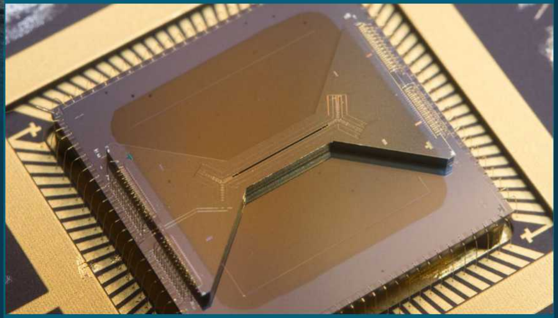
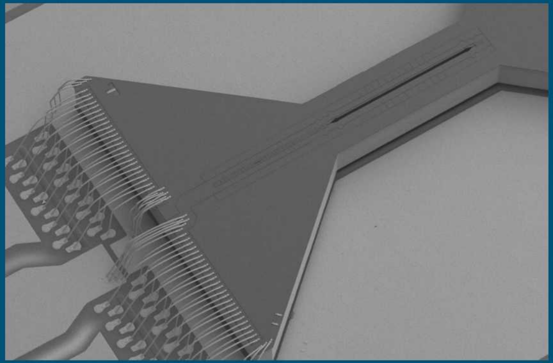
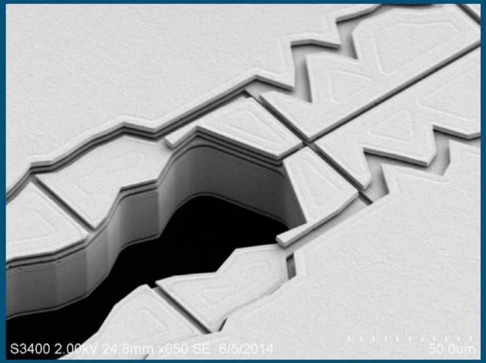
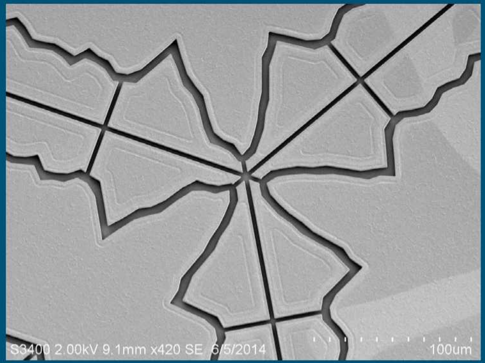
SAND2019-14775PE

Science meets Engineering:
Design and Realization of the Quantum Scientific Computing Open User Testbed (QSCOUT)









PRESENTED BY

Peter Maunz, Sandia National Laboratories

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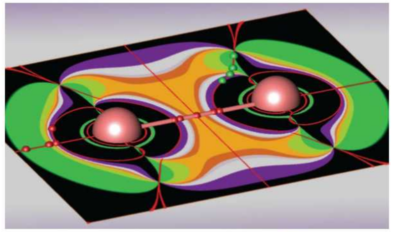
Quantum information

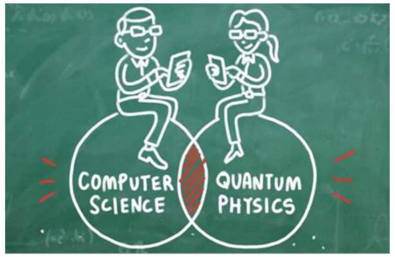


Quantum chemistry

- Calculation of molecular potentials
- Nitrogen and Oxygen fixation, development of catalytic converters

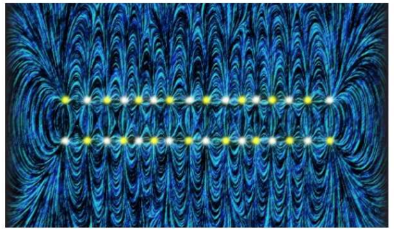
Medicine

- Structure-based drug development



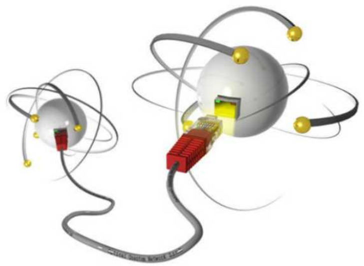
Quantum computing

- Number factorization (Shor's algorithm)
- Search in unstructured data, searching for solutions to hard problems (Grover's search algorithm)



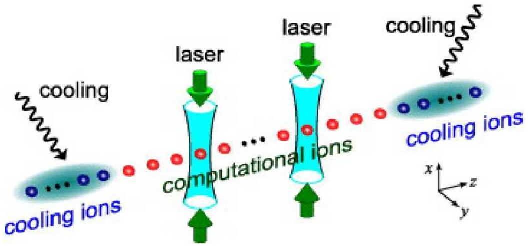
Quantum simulation

- Simulating many-body systems
- Already for about 20 qubits not possible to simulate classically.



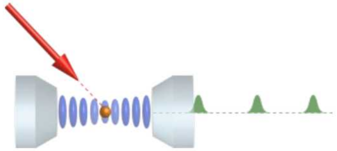
Quantum Communication

- Securing a quantum channel



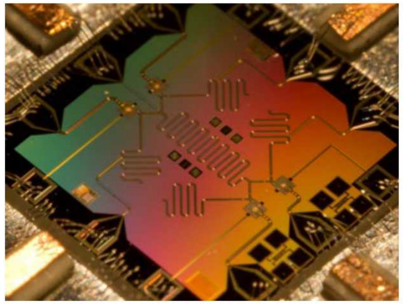
Trapped Ions

- Blatt and Wineland "Entangled States of Trapped Atomic Ions." *Nature* 453, 1008–15 (2008).
- Monroe and Kim. "Scaling the Ion Trap Quantum Processor." *Science* 339, 1169 (2013)



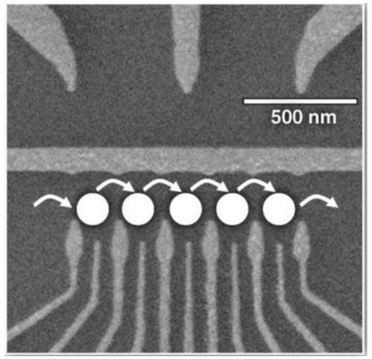
Neutral Atoms

- Rydberg states
- Atoms in cavities



Superconducting Josephson junctions

- Devoret and Schoelkopf. "Superconducting Circuits for Quantum Information: An Outlook." *Science* 339, 1169 (2013).



Quantum dots

- Awschalom, et al., "Quantum Spintronics: Engineering and Manipulating Atom-Like Spins in Semiconductors." *Science* 339, 1174 (2013).

Trapped Ion processors

QSCOUT

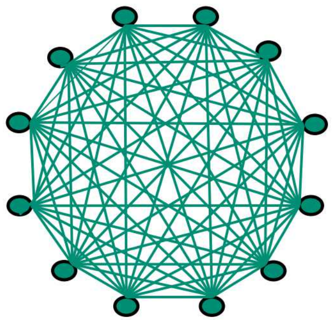
Best available qubits with history of reliability and quality

- Ions (qubits) are identical
- Near-ideal prep and measure
  - Error < 8×10^{-4}
- No idle errors (long coherence times)
  - Coherence time > 15min possible
- Lowest gate errors
  - Single-qubit error < 1×10^{-4}
  - Two-qubit error < 1×10^{-3}
- Single chain qubit registers demonstrated
- Low crosstalk

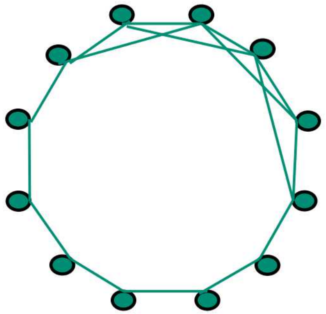
Reconfigurable in software

- Optimal for any application
- Change between quantum computer and quantum simulator is change in control
- All-to-All Connectivity
- Ideal for emulating other qubit systems

Trapped Ions:
fully connected



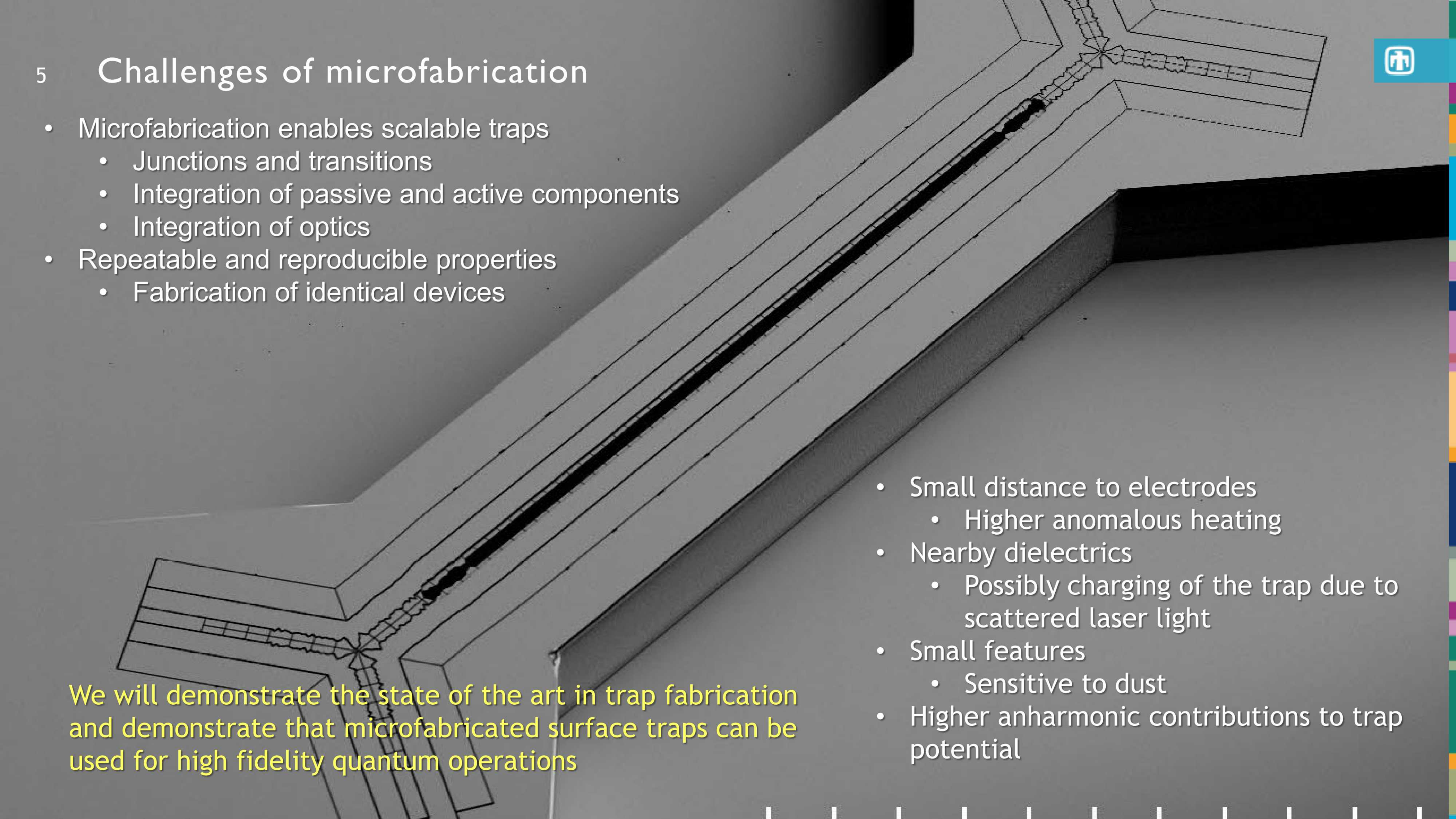
Solid State:
2D nearest neighbor coupling



Why microfabrication

- Microfabrication enables scalable traps
  - Junctions and transitions
  - Integration of passive and active components
  - Integration of optics
- Repeatable and reproducible properties
  - Fabrication of identical devices

Challenges of microfabrication

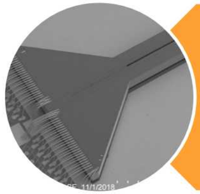


- Microfabrication enables scalable traps
  - Junctions and transitions
  - Integration of passive and active components
  - Integration of optics
- Repeatable and reproducible properties
  - Fabrication of identical devices

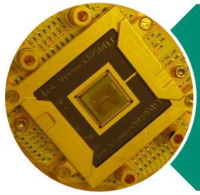
- Small distance to electrodes
  - Higher anomalous heating
- Nearby dielectrics
  - Possibly charging of the trap due to scattered laser light
- Small features
  - Sensitive to dust
- Higher anharmonic contributions to trap potential

We will demonstrate the state of the art in trap fabrication and demonstrate that microfabricated surface traps can be used for high fidelity quantum operations

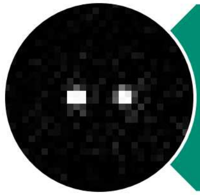
Outline



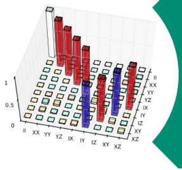
Trap fabrication capabilities



HOA trap

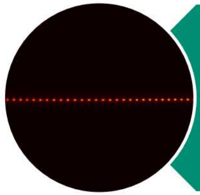


Classical control



Quantum operations

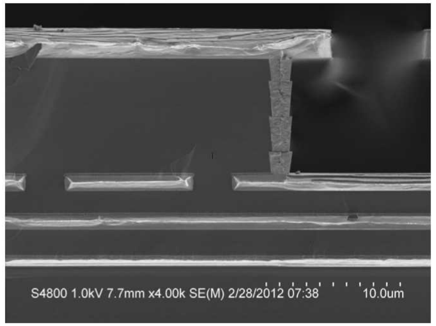
QSCOUT Quantum testbed

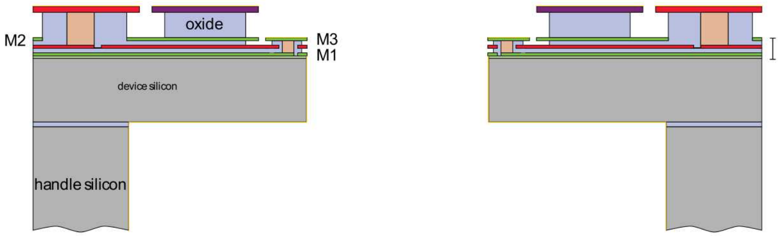


QSCOUT System engineering

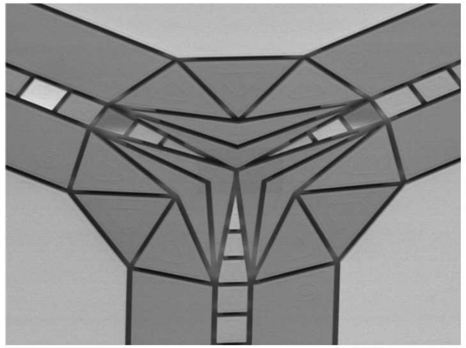
Trap fabrication capabilities

- Based on CEMOS back of line
- Crucial capabilities outside CMOS integrated
- Up to 6-level metallization
  - Planarized
  - Islanded electrodes
  - Reduced rf capacitance
  - Any electrode geometry can be realized
- Removed dielectric (better shielding)
- Integrated trench capacitors for rf shunting
- Loading holes and slots
- Release singulation (e.g. bowtie shapes)

