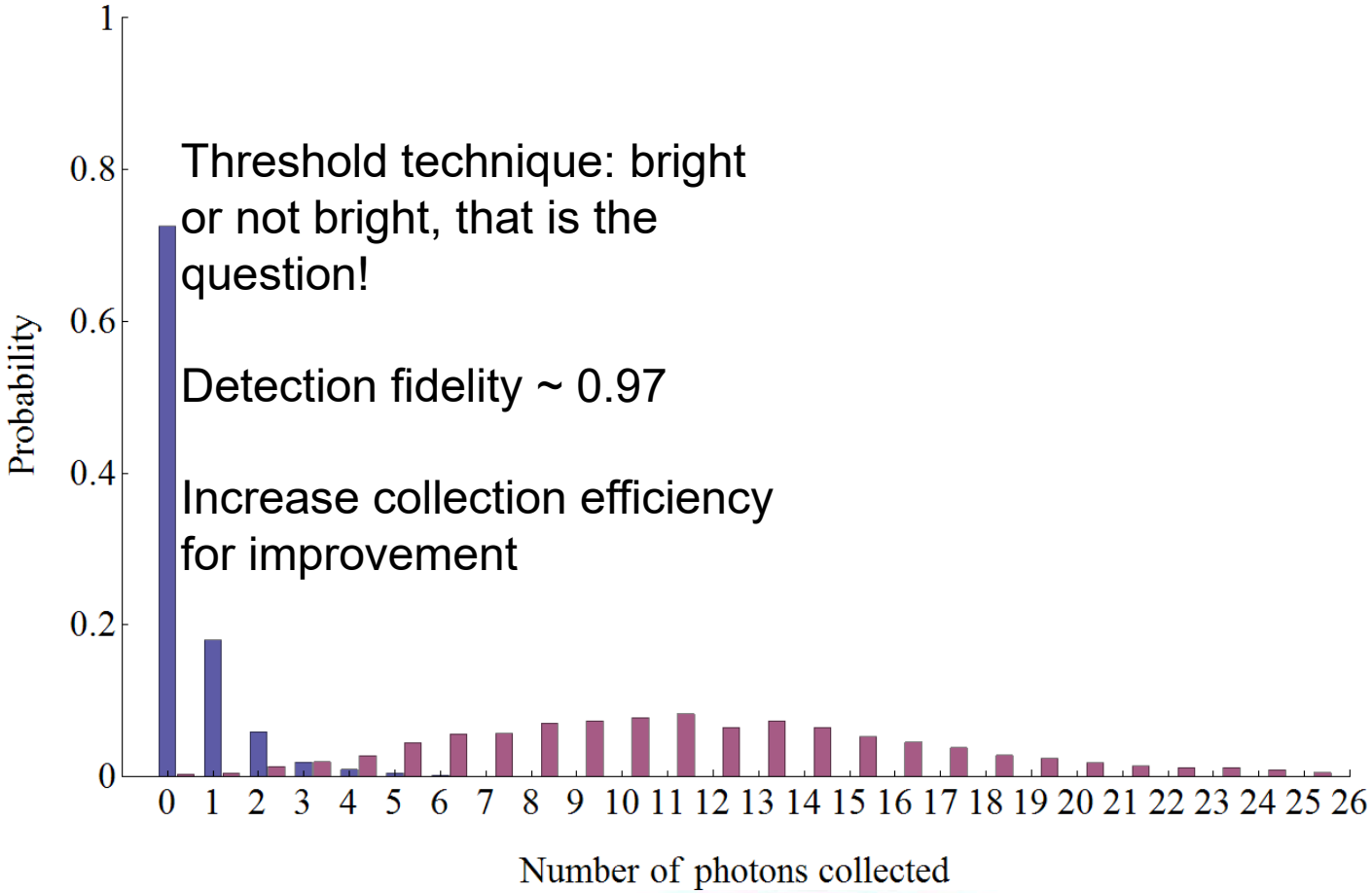
Yb ions

- State detection



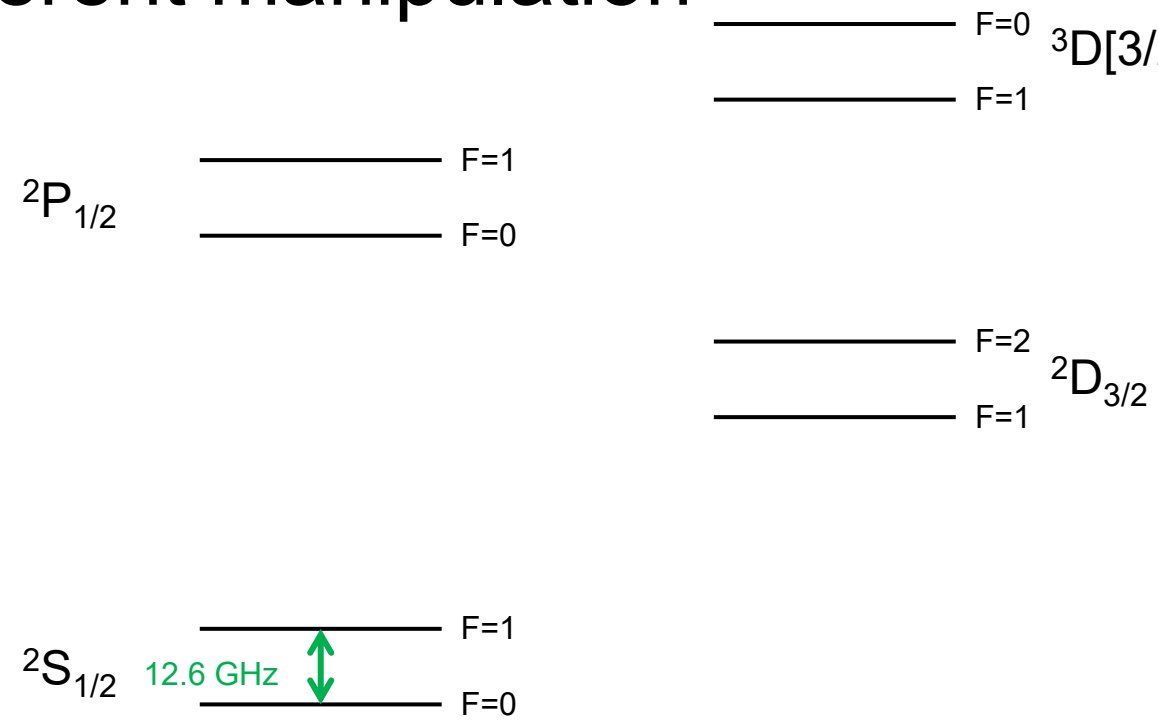
Yb ions

- State detection



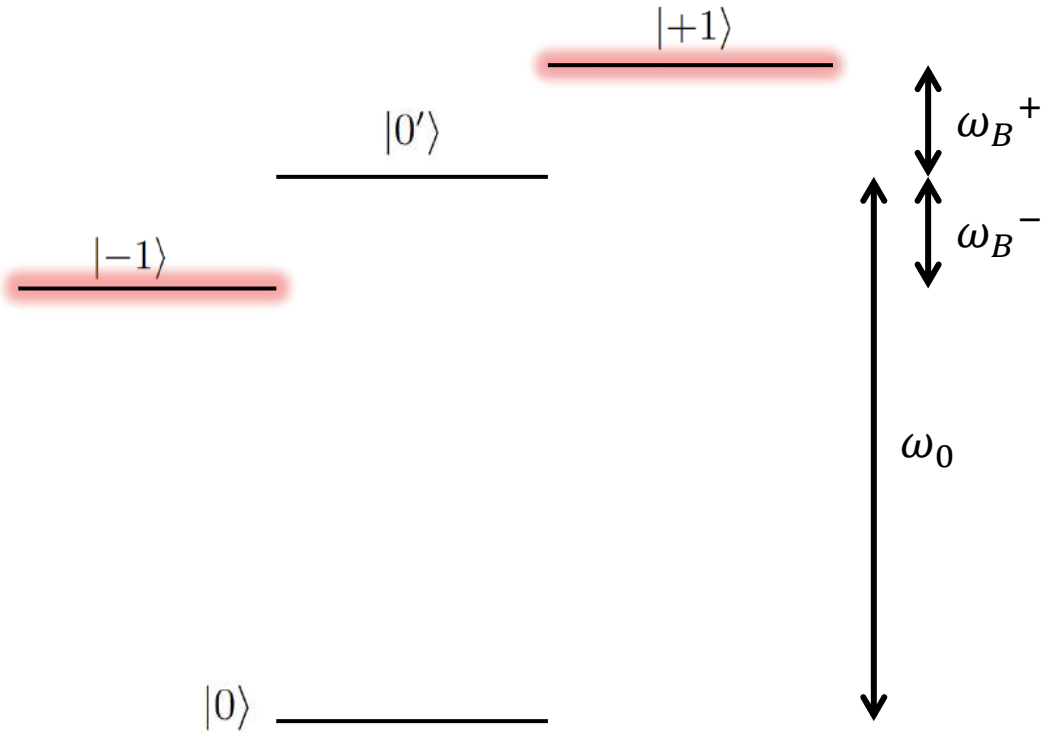
Yb ions

- Coherent manipulation



Is ion detection a coherent process?
What processes lead to incoherence?

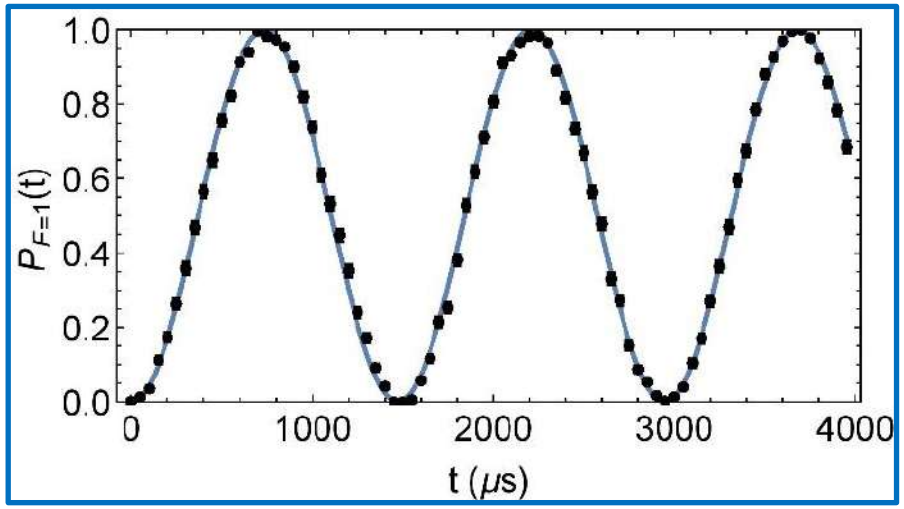
Zeeman states

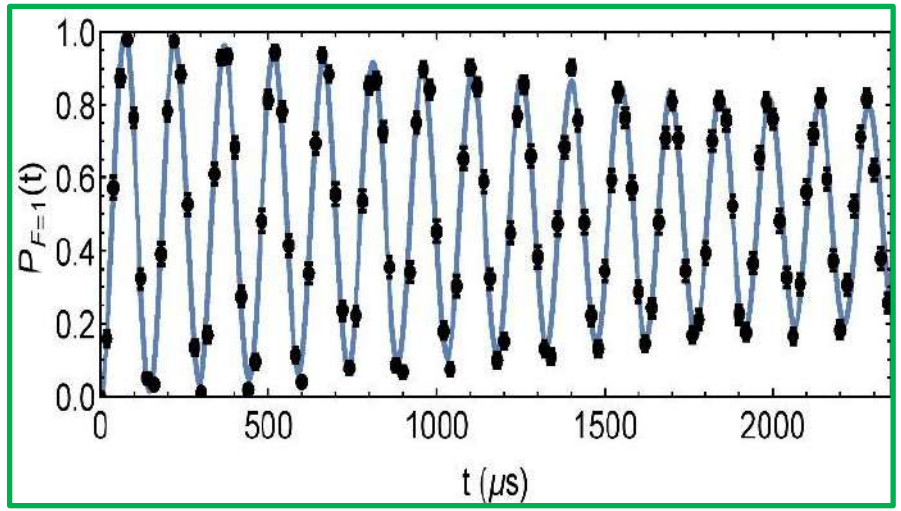


Fluctuations in the magnetic field causes dephasing

Gives rise to short coherence times

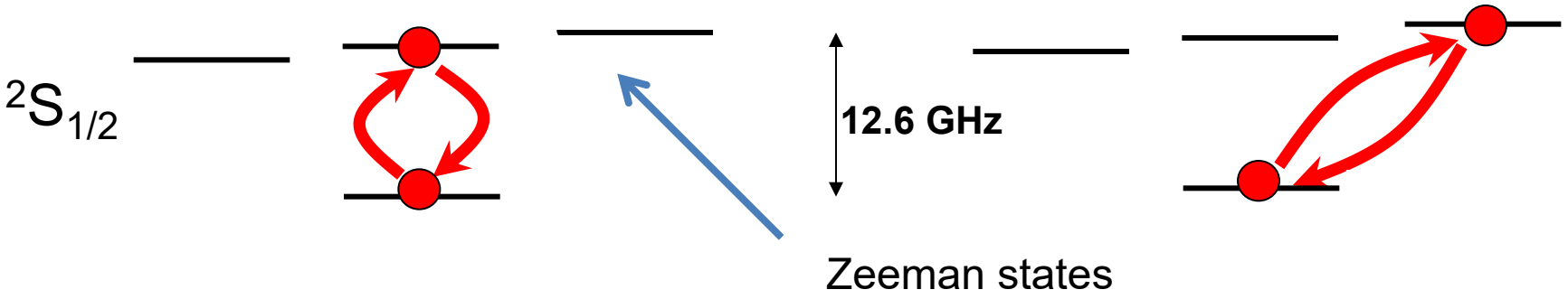
Rabi Flopping





- Long decoherence time of ≈ 1s between two magnetic field insensitive states
- No visible decoherence

- Coherence time of ≈ 2ms when using magnetic field sensitive state
- Decoherence due to fluctuating magnetic fields



How to do computations?

Computations consist of a series of quantum gates* and ion transport operations

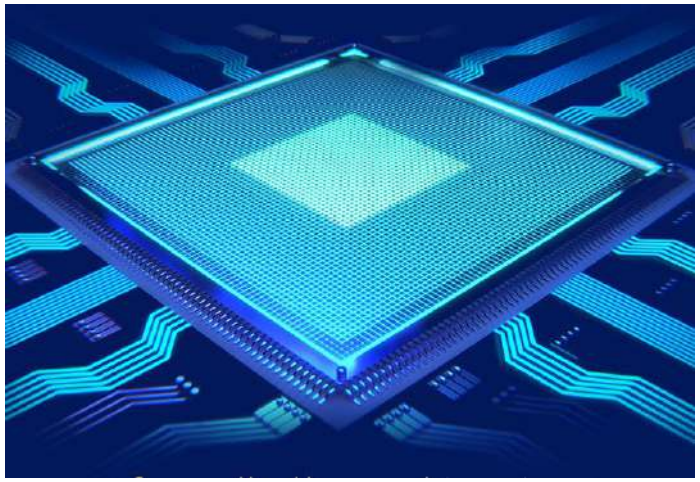
*Quantum gates are logical operations with 1 or two quantum bits.
Example: Depending on the state of qubit 1, flip the state of qubit 2

How to execute quantum gates

Most research groups and companies use laser beams for executing quantum gates

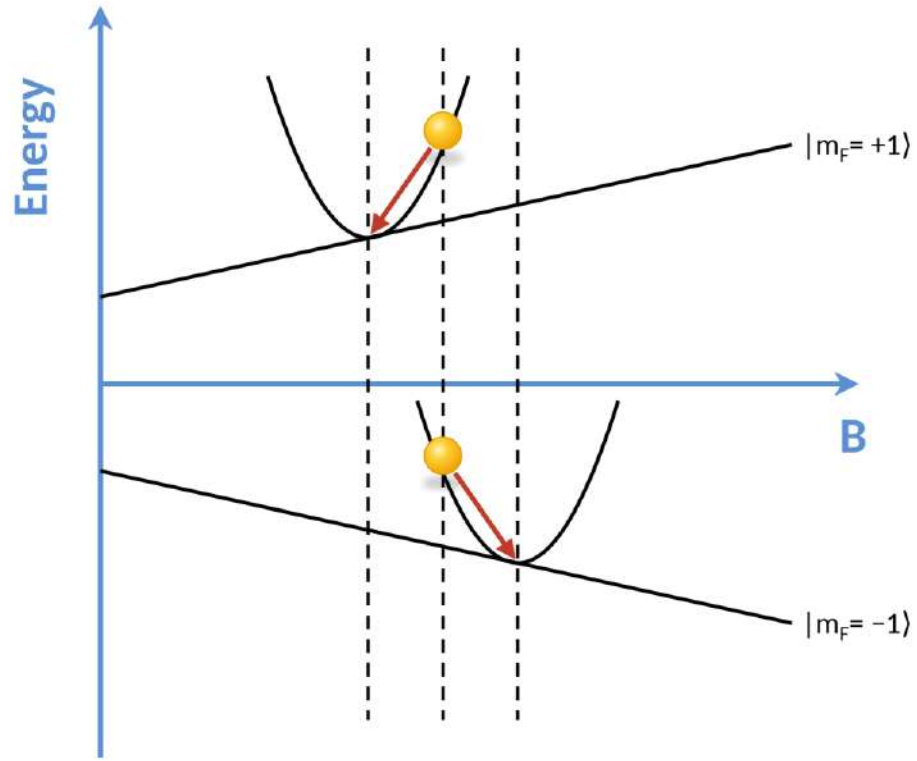
Such an approach might be hard to scale to millions of qubits

We make use of global microwave fields instead.



This approach allows execution of quantum gates via the application of voltages to a microchip!

Motional coupling with a magnetic field gradient



Magnetic field gradient gives rise to a state dependent force.

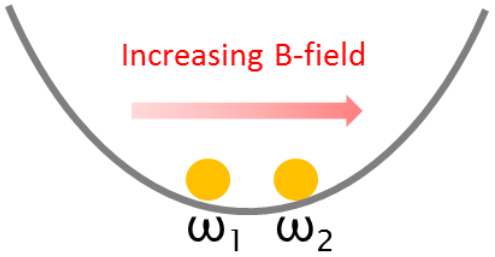
The spin-dependent force is given by:

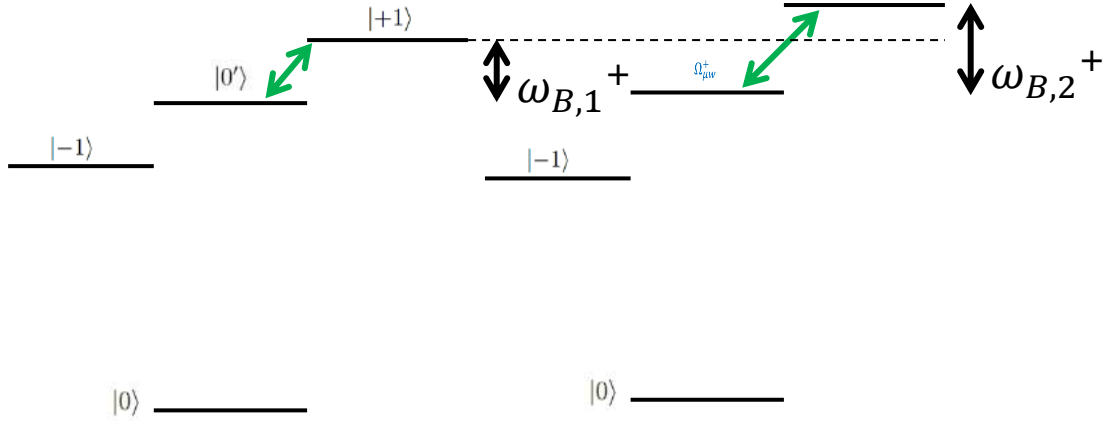
$$\Omega_g = \frac{1}{4}\sqrt{\frac{\hbar}{M\omega_m}}\frac{\partial B}{\partial z}\frac{\partial \omega_0}{\partial B}$$

- The two qubit states give rise to an oppositely directed force within a magnetic field gradient
- Requires the use of magnetic field sensitive states.

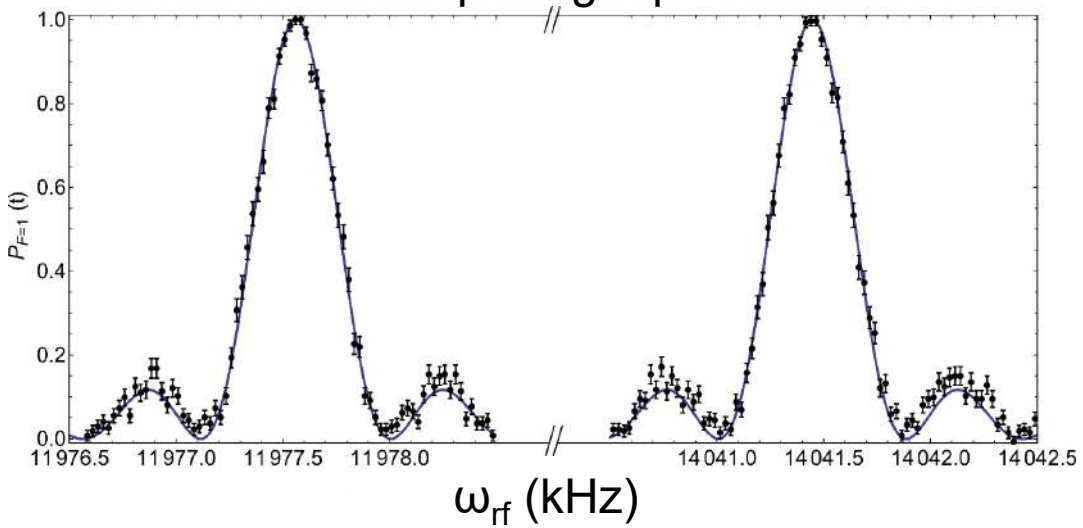
F. Mintert and C. Wunderlich, Phys. Rev. Lett. 87, 257904 (2001)
D.J. Wineland et al., J. Res. NIST 103, 259 (1998)

Individual addressing using dressed states below fault-tolerant threshold





Ion – ion spacing: 6μm

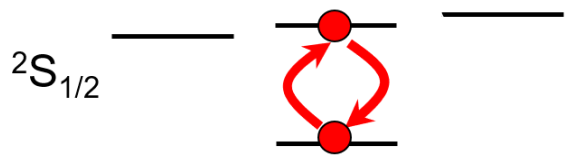


Δω = frequency splitting
Ω = Rabi frequency

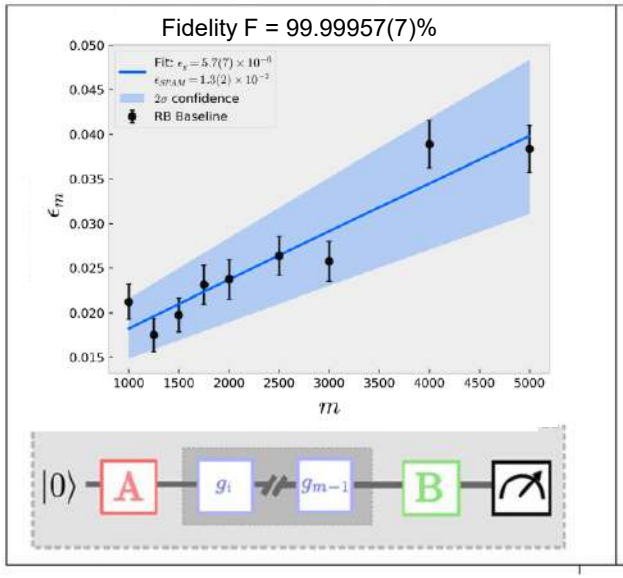
Cross-talk: $\Omega^2/2(\Omega^2+\Delta\omega^2) < \mathbf{10^{-8}}$

Single qubit gates

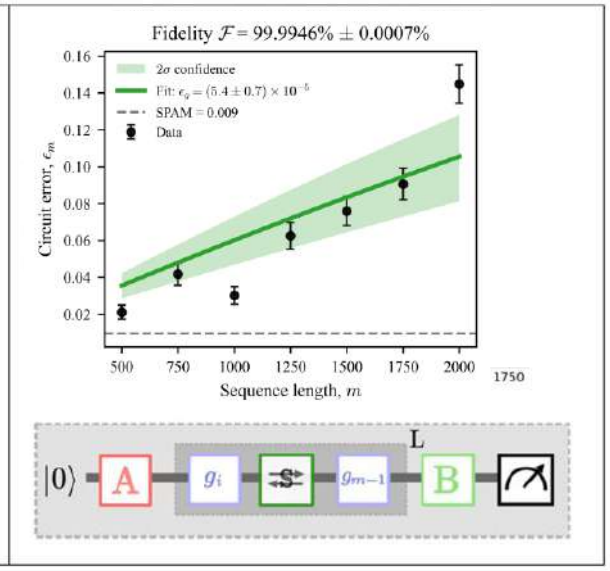
- Single qubit gates can be carried out using global microwave fields
- We have carried out randomized bench marking.
- We demonstrate that the execution of single qubit gates and the execution of single qubit gates interleaved with transport results in fidelities above 99.999%

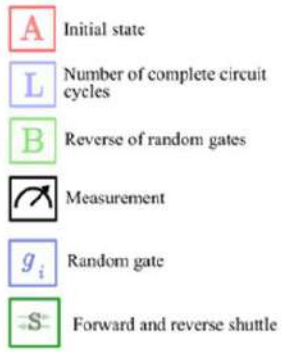


Single qubit gates inside a B-field

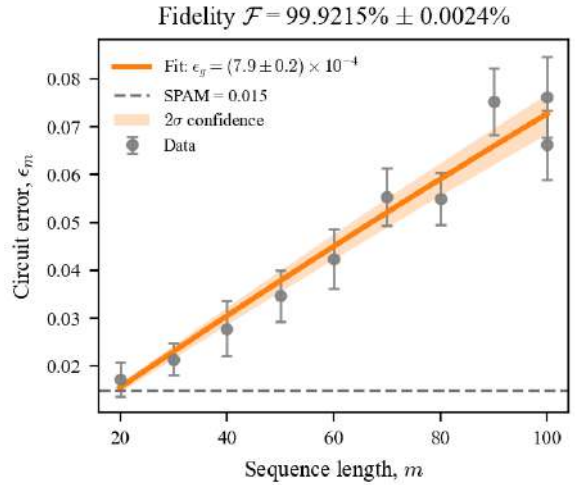


Single qubit gates interleaved with transport





Single qubit gates interleaved with transport while gradient is turned on



We phase compensate for the phase picked up during transport.

Quantum computing with global fields

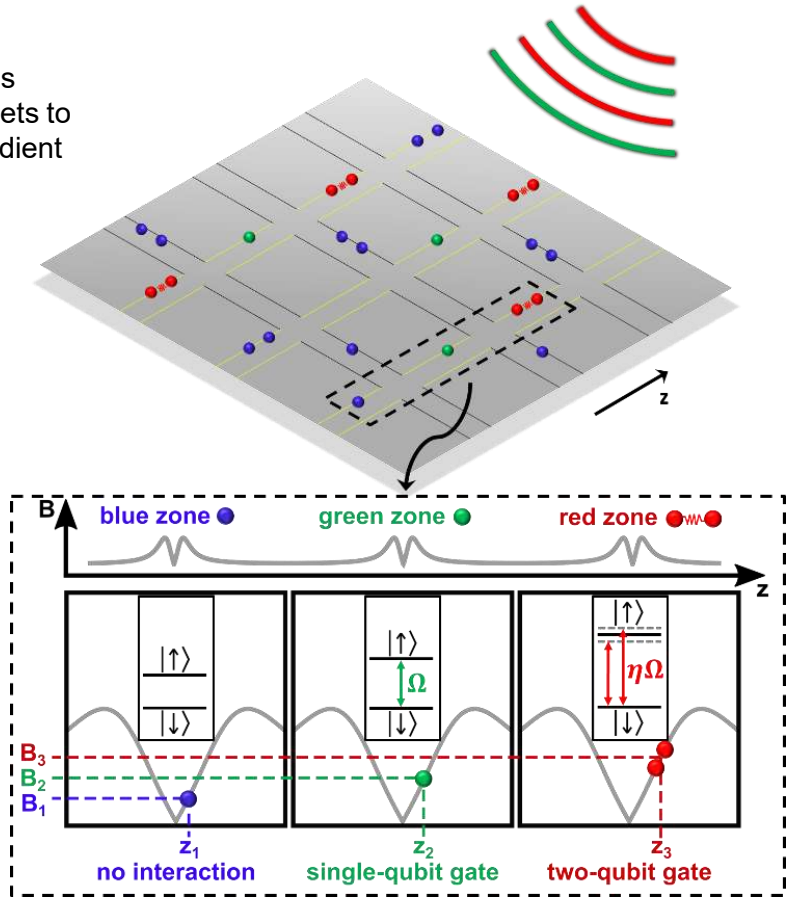
Concept:

Quantum gates are executed via the application of voltages and global radiation fields.

In previous quantum computer architectures: Number of radiation fields required for quantum gate implementation scales with the number of qubits to be used in the quantum computer.

This scaling vanishes for this new scheme.

Use of current carrying wires instead of permanent magnets to generate magnetic field gradient

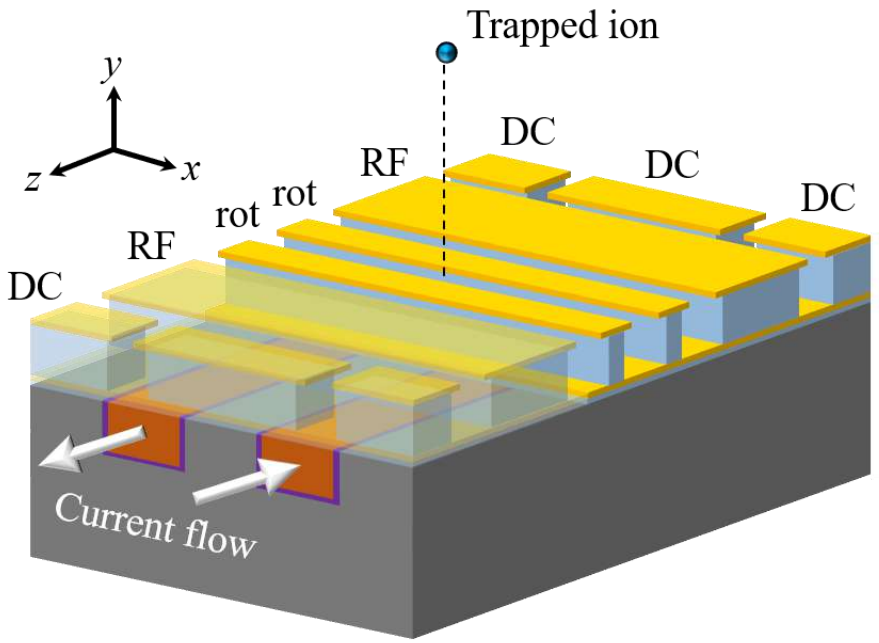


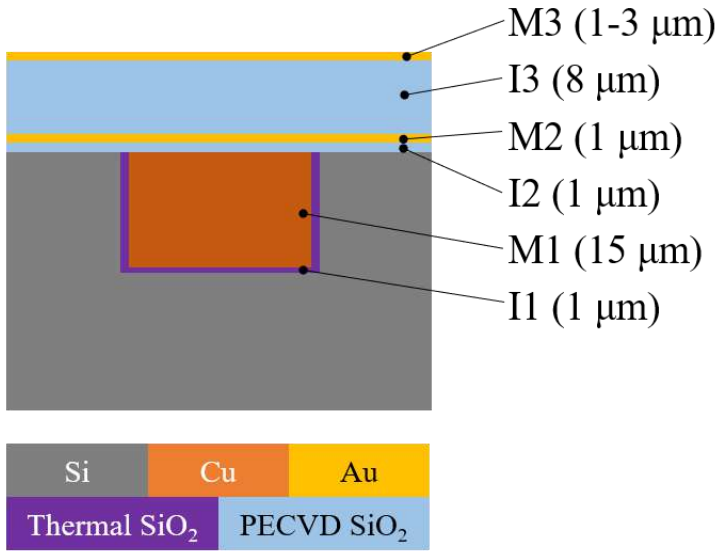
Voltages applied to local trap electrodes place the ion in the correct part of the local B-field gradient making the ion resonant with a set of global radiation fields, effectively executing a particular quantum gate.

