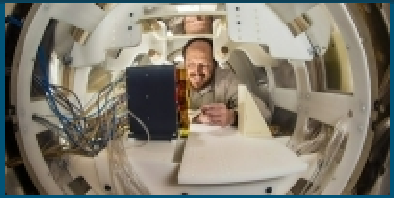
SAND2021-15276C

Sandia National Laboratories

The Influence of Material Choices on Trapped Ion Performance




Todd A. Barrick, Brian McFarland, Melissa Revelle, Daniel Stick

Sandia National Laboratories

Materials Research Society, Fall Meeting and Exhibit

Boston, Massachusetts

December 7th, 2021

U.S. DEPARTMENT OF ENERGY NNSA

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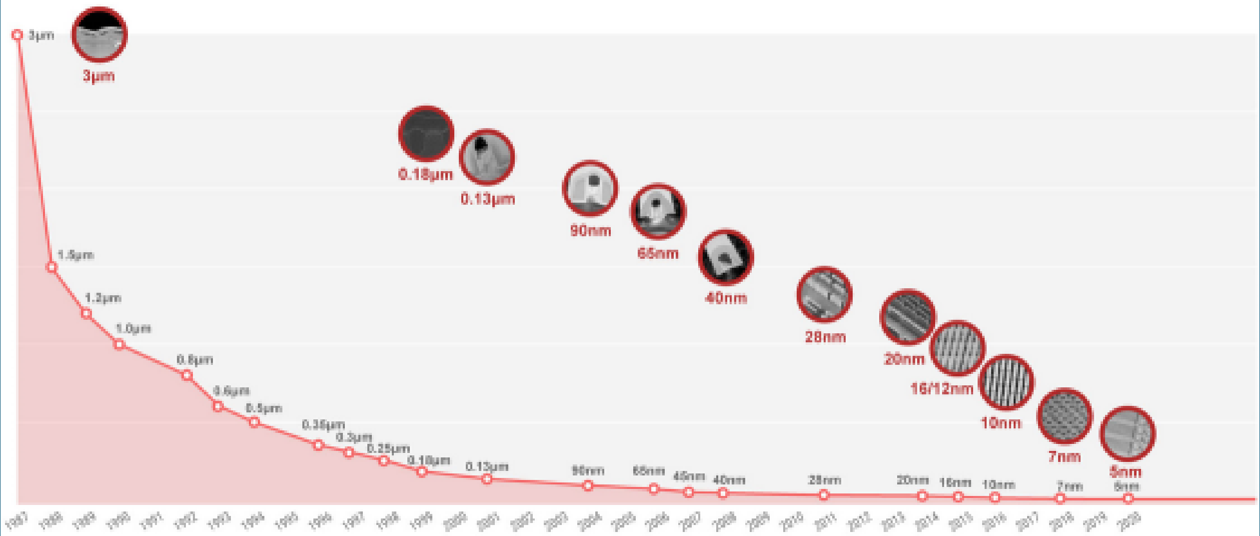
Overview

- Intro to Trapped Ion Quantum Computing
- Ion Trapping at Sandia National Laboratories
- Noise Mechanisms in Ion Traps
- The Experiment
- Wrap Up

Quantum Computing Motivation

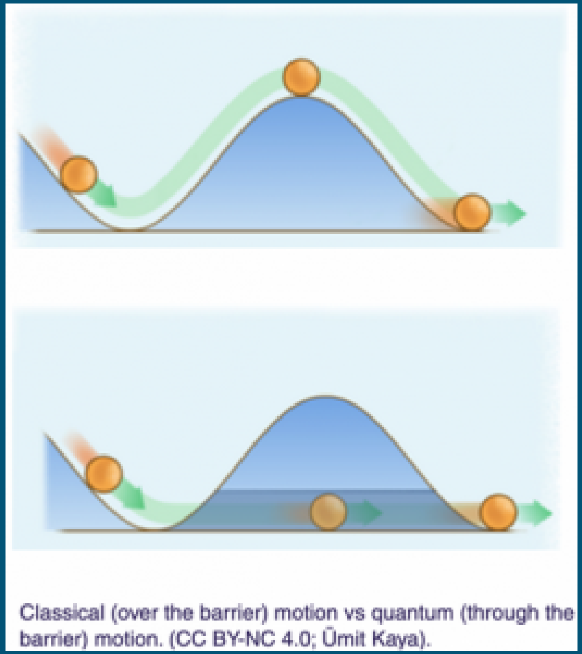
"Moore's Law has finished…" ~ Jensen Huang, CEO, NVIDIA



Processing technology over the years. Taiwan Semiconductor Manufacturing Company (TSMC). https://www.tsmc.com/english/dedicatedFoundry/technology/logic/l_5nm

We are starting to see the limits of processor speed ups, though the debate on when Moore's Law will end is on-going. It is broadly recognized that we are reaching the end.

As the size of the transistors continues to decrease, they eventually stop behaving classically and start behaving according to quantum mechanics. Eventually they become small enough that electrons tunnel directly through.

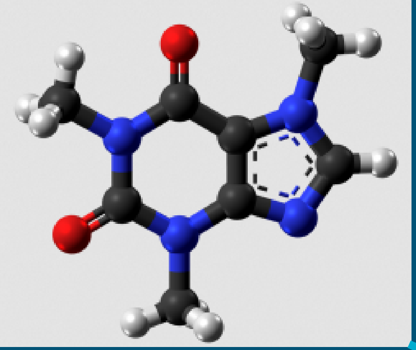


Electron Tunneling. Sifted. https://sifted.eu/articles/computer-chips-quantum-fingerprints/

Quantum Computing Motivation – Part 2

Quantum computers will can solve problems that classical computers could not possibly solve…

Bob Sutor - Vice President, IBM Q Strategy & Ecosystem, https://www.ibm.com/blogs/research/author/bob-sutor/2021

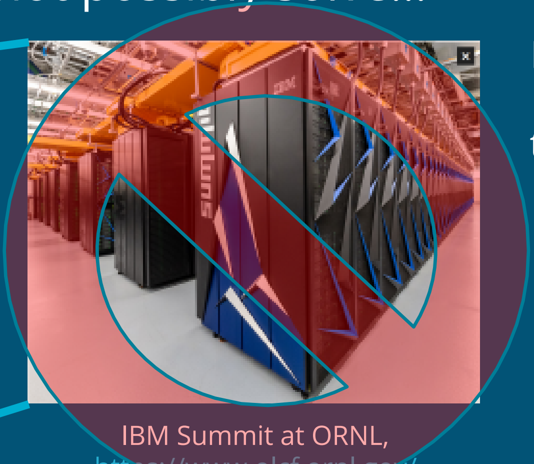


Ball-Stick Model of Caffeine Molecule, $C_8H_{10}N_4O_2$, https://commons.wikimedia.org/wiki/File:Caffeine_molecule_ball_from_xtal_(1).png

10^{48}

(1's & 0's)

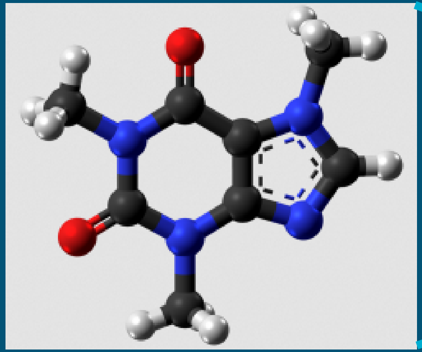
The amount of storage required to represent 1 Caffeine Molecule



IBM Summit at ORNL, https://www.olcf.ornl.gov/summit/, 2021

Number of Atoms on the Earth ~ 10^{50}

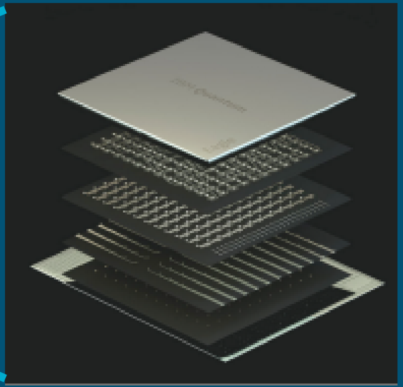
One 5nm transistor is about 10 atoms



("perfect")

160 qubits

The number of qubits to represent 1 Caffeine Molecule

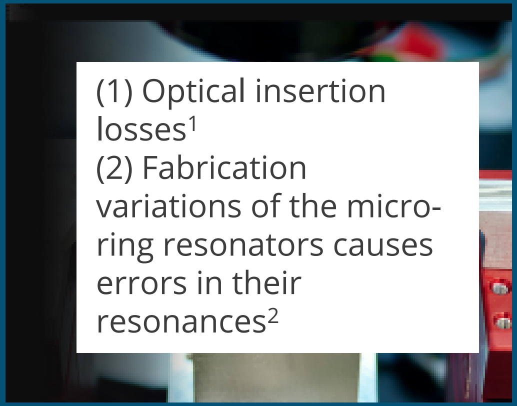


IBM Eagle – 127 qubit processor, https://newsroom.ibm.com/2021-11-16-IBM-Unveils-Breakthrough-127-Qubit-Quantum-Processor, 2021

CNBC. "The Hype Over Quantum Computers, Explained." *YouTube,* Narrated by Mackenzie Sigalos, CNBC, 10 Jan. 2020 https://www.youtube.com/watch?v=u1XXjWr5frE.

