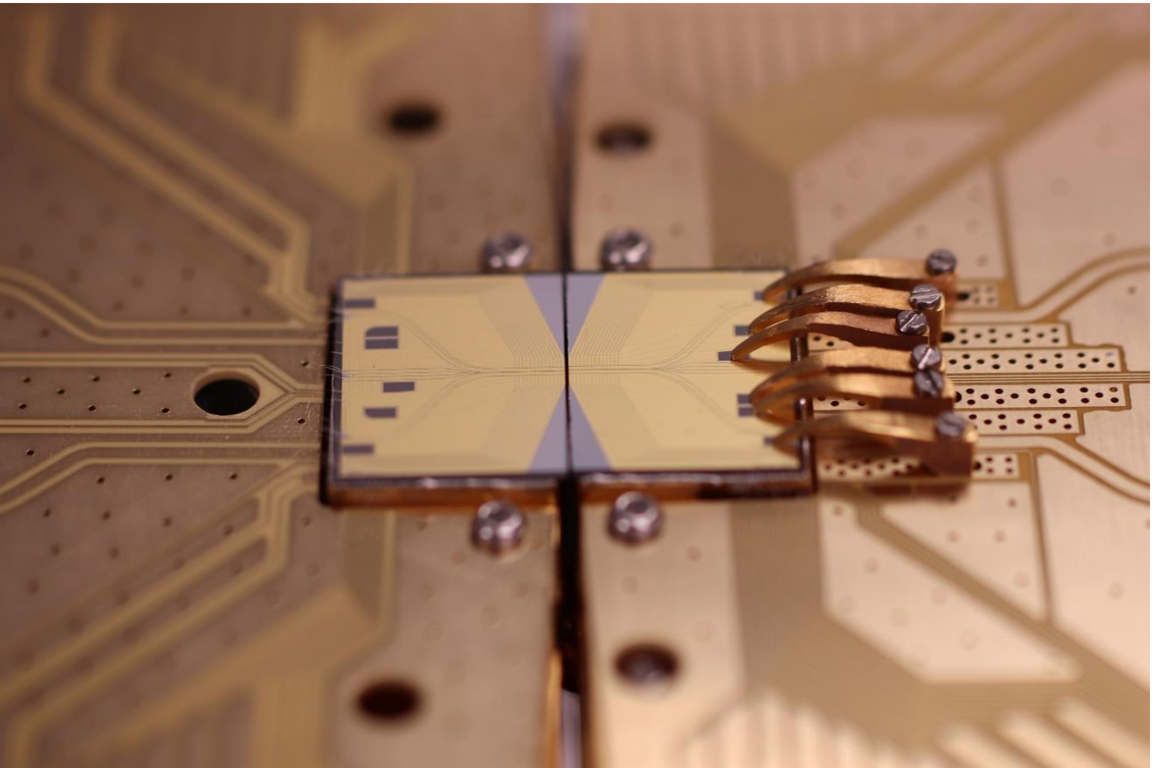
Building quantum computers for disruptive industry applications



Winfried K. Hensinger

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Sussex Centre for Quantum Technologies

Universal Quantum Ltd

Universal Quantum Deutschland GmbH

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

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

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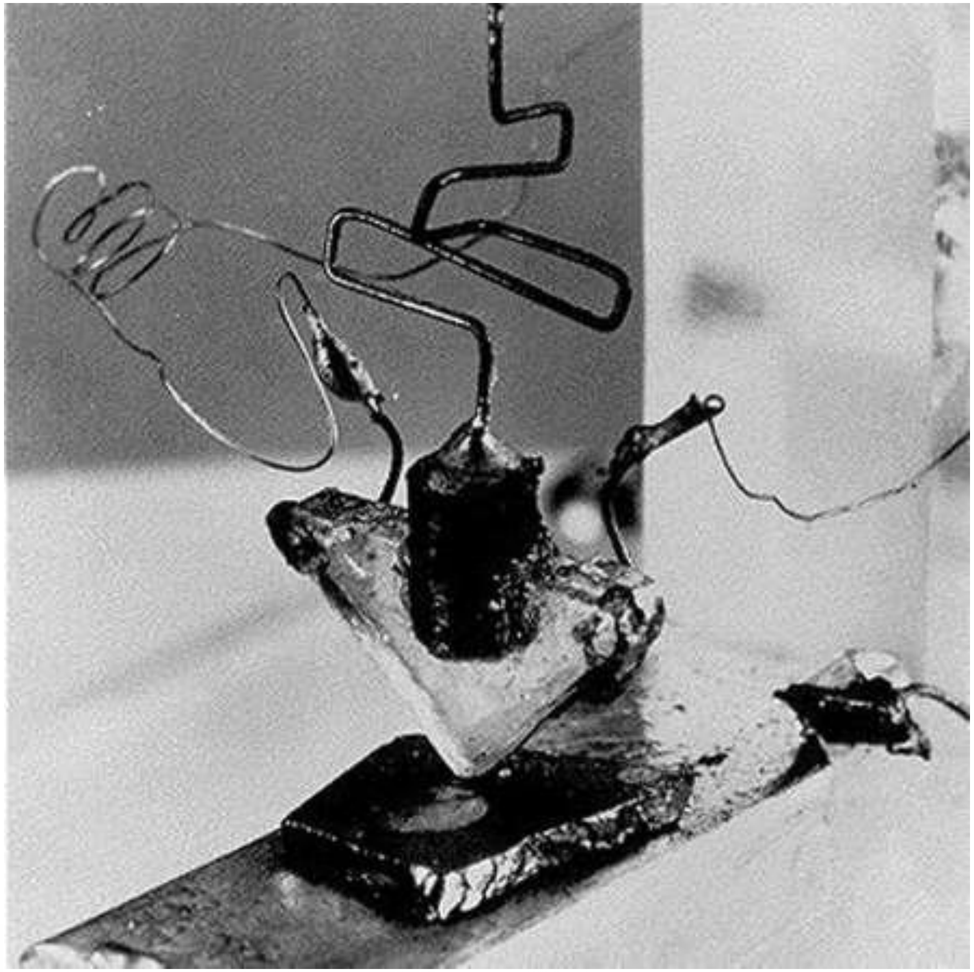
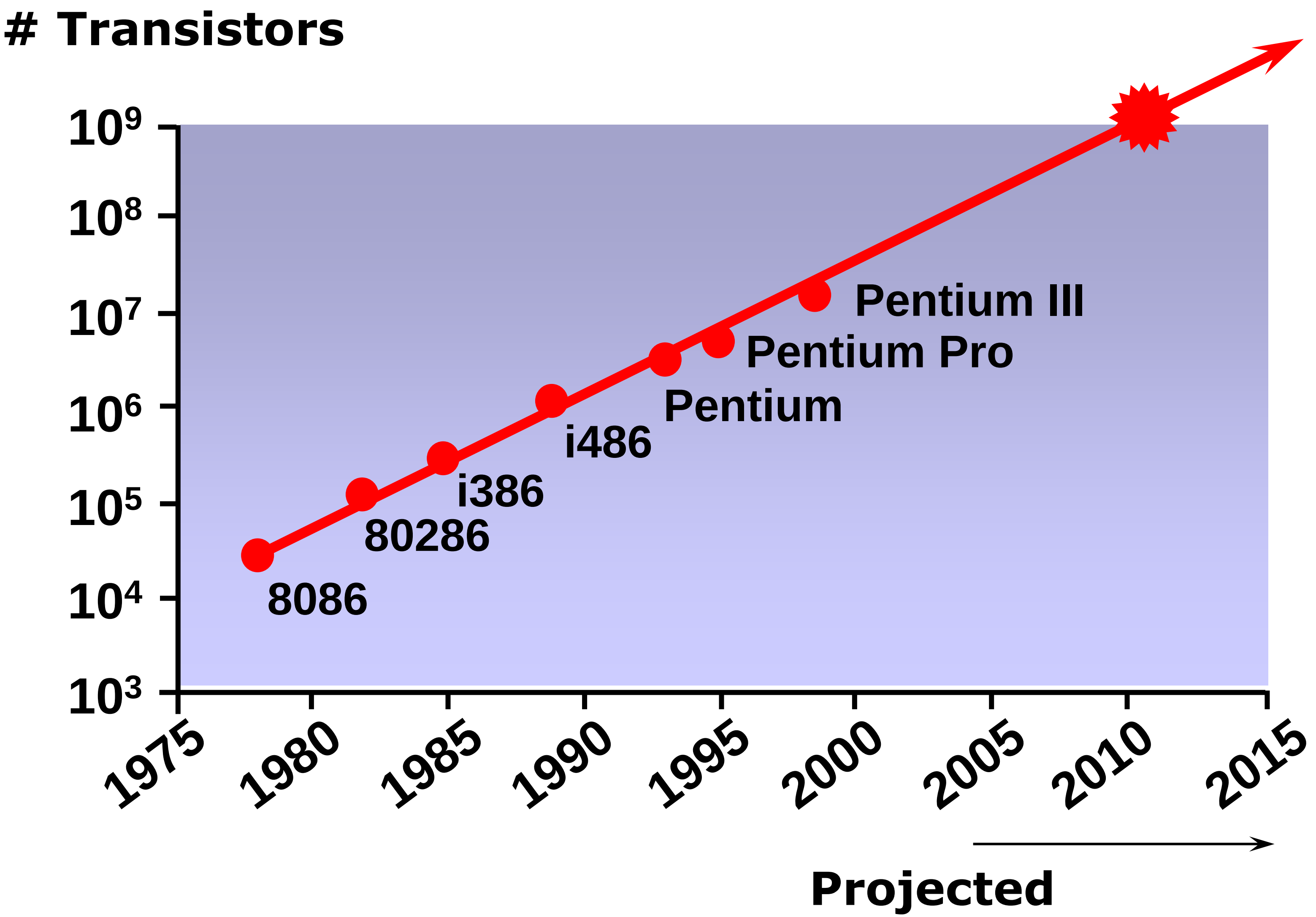
A transistor



The first solid-state transistor (Bardeen, Brattain & Shockley, 1947)

The end of Moore's law



Source: Intel

The end of Moore’s law

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CNET › Tech Industry › Keeping up with Moore's Law proves difficult for Intel

Keeping up with Moore's Law proves difficult for Intel

For the last 40 years, Moore's Law predicted that processors could double in power every two years. Intel acknowledges that it's on more of a two-and-a-half-year cycle.

Source: CNET

Very small transistors?

"There's Plenty of Room at the Bottom"
(1959 APS annual meeting)

Richard Feynman

"When we get to the very, very small world – say circuits of seven atoms - we have a lot of new things that would happen that represent completely new opportunities for design. **Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics…**"

Quantum physics weirdness

- A mechanical object being at two places at the same time
- An atom moving forward and backward simultaneously
- An object tunnelling through a solid wall
- Entanglement – spooky action at a distance

Quantum Computing

- Quantum computers form a new type of technology little to do with conventional computing.

- Development of quantum computers may follow a similar trajectory as the development of computers.

So what can a quantum computer do?

It can solve certain problems which would take the fastest supercomputer billions of years to compute.

It changes the actual scaling how long such a problem takes to compute.

Known quantum algorithms

Disruptive for a variety of industry sectors such as finance, pharmaceuticals and chemical industry

Algorithms available for:
Search, Factoring, Optimization, Machine Learning, ….

Listing of most known algorithms:
http://math.nist.gov/quantum/zoo/

Application examples:

- Defeating RSA encoding which relies on the computational difficulty of factorizing large numbers
- Understanding nitrogen fixation which may lead to more efficient fertilizer production
- A better understanding of protein folding may help find a cure for Dementia

Simulating other quantum systems

Digital Quantum simulation

Any physical system can be fully simulated by applying quantum theory.

Normal computers are not powerful enough to solve the full quantum equations describing most systems.

Therefore, one can tackle many scientific challenges if one possesses a quantum computer.

Motivation: Quantum Computing

Have we discovered the most important quantum computer applications yet?

Let's look at history

"I think there is a world market for maybe five computers"

Thomas Watson, chairman of IBM, 1943

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Granddaddy of computers turning 50

COMPUTERS from Page 1A

"Without it, we wouldn't have the space program, we wouldn't have modern airplanes," said Michael Williams, editor in chief of the Annals of the History of Computing. "Pilots would still be trying to fly by looking outside the window occasionally."