Trapped-ion quantum logic with global radiation fields, S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016)

Ion microchips with current carrying wires

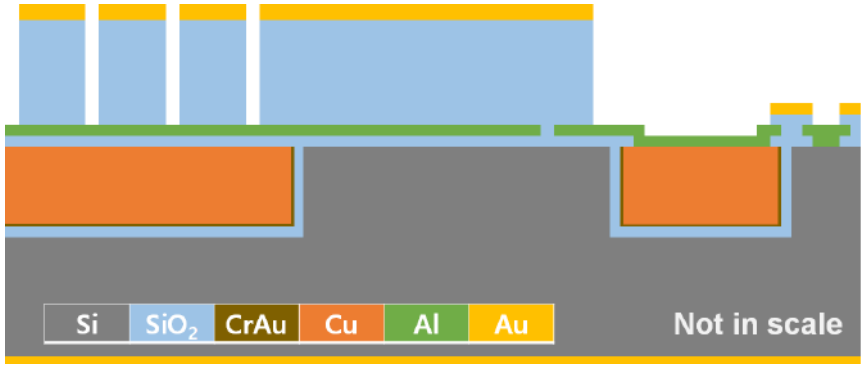
- 15 μm Cu wires / 1 μm Au ground plane / 8 μm PECVD oxide / 1-3 μm Au top electrodes
- Breakdown voltage of ~240 V_{amp}
- Developed by both in-house capability and industrial partners

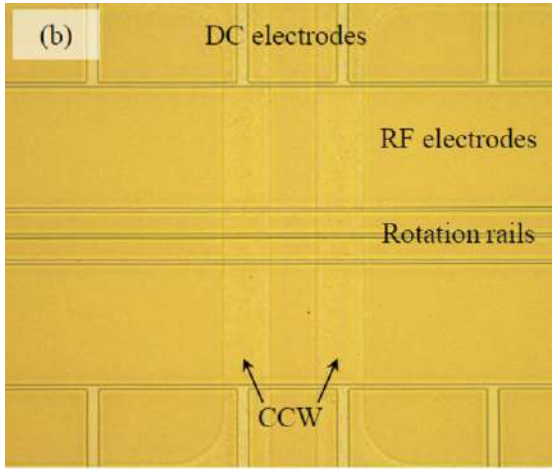


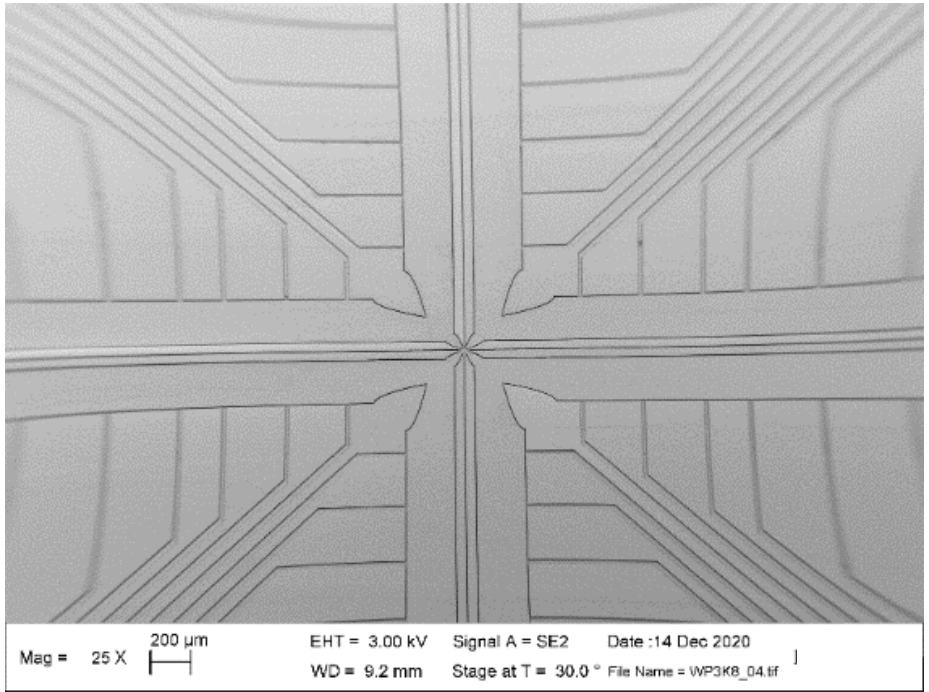


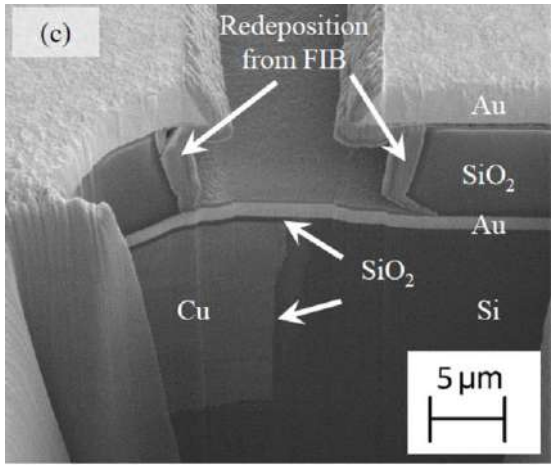
Fabrication of Surface Ion Traps with Integrated Current Carrying Wires enabling High Magnetic Field Gradients
Martin Siegele-Brown, Seokjun Hong, Foni R. Lebrun-Gallagher, Samuel J. Hile, Sebastian Weidt, and Winfried K. Hensinger, Quantum Sci. Technol. 7, 034003 (2022)

Ion microchips with integrated current-carrying wires









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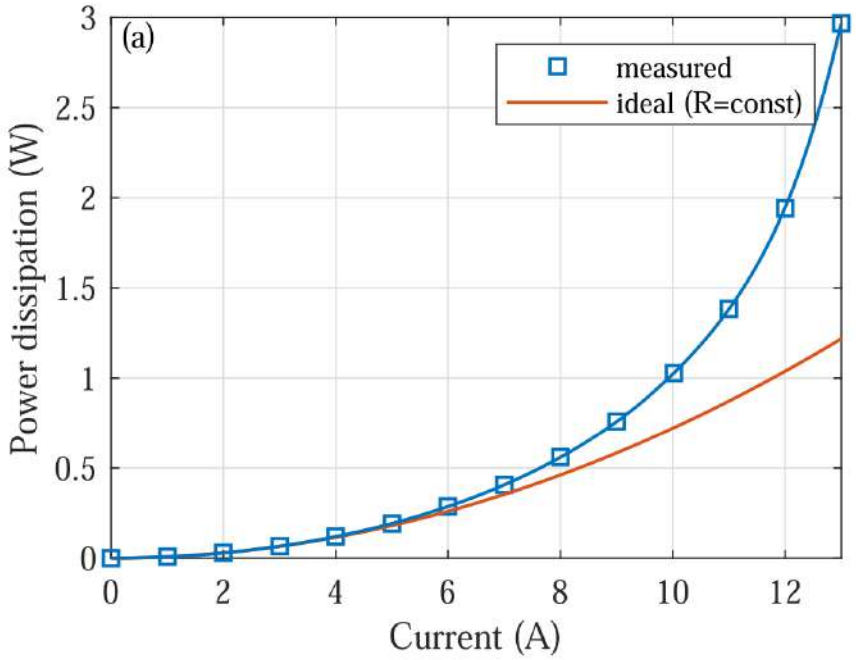
Power dissipation



The rise in resistivity by a factor of 1.43 corresponds to a rise in temperature of the CCWs from 38 K to 43 K.

Fabrication of Surface Ion Traps with Integrated Current Carrying Wires enabling High Magnetic Field Gradients
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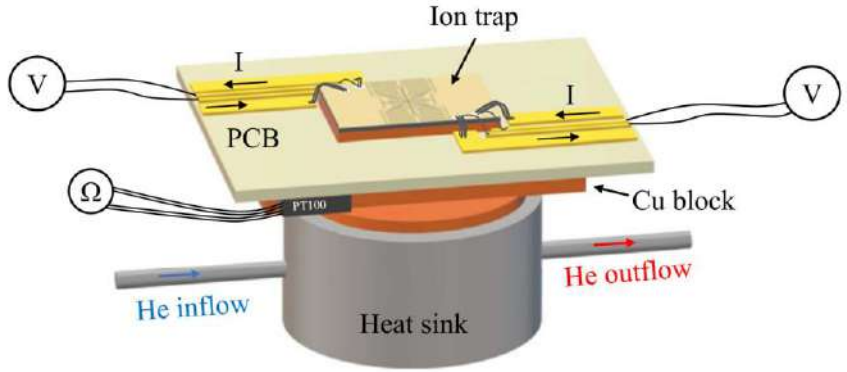
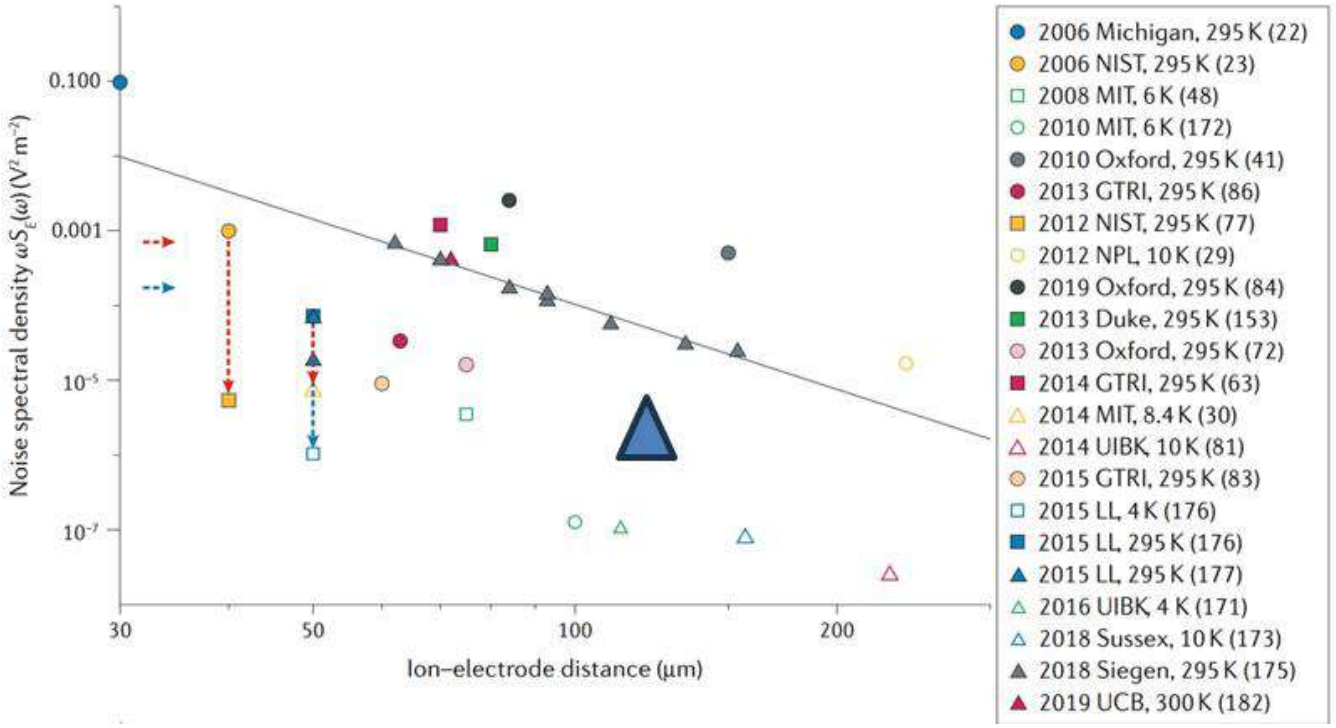
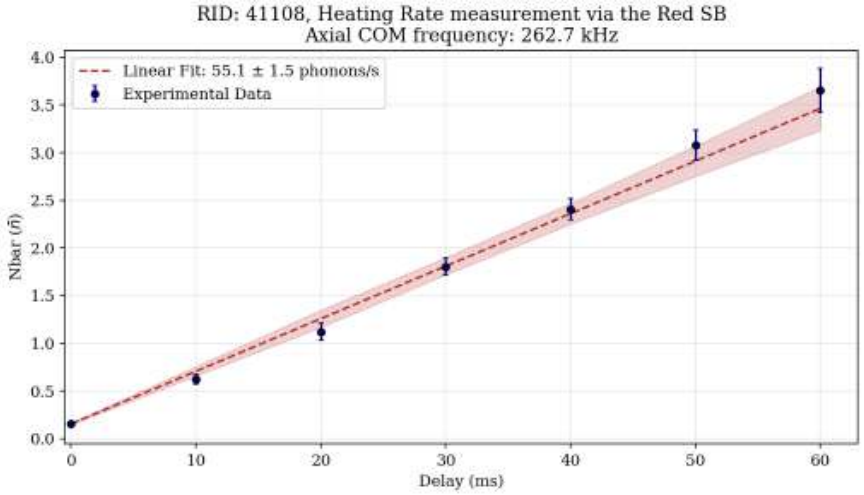
Test setup



- Continuous currents of 13A can be applied resulting in magnetic field gradients of 144 T/m at an ion height of 125 µm
- The expected two-qubit gate fidelity depends on the magnitude of the magnetic field gradient, we should be able to demonstrate >99.9% with this magnetic field gradient (previous demonstration of 98.5% with 24 T/m).

A really promising heating rate



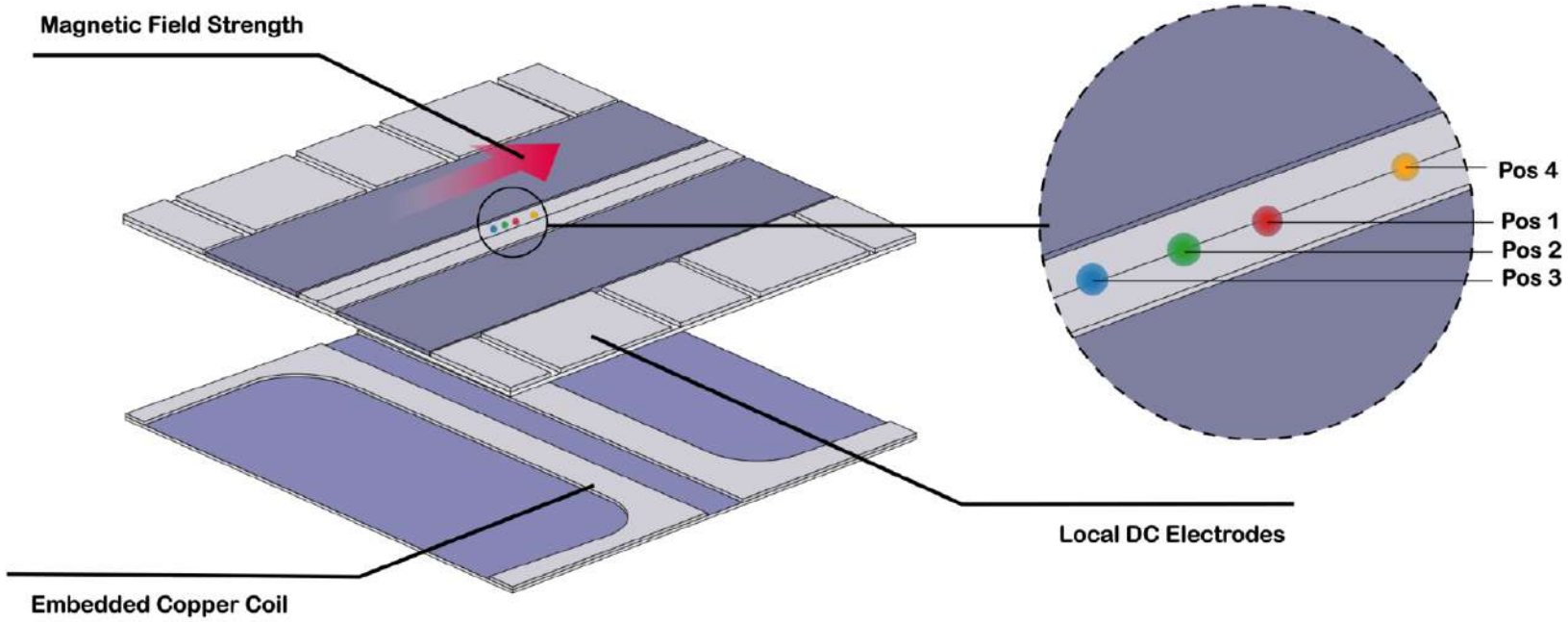


Heating rate:

- 55 phonons per second at 262 kHz secular frequency on COM,
- < 1 per second on stretch mode
- $\omega S_E = 7 \times 10^{-7} V^2/m^2$ at 100 K with more gains to be expected when going to 60 K.

Voltage controlled quantum logic

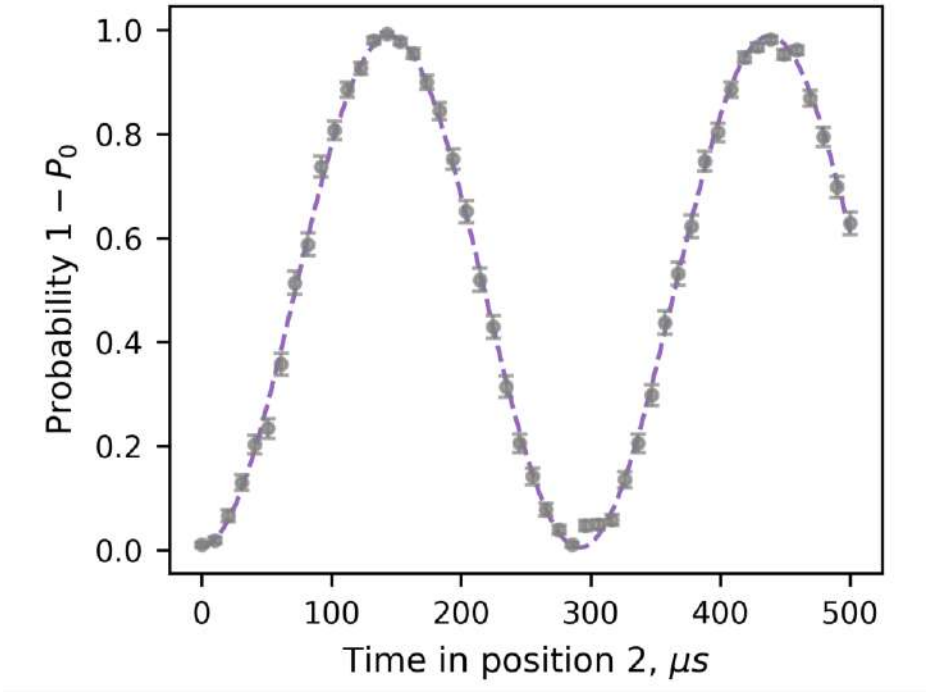
- The ion is moved by varying the voltages on the DC electrodes, thereby allowing single qubit gates to be executed via voltage control.
- This technique enables us to achieve arbitrary rotations on the Bloch sphere.
- We obtain a native gate set by selecting three positions of the ion inside the magnetic field gradient Z_1, Z_2, Z_3 so that $\delta(Z_1)$, = Ω, $\delta(Z_3)$ = $-\Omega$ and $\delta(Z_2) = 0$

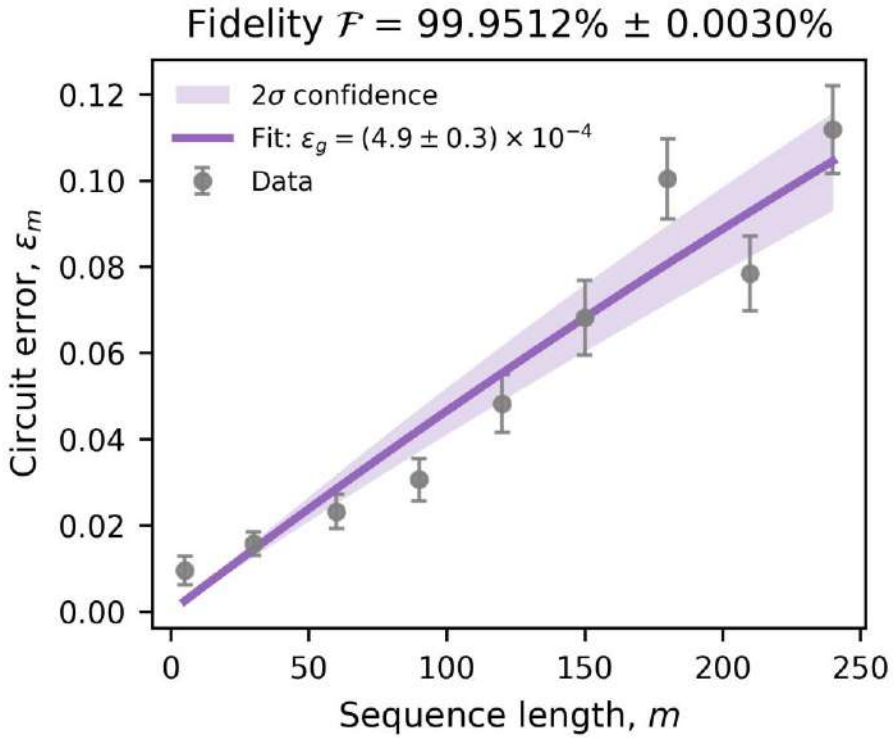


This gives rise to three position dependent rotation Hamiltonians: $H(Z_1) = \Omega(\sigma_X - \sigma_z)/2$, $H(Z_2) = \Omega\sigma_X/2$, and $H(Z_3) = \Omega(\sigma_X + \sigma_z)$.

Voltage controlled arbitrary single qubit gates in a static magnetic field gradient
Finn O'Dwyer, Sahra Kulmiya, Thomas Clarke, Ru Morgan, Samuel J. Hile, Sebastian Weidt, and Winfried K. Hensinger, in preparation (2026)

Voltage controlled quantum logic





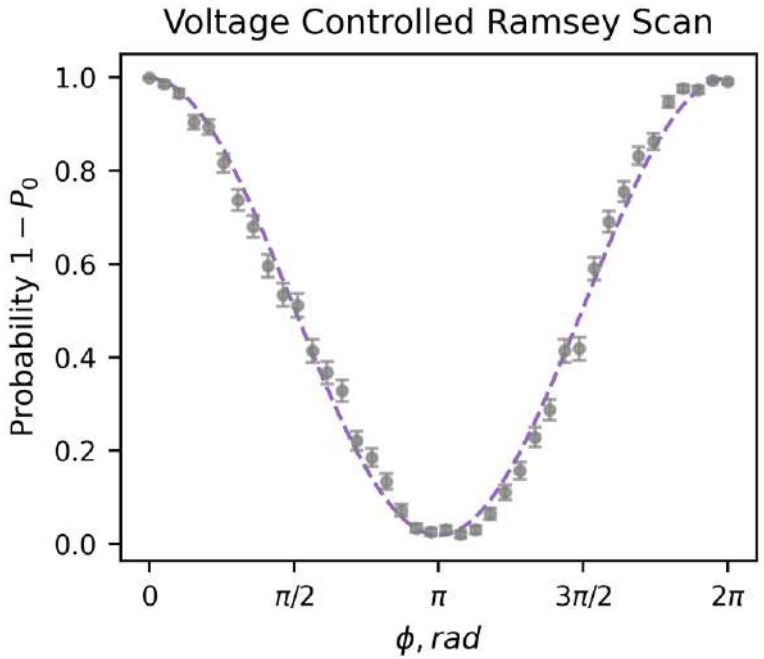
1. The ion's spin state is prepared in |0> and transported to P_4, then the radiation field is switched on.
2. The ion is transported to P_2 for time t, then back to P_4.
3. The radiation field is switched off and the ion's spin state is measured.

Randomized benchmarking of the Clifford gates achieves an average fidelity per gate F = 99.951± 0.003%

Voltage controlled arbitrary single qubit gates in a static magnetic field gradient
Finn O'Dwyer, Sahra Kulmiya, Thomas Clarke, Ru Morgan, Samuel J. Hile, Sebastian Weidt, and Winfried K. Hensinger, in preparation (2026)

Voltage controlled quantum logic

Implementing a Ramsay scan using voltage control, without changing the phase of the global driving field.



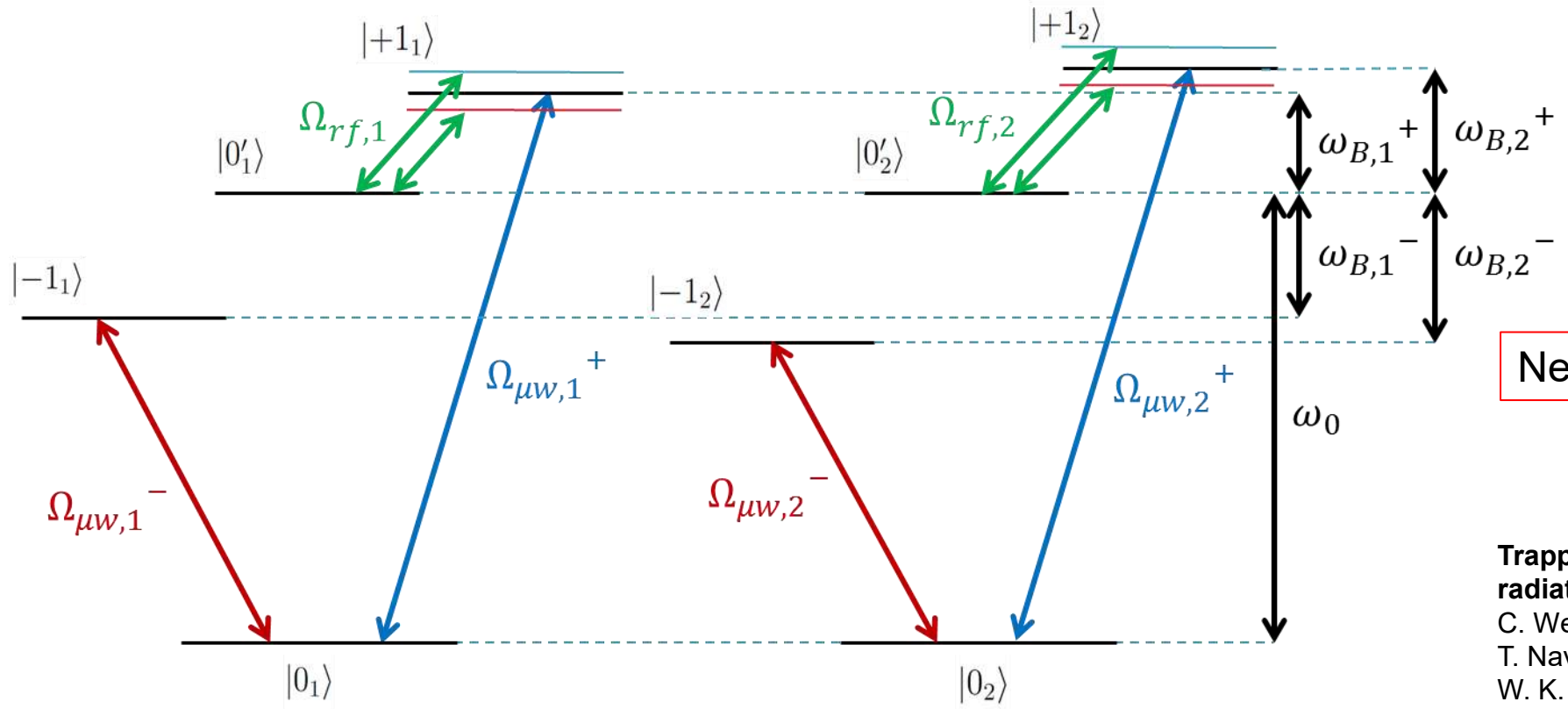
- The population measured in $F = 1$ as a function of rotation axis ϕ.
- The ion is prepared in 0 and begins in P_2 when the radiation is switched on.
- The qubit undergoes a $R(\pi/2, 0)$, then is shuffled in $[P_1, P_3]$ to give rise to the appropriate decomposition to rotate the qubit by $R(\pi/2, \phi)$

Voltage controlled arbitrary single qubit gates in a static magnetic field gradient
Finn O'Dwyer, Sahra Kulmiya, Thomas Clarke, Ru Morgan, Samuel J. Hile, Sebastian Weidt, and Winfried K. Hensinger, in preparation (2026)

Exploration of new microwave two-qubit gate mechanisms

- Is the gate robust to noise?
- Is it simple to implement and as such easy to scale?
- Does it work with hot ions?
- Can you use mixed species sympathetic cooling?

Our original microwave gate: Entanglement using microwave dressed states



Need to drive 8 transitions!

Trapped-ion quantum logic with global radiation fields, S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016)

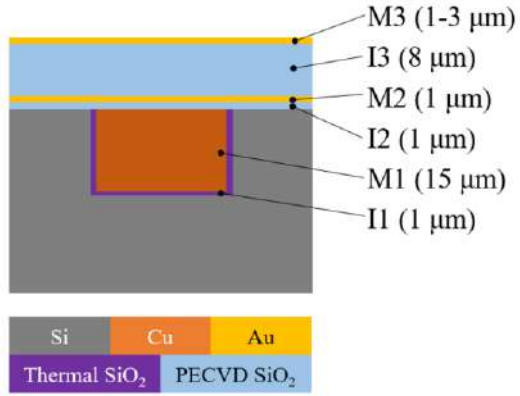
This gate requires 8 radiation fields.

Can we use far fewer to simply scaling?

A new oscillating gradient gate

- We demonstrated for the first time in the world a $\sigma_z\sigma_z$ two-qubit gate through an axial motional mode implemented via a near-motional oscillating magnetic field gradient.
- Idea first proposed by C. Ospelkaus et al. [1] and further developed by R. Sutherland et al. [2]
- David Wineland felt this gate predicted this gate could not be done as the electric field components of the oscillating gradient would excite the motion and heat the ion.
- We realized the chips we have developed should allow us to use this gate mechanism as the ground plane is shielding the electric fields:

Ground plane shielding the electric fields of the oscillating gradient from the ion



[1]: Trapped-Ion Quantum Logic Gates Based on Oscillating Magnetic Fields
C. Ospelkaus, C. E. Langer, J. M. Amini, K. R. Brown, D. Leibfried, and D. J. Wineland, Phys. Rev. Lett. 101, 090502 (2008)
[2]: Versatile laser-free trapped-ion entangling gates,
R.T Sutherland, R. Srinivas, S.C. Burd, D. Leibfried, A.C. Wilson, D.J. Wineland, D.T.C. Allcock, D.H. Slichter and S.B. Libby, New J. Phys. 21 0330332019 (2019)

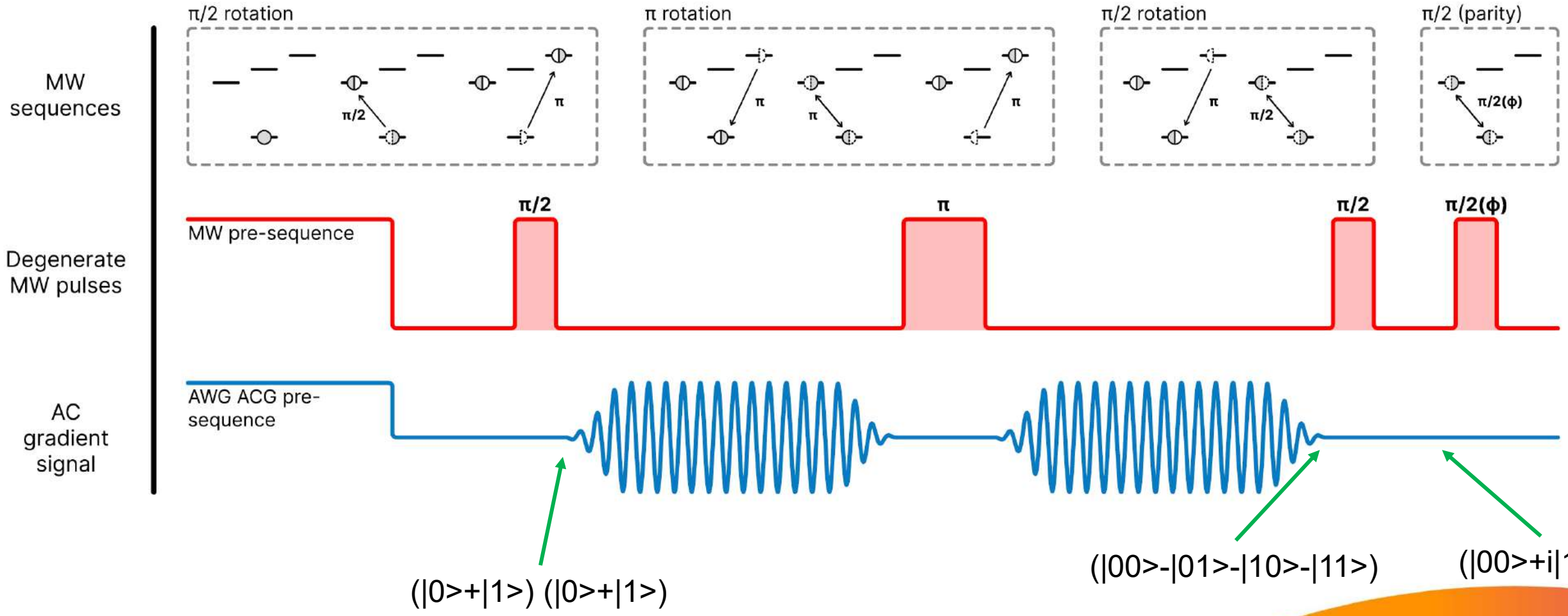
A new oscillating gradient gate

- We achieved entanglement of two $^{171}Yb^{+}$ ions in approximately 320 μs using the axial breathing mode at 500 kHz.