Examples of Quantum Platforms

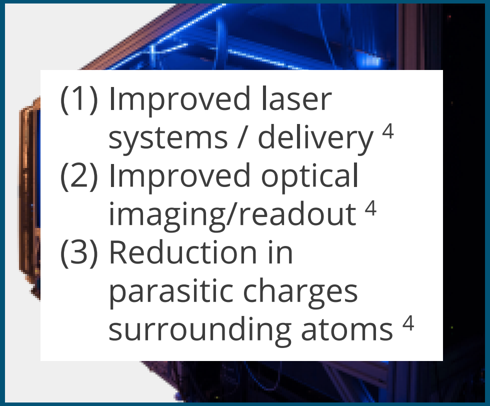
Silicone Photonics



(1) Optical insertion losses[1]
(2) Fabrication variations of the micro-ring resonators causes errors in their resonances[2]

Silicone Photonics device for quantum computing, Xanadu, https://www.xanadu.ai/hardware

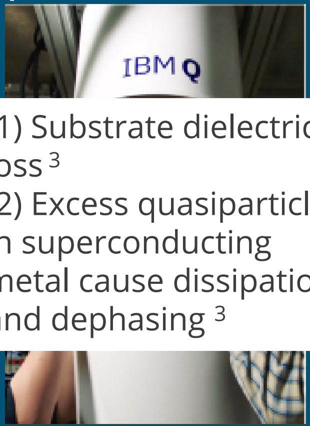
Neutral Atoms



(1) Improved laser systems / delivery [4]
(2) Improved optical imaging/readout [4]
(3) Reduction in parasitic charges surrounding atoms [4]

Phoenix 100 qubit neutral atom system, Atom Computing, https://atom-computing.com/quantum-computing-technology/

Superconducting



(1) Substrate dielectric loss [3]
(2) Excess quasiparticles in superconducting metal cause dissipation and dephasing [3]

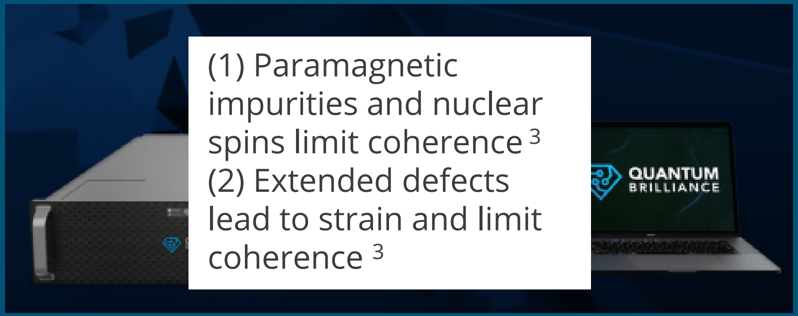
IBM – Q Superconducting Quantum Computer, IBM, https://www.ibm.com/quantum-computing/ibm-q-network/

Topological

Defect density in nanowires [3]

"Azure" topological quantum computer, Microsoft, https://azure.microsoft.com/en-us/solutions/quantum-computing/

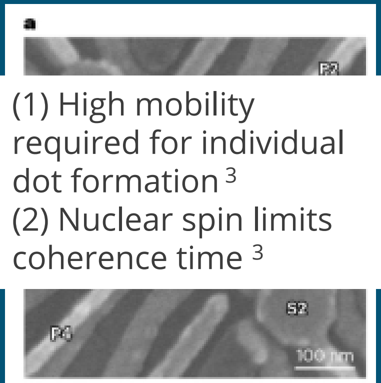
Nitrogen Vacancies (NV)



(1) Paramagnetic impurities and nuclear spins limit coherence [3]
(2) Extended defects lead to strain and limit coherence [3]

Quantum Brilliance (NV) System, https://quantumbrilliance.com/quantum-brilliance-hardware

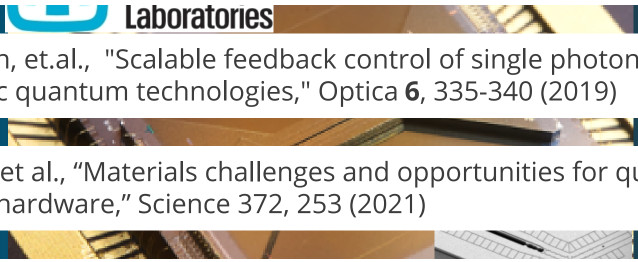
Quantum Dots



(1) High mobility required for individual dot formation [3]
(2) Nuclear spin limits coherence time [3]

Four Quantum Dot Device, Hendrickx, N.W., Lawrie, W.I.L., Russ, M. *et al.* A four-qubit germanium quantum processor. *Nature* **591,** 580–585 (2021). https://doi.org/10.1038/s41586-021-03332-6

Trapped Ions



(1) Paesani, S., *et al.* Near-ideal spontaneous photon sources in silicon quantum photonics. *Nat Commun* **11,** 2505 (2020). https://doi.org/10.1038/s41467-020-16187-8

(2) J. Carolan, et.al., "Scalable feedback control of single photon sources for photonic quantum technologies," Optica **6**, 335-340 (2019)

(3) de Leon et al., "Materials challenges and opportunities for quantum computing hardware," Science 372, 253 (2021)

(4) L. Henriet, et.al., "Quantum computing with neutral atoms," Quantum 4, 327 (2020).

Sandia National Laboratories

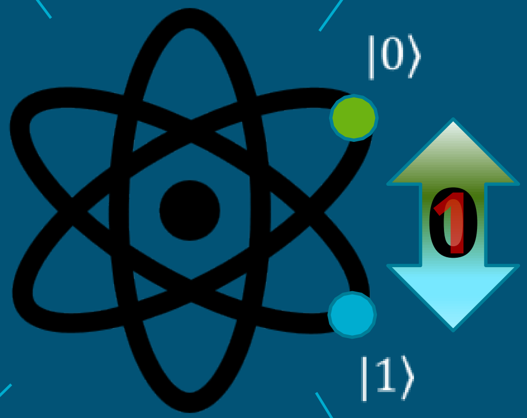
So Why Ions?

Atoms are identical

Multiple Species to choose from
(Ca, Yb, Be, Mg, Ba, …)

Long Coherence Times (>50s)
https://www.nature.com/articles/s41566-017-0007-1.pdf?origin=ppub