ENIAC long ago outgrew its usefulness as a number cruncher — a $40 calculator has more computing power.

But it has not lost its relevance.

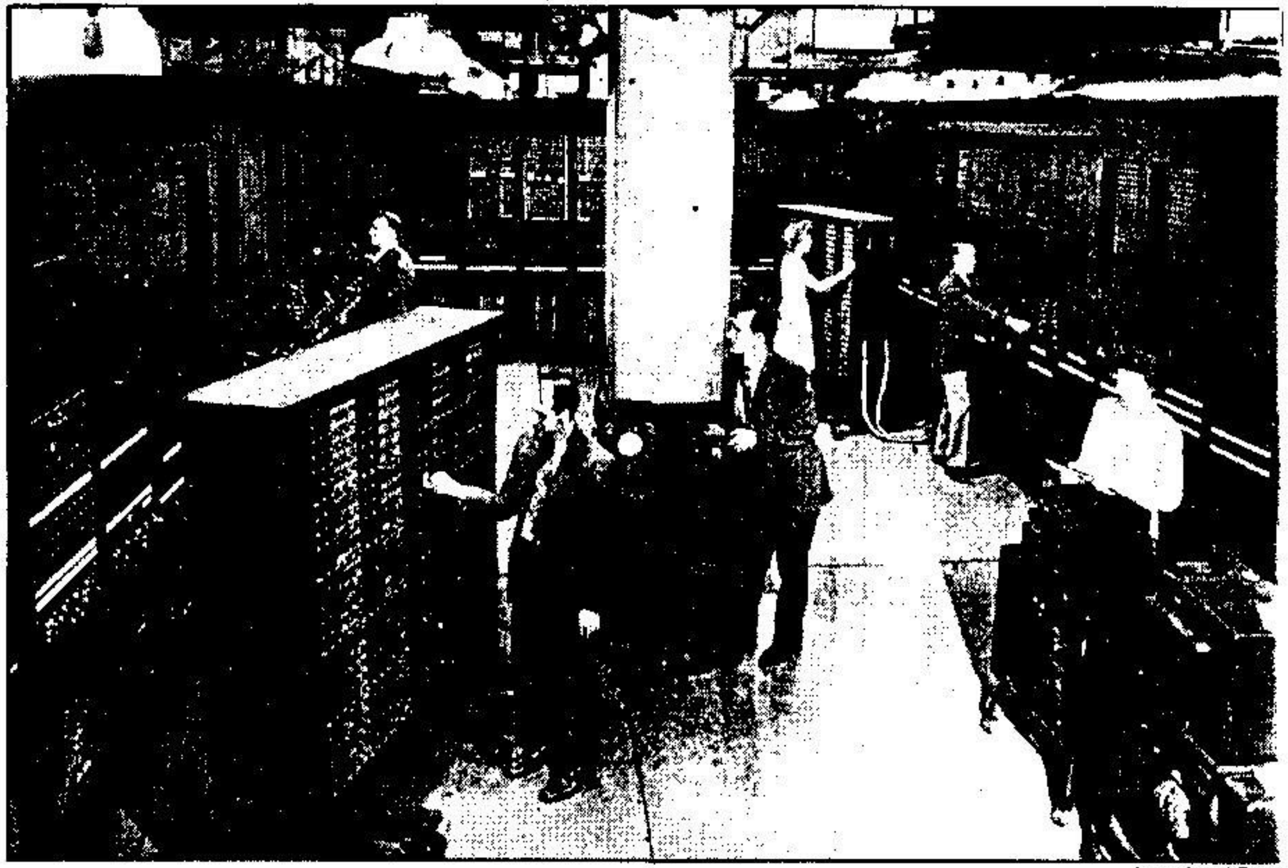
The university planned an entire year of events to honor ENIAC's birthday, including turning on part of the original machine. Vice President Al Gore will throw a switch Wednesday, the day of the anniversary, and ENIAC will count from 46 to 96.

The Postal Service will unveil a stamp commemorating "The Birth of Computing." And Garry Kasparov, the World Chess Federation champion, this week is playing against IBM's "Deep Blue" computer.

The original assemblage of wires, vacuum tubes, resistors and switches was constructed in about a year and a half at the university's Moore School of Electrical Engineering.

When fully operational, ENIAC filled up a 30-by-50-foot room. Every second it was on, it used enough electricity — 174 kilowatts — to power a typical Philadelphia home for 1½ weeks.

Costing more than $486,000, ENIAC might never been attempted were it not for World War II.



Associated Pres

CALCULATING MINDS: J. Presper Eckert, left foreground, and John Mauchly, near pole, masterminded ENIAC, pictured in undated photo from the University of Pennsylvania Archives.

"A lot of people said we were dreaming," said Herman Goldstine, who served as liaison between the Army and ENIAC team.

"The electronics people said there were too many vacuum tubes and it would never run. The mathematics people said there were no problems complex enough that computers were needed."

The Army provided both the complex problems and the money.

John Mauchly, one of two masterminds behind ENIAC, knew the Army was having a terrible time working out the complicated firing tables to help gun crews aim new artillery being used against German forces.

Each firing table had to list numbers for hundreds of potential trajectories. Calculating a single trajectory could take 40 hours using a mechanical desktop calculator, and 30 minutes using a sophisticated machine called a differential analyzer.

Mauchly, then 32, bravely told Army officials his machine could do the job in a matter of minutes.

ENIAC was completed just as the war was ending, too late for those artillery tables.

However, it fulfilled another military purpose. During test runs in 194 it did millions of calculations on thermonuclear chain reactions, predicting the destruction that could b caused by the hydrogen bomb.

So how do you built a quantum computer?

A <u>quantum computer</u> hosts quantum bits which can store superpositions of 0 and 1

classical bit: 0 or 1

quantum bit: $\alpha|0\rangle + \beta|1\rangle$

What does that really mean for a computer?

Classical computer with 2 bits

0	1

Quantum computer with 2 bits

0	0
0	1
1	0
1	1

Four numbers and all at the same time!

Conventional computer with 100 bits: one number

Quantum Computer with 100 bits: 1267650600228229401496703205376 different numbers

In general 2^N combinations where N is the number of bits.

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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!

Machines built by IBM and Google machines currently have ~100 qubits

What kind of technology to use?

Many platforms have been tried (and are still be developed).

The leading platforms are:

- Superconducting circuits - the computer chips needs to be cooled to -273°C!
- Individual charged atoms (ions) – chip can be at room temperature or mild cooling to liquid Nitrogen temperatures

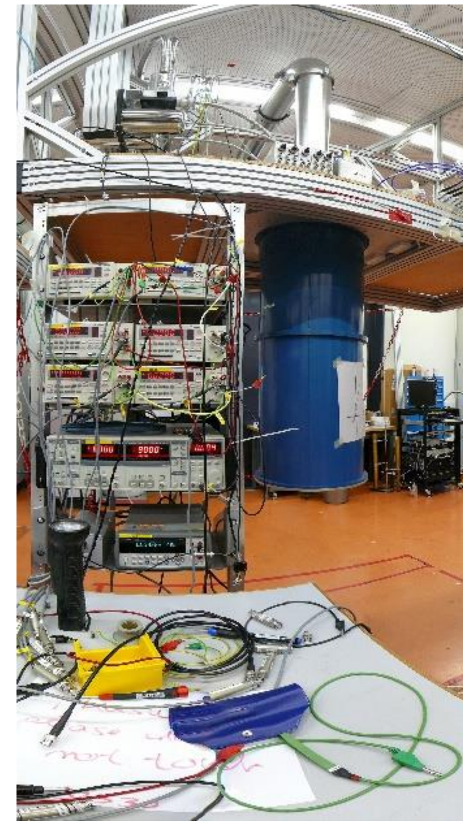
Why trapped ions?

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

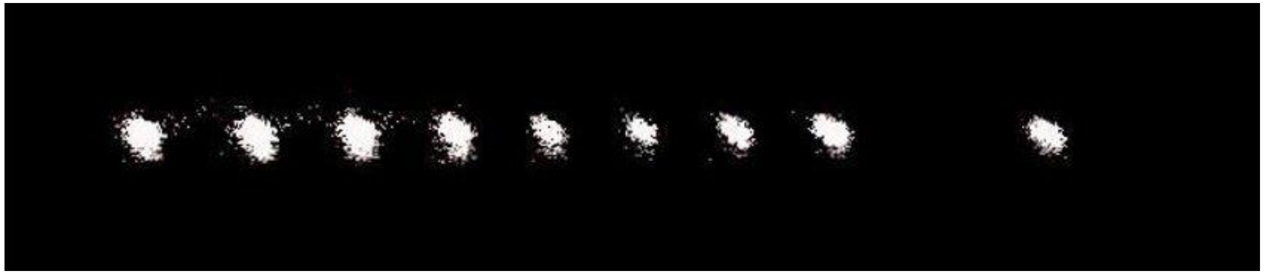
Superconducting qubits:

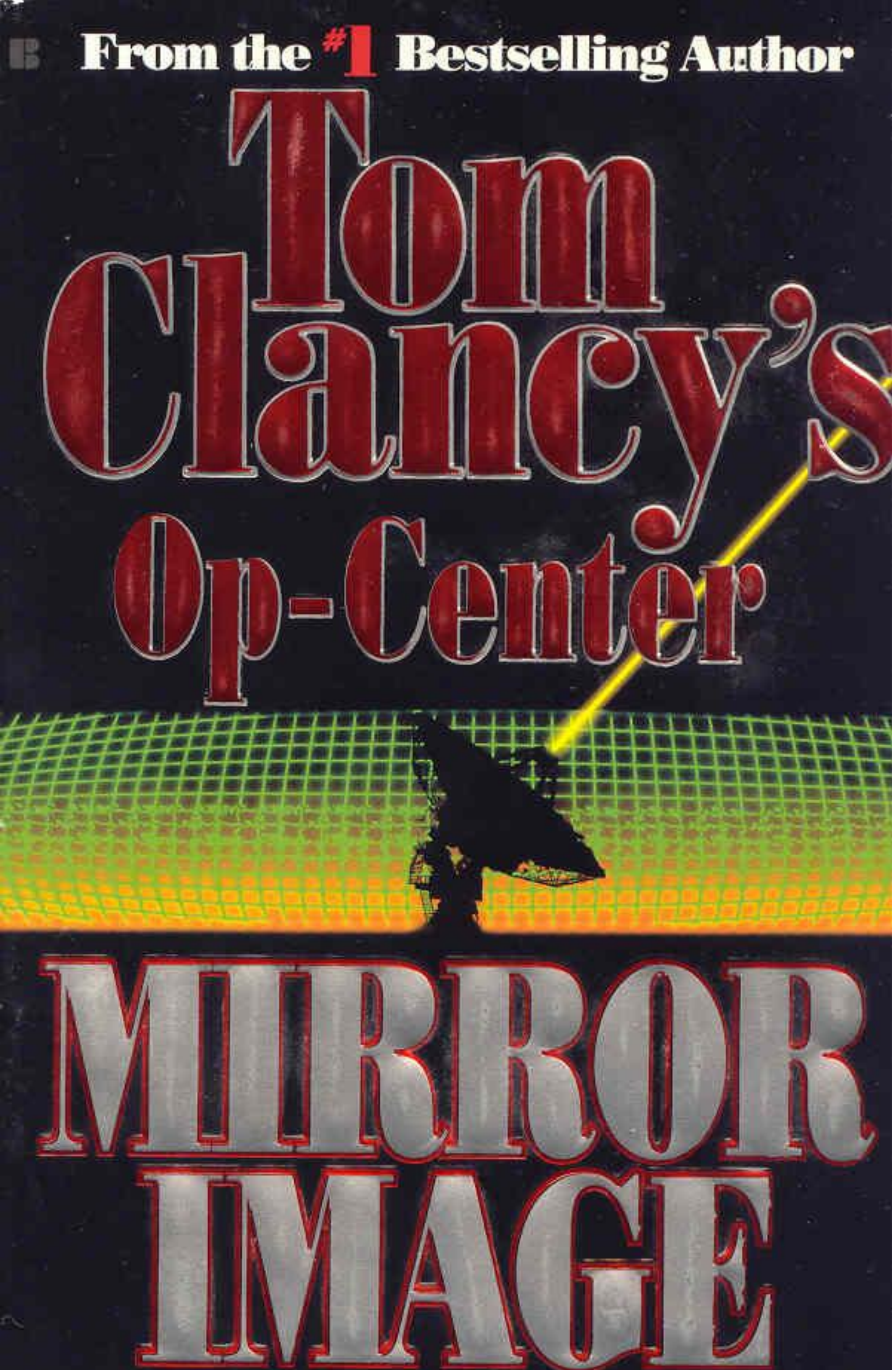
- -273°C (milli-Kelivin) requires a dilution refrigerator
- Very little cooling power available at that temperature (~mW)
- Large amplitude correlated errors (due to cosmic rays)



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

Single charged atoms (ions) are quantum bits





by executives doing surprisingly little. Psychologist Liz Gordon was chewing nicotine gum in the smoke-free room, nervously twirling a lock of short brown hair, sipping her dark coffee with three sugars and reading the new week's supermarket tabloids.