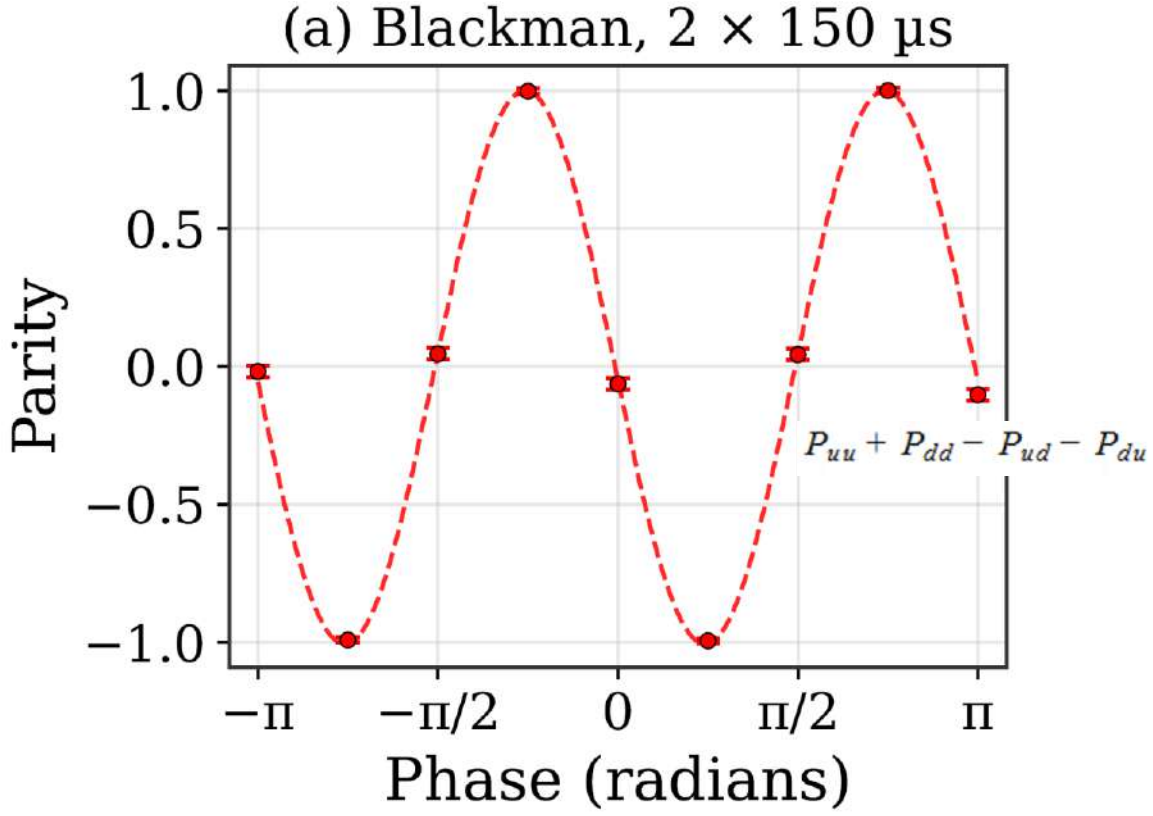
- All operations were performed in a microfabricated surface trap with an ion height of 120 μm and the gate is made robust using Walsh modulation. We can also use Adiabatic Elimination of Spin-motion Entanglement (AESE) making it even more robust.

- The gate only requires one rf field relaxing gate calibration requirements along with resonant microwave pulses for dynamical decoupling and mapping.

How does it work



Demonstration of this entangling gate at Sussex



- Using amplitude of the parity as the lower bound for fidelity, we obtain a fidelity:

$$100.0^{+0.0}_{-0.4}\%$$

- $\bar{n}$ = 50, (worse than Doppler limit of ~20), meaning this is the hottest high-fidelity gate ever realized.
- The gate is achieved in 320 μs.
- It does not require ground state cooling.
- Because it uses the axial mode, it allows for mixed-species sympathetic cooling as a world first for any oscillating gradient gate.

All-electronic Geometric Phase gate on Doppler-cooled trapped-ions using an axial mode
P. Rahimi, C. Knapp, P. Zantis, T. Maddock, S. Hile, M. Siegele-Brown, J. Randall, S. Weidt, and W. K. Hensinger, in preparation

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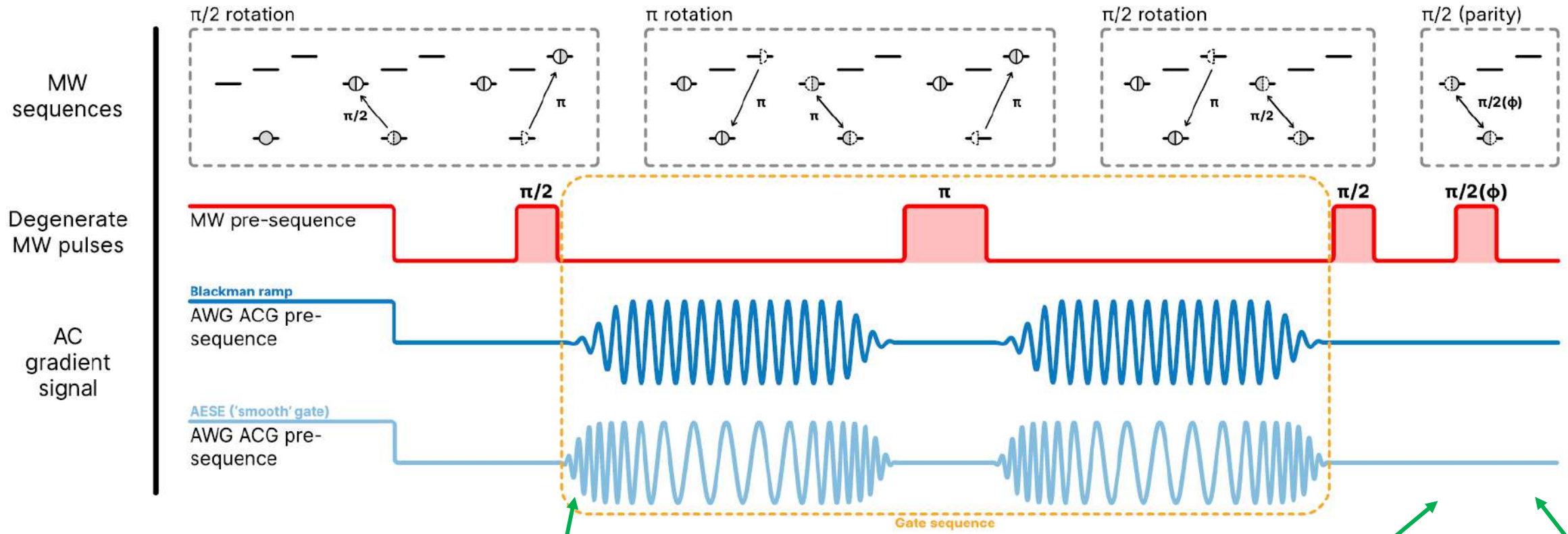
Ultra-robust version of the gate using AESE

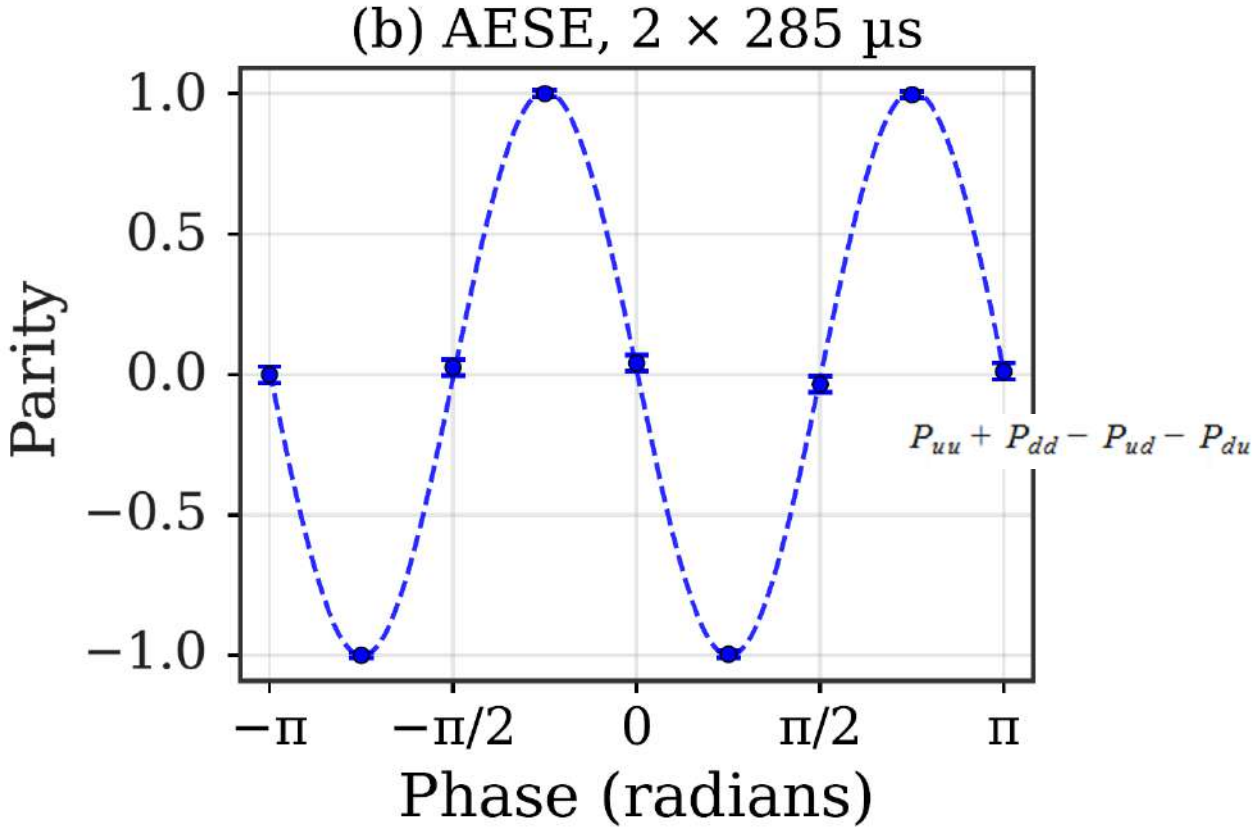


(|0>+|1>) (|0>+|1>)

(|00>-|01>-|10>-|11>)

(|00>+i|11>)

Ultra-robust version of the gate using AESE



- Using amplitude of the parity as the lower bound for fidelity, we obtain a fidelity:

$$100.0^{+0.0}_{-0.3}\%$$

- Average n = 50, worse than Doppler limit of ~20), meaning this is the hottest high-fidelity gate ever realized.
- The gate is achieved in 594 μs.
- The gate is incredibly robust to secular frequency noise and drifts.

All-electronic Geometric Phase gate on Doppler-cooled trapped-ions using an axial mode
P. Rahimi, C. Knapp, P. Zantis, T. Maddock, S. Hile, M. Siegele-Brown, J. Randall, S. Weidt, and W. K. Hensinger, in preparation

Adiabatic Elimination of Spin-motion Entanglement (AESE) developed by R. Sutherland

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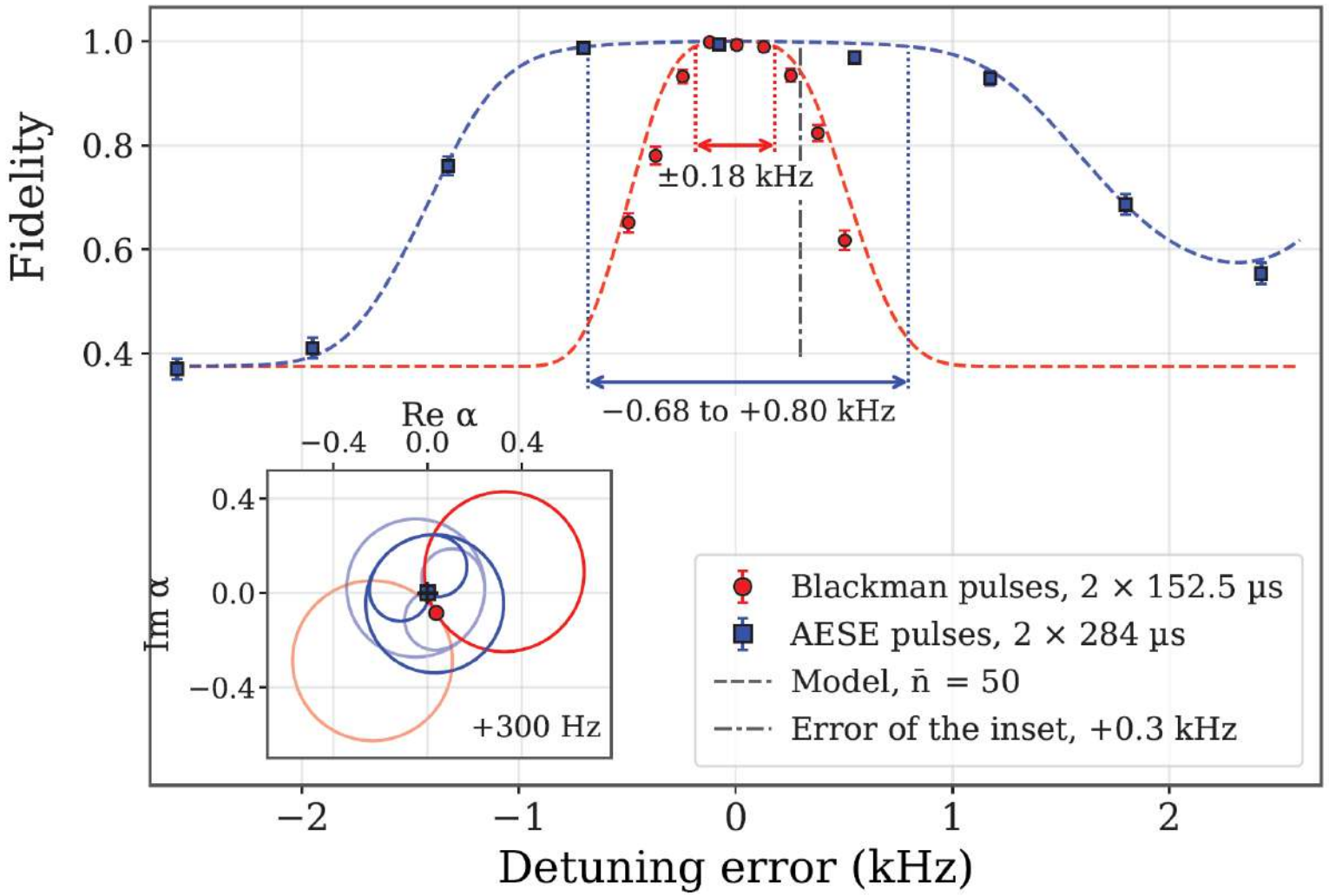
So how robust is AESE?



All-electronic Geometric Phase gate on Doppler-cooled trapped-ions using an axial mode
P. Rahimi, C. Knapp, P. Zantis, T. Maddock, S. Hile, M. Siegele-Brown, J. Randall, S. Weidt, and W. K. Hensinger, in preparation

Why is this gate useful for scaling?

- It is the hottest high-fidelity gate realized so far. This means transport ions can be done more efficiently, with higher speed and less calibration requirements (meaning faster quantum computing clock speeds).
- It only uses a single slowly oscillating field with a few hundred kilo Hertz.
- The gate does not need microwave fields and only one rf field relaxing gate calibration requirements.
- The gate is extremely robust to charge up and electric fields (variations in secular frequency).

Why is it important to carry out an oscillating gradient gate on the axial mode?

- Our demonstration is the first oscillating gradient gate on the axial mode, previous demonstrations such as the result by Oxford Ionics were on the radial mode.
- You cannot easily cool the radial mode with mixed-species sympathetic cooling because of the mass difference between ions. And same species sympathetic can scramble the qubit state unless the qubit is shelved (omg qubits)
- Doing the gate on the axial mode enables mixed-species sympathetic cooling.

How to increase the fidelity and gate speed?

- Increase secular frequency (Doppler temperature goes down, heating rate goes down, currently limited by 125 μm ion – electrode distance)
- Next generation chips have 75 μm ion – electrode distance
- Increase oscillating gradient amplitude (currently only at 27 T/m)
- Reduce Eddy currents (currently caused by heatsink) causing a displacement in the magnetic field nil of the oscillating gradient (currently 40 μm displacement!)
- Increase coherence time with mu-metal shield around the setup
- Anticipated resulting gate time: 60 μs and gate fidelity >99.99%

How to measure the increase in fidelity

➢ Improve SPAM

Currently 95% with camera detection

How to improve SPAM:

- Use SPADS for detection
- Use shuttling and read each ion sequentially capitalizing on single ion SPAM of 99.2%
- Shelving laser at 435nm to $D_{3/2}$

➢ Randomized benchmarking

How does the gate actually work?

The ACZZ gate

- The $\sigma_Z \otimes \sigma_Z$ operator:

$$\begin{pmatrix} e^{\frac{-i\pi}{4}} & 0 & 0 & 0 \\ 0 & e^{\frac{i\pi}{4}} & 0 & 0 \\ 0 & 0 & e^{\frac{i\pi}{4}} & 0 \\ 0 & 0 & 0 & e^{\frac{-i\pi}{4}} \end{pmatrix}$$

- The ACZ Hamiltonian (one ion):
  standard sideband term in ion frame

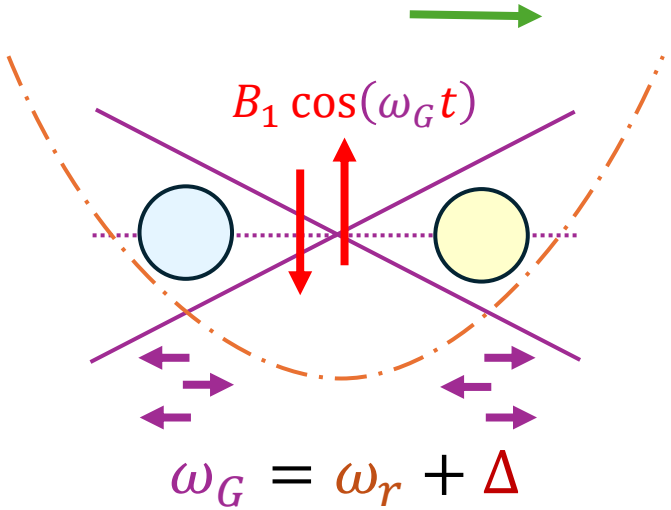
$$\Omega_G(t)\cos(\omega_G t)\,\hat{\sigma}_Z \hat{a}\, e^{-i\omega_r t}$$

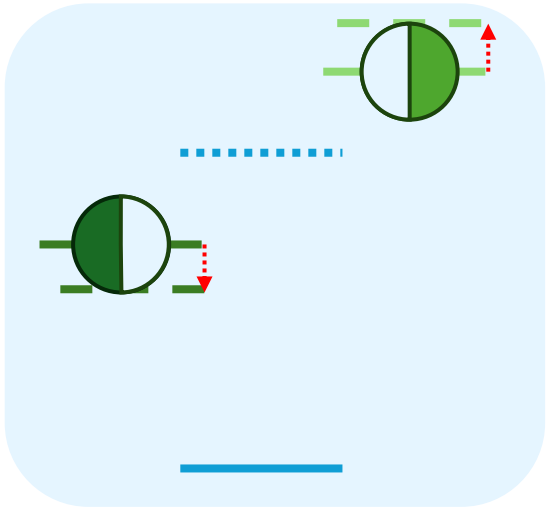
ω_r secular frequency

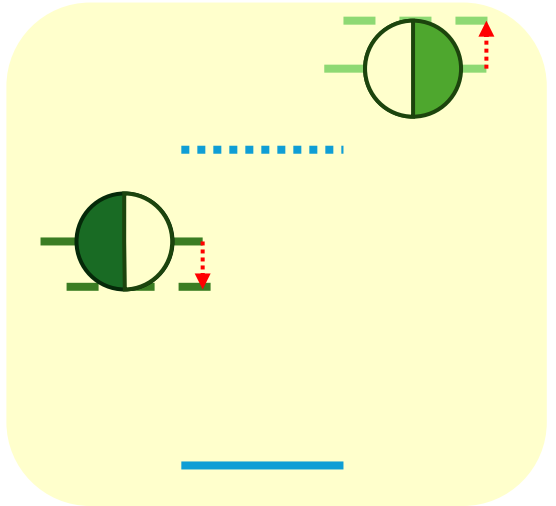
ω_G AC gate drive frequency

Ω_G AC gate drive amplitude

ω_r = 471 kHz B_0 =1.65 mT Ω_G = 17.6 T/m (0-pk) Δ = 5.6 kHz







ϵ_{LS} = 1.5 MHz

23 MHz

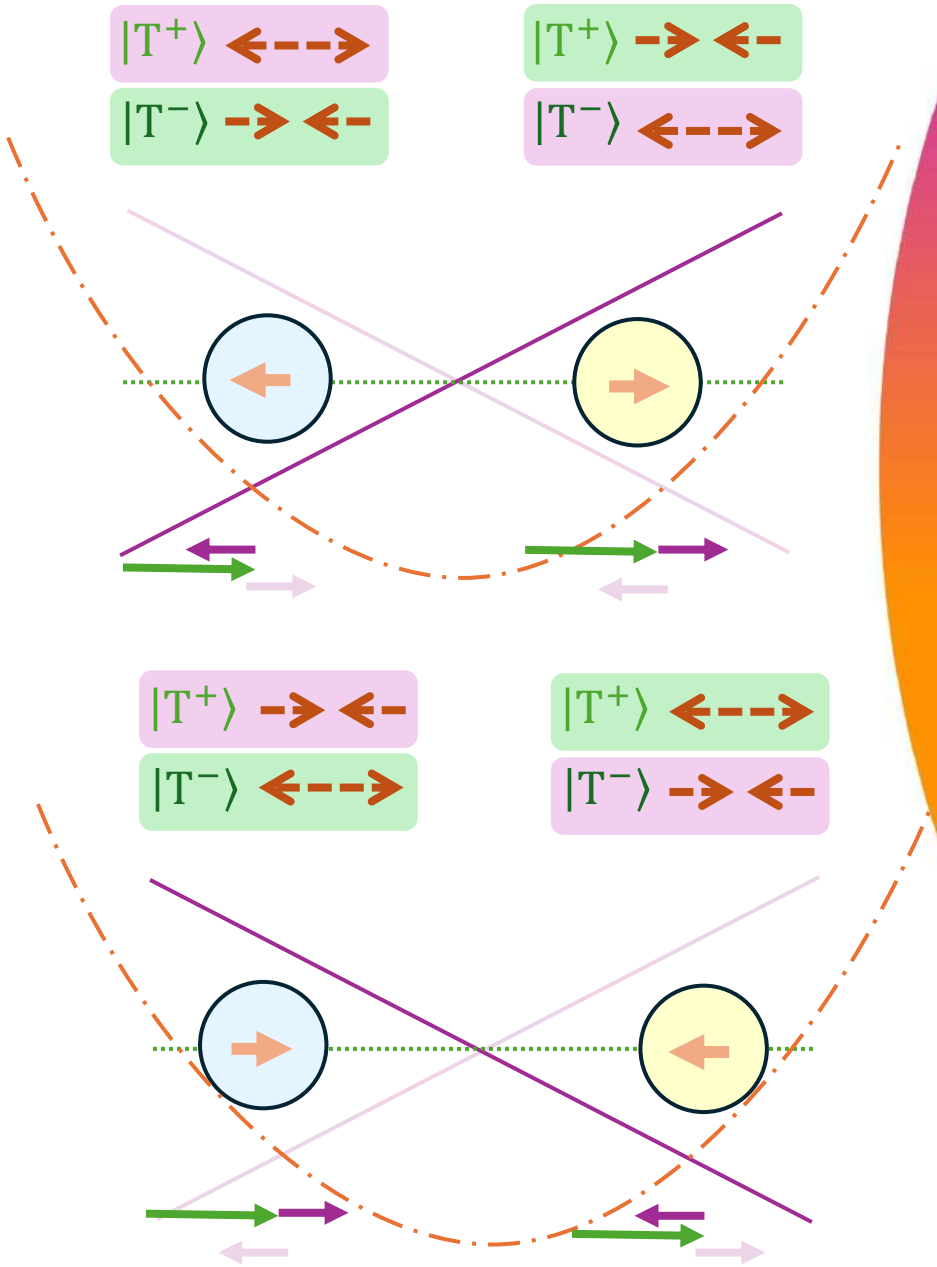
12.6 GHz

Spin dependent forces

- In the positive phase of the AC gradient…
  - *Ion 1:* $|T^+\rangle$ forced left, **increased** separation; $|T^-\rangle$ forced right, **reduced** separation …*to minimise energy*
  - *Ion 2*: just the opposite
- In the negative phase, the stretch mode oscillator has (**nearly**) also flipped ion displacement around
  - Ion1's $|T^+\rangle$ feels **reduced** separation, which constructively adds to the previous **increased** separation
- So the state combinations trace phase-space paths…

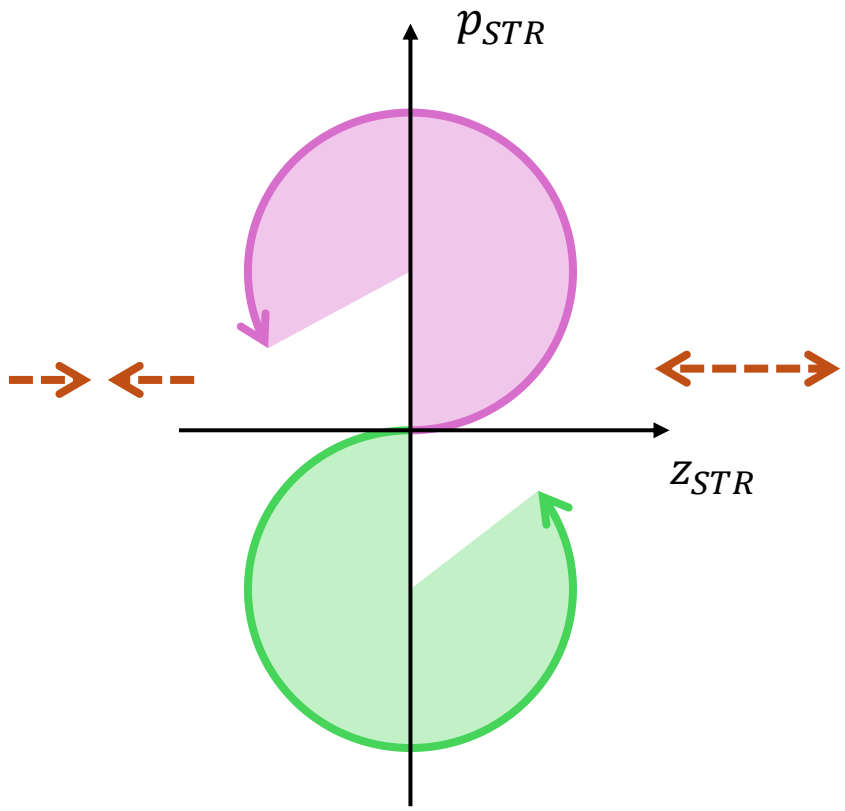
$\omega_r = 471$ kHz

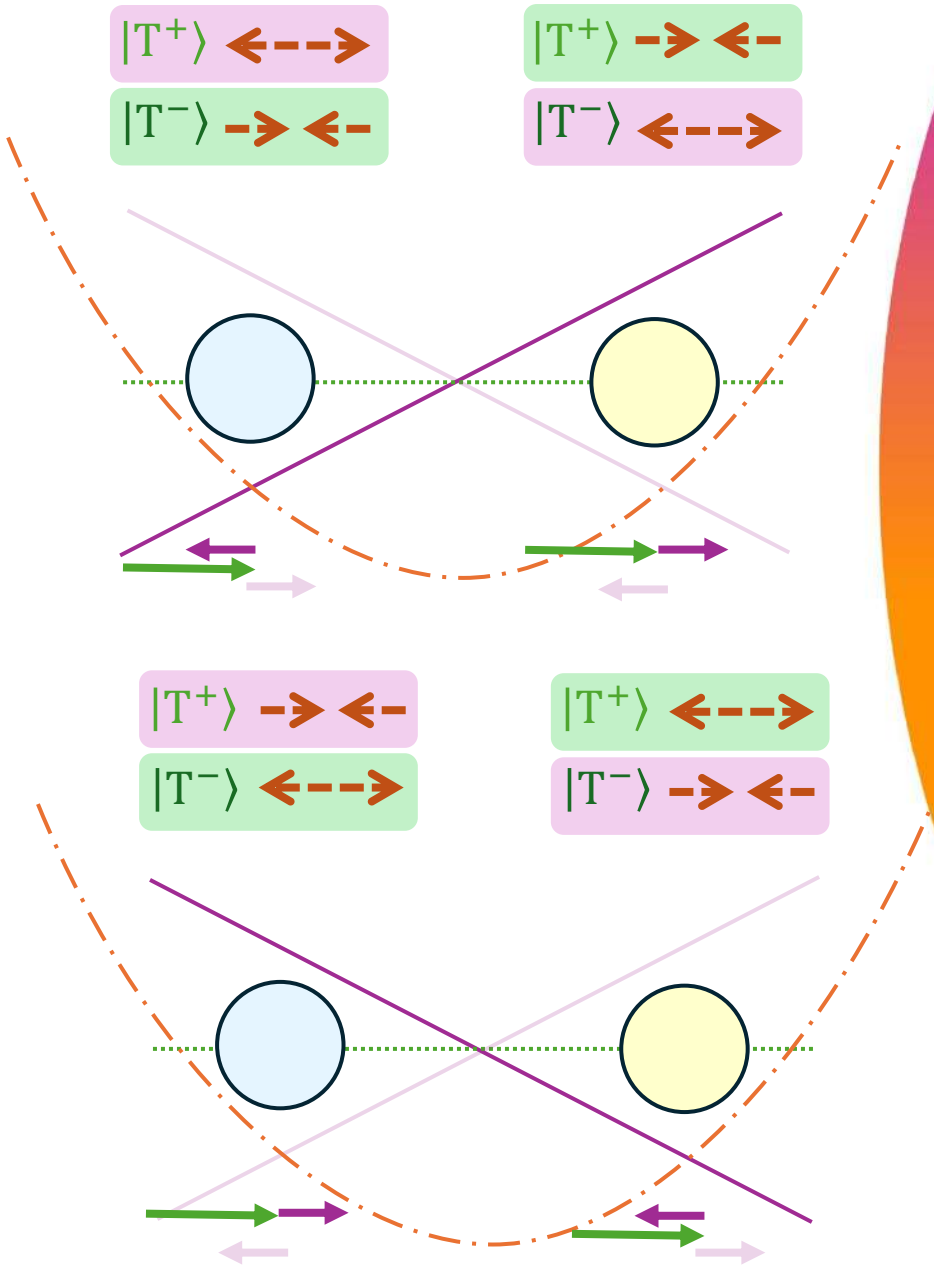
$\Delta = 5.6$ kHz



Spin dependent forces

- So the different parts of the superposition trace phase-space paths…

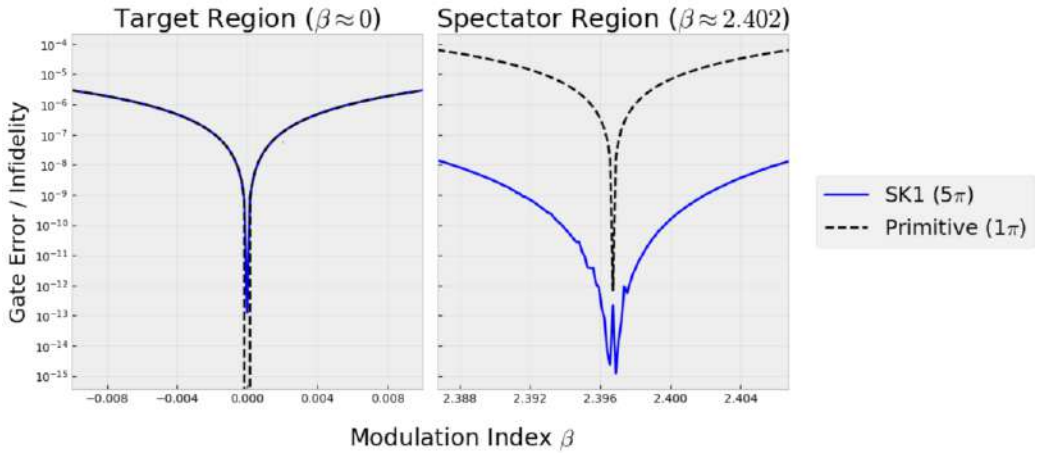




So how about single qubit addressing using an oscillating gradient?