$|0\rangle$



superposition
$\alpha|0\rangle + \beta|1\rangle$

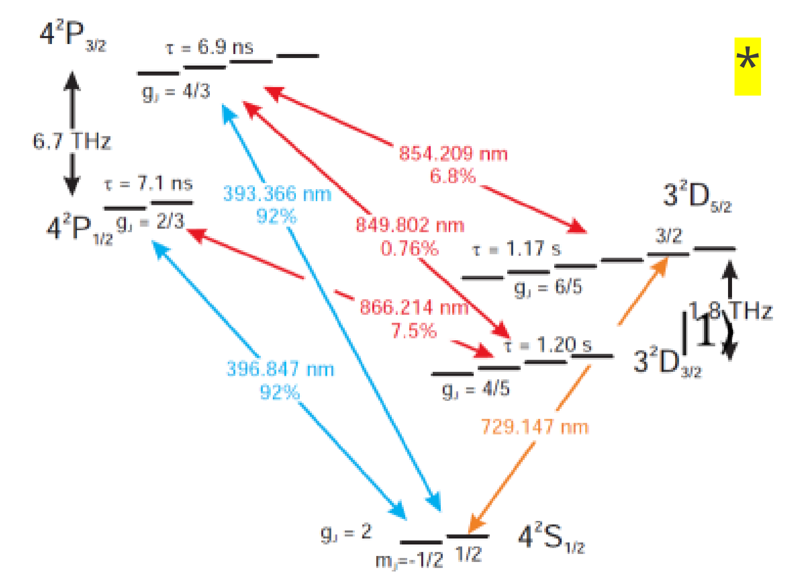
$|1\rangle$

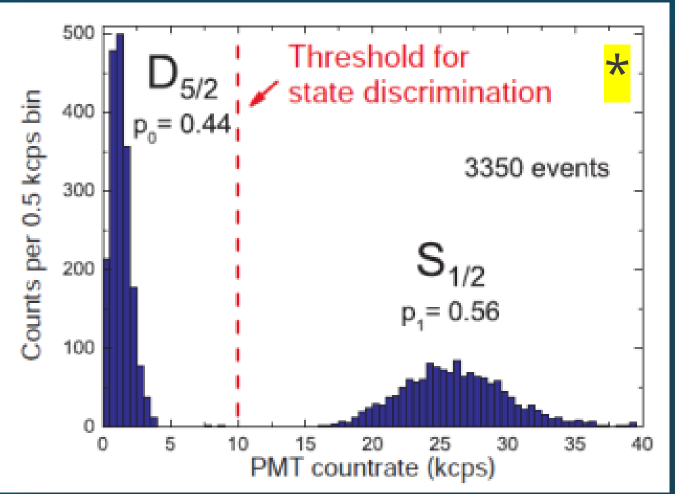
We can isolate them (mostly)

Lowest Error Rates Demonstrated
(the lower we get/the less we need/the smaller the system)

"Easy" to control
(1) RF
(2) DC
(3) Lasers

Calcium Energy Diagram





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

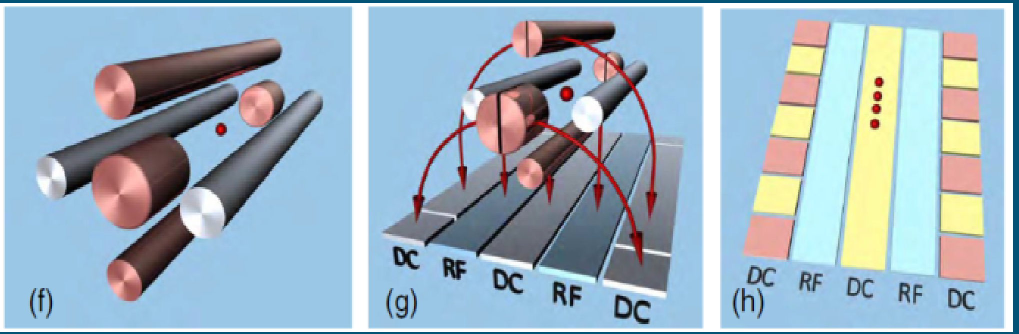
Ion traps: advantages/challenges of microfabricated traps

Advantages

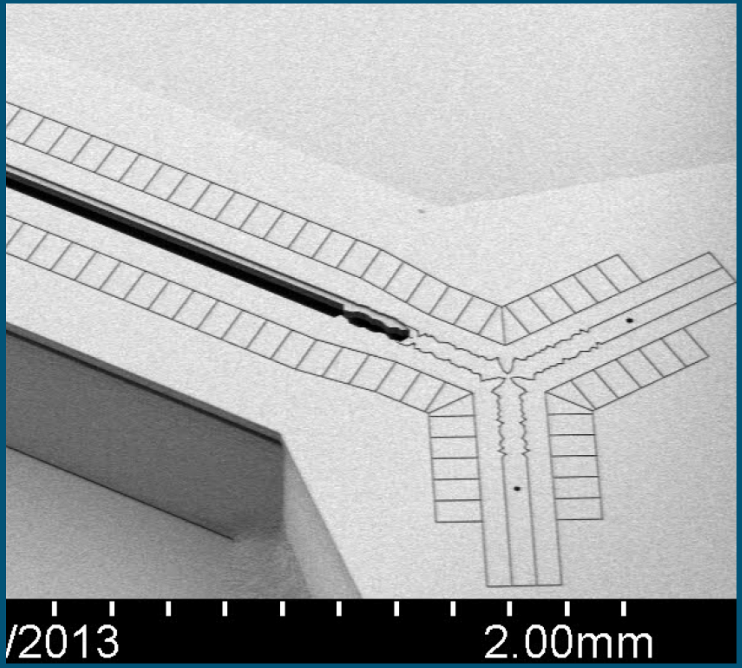
- More manufacturable ("scalable")
- Consistent geometry -> consistent behavior
- Greater field control (more electrodes)
- 2D geometry
- Integration of other technologies (waveguides, detectors, filters…)
- Laser access

Challenges

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

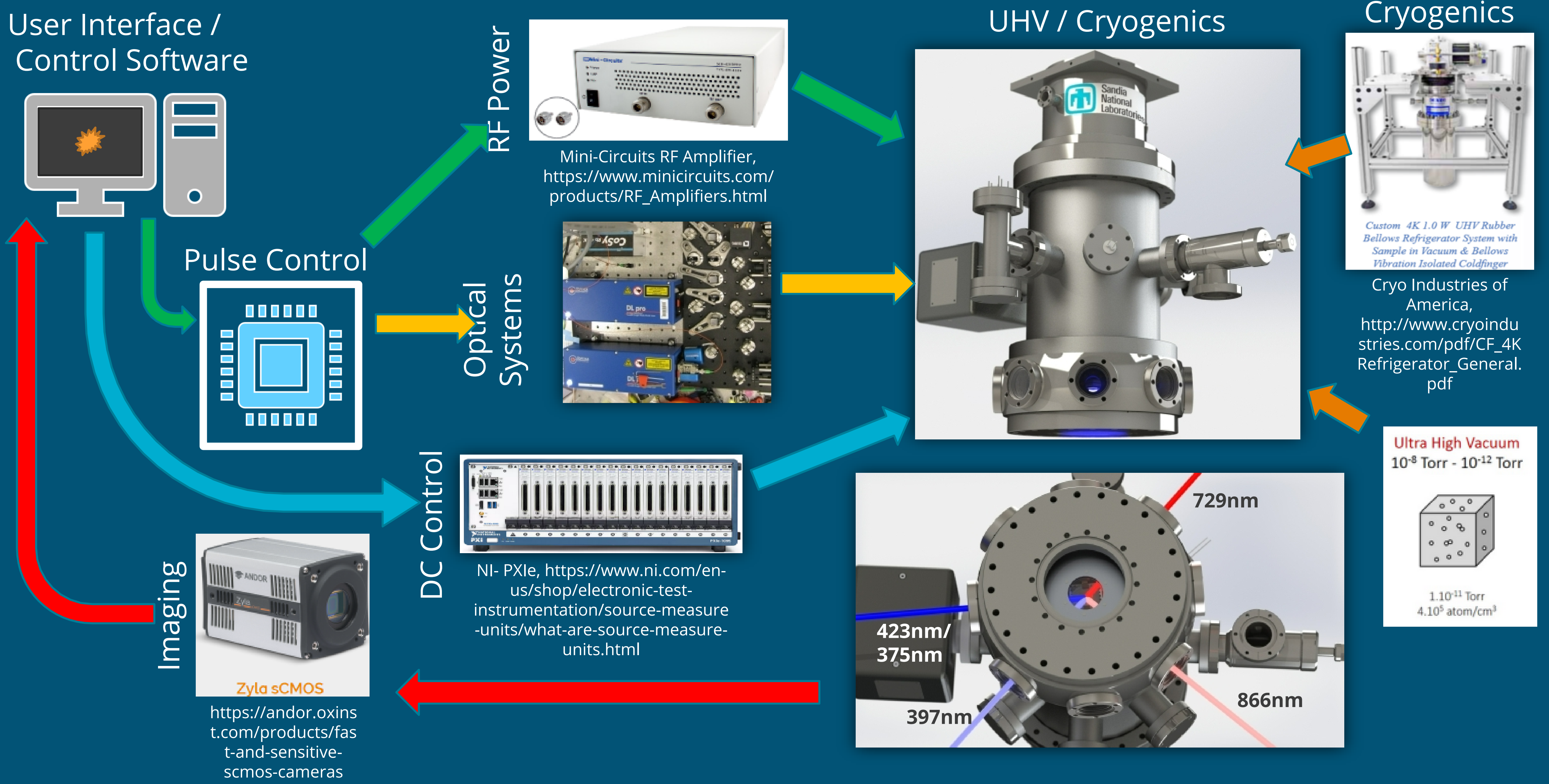


Ion-trap measurements of electric-field noise near surfaces
M. Brownnutt, M. Kumph, P. Rabl, and R. Blatt
Rev. Mod. Phys. 87, 141