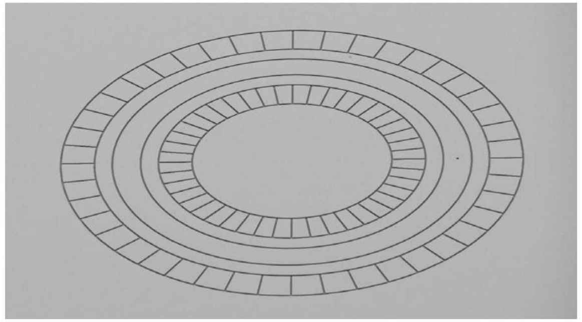


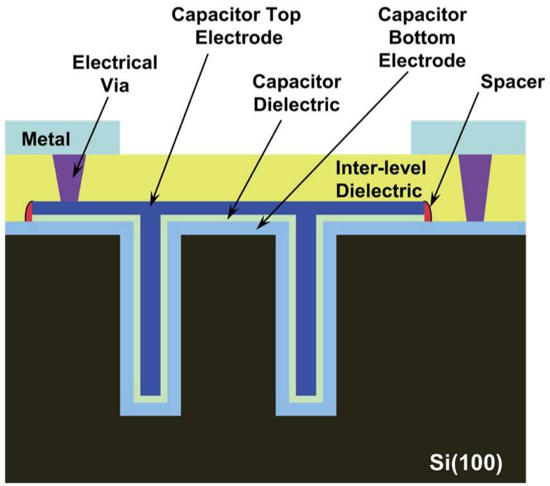


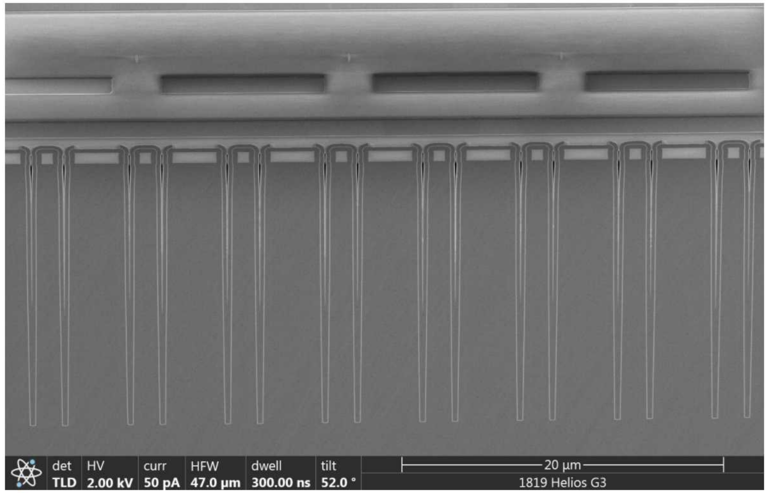
Switchable Y Junction



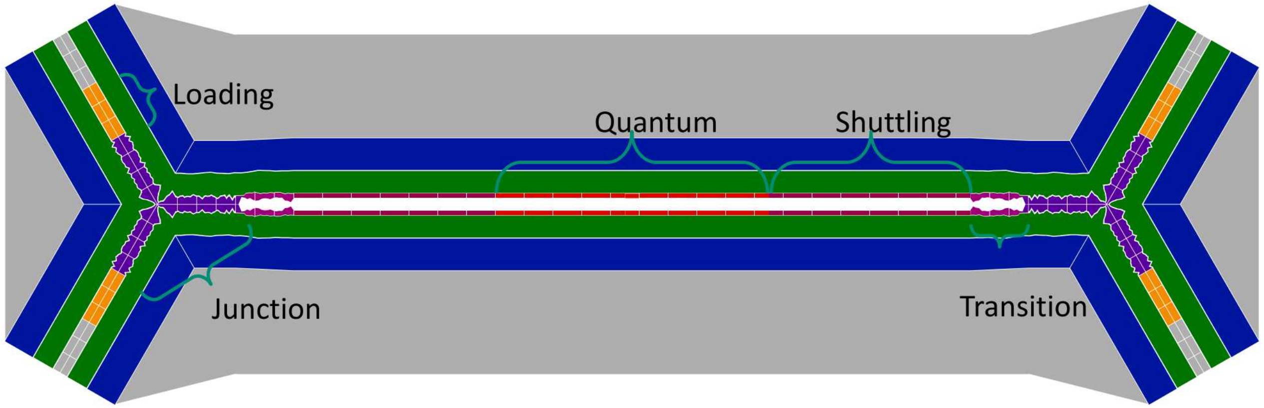
Ring Trap

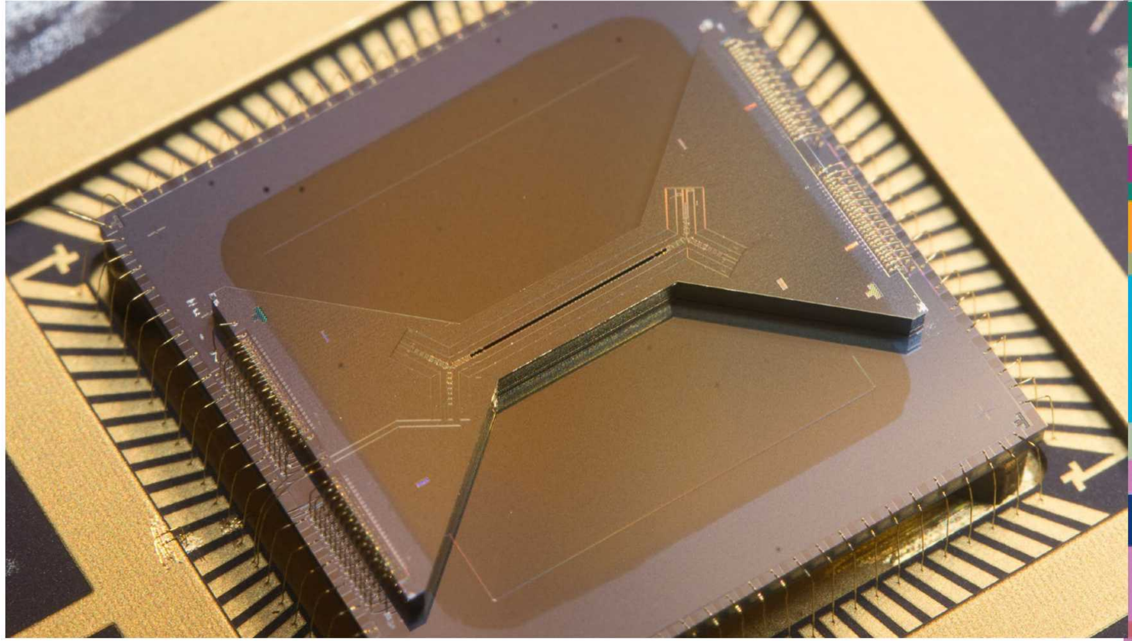






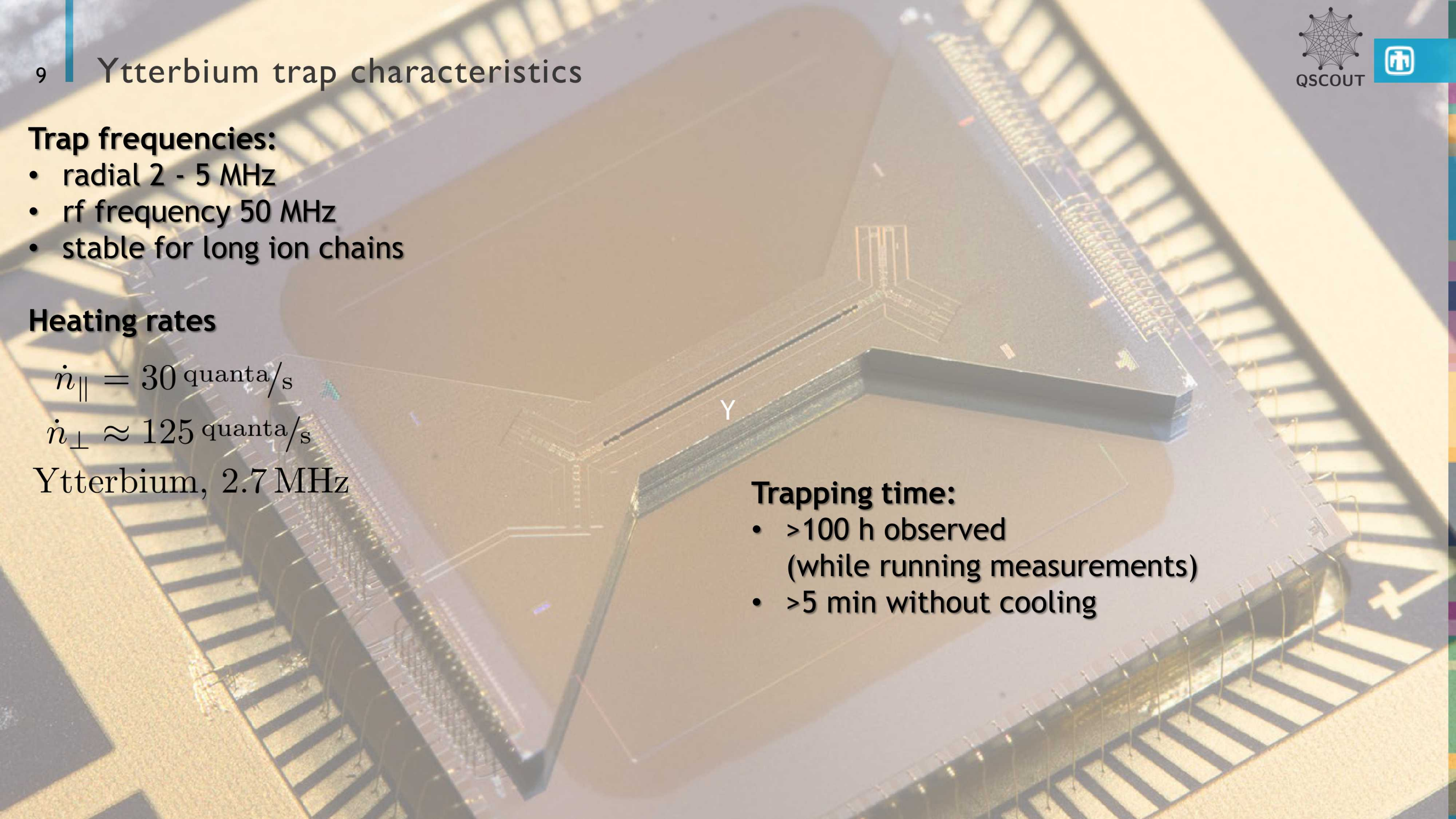
High Optical Access trap HOA-2





- Excellent optical access rivaling 3-D
  - 2π for imaging
  - NA=0.2 through slot
  - NA=0.12 skimming surface
- High trap frequencies (characteristic distance 140μm)
- Full control over principal axes orientation
- Junctions
- Transitions between slotted and above-surface trap regions

Ytterbium trap characteristics



Trap frequencies:

- radial 2 - 5 MHz
- rf frequency 50 MHz
- stable for long ion chains

Heating rates

$$\dot{n}_{\parallel} = 30\,{}^{\mathrm{quanta}}\!/\!{}_{\mathrm{s}}$$

$$\dot{n}_{\perp} \approx 125\,{}^{\mathrm{quanta}}\!/\!{}_{\mathrm{s}}$$

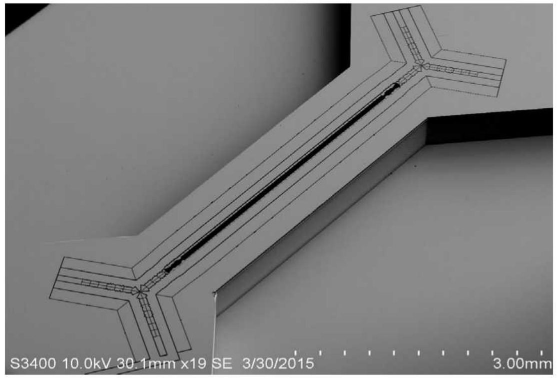
$$\mathrm{Ytterbium},\ 2.7\,\mathrm{MHz}$$

Trapping time:

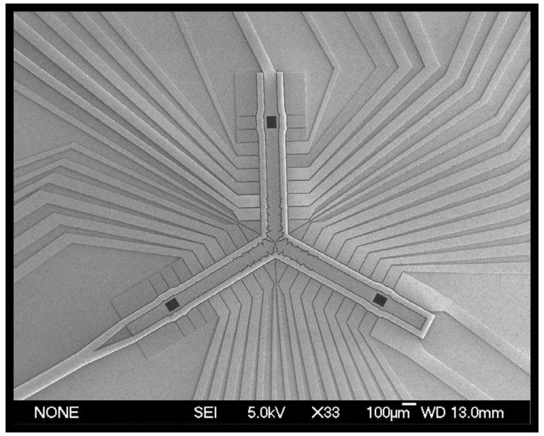
- >100 h observed (while running measurements)
- >5 min without cooling