Single qubit addressing with an oscillating gradient

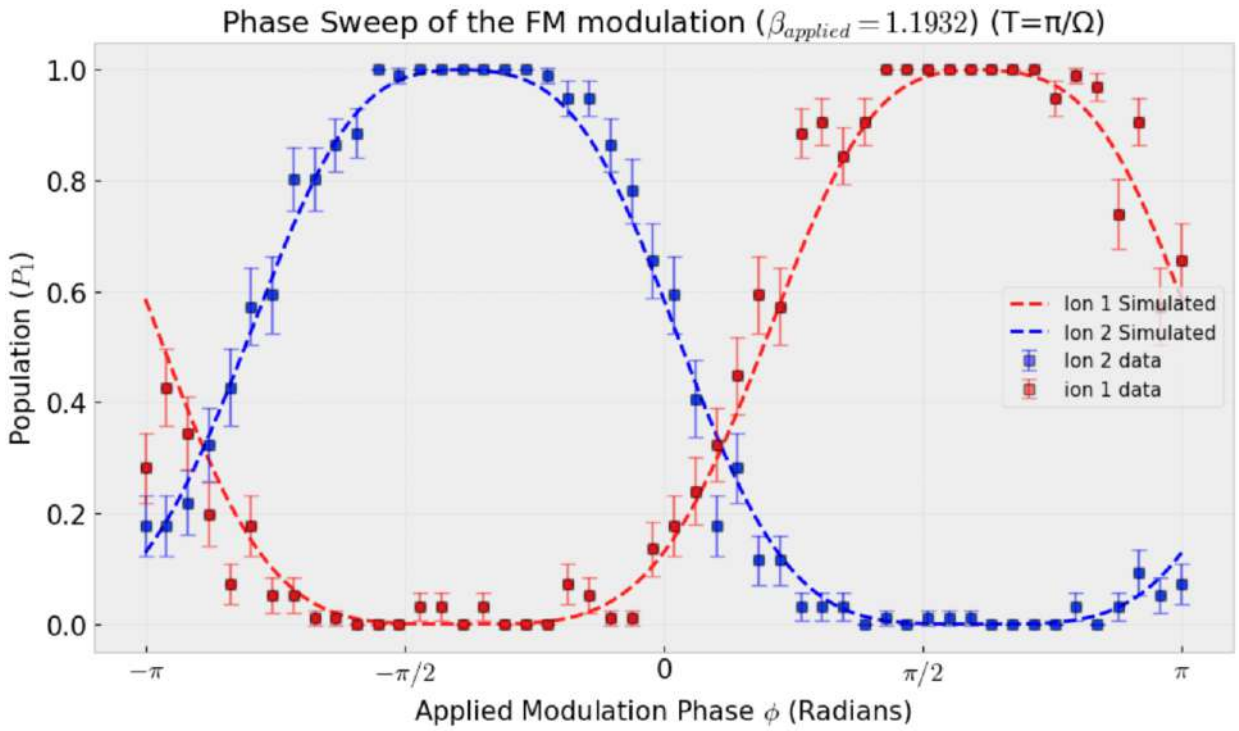
- The oscillating gradient is applied via two counterpropagating submerged current-carrying wires each containing the oscillating current with a magnetic field nil located half way between the two wires above the chip.
- Two ions are located symmetrically around this nil point.
- The resulting σ_z frequency modulation of the qubit transition at the location of each of the ions is therefore 180º out of phase for the two ions.
- By applying a single-qubit microwave pulse modulated at the frequency of the oscillating gradient and choosing an appropriate phase, we can select which qubit to drive (0º for one ion and 180º degrees for the other).



- When frequency modulating the single qubit gate driving field, we essentially set the effective modulation index to zero for the target ion meaning a single qubit gate is executed with very small error as shown on the y-axis of the left diagram.
- At the same time the modulation index is doubled for the spectator ion, meaning, the transition cannot be driven and the second qubit's state remains unchanged with the cross talk error shown on the y-axis of the right diagram.
- A pulse shaped version (SK1) provides for even more impressive cross-talk suppression

Single qubit addressing with an oscillating gradient

First experimental results



- Proof of principle demonstration of our technique for individual addressing with an oscillating gradient.
- By changing the phase of applied modulation we can either excite ion 1 (red) or ion 2 (blue) while retaining the respective other ion in their original state.

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How to go to large numbers of qubits?

In 2017, we released the first blueprint to construct a large scale quantum computer capable of solving interesting problems beyond the capabilities of the fastest supercomputers.

Led by Sussex university, this was an international collaboration including Google, Riken, Aarhus University and Siegen University

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)

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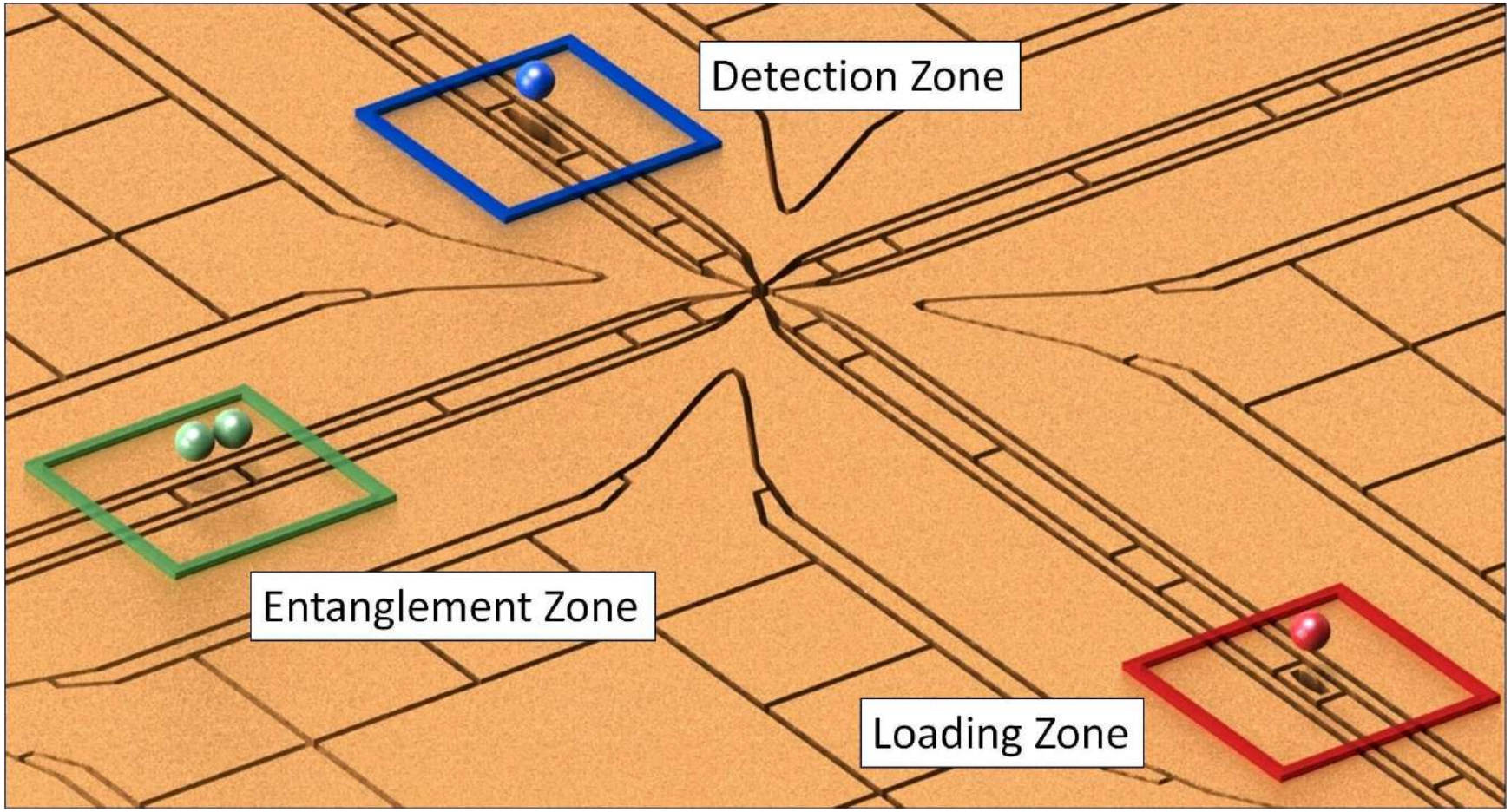
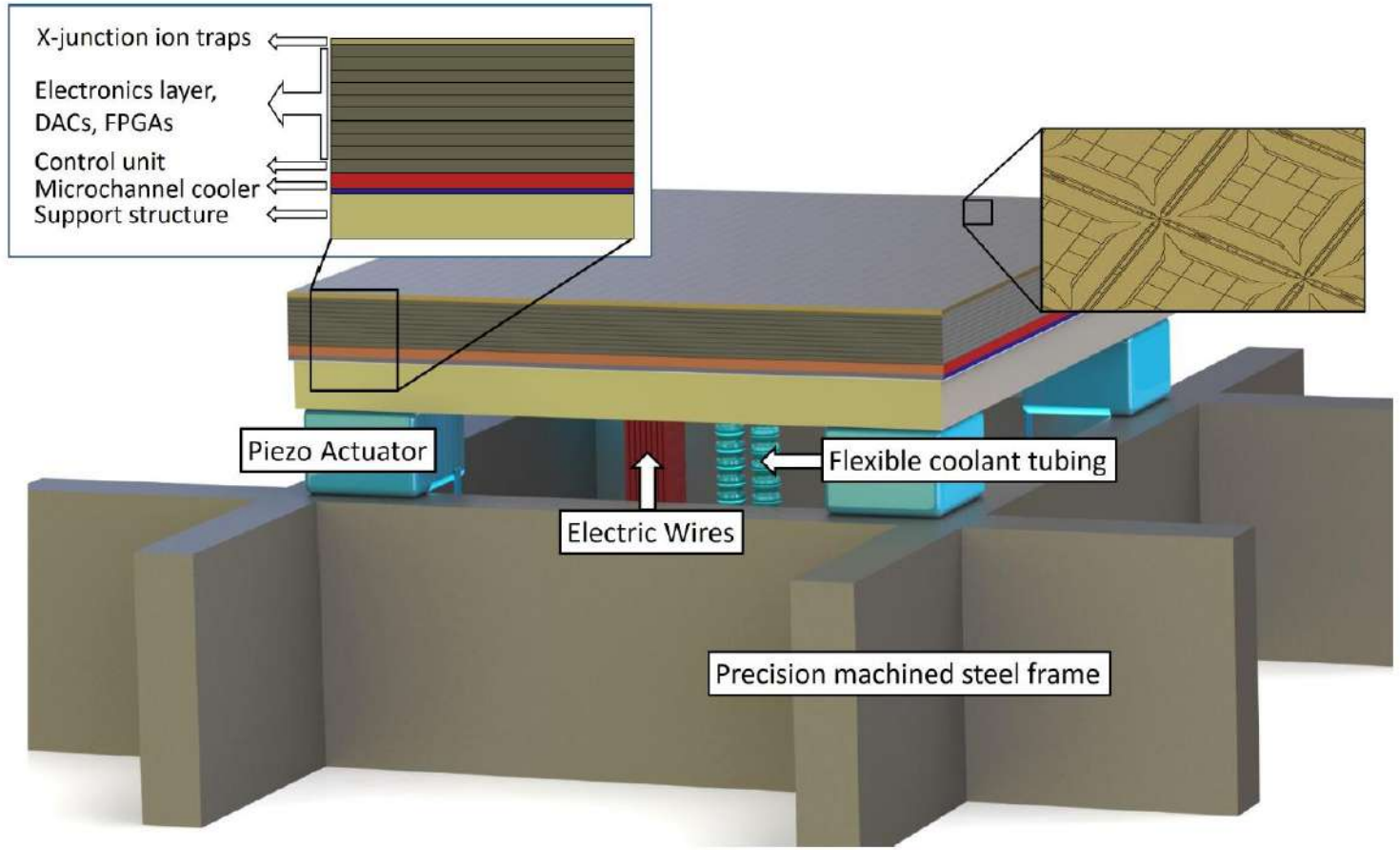
Surface array of X-junctions on a chip



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)

Our blueprint:

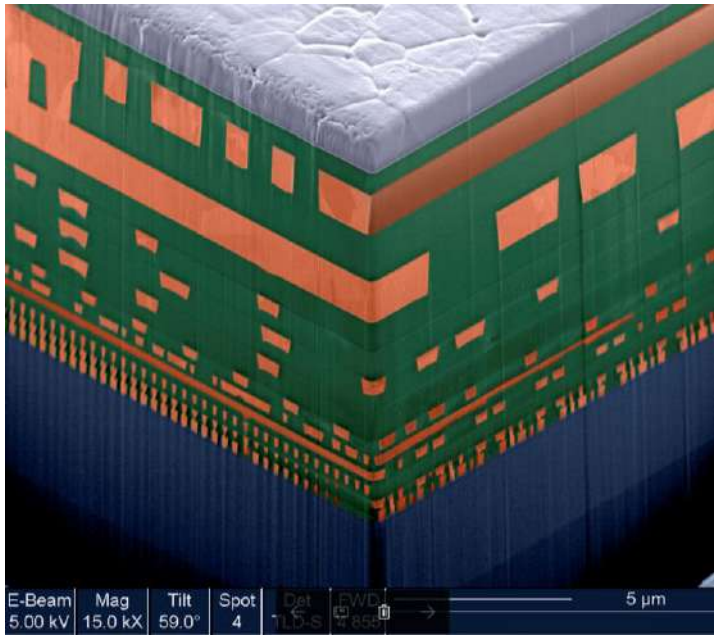
Electronic quantum computing module via standard Silicon Foundry processes



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)

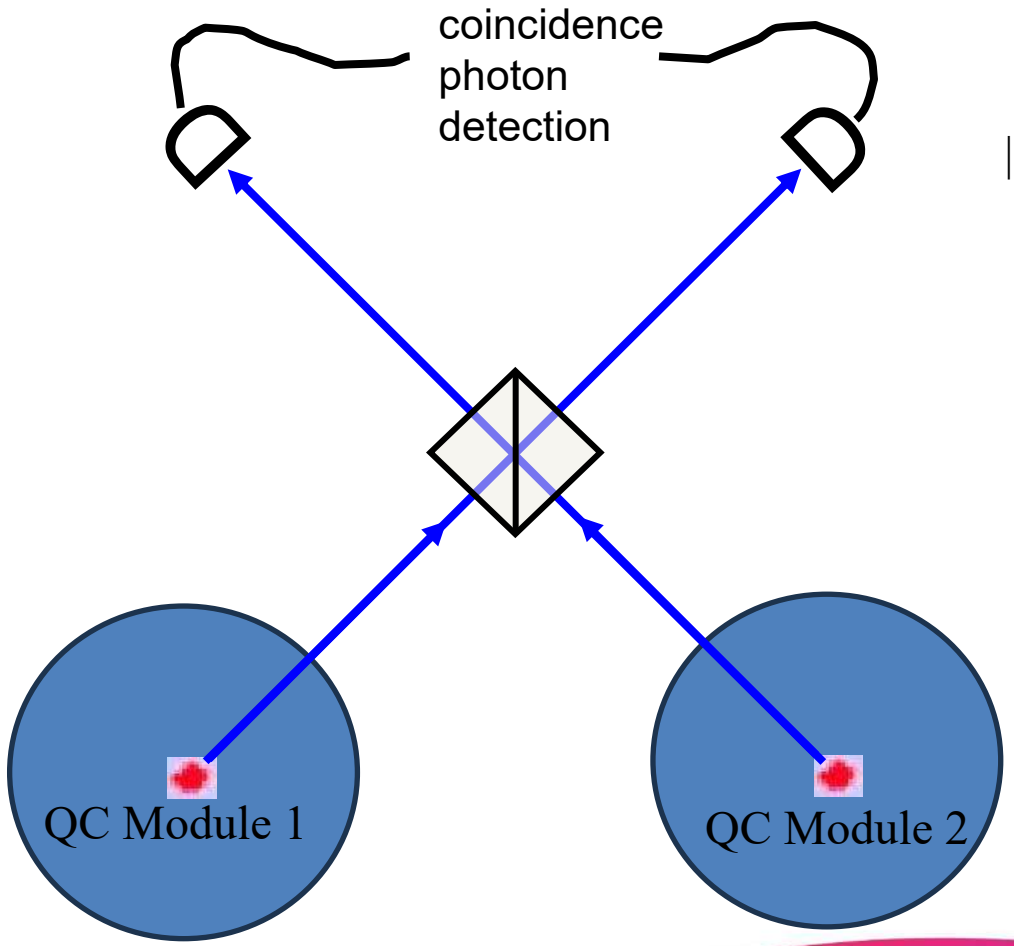
For comparison:
Classical computer architecture



IBM microprocessor chip:
Layer of transistors connected
via multiple layers of wiring

How to make modular quantum computers?

Option 1: Photonic interconnects



$$|\Psi\rangle = \left(|\downarrow\rangle_1|V\rangle_1 + |\uparrow\rangle_1|H\rangle_1\right)\otimes\left(|\downarrow\rangle_2|V\rangle_2 + |\uparrow\rangle_2|H\rangle_2\right)$$

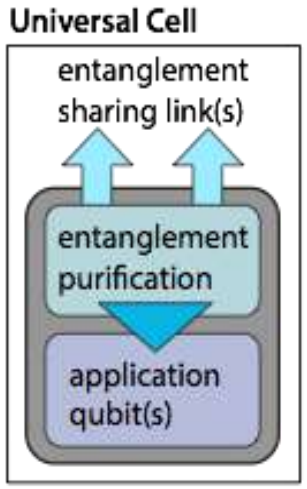
upon coincidence photon detection

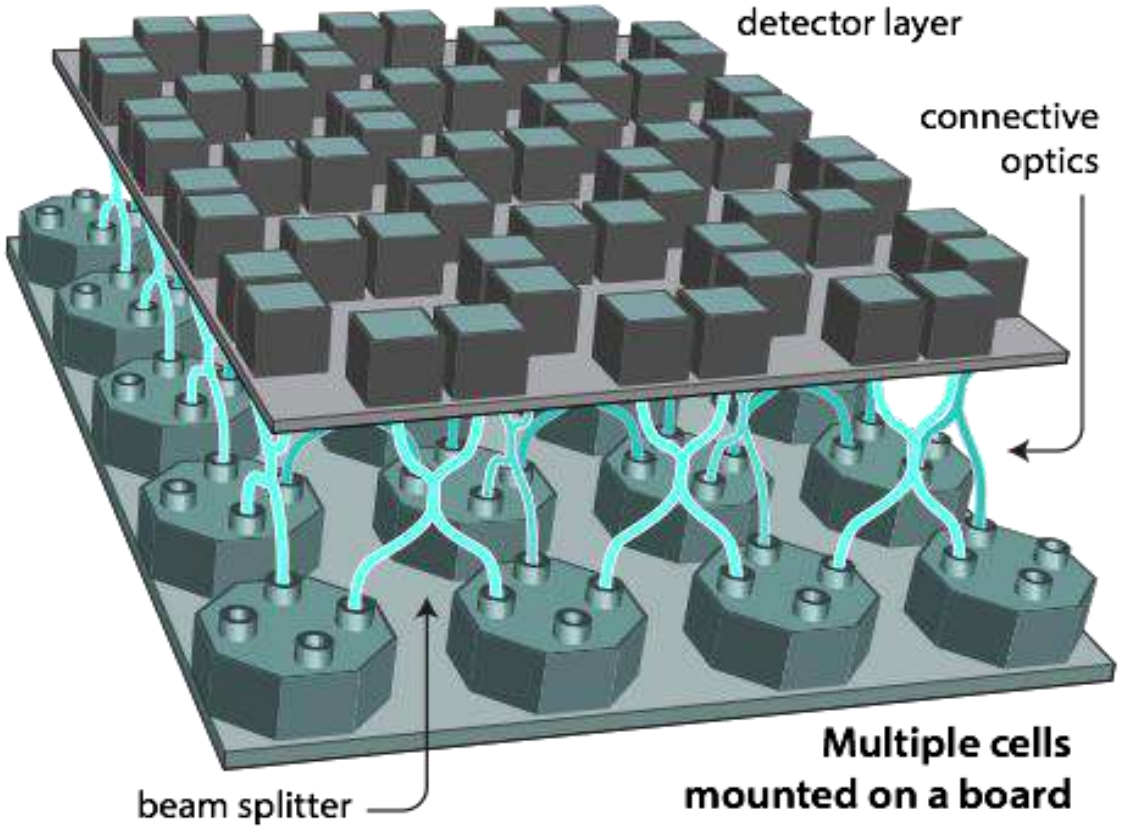
$$|\Psi\rangle \Rightarrow |\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_2|\downarrow\rangle_2$$

Chris Monroe, Duke University

Option 1: Photonic interconnects

Optically linked array of quantum computing modules…

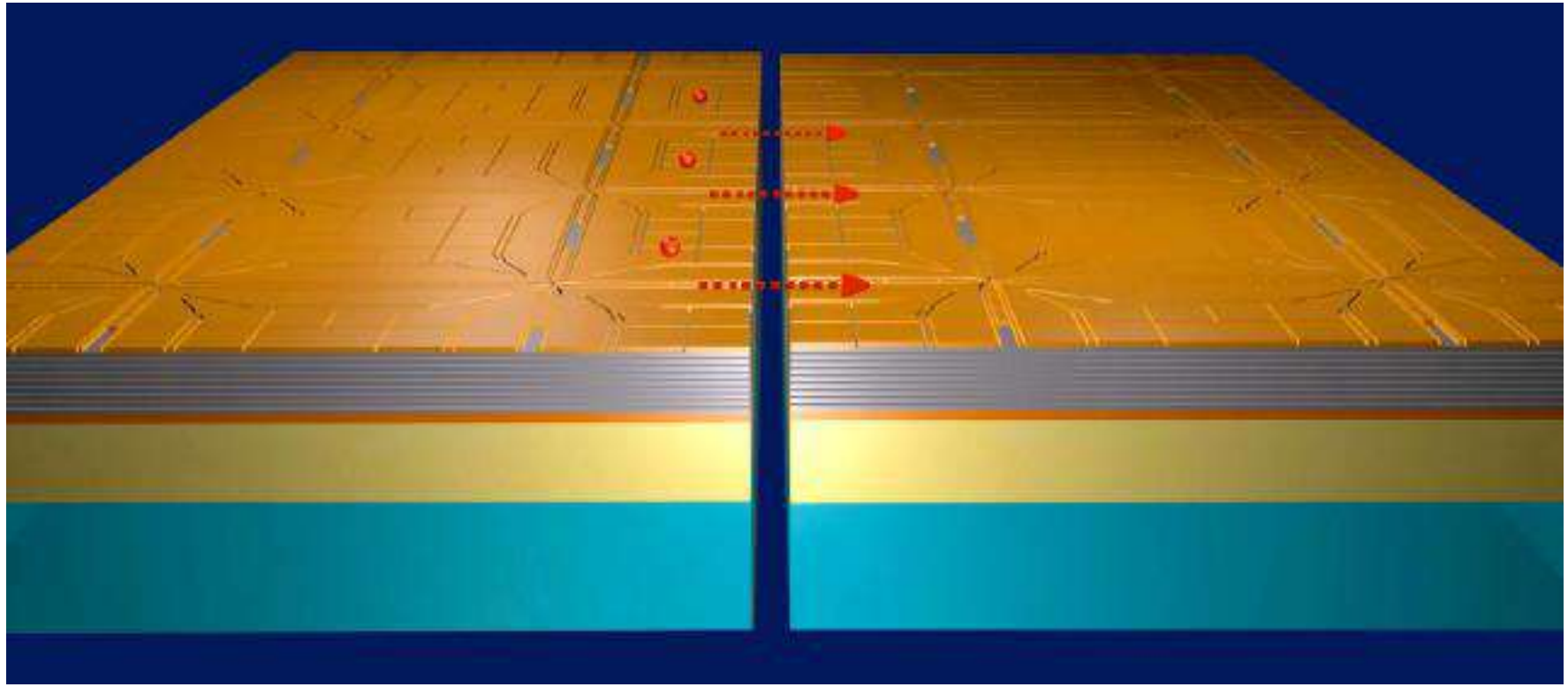


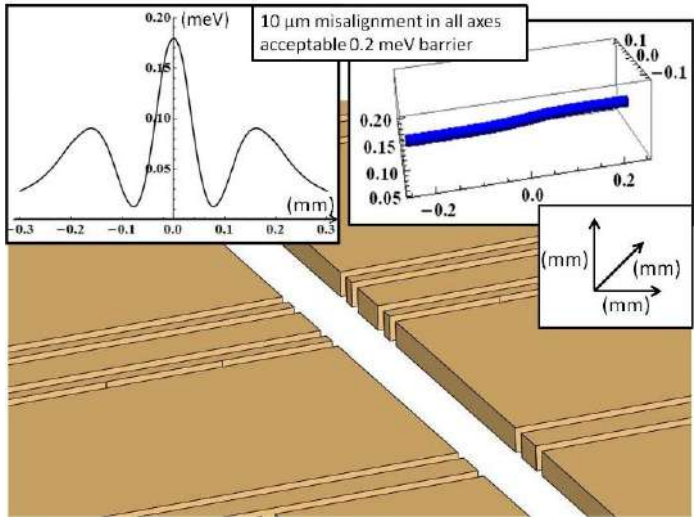


Pioneered by Chris Monroe's group
Current record: 250 1/s at 94% fidelity (Duke group), meaning a few 1s 1/s after distillation

- Effective connection rate between modules too slow

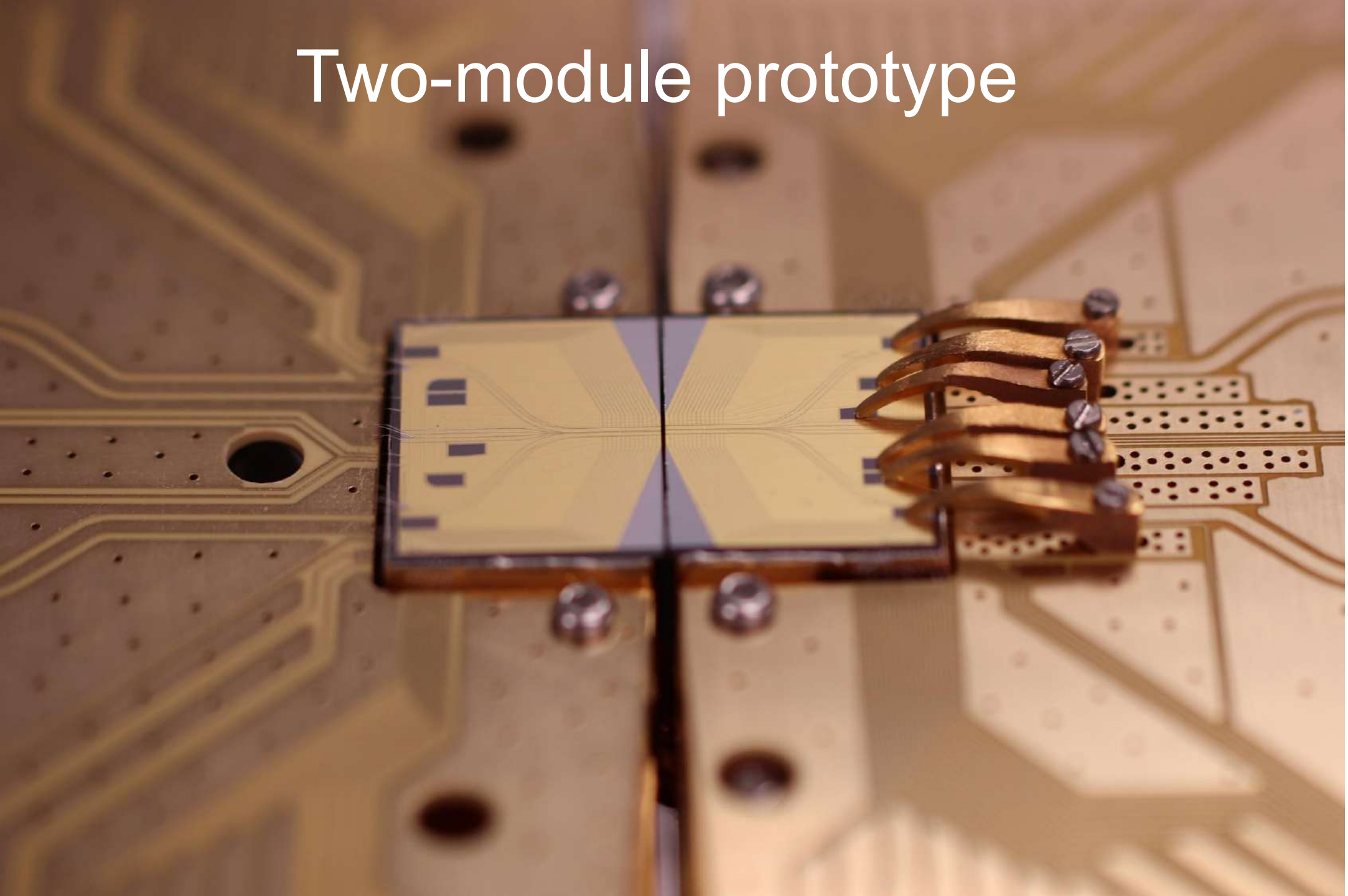
Option 2:
We proposed to connect modules with electric field links



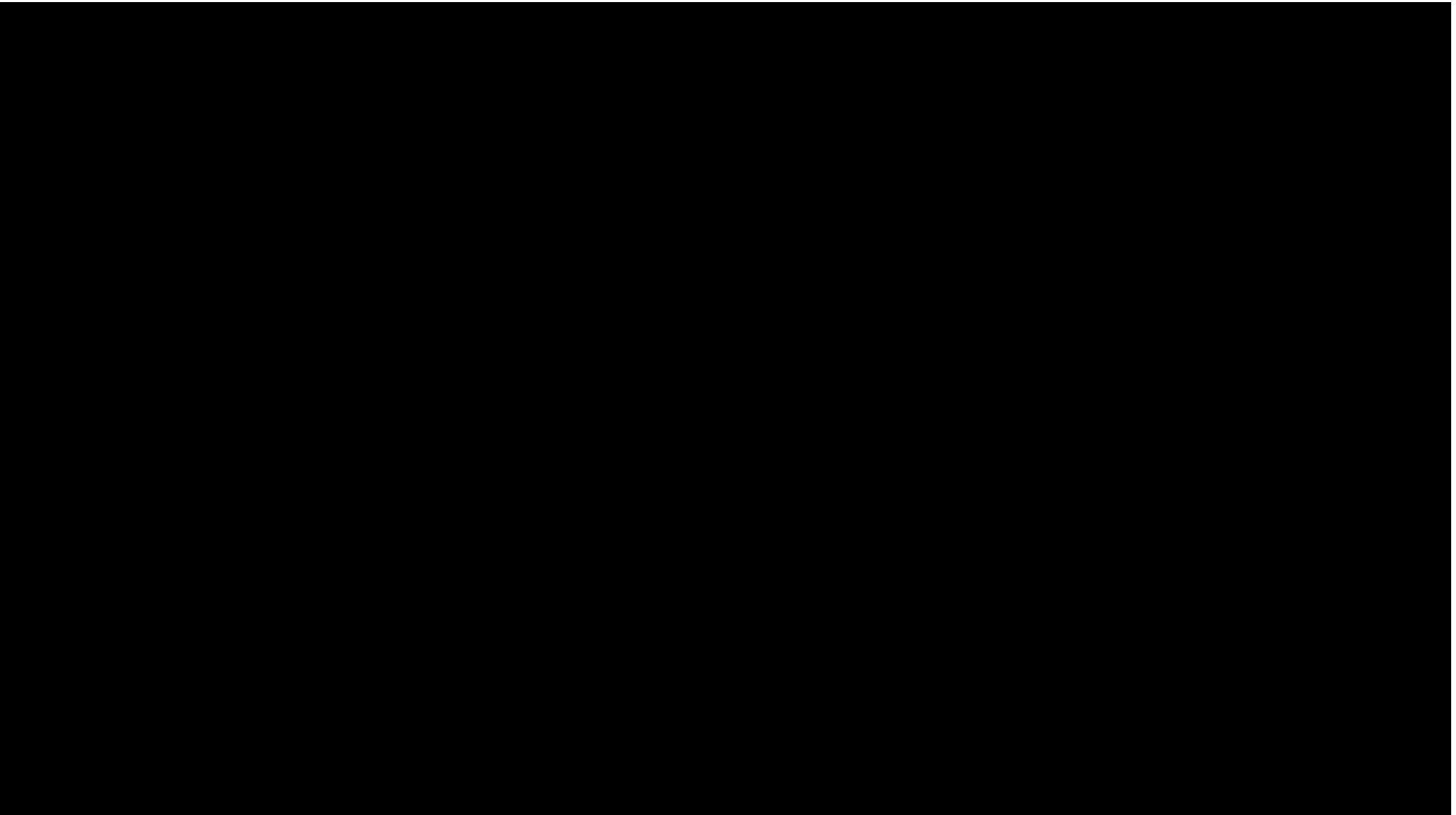


Blueprint for a microwave trapped ion quantum computer,
B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich, and W.K. Hensinger, Science Advances 3, e1601540 (2017)

