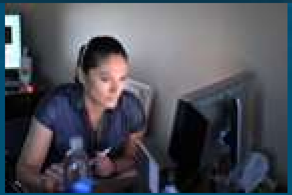
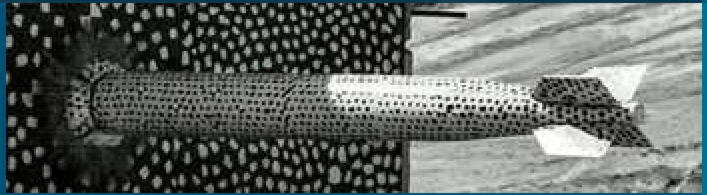
SAND2021-5953PE

Surface ion traps for quantum computing





May 17, 2021

Daniel Stick, Sandia National Laboratories

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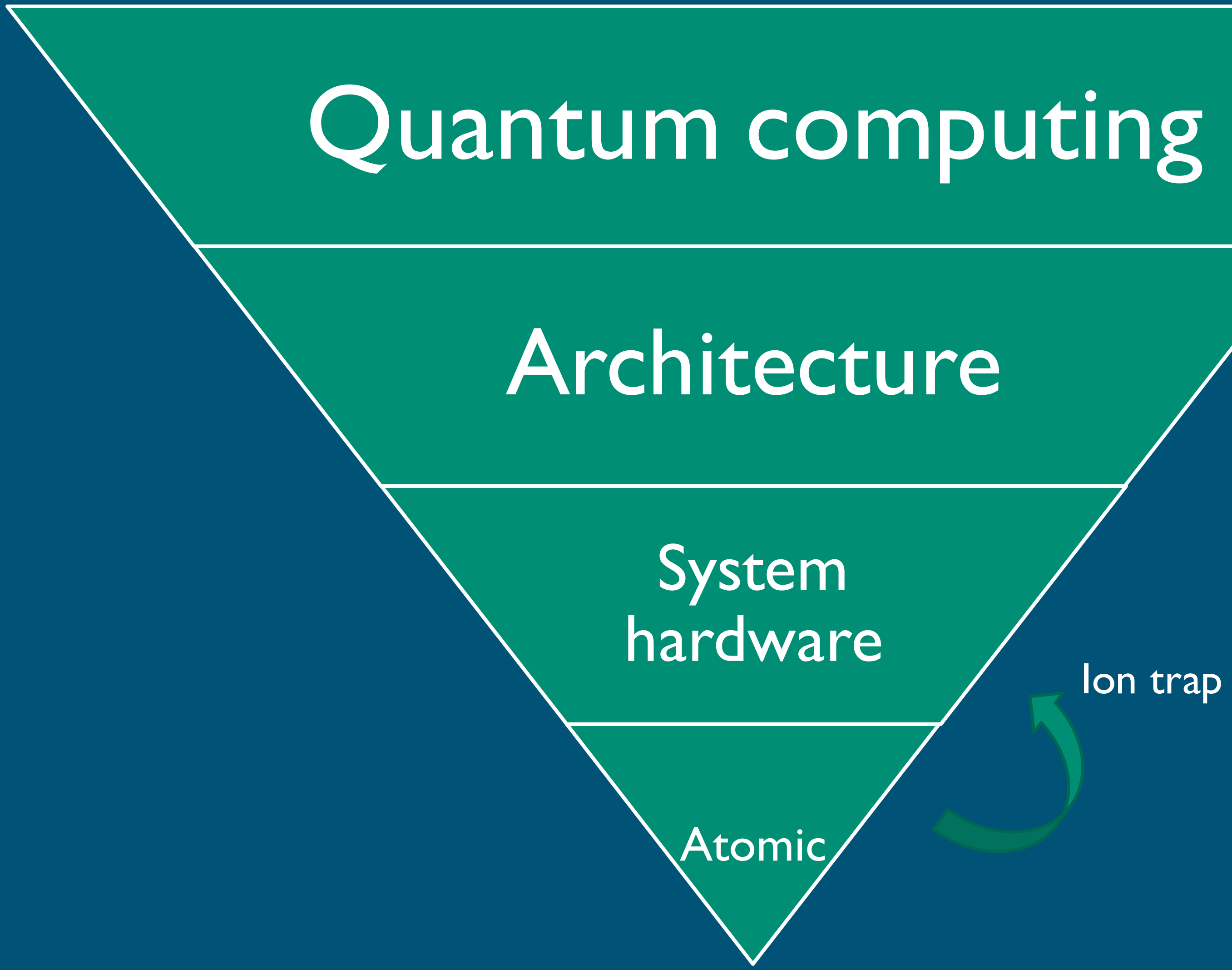
Overview


Quantum computing
Architecture
System hardware
Atomic
Ion trap

Trapped Ion Quantum Computing: quantum computing level

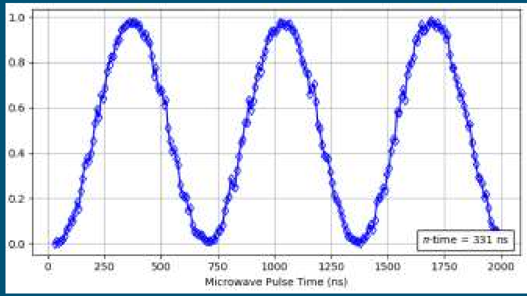
Classical computers

- Discrete states:
  - $|0\rangle$ or $|1\rangle$ (or $|10\rangle$ or $|11\rangle$ ...)
- Only "local" operations

versus…

Quantum computers

- Superposition states:
  - $\alpha|0\rangle+\beta|1\rangle$ (or $\gamma|10\rangle + \delta|11+\ldots\rangle$



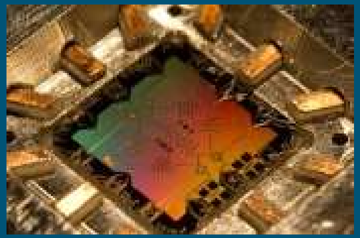
- Entanglement (non-classical states)
  - $\alpha|00\rangle+\beta|11\rangle$

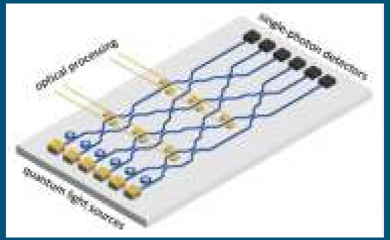
Exponential speedup for particular algorithms

- Quantum simulations
- Optimization/machine learning
- Factoring (Shor's algorithm)
- And there are caveats and limits within these categories!

There are multiple viable technologies

- Ion traps
- Superconducting JJ
- Neutral atoms
- Solid state: quantum dots/donors
- Photons





Trapped Ion Quantum Computing: architecture level

QCCD architecture

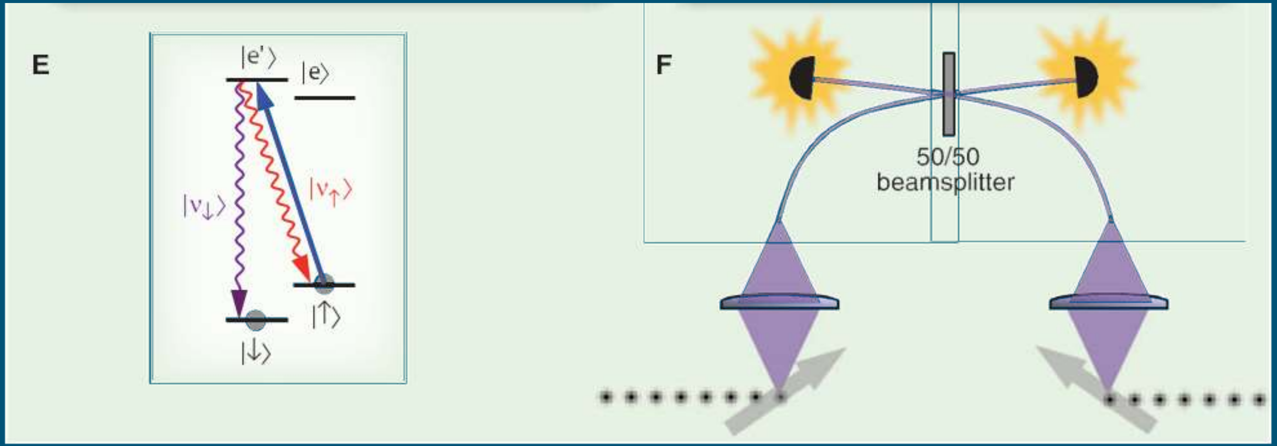
"Architecture for a large-scale ion-trap quantum computer," D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002).

- Originally proposed in 2002
- Achieves ND connectivity using ion transport (at cost of transport time)
- Strengths: all primitives demonstrated
- Weaknesses: transport speed, motional heating during transport

MUSIQC architecture

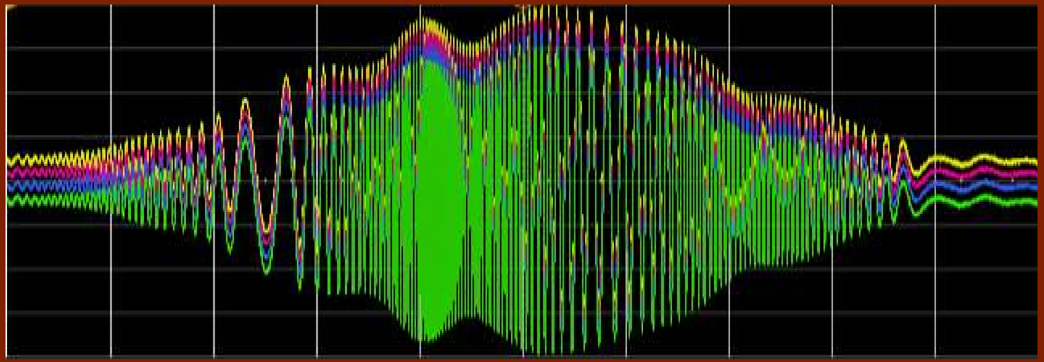
"Large Scale Modular Quantum Computer Architecture with Atomic Memory and Photonic Interconnects," C. Monroe, R. Raussendorf, A. Ruthven, K. R. Brown, P. Maunz, L.-M. Duan, J. Kim, Phys. Rev. A 89, 022317 (2014).