Operations Support Officer Matt Stoll was playing poker with Environmental Officer Phil Katzen. There was a small mound of quarters between the men and, instead of cards, both of them were using laptops linked by a cable. As she walked past them, Ann could tell Stoll was losing. He freely admitted that he had the worst poker face on the planet. Whenever things weren't going well, whether he was playing cards or trying to fix a computer responsible for the defense of the free world, sweat collected on every pore of his round, cherubic face.

Stoll surrendered a six of spades and a four of clubs. Phil dealt him a five of spades and a seven of hearts in return.

''Well, at least I've got a higher card now,'' Matt said, folding. ''One more hand,'' he said. ''Too bad this isn't like quantum computing. You confine ions in webs of magnetic and electric fields, hit a trapped particle with a burst of laser light to send it into an excited energy state, then hit it again to ground it. That's your switch. Rows of ions in a quantum logical gate, giving you the smallest, fastest computer on earth. Neat, clean, perfect.''

''Yeah,'' Phil said, ''too bad this isn't like that.''

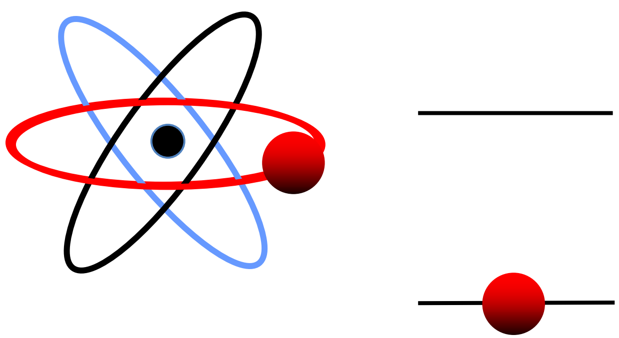
''Don't be sarcastic,'' Stoll said as he popped the last of a chocolate-covered doughnut in his mouth, then washed it down with black coffee. ''Next time we'll play baccarat and things will be different.''

''No they won't,'' Katzen said, sitting back as he

How to encode the quantum bit into a single atom?

The trajectory of an electron determines the internal state of the atom

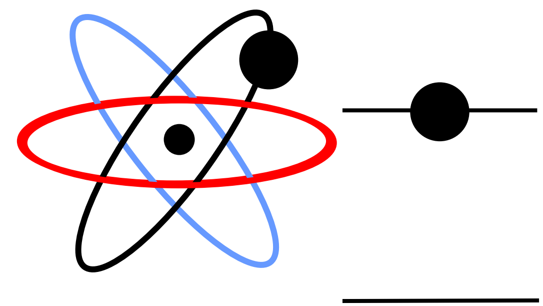
state $|0\rangle$



$|0\rangle$

Use lasers or microwaves to go to other state

state $|1\rangle$

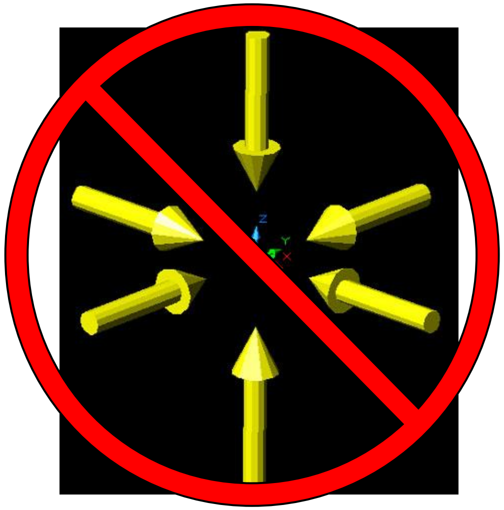


$|1\rangle$

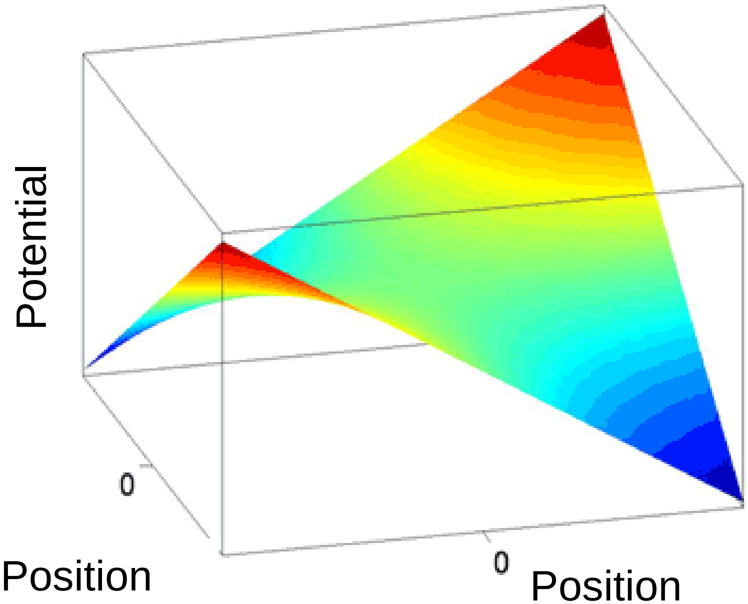
How to trap ions*?

*: Ions are charged atoms

How to trap an ion



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



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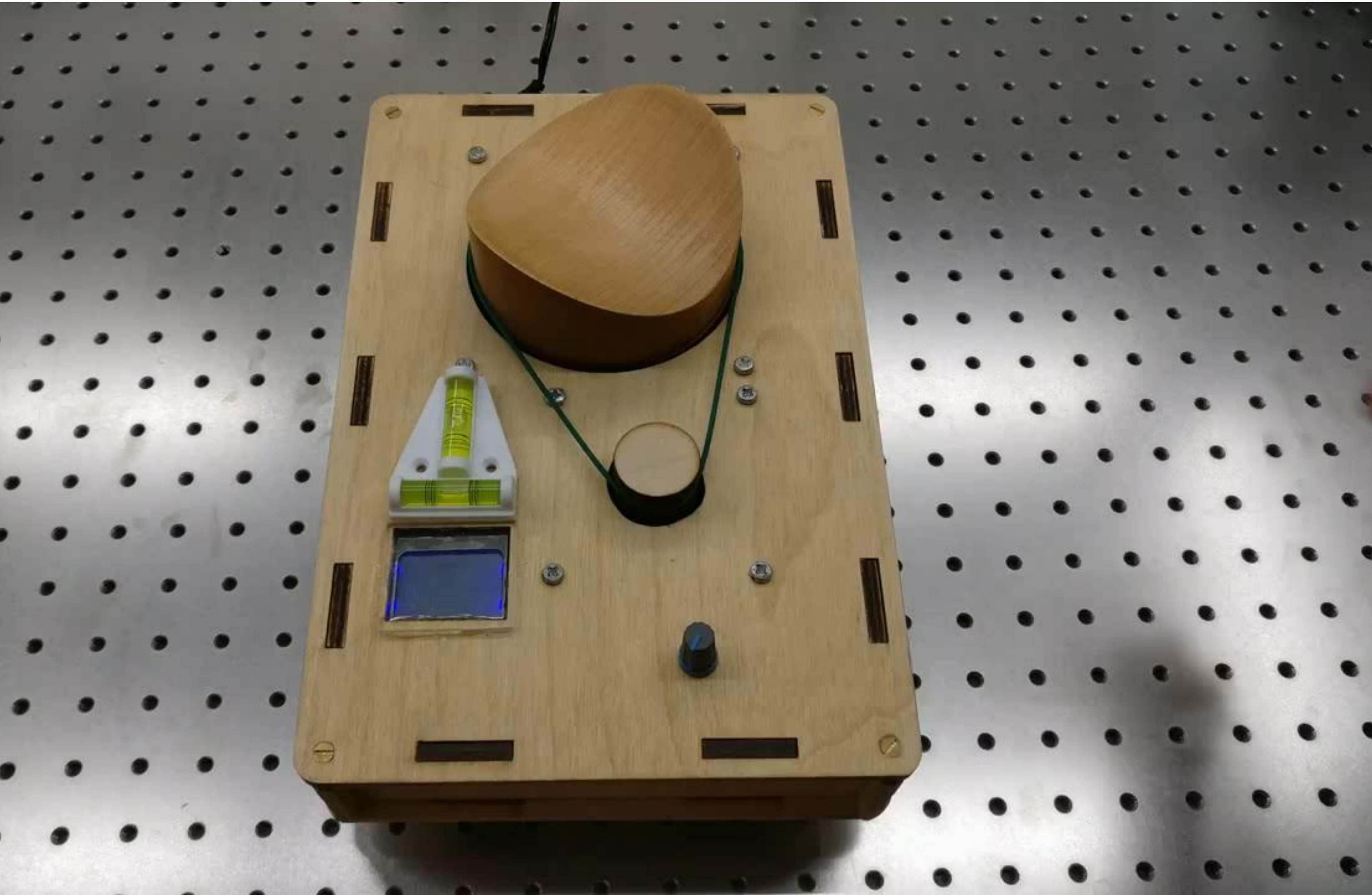
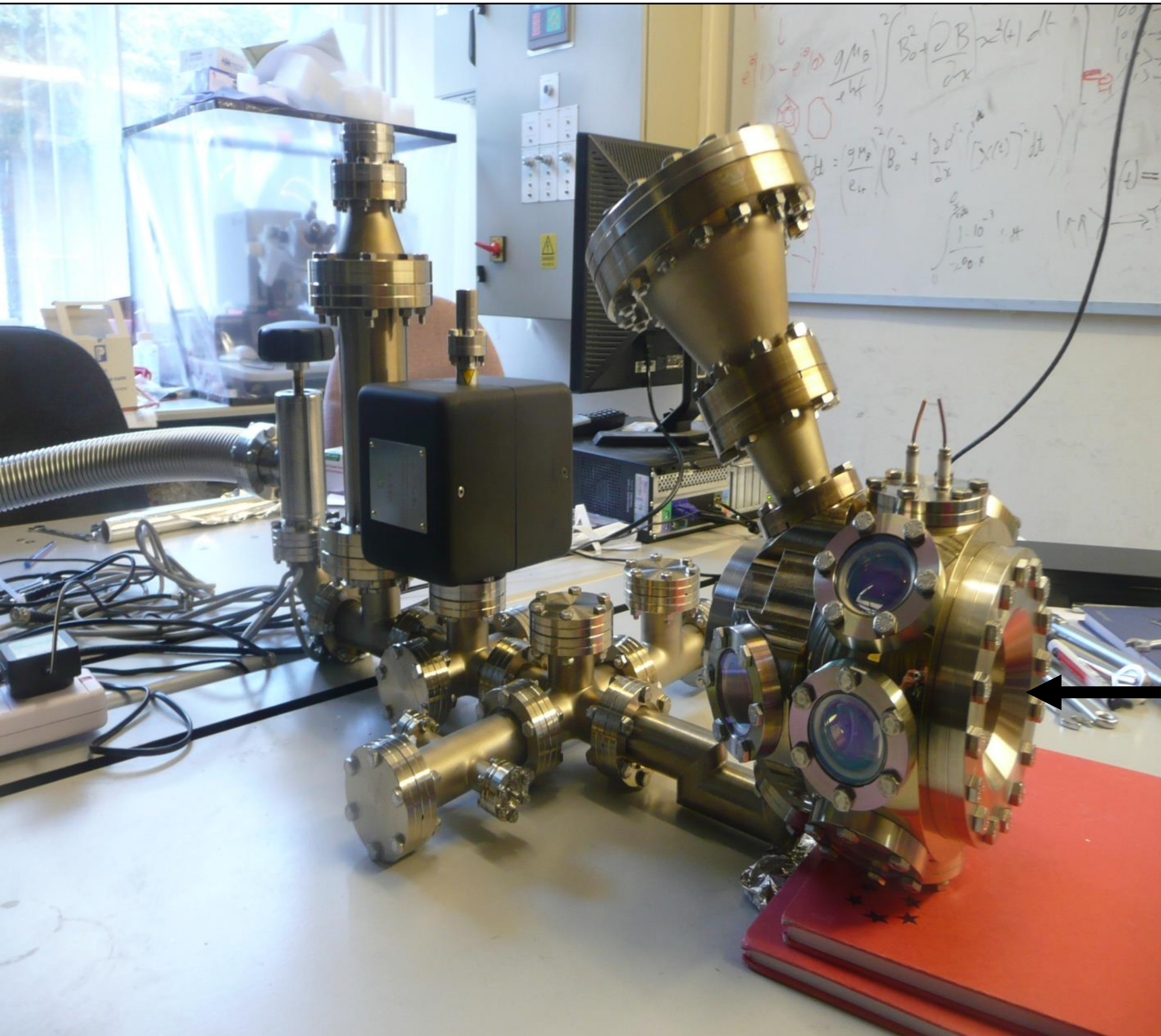
How to trap an ion