Two-module prototype

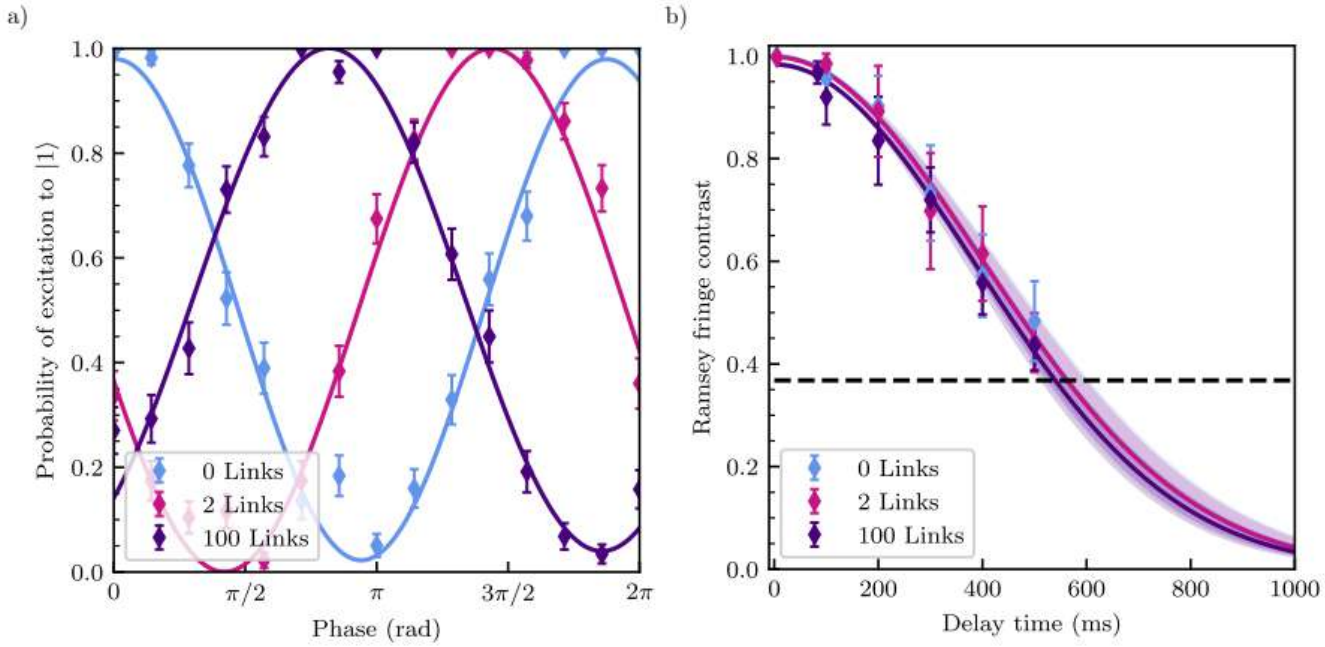


Demonstration of the electric-field link architecture



Demonstration of electric field links between Ion-Trap Microchip Modules

- Connection rate between modules: 2424 s^{-1}
  (Best demonstration using photonic interconnects: Connection rate between modules: 250 s^{-1} at Duke)
- Transmission error: 0.00007% (via ion loss)
  (Best demonstration with photonic interconnects: 6% Transmission error at Duke)
- The connection rate is only limited by the update rate of the digital to analogue converters of the card connected to the electrodes (around 130 kS/s), limitations in secular frequency and the 47 kHz cut-off frequency of the filter.
- Phase coherence of the qubit is fully preserved with no measurable loss of coherence of the qubit (measurement accuracy implies a lower bound of 99.95)



A High-Fidelity Quantum Matter-Link Between Ion-Trap Microchip Modules
M. Akhtar, F. Bonus, F. R. Lebrun-Gallagher, N. I. Johnson, M. Siegele-Brown, S. Hong, S. J. Hile, S. A. Kulmiya, S. Weidt and W. K. Hensinger,
Nature Communications 14, 531 (2023)

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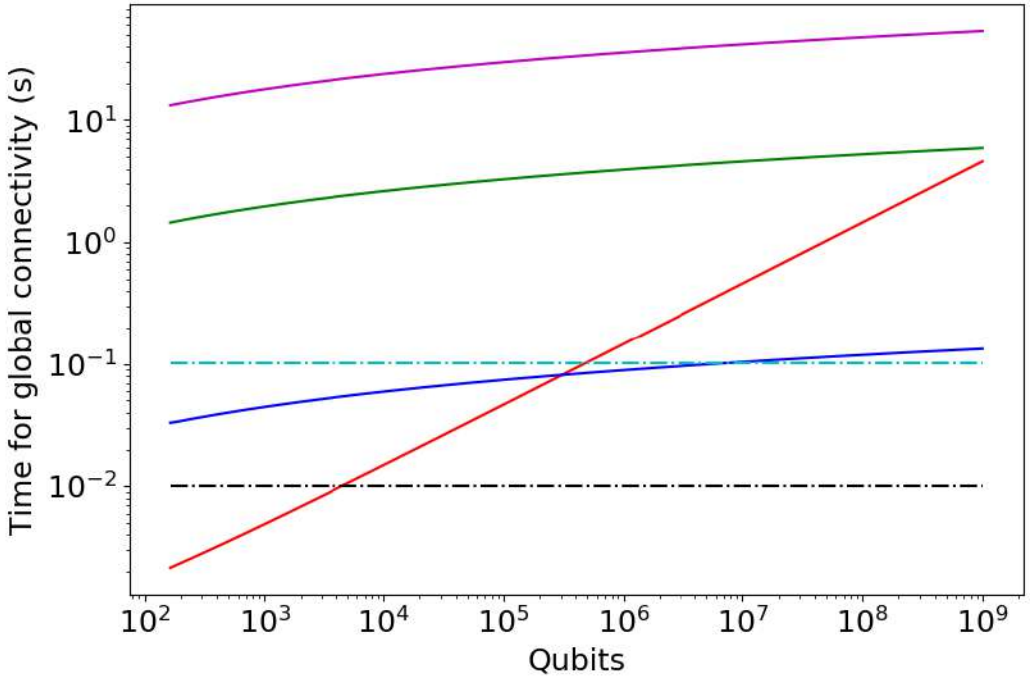
Comparing the electric field link architecture with photonic interconnects



Shuttling based approach. [1] [2]

Photonic interconnects butterfly network with **4** connections per module and qubit (space) overhead of 2. [3] [4]

Photonic interconnects butterfly network with **4** connections per module and qubit (space) overhead of 1. [3] [5]

Photonic interconnects butterfly network with **12** connections, S=1, but only lower-bounded (actual scaling may be worse). [3] [5]

Time required for a 1% error with a coherence time of 1s

Time required for a 1% error with a coherence time of 10s

Time costs of individual operations are motivated by **recent** experimental results: Shuttled 280µm in 12.8 µs [1] extrapolates to 114 µs to shuttle between adjacent X-Junctions. Photonic interconnects performed at a rate of $182s^{-1}$ [3] and level 3 purification effectively reduces this rate by a factor 6 [6]. Assuming a network of modules with one data qubit per module.

[1] – Kaufmann et al. "High fidelity Preservation of Quantum Information during Trapped-Ion Transport". Physical Review letters, vol 120, no.1. 2018 [2] – Webber et al. "Efficient Qubit Routing for a Globally Connected Trapped Ion Quantum Computer". Advanced Quantum Technologies. Volume 3, Issue 8. 2020. [3] Stephernson et al. "High-rate, High-Fidelity Entanglement of Qubits Across an Elementary Quantum Network". Phys Rev Lett. 124.110501. 2020. [4] Stephen Brierley. "Efficient implementation of Quantum circuits with limited qubit interactions". Arxiv 1507.04263. [5] Steven Herbert "On the depth overhead incurred when running quantum algorithms on near-term quantum computers with limited qubit connectivity". Arxiv 1805.12570. [6] Ramil Nigmatullin et al. "Minimally complex ion traps as modules for quantum communication and computing". New J. Phys. 18 103028 2016.

Comparing the electric-field link architecture with photonic interconnects

Back-of-the-envelope calculation to verify all-to-all connectivity:

- Demonstrated decoherence time for ions:
  ~ 10h (Kihwan Kim group)
- Demonstrated fast ion transport
  ~70m/s (Ferdinand Schmidt-Kaler group, NIST group)
- Size of a quantum computing hosting around 100 000 ions
  ~ 2.5 m x 2.5 m (characteristic qubit size is determined by ion-electrode distance)

➢ **True all-to-all connectivity in the electric-field link architecture for at least 100 000 qubits enabling deployment of qLDPC QEC codes at that scale.**

Why we work to scale up making use of the electric field link architecture rather than using photonic interconnects

Electric field link architecture does not require:

- On-chip cavities (still not mature enough and complicated to create)
- High NA objectives (that may take one week to align),
- N-to-N switches (that are limited in N and introduce photon loss)

Number of interconnects per quantum computing module:

- Photonic interconnects: Number of connections limited by microscope objective size, e.g. **1 connection per module**
- Electric field link architecture: Many parallel electric field links enable **many parallel connections per module** significantly increasing connection bandwidth between quantum computing modules.

The size of the resulting quantum computer depends on the characteristic qubit size

- Electric field link architecture: Characteristic qubit size: Ion-electrode distance **~50 µm per ion**
- Photonic interconnect architecture: Characteristic qubit size: Size of vacuum system divided by number of ions: 10 cm /100 ions **~1 mm per ion**
- A quantum computer using photonic interconnects will **1-2 orders of magnitude larger in length** for the same number of qubits or at **least hundred times larger in area.**

Scaling to large qubit numbers:

Developing advanced ion microchip features

Microchips inner segmented electrodes

Simplified process flow



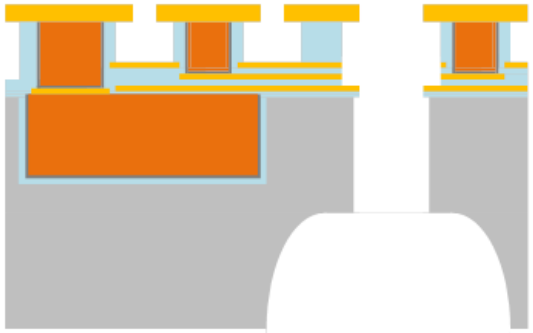
CCWs



1st ground shield



Routing layer



Loading slot



2nd ground shield

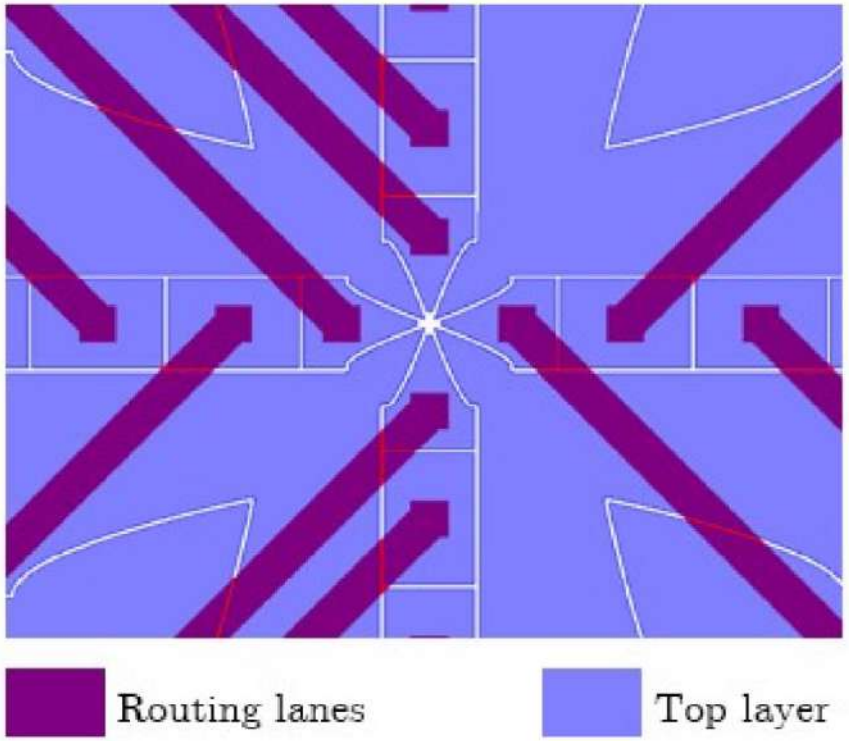


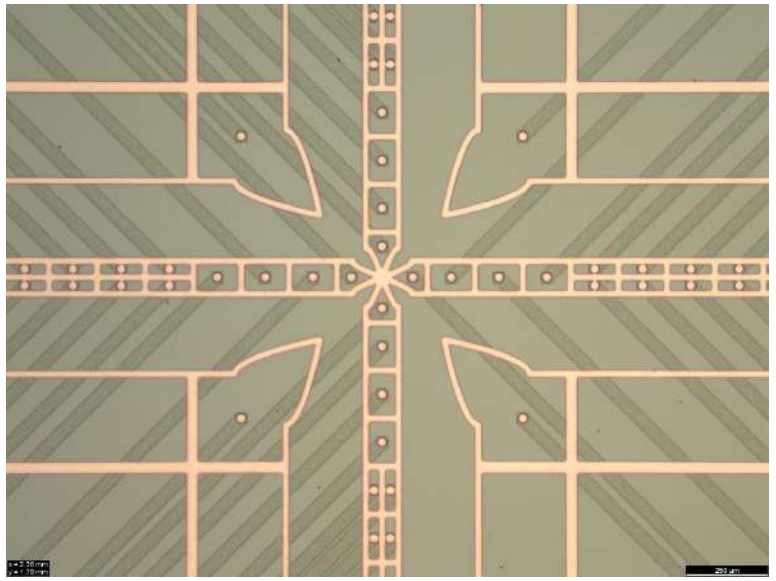
vias

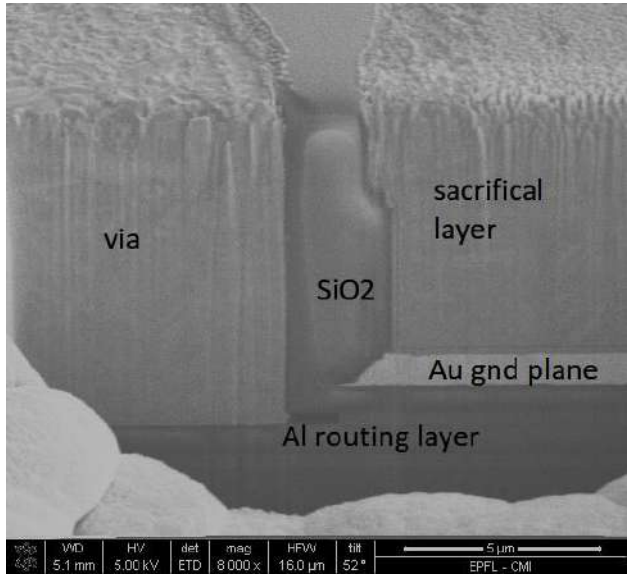


Top layer

Microchips inner segmented electrodes

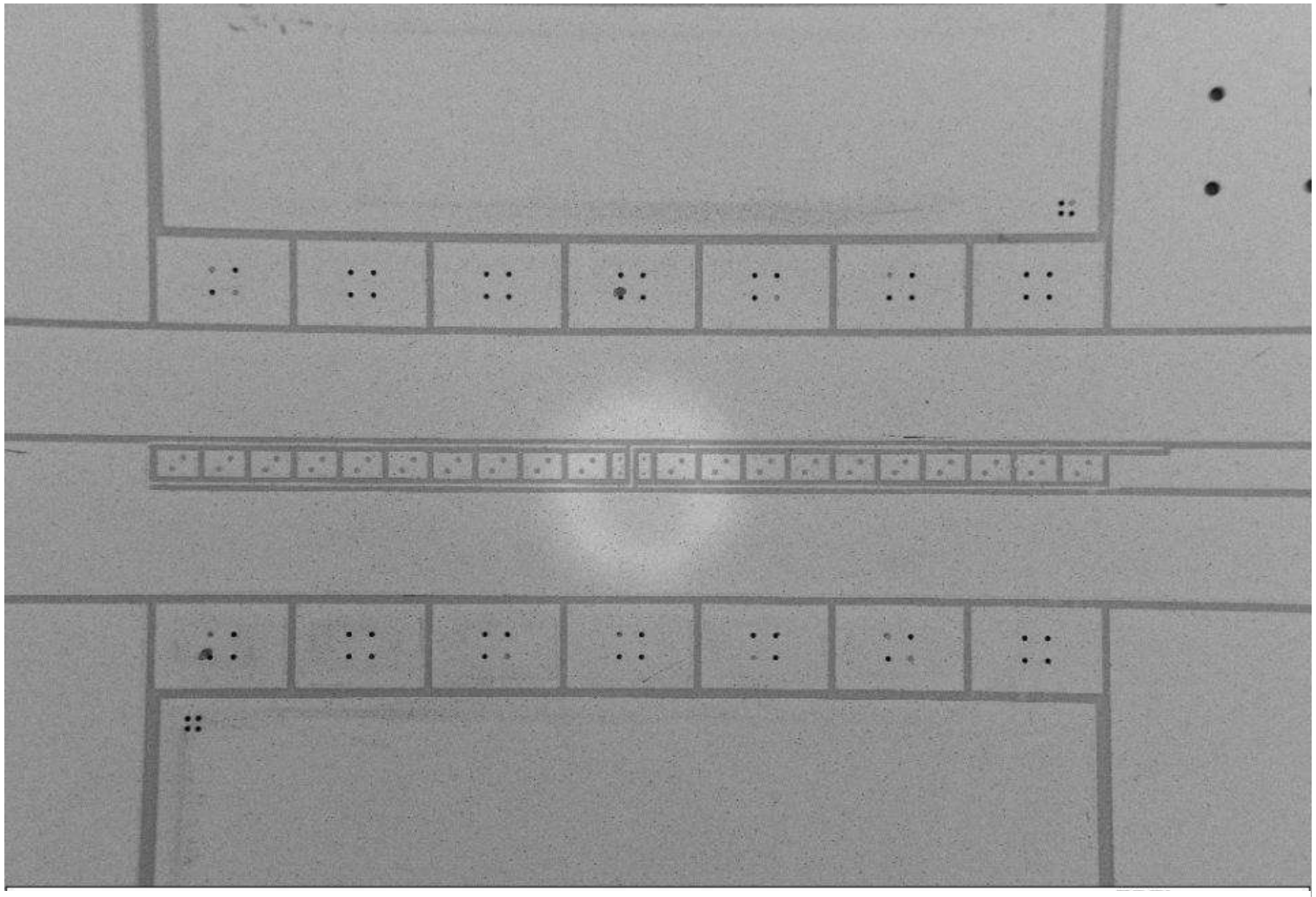




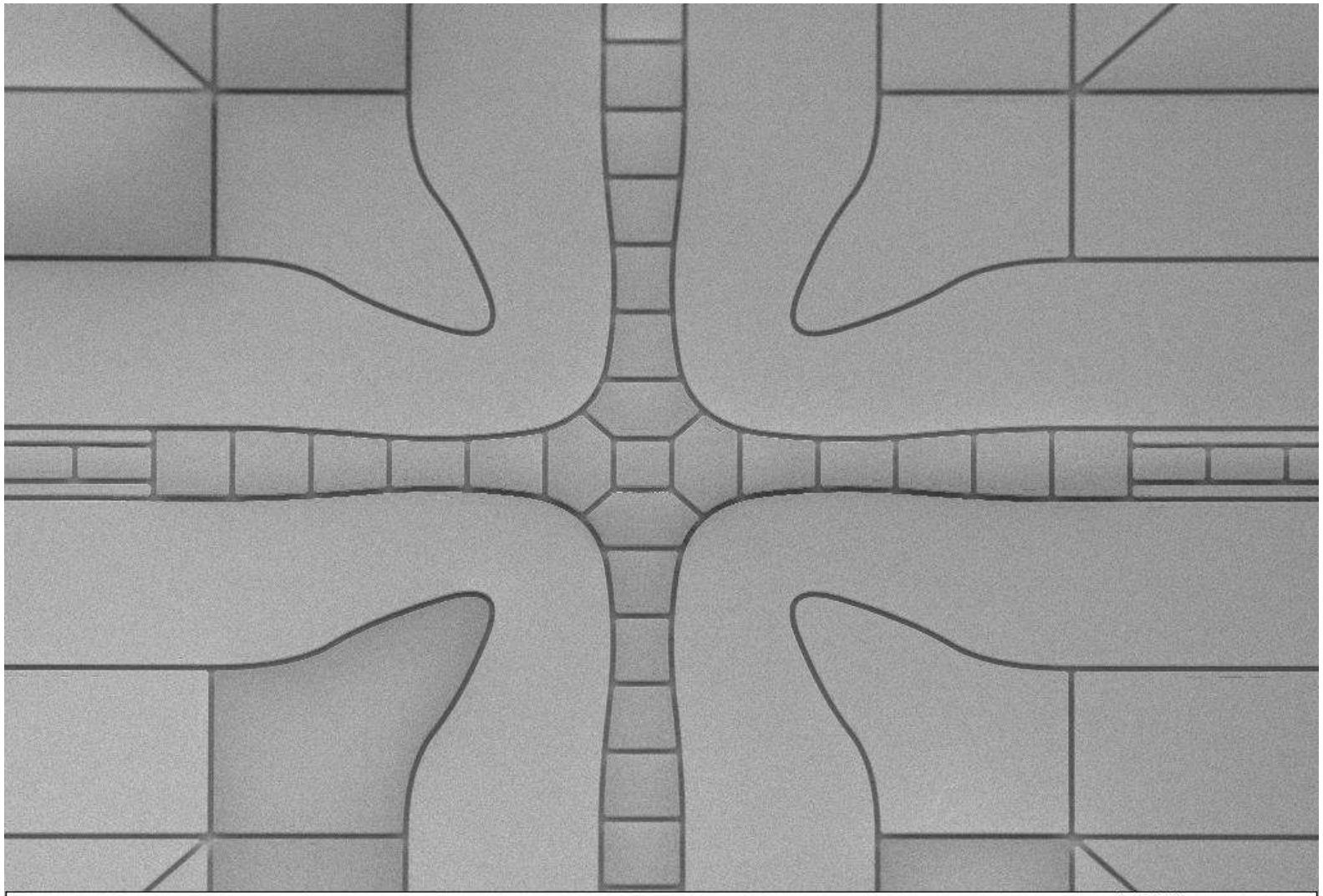


Design and optical microscope and SEM image after FIB cut. Shown before top layer deposition and removal of sacrificial lyer

New generation with inner segmented electrodes and integrated microwave antennas



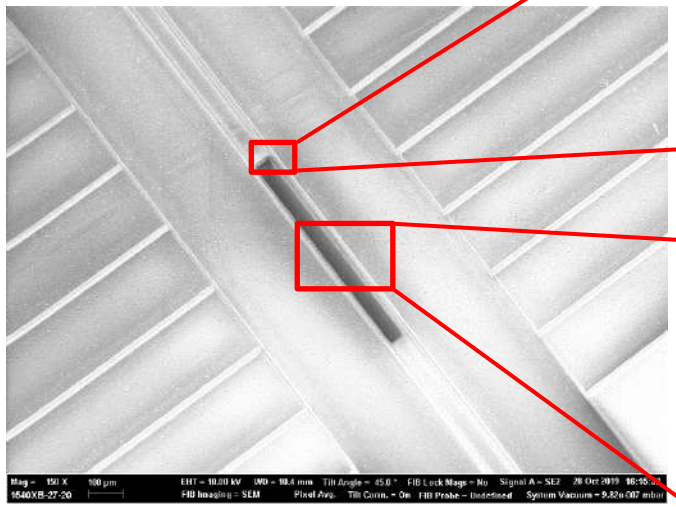
New generation with inner segmented electrodes and integrated microwave antennas

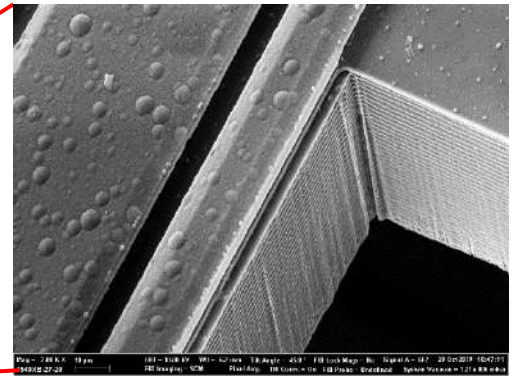


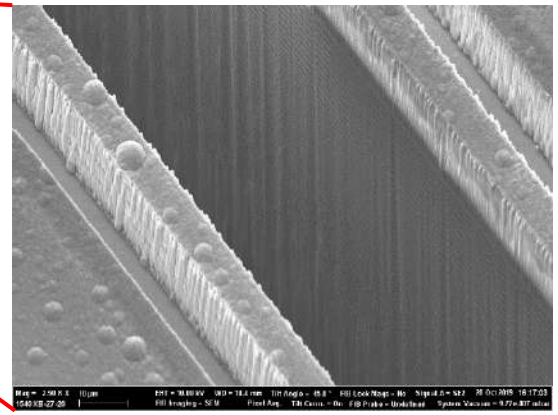
Integration of detectors and ovens into the ion microchip



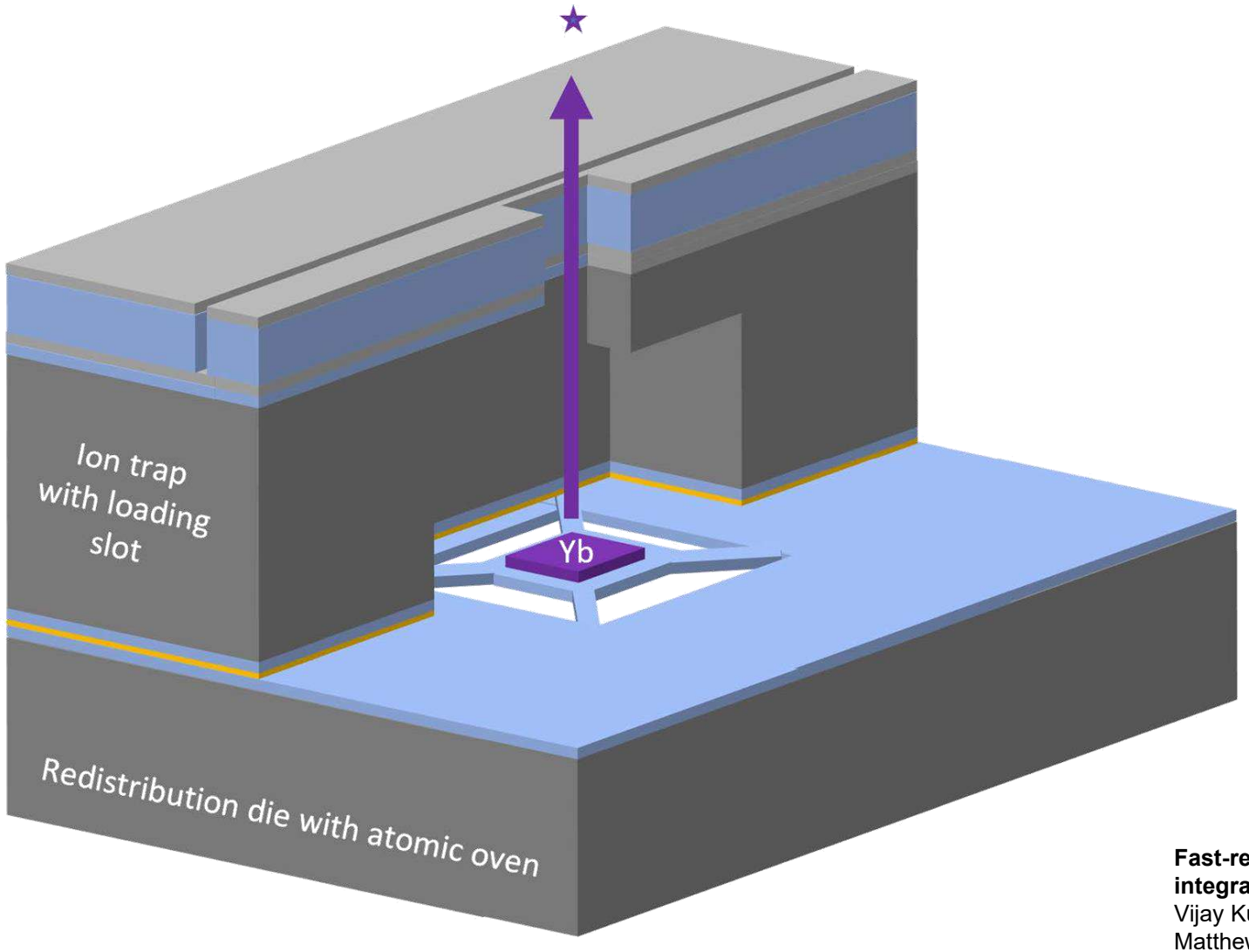
Backside access hole for device integration







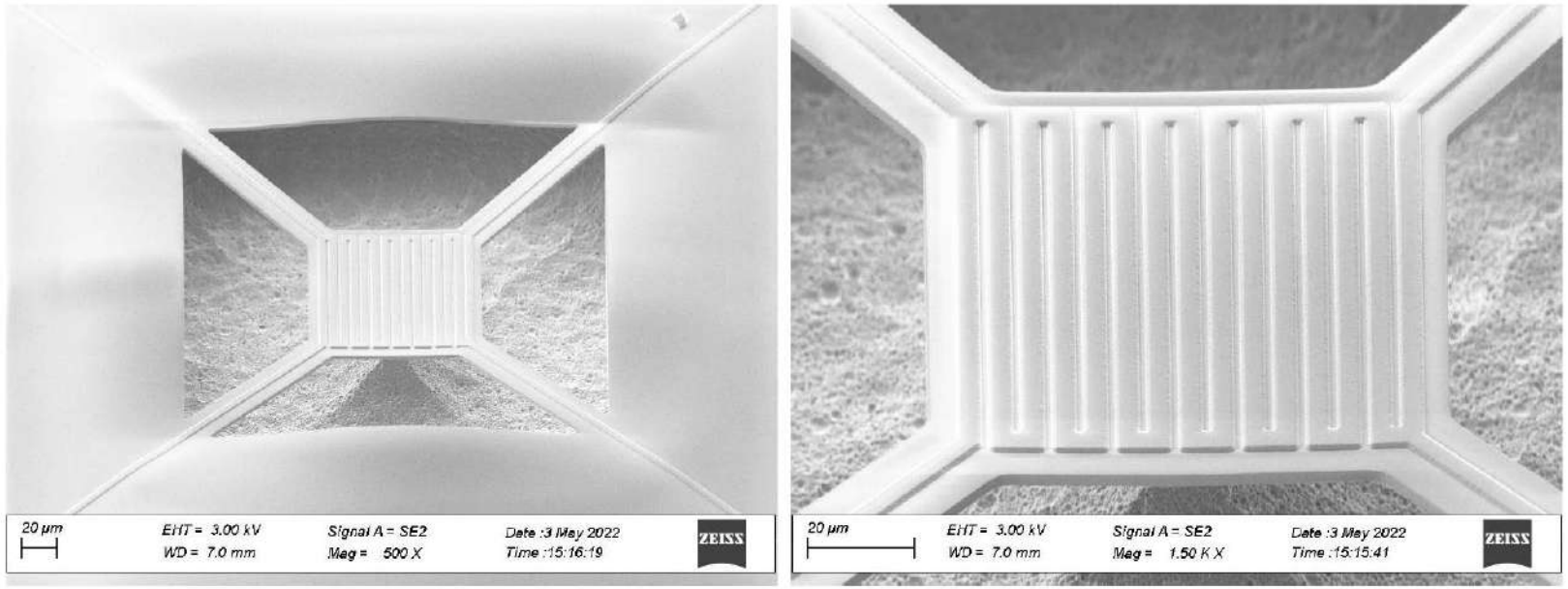
Integrated micro-oven for Ytterbium loading



Fast-response low power atomic oven for integration into an ion microchip
Vijay Kumar, Martin Siegele-Brown, Parsa Rahimi, Matthew Aylett, Sebastian Weidt, and Winfried K. Hensinger, Appl. Phys. Lett. 126, 264001 (2025)

Integrated micro-oven for Ytterbium loading

- SEM images with 500x (left) and 1500x (right) magnification of the fabricated microhotplate before depositing ytterbium.