- Originally proposed in 2014
- Achieves ND connectivity using a combination of ion transport, radial mode operations, and photonic interconnects
- Strengths: photons are a transportable, potentially universal qubit, all primitives demonstrated, "modular"; faster early scaling
- Weaknesses: lacks scalable demonstration of photonic interconnect

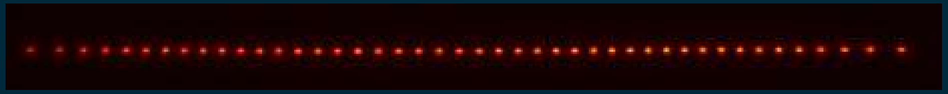


Trapped Ion Quantum Computing: system hardware level

Electrical control system

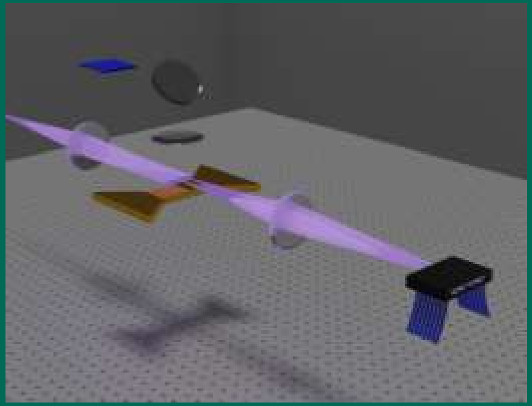


Imaging

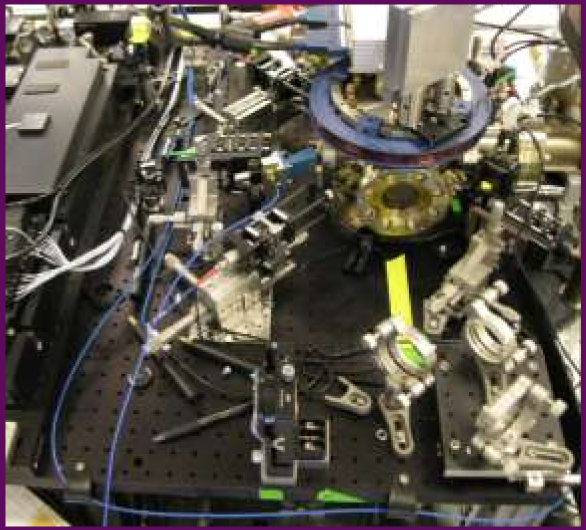


Lasers

Optical modulators & delivery

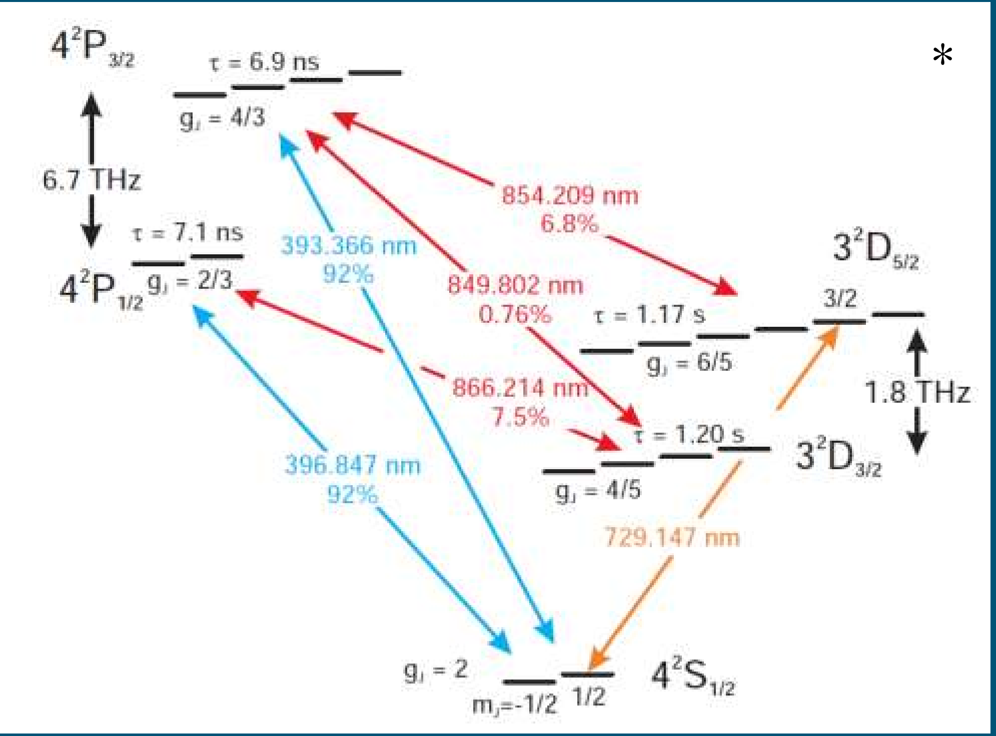


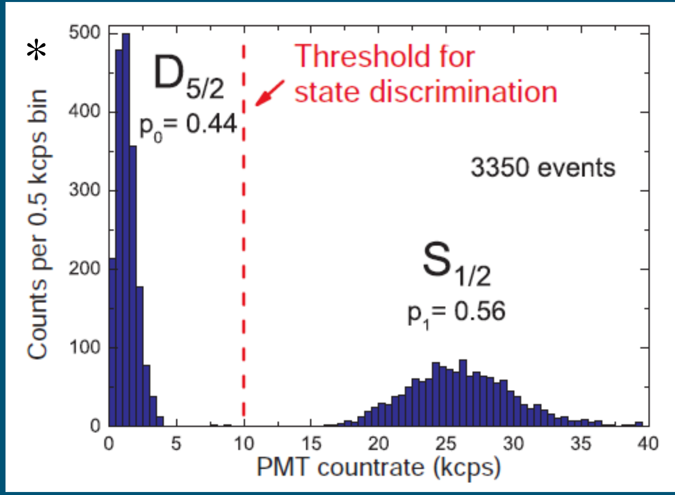
Vacuum/cryo chamber

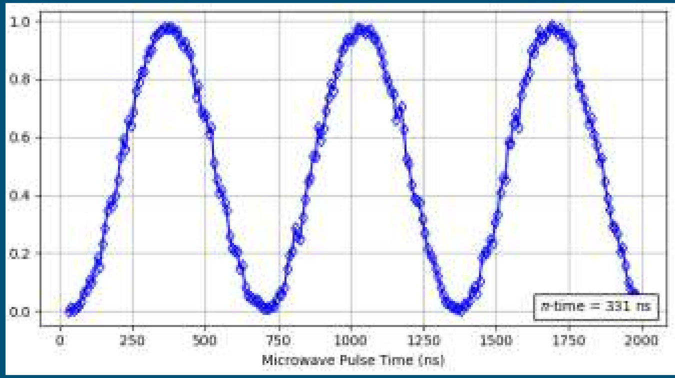


Trap + package

Trapped Ion Quantum Computing: atomic level







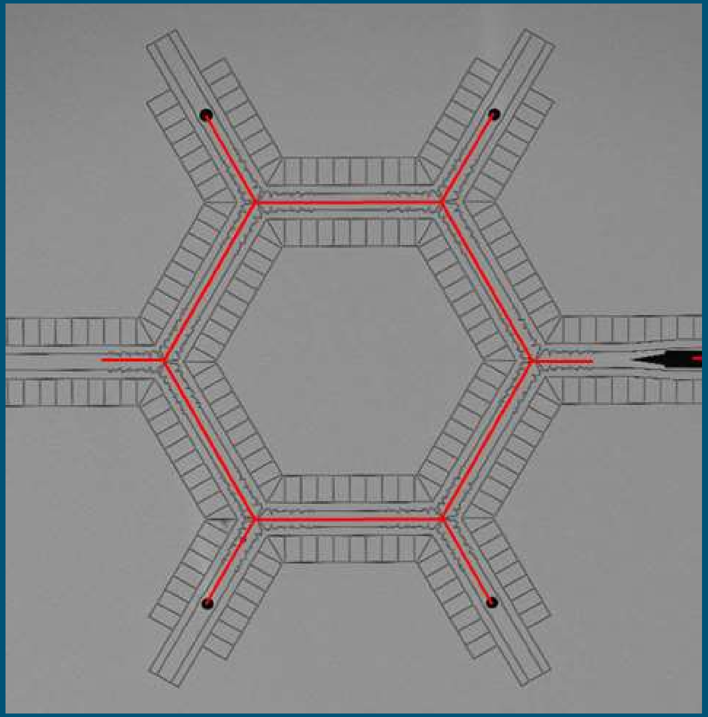
* “Precision spectroscopy and quantum information processing with trapped calcium ions”, Jan Benhelm PhD Thesis (2008)

Physical errors (best demonstrations from multiple groups)

- 1Q error: 1e-5
- 2Q error: 1e-3
- Detect, prep: <1e-4
- T1: 1s … infinite
- T2: 10 ms … 10 s

Trapped Ion Quantum Computing: trap level

- Using electric fields we can trap multiple individual ions, move them around, and probe them with lasers
- Stored in an ultra-high vacuum environment at room or cryogenic temperatures
- Lasers are tuned based on the atomic structure of the ion.
  - Many species are used (Ca, Yb, Be, Mg, Ba, …)
  - Used to perform quantum operations (microwaves can do the same thing)



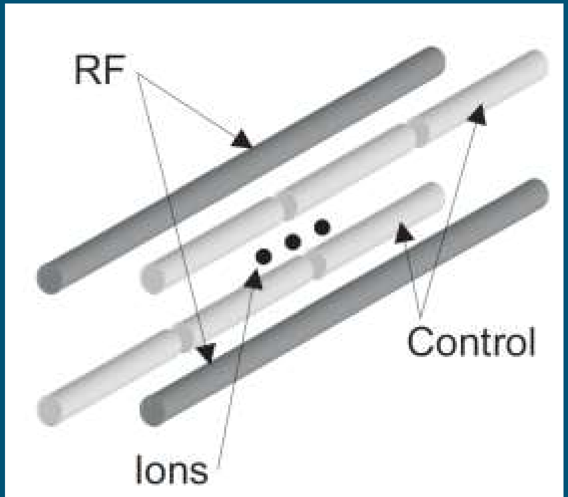
Ion traps: advantages/challenges of microfabricated traps

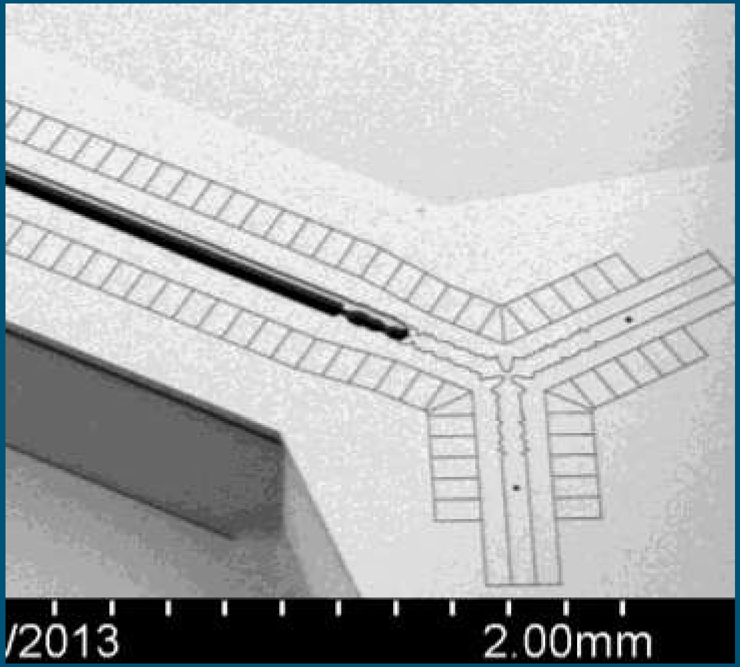
Advantages

- More manufacturable (“scalable”)
- Consistent geometry -> consistent behavior
- Greater field control (more electrodes)
- 2D geometry
- Integration of other technologies (waveguides, detectors, filters…)
- Laser access

Challenges

- Low depth (ion lifetime), anharmonicities in potential
- Proximity to surface (charging, heating)
- Delicate (dust, voltage)
- Capacitance (high power dissipation)