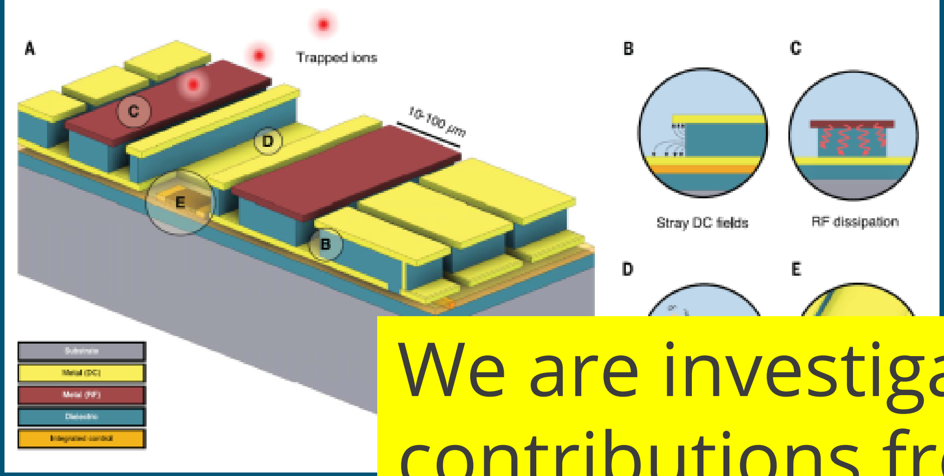


Sandia Microfabricated Trap

The Hardware



Introduction to Noise in Ion Trap Quantum Computing



N. P. de Leon, et.al., “Materials ... computing hardware,” Science ... https://doi.org/10.1126/scienc...

Noise in any quantum system contributes to the decoherence of the encoded information or the loss of the qubit.

Reduction / Elimination of contributing noise sources ... computer.

We are investigating E-Field Noise contributions from dielectrics in proximity of the ion as well as contributions from AC filtering capacitors on DC electrodes

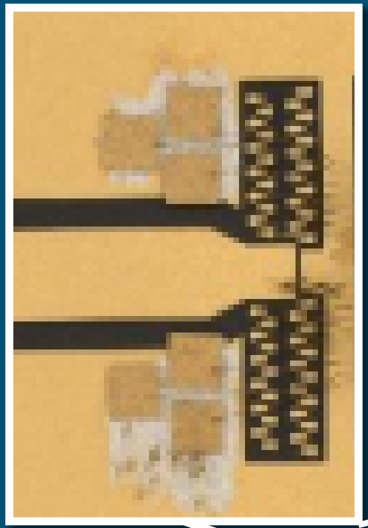
	Noise			
	“Technical Noise”	DAC Cards, Johnson Noise, Ambient Laboratory Fields, etc. *		
(B)	Stray DC Fields	Dielectric Bulk, External Sources	Charging up of the dielectric (e.g. lasers)	Shifting Ion off RF null
(C)	RF Dissipation	Dielectric Bulk	RF loss within the dielectric (loss tangent) – heating of trap, other dielectric dissipation effects	Thermally generated electric field noise, drift in the ion position
(D)	Surface-related Electric field noise	Metallic Electrode Surfaces (e.g. patch potentials, contamination)	Electric field noise generated on the surface nearest the ion	Heating of the motional modes
	Ion Loss	Vacuum, Electrical, etc.	Poor vacuum environment, unstable electronic environment, poor laser stability	Ion disappears

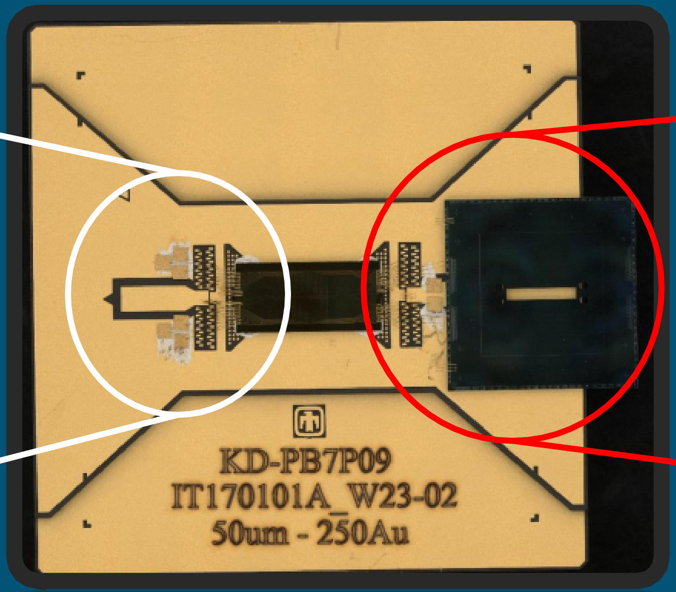
* M. Brownnutt, *et al*, Ion-trap measurements of electric-field noise near surfaces, Rev. Mod. Phys. **87**, 1419-1482, (2015)