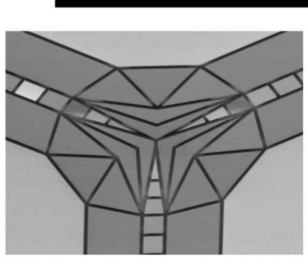
Some of Sandia's Traps

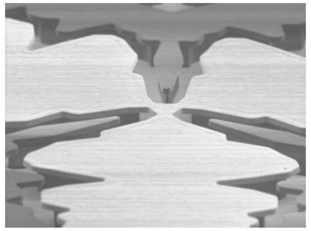
High Optical Access (HOA) trap



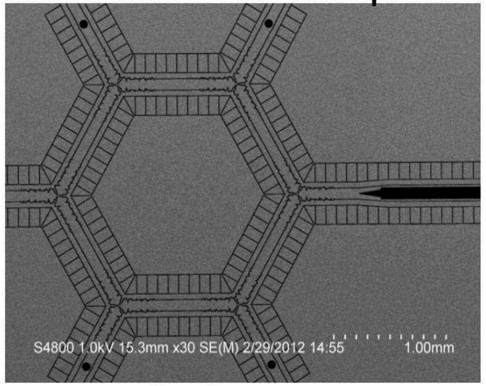
Y-junction traps



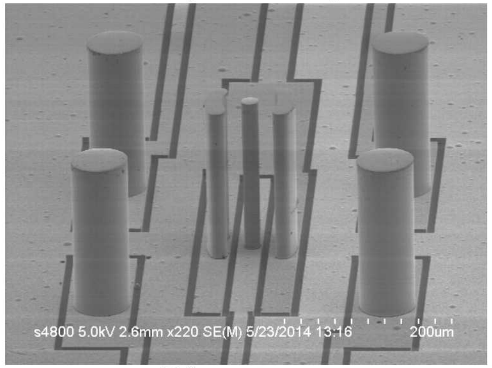




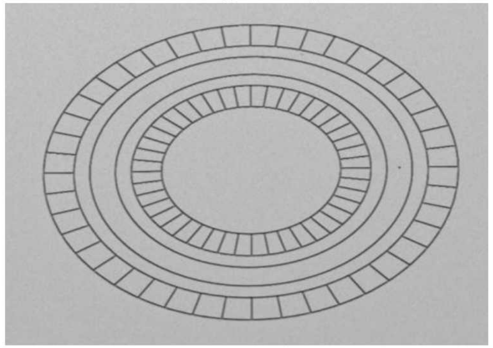
Circulator trap



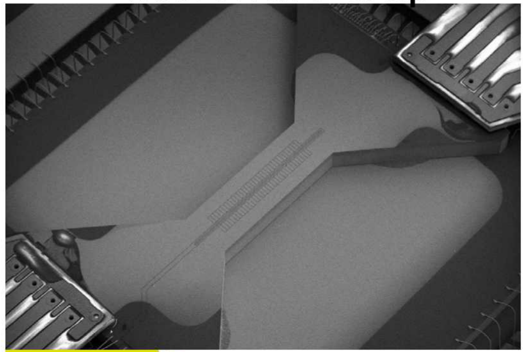
Stylus trap

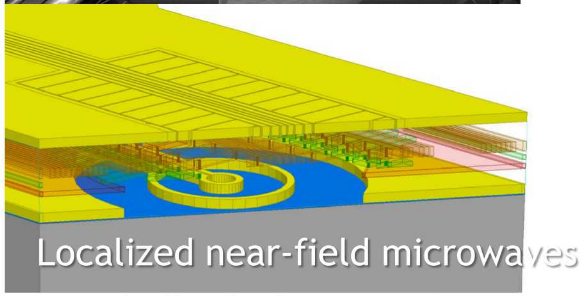


Ring trap

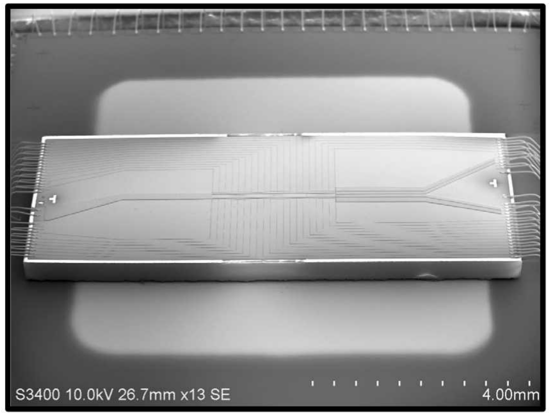


Microwave trap

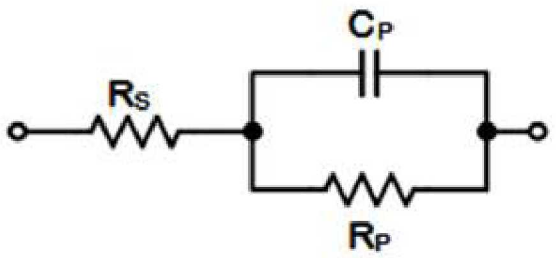




EPICS trap

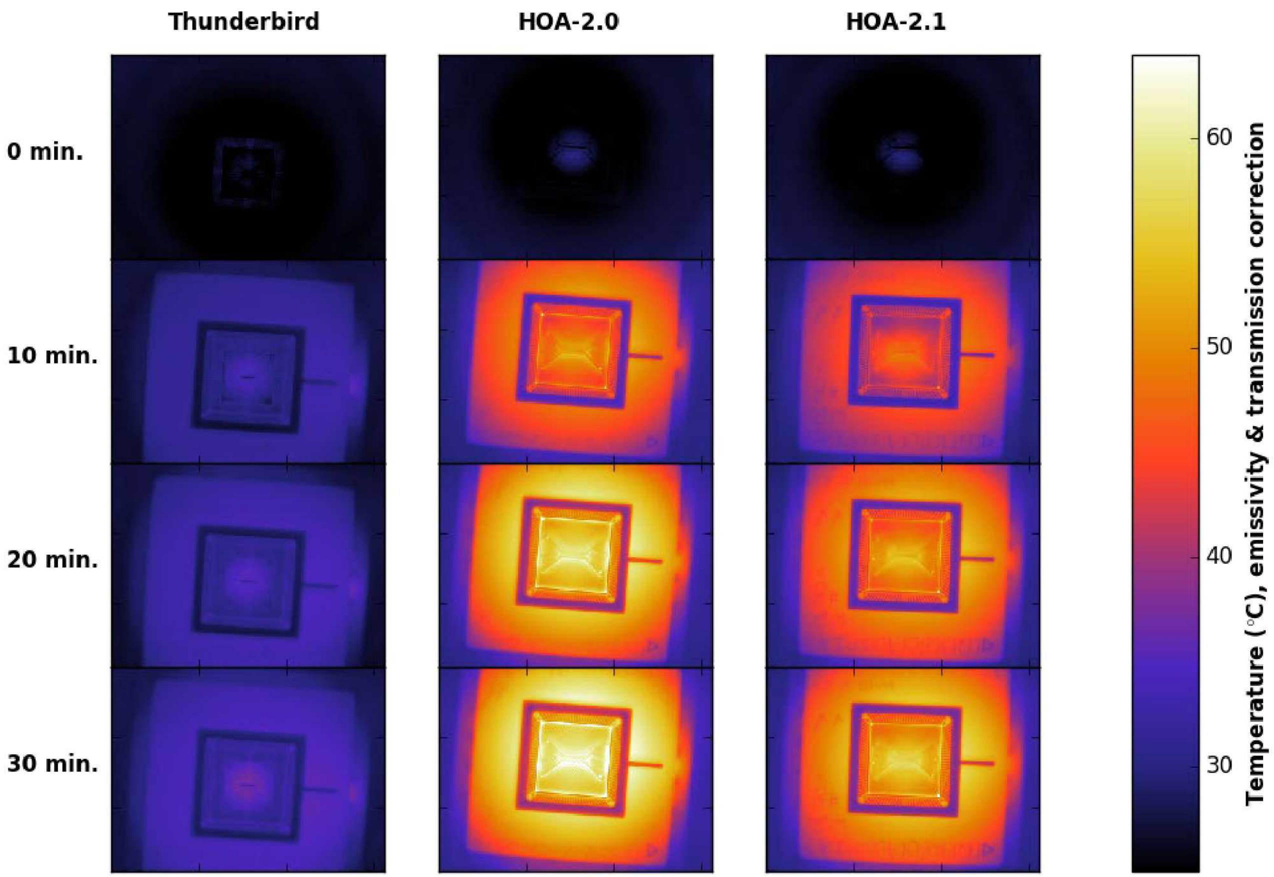


RF dissipation



$$P_s \approx \frac{1}{2} R_s U^2 \omega^2 C_p^2$$

$$P_p = \frac{1}{2} \frac{\omega U^2}{R_p}$$

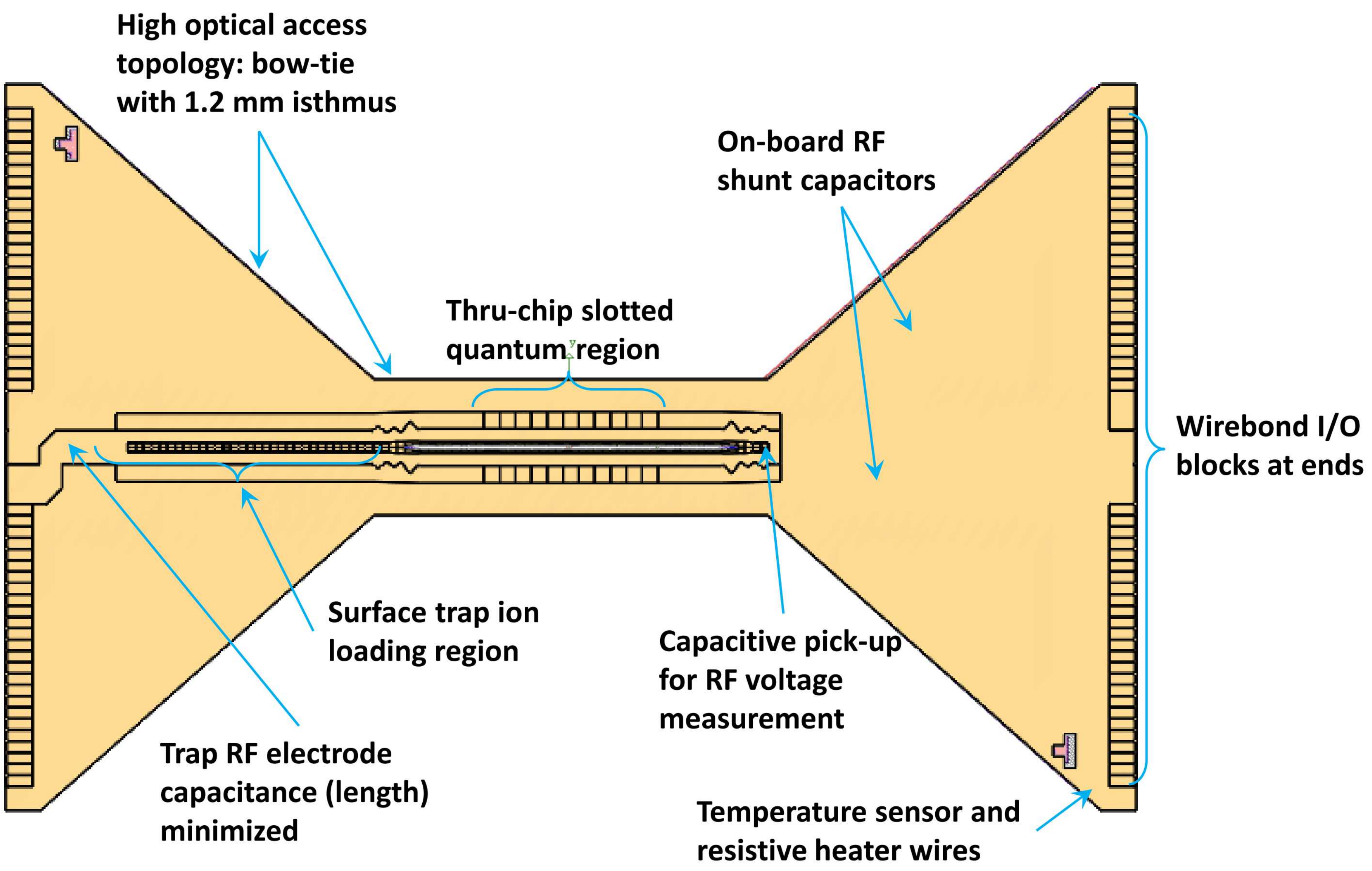


RF Voltage at trap (~280 V)

For 100 V amplitude at 100 MHz:

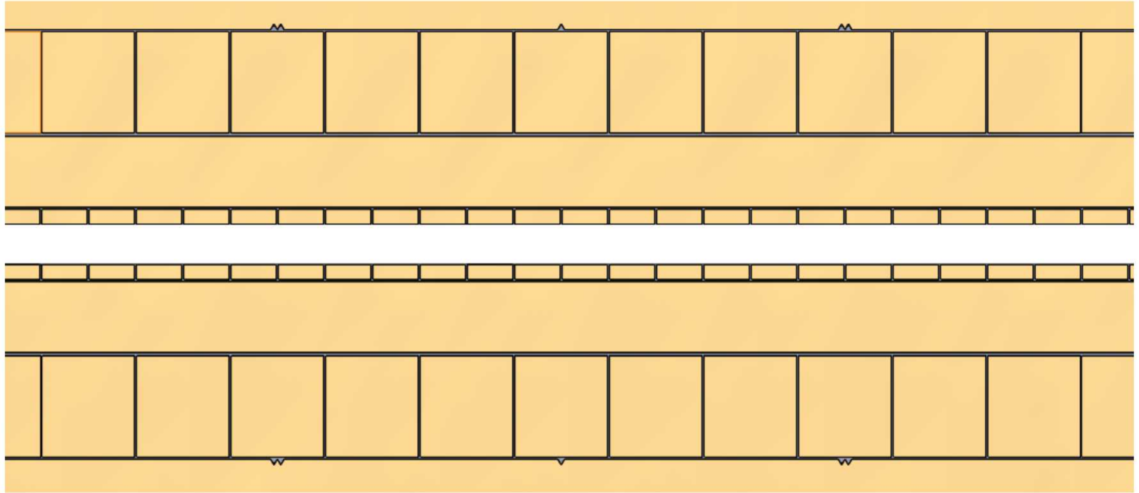
Trap	Temp	C_p	R_s	R_p	P_s	P_p
HOA-2	300 K	7.6 pF	1.2 Ω	1.2 MΩ	140 mW	4.2 mW
	4 K		0.5 Ω		60 mW	
HOA-2.1	300 K	7.6 pF	0.9 Ω	1.6 MΩ	100 mW	3.1 mW
	4 K		0.5 Ω		60 mW	
Thunderbird	300 K	2.4 pF	0.6 Ω	1.5 MΩ	6.7 mW	3.3 mW

Phoenix trap fabrication
Original plans for Phoenix



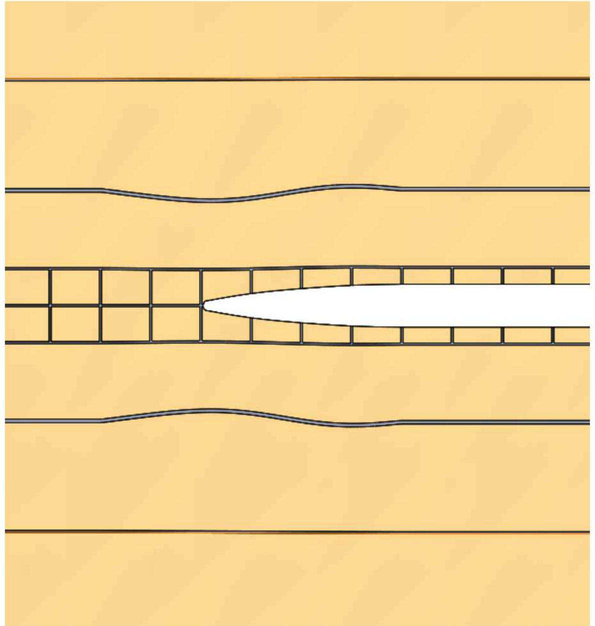
Phoenix trap fabrication
Trap features

QSCOUT



Quantum region

- Segmentation of 22 inner electrode pairs and 11 outer pairs for better control of ion chains and spatial re-ordering of ions
- 22×70µm = 1540µm long
- Ion height 70µm

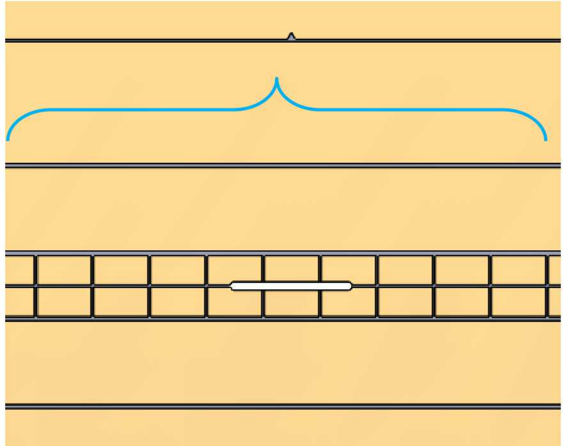


Transition

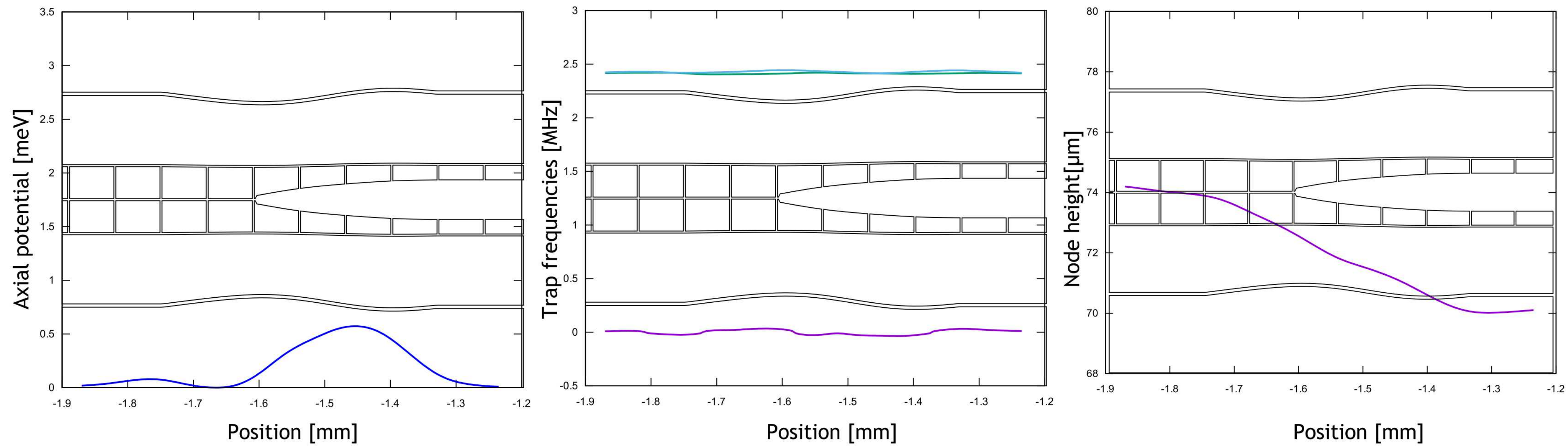
- 9 degrees of freedom
- Low spatial frequencies