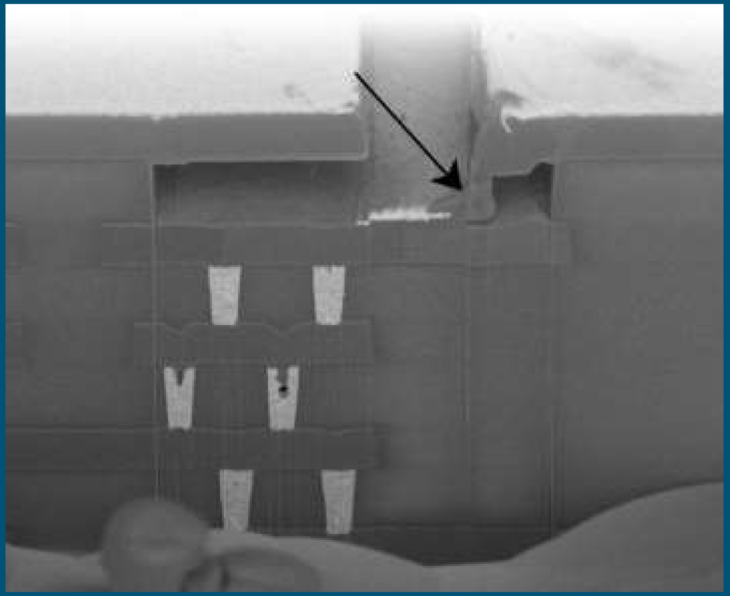
Ion traps: derived requirements

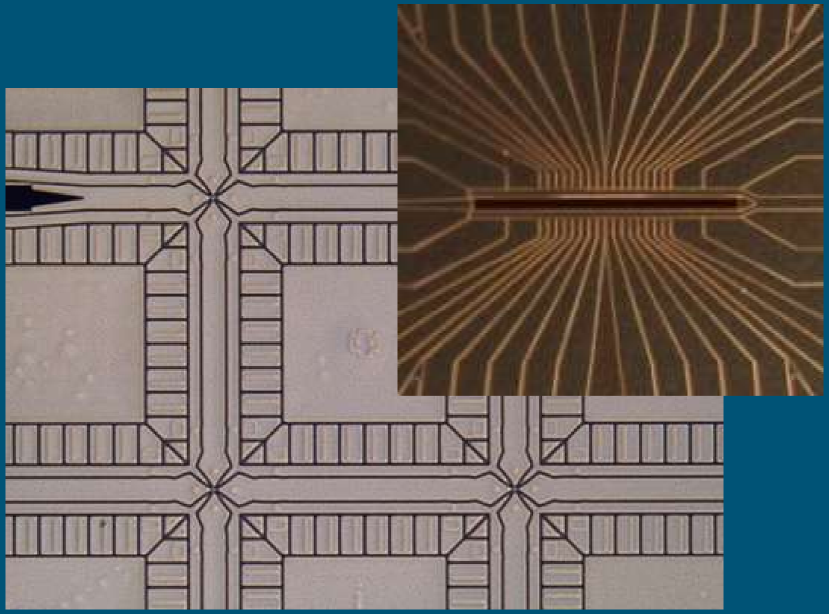
Essential capabilities

- Store ions for long periods of time (hours)
- Move ions to achieve 2D connectivity
- Support high fidelity operations
- Uniform performance

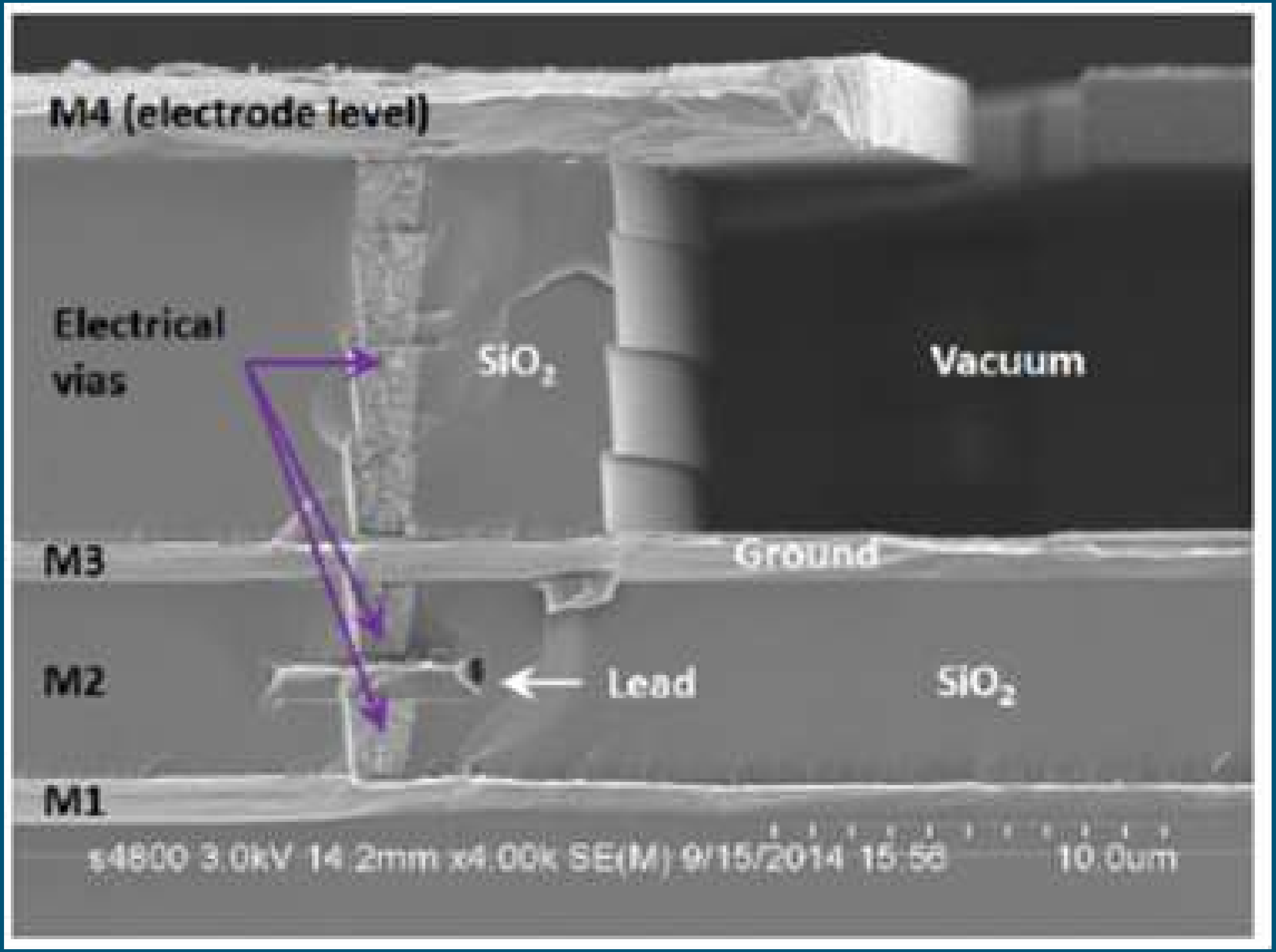
Derived requirements

- Voltage breakdown >300 V @ ~50 MHz
- Backside loading hole
- Multi-level lead routing for accessing interior electrodes
- Standardization [lithographically defined electrodes]
- Overhung electrodes
- High optical access [high NA delivery and collection optics]



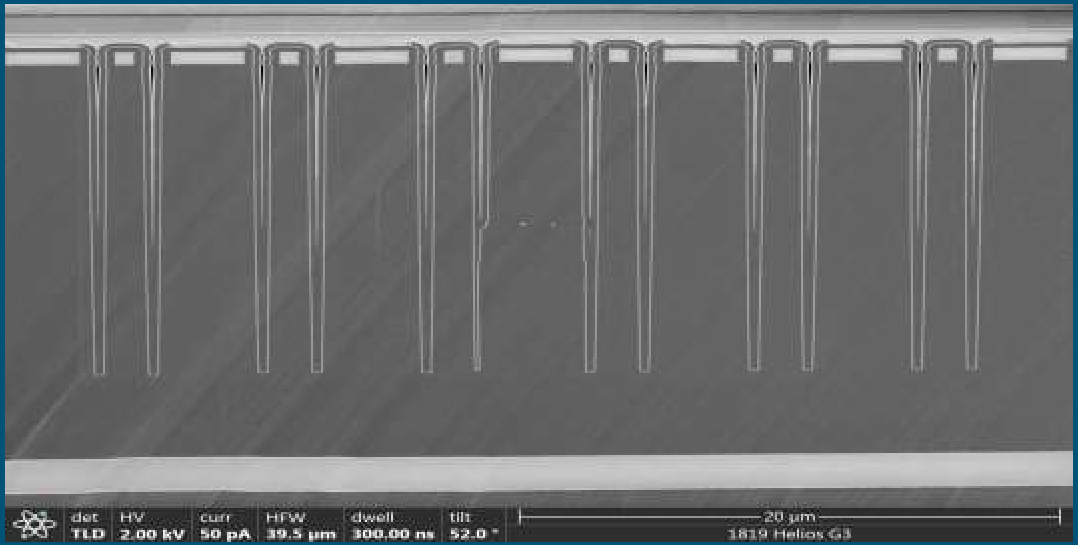


Ion traps: multiple metal levels



Ion traps: trench capacitors and loading holes

Capacitors



Interposer (current)

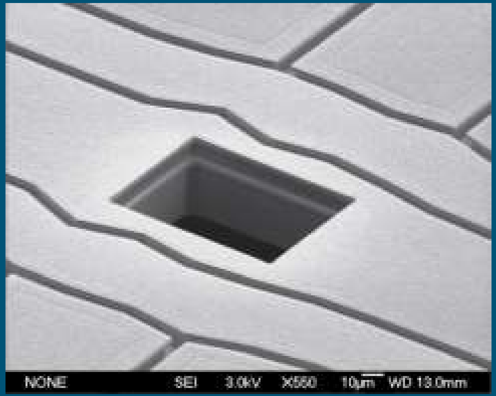
- 20V max voltage
- 1nF capacitance

On chip

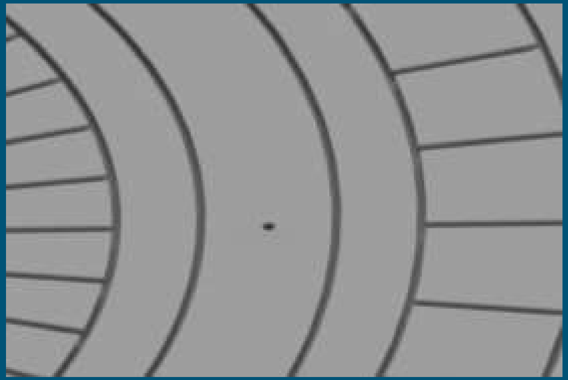
- 15V max voltage
- 200pF capacitance (but low inductance)
- Up to 200 capacitors can be located within the isthmus

