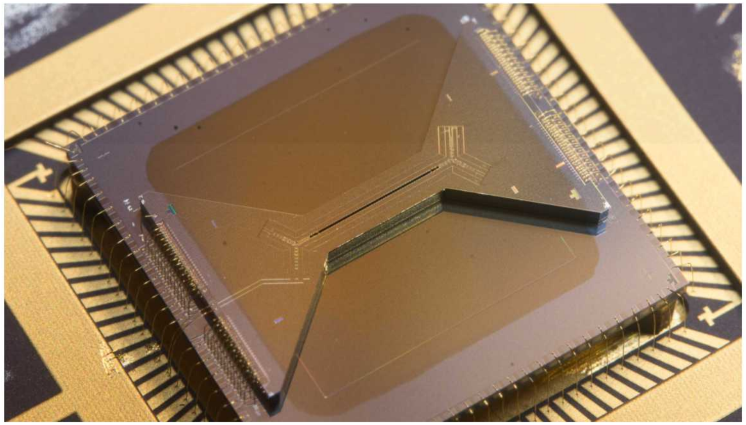
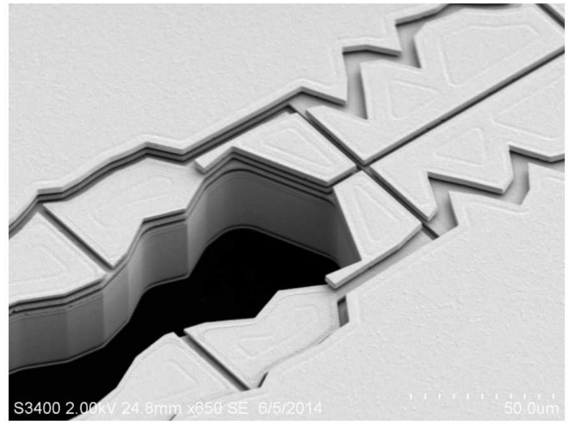
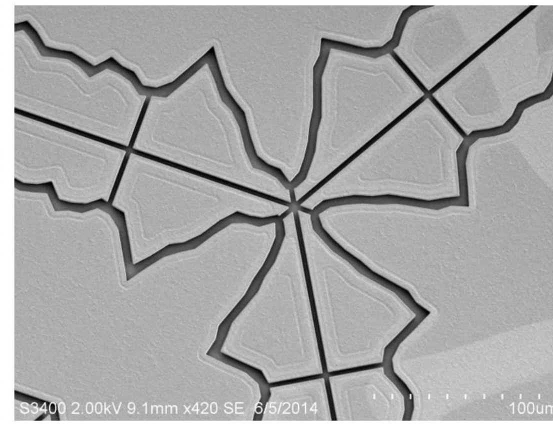
SAND2018-11538PE







Trapped Ion Experiments at Sandia National Laboratories

Waterloo 2018

Susan Clark, Sandia National Laboratories

IARPA

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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AMO Physics at Sandia

Trapped Ions:

- Surface trap fabrication
- Ion shuttling and reordering
- Characterization of high fidelity quantum gates with Gate Set Tomography (GST)
- Ion Clocks

Neutral Atoms:

- Two-qubit gates
- Atom interferometry

Solid State (AMO-like):

- Phosphorous donors in Silicon
- Quantum Dots
- CINT

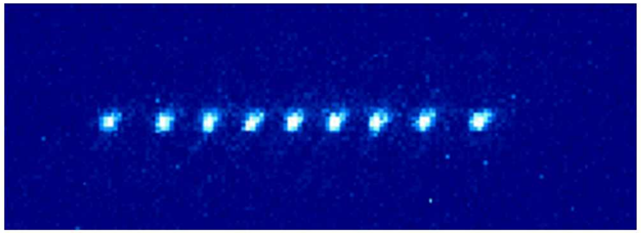
Uses of Trapped Ions

Mass Spectrometry: Identify substances by mass to charge ratio

Isotope dating and tracking, Trace gas analysis, protein characterization, space exploration (mars rover), antiproton storage at CERN, drinking water safety…

Precision clocks: Narrow transitions allow for accurate time standards

Quantum information: Electron spin for simulation and memory



Ions for Quantum Information

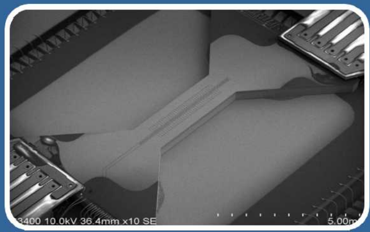
Quantum Experimental Platforms answer questions about:

1) The nature of information
2) Fundamentals of quantum mechanics
3) Secure information transfer
4) Simulating more complicated systems
5) New types of computing resources for certain problems

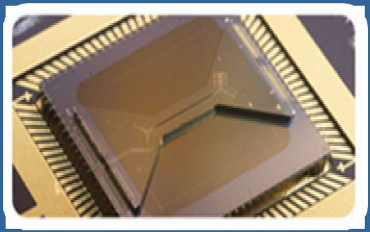
Main Advantages of Ions:

Well understood and mature system
Main sources of error are classical control problems (microwaves/lasers/electric field noise/varying magnetic fields)

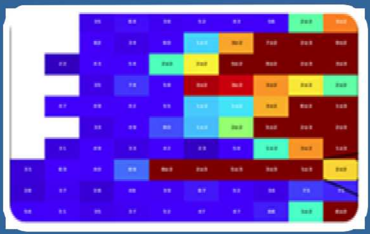
Outline



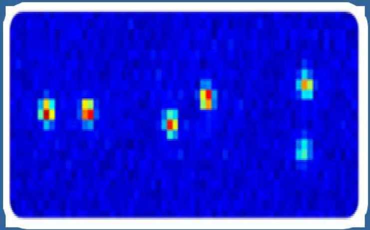
Trap fabrication, advantages and challenges



Example trap designs: High Optical Access trap & Microwave trap



Characterization of quantum gates using Gate Set Tomography (GST)

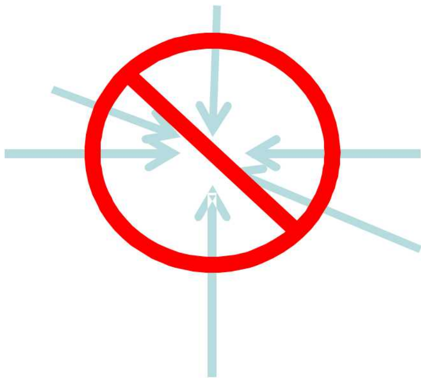


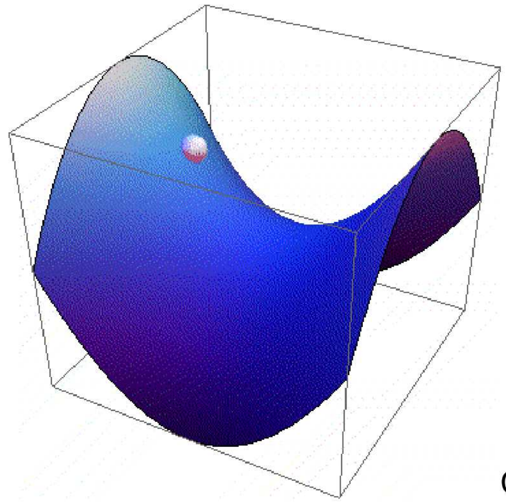
Recent Results in Surface Traps: Ion shuttling, high fidelity operations, sympathetic cooling

Earnshaw's Theorem and Ion Trapping

Trapping requirement: A restoring force when displaced from trap center (in any direction)

Cannot use static electric fields to trap a charge
Field lines cannot cross, and must start/end on sources/drains

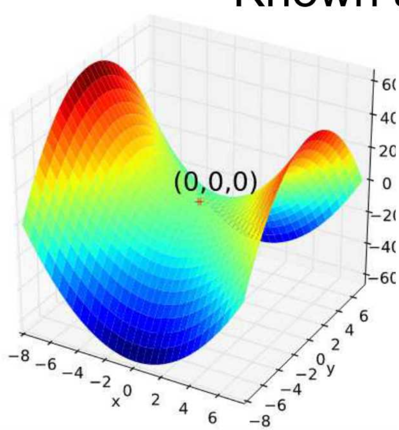


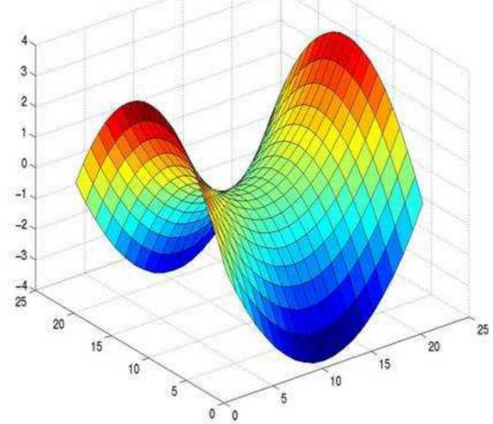


create
s

Courtesy of Wes Campbell

Known as saddle points



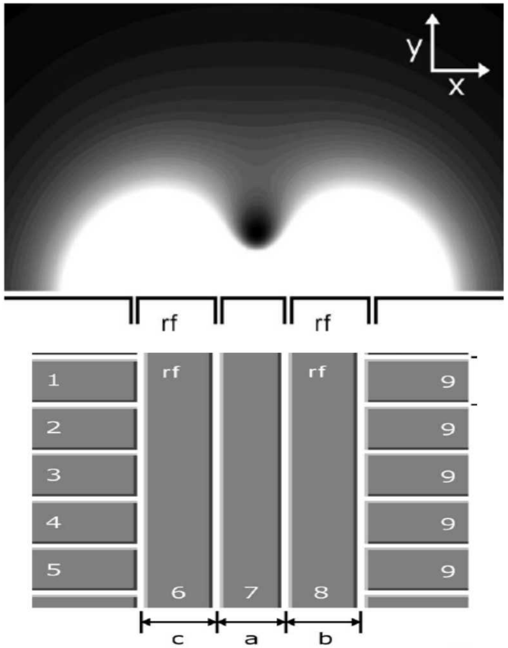


Before ion escapes, field reverses!