Loading region

- 5 electrode pairs
- Loading slot 180um x 3um

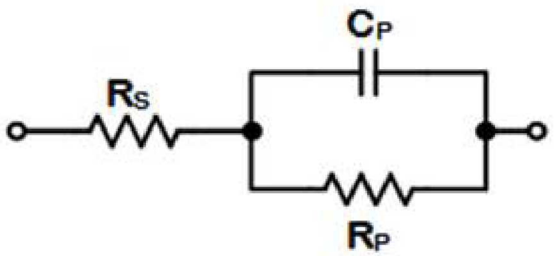


Phoenix trap
Transition characterization



- Transition between slotted and above surface parts of trap is optimized to minimize variations in the trace of the curvature tensor
- RF pseudopotential hump is about 0.5meV for a 2.5MHz radial trap frequency
- Ion height above slot and above surface differs to keep trap frequencies (trace of curvature tensor) constant

Rf-dissipation in traps electrical characterization



R_s : Series resistance (lead resistance)

R_p : (rf) parallel resistance (dielectric absorption)

C_p : capacitance

For 100 V amplitude at 100 MHz:

Trap	Temp	C_p	R_s	R_p	P_s	P_p
Phoenix-0 (measurement)	300 K	4 pF	0.4 Ω		5 mW	
Phoneix-surface (calc.)	4 K		0.05 Ω		1 mW	
Phoenix-slotted (calc.)	300 K	5.5 pF	0.4 Ω		9.4 mW	
	4 K		0.05 Ω		1.4 mW	
HOA-2.1	300 K	7.6 pF	0.9 Ω	1.6 MΩ	100 mW	3.1 mW
	4 K		0.5 Ω		60 mW	
Thunderbird	300 K	2.4 pF	0.6 Ω	1.5 MΩ	6.7 mW	3.3 mW

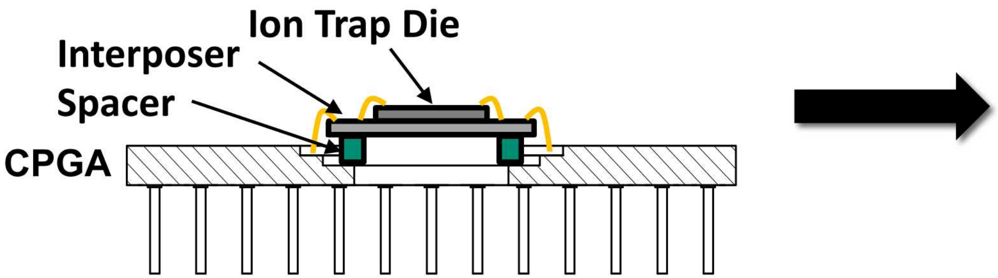
$$P_s \approx \frac{1}{2} R_s U^2 \omega^2 C_p^2$$

$$P_p = \frac{1}{2} \frac{\omega U^2}{R_p}$$

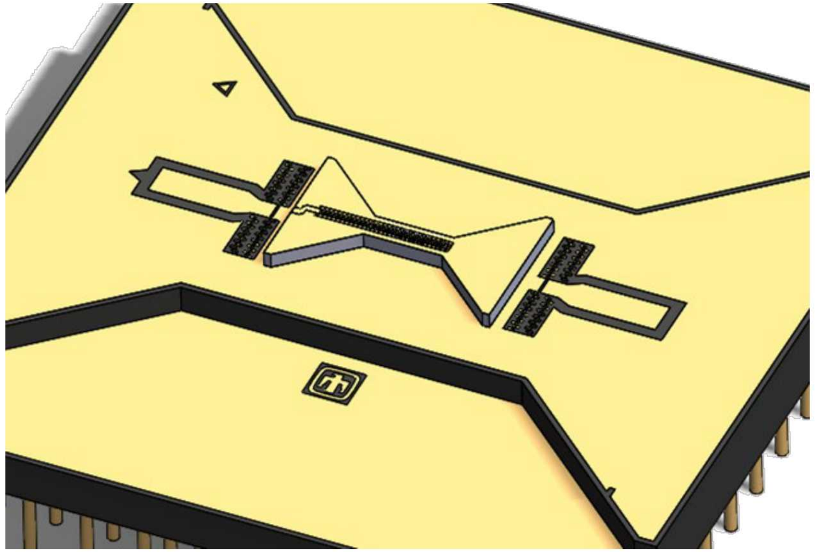
QSCOUT

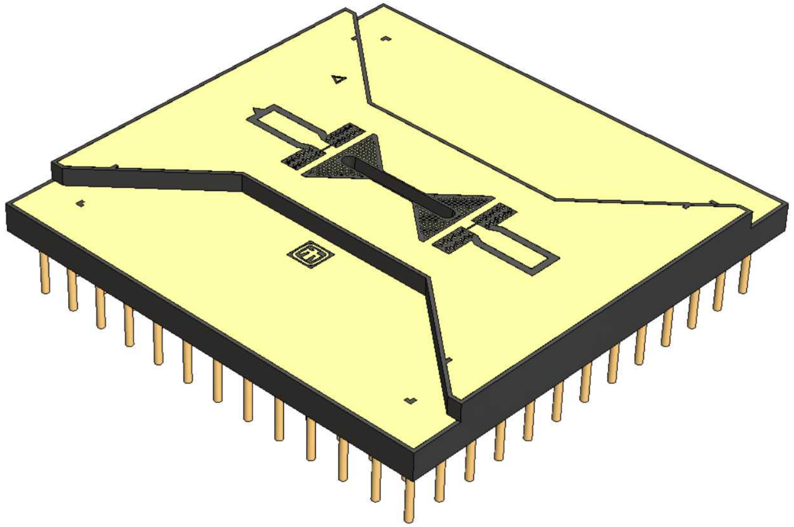
Custom trap package

Legacy 4 Level CPGA Packaging Assembly



Simplified 2 part assembly





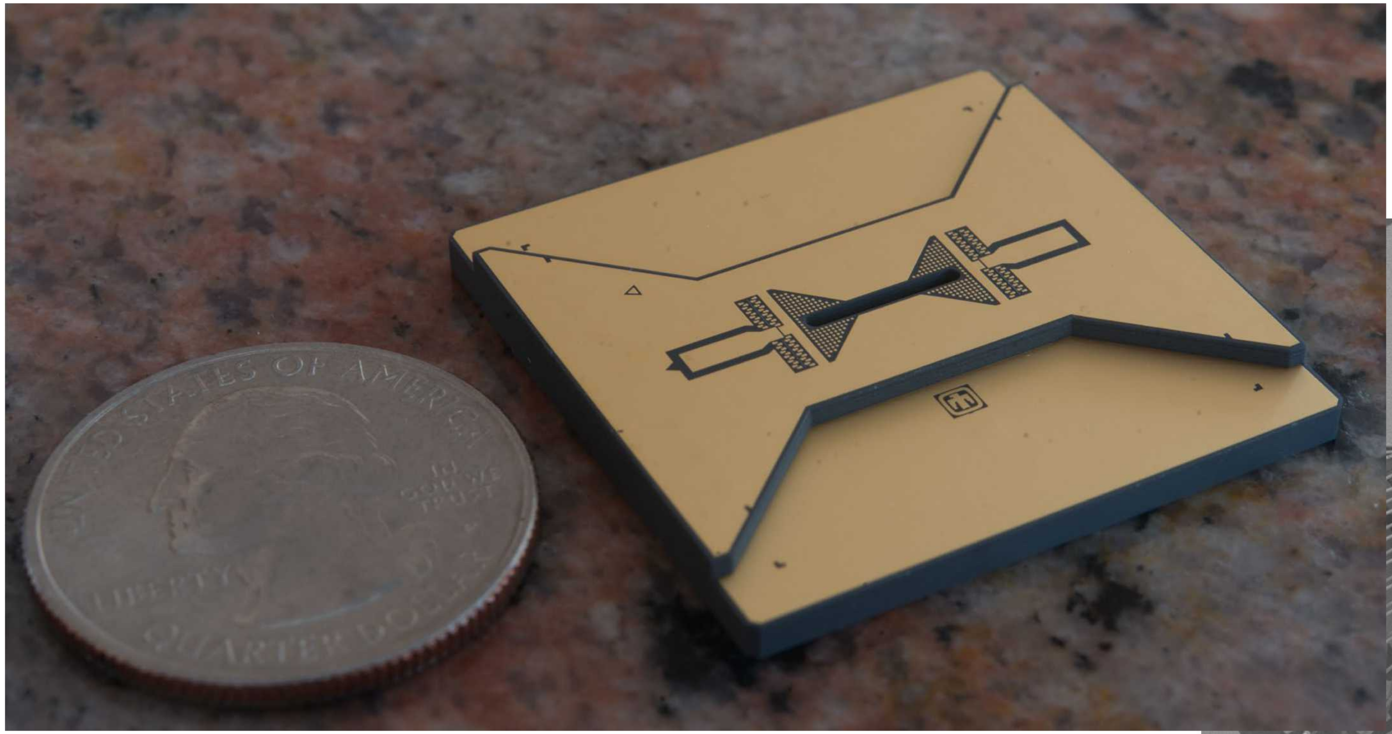
Objectives:

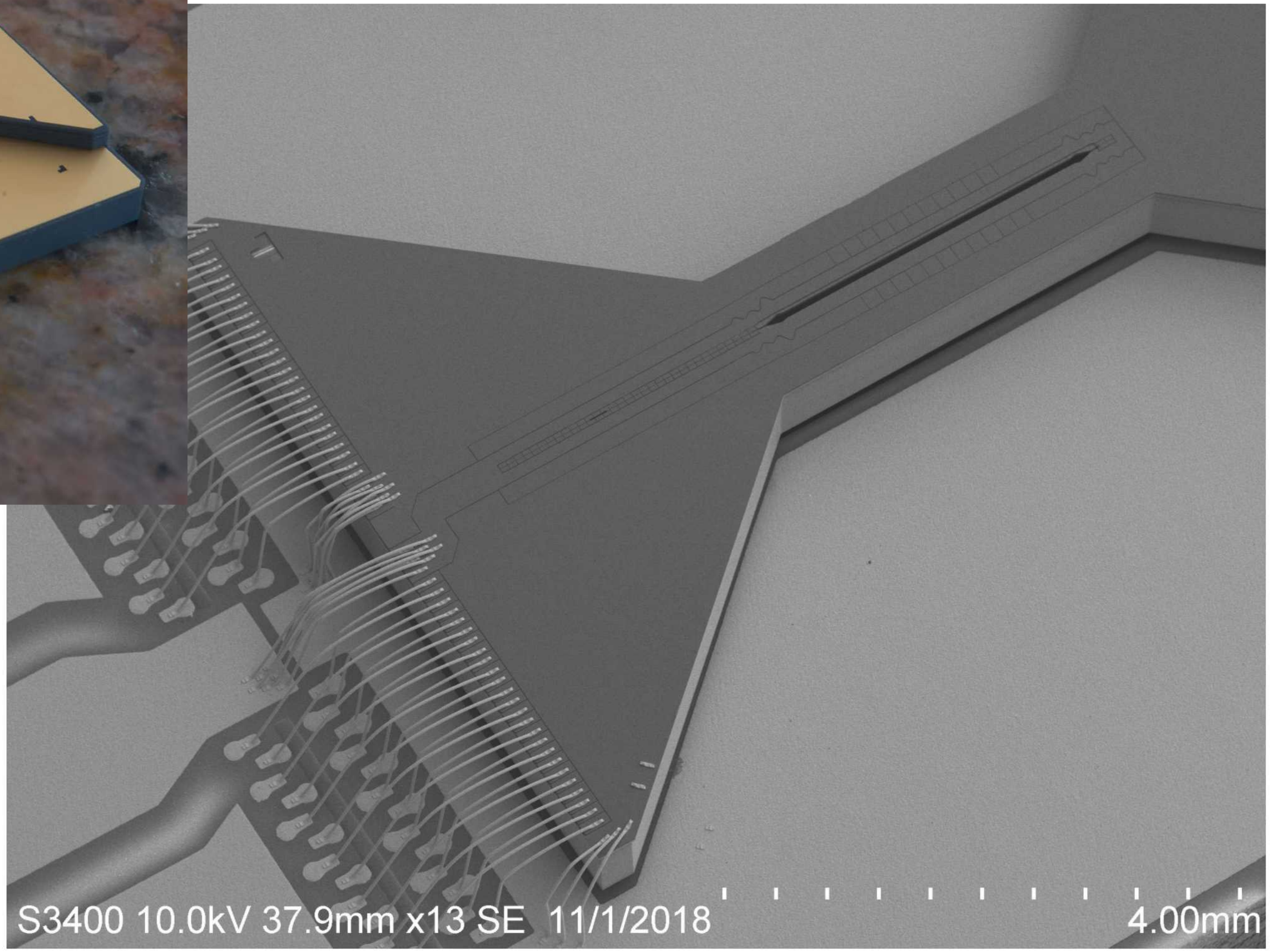
- Improved rf- and ground performance
- Compatible with bowtie chip without interposer
- Simplified assembly
- Backwards compatibility with MQCO package

Properties:

- AlN for improved thermal conductivity and reduced thermal expansion vs Al_2O_3
- Two rf connections with minimized capacitance (3pF) and resistivity (50mOhm)
- Backwards compatible with prior HOA devices
- Metal coverage of top surface
- All metal is signal or ground (no floating metals)