Loading holes

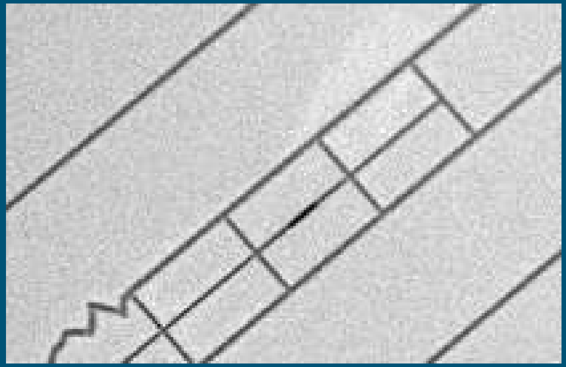
50µm×80µm
modulation necessary



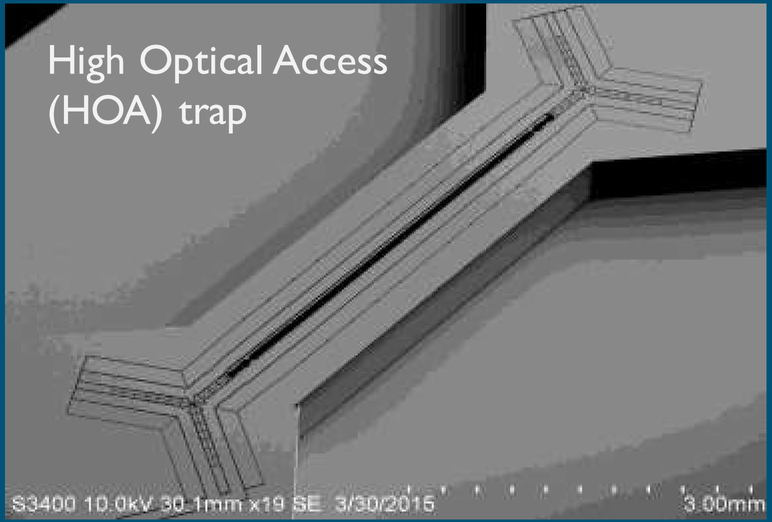
10µm hole
still perturbs the field

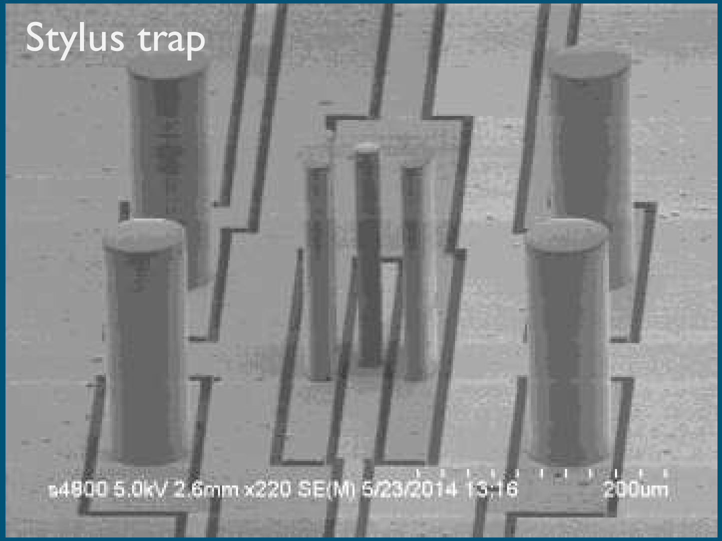


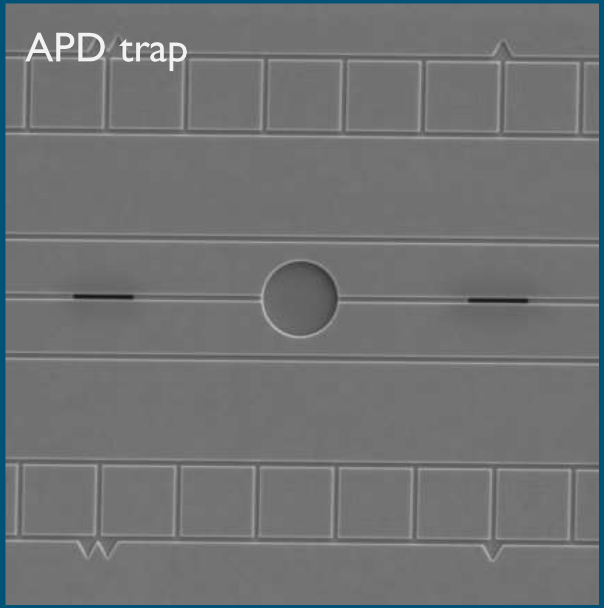
3µm×20µm

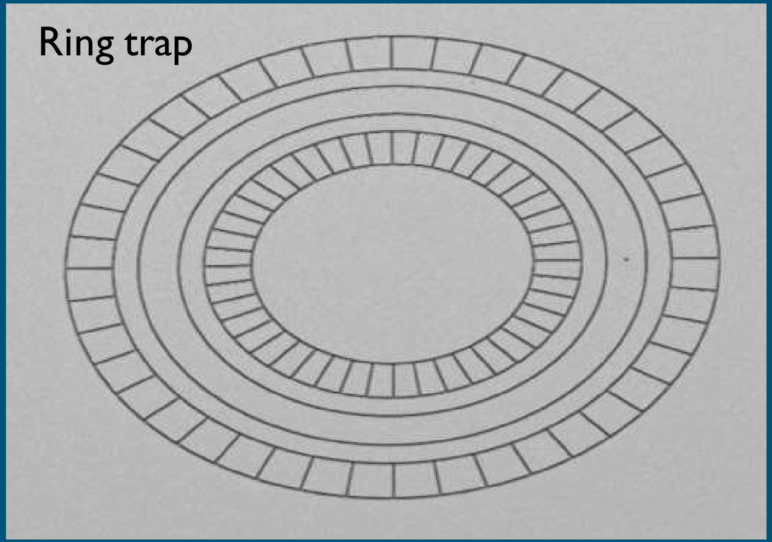


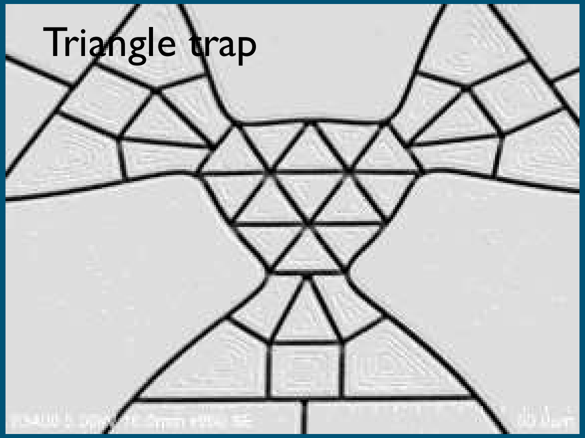
Ion traps: Sandia's trap zoo (partial list)

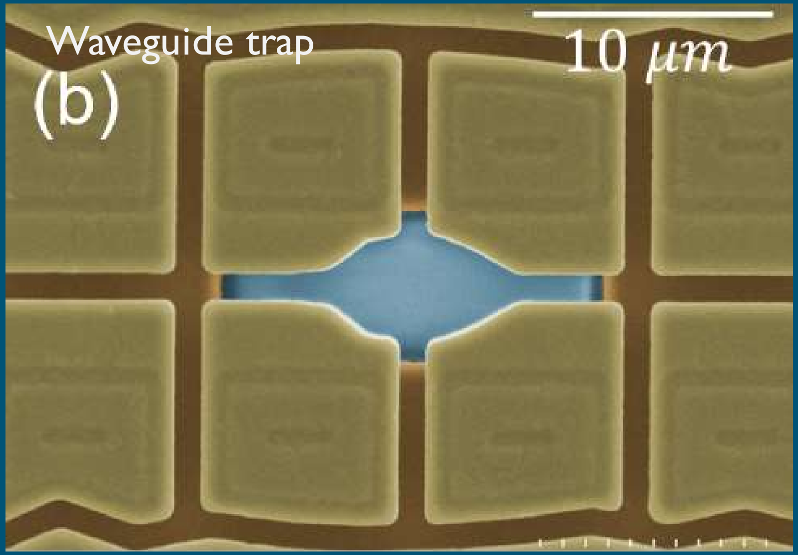








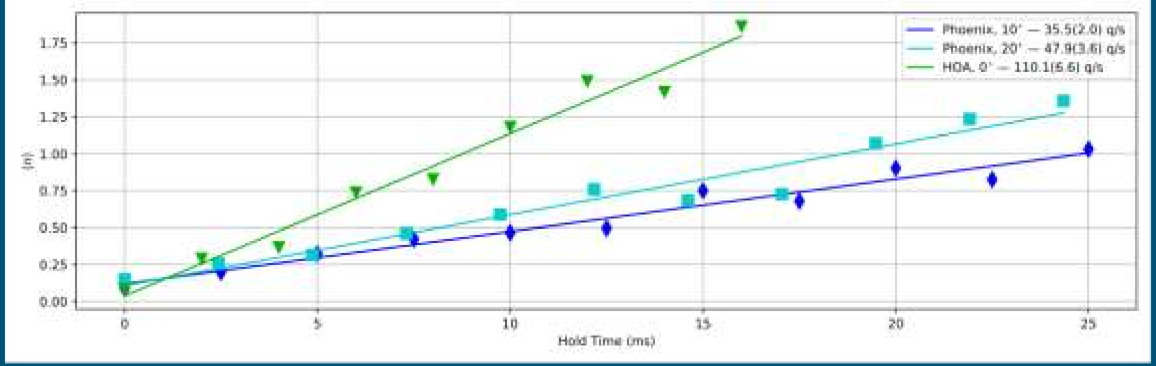


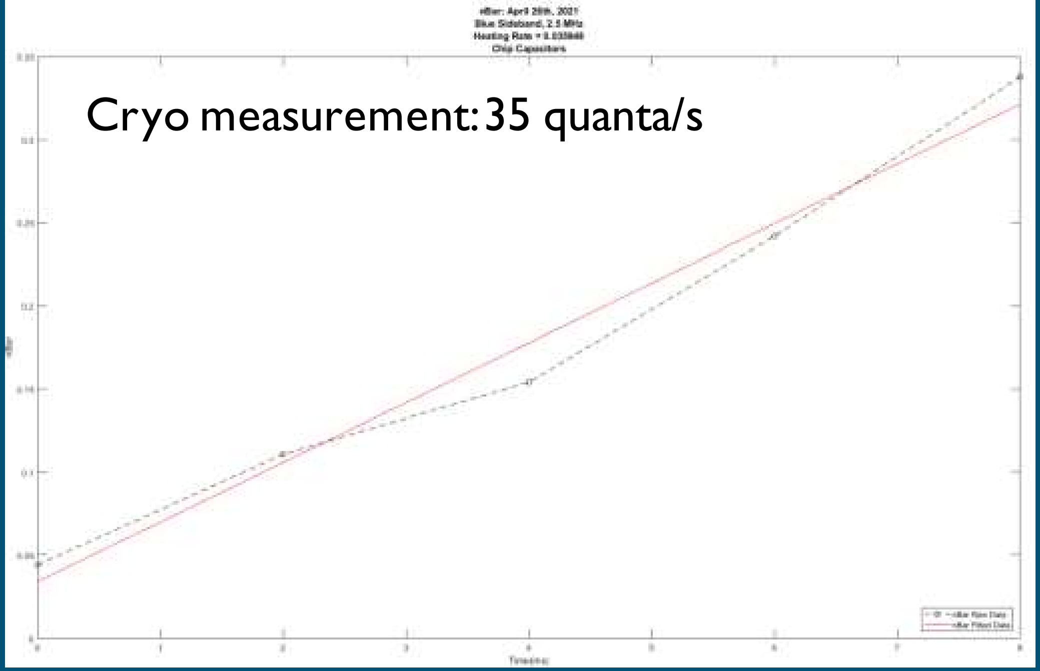


Trap characterization: motional heating

Electric field noise on the trap electrodes heats the ion. This can be due to a variety of sources (Johnson noise of resistors, DAC voltage noise, …) but these can be reduced to a low level, leaving "anomalous heating sources".