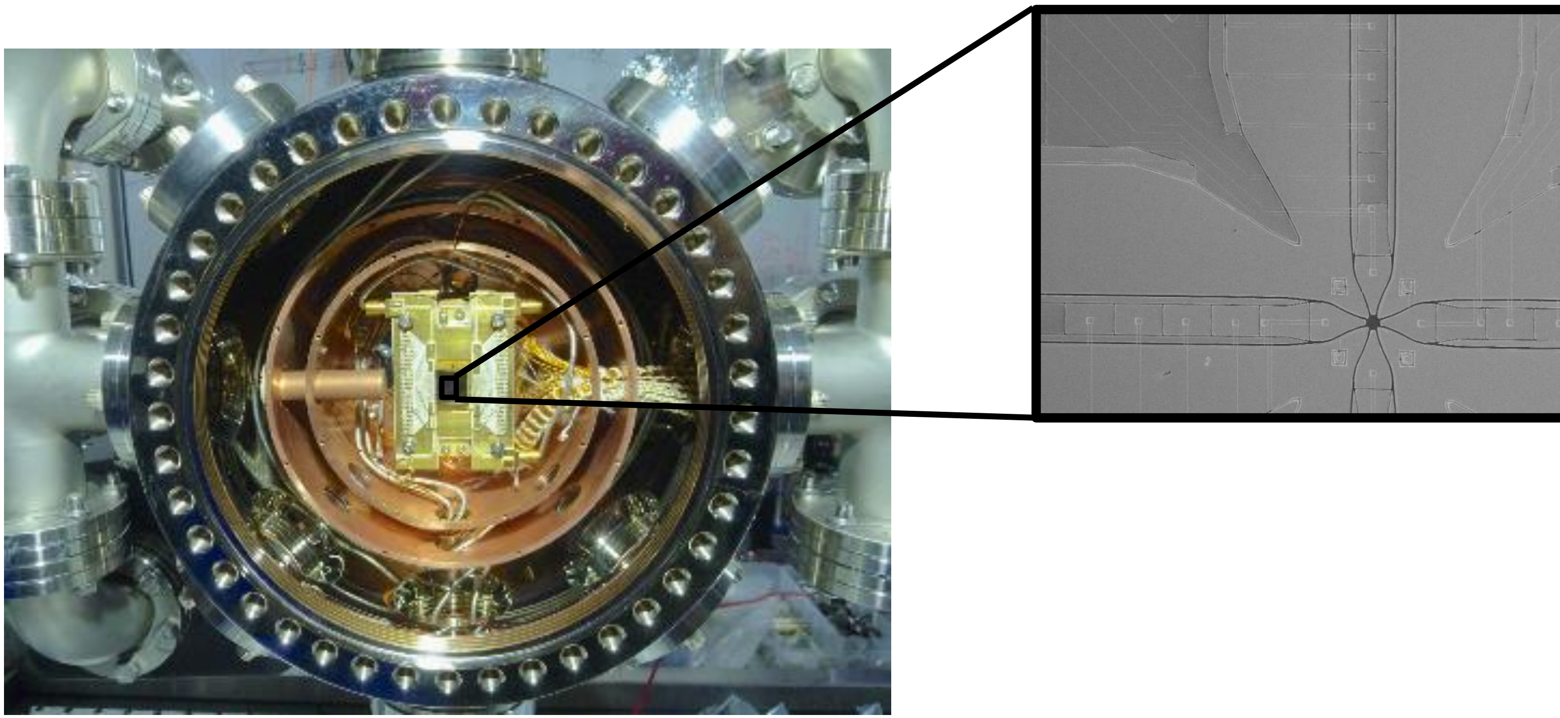
Vacuum system



Better vacuum than if you were to step out a Space Shuttle

Trapped ions

Quantum computer microchip



Microchip developed at the University of Sussex

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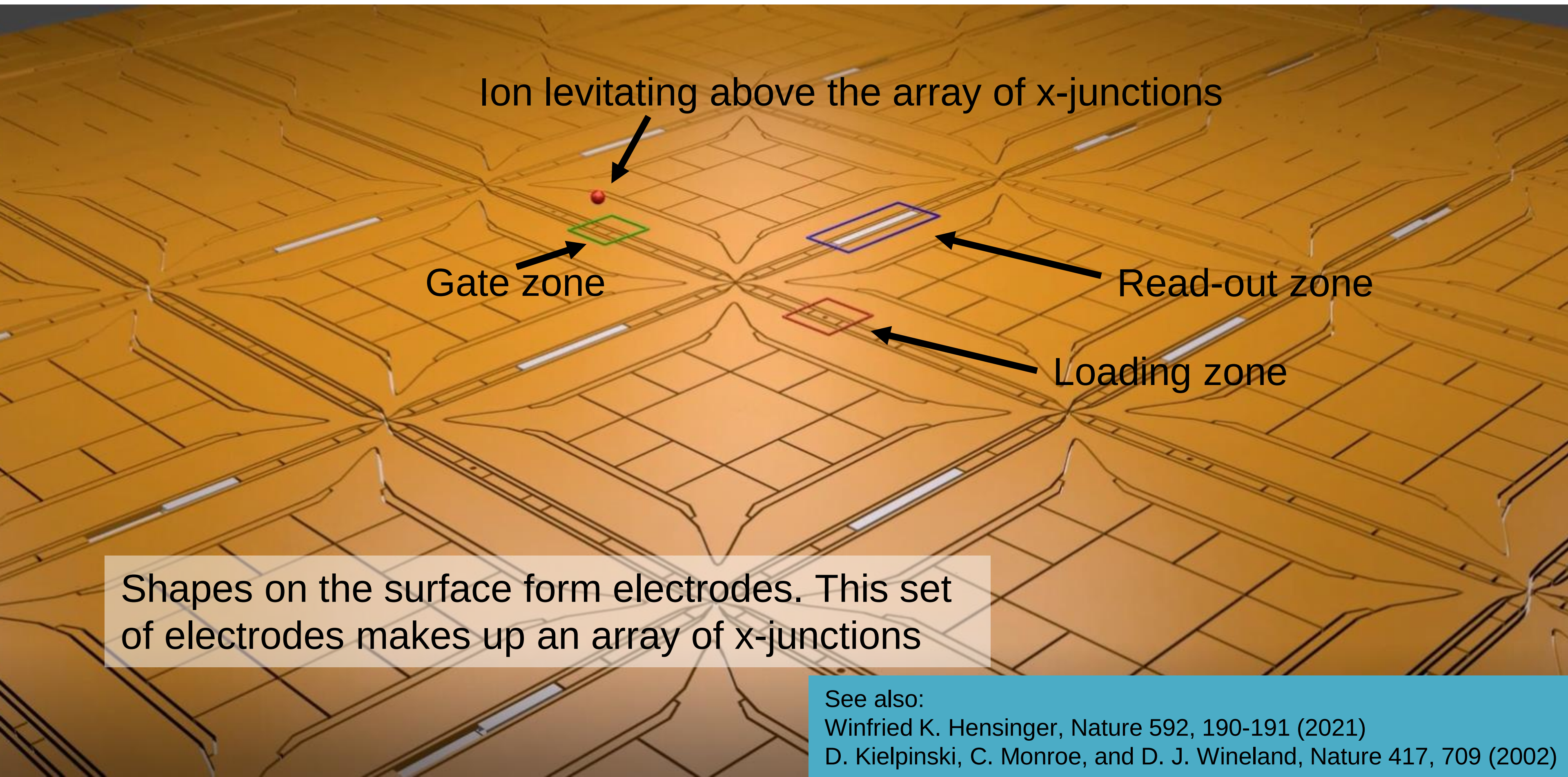
An ion trap quantum computer

- 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

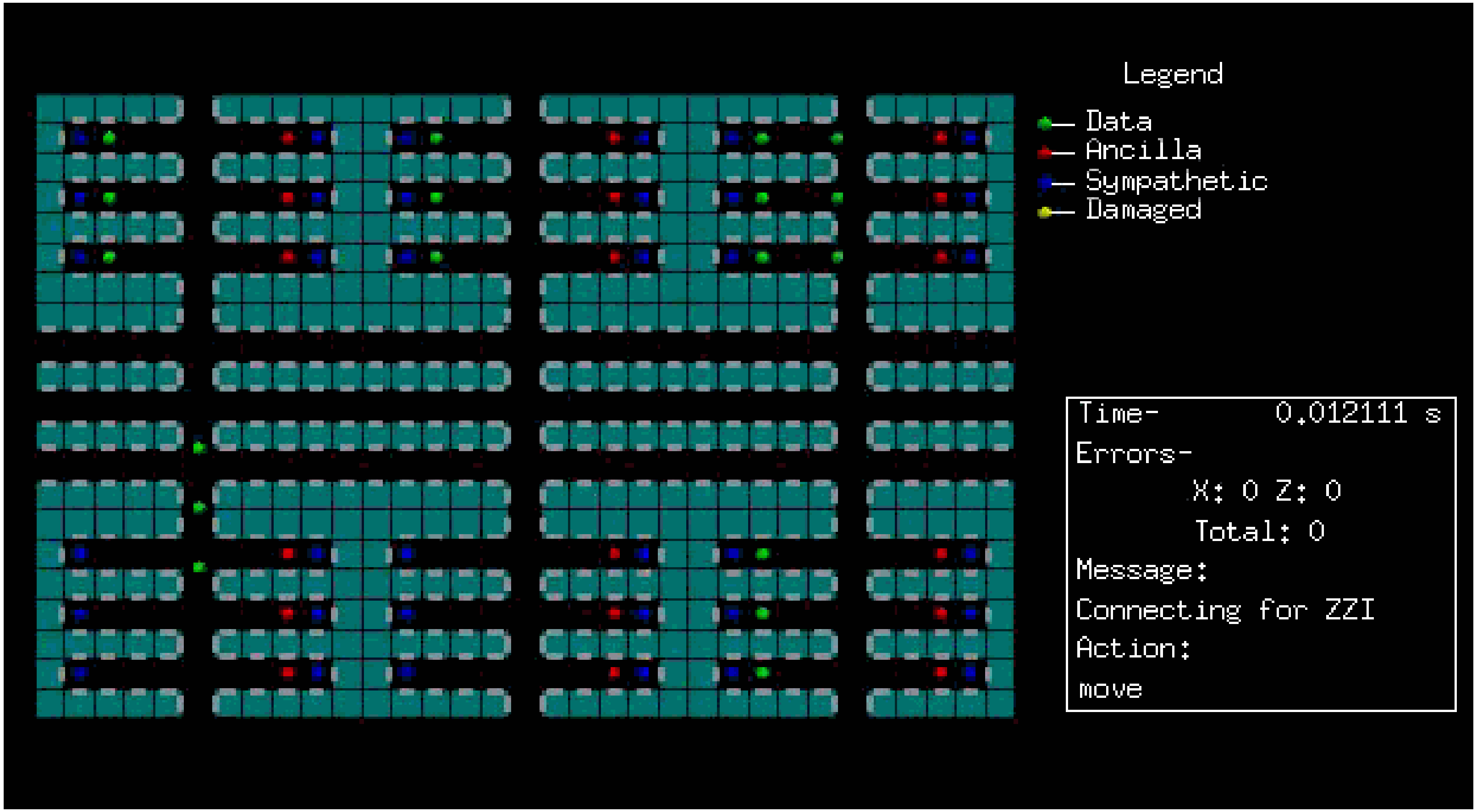
See also:
Winfried K. Hensinger, Nature 592, 190-191 (2021)
D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002)

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

A quantum algorithm…



Ike Chuang, MIT

How to implement a quantum gate?