The Devices

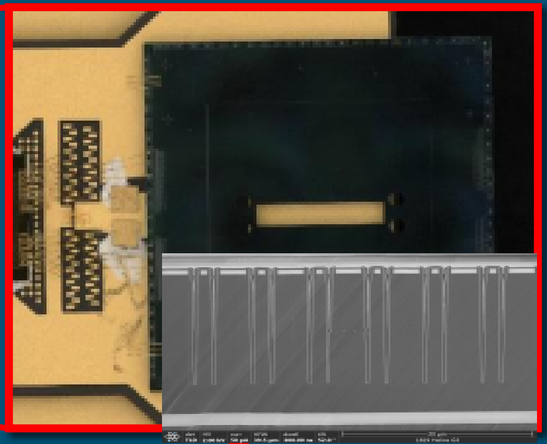
The Canary Trap

1nF Chip Based Capacitors

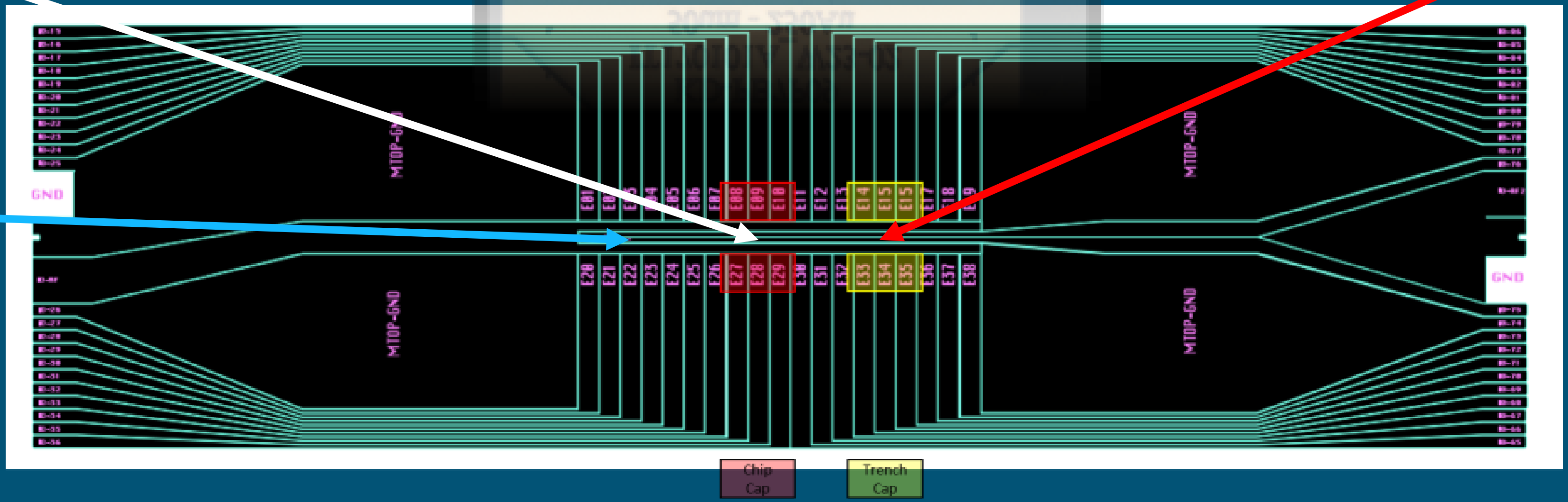




1nF Trench Capacitors



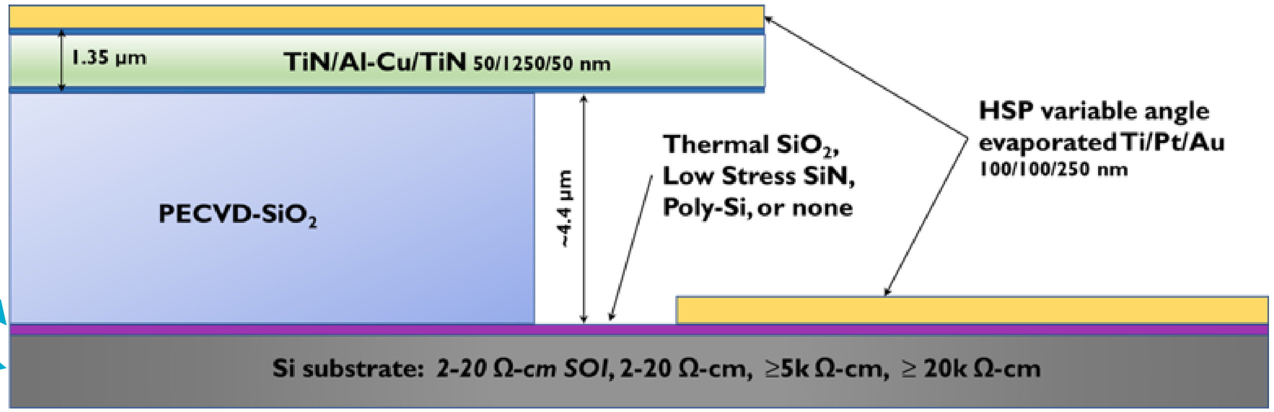
No Capacitors



The Device Stack up

Varied Substrate Passivation Layer
- Polysilicon
- SiO_2
- Low Stress SiN
- No Film

Varied Substrate
- Si 2 Ω – 20 Ω - cm
- Silicon on Insulator (SOI) 2 Ω– 20 Ω - cm
- Si (H-Res) > 5kΩ - cm
- Si (UH-Res) > 20kΩ - cm



Heating Rates

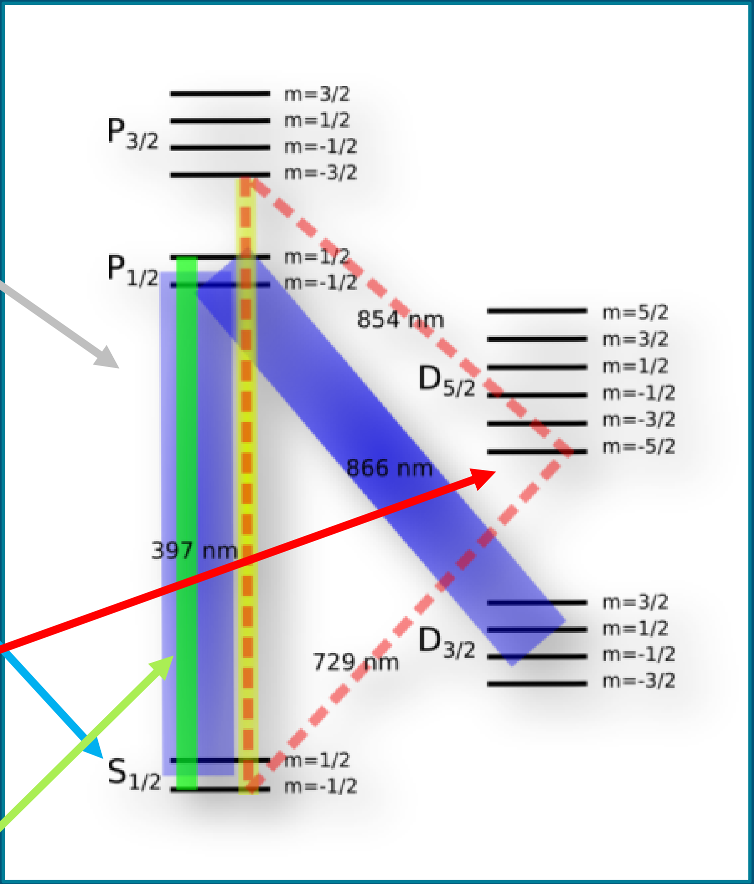
Sideband Cooling (Motion Ground State)

Cool to Doppler Limit (See Blue)

State Preparation (See Red Dash)

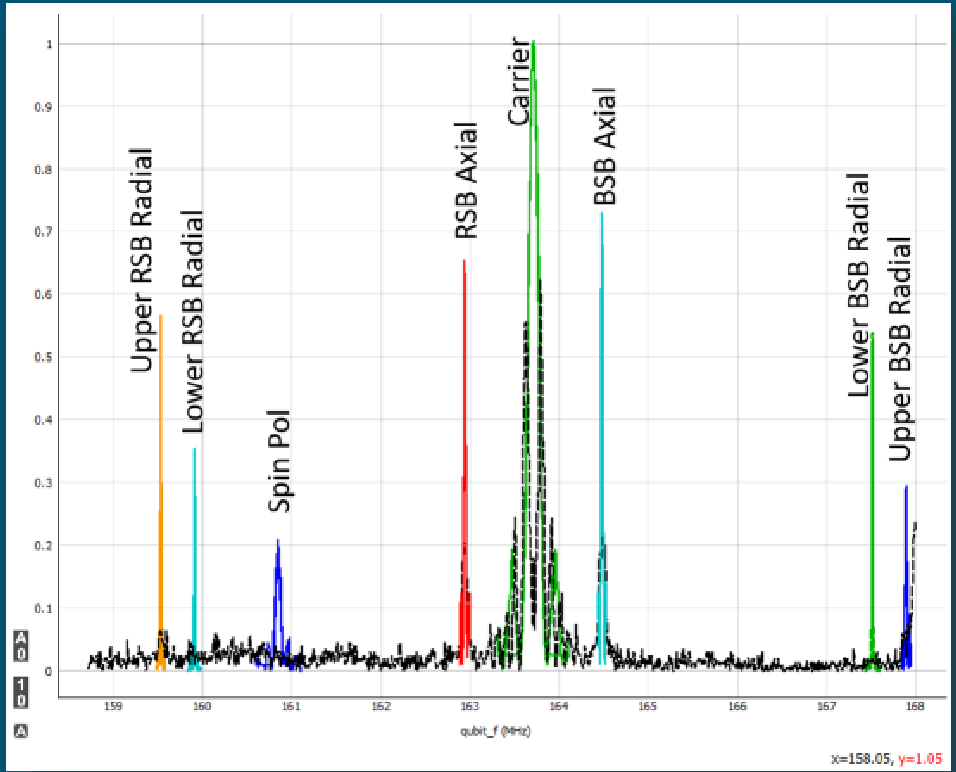
Sideband Cool on Carrier Axial RSB (See Red Dash)

Detect State (See Green)



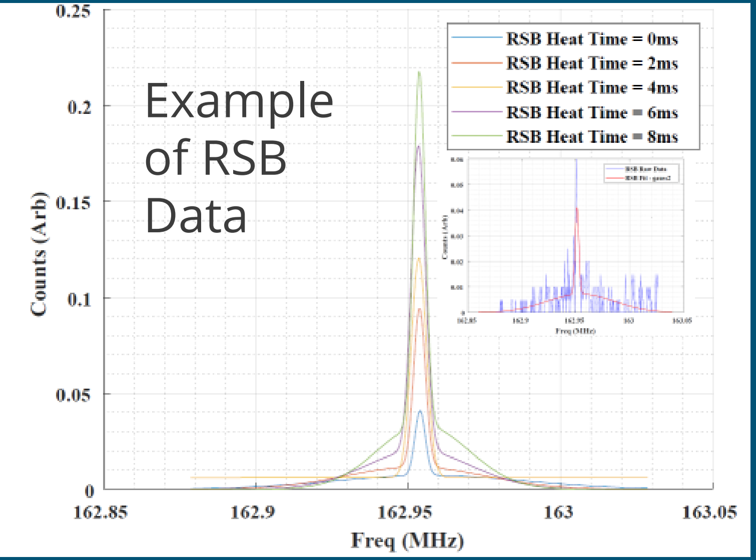
“Resolved Sideband Cooling.” *Wikipedia*, 27 Sept. 2021, en.wikipedia.org/wiki/Resolved_sideband_cooling. Accessed 26 Nov. 2021.