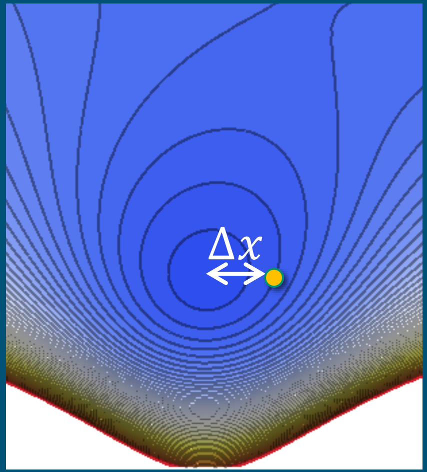
- Many groups have studied dependence on trap temperature, surface treatment, frequency
- Recently several groups have observed that heating at cryogenic temperatures does not drop as expected with multi-metal level silicon traps. We are collecting data on variants (capacitor, substrate resistivity, additional films like polysilicon, nitride, oxide, and ion height)

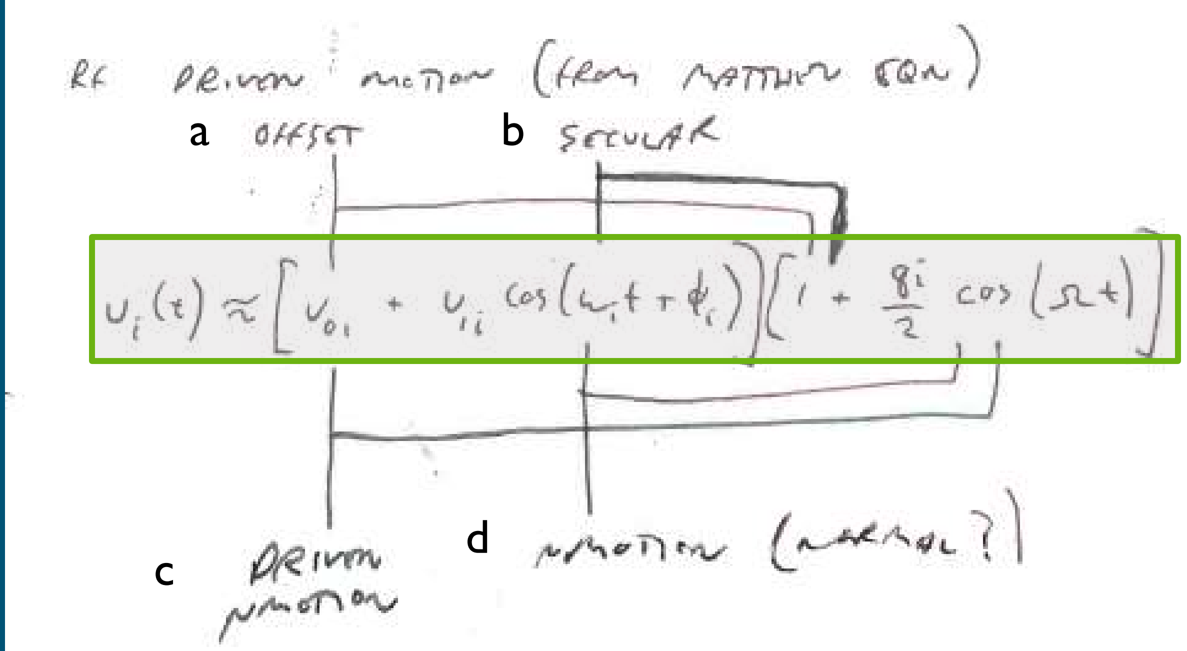


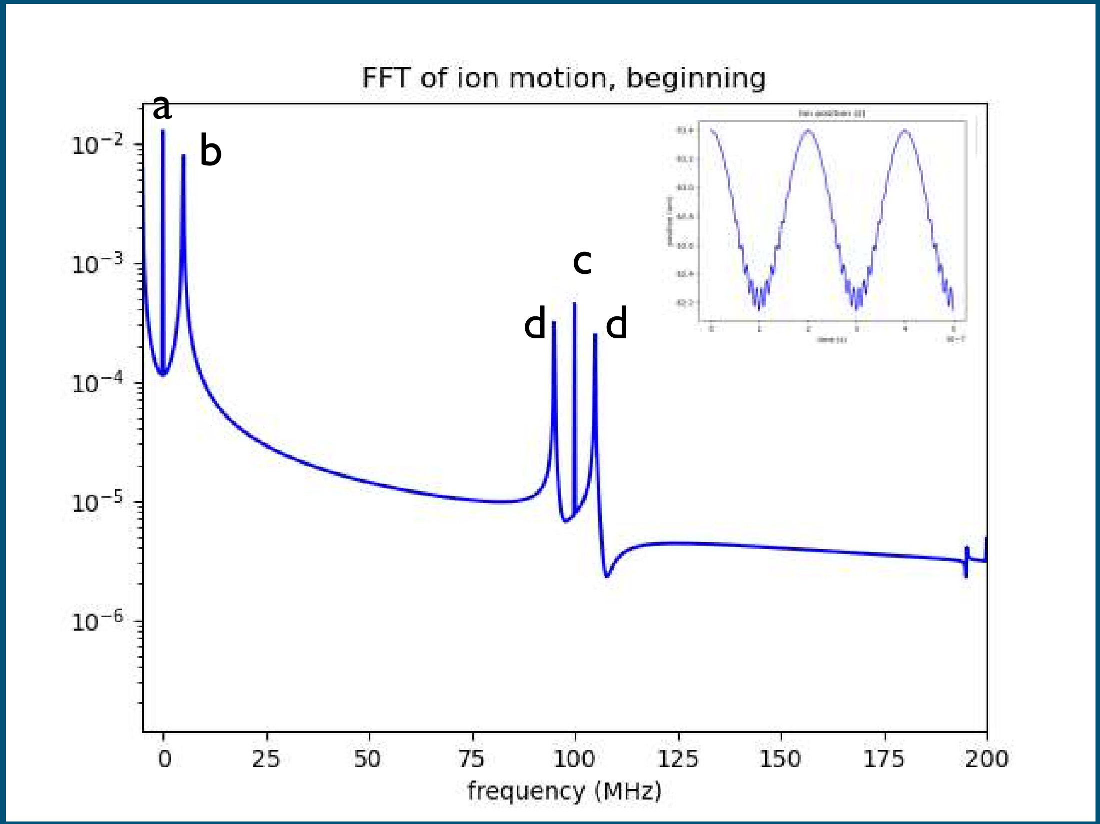


Trap characterization: background electric field

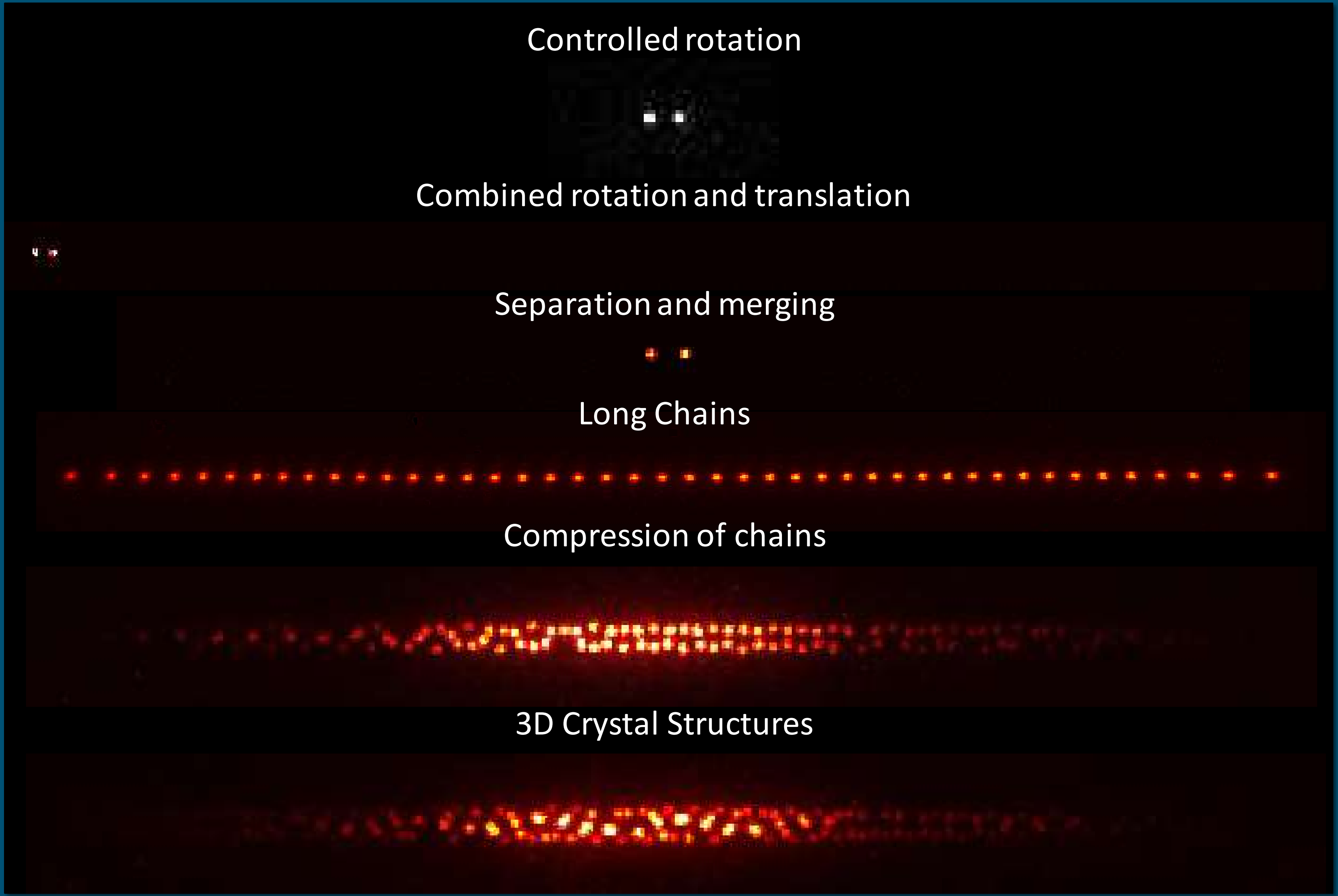
Positioning an ion at the RF null to eliminate driven micromotion