Traditionally this is done by interacting two ions with laser beams for each trapped ion qubit.

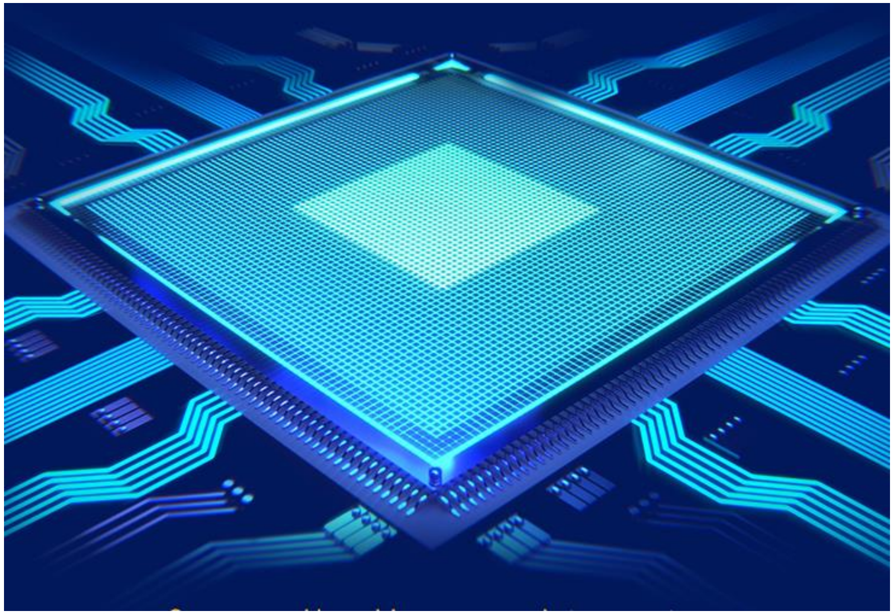
Not easy with lots of qubits

However, remember there will be millions of trapped ions, so this means **millions of laser beams** that need to be **aligned as good as 1/100 of a millimetre!**

Not easy!

But there is another way…

There is another way – execute quantum gates by applying voltages to a microchip - analogous to a conventional computer chip - making use of microwave technology



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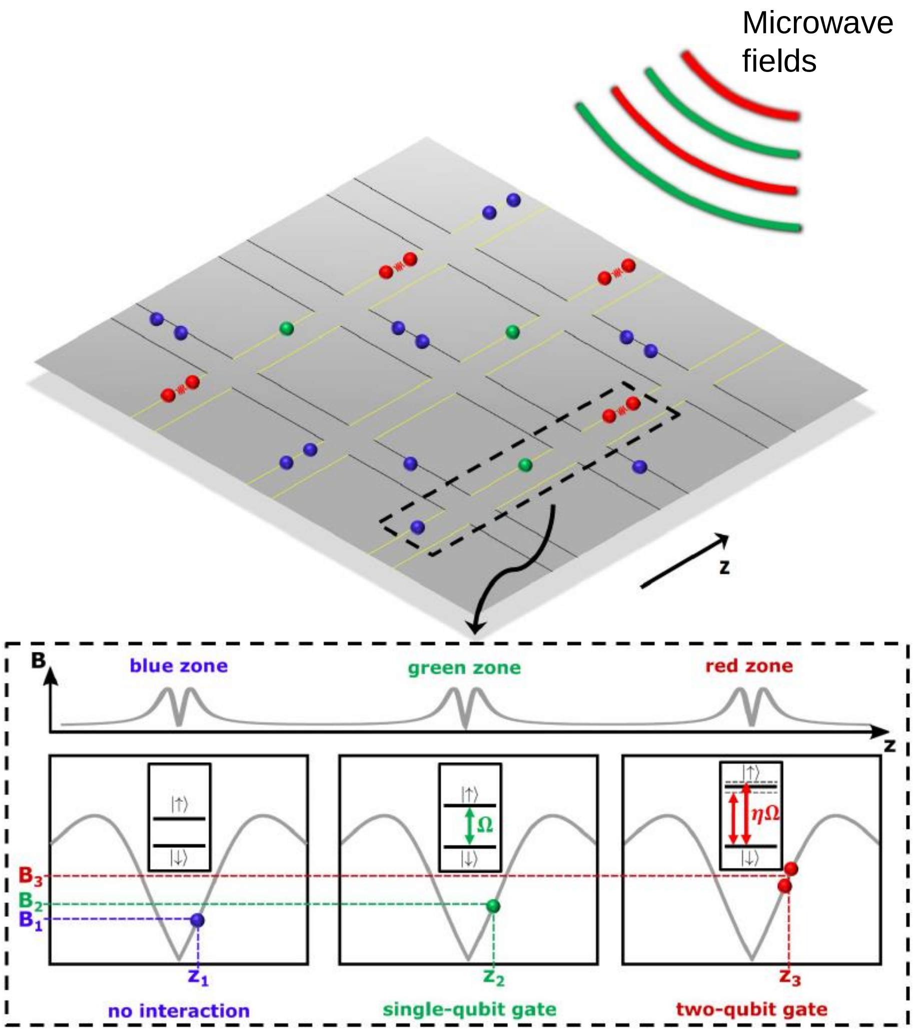
Trapped-ion quantum logic with global radiation fields, S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Phys. Rev. Lett. 117, 220501 (2016)

Quantum computing with global fields

Quantum gates are executed by the application of voltages on a microchip using global microwave fields (rather than using laser beams):

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.



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)

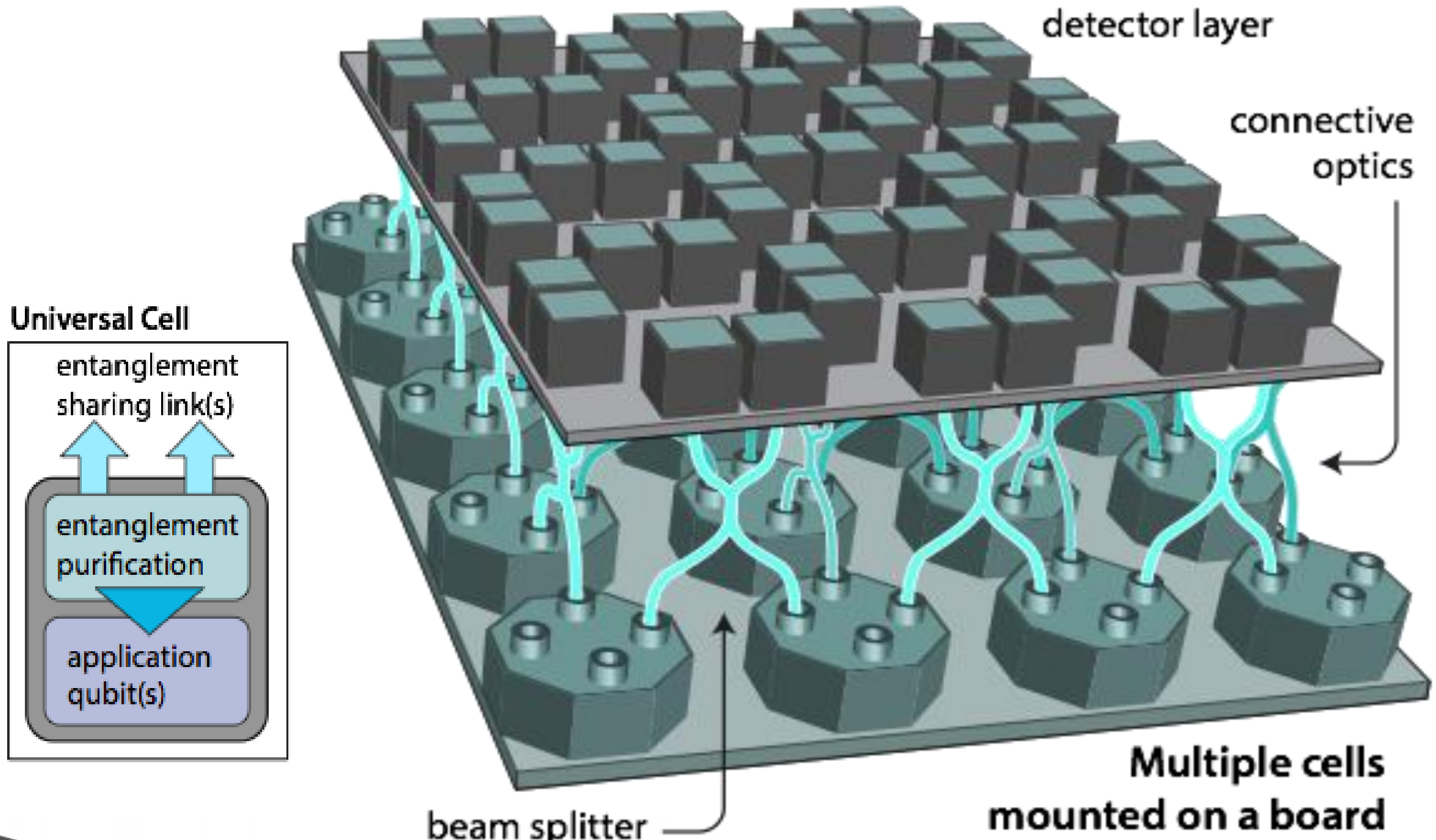
One microchip can only hold so many qubits.

Many applications require more qubits than fit on a single chip.

How to make a quantum computer modular in order to allow for a sufficient number of qubits?

Option 1: Connect modules using light particles (photons)

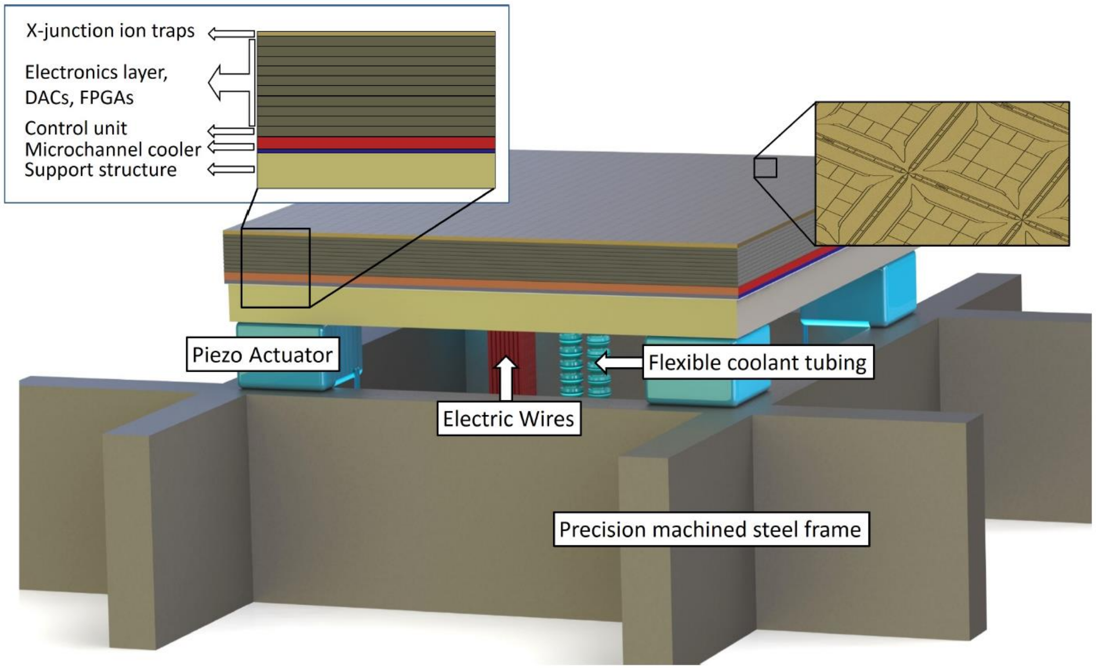
Optically linked array of quantum computing modules…

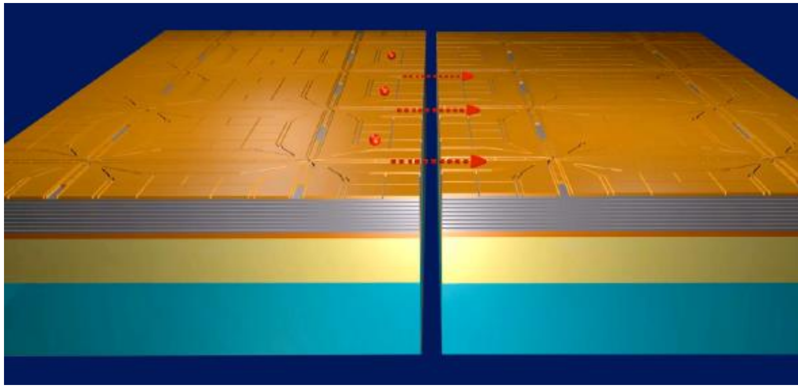


Connection speed record is 180 1/s at 94% fidelity (~1 1/s after distillation).