Various trap geometries

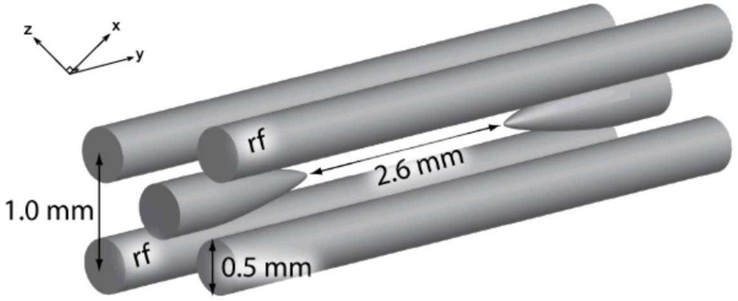
Use a combination of static and rf fields to trap ions
Various geometries possible

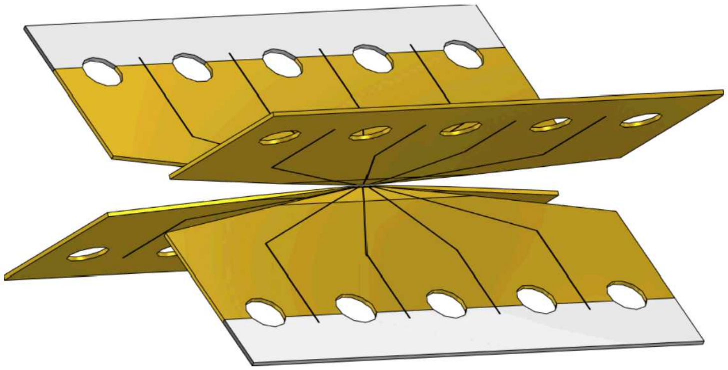
Pesudopotential well (dark area) formed along the axis of a surface trap



Electrodes from above

House, PRA **78** 033402 (2008)

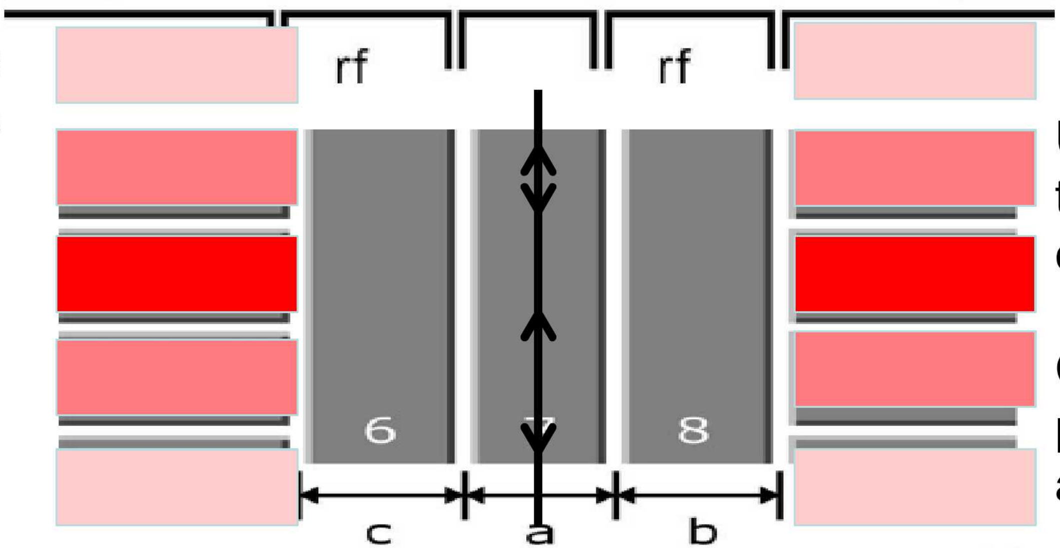




Need for DC fields

Looking at trap from above

Still free to move along axis



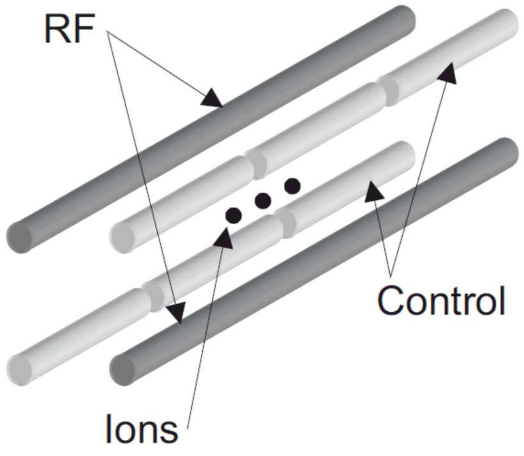
Use DC fields on the electrodes to confine

Creates a trapping potential along axis

Advantages/Challenges vs 3D

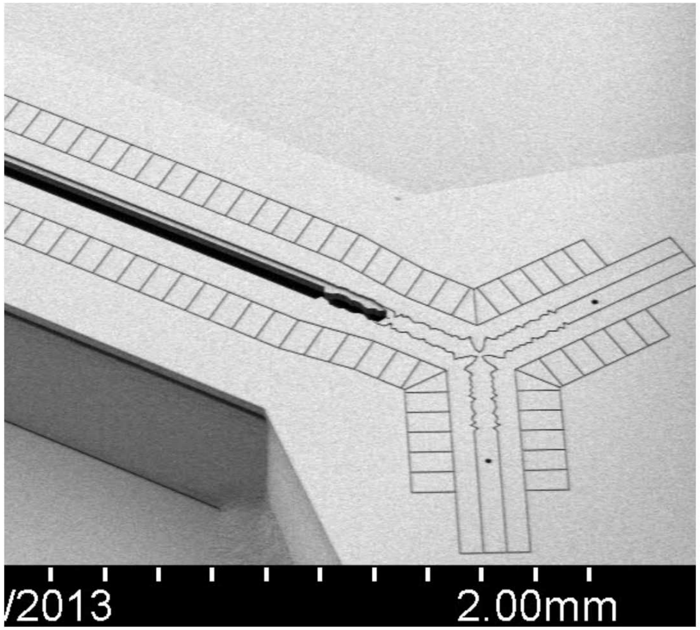
Advantages

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

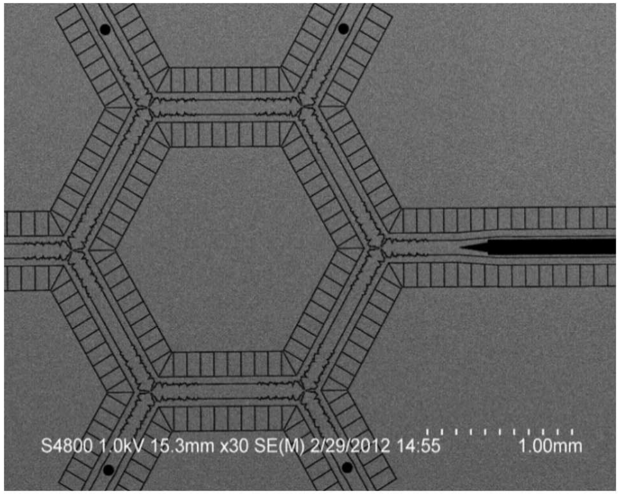


Challenges

- Lower depth (ion lifetime), anharmonicities in potential
- Proximity to surface (charging, heating)
- Delicate (dust, voltage)
- Capacitance
- Laser access



Capabilities & Requirements



Essential capabilities

- Reliable and consistent operation
- Store ions for long periods of time (hours)
- Move ions to achieve 2D connectivity
- Support high fidelity operations

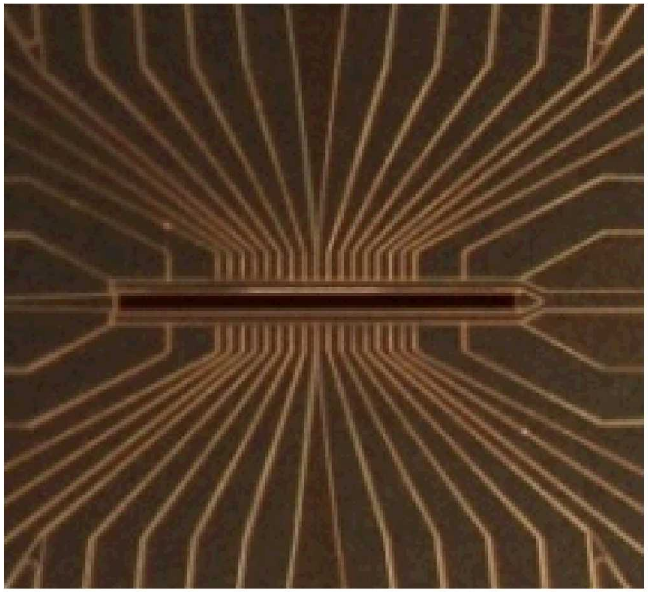
MESA facility

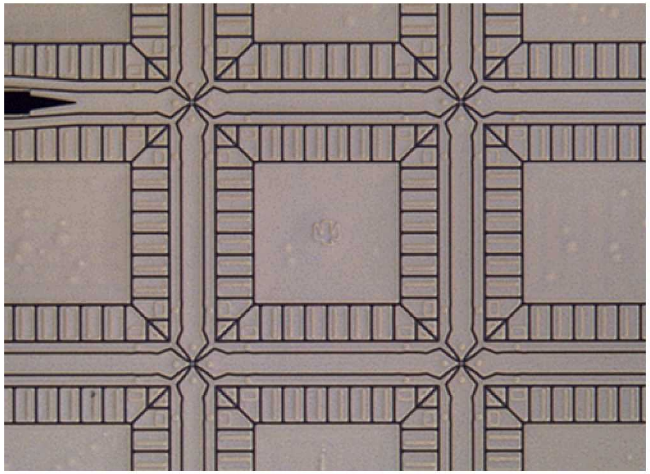
- Radiation hardened CMOS
- Leverages reliability of NW processing
- Large feature sizes (350 nm) match well with trap requirements