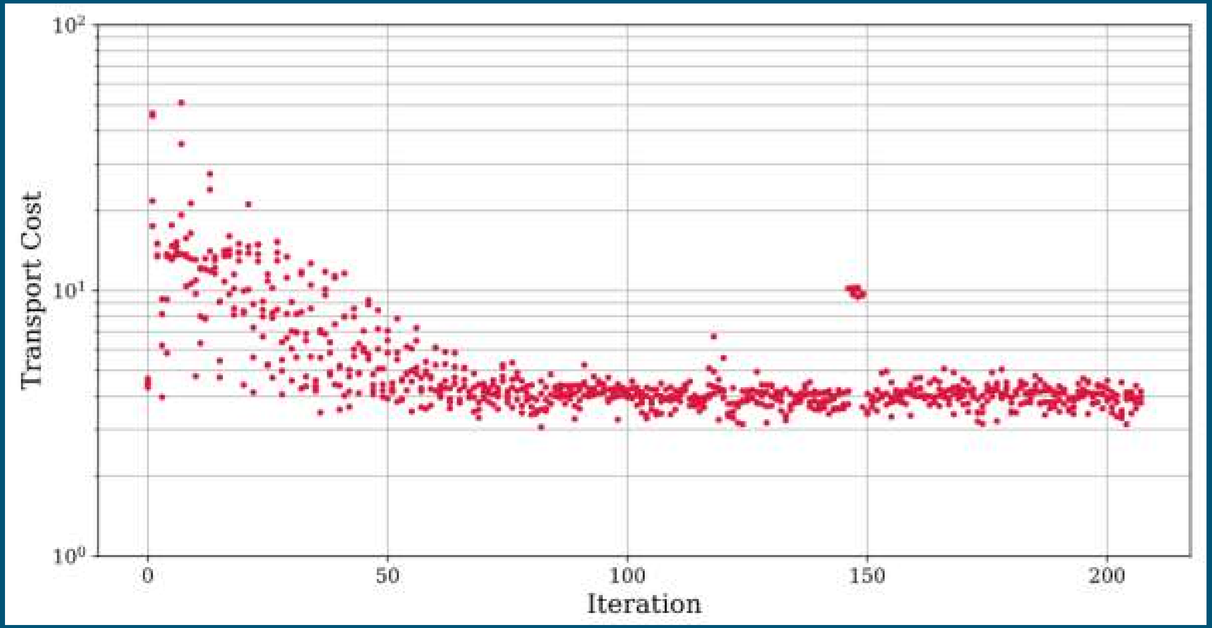
Trap characterization: controlled transport



Trap characterization: controlled transport

Using Nelder-Mead optimization

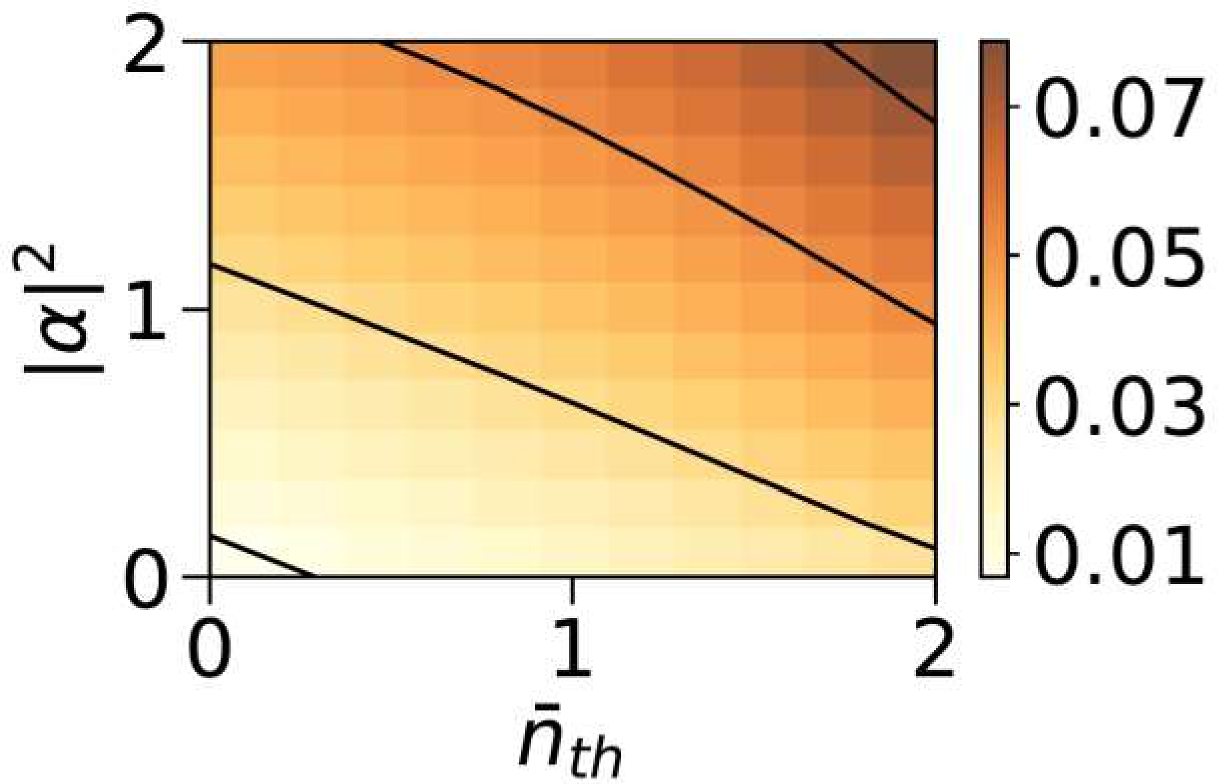
- What is this optimizing?
  - Inaccuracies in simulation
  - Background electric field
  - Variation of filter components
- Optimization protocol
  - 3 Bezier coefficients
  - 6 axial frequency points
- Measurement
  - 120 iterations with short probe
  - Followed by 200 iterations at a longer probe time
  - Varied delay time at end point
- Velocity: 0.5 electrodes/μs. (6 μs to go 210 μm)

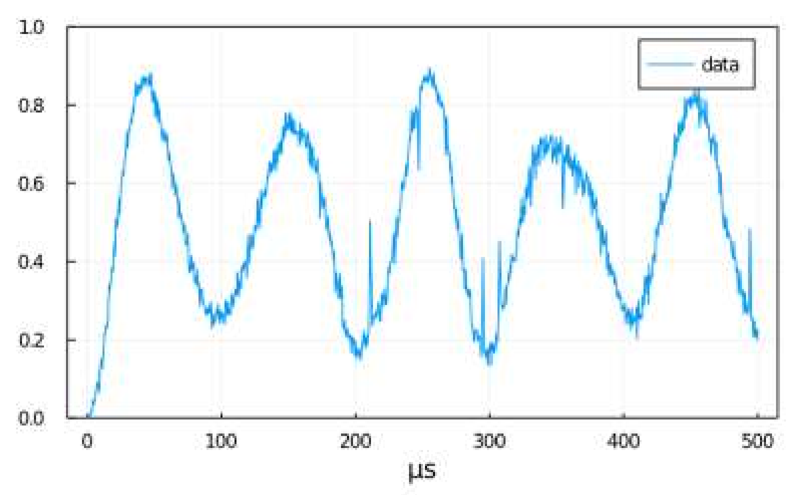


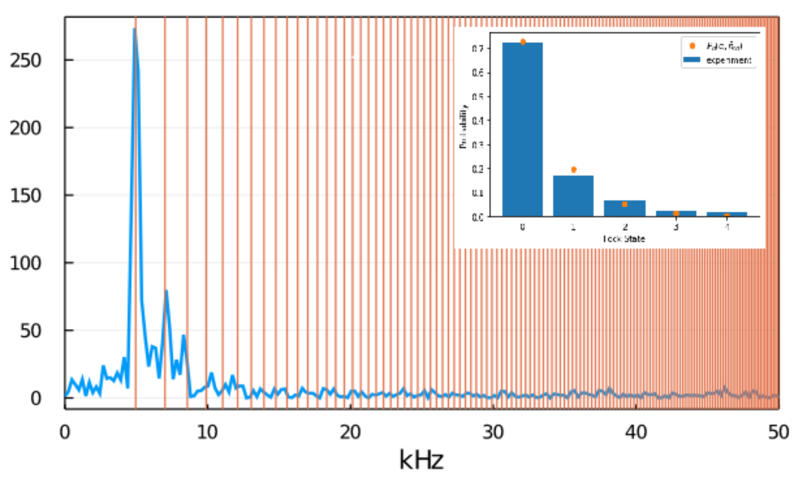
offset	$\bar{n}$
0 steps	0.38 ± 0.04
3 steps	0.71 ± 0.10
6 steps	0.58 ± 0.07
9 steps	0.26 ± 0.03

Quantum operations: motional excitation and infidelity

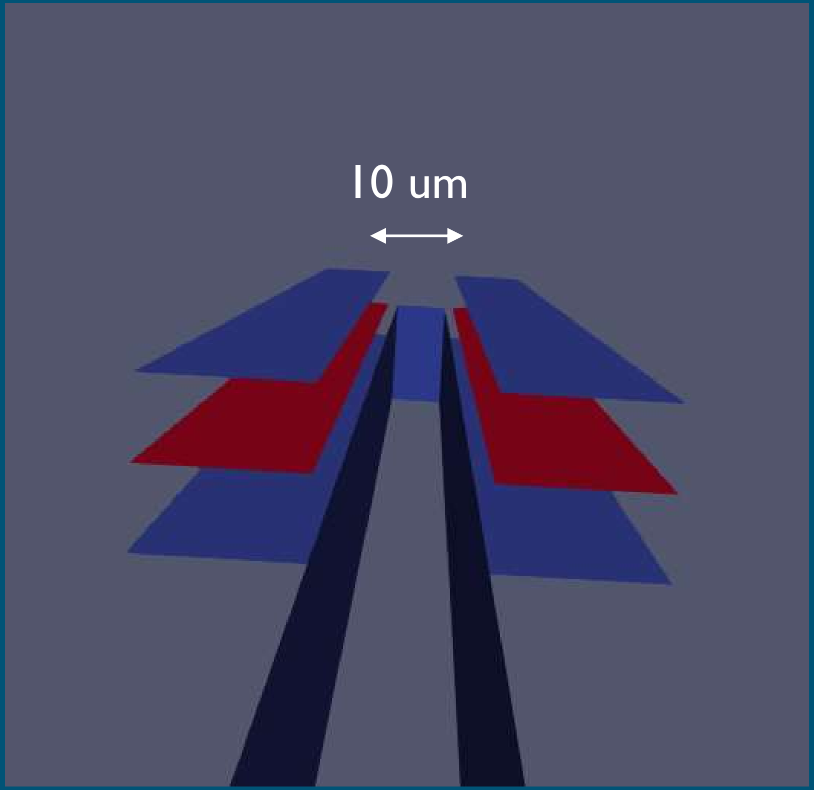
Infidelity vs coherent and thermal motional excitation