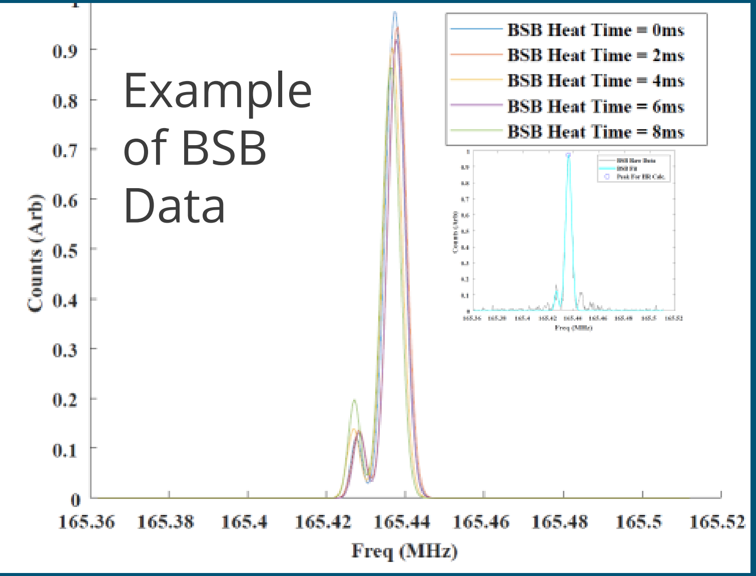
729nm Spectrum



We cool beyond the Doppler cooling limit by using Resolved Sideband Cooling to put the ion in the motional ground state (as cold as we can get it, μK Temp).

Heating Rates – cont’d

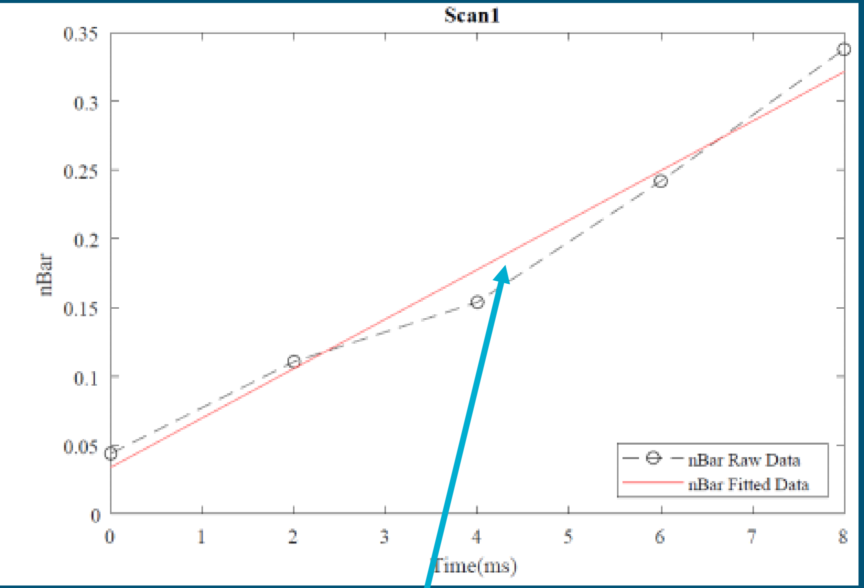




$$\frac{\frac{RSB_{Peak}}{BSB_{Peak}}}{1-\frac{RSB_{Peak}}{BSB_{Peak}}} = \bar{n}$$

Heating of the ion after being cooled to the motion ground state is due to fluctuating electric fields that couple to the ions charge, resonant with its natural state of motion.