Capabilities & Requirements

Derived requirements

- Standardization (lithographically defined electrodes)
- Multi-unit production
- Multi-level lead routing for accessing interior electrodes
  - Connecting both control and RF electrodes
  - Any 2D topology is possible
- Voltage breakdown >300 V @ ~50 MHz
- Overhung electrodes
- Low electric field noise (heating)
- Backside loading holes
- Trench capacitors
- High optical access (delivery and collection)





Capabilities & Requirements

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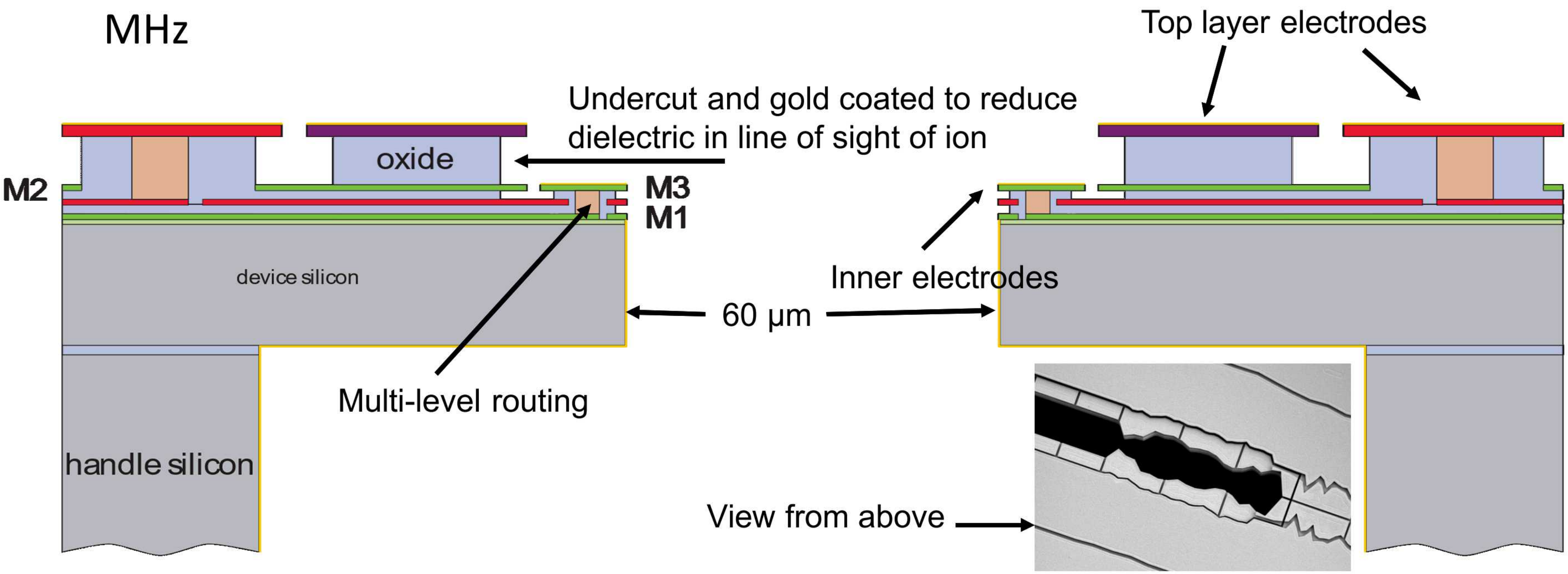
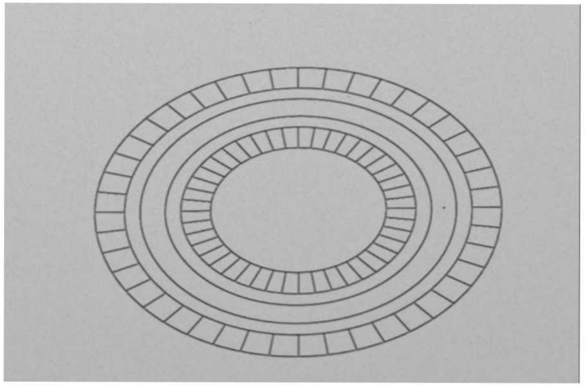
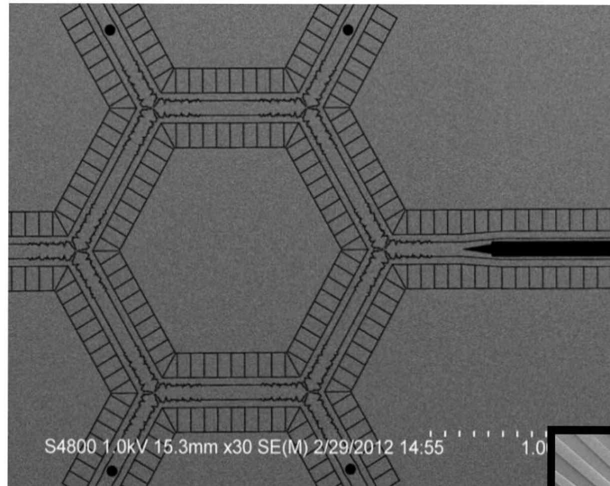


Unique Traps From Sandia

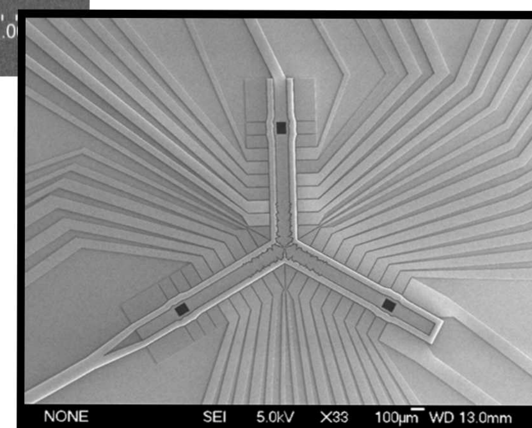


Ring trap

Tabakov, B et al. *Phys. Rev. Applied* **4**, 031001 (2015).

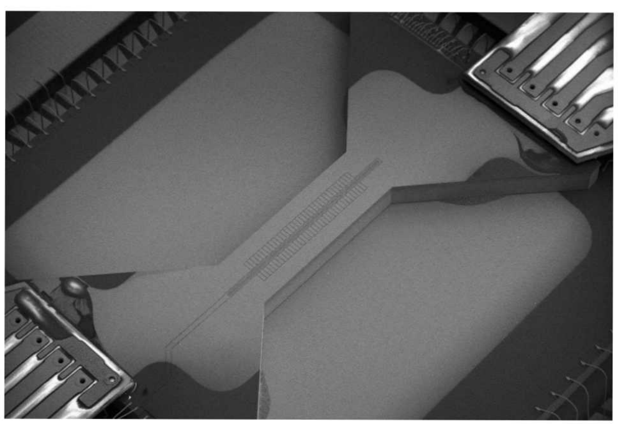


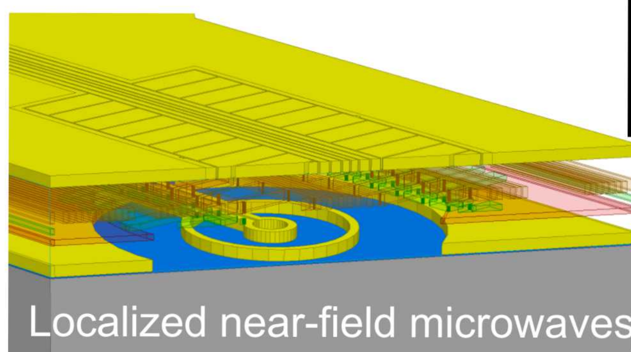
Circulator Trap



Y-junction trap

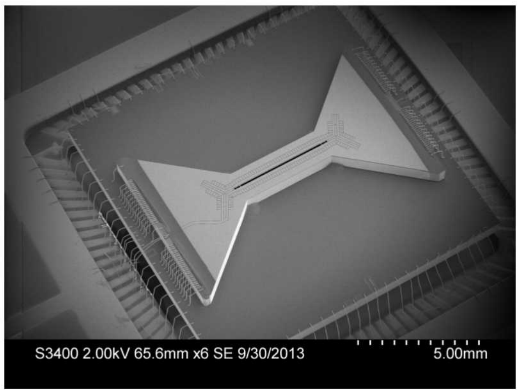
Microwave trap

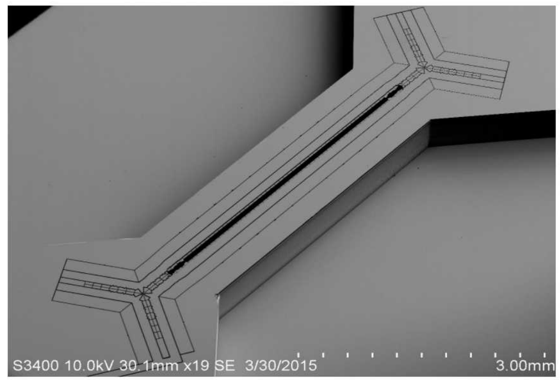


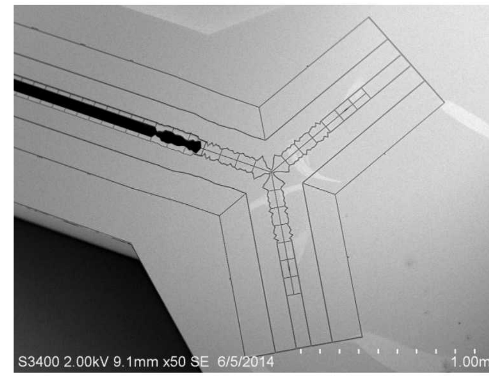


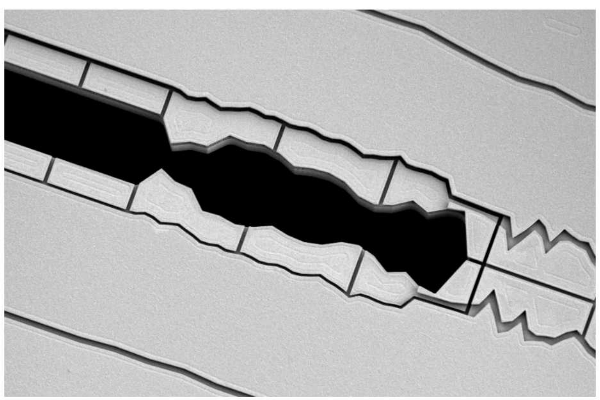
330 ns π-time, 10^{-5} single qubit gate errors