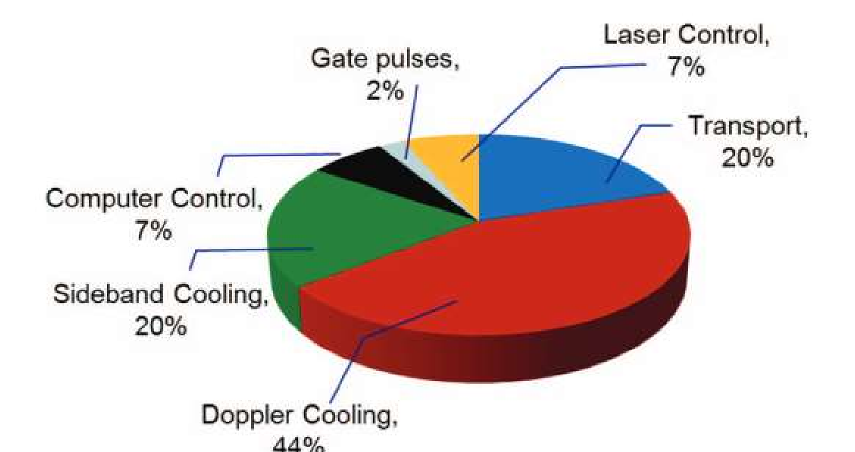




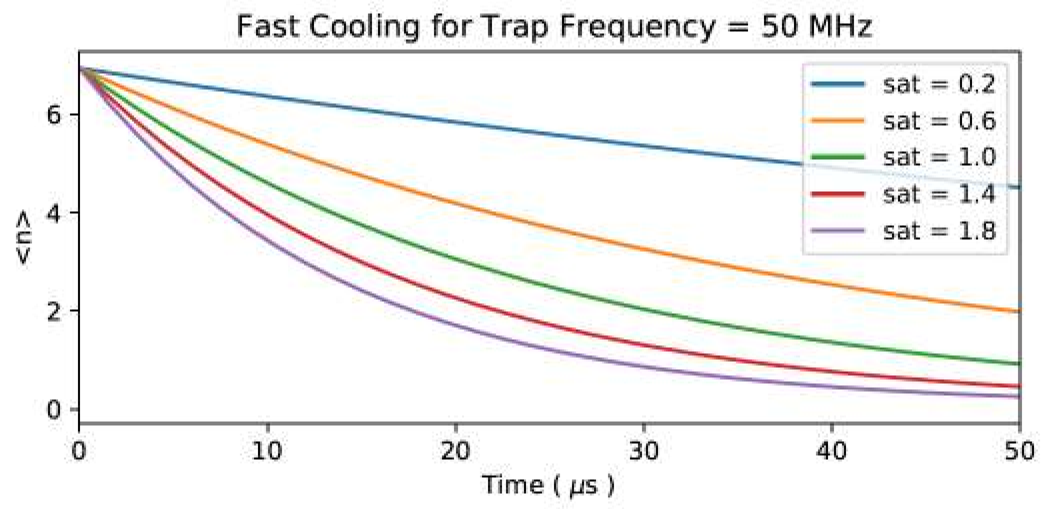


Very miniaturized traps: high frequency





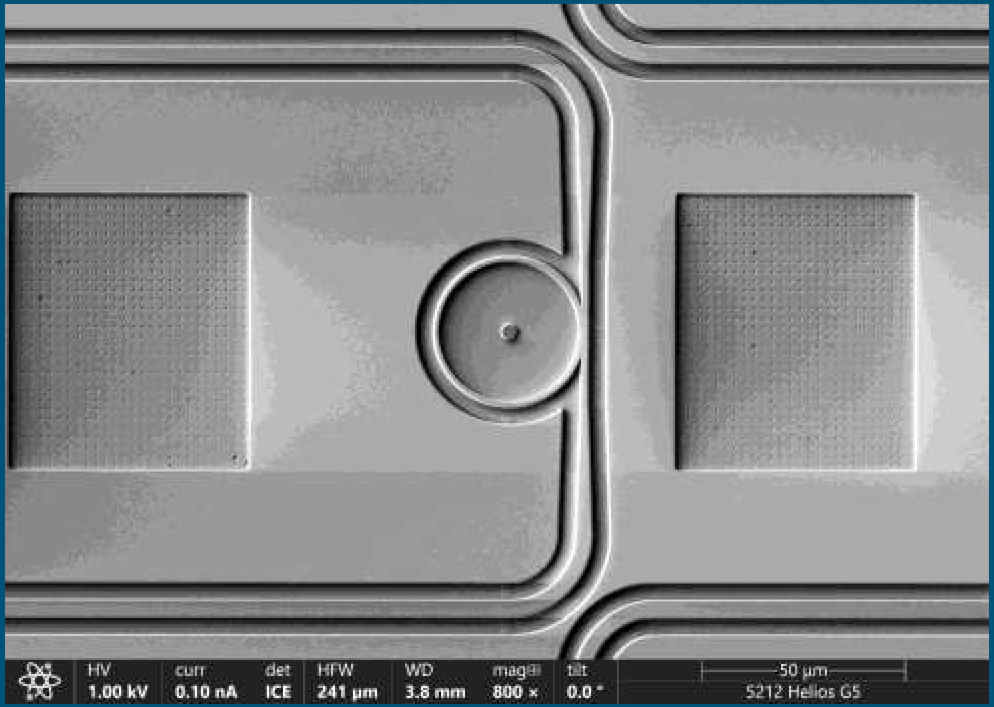
Bowler, *et al.* Rev. Sci. Inst **84,** 033108 (2013)

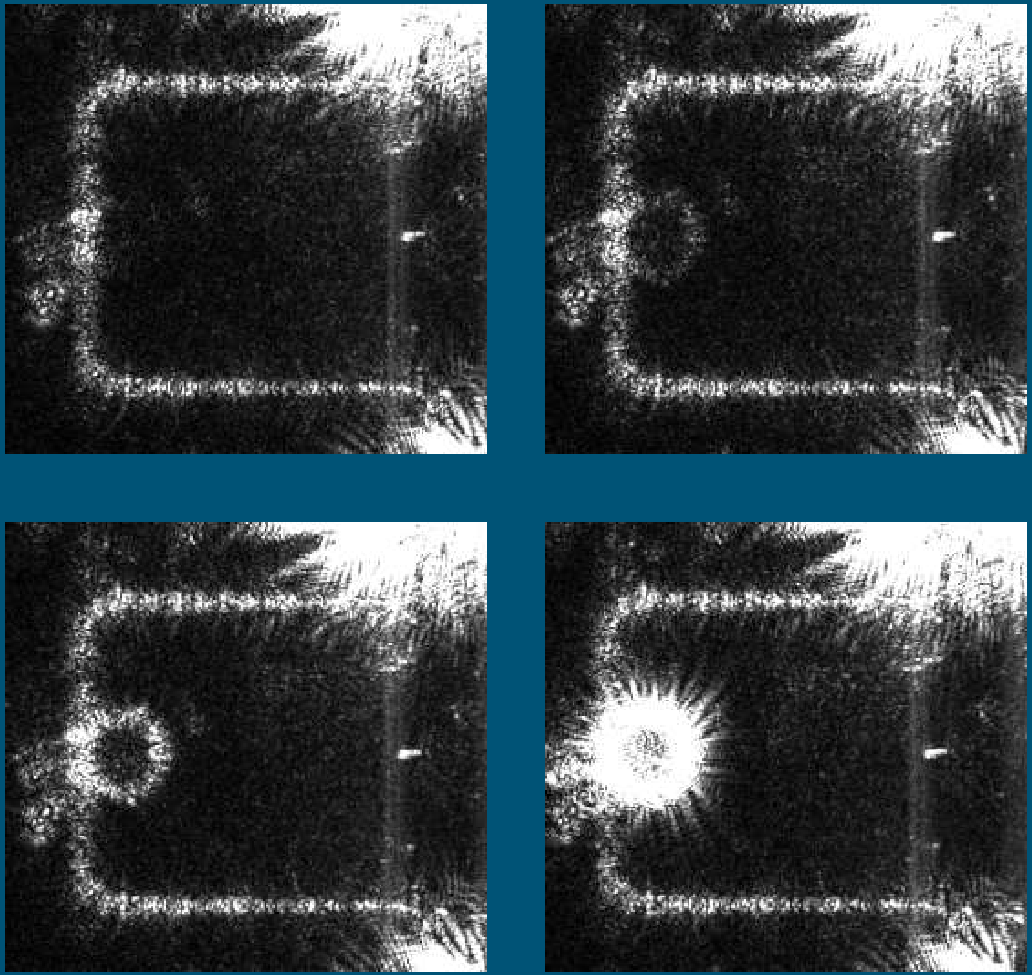


Can achieve trapping strengths (frequencies) of 50 MHz to 100 MHz, compared to current traps with 5 MHz to 10 MHz trapping strengths.

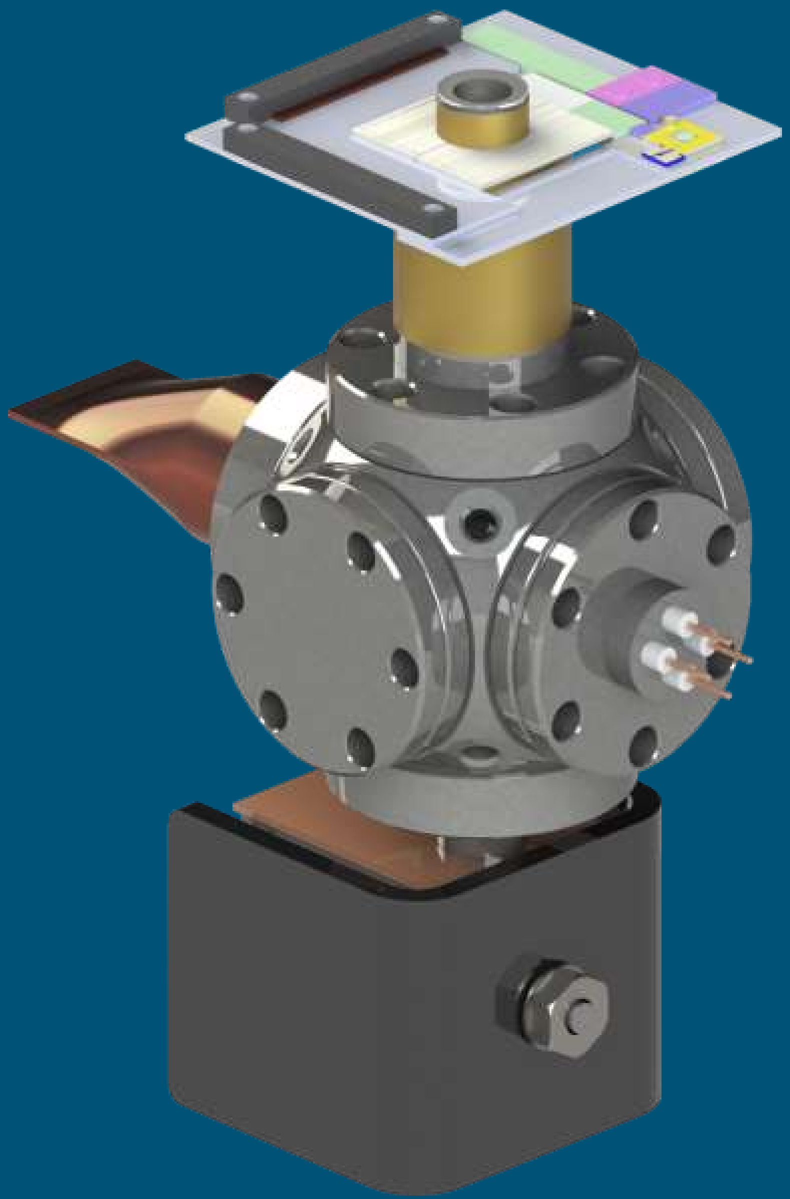
Optical modulators: piezo-activated aluminum nitride rings

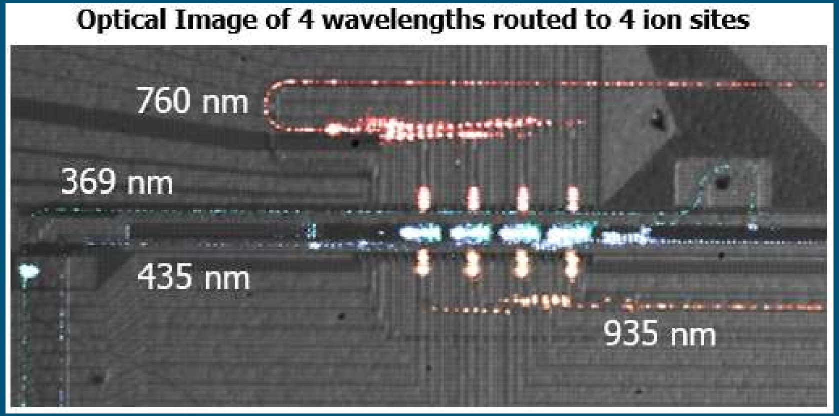
On-chip optical modulators can make the devices more compact, robust, and reproducible. However the wavelength, size limitations, and process compatibility make this a challenging problem.