- To slow to build a practical device.

Option 2: Use electric fields to connect modules





Modules are connected via electric fields

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)

Option 2: Use electric fields to connect modules

- Simpler engineering

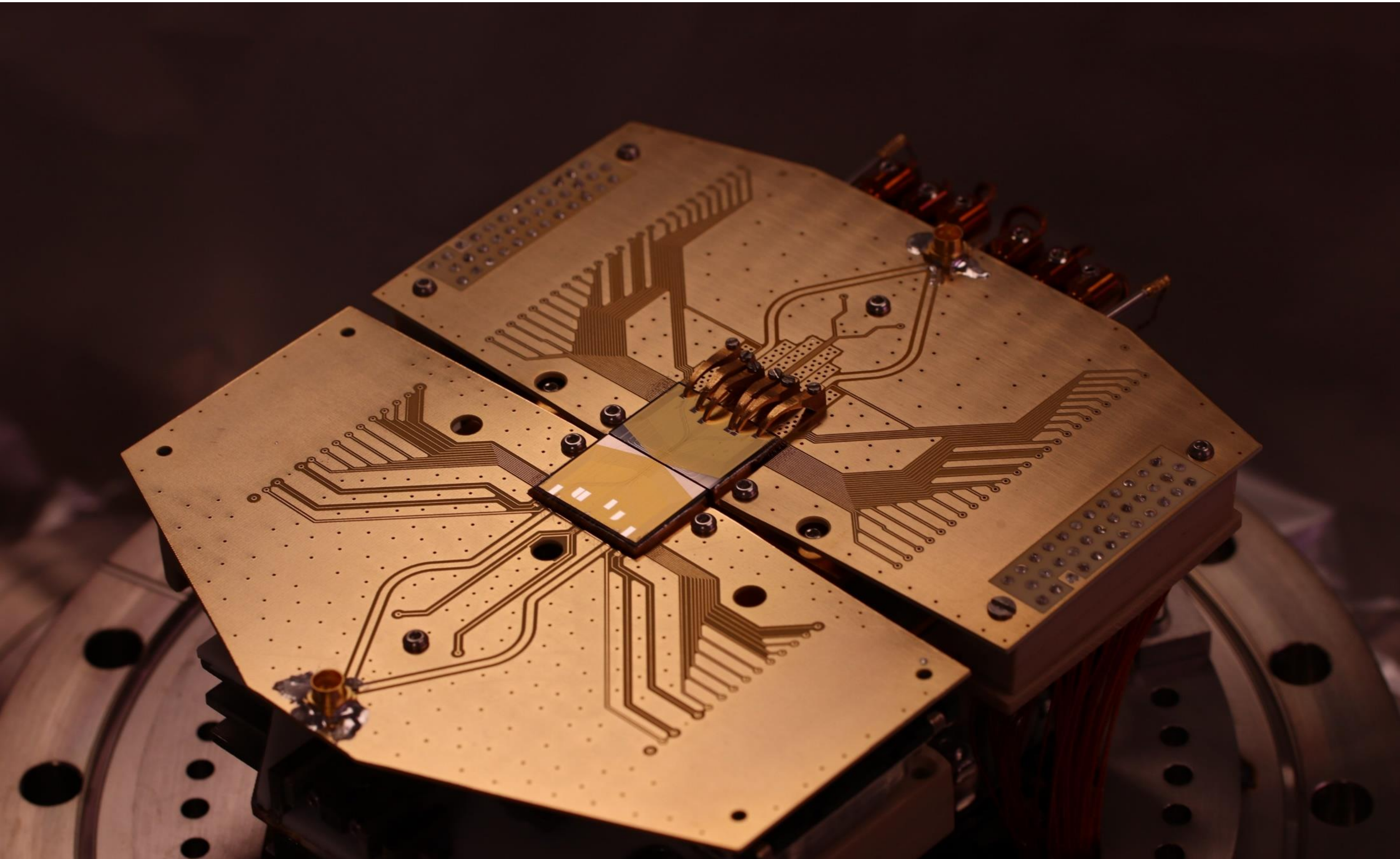
- High connection speeds between modules are readily achievable (four order of magnitude faster than optical interconnects!)

- Allows for variable connectivity

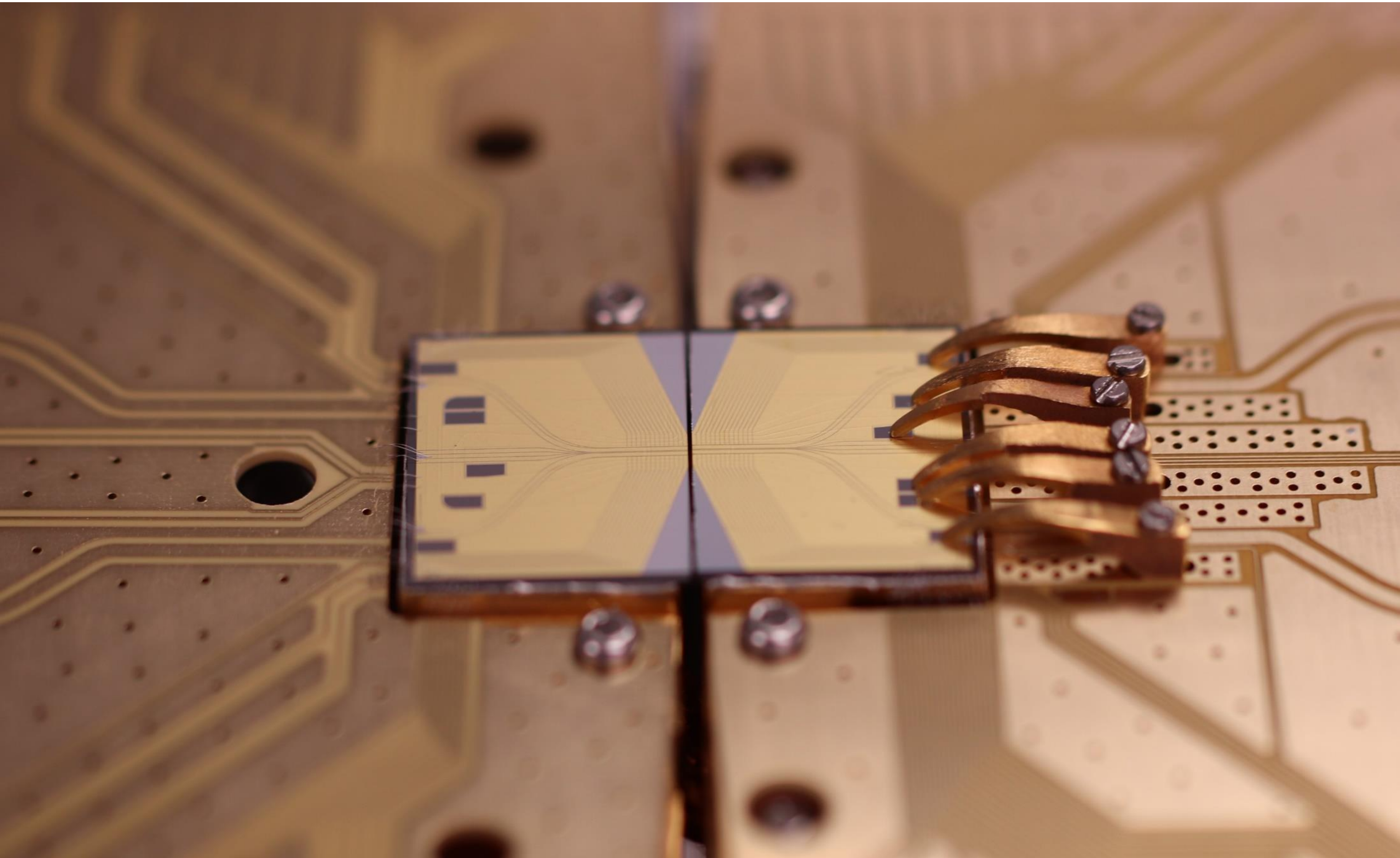
Blueprint for a microwave trapped ion quantum computer, B. Lekitsch, S. Weidt, A.G. Fowler, K. Mølmer, S.J. Devitt, Ch. Wunderlich, and W.K. Hensinger, Science Advances 3, e1601540 (2017)

The prototype

Two-module prototype



Two-module prototype



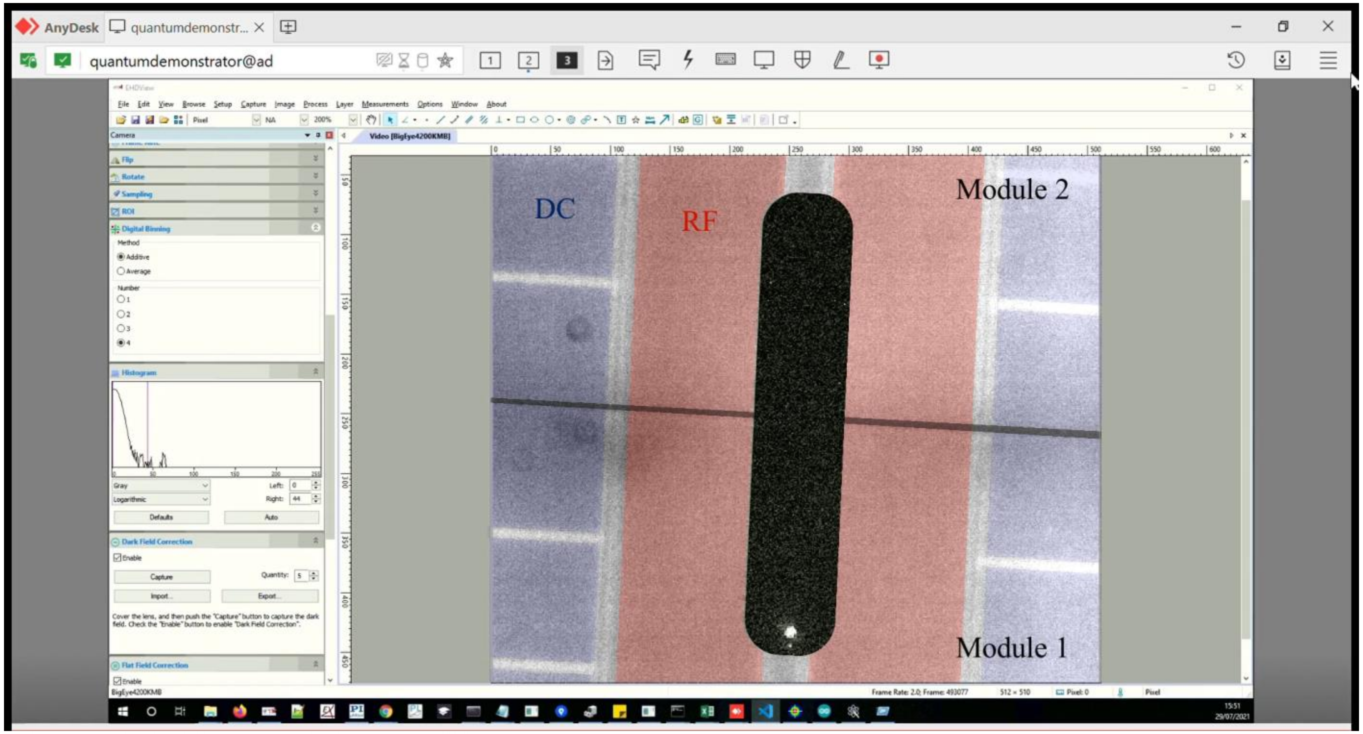
A High-Fidelity Quantum Matter-Link Between Ion-Trap Microchip Modules

- Rate of 2424 s^{-1} (410 μs) single trip (distance 692 μm)
  - Oxford using photonic interconnects: 180 1/s
- 99.999993 % Ion transport success fidelity
  - Oxford success rate using photonic interconnects: 94%
- The transfer speed is only limited by the update rate of the digital to analogue converters of the card connected to the electrodes (around 130 kS/s) and the 47 kHz cut-off frequency of the filter.