Custom trap package Is available



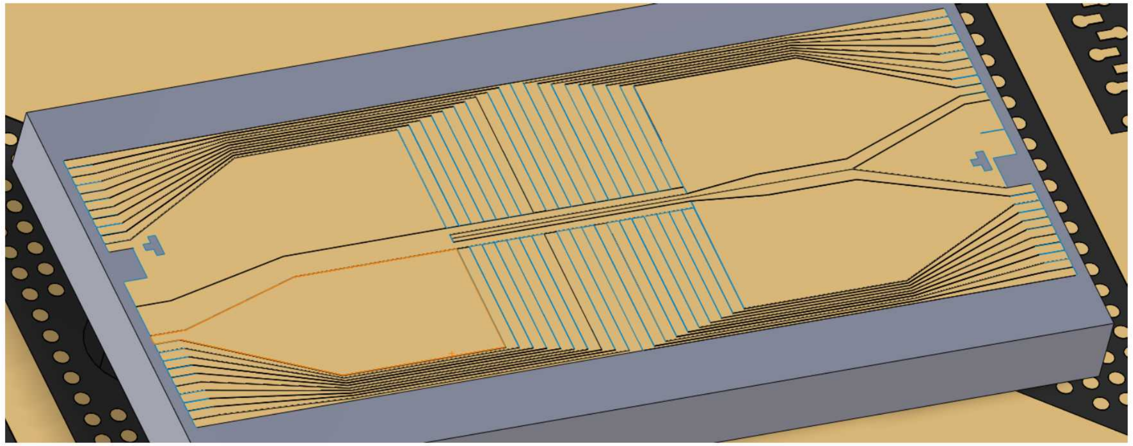


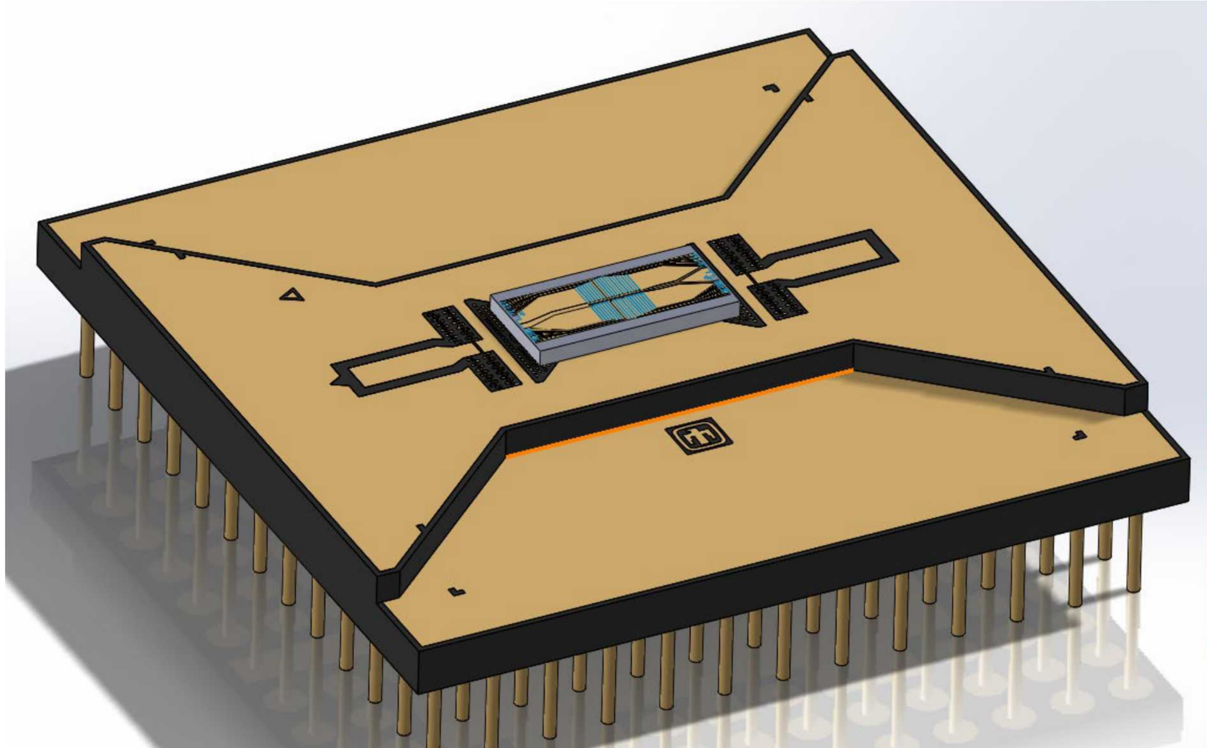
Compared to commercial off the shelf package
- Top surface mostly metal (grounded)
- Low resistance of rf and ground paths (massively parallel vias, routing on outer layers)

Ion heating at cryogenic temperatures

QSCOUT

- While ion heating rates at room temperature are good
- Heating rates do not go down as expected when cooling to cryogenic temperatures
- Possible sources of this excess heating
  - **Silicon substrate (ground plane always is the return path for rf currents)**
  - **Vias**
  - **Trench capacitors**
- Scientific approach: investigate influence of silicon substrate
- Use simple single-metal-layer trap on different substrates:
  - Standard silicon 2-20Ω·cm
  - High resistivity silicon >5kΩ·cm
  - Float-zone silicon >20kΩ·cm





Sandia traps in operation

QSCOUT

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University of Maryland

universität innsbruck

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MIT Lincoln Laboratory

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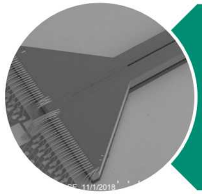
ARL

Sandia National Laboratories

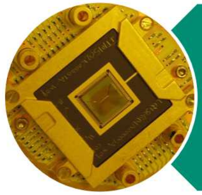
W
University of Washington

AFRL

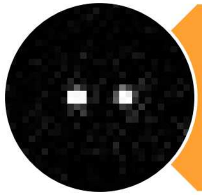
Outline



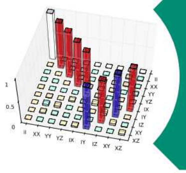
Trap fabrication capabilities



HOA trap

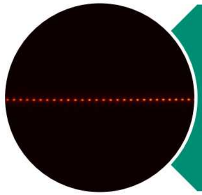


Classical control



Quantum operations

QSCOUT Quantum testbed



QSCOUT System engineering

Calculating voltage solutions

- Boundary element simulation for surface electrode geometry

$$\mathcal{H} = \begin{pmatrix} \frac{\partial \phi}{\partial x \partial x} & \frac{\partial \phi}{\partial x \partial y} & \frac{\partial \phi}{\partial x \partial z} \\ \frac{\partial \phi}{\partial y \partial x} & \frac{\partial \phi}{\partial y \partial y} & \frac{\partial \phi}{\partial y \partial z} \\ \frac{\partial \phi}{\partial z \partial x} & \frac{\partial \phi}{\partial z \partial y} & \frac{\partial \phi}{\partial z \partial z} \end{pmatrix}$$

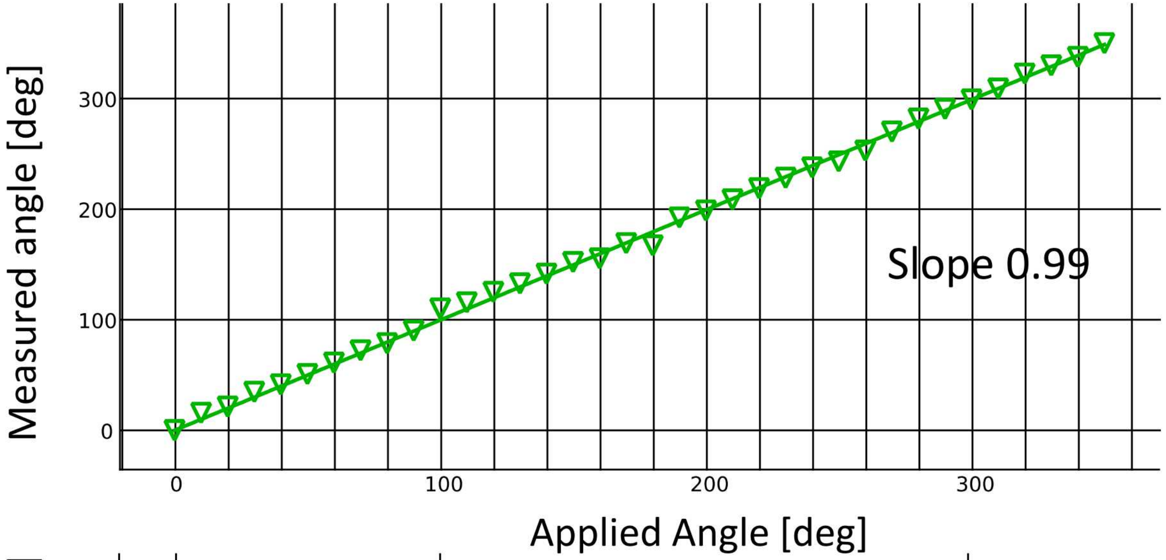
- Symmetric curvature tensor
- 6 degrees of freedom
- Determines trap frequencies and principal axes rotations
- Traceless for static fields
- Trace is generated by rf pseudopotential

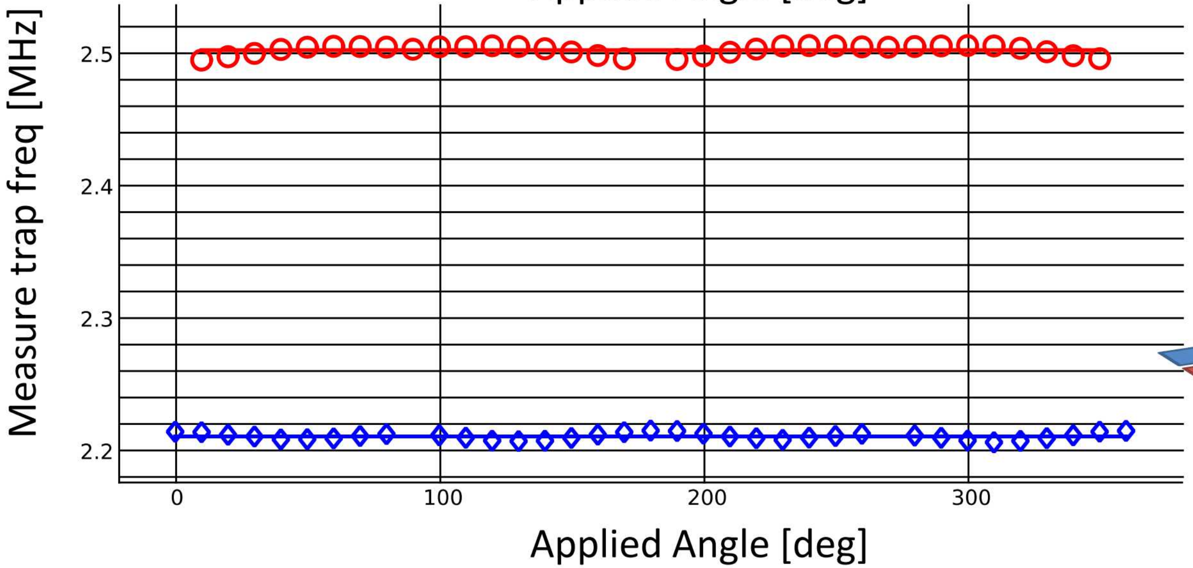
- Calculate voltage solutions to independently control curvature tensor elements and fields at ion locations
- Use pseudo-inverse to get well-defined solution using nearby electrodes with minimal voltages
- Generate solution for any trap configuration from these basis-solutions

Advantages of parametric trapping solutions:
- Primitives are in terms of curvature tensor elements and can be applied at any location in the trap.
- Shuttling primitives can be easily combined

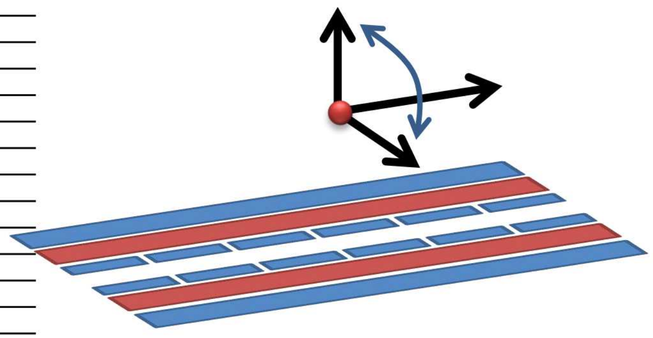
Example:
- Rotating ion crystal while translating through the trap

Principal axes rotation



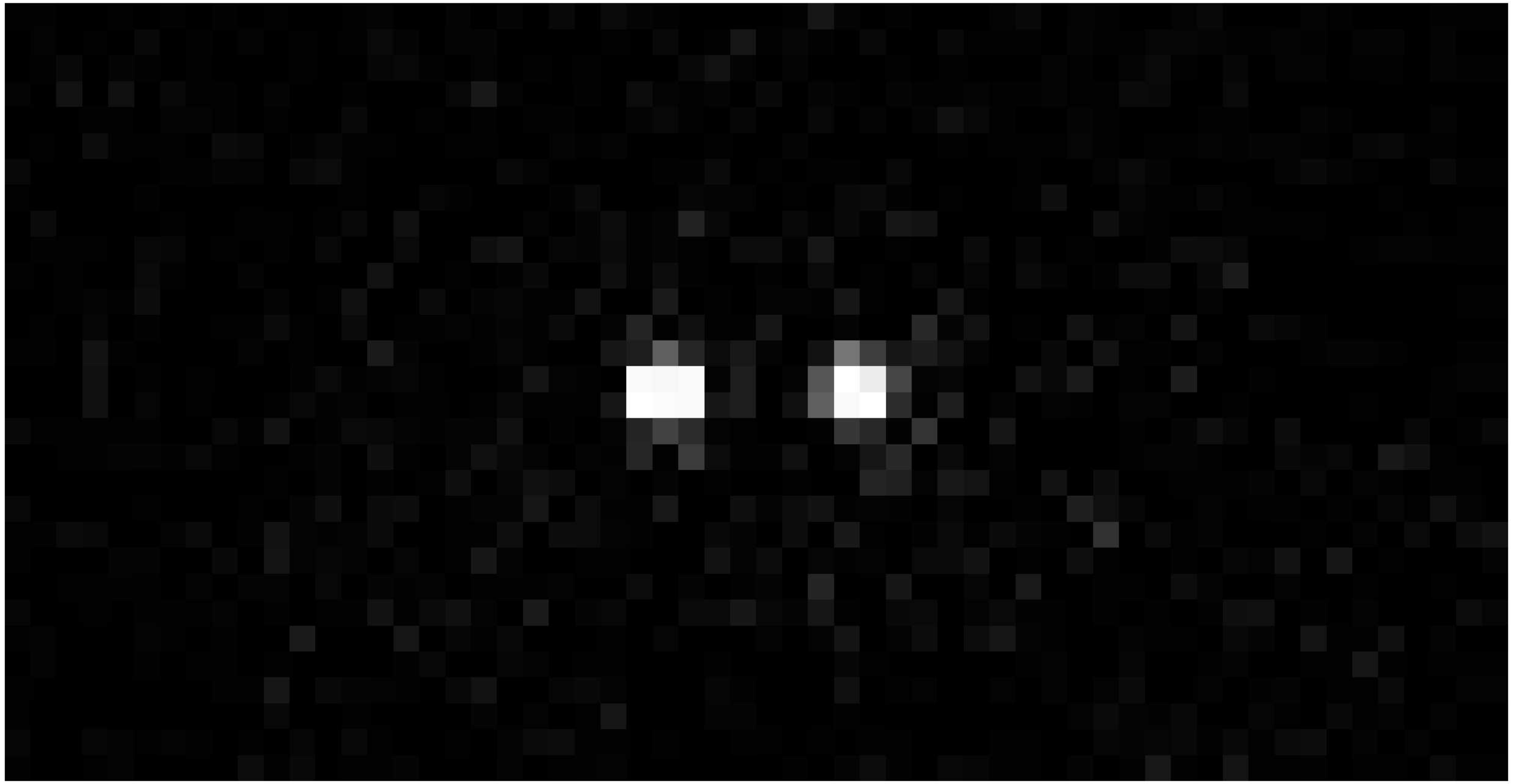


- Do we understand the trapping fields?
- Principal axes rotation realized as in simulation
- No change in trap frequencies