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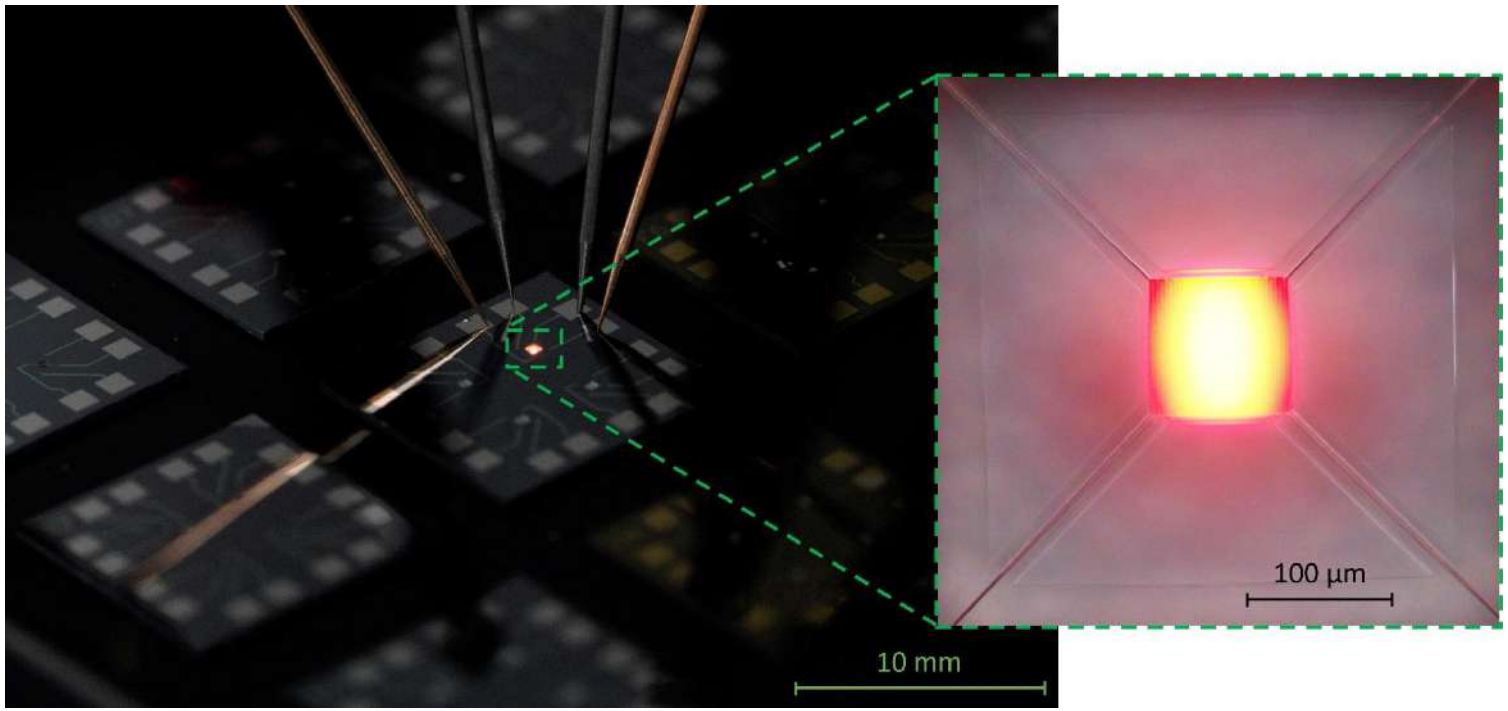
Integrated micro-oven for Ytterbium loading

Photograph of heated micro-hotplate with inlay showing a 20x magnification microscope image of the hotplate at the power dissipation of 38mW.



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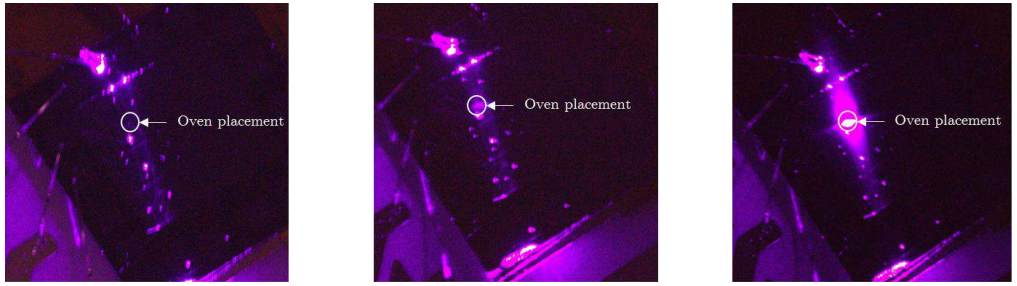
Integrated micro-oven for Ytterbium loading

Images from micro oven fluorescence test. Under the application of a 399nm laser beam we expect to see fluorescence from an emitted ytterbium flux.



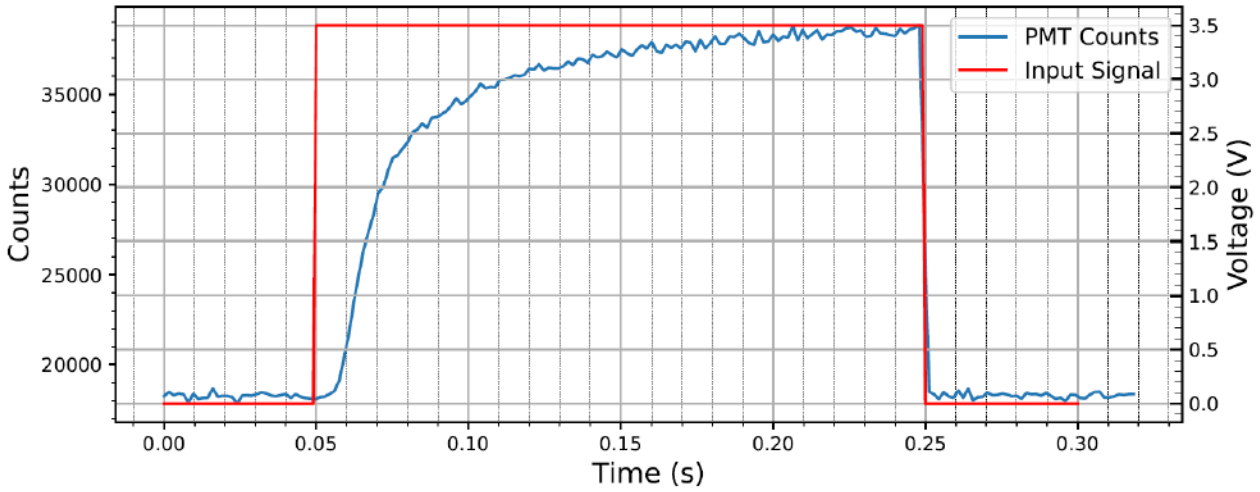
(a) (b) (c)

(a) Comparison image with no current applied to the atomic oven.

(b) Initial fluorescence seen at 7.5mA applied current.

(c) Strong fluorescence seen at 8.2mA applied current.

Time until fluorescence is observed



Ovens loads two orders of magnitude faster while dissipating two orders of magnitude less power!

Fast-response low power atomic oven for integration into an ion microchip
Vijay Kumar, Martin Siegele-Brown, Parsa Rahimi, Matthew Aylett, Sebastian Weidt, and Winfried K. Hensinger, Appl. Phys. Lett. 126, 264001 (2025)

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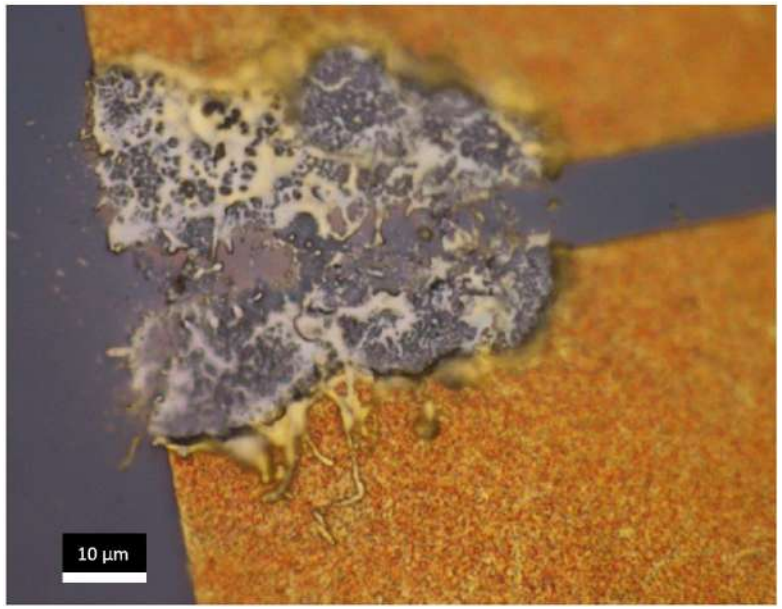
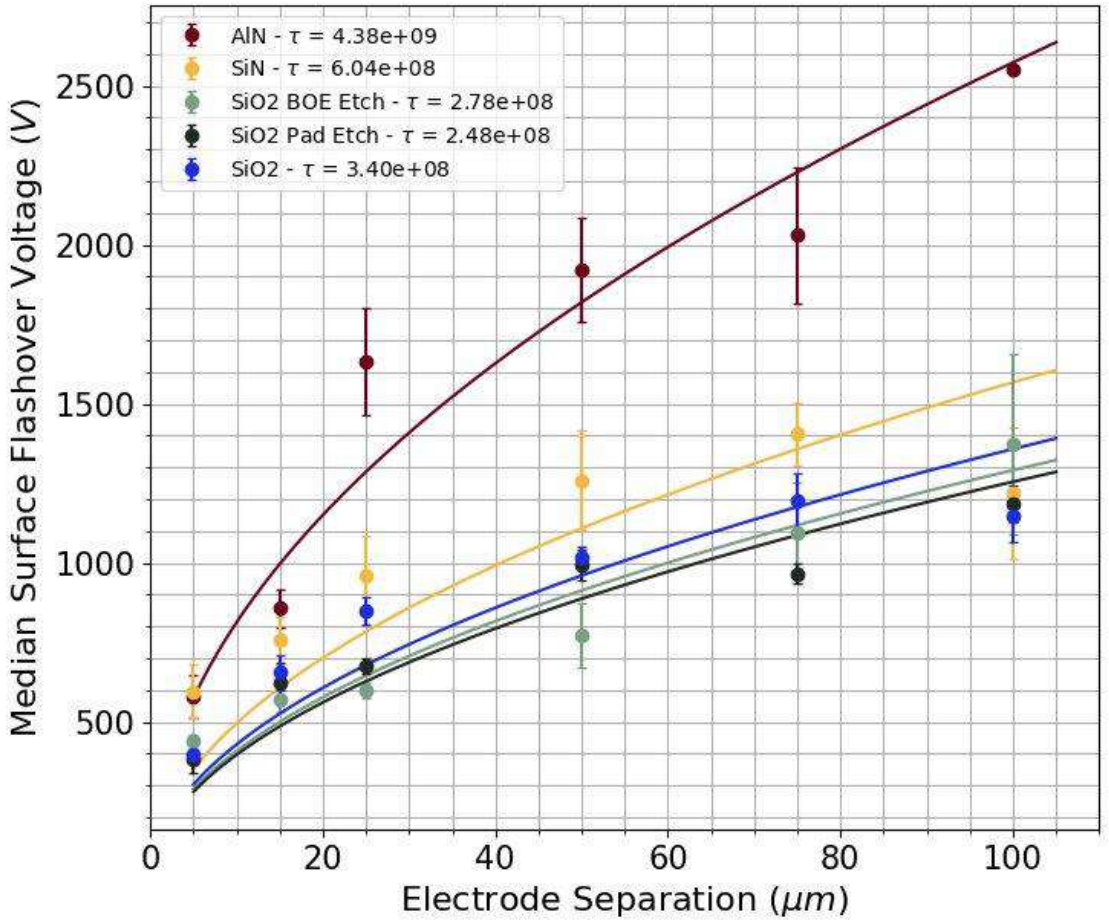
How can we make deeper ion traps?

Making ion traps with deep trap depths and long ion lifetimes



Sample damage from surface breakdown



In-vacuum surface flashover of SiN, AlN, and etched SiO2 thin films at micrometer scales
Vijay Kumar, Martin Siegele-Brown, Matthew Aylett, Sebastian Weidt, and Winfried Karl Hensinger, Mater. Quantum Technol. 6, 025501 (2026)

Pushing fidelities to the ultimate limit

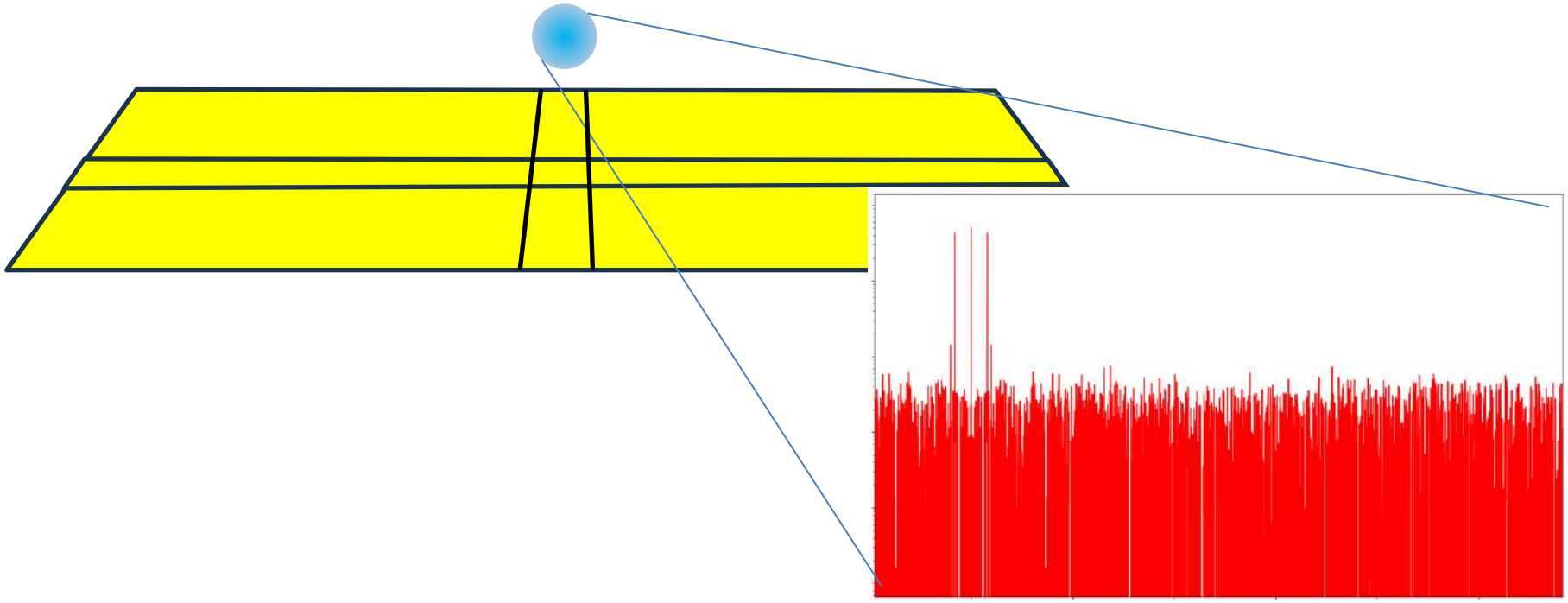
- Microwave gate can achieve world-leading fidelities, see nice demonstration by Oxford Ionics
- Path to extreme fidelities requires you to really understand system errors.
- Quantum computing, Quantum sensing and Quantum clocks are great friends!

Calibration of a Quantum Computer

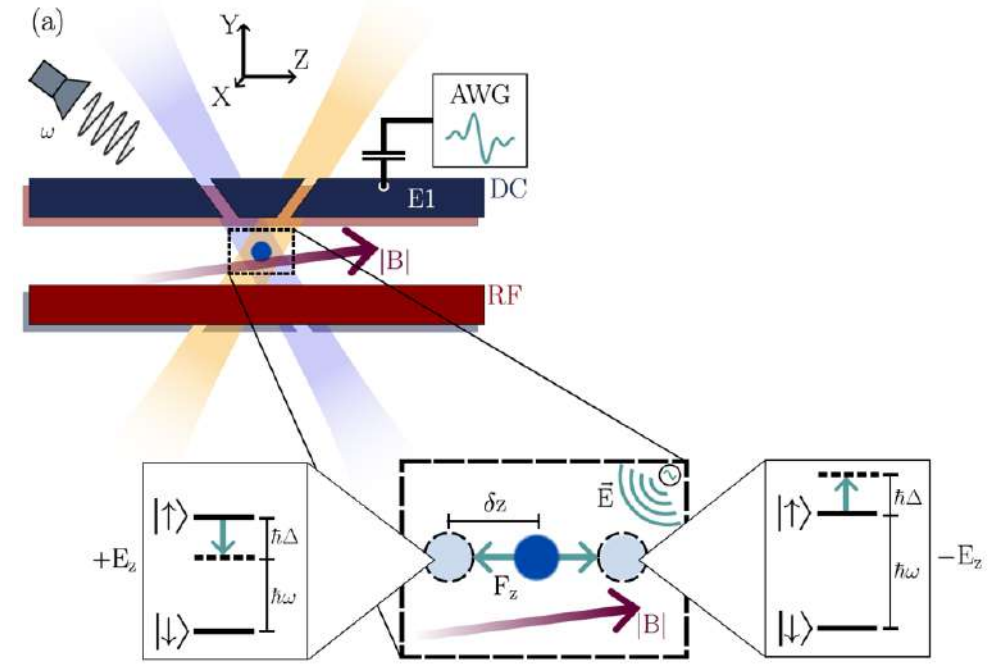
Noise spectroscopy within quantum computing systems

The noise spectroscopy techniques can be applied to trapped Ion QC systems in order to track down frequency domain noise

This mechanism can inform the dynamical decoupling techniques that may be implemented to optimise qubit gate fidelities



Sensing electric fields – but using energy level separation of spins!



Ultrasensitive single-ion electrometry in a magnetic field gradient,
F. Bonus, C. Knapp, C.H. Valahu, M. Mironiuc, S. Weidt and W.K. Hensinger, Nature Physics 21 189–1195 (2025)

How it works

Sensitivity of the spin state transition frequency to changes in the electric field:

$$\frac{\partial \omega}{\partial \mathrm{E_i}} = \frac{\partial \omega}{\partial \mathrm{B}} \frac{\partial \mathrm{B}}{\partial \mathrm{r_i}} \frac{\partial \mathrm{r_i}}{\partial \mathrm{E_i}}$$

ω: Transition frequency

Sensitivity of the transition frequency to changes in the magnetic field: $\frac{\partial \omega}{\partial \mathrm{B}}$

Magnitude of the magnetic field gradient: $\frac{\partial \mathrm{B}}{\partial \mathrm{r_i}}$

Change in position for a given change in electric field at the ion:

$$\frac{\partial \mathrm{r_i}}{\partial \mathrm{E_i}} = \mathrm{q}/\mathrm{m}\nu_\mathrm{i}^2$$

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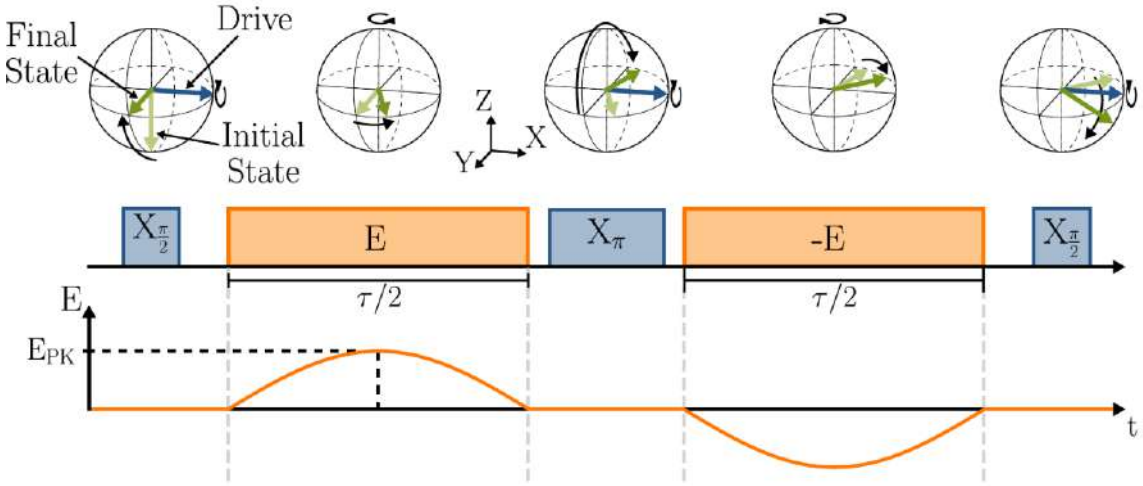
Measurement of DC and AC signals at well-defined frequencies and phases:

Hahn-echo type sequence

Measurement protocol

Hahn-echo type sequence, where the electric field signal is applied during the free procession time τ:



Measure a signal with frequency:
$\omega_\epsilon/2\pi = 1/\tau$

The total accumulated phase over the signal duration τ:

$$\phi = \int_0^{\frac{\tau}{2}} \Delta(t)dt - \int_{\frac{\tau}{2}}^{\tau} \Delta(t)dt$$ which is a function of the electric field amplitude δE(t) and τ

The electric field amplitude is linearly increased for each interaction time τ , leading to sinusoidal oscillations in the $P_\uparrow$: $P_\uparrow = \frac{1}{2} + \frac{A}{2}\sin\left(\frac{2\pi}{\kappa}E\right)$ (κ is the electric field required to induce a 2π phase rotation of the spin)

We extract the resulting maximal derivative $\frac{\partial P_\uparrow}{\partial E}$ and use this to calculate the minimum detectable electric field:

$$E_{min} = \sigma_{tot}\left(\frac{\partial P_\uparrow}{\partial E}\right)^{-1}$$ where σ_{tot} is the total readout uncertainty due to quantum projection noise and classical readout noise

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Nature Physics 21 189–1195 (2025)

Sensitivity

The sensitivity, defined as the minimum detectable signal measured over one second of averaging, is then calculated as:

$$S = E_{min}\sqrt{t_{exp}}$$

$t_{exp} = N(\tau + t_m)$ is the total experimental duration

where

N is the number of measurements of the spin state,

t_m is the overhead associated with initialisation, manipulation, and readout of the sensor

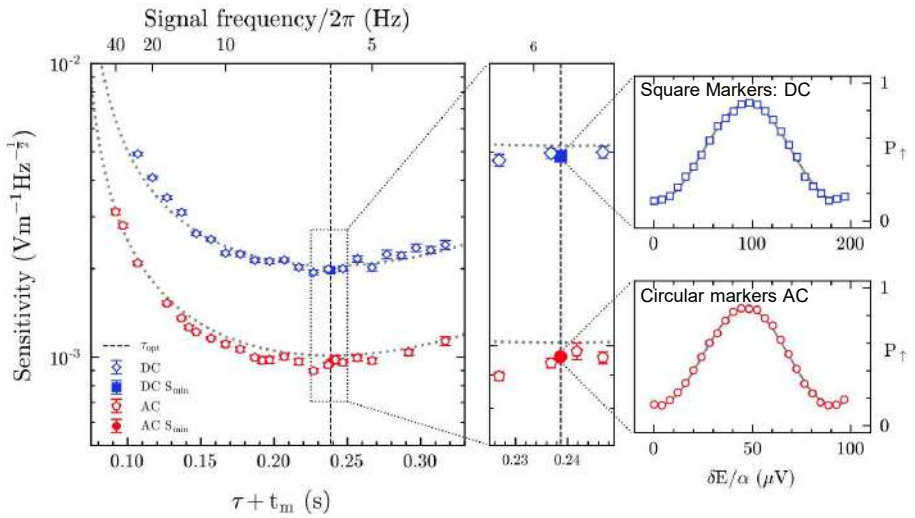
Sensitivity of AC and DC sensing sequences against shot duration, $\tau + t_m$ for evolution times ranging from τ = 25 ms to τ = 250 ms, corresponding to signal frequencies of $\omega_\epsilon/(2\pi)$ = 40 Hz to $\omega_\epsilon/(2\pi)$ = 4 Hz.

Measurements of the sensitivity near the optimal evolution time τ_{opt} = 172(2) ms.

The measured probability $P_\uparrow$ against applied electrode voltage, $\delta E/\alpha$ with a least squares fit to a sine wave.
($\delta E = 2/\pi \times E_{Peak}$ for DC sensitivity measurements at S_{min})

$$\alpha = \frac{\partial E}{\partial V} = \frac{\partial \omega}{\partial V}\frac{\partial E}{\partial z}\left(\frac{\partial B}{\partial z}\frac{\partial \omega}{\partial B}\right)^{-1}$$

Dotted grey lines on the main plot are the theoretically expected curves for DC and AC sensing.



We measure a minimum AC sensitivity:
$S^{AC}_{min} = 960(10)\times10^{-6}\,Vm^{-1}Hz^{-0.5}$
(at a signal frequency of $\omega_\epsilon = \tau^{-1} = 5.82$Hz)

We measure a minimum DC sensitivity:
$S^{DC}_{min} = 1.97(3)\times10^{-3}\,Vm^{-1}Hz^{-0.5}$

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Nature Physics 21 189–1195 (2025)

Measurement of stochastic signals that feature a discontinuous phase evolution over the measurement interval:

The quantum electric field noise spectrum analyser.

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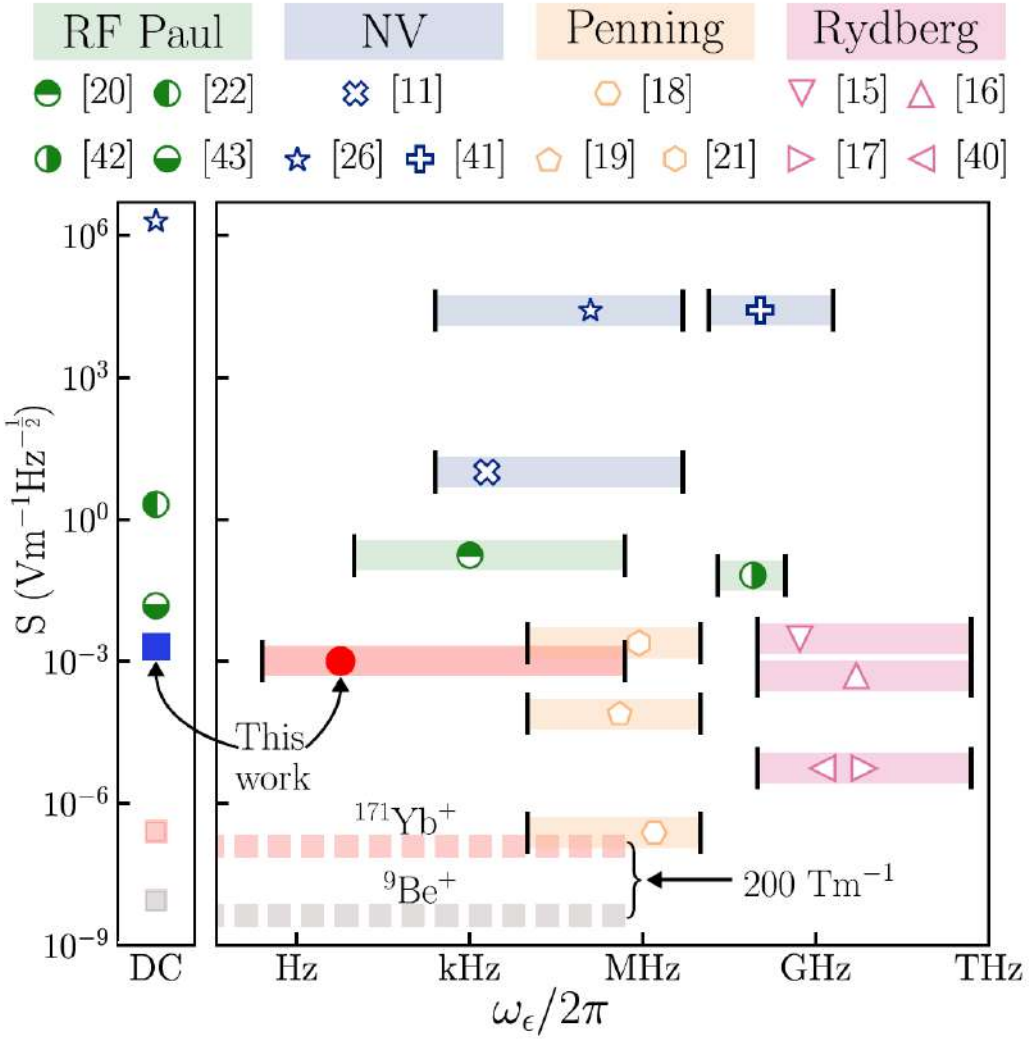
Nature Physics 21 189–1195 (2025)

How does this compare with other sensors?



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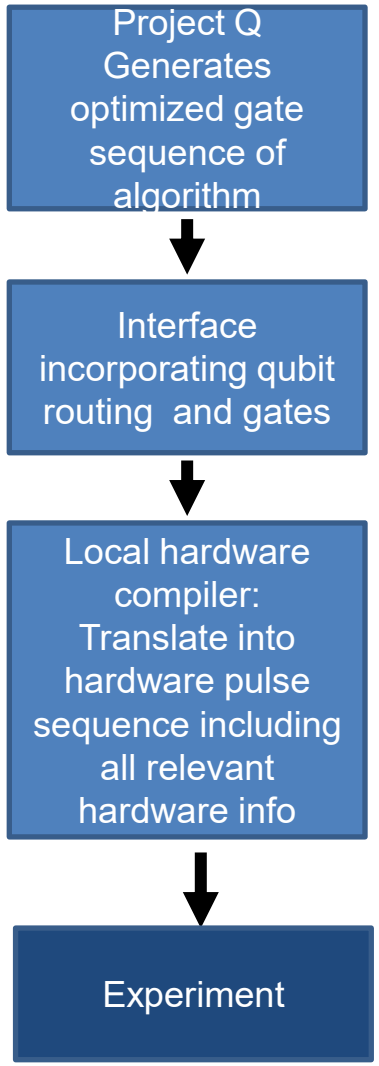
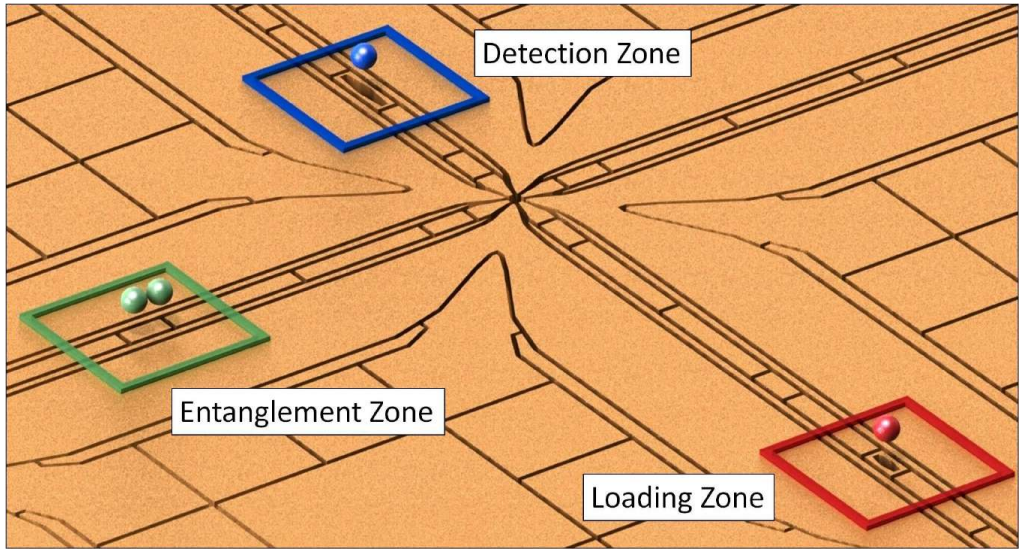
Ultrasensitive single-ion electrometry in a magnetic field gradient, F. Bonus, C. Knapp, C.H. Valahu, M. Mironiuc, S. Weidt and W.K. Hensinger,
Nature Physics 21 189–1195 (2025)

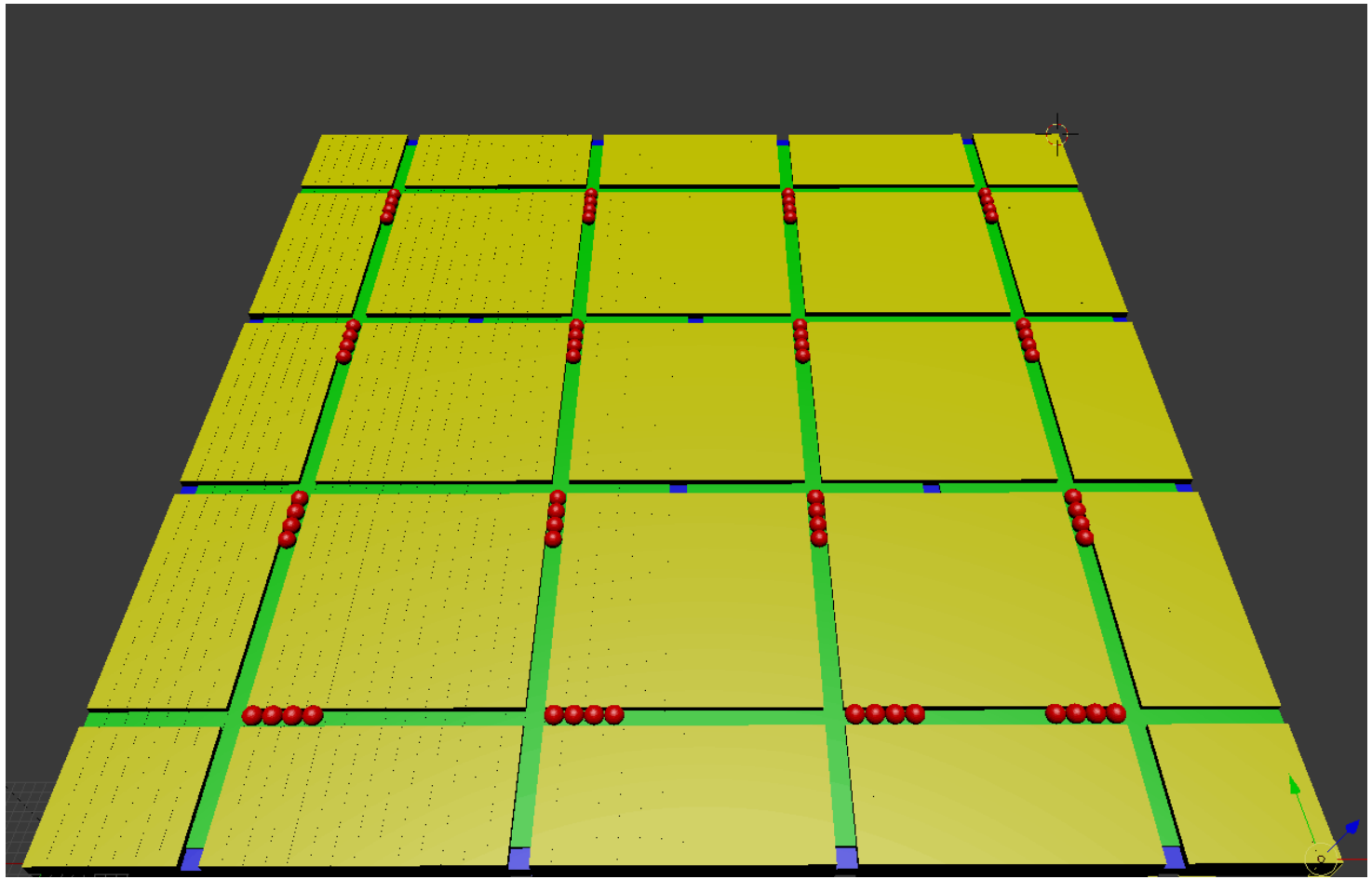
Development of the full stack for quantum computer control