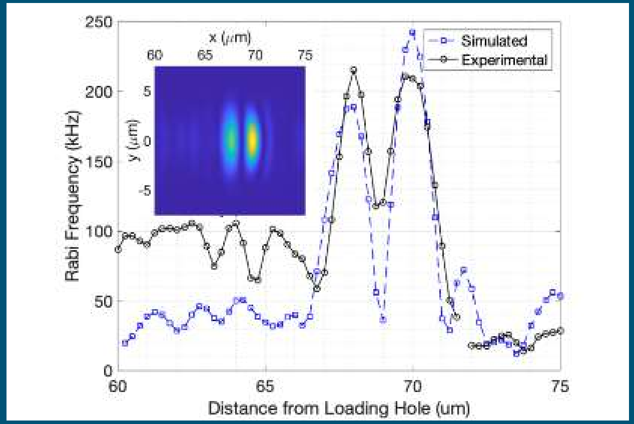


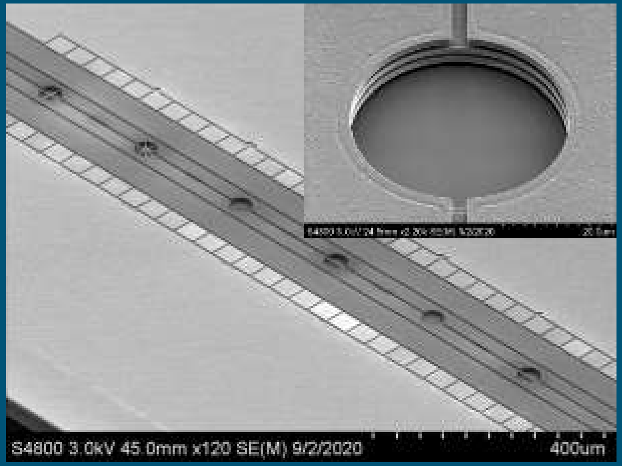


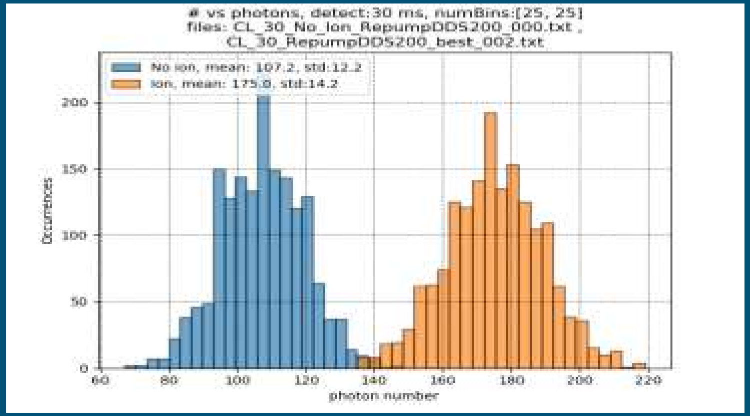
Ion clocks: integrated technology







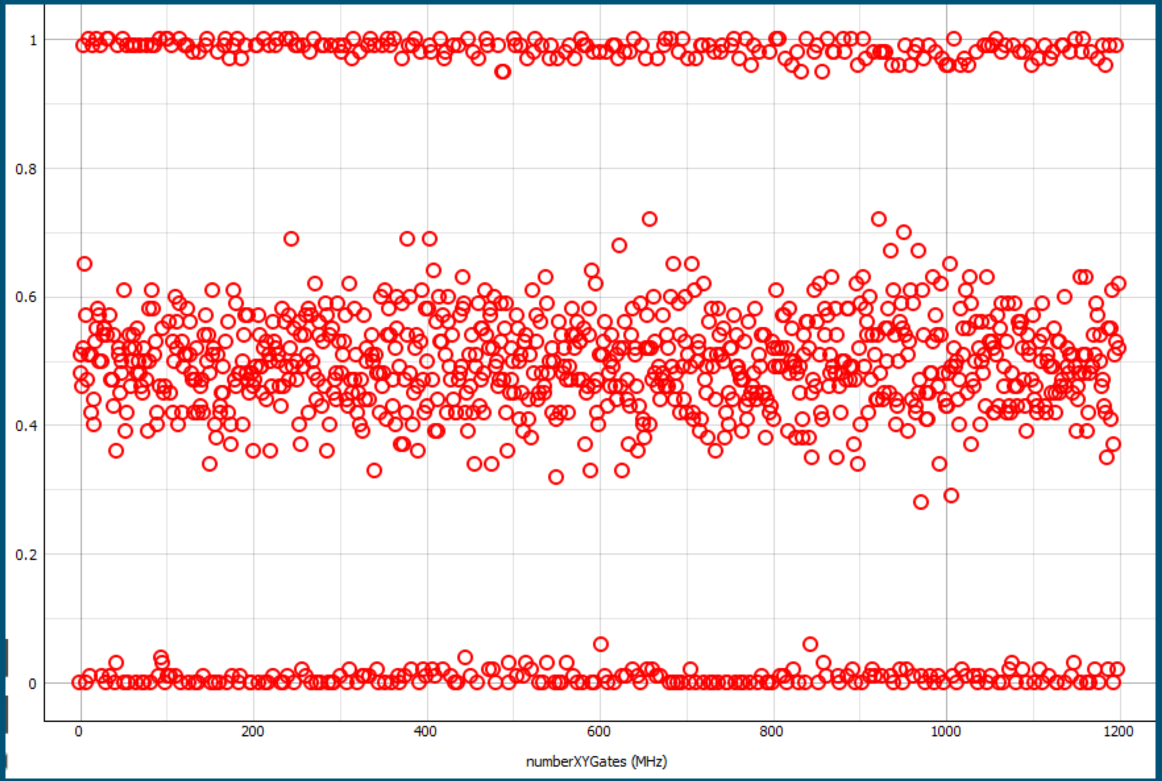


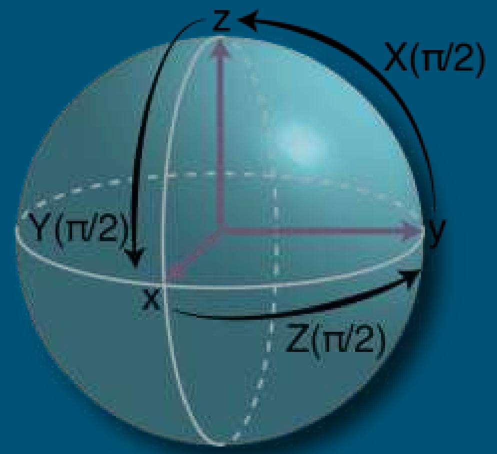


Errors: calibrating and understanding errors in QC

Gate Set Tomography (GST)

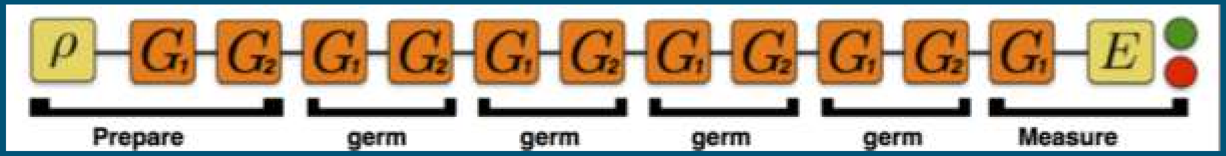
- No calibration required
- Detailed debug information
- Efficiently measures performance characterizing fault-tolerance (diamond norm)
- Amplifies errors
- Detects non-Markovian noise
- Robin Blume-Kohout, Kevin Young, Eric Nielsen, SNL





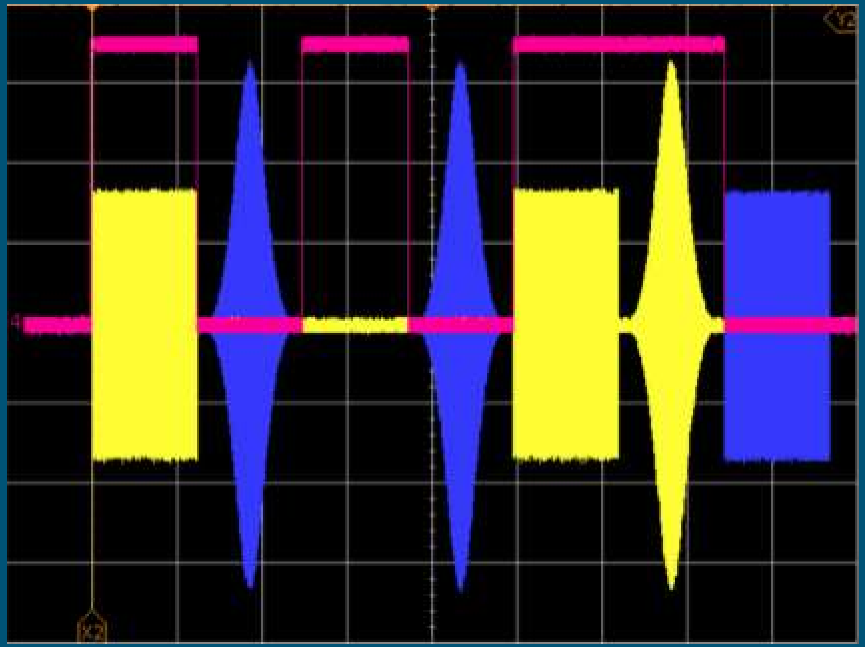
Desired "target" gates:

G_i	Idle (Identity)
G_x	$\pi/2$ rotation about x-axis
G_y	$\pi/2$ rotation about y-axis



Ion trapping at Sandia

- QSCOUT: Quantum Scientific Open User Testbed
  - https://www.sandia.gov/quantum/Projects/QSCOUT_Call2021.html
  - **Proposals due June 18!**
- Quantum Systems Accelerator (NQI center)
  - Many collaborators, electronics and fabrication
- QSENSE (NQI collaboration with Jim Plusquellic, Eirini Tsiropoulou, Nafis Irtija)
  - FPGA control system
- DARPA TICTOC (ion clock)
- DOE
  - Light modulation
  - Light delivery
  - Single mode light collection
- IARPA LogiQ
  - Trap characterization, collaboration
- LPS
  - High frequency, very small ion traps



We are frequently looking for postdocs (including now)!

Acknowledgments

Experiments
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Megan Ivory
Ryan Law
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Melissa Revelle
Will Setzer
Jon Sterk
Dan Stick
Josh Wilson
Christopher Yale

Trap design, fab, packaging
Matthew Blain
Jason Dominguez
Ray Haltli
Ed Heller
Tipp Jennings
Becky Loviza
John Rembetski
Corrie Sadler
Ben Thurston
Jay Van Der Wall

Integrated optics
Daniel Dominguez
Matt Eichenfield
Mike Gehl
Galen Hoffman
Rex Kay
Andrew Leenheer