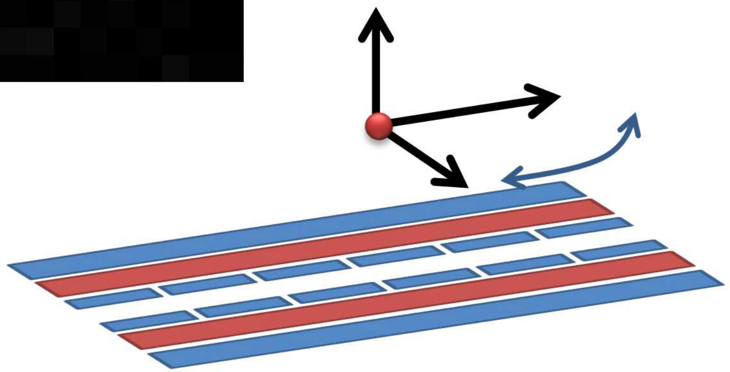
The simulations accurately describe the fields and curvatures generated by the trap

Rotation of ion chains

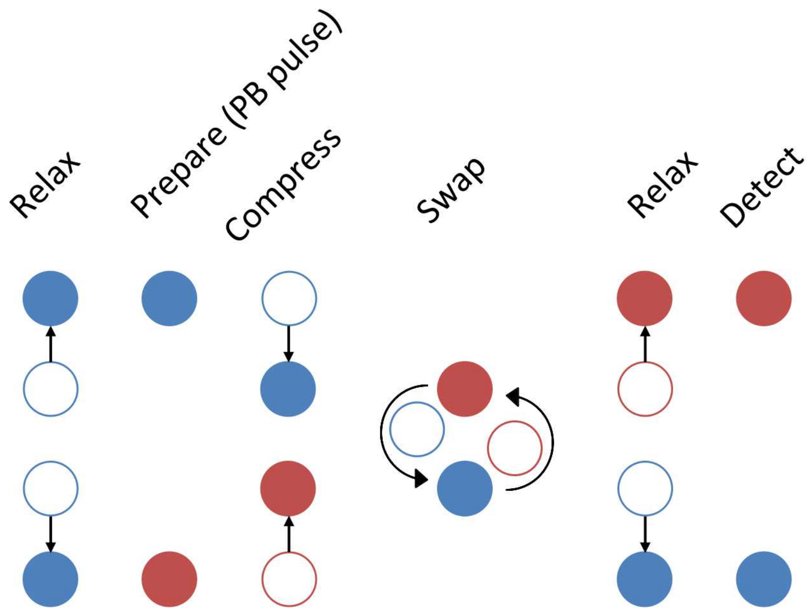


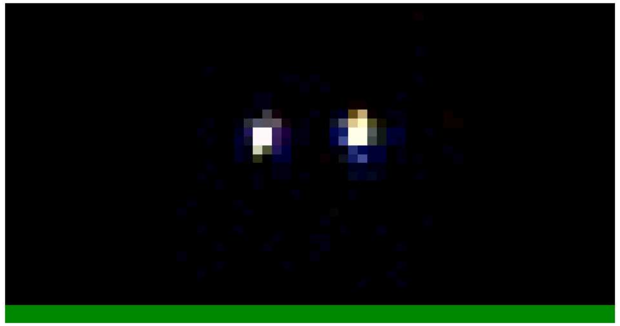
To be characterized as function of swapping time

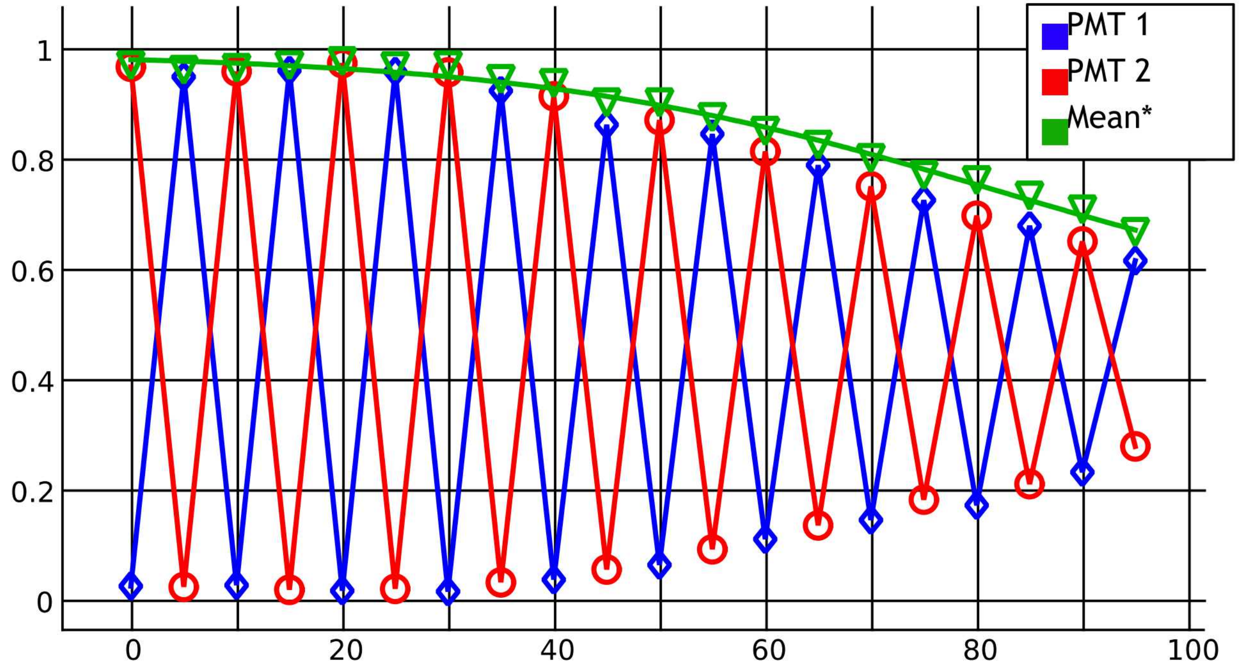
- Swapping fidelity
- Accumulated motion



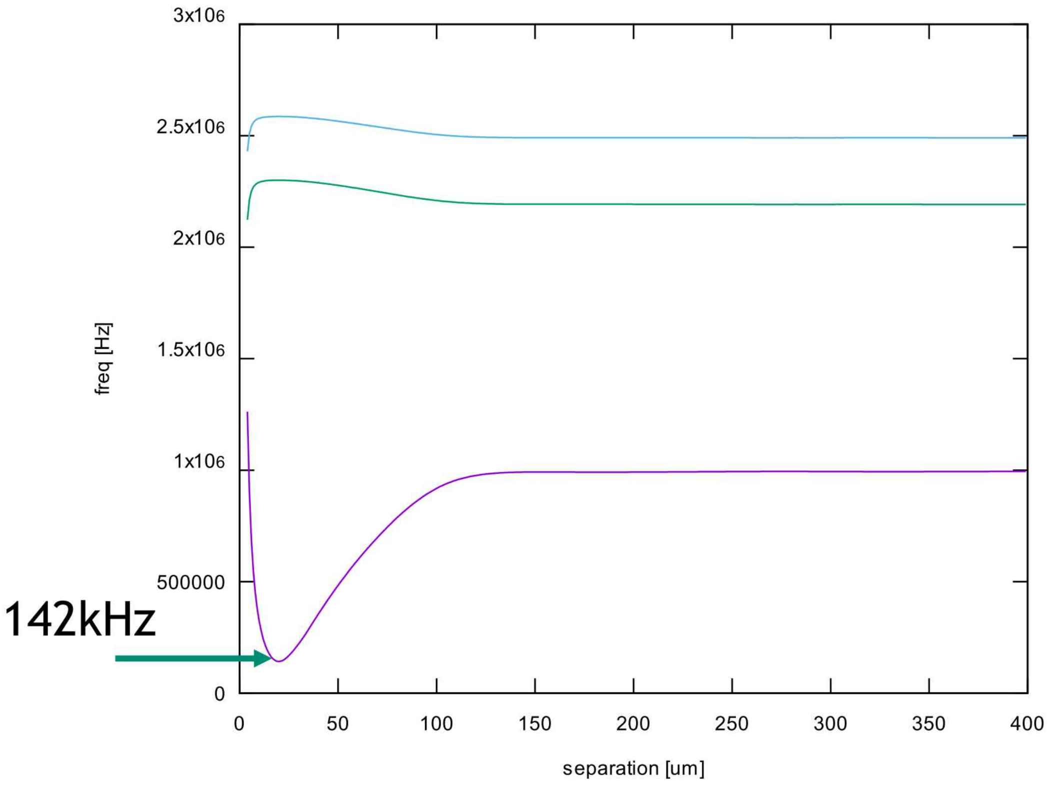
Measuring swap fidelity

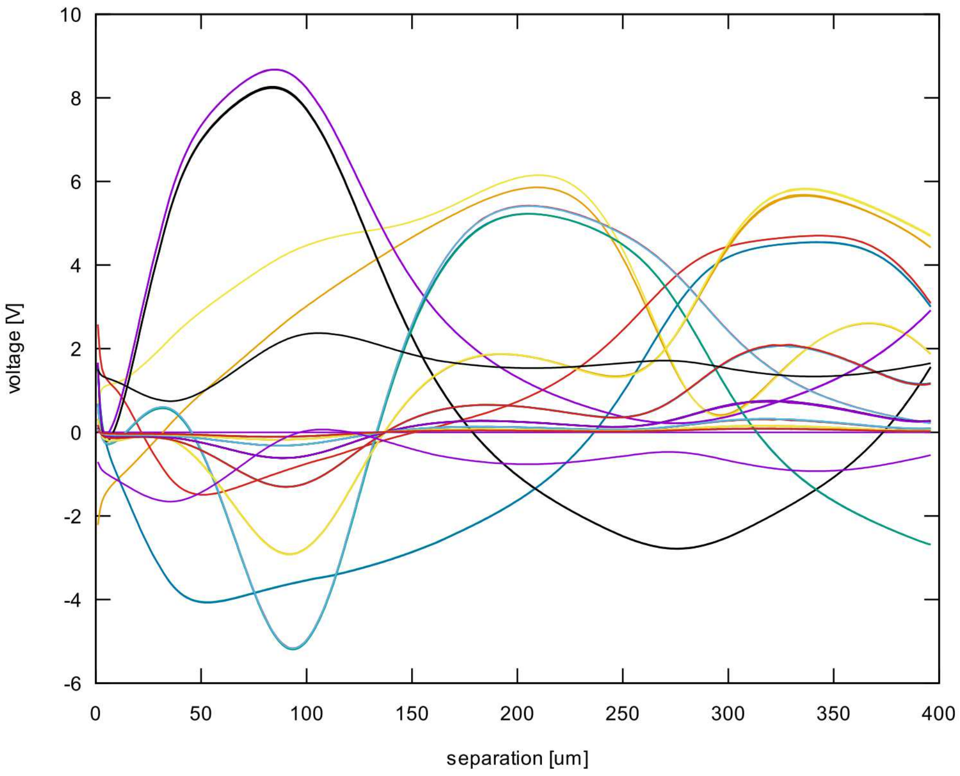


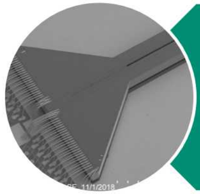




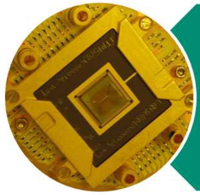
Separation and merging of ions







Trap fabrication capabilities



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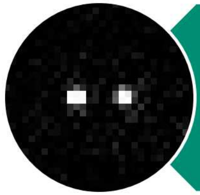

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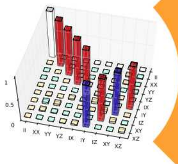
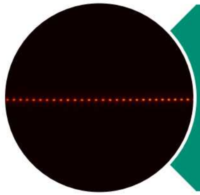


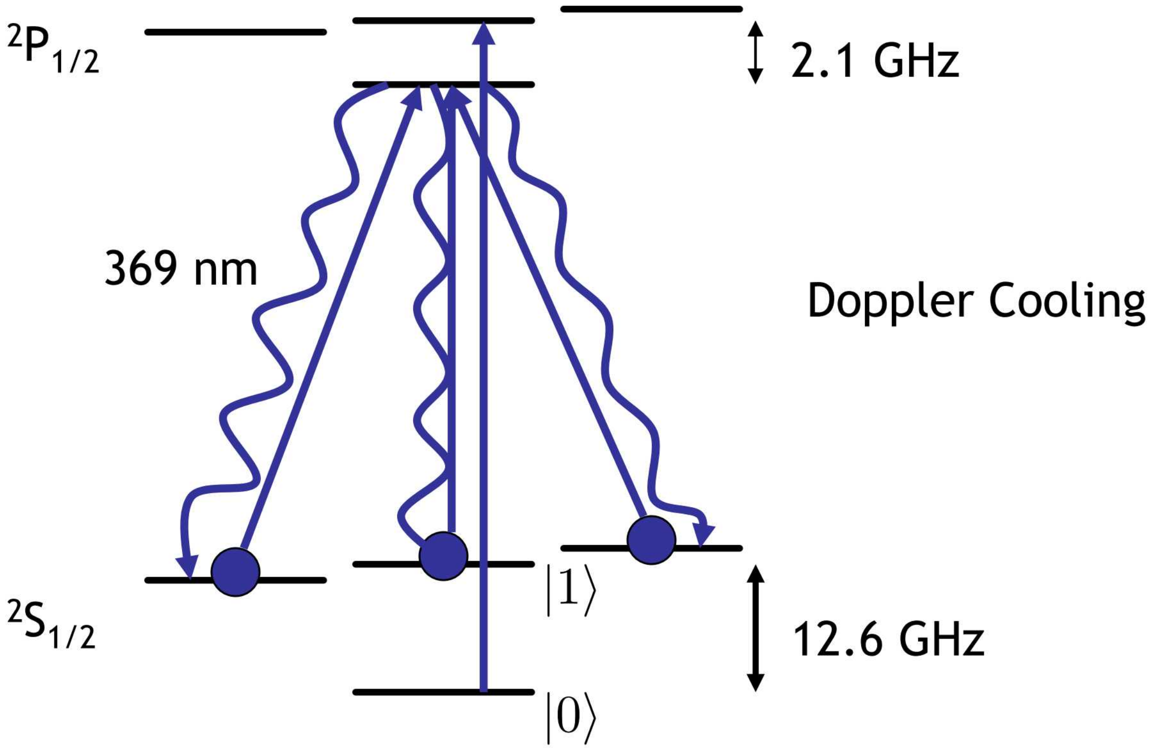
Quantum operations

QSCOUT Quantum testbed



QSCOUT System engineering

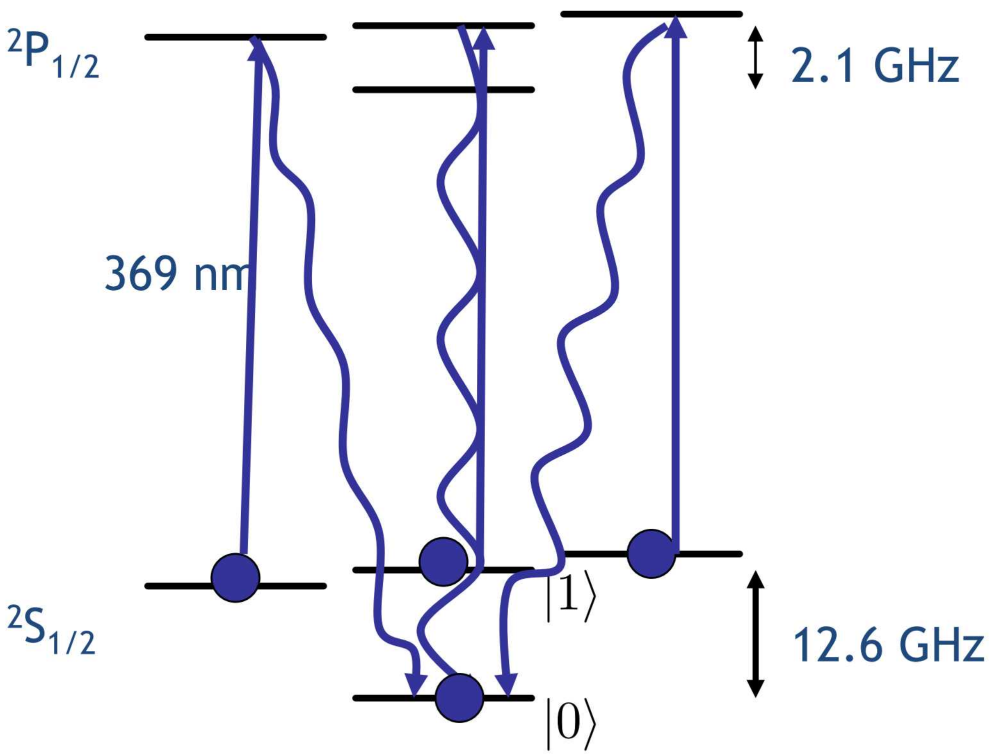
The Ytterbium Qubit



clock state qubit, magnetic field insensitive.