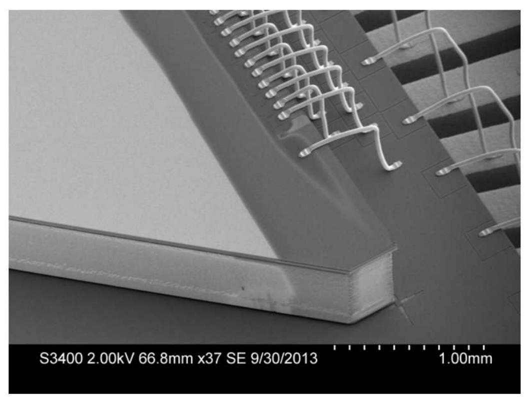
High Optical Access (HOA)

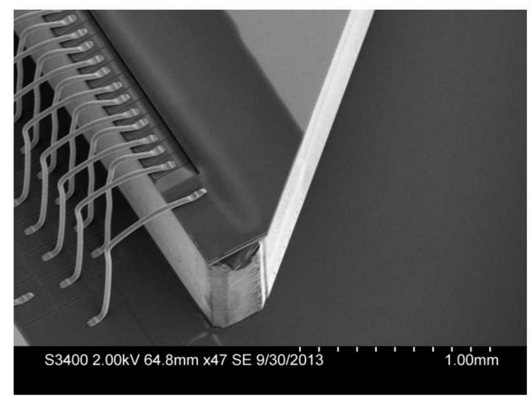




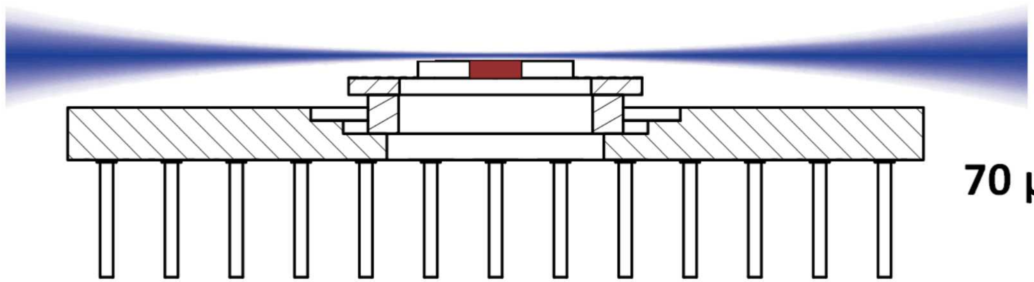








High Optical Access (HOA)

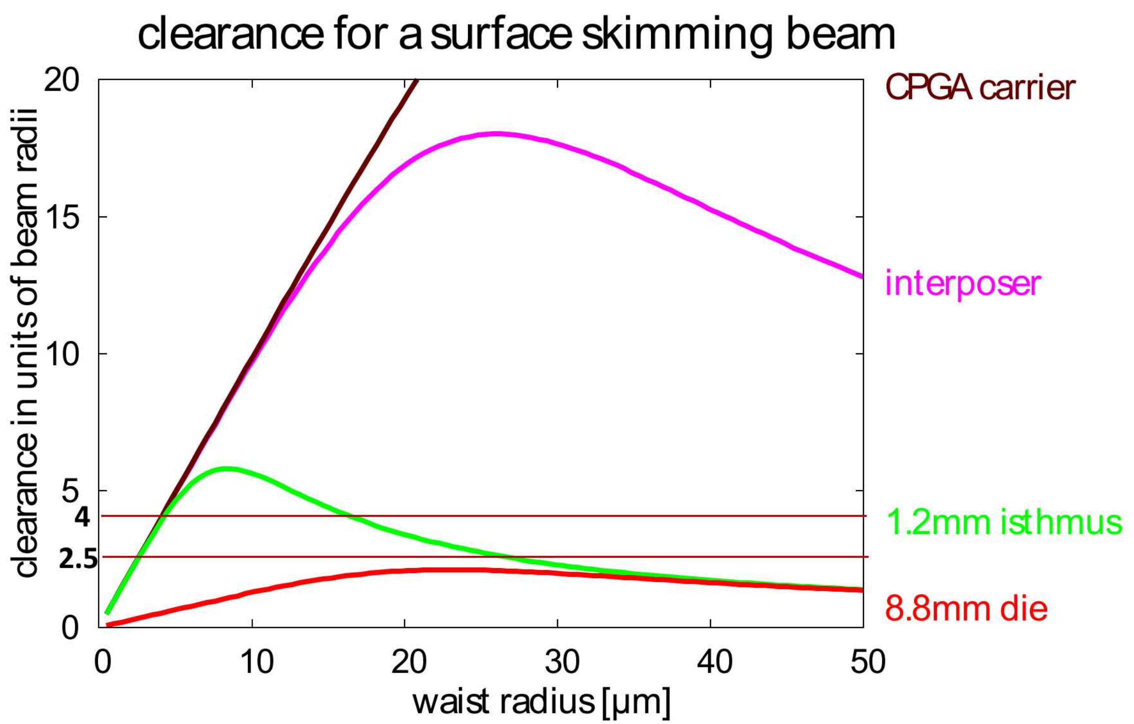


70 µm ion height

4: $<2\times10^{-14}$

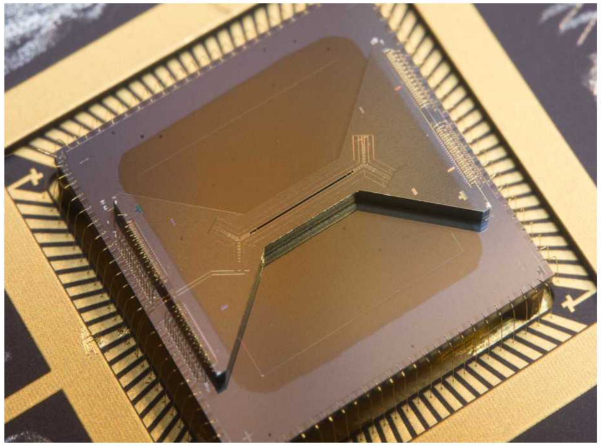
3: $<2\times10^{-8}$

2.5: $<3\times10^{-6}$



4 µm waist is possible

High Optical Access (HOA)