- A quantum circuit is not enough to describe a large scale trapped ion quantum computer
  - The gate set is different
  - Ions can be shuttled
  - Algorithm translated on specific hardware, e.g. single X-junction trap
- New hardware syntax developed for QCCD architectures
  - Makes use of shuttling primitives
  - Includes all other required operations



Ion transport

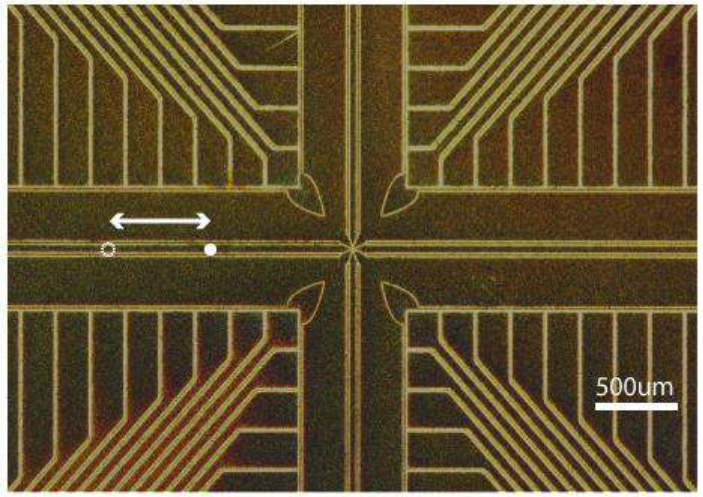




Characterisation and development of key quantum computing primitives

UNIVERSITY OF SUSSEX
BRIGHTON

Development of ‘shuttling primitives’

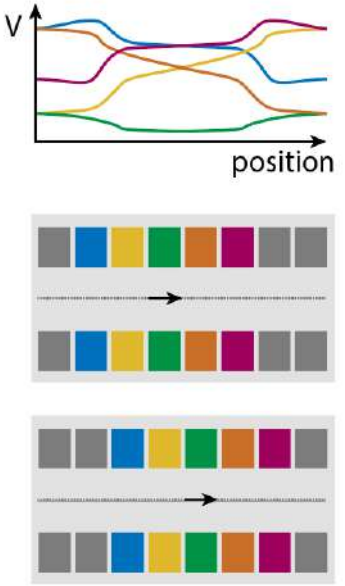


Optimised a library of ‘building block’ primitives:

- Linear shuttle
- Corner shuttle
- Split 2 ions
- Merge 2 ions
- Swap 2 ions

The shuttling part of an algorithm achieved by copy-paste with these primitives

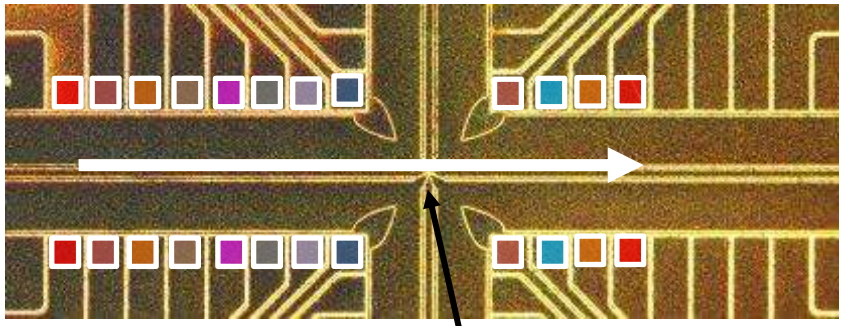
Example: Linear shuttling primitive

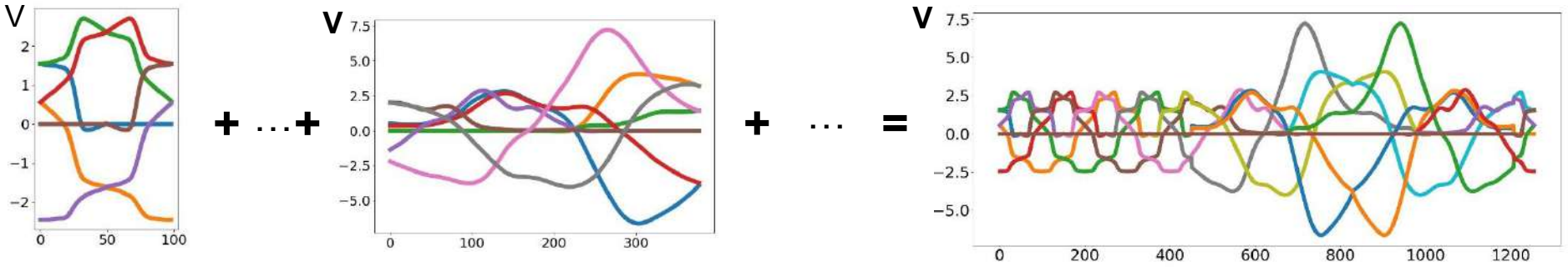


Example: Using primitives to shuttle ions through an X-junction

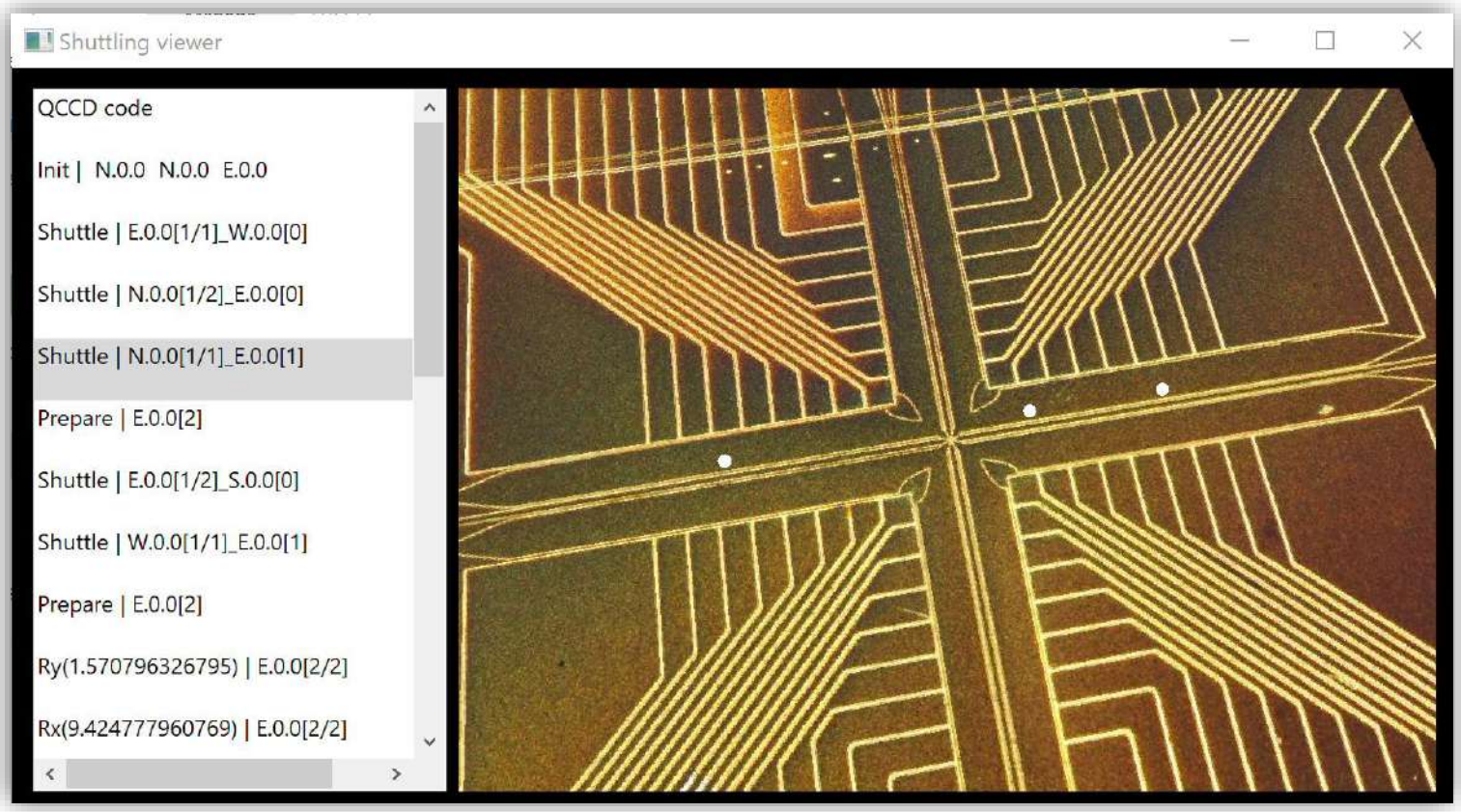
Adding primitives to obtain shuttling sequence:

- Implement concatenated waveforms for complex shuttling protocols





Second layer in the stack

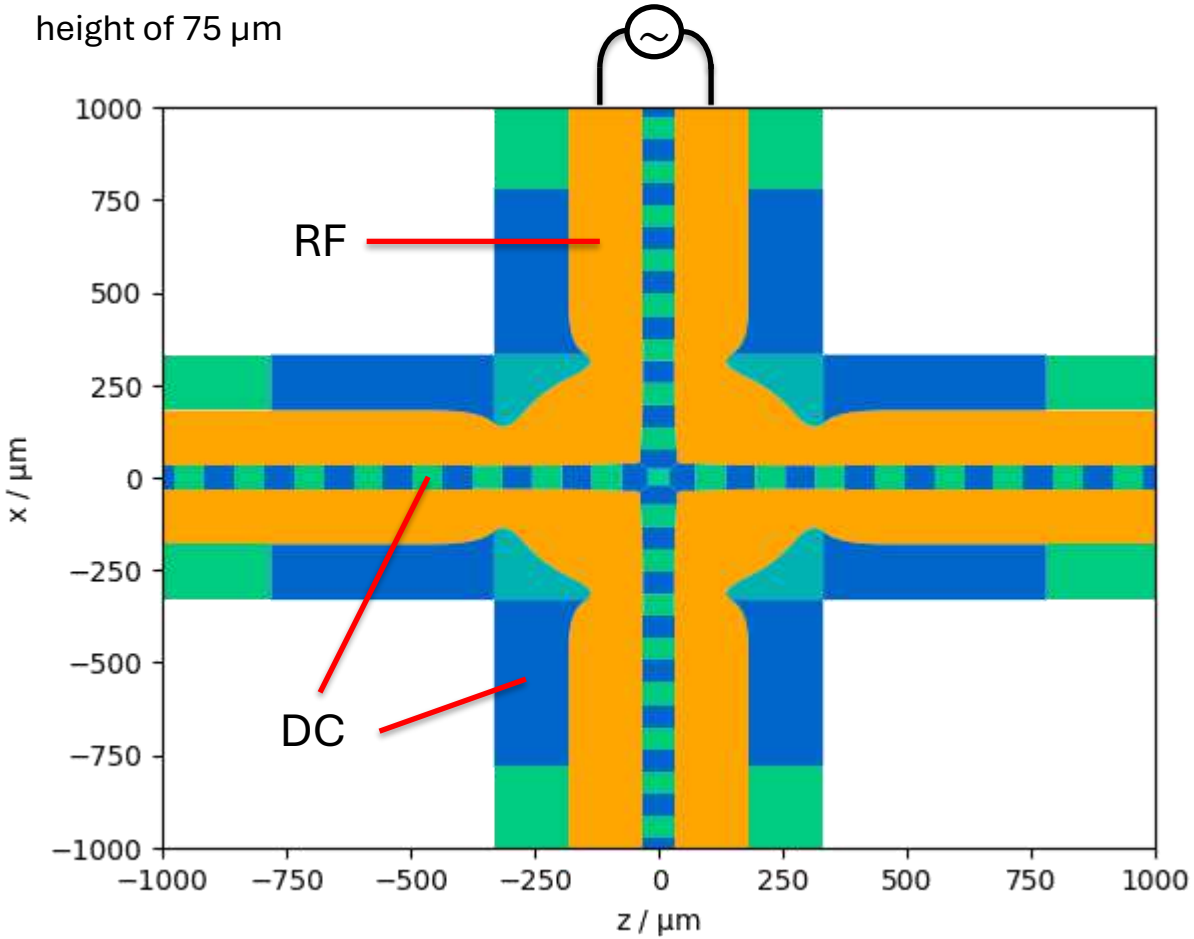


Development of ultra-rapid transport X-junctions

- Ion transport is a significant part of the overall clock cycle time
- Quantinuum showed encouraging results with traversal times of 600 microseconds
- This time scale will significantly affect the overall clock cycle time
- We are developing a new generation of X-junctions enabling ultra-rapid transport in 60 microseconds
- Our work will allow to reduce clock cycle time by around an order of magnitude!

How to design a good junction with surface traps

Gate zone ion height of 75 μm



Large RF barrier → Excess micromotion

However...

Optimising exclusively for small RF barrier → Low secular frequencies $\omega_0, \omega_1, \omega_2$

Get low excitations using...

Transport along surface of constant total confinement (CTC) [1,2] given by → Optimise junction along CTC path

$$\sum_i \omega_i^2 \propto \mathrm{Tr}\left((\partial^2 \phi_{\mathrm{RF}})^2\right) = \text{const.}$$

CTC path used in first demonstration of low excitation corner transport on a surface trap at Quantinuum [2].

[1] Chi. Zhang et al., New J. Phys. 24 073030 (2022)
[2] W. Burton et al., Phys. Rev. Lett. 130, 173202 (2023)

Diabatic corner transport

The goal of shuttling an ion such that it ends up in the ground state of its final Hamiltonian can be understood as an optimization problem, with motional excitation as the figure of merit.

Instead of finding a suitable protocol as result of an optimization, one can also design suitable shuttling protocols more directly with the framework of quantum invariants.

$$\frac{\partial \hat{I}(t)}{\partial t} = i\left[\hat{I}(t), \hat{H}(t)\right]$$

Optimal Control with a Multidimensional Quantum Invariant
Modesto Orozco-Ruiz, Selwyn Simsek, Sahra A. Kulmiya, Samuel J. Hile, Winfried K. Hensinger, and Florian Mintert,
Physical Review A 108, 022601 (2023)

Deriving optimal junctions

Cost function
$C(w_1, w_2, \dots)$

Weights

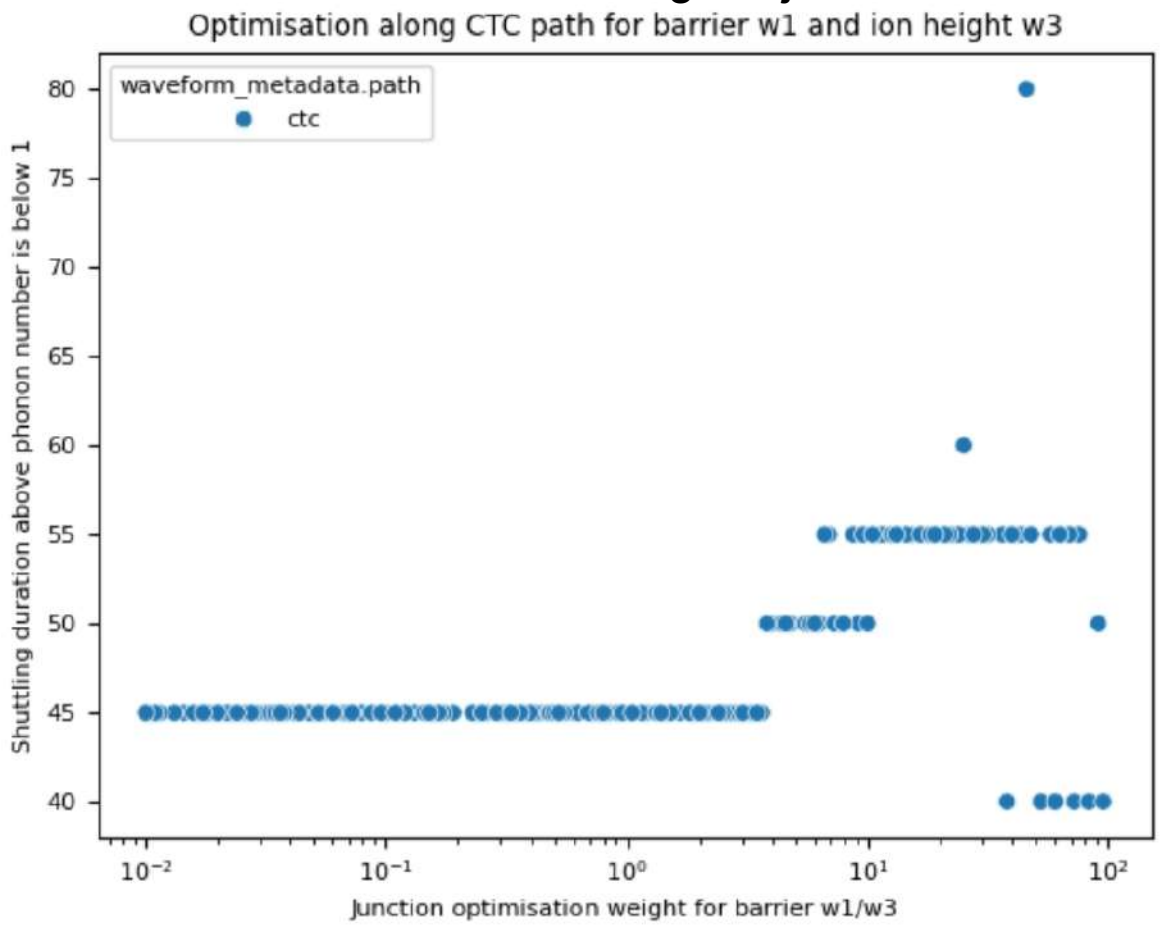
Junctions

Durations

Waveforms

Phonon excitation from classical simulations [5]

Left turn through X-junction



1 MHz axial secular frequency

Large RF barrier, low drop in ion height

Small RF barrier, high drop in ion height

Fixed confinement

[5] M. Marciante, et al., Phys. Rev. A, 82, 033406 (2010)

Deriving optimal junctions

Cost function
$C(w_1, w_2, \dots)$

Weights

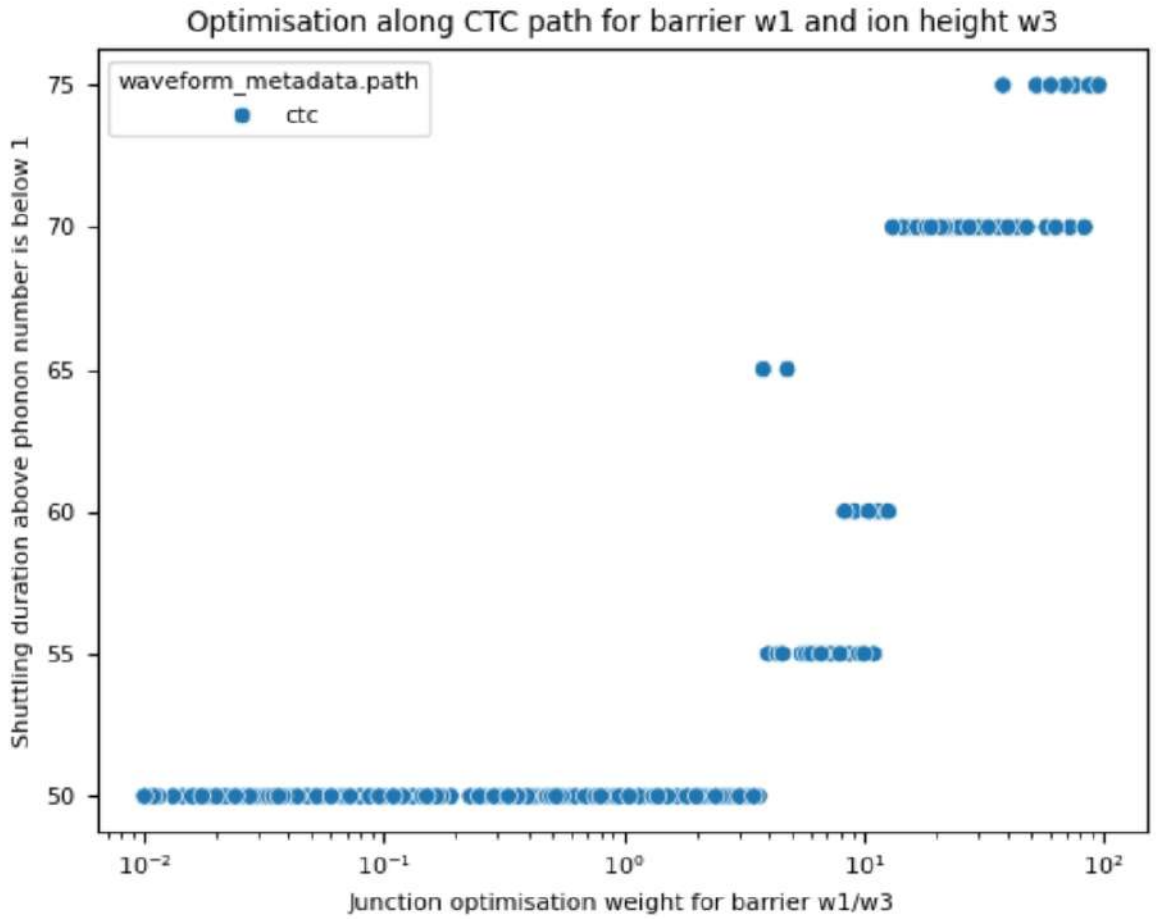
Junctions

Durations

Waveforms

Phonon excitation from classical simulations [5]

Straight through X-junction



1 MHz axial secular frequency

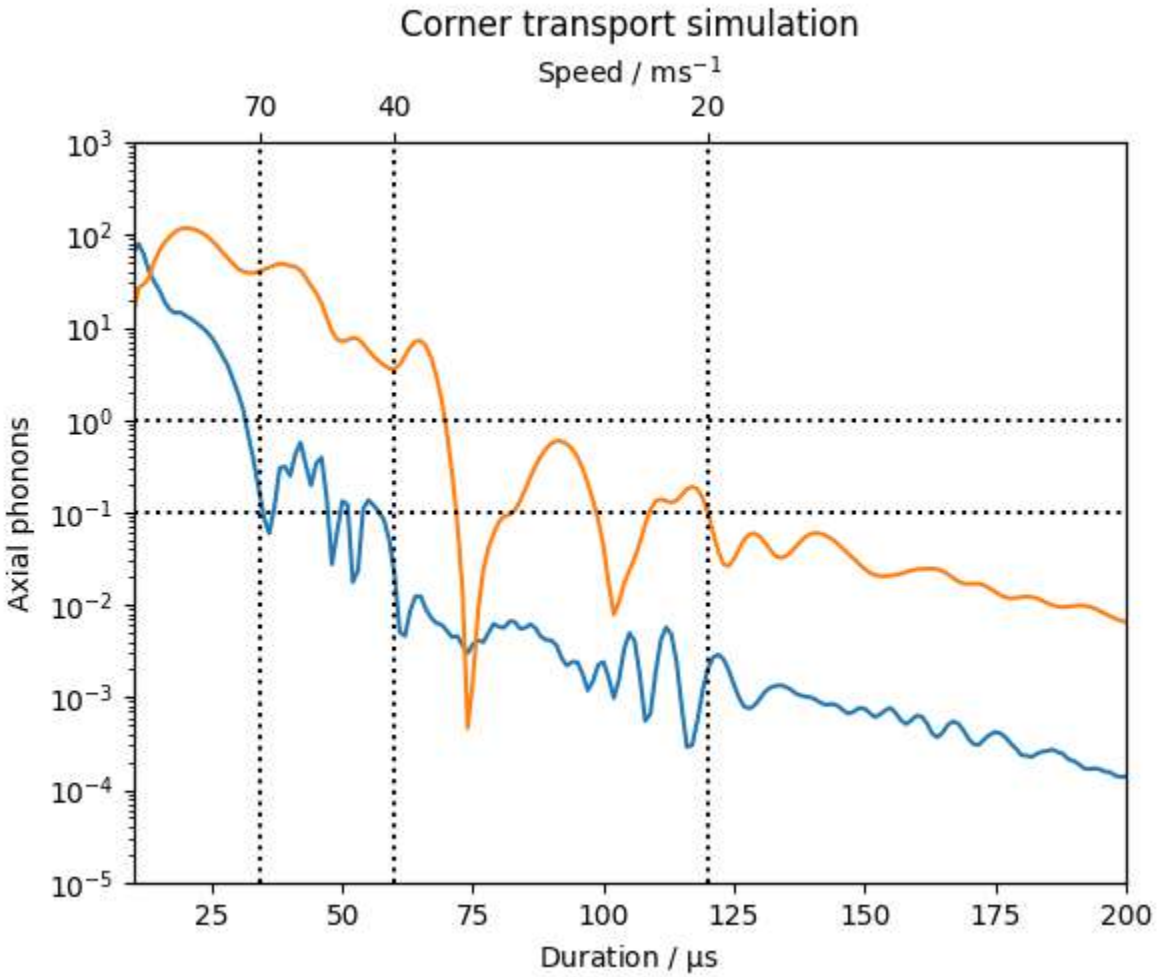
Large RF barrier, low drop in ion height

Small RF barrier, high drop in ion height

Fixed confinement

[5] M. Marciante, et al., Phys. Rev. A, 82, 033406 (2010)

Promising junction candidate



- Initial and final positions each 1200 µm from centre
- 1.3 MHz axial secular frequency
- Ion starts with zero excitation
- Speed stated corresponds to linear section on the path
- Quantinuum: 600 µs, our result < 60 µs

Ion motion in the junction is typically modelled using the pseudo potential, which follows from:

2nd order Taylor expansion of the potential

+

Small 2nd derivatives

We can construct better models using:

Excess micromotion ansatz (with Fourier decomposition)

+

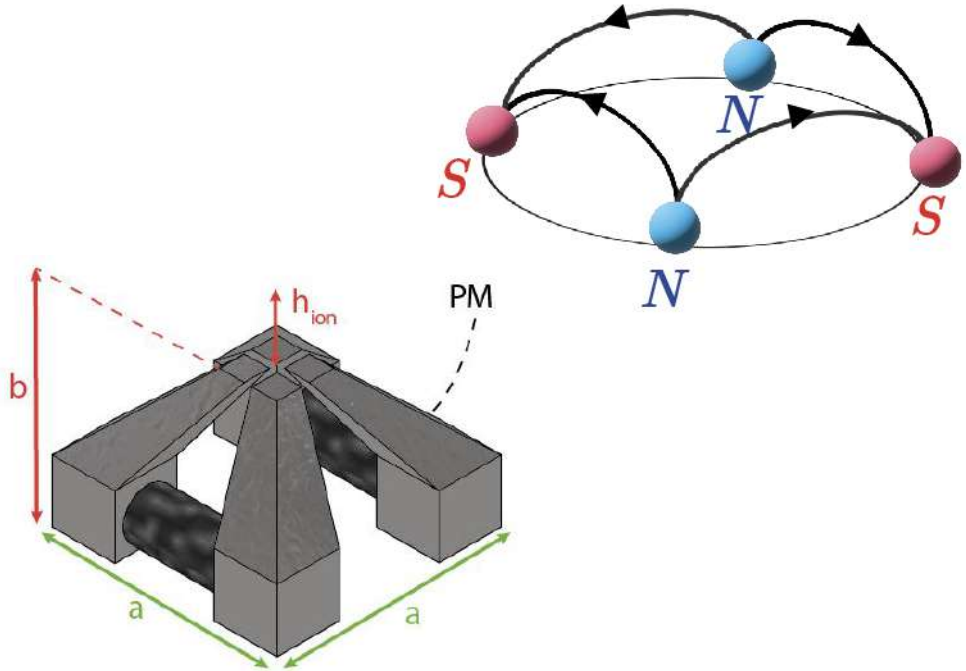
The exact potential at the instantaneous position

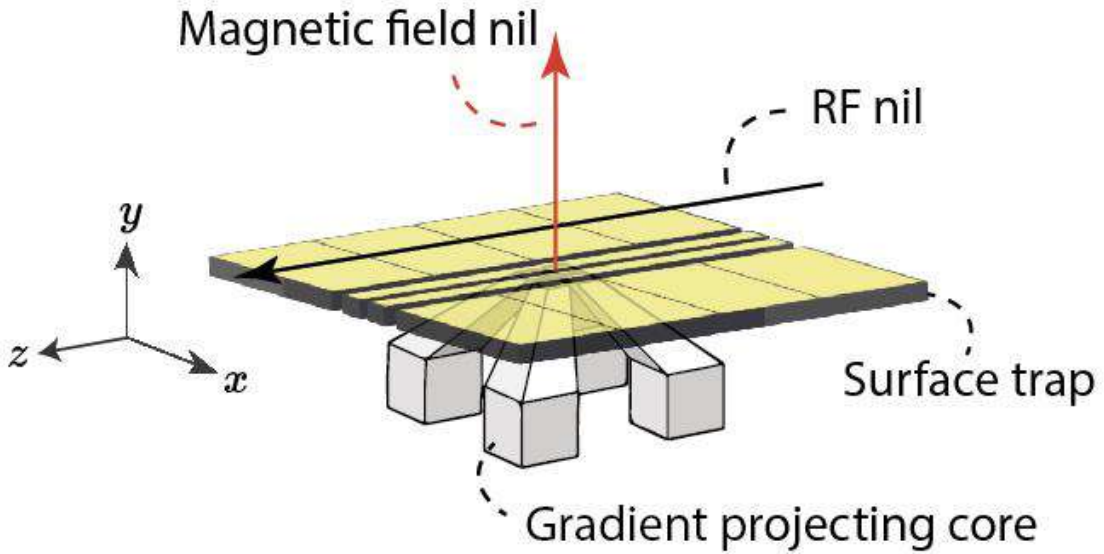
A new way to create magnetic field gradients

What about a billion qubit quantum computer, how could we reduce power dissipation close the ion because of the current carrying wires?

Is it possible to remove noise on the current carrying wires?