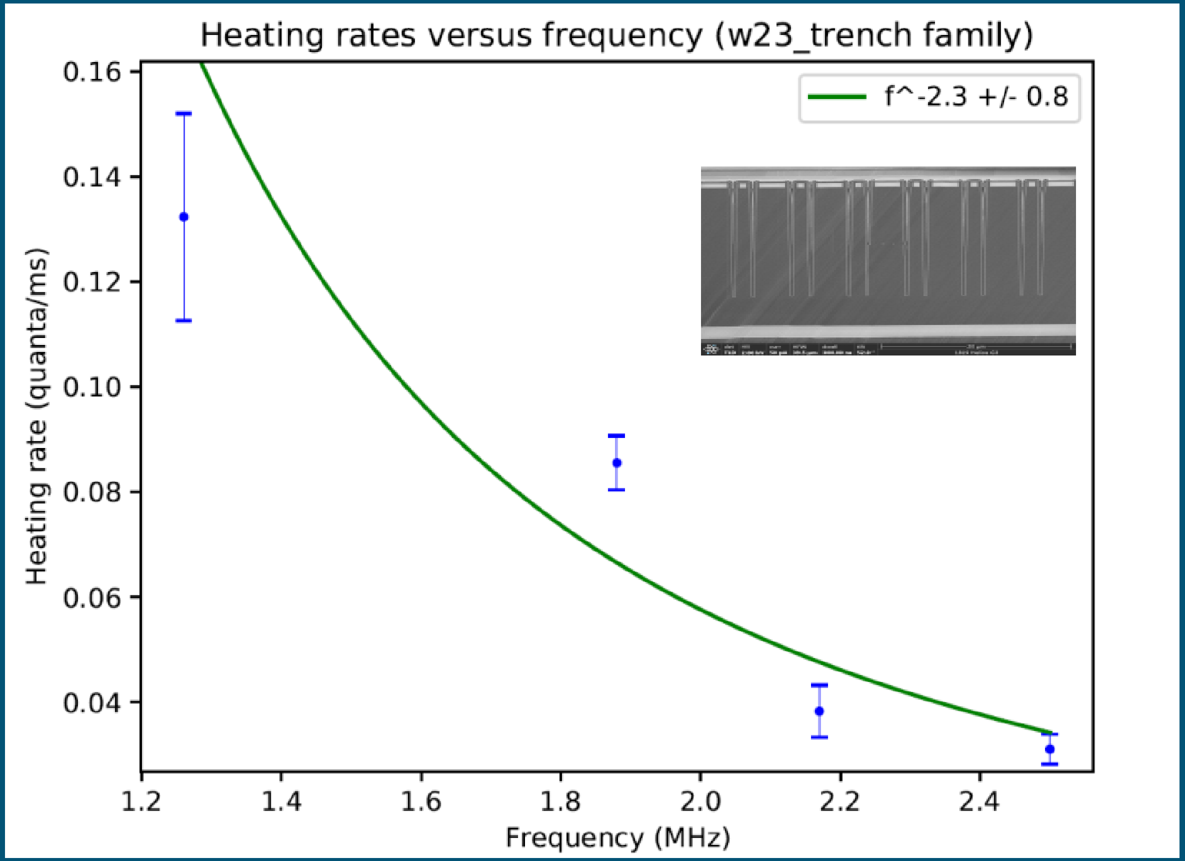
n_{bar} vs. uncooled time



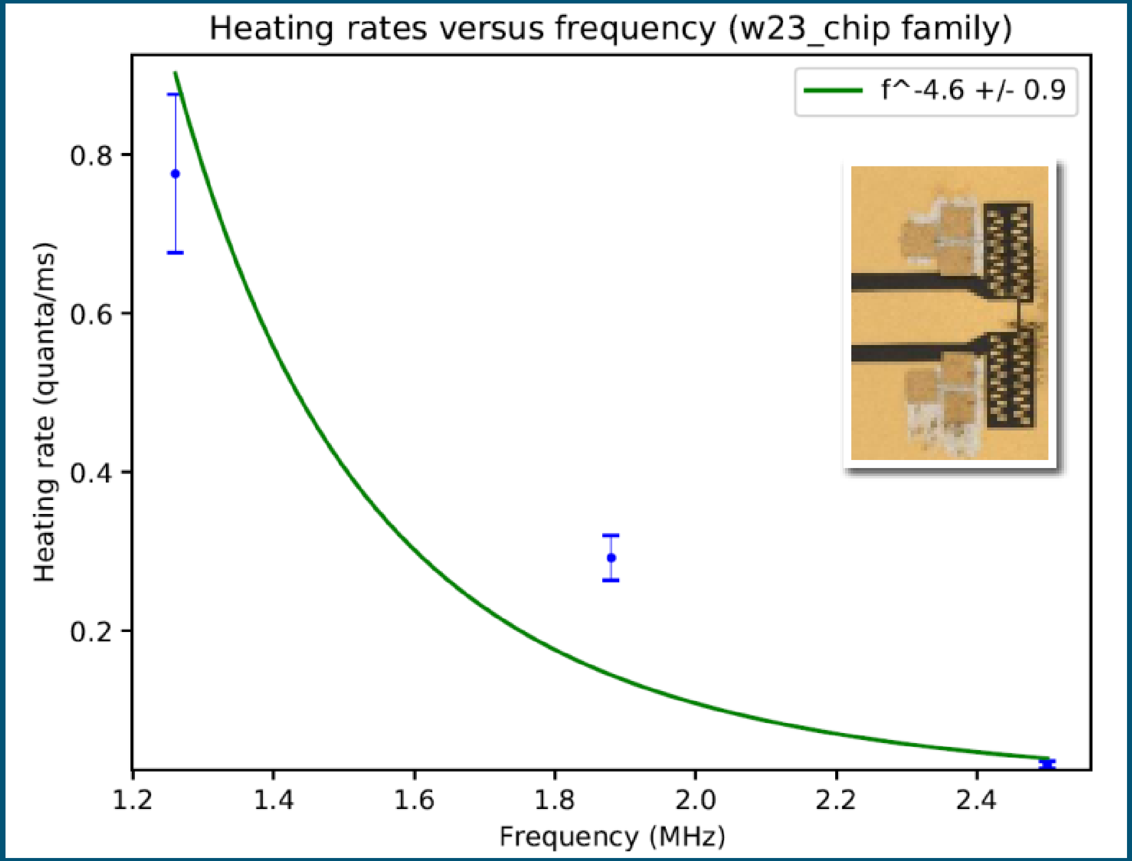
The Slope of n_{bar} vs. uncooled time gives us the heating rate

Results

Trench Capacitors



Chip Capacitors



Summary:

- Reduced Heating Rate in Trench Capacitors Compared to Chip Capacitors
- Good Heating Rates in both at high Axial Frequency (~30q/s)
- Initial Indications (1 device measurement) show that Heating Rates were improved having a passivation layer between the electrode and the silicon substrate (other similar device measurements show >1000q/s)

Our Mission

Sandia's Quantum Information Program

Quantum Information Expertise

Qubits: qubit design / development / fabrication / test, entanglement, noise modeling, design tools

Quantum engineering: architectures, robust controls for quantum gates, qubit and quantum processor performance characterization

Algorithms/apps: algorithm development, demonstration of few-qubit applications

Modeling and Simulation: quantum device modeling, design toolkits, error correction simulators

Communication: Quantum Key Distribution (QKD), photon source development, single photon detectors, quantum networking

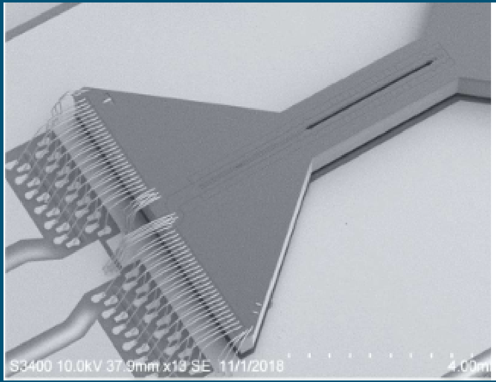
Sensing: ultra-high precision timing, acceleration sensing, magnetometry, and electric field sensing; sensing employing both atom and matter wave interferometry

Engineering: dramatic size-, weight-, and power- reductions for QKD, atomic clocks, and atom interferometers – lasers, photon source, control electronics, integrated photonics, vacuum packaging and systems

Quantum Scientific Computing Open User Testbed

QSCOUT provides scientists free and complete access to the only open quantum computing testbed based on trapped ions in the world. It gives the scientific community a new level of programming control and execution for improving quantum computer science. QSCOUT is a quantum computer for scientists, by scientists. (First round 2->3 ions)
https://www.sandia.gov/quantum/Projects/QSCOUT.html

The Ion Trap Foundry



- **Trapped ion qubits:** Sandia designs and fabricates MEMS-scale surface electrode ion traps which isolate ions by applying electromagnetic fields. These produce an exceptionally pure environment for manipulating the system's atomic states, providing high-fidelity operations for one- and two-qubit manipulations. Sandia hosts an ion trap foundry that has provided the world's best surface electrode ion traps to 12 institutions in 5 countries. Among other accomplishments, the Sandia High Optical Access (HOA) trap has achieved the highest two-qubit gate fidelity in any surface trap.

https://www.sandia.gov/quantum/

Conclusion

- Initial Results Indicate Improvement with Passivation Layer (possible charge screening)
  - Support theory of dielectric bulk noise
- Large divergence between Chip Based Capacitors and Trench Capacitors
- Further evidence that material investigations are important to moving the field forward
- Sandia has a multidiscipline quantum effort and welcomes collaboration

Acknowledgments

Experiments
Todd Barrick
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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

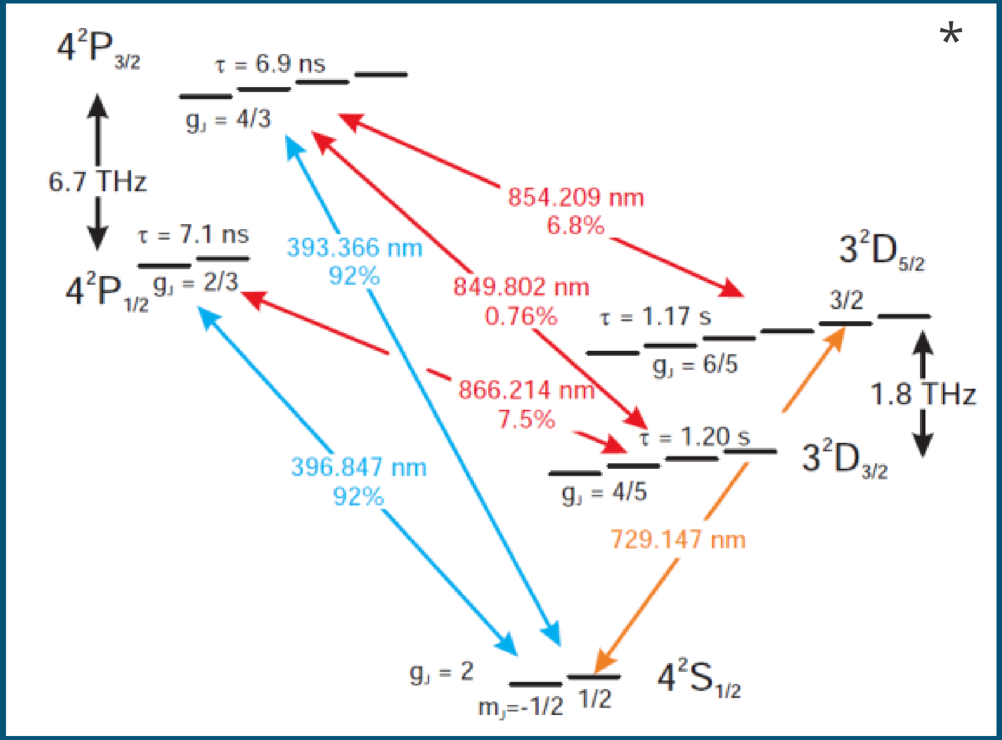
Integrated optics
Daniel Dominguez
Matt Eichenfield
Mike Gehl
Galen Hoffman
Rex Kay
Andrew Leenheer

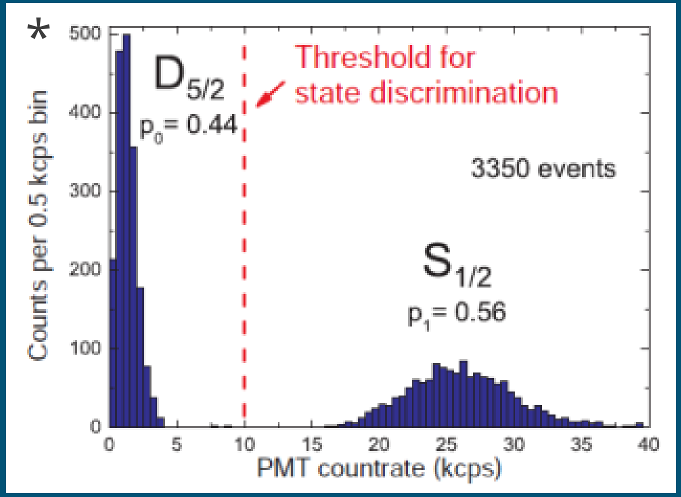
THANK YOU

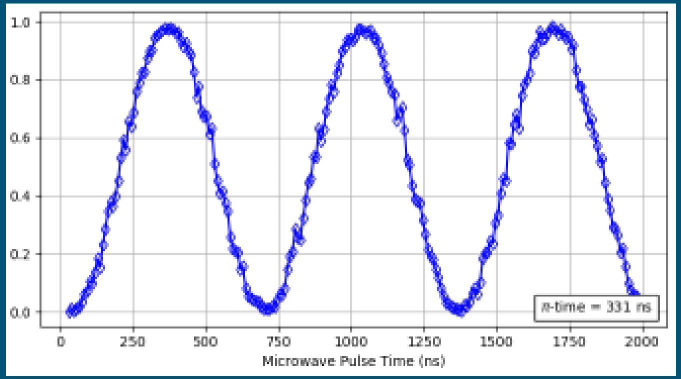
Questions?