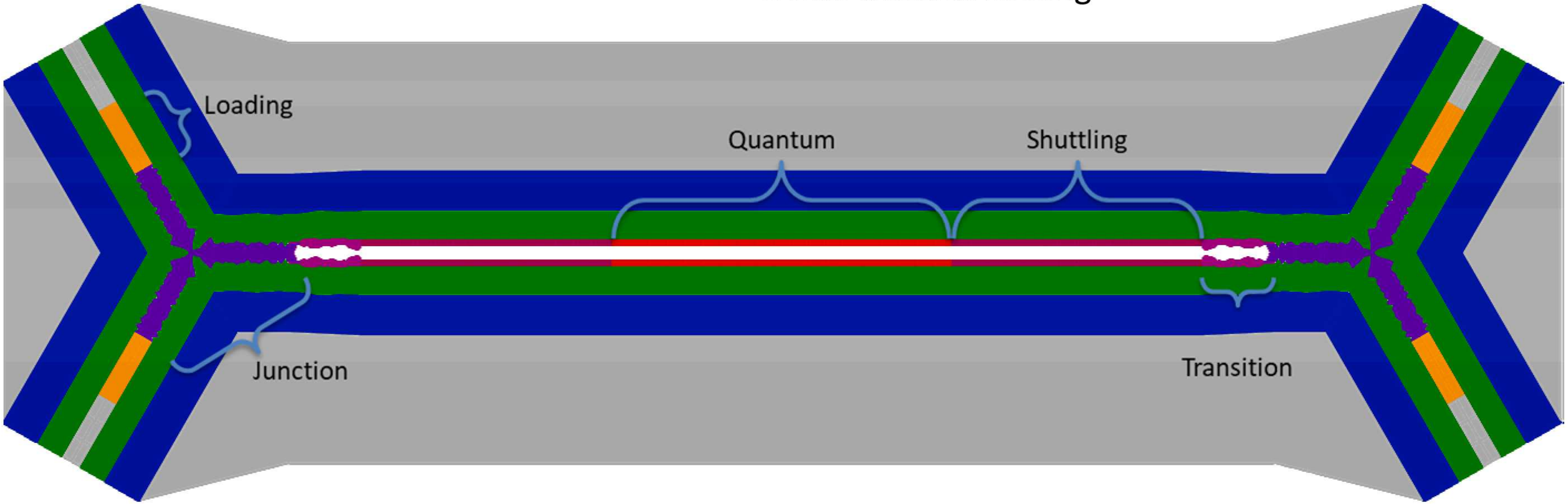


Optical access

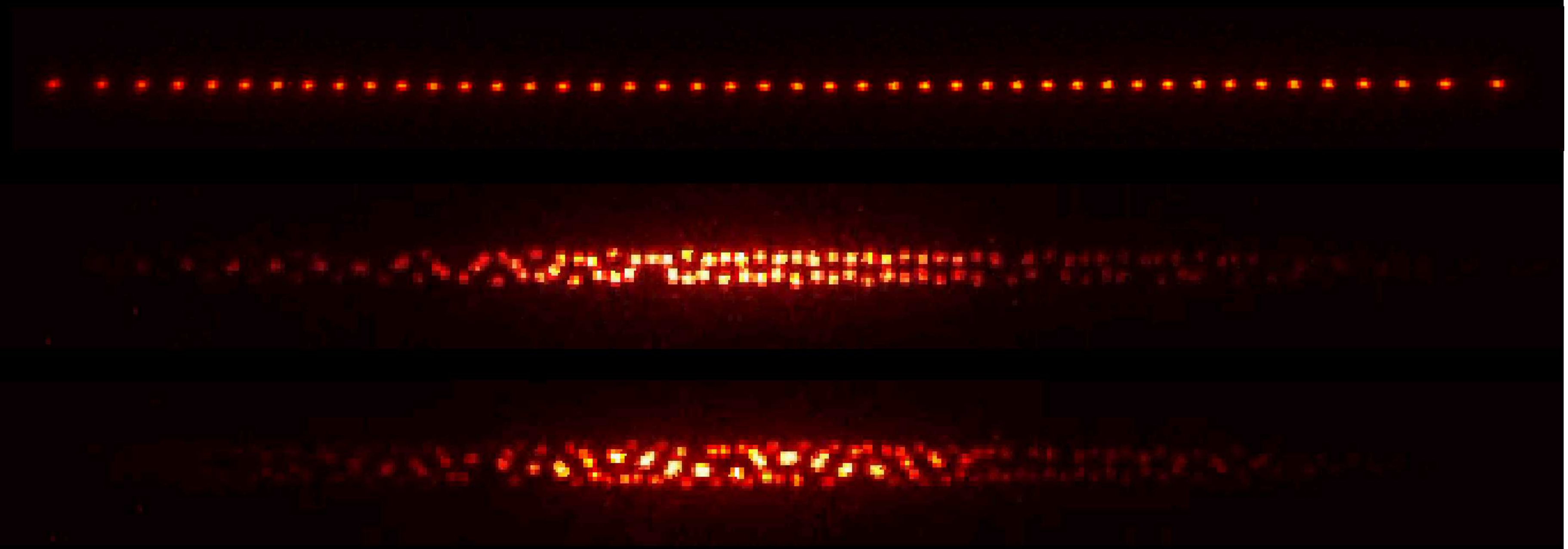
- Excellent optical access rivaling 3-D

Trap strength (Typical Yb^{+})

- Radial trap frequency 2 - 5 MHz
- RF frequency 50 MHz
- Stable for long ion chains
- Low heating rates (30 q/s parallel to surface, 125 q/s perpendicular)
- >100 h observed (while running measurements)
- >5 min without cooling



Trapped ion chains



- Observed storage times between
  - 16 min for long linear chain
  - 16 h for 3d crystal
- Most likely limited by background collisions
- Property of vacuum conditions
- Losing all ions at once (one might come back)

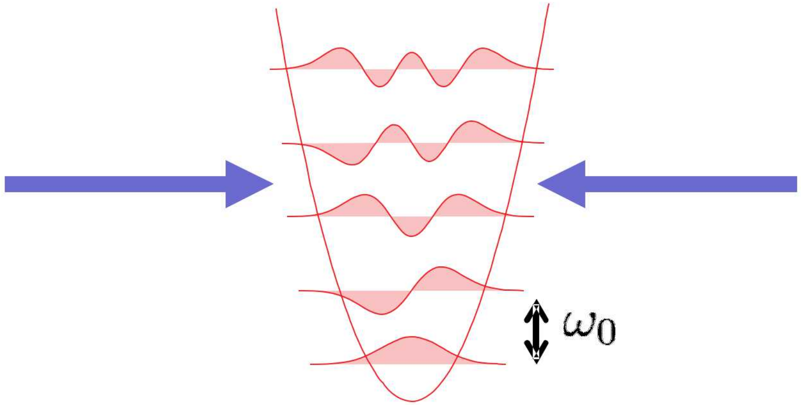
Electric Field Control

When ions are trapped, they exhibit vibrational modes the trapping directions.
Secular Frequency: One for each trapping direction

The motional modes are important:

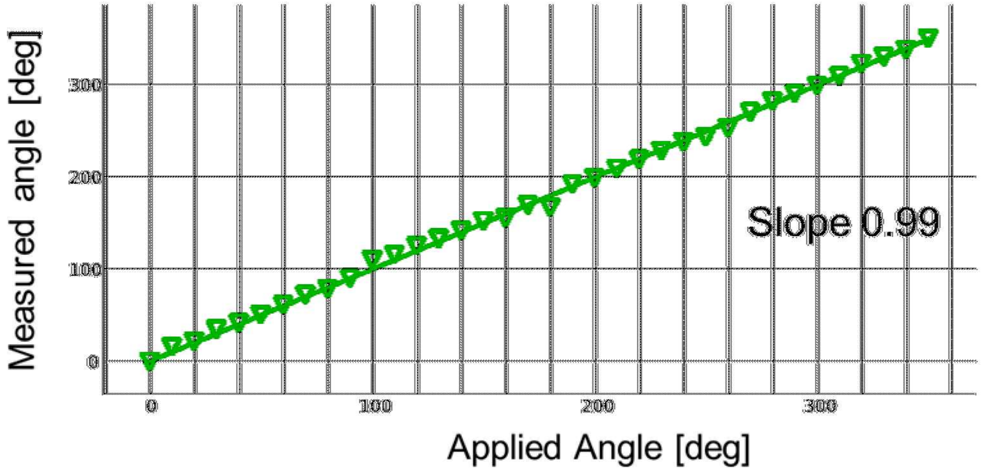
- Interactions between ions
- Allow for cooling to the ground state
- Dictate sensitivity to noise sources

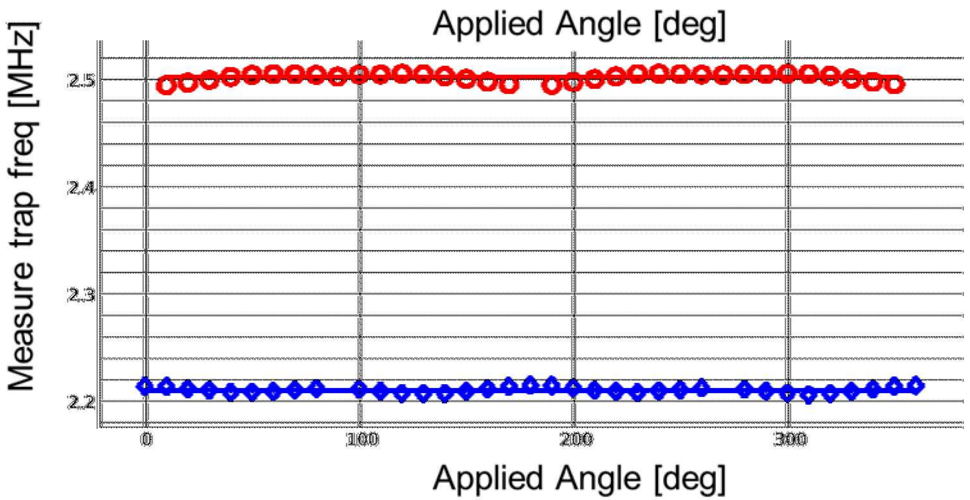
The frequency of the modes are controlled by the strength of the trap



Stronger fields have the effect of a narrowing the well, and thus larger secular frequencies

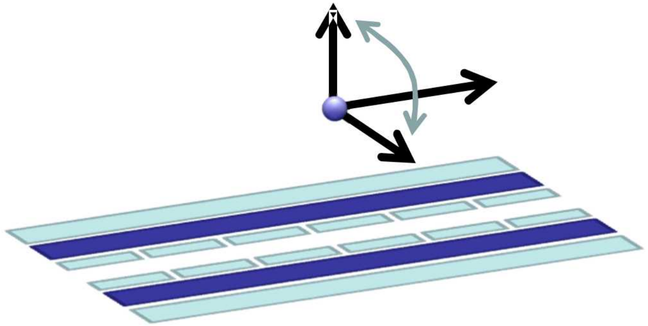
Electric Field Modeling from Trap Design is Accurate