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)

A High-Fidelity Quantum Matter-Link Between Ion-Trap Microchip Modules

Thousands of round trips, 10 km distance!



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Nature Communications 14, 531 (2023)

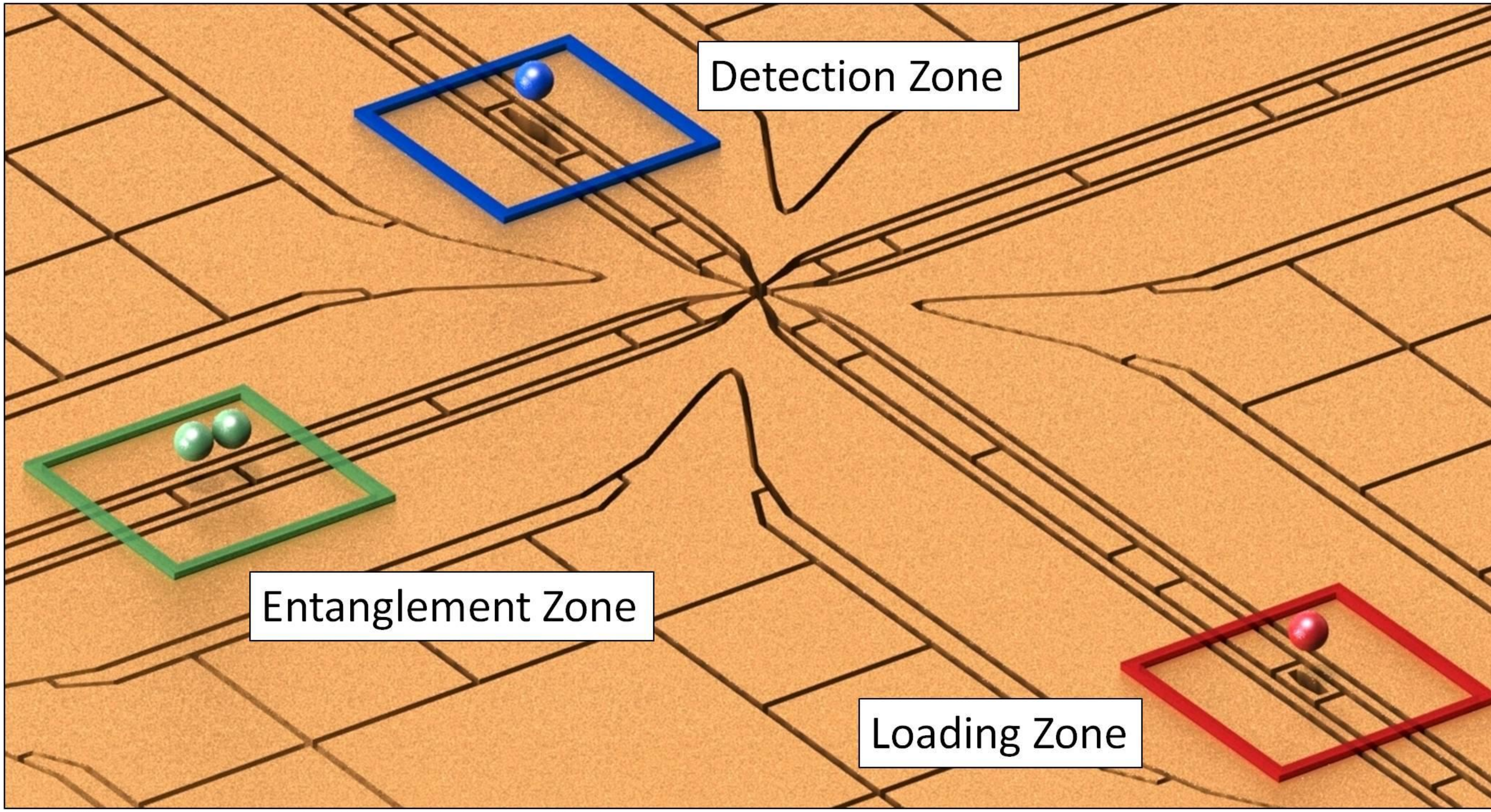
How to build a quantum computer?

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)

Surface array of X-junctions on a chip



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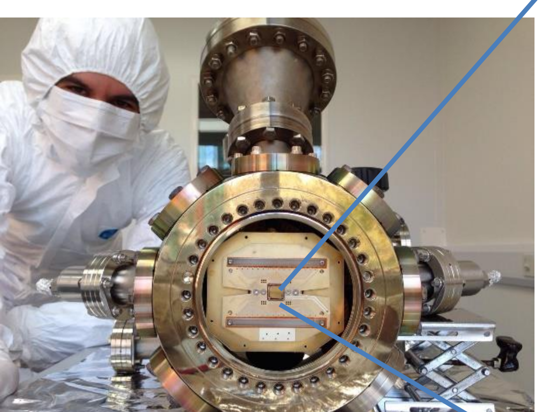
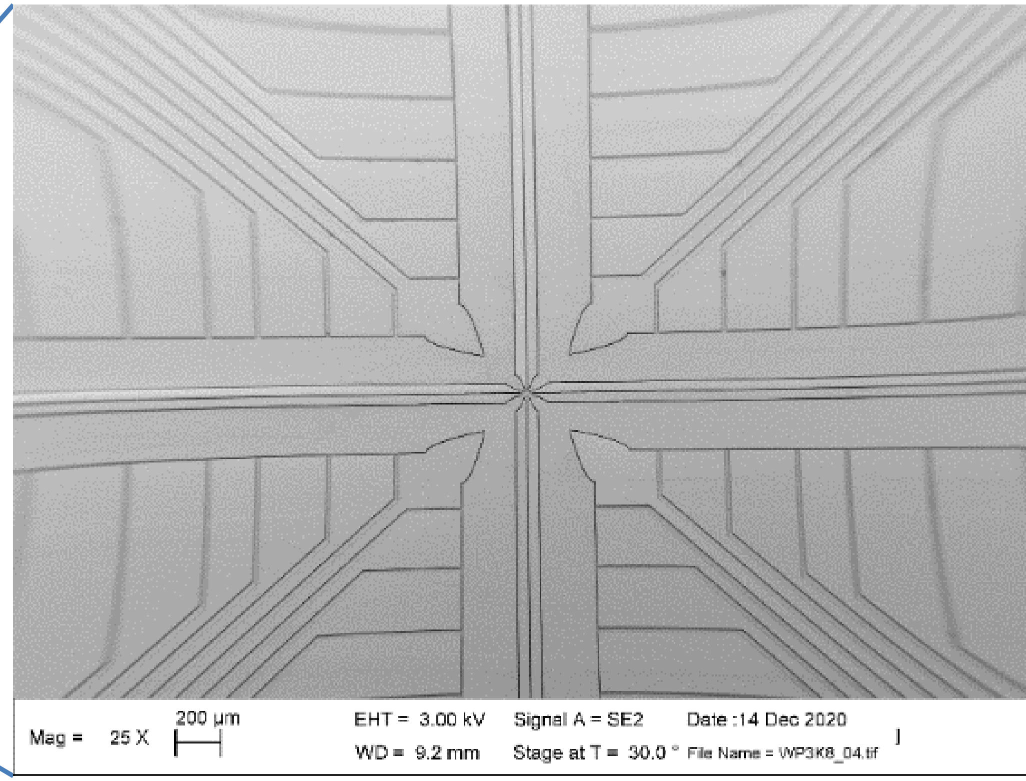
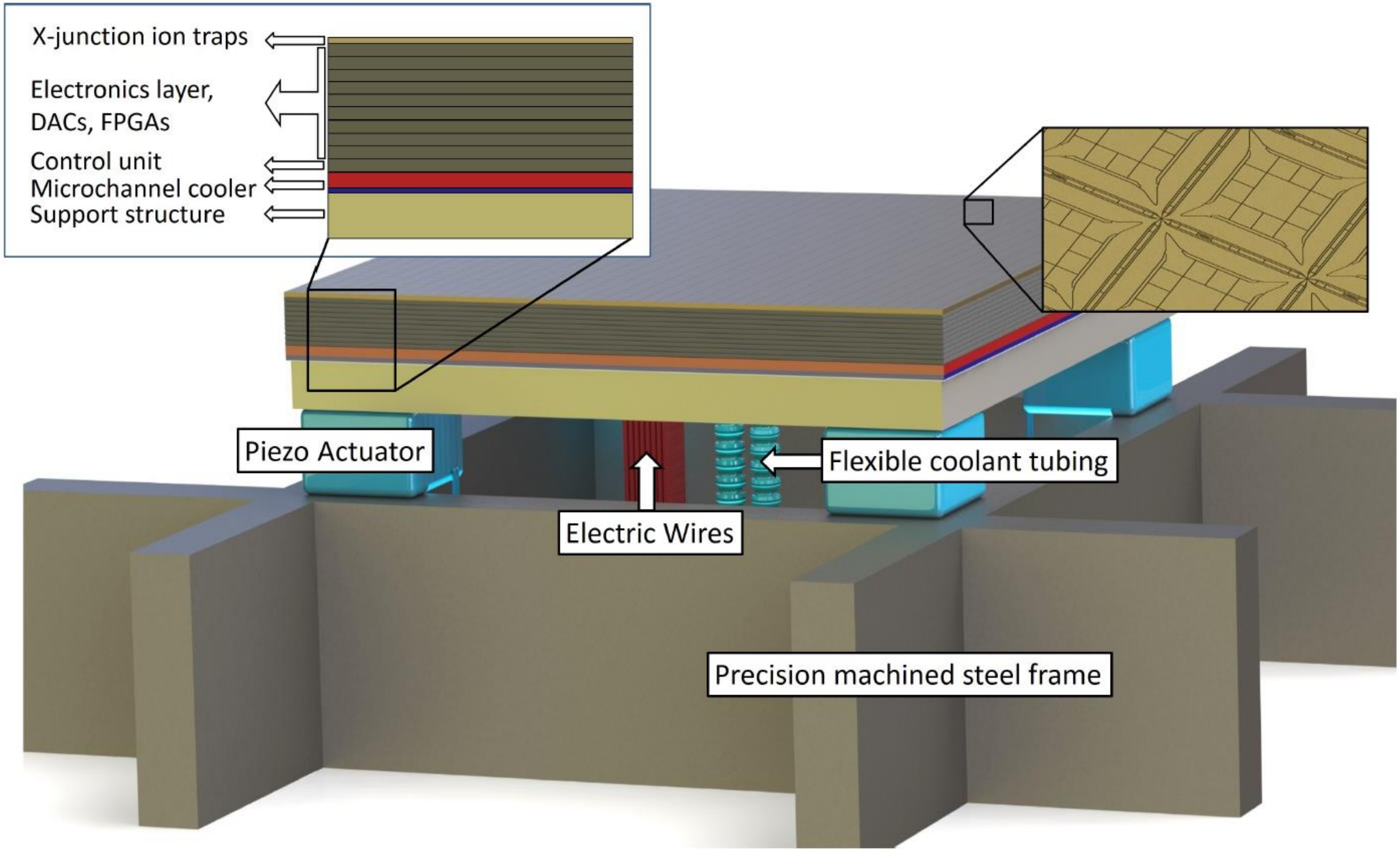
X-Junction quantum computer microchip





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)

Electronic Quantum Computer Module



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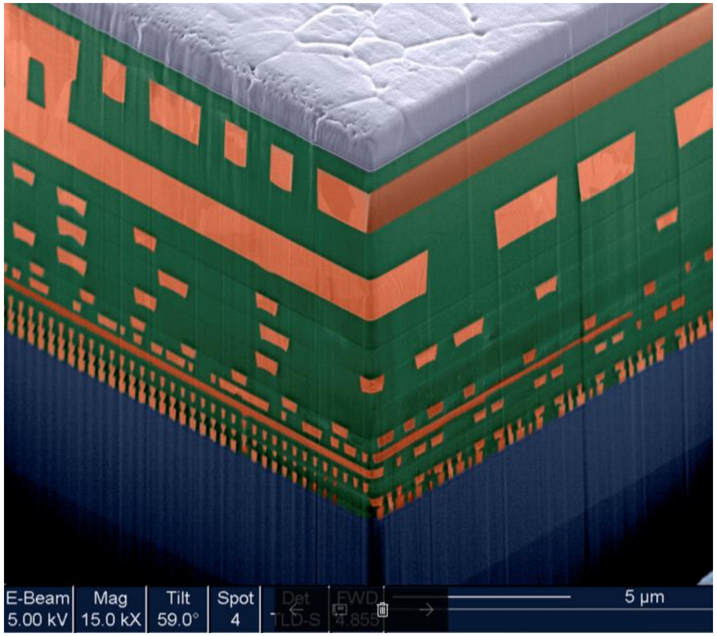
For comparison:
Classical computer architecture



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

How to construct *a million qubit* quantum computer

NQIT

UNIVERSITY OF SUSSEX

How to construct
a microwave trapped-ion
quantum computer

How are we going about building practical quantum computers?