Ring Quadrupole Arrangement (RQA) gradient-projecting core

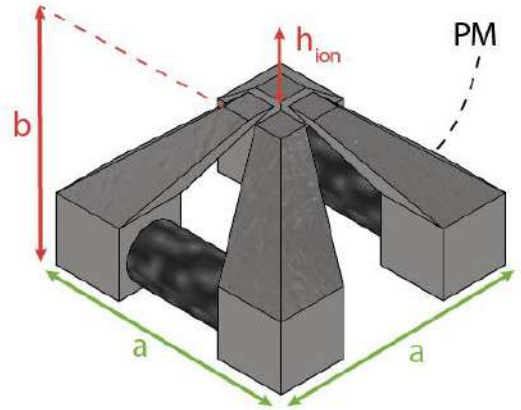


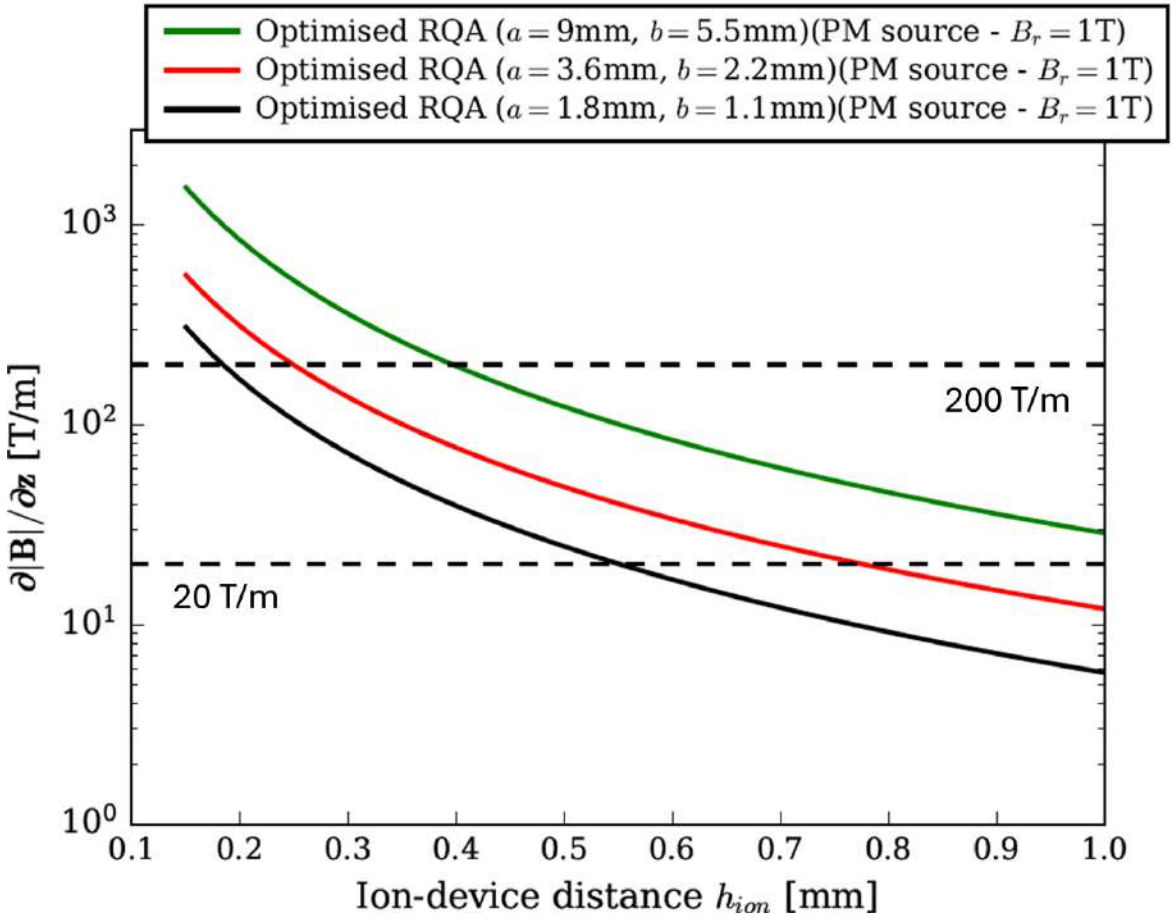


The Saturable Electronic Reluctance Switch: Switchable ow-power and low-noise generation of magnetic fields using permanent magnets,
P.D. Taylor-Burdett, C.A. Burhan, S. Mason, F.R. Lebrun-Gallagher, S. Weidt, W.K. Hensinger, arXiv:2605.05158 [quant-ph] (2026)

Achievable gradients

- COMSOL simulations for scaled-down RQA cores.
- Magnetised with proportionately scaled-down permanent magnets (PM)





The Saturable Electronic Reluctance Switch: Switchable ow-power and low-noise generation of magnetic fields using permanent magnets,
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So we have a large gradient with very low noise because it’s a permanent magnet.

But can we turn it on or off?

We invented a switchable permanent magnet device that does not require altering the magnet's magnetisation* :

Saturable Electronic Reluctance Switch (SERS Device)

* Altering a magnet's magnetisation typically requires large field pulses and produces excessive power dissipation in high frequency applications.

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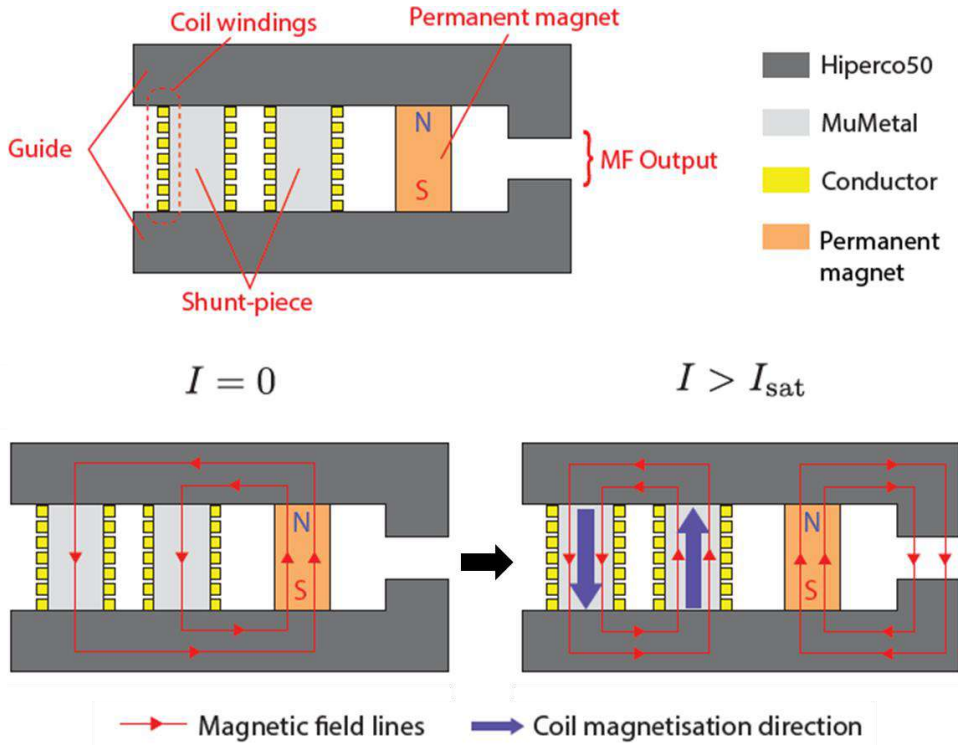
The SERS Device



$I = 0$ (OFF)

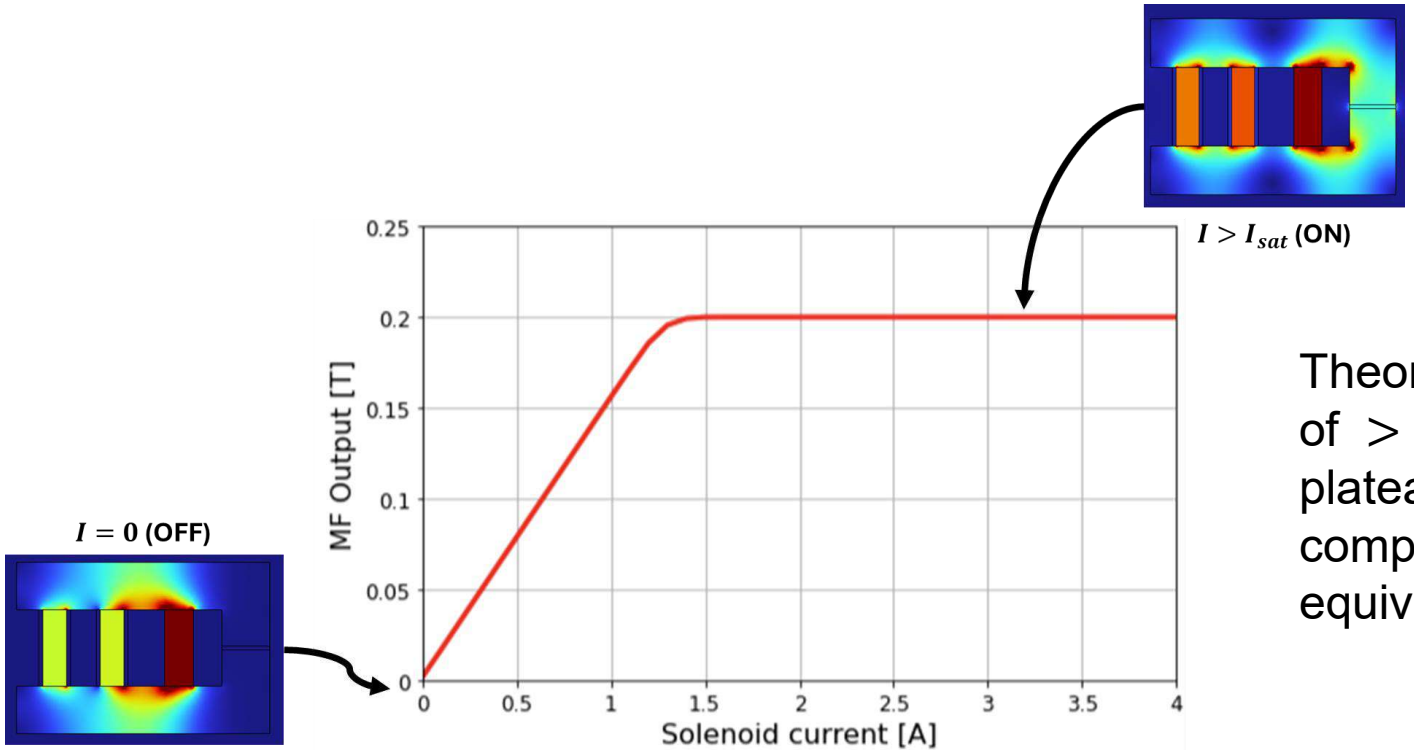
- PM flux is shunted away from the air-gap by ***low-reluctance*** shunts.

$I > I_{sat}$ (ON)

- Both shunts are saturated by the coils and become ***high-reluctance***.
- PM flux is directed to the operating air gap.
- Anti-parallel shunt and coil magnetisations contributions cancel.

The Saturable Electronic Reluctance Switch: Switchable ow-power and low-noise generation of magnetic fields using permanent magnets,
P.D. Taylor-Burdett, C.A. Burhan, S. Mason, F.R. Lebrun-Gallagher, S. Weidt, W.K. Hensinger, arXiv:2605.05158 [quant-ph] (2026)

SERS device magnetic-field output



Theoretical increase in gradient stability by a factor of $> 10^5$ vs CCWs by analyzing the gradient of the plateau at the operating current of 2.5 A and comparing this to a solenoid generating the equivalent magnetic field.

The Saturable Electronic Reluctance Switch: Switchable ow-power and low-noise generation of magnetic fields using permanent magnets,
P.D. Taylor-Burdett, C.A. Burhan, S. Mason, F.R. Lebrun-Gallagher, S. Weidt, W.K. Hensinger, arXiv:2605.05158 [quant-ph] (2026)

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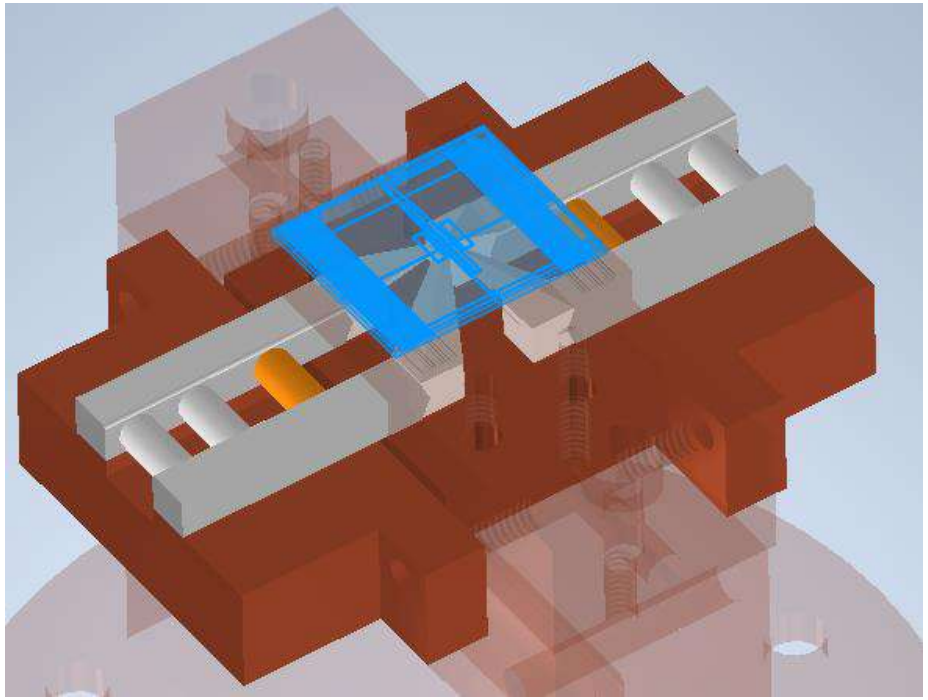
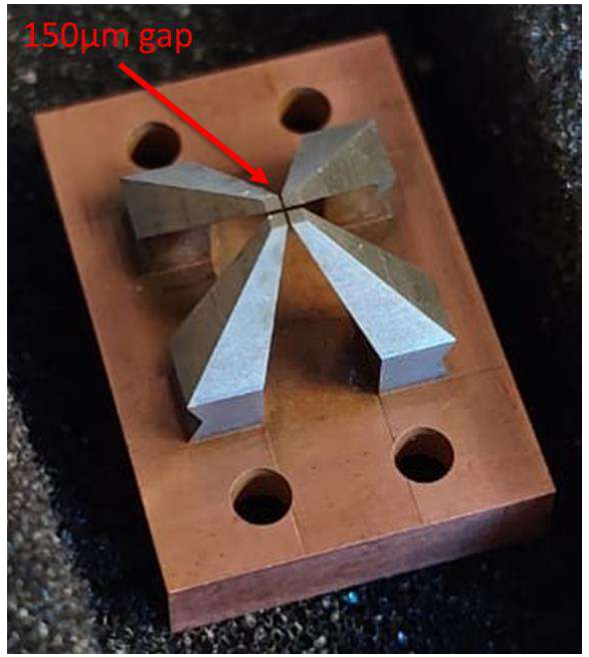
The prototype device



Design of in-vacuum prototype (Ion trap in blue)



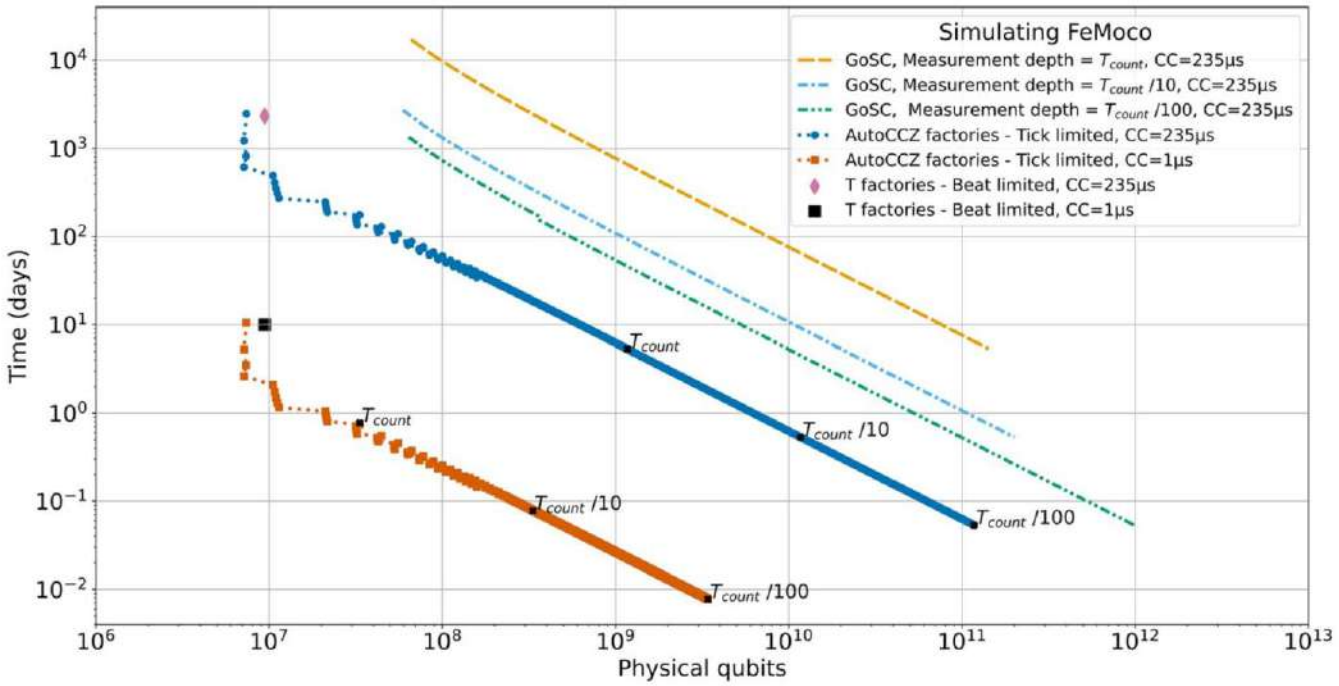
9 x 9 x 5.5 mm RQA core prototype

The Saturable Electronic Reluctance Switch: Switchable ow-power and low-noise generation of magnetic fields using permanent magnets,
P.D. Taylor-Burdett, C.A. Burhan, S. Mason, F.R. Lebrun-Gallagher, S. Weidt, W.K. Hensinger, arXiv:2605.05158 [quant-ph] (2026)

So what about the relatively slow clock speed of trapped ions?

Time to reach quantum advantage as a function of clock cycle time and number of qubits

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



- 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.
- Slower clock cycle time makes decoding and classical compute requirements much easier.

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)

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How are we going about building practical quantum computers?

Universal Quantum

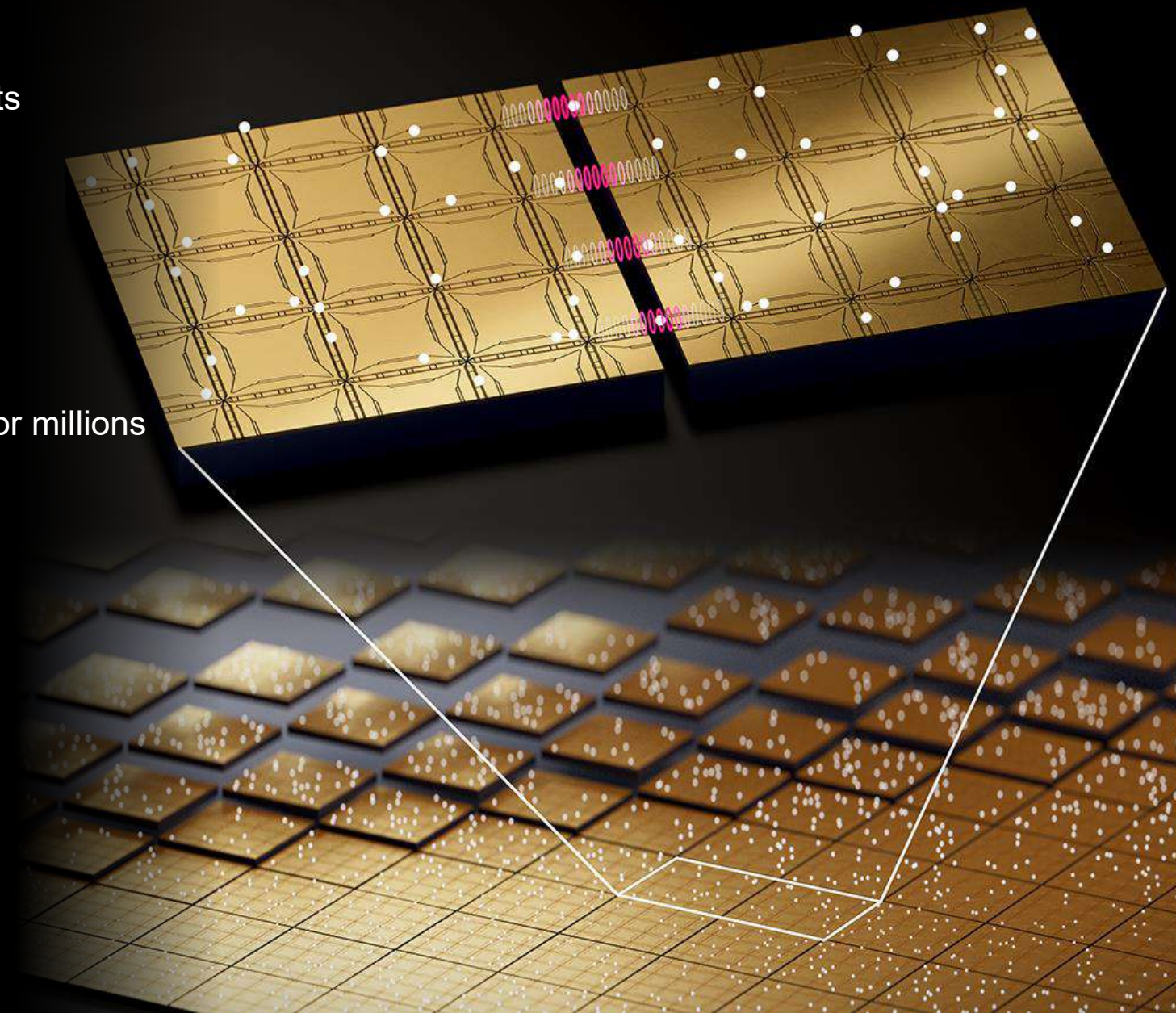


A research group cannot construct practical quantum computers, this requires a company in order to produce reliable engineering devices beyond proof-of-principle.

Universal Quantum, based in UK, Germany, Denmark and US, is a full stack quantum computing company, with a team of more than 100, on a mission to develop practical commercial large scale quantum computers based on trapped ions along with relevant application and software solutions.

UQConnect enables powerful chip scaling

- Stable, high-performing trapped-ion qubits
- Shuttling architecture for long-range, full connectivity
- Simple and scalable microwave control for millions of qubits
- Fast modular scaling at 2,424 links/sec between iQPUs
- Reliable chip connections with 99.999993% fidelity
- Built for utility: unlimited scalability through chip tiling



The iQPU is a fully integrated processor.

(using standard Silicon foundry processes) to deliver our architecture

- Worlds largest and most advanced quantum ion trap chip @ **>400MM2**
- Production on **200MM** commercial foundry line
- **One design foundation** for single and multi-chip quantum computers
- Advanced **CMOS interposer** technology
- Designed using **industry standard tools** with modified PDK at commercial fab





Nordics

- Multiple partnerships established, particularly in the algorithm and Life Sciences spaces
- Legal entity based in Denmark

US

- Located in Palo Alto, California
- Established US entity

UK

- Global headquarter in south of UK
- Global lab facilities for UQ
- Multiple commercial projects sold
- Integral part of the ecosystem and government decision-making process

Germany

- Universal Quantum Deutschland based in Hamburg
- Building two quantum computers for DLR
- Largest global single company contract in the quantum industry (EUR 67M)

Japan

- MOU signed with AIST

Singapore

- Collaborations with multiple key players

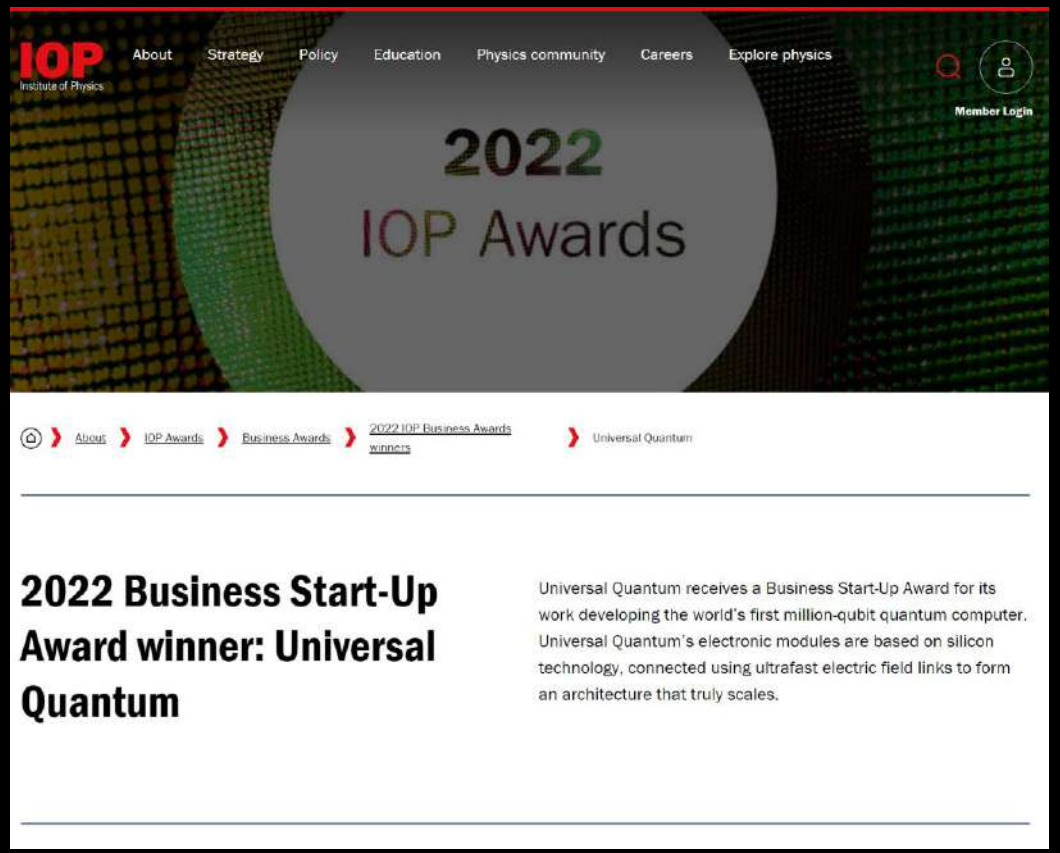
Australia

- Investment deal complete

To deliver on our mission, we are investing in global centres of excellence, harnessing the very best pools of expertise

Validation

We have been awarded the 2022 Institute of Physics Business Start up award.







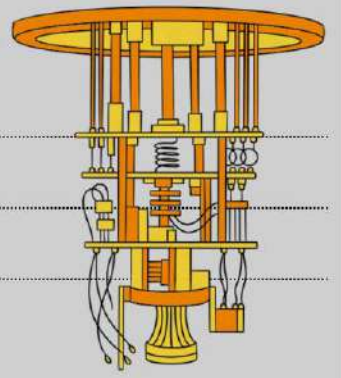
Validation

Bloomberg identified us as one of the 2023 Top 25 UK Startups to watch.





Universal Quantum



FOUNDERS
Winfried Hensinger and Sebastian Weidt

ESTABLISHED
2018

BUSINESS
Taking quantum computing up to 11

Quantum bits, or qubits, are the building blocks of quantum computers and are measured in dozens or, rarely, hundreds. International Business Machines Corp. wants to build a 100,000-qubit machine within a decade. But this University of Sussex spinoff isn't impressed. It says it will build a 1 million-qubit computer to help humanity solve some of its most complex challenges.

Universal Quantum Ltd. won one of the largest-ever government quantum computing contracts last year when the German Aerospace Center awarded it a €67 million ($71 million) deal.

"But the country's startups showed up in force. More than 1,500 applications came in for this inaugural list. The final 25 companies were created by people with a vast array of experiences and backgrounds from all over the UK. "

These Are the Top 25 UK Startups to Watch This Year

Bloomberg unveils innovative companies reinventing medicine, entertainment, finance, autonomous driving, data analysis and more.

By Isabella Ward, Helen Chandler-Wilde and Amy Thomson
Illustrations by Rosie Barker
24 October 2023 at 05:01 BST

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Gift this article

Bloomberg set out to find 25 UK startups that were thriving in 2023, and we were a little nervous. The year did not begin well, as we noted when we kicked off the search in June. Fears about a recession were rising, expenses were going up, and the venture capital firms and investors that provided fuel for the country's startups had scaled back. Arm Holdings Plc, the Cambridge-born semiconductor designer that's put its technology in almost every smartphone, decided to list in New York, in what felt like an existential crisis for London's 300-year-old exchange.

But the country's startups showed up in force. More than 1,500 applications came in for this inaugural list. The final 25 companies were created by people with a vast array of experiences and backgrounds from all over the UK. They're all working on new, innovative ideas that have caught the eye of investors and customers and impressed us with their plans to improve everything from the environment to kids' entertainment.

Validation

Universal Quantum has been placed in the 2024 Sunday Times Best Places to Work List.



THE TIMES
THE SUNDAY TIMES

View today's edition

UNIVERSAL QUANTUM

Staff are encouraged to think big at this spinout from the University of Sussex, which is building quantum computers that help industries overcome challenges such as energy efficiency. The Brighton-based enterprise, which was awarded £53.5million last year by the German Aerospace Center to build two quantum computers, gives its 56 employees personal development budgets. An annual wellbeing retreat helps them to recharge their batteries.

universalquantum.com

Universal Quantum is part of the 2026 Tech Nation Future Fifty cohort and announced by Chancellor Rachel Reeves





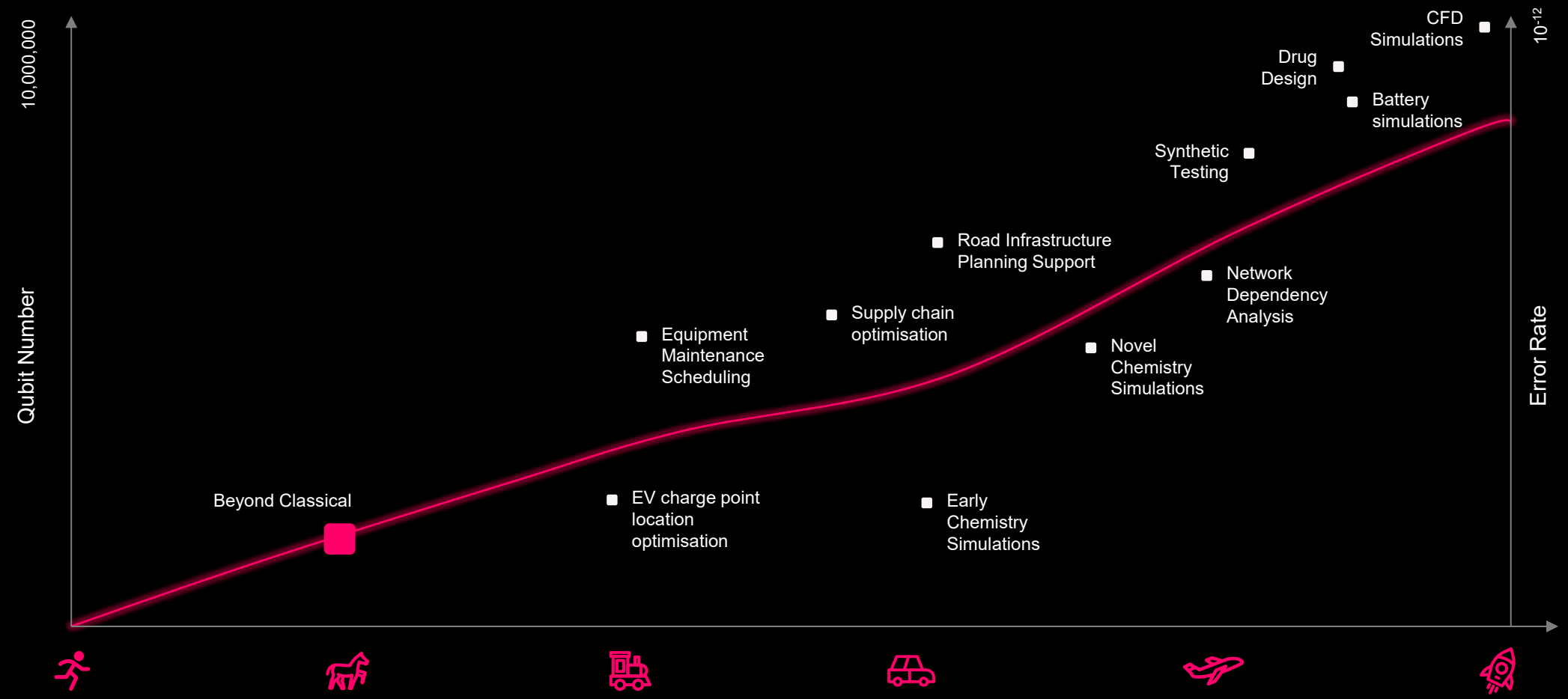
25 high-impact scaleups across AI, healthtech, aerospace and climatetech join Tech Nation's prestigious Future Fifty programme, the UK's flagship scaleup initiative, which counts 35% of the nation's unicorns amongst its alumni.

Validation



DCVC
FIRGUN ventures
hoxton ventures
NAUTAPITAL
iqt IN-Q-TEL
MAIN SEQUENCE
VILLAGE GLOBAL
TVC
LAROCA
7
INTEGRAL
IAG CAPITAL PARTNERS
INVUS
HOSTPLUS
edbi

Quantum computers currently don't have the scale to solve ambitious challenges



So what do we know?

- Trapped ions are a mature platform to build practical quantum computers
- Microwave technology helps scaling to millions of qubits
- Fully electronic quantum computing modules:
  Gates are executed by the application of a voltage to a chip with fidelity above the fault-tolerant threshold
- Our electric field link technology enables a fully modular quantum computing approach with large bandwidth and low-error connections between quantum computing modules.
- A new generation of microchips and ways to generate magnetic field gradients will enable efficient use of the technology at the million qubit scale.

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

UNIVERSITY OF SUSSEX BRIGHTON

Want to help?



Hamburg. Germany







Brighton, UK



Universal Quantum:
We are recruiting engineers, quantum physicists (experiment and theory), as well as many operational roles in Brighton, UK and Hamburg, Germany.

Research Group:
We are recruiting PDRAs and PhD students