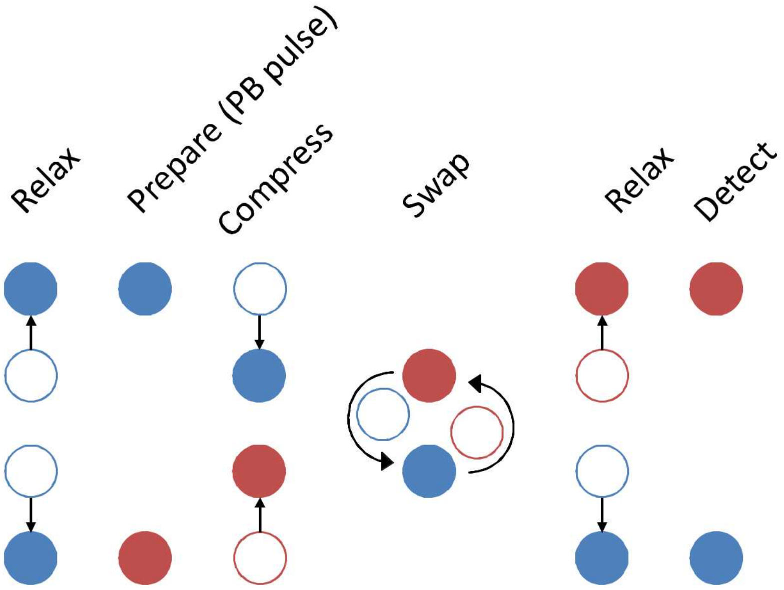


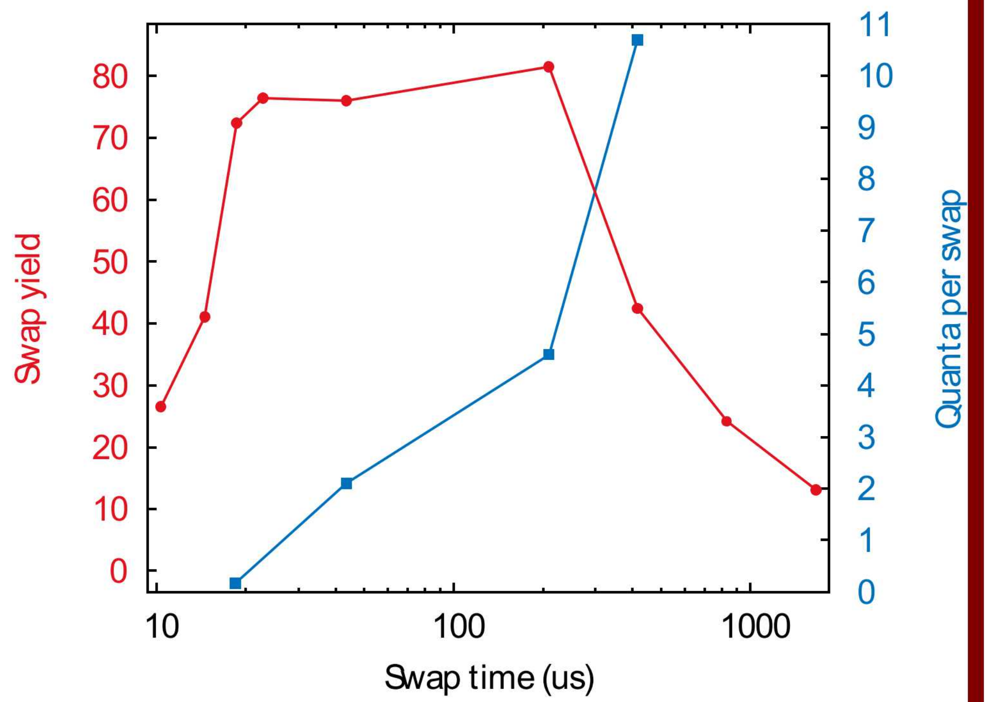
Electric field control

- Do we understand the trapping fields?
- Principal axes rotation realized as in simulation
- No change in trap frequencies
- The simulations accurately describe the fields and curvatures generated by the trap



Electric Field Control from Surface Traps: Swapping ions



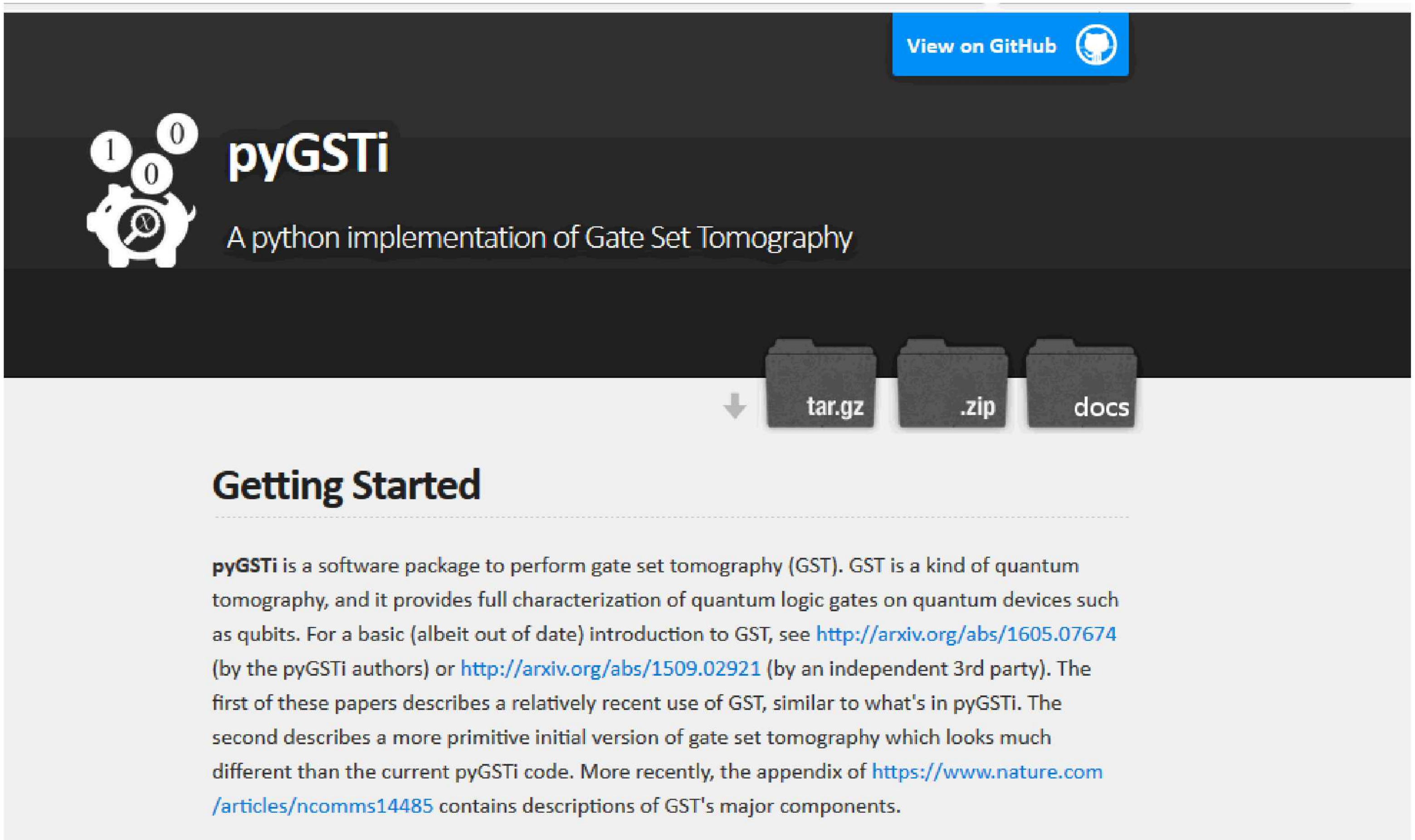


Advantages of parametric trapping solutions:

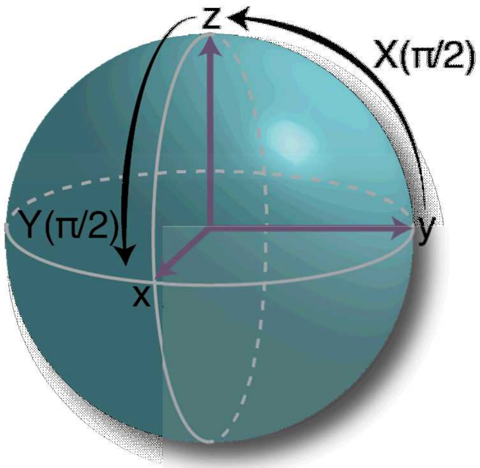
- Primitives in terms of curvature tensor elements and can be applied at any location in the trap.
- Shuttling primitives can be easily combined
- Example: rotating ion crystal while translating through the trap

Testing High Fidelity Operations with GST

Gate Set Tomography, developed at Sandia
Robin Blume-Kohout, Erik Nielsen, et al.
http://www.pygsti.info/
Available on GitHub: https://github.com/pyGSTio/pyGSTi



How Gate Set Tomography (GST) Works



Start with a few gates that you want to test:

X: π/2 rotation about x-axis
Y: π/2 rotation about y-axis
i: idle gate (do nothing)

GST uses those gates to form **"germs"** which are small sets of these primitive gates

X, Y, i, XY, XYi, XiY, Xii, Yii, XXiY, XYYi, XXYXYY

GST uses a small set of **"fiducials"** made of the primitives for preparation and measurement (six orthogonal poles)

{}, X, Y, XX, XXX, YYY

Using combinations of

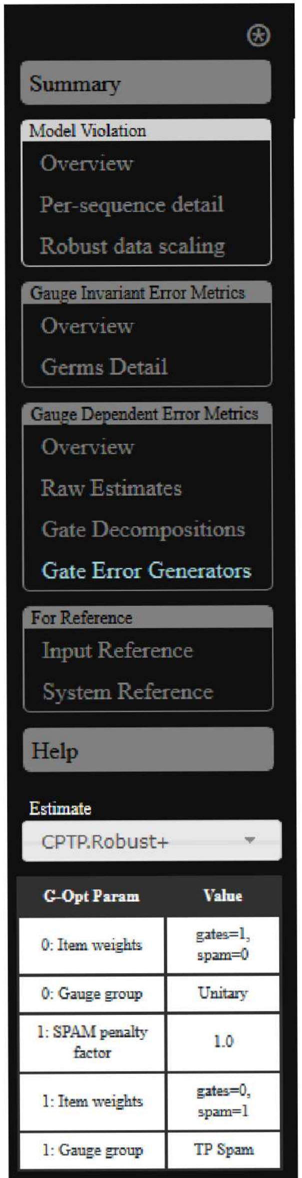
fiducial1 – (germ)^n – fiducial2

To make strings of gates that are applied to the system

GST is:

-**Self Consistent** (fiducials are not assumed perfect)
-**Efficient** (repeating germs amplifies the errors)
-**Sensitive** (germs chosen to be sensitive to all types of errors)

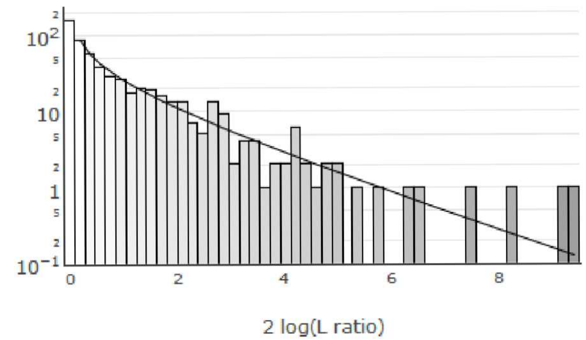
Information that GST Reports

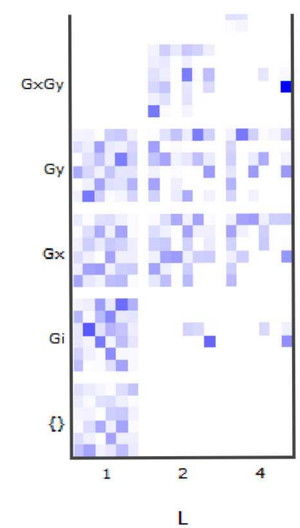


Many different ways to report fidelity
Ask your theorist which is preferred!
GST gives you all of these:

- Entanglement Infidelity
- Average Gate Infidelity
- Non-Unitary Entanglement Infidelity
- Non-Unitary Average Gate Infidelity
- ½ Diamond-Distance
- ½ Non-Unitary Diamond-Distance
- Randomized Benchmarking Number
- Eigenvalues and Matrices
- Gate Decompositions
- Gate Error Generators
- Estimated Rotation Angles
- Rotation Angles between Gates

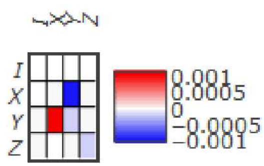
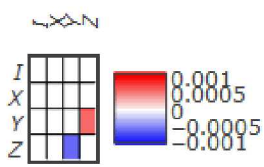
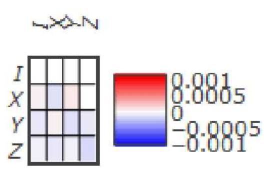
Along with visuals to more quickly detect patterns of errors





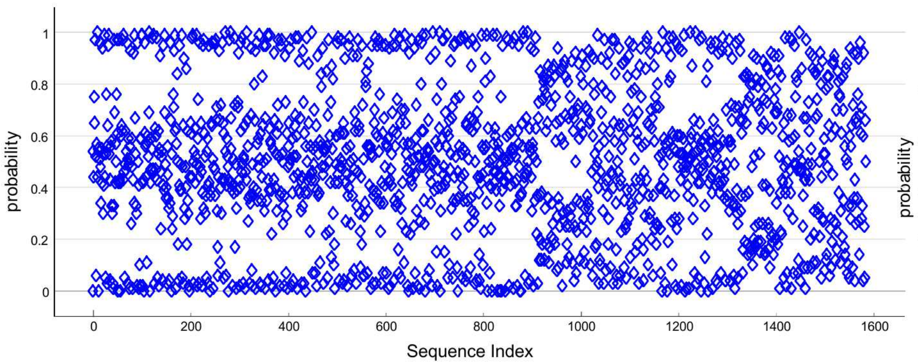
Information that GST Reports

Different Types of Error Generators

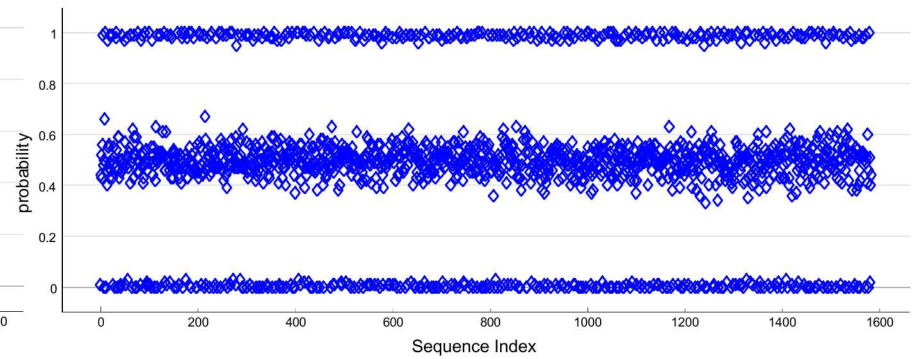
Gate	Error Generator	Pauli Hamiltonian Projections	Pauli Stochastic Projections	Pauli Affine Projections
Gi		Power 0.96 Q1 I X Y Z 0, 1m5, 5m6, 5m4	Power 0.032 Q1 I X Y Z -1m4, 9m5, 9m6, 1m6	Power 0.00075 Q1 I X Y Z 0, 1m5, -2m5, -3m5
Gx		Power 1 Q1 I X Y Z 0, -3m4, 4m6, 4m6	Power 0.00011 Q1 I X Y Z -4m6, 4m7, 2m6, 2m6	Power 6.1e-05 Q1 I X Y Z 0, 6m6, -2m6, -2m6
Gy		Power 0.041 Q1 I X Y Z 0, 4m6, 2m5, -4m6	Power 0.59 Q1 I X Y Z -1m4, 3m5, 3m5, 3m5	Power 0.15 Q1 I X Y Z 0, 4m5, -9m5, -6m5

GST – Microwaves (horn)

Raw data poor gates

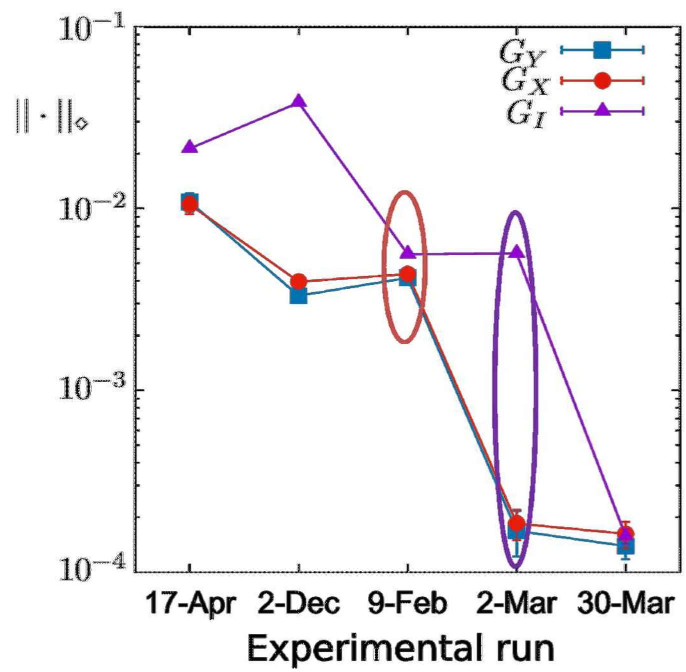


Raw data good gates



Gate	Rotn. axis	Angle
G_I	0.5252 -0.009 0.8506 -0.0244	0.001699π
G_X	-3×10^{-6} -1 -3×10^{-5} -0.009	0.501308π
G_Y	-0.2474 0.0001 0.9689 -0.0001	0.501366π

Gate	Rotn. axis	Angle
G_I	-0.0035 0.014 -0.9999 0.0006	0.001769π
G_X	-3×10^{-5} -1 1×10^{-4} 0.0006	0.500007π
G_Y	0.1104 4×10^{-5} 0.9939 0.0005	0.50001π



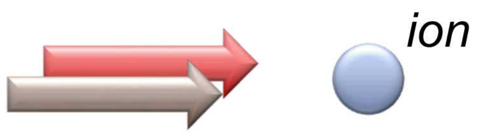
Microwave Gates using Microwave Trap (Single Qubit)

GST Results

Gate	Gi	Gx	Gy
Ent. Infidelity	1.4×10^{-5}	3.5×10^{-5}	2.1×10^{-5}
Avg. Gate Infidelity	9.2×10^{-6}	2.3×10^{-5}	1.4×10^{-5}
Non-U. Ent. Infidelity	1.4×10^{-5}	3.5×10^{-5}	2.1×10^{-5}
Non U. Avg. Gate Infidelity	9.2×10^{-6}	2.3×10^{-5}	1.4×10^{-5}
½ Diamond-Dist.	6.5×10^{-4}	2.4×10^{-4}	1.3×10^{-4}
½ Non-U. Diamond-Dist	1.4×10^{-5}	3.9×10^{-5}	2.3×10^{-5}

Entanglement Infidelity $< 3.5 \times 10^{-5}$
½ diamond norm $< 6.5 \times 10^{-4}$
} Indicates Systematic Error