Universal Quantum -
a quantum computing company

- A research group cannot construct practical quantum computers, this requires a company in order to produce reliable engineering devices beyond proof-of-principle.
- Founded in 2018, Universal Quantum, based in UK and Germany, is a full stack quantum computing company with a mission to develop practical commercial utility-scale quantum computers based on trapped ions along with relevant application and software solutions.
- Universal Quantum is focussing on developing fully electronic quantum computing modules made via Silicon Foundry microfabrication as the core of a fully modular architecture.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Scientists plan to build new quantum computing facility in Brighton

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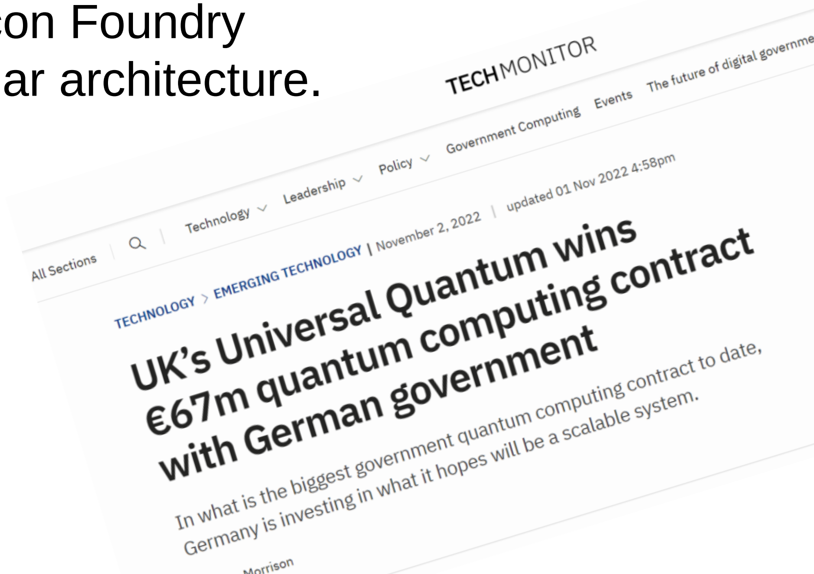
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TECHNOLOGY > EMERGING TECHNOLOGY | November 2, 2022 | updated 01 Nov 2022 4:58pm

UK's Universal Quantum wins €67m quantum computing contract with German government

In what is the biggest government quantum computing contract to date, Germany is investing in what it hopes will be a scalable system.

Universal Quantum -

building quantum computers for disruptive industry applications

Validation and Venture Capital

Working together.
Our major seed investors are:

We have raised ~£10M from household name investors including:

VILLAGE GLOBAL

hoxton ventures

FoundersX FUND THE FUTURE

Propagator | Ventures

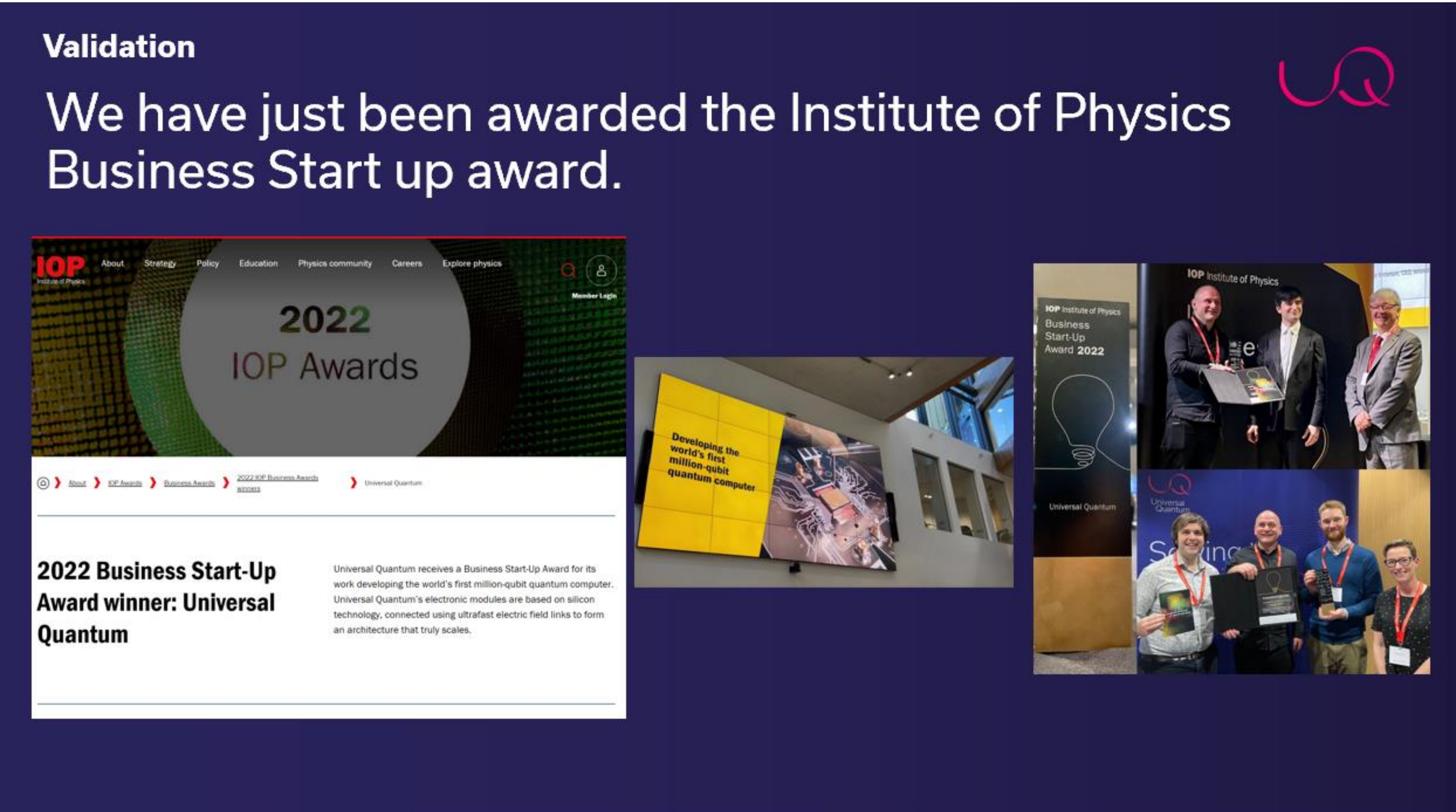
Luminous Ventures

LAROCA CAPITAL GMBH

Universal Quantum

Universal Quantum -

building quantum computers for disruptive industry applications



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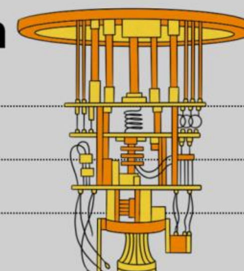
Validation

Bloomberg identified us as one of the 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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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. We have London-based fintechs, AI-generated avatars, data science that helped map the Covid-19 pandemic and a group building quantum computers in Haywards Heath. There are names you've seen in the shops and in the news, as well as some you've probably never heard of. 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.

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The UK trusts us to build them the first error corrected quantum computer

Consortium grant value[1]	£7.6m	£6.5m	£7.6m
Scope	Developing the first truly scalable error corrected quantum computer	Development of cryo-CMOS to enable the next generation of scalable quantum computers	Building the quantum operating system for every quantum computer worldwide
Consortium partners/ suppliers	Rolls Royce, SIAPARTNERS, QURECA, University of Sussex, Imperial College London, riverlane, Diamond Microwave, Edwards	surecore, Synopsys, Semiwise, Oxford Instruments, University of Glasgow, seeqc	arm, HITACHI Inspire the Next, oxford ionics, OQC, NPL, riverlane, seeqc

Universal Quantum

(1) Universal Quantum receives £4.1m in cash and ~£13m in 3rd party development costs spent across various consortium members

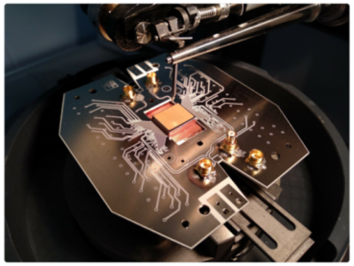
Universal Quantum Deutschland -

building quantum computers for disruptive industry applications

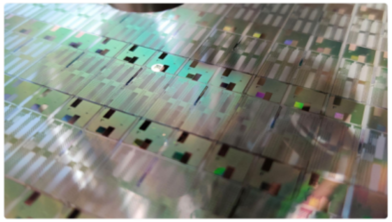
Building and developing the very best quantum computers - in Germany

- Universal Quantum Deutschland GmbH, located in Hamburg, was founded in 2021 to :
  - Engage with the European market
  - Make use of German talent
  - Engage with the German quantum computing ecosystem
- Universal Quantum Deutschland was awarded two tenders by DLR:
  - Legato: Prototype trapped ion quantum computer with four interconnected modules
  - Toccata: Trapped-ion quantum computer with at least 50 qubits and error correction
- The technology to be demonstrated in both machines will showcase the possibility to construct quantum computers with millions of qubits for fault-tolerant quantum computing.

Toccata: Trapped-ion quantum computer with at least 50 qubits and error correction



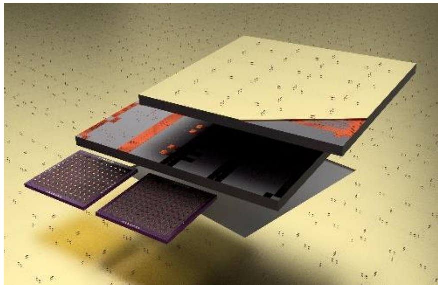
Legato: Prototype trapped ion quantum computer with four interconnected modules



How is Universal Quantum different?

- Operating temperature of device:
  Our technology operates with mild cooling at 70K, we do not need to cool close to absolute zero in a dilution refrigerator.
- How we execute gates:
  Other ideas for building practical quantum computers with trapped ions involve aligning pairs of individual laser beams with an accuracy of 10 µm to execute quantum computations for every qubit, millions of qubits would require millions of pairs of laser beams. Our approach replaces these laser beams with voltages applied a microchip analogous to the operation of classical transistors.
- Modularity:
  While others make use of optical fibre connections to connect individual quantum computing modules, our approach will use electric field connections resulting in connection speeds between modules up to four orders of magnitude faster.
- Silicon microchip platform
  We use standard silicon-based fabrication techniques to build an integrated Quantum Processing Unit (iQPU) that can act as a standalone quantum computer.

iQPU



So what do we know?

- Quantum computers can solve certain problems the fastest supercomputer would take billions of years to solve.
- Quantum computers will be disruptive across numerous industry sectors.
- The most interesting applications for quantum computers will require millions of qubits.
- We make use of microwave technology, such as used in mobile phones, to build machines that can scale to millions of qubits.
- Quantum technologies will form a new industry sector in Germany and around the world.

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

Would you like to help?