Trapped Ion Quantum Computing: atomic level

- 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)







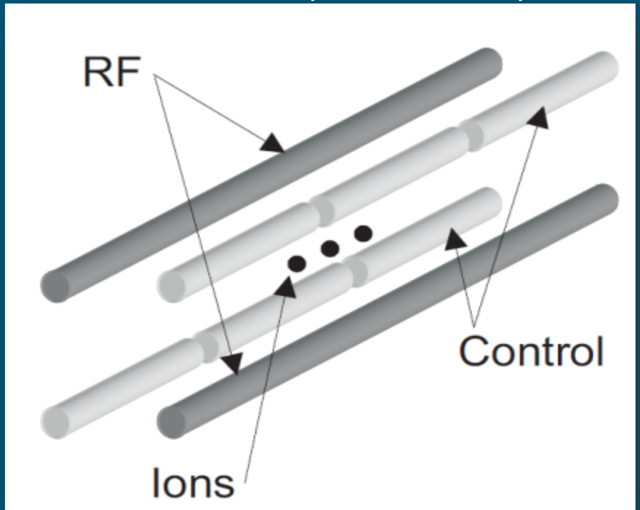
* "Precision spectroscopy and quantum information processing with trapped calcium ions", Jan Benhelm PhD Thesis (2008)

Physical errors (best demonstrations from multiple groups)

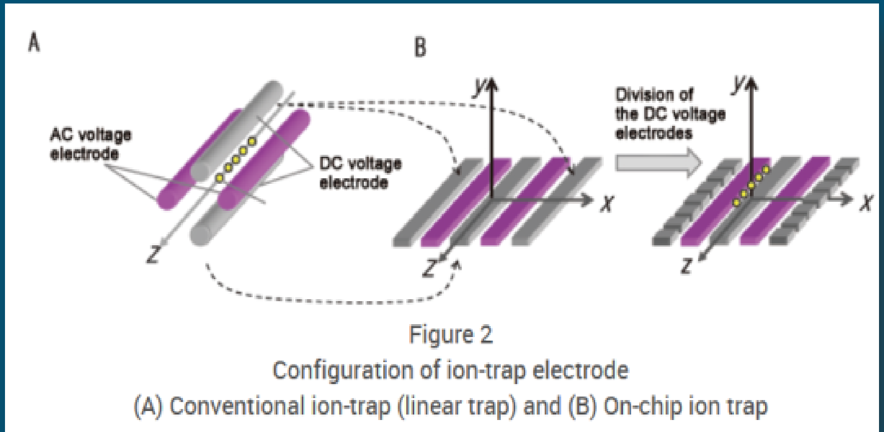
- 1Q error: 1e-5
- 2Q error: 1e-3
- Detect, prep: <1e-4
- T1: 1s … infinite
- T2: 10 ms … 10 s

How it Works

Basic Concept: The Quadrupole Ion Trap

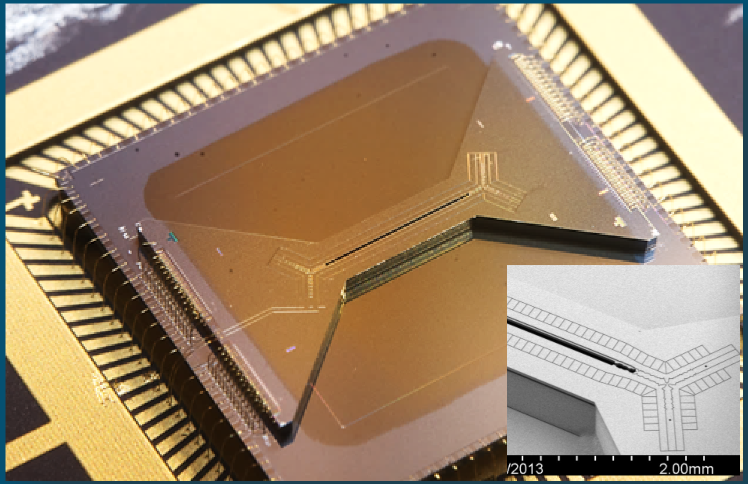


The Conversion from 3D to 2D

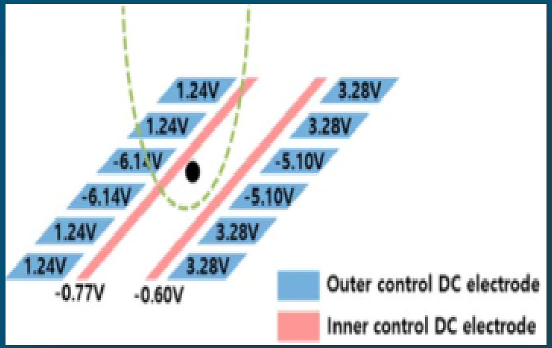


Configuration of ion-trap electrode. National Institute of Information and Communications Technology (NICT). https://www.nict.go.jp/en/quantum/about/trapped-ion/english.html. 2021

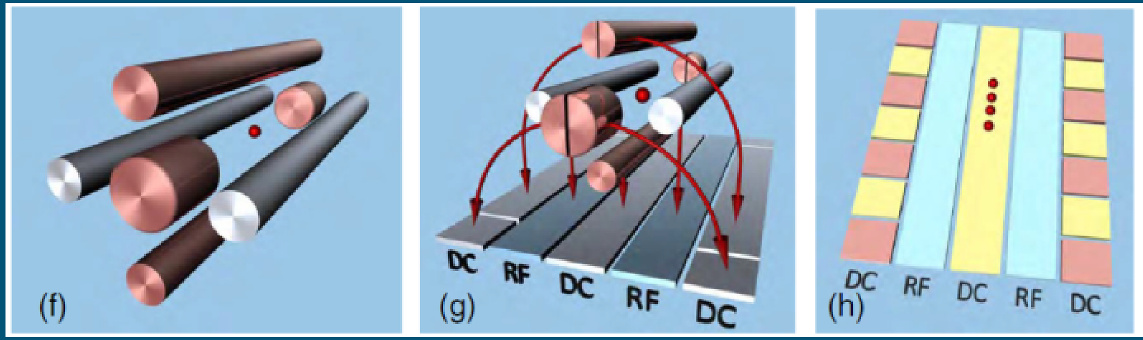
Sandia Chip-Based Surface Ion Trap



Example of DC Axial Confinement

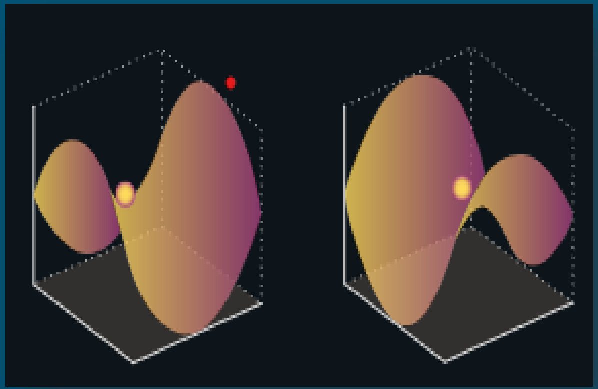


Minjae Lee et al 2021
Jpn. J. Appl. Phys.60 027004



Ion-trap measurements of electric-field noise near surfaces
M. Brownnutt, M. Kumph, P. Rabl, and R. Blatt
Rev. Mod. Phys. 87, 141

Example of RF Confinement



Particle in a saddle potential. IonQ. https://ionq.com/technology, 2021