Laser based Raman gates



co-propagating beam geometry

- Motion independent
- No optical phase imprinted

- BB1 dynamically compensated pulse sequences

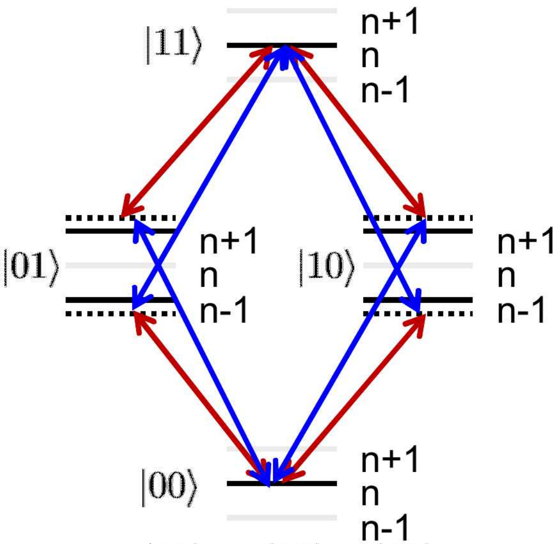
GST results:

95% confidence intervals

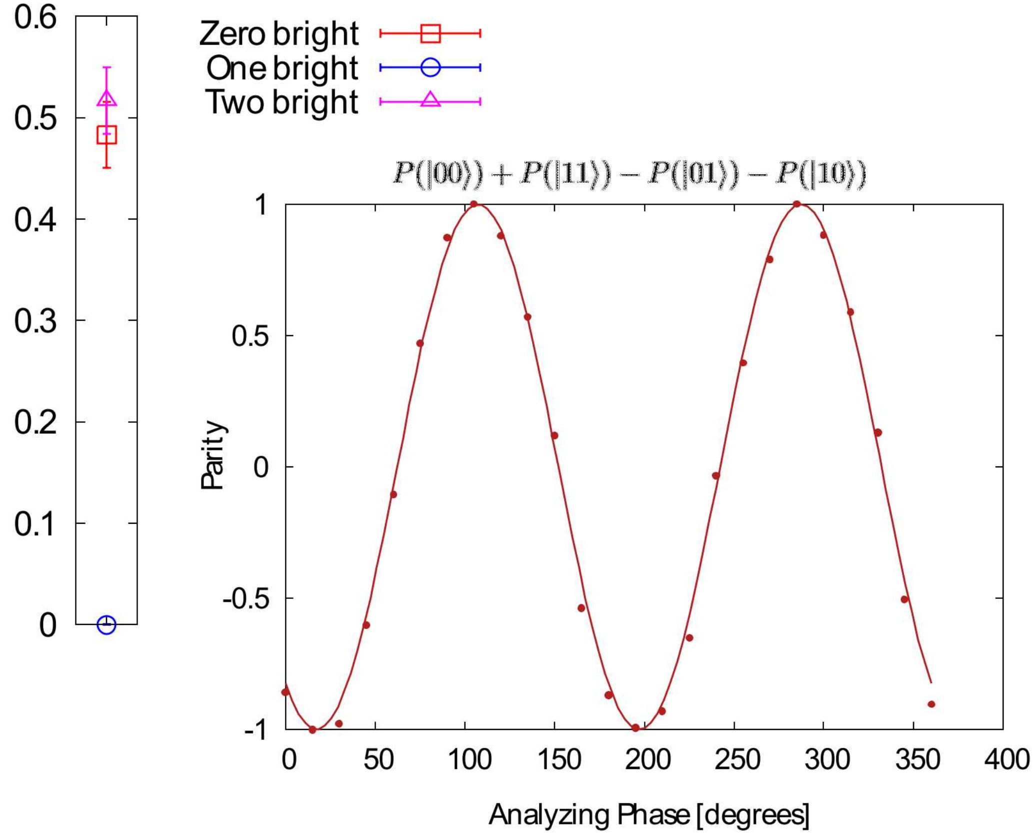
	Conventional pulses		Gapless pulses	
Gate	Process Infidelity	1/2 ◇-Norm	Process Infidelity	1/2 ◇-Norm
G_I	$0.05(2) \times 10^{-4}$	$12(1) \times 10^{-4}$	$1.1(1) \times 10^{-4}$	$5.3(2) \times 10^{-4}$
G_X	$1.3(1) \times 10^{-4}$	$4(2) \times 10^{-4}$	$0.5(1) \times 10^{-4}$	$2(6) \times 10^{-4}$
G_Y	$1.6(4) \times 10^{-4}$	$4(3) \times 10^{-4}$	$0.7(1) \times 10^{-4}$	$4(9) \times 10^{-4}$

Mølmer-Sørensen gates

- Mølmer-Sørensen gates [1]
- All two-qubit gates implemented using Walsh compensation pulses [2]



$|00\rangle \rightarrow |00\rangle + |11\rangle$

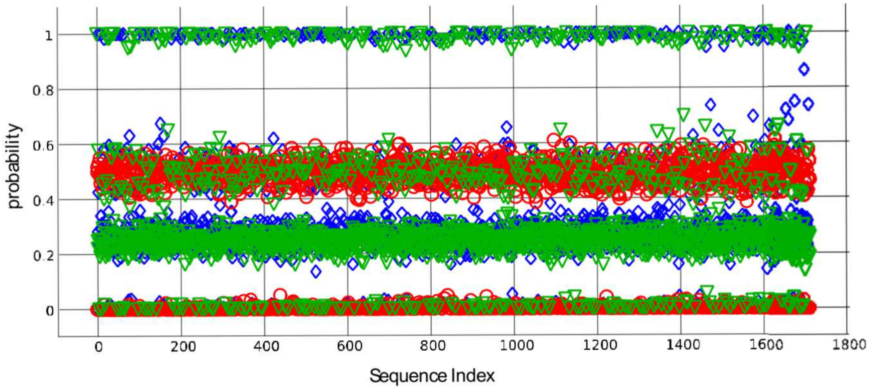


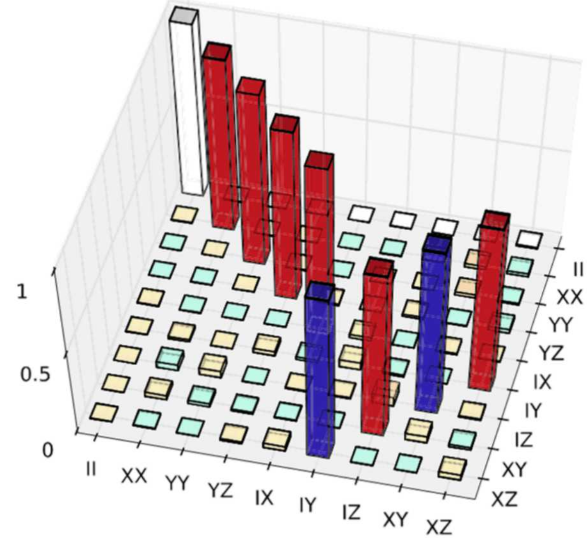
$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c \approx 0.995$$

[1] K. Mølmer, A. Sørensen, PRL 82, 1835 (1999)

[2] D. Hayes et al. Phys. Rev. Lett. 109, 020503 (2012)

GST on symmetric subspace





Gate	Process infidelity	$\frac{1}{2}$ Diamond norm
G_I	$1.6 \times 10^{-3} \pm 1.6 \times 10^{-3}$	$28 \times 10^{-3} \pm 7 \times 10^{-3}$
G_{XX}	$0.4 \times 10^{-3} \pm 1.0 \times 10^{-3}$	$27 \times 10^{-3} \pm 5 \times 10^{-3}$
G_{YY}	$0.1 \times 10^{-3} \pm 0.9 \times 10^{-3}$	$26 \times 10^{-3} \pm 4 \times 10^{-3}$
G_{MS}	$4.2 \times 10^{-3} \pm 0.6 \times 10^{-3}$	$38 \times 10^{-3} \pm 5 \times 10^{-3}$

95% confidence intervals

Process fidelity of two-qubit Mølmer-Sørensen gate > 99.5%

Summary

Surface Traps fabricated at Sandia demonstrate a many building blocks for larger systems: Good Platform for Future

- Ion shuttling and position control
- High fidelity quantum operations

Leveraging DOE facilities

- MESA facility – capabilities align well with trap requirements
  - Engineers and technologists essential to fabricating and packaging the many traps needed at SNL and academic/commercial partners
- Engineering and simulations
  - Microwave design
  - Quantum theory – tomography and error correction

Future research

- Next Slide!

Future Work with Ions at Sandia

Department of Energy

Department of Energy Announces $218 Million for Quantum Information Science

SEPTEMBER 24, 2018

Home » Department of Energy Announces $218 Million for Quantum Information Science

Field Will Shape Future of Information Processing

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced $218 million in funding for 85 research awards in the important emerging field of Quantum Information Science (QIS). The awards were made in conjunction with the White House Summit on Advancing American Leadership in QIS, highlighting the high priority that the Administration places on advancing this multidisciplinary area of research, which is expected to lay the foundation for the next generation of computing and information processing as well as an array of other innovative technologies.

Future Work with Ions at Sandia

QSCOUT: DOE funded, goal of making a stable, public platform (testbed) from trapped ions for the scientific community to perform experiments

LogiQ: IARPA funded, goal of making a logical qubit with errors rates less than the physical qubits that compose it

www.sandia.gov → Careers → View All Jobs

Postdoctoral Appointee – AMO Physics Job ID 663692
Ion Trapping
Peter Maunz (plmaunz@sandia.gov)

Postdoctoral Appointee – AMO Physics Job ID 663398
Atomic Sensing and Clocks
Peter Schwint (pschwin@sandia.gov)

Two-qubit gates in Rydberg atoms, atom interferometers
Grant Biedermann (gbeider@sandia.gov)

Summary

Surface Traps fabricated at Sandia demonstrate many building blocks for larger systems:

- Ion shuttling and position control
- High fidelity quantum operations
- Beginning sympathetic cooling

Leveraging DOE facilities

- MESA facility – capabilities align well with trap requirements
  - Engineers and technologists essential to fabricating and packaging the many traps needed at SNL and academic/commercial partners
- Engineering and simulations
  - Microwave design
  - Quantum theory – tomography and error correction

Future research

- DOE testbed
- LogiQ research

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