S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

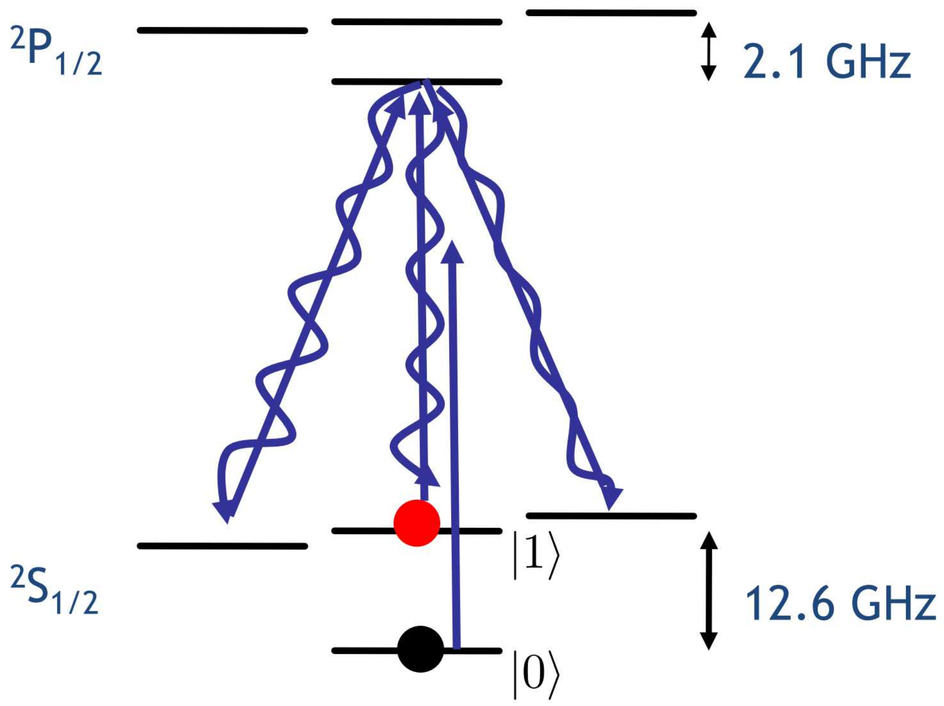
state initialization

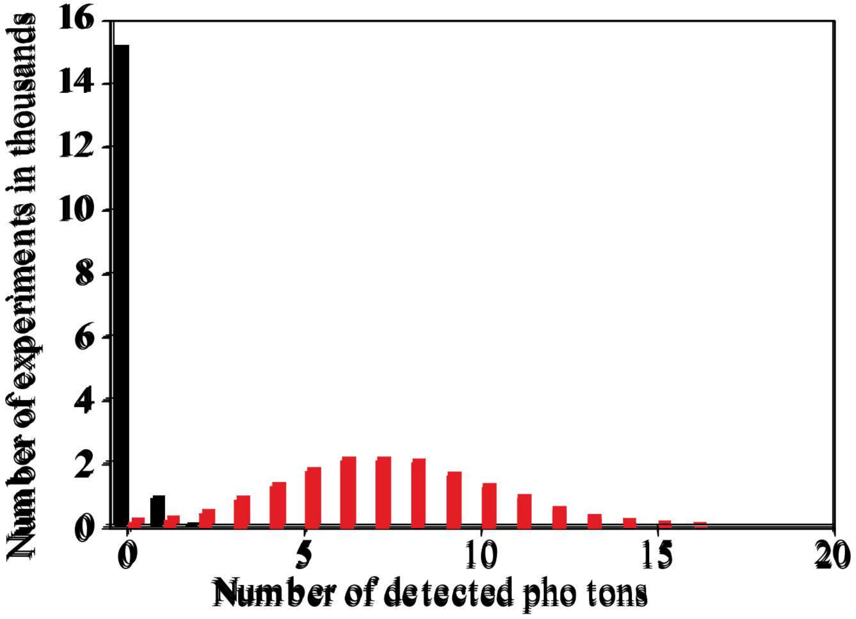


clock state qubit, magnetic field insensitive.

S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

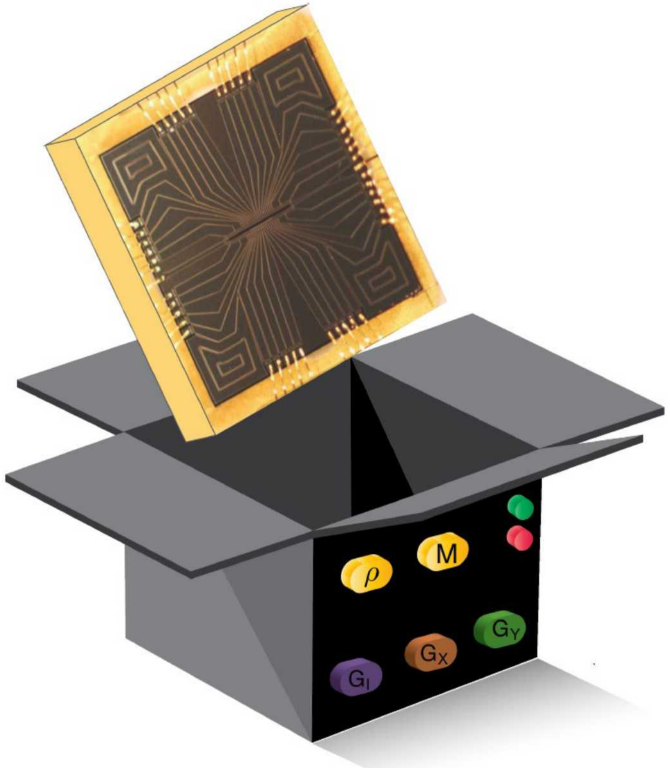
$^{171}Yb^{+}$ state detection





S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

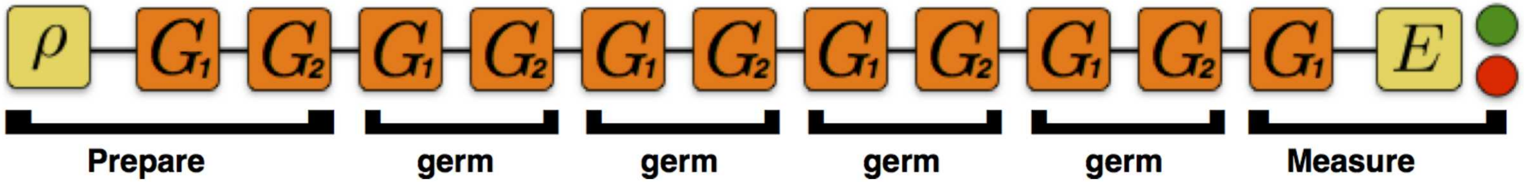
Gate Set Tomography (GST)



Developed at Sandia by
QCVV team

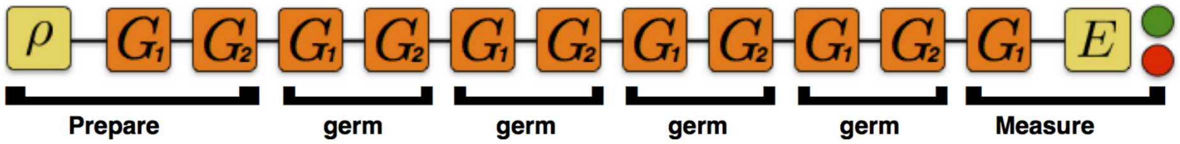
- No calibration required
- Detailed debug information
- Efficiently measures performance characterizing fault-tolerance (diamond norm)
- Detects non-Markovian noise

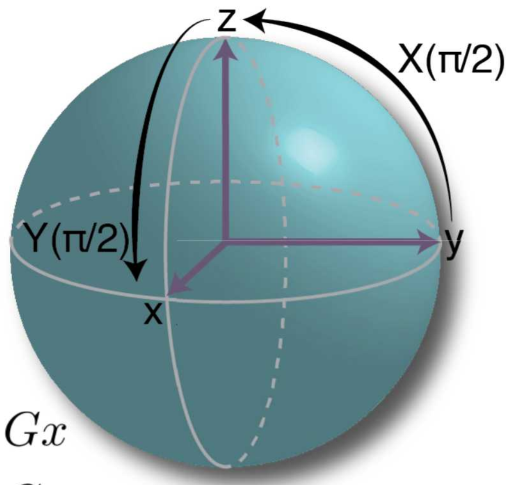
Uses structured sequences to amplify all possible errors



GST sequences

Single qubit BB1 compensated microwave gates on $^{171}Yb^{+}$





Desired "target" gates:

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

Fiducials:

$\{\}$

Gx

Gy

$Gx \cdot Gx$

$Gx \cdot Gx \cdot Gx$

$Gy \cdot Gy \cdot Gy$

Approximately prepare 6 points on Bloch sphere

Germs:

Gx

Gy

Gi

$Gx \cdot Gy$

$Gx \cdot Gy \cdot Gi$

$Gx \cdot Gi \cdot Gy$

$Gx \cdot Gi \cdot Gi$

$Gy \cdot Gi \cdot Gi$

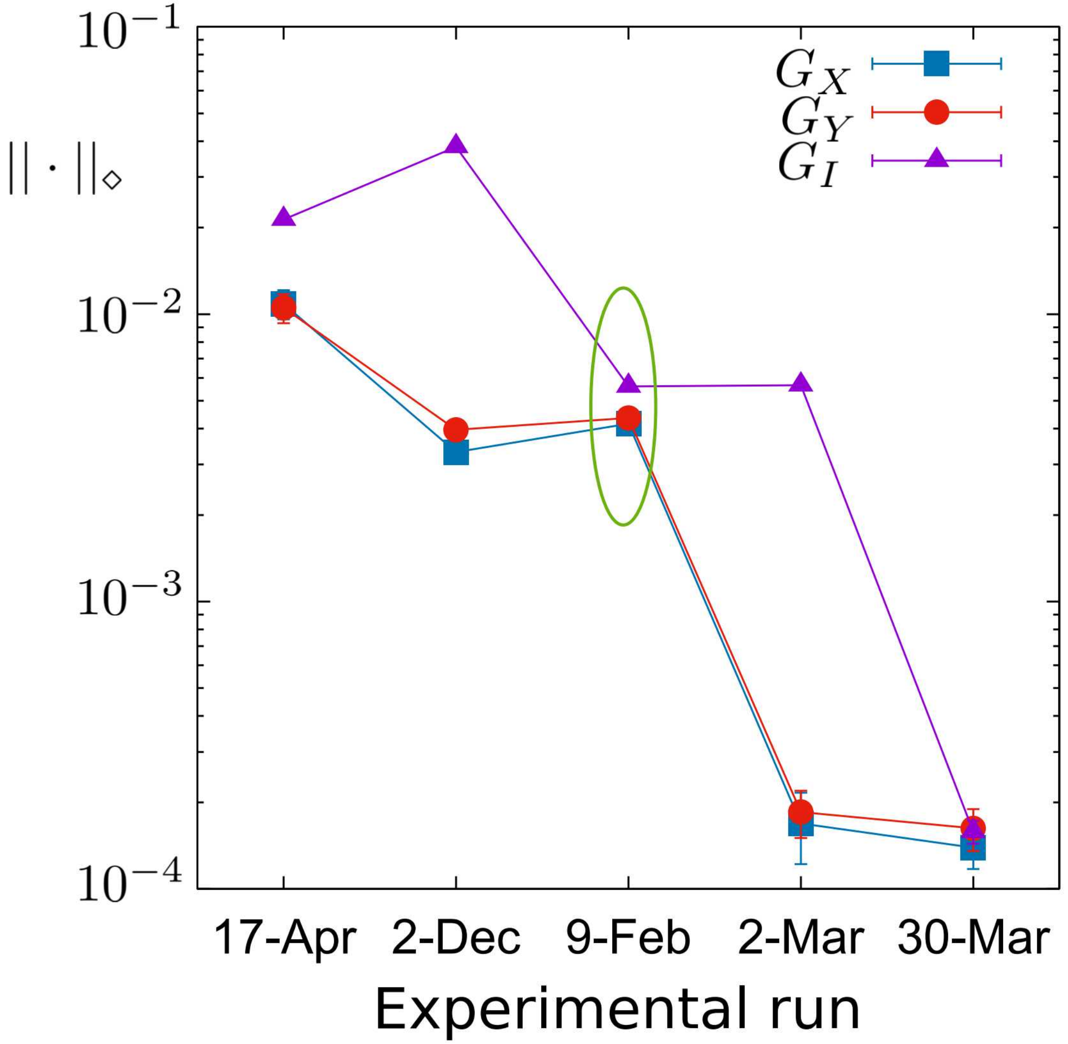
$Gx \cdot Gx \cdot Gi \cdot Gy$

$Gx \cdot Gy \cdot Gy \cdot Gi$

$Gx \cdot Gx \cdot Gy \cdot Gx \cdot Gy \cdot Gy$

GST: debugging microwave 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



GST: debugging microwave gates

Gate	Rotn. axis	Angle
G_I	0.5252 -0.009 0.8506 -0.0244	0.001699π
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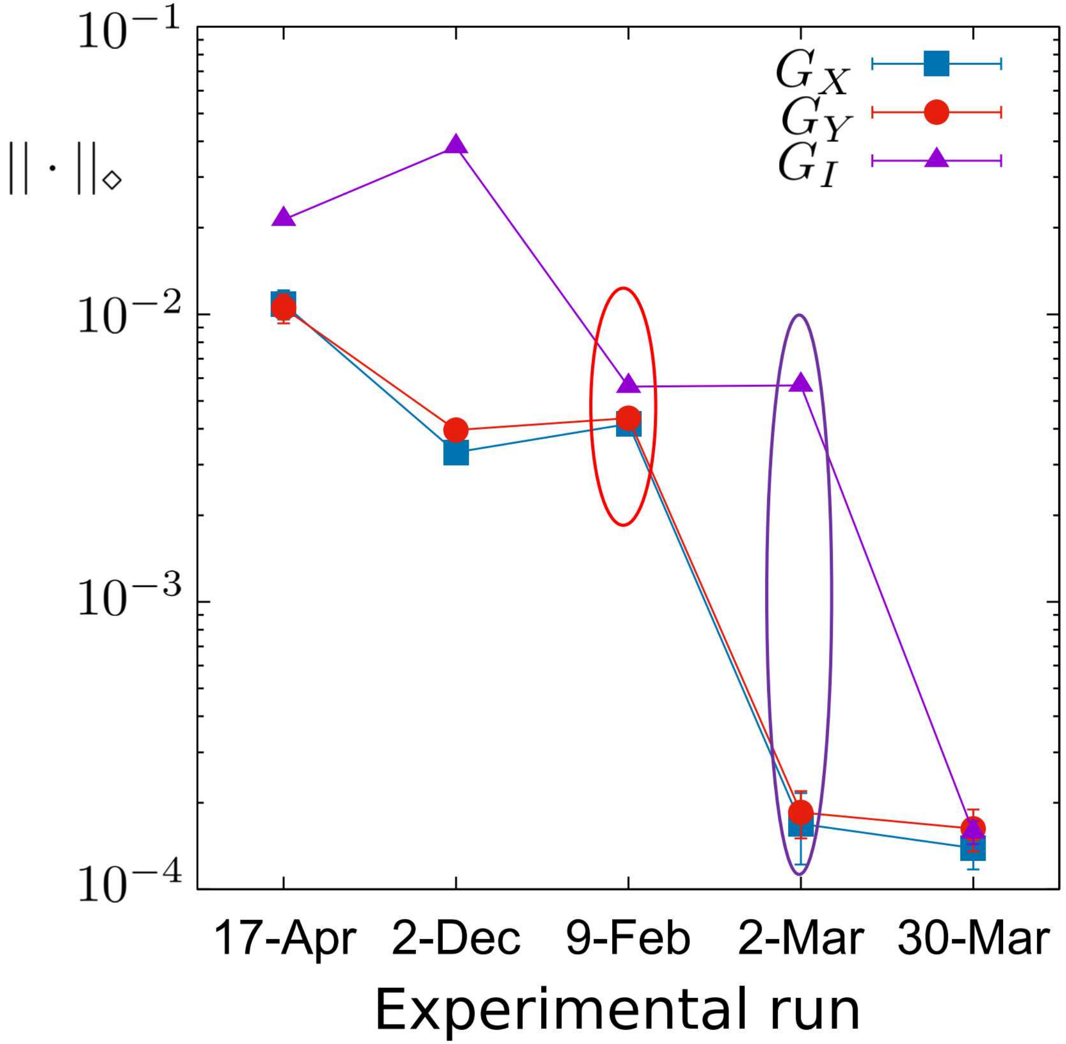
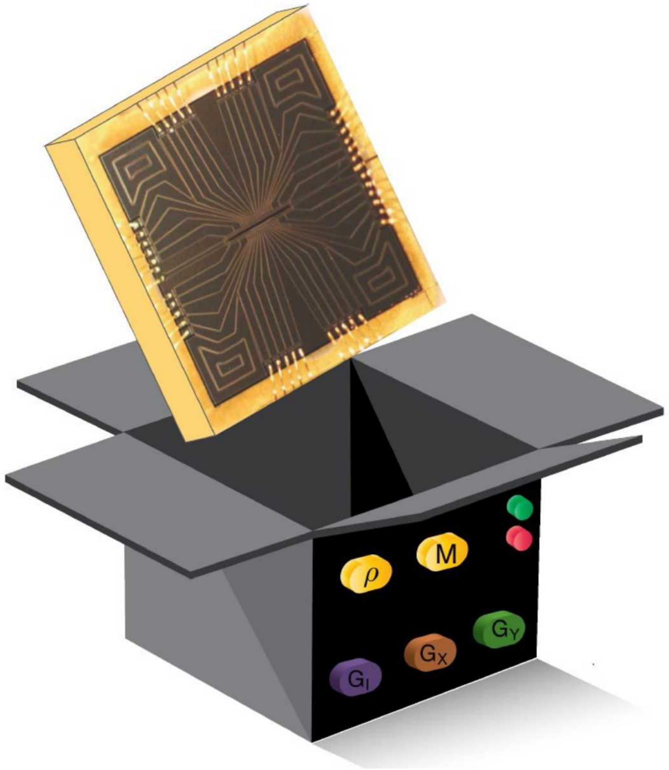
G_Y	-0.2474 0.0001 0.9689 -0.0001	0.501366π

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



Context and time dependency of gates



Assumptions:

- Qubits in a box
- Pressing a button always executes the exactly same operation
- Independent from context (gates executed before)
- Independent from when a gate is executed

GST uses a large (over-complete) number of sequences.

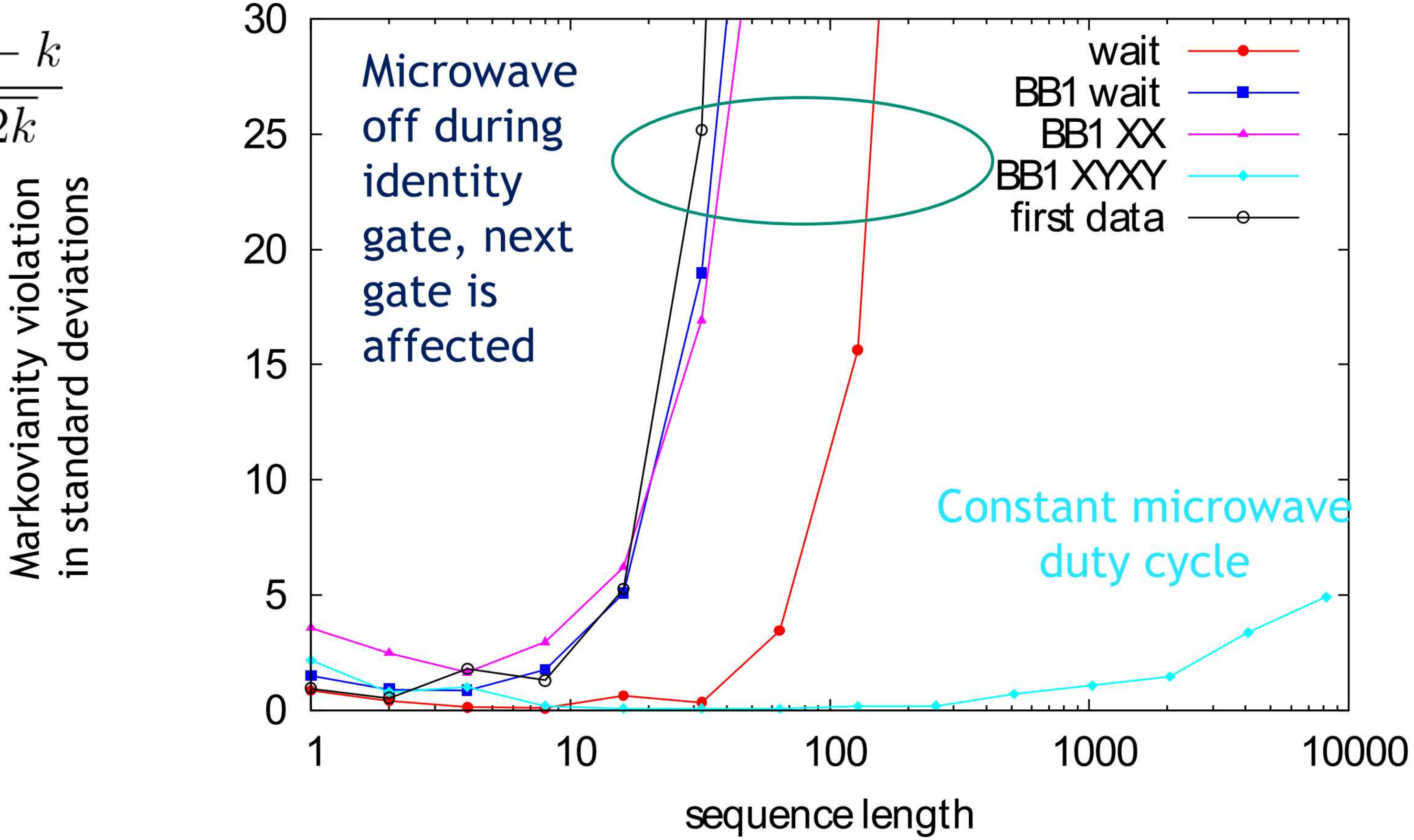
We can look whether the assumptions are satisfied

Ongoing work to improve and distinguish detection of context and time dependence of classical control

GST model violation

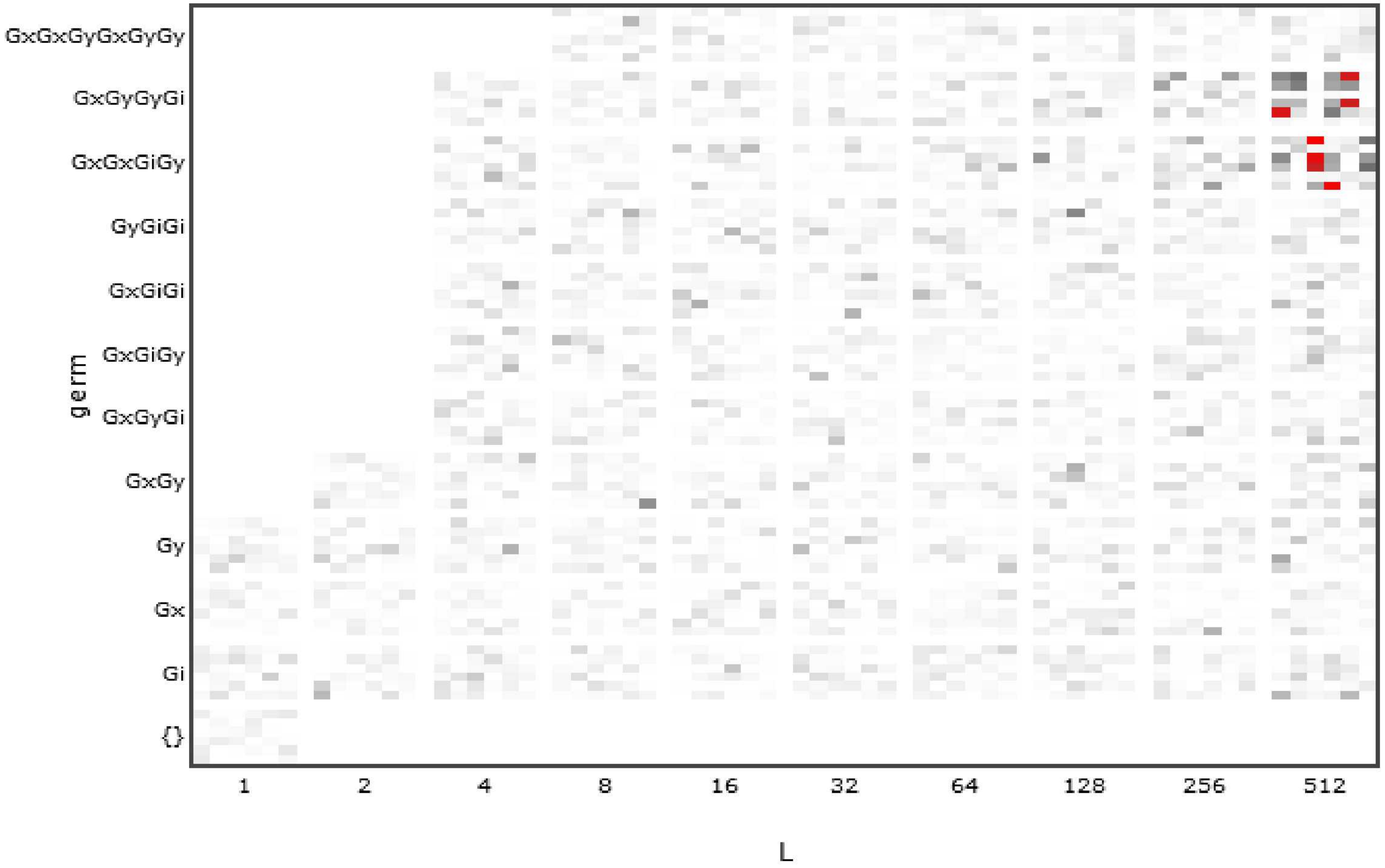
The χ^2 values from the fits are expected to follow a χ^2 distribution with mean k and standard deviation $\sqrt{2k}$

$$\frac{\chi^2 - k}{\sqrt{2k}}$$



BB1 decoupled gates with decoupled identity have very small non-Markovian noise

GST model violation



- Identifying problems due to context dependency and drift

- Red boxes show sequences which violate the Markovian model
- For a Markovian realization with 95% probability there are no red boxes
- These sequences show context dependency of gates

- X- and Y- gates behave differently if applied after an I gate

GST: Microwave results

Best results for microwave single qubit gates:

- BB1 dynamically compensated pulse sequences
- Decoupling sequence for identity gate
- Drift control for π-time and qubit frequency

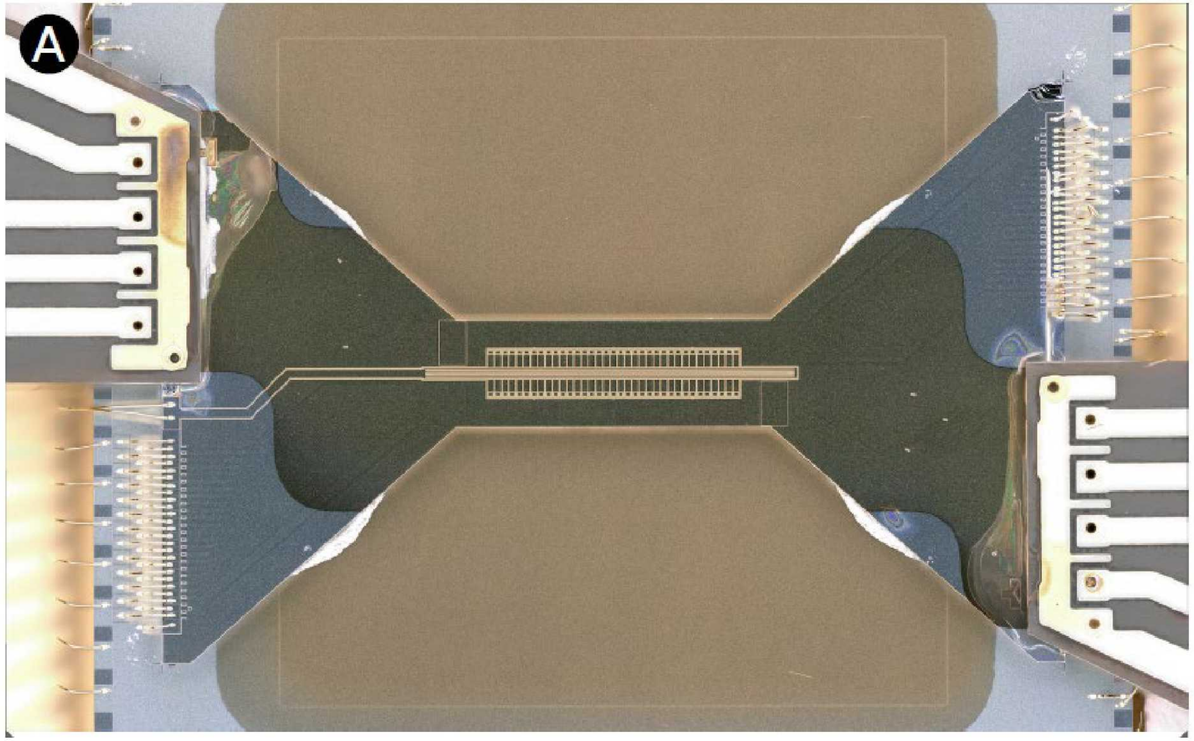
95% confidence intervals

Gate	Process Infidelity	1/2 ◇-Norm
G_I	$6.9(6) \times 10^{-5}$	$7.9(7) \times 10^{-5}$
G_X	$6.1(7) \times 10^{-5}$	$7.0(15) \times 10^{-5}$
G_Y	$7.2(7) \times 10^{-5}$	$8.1(15) \times 10^{-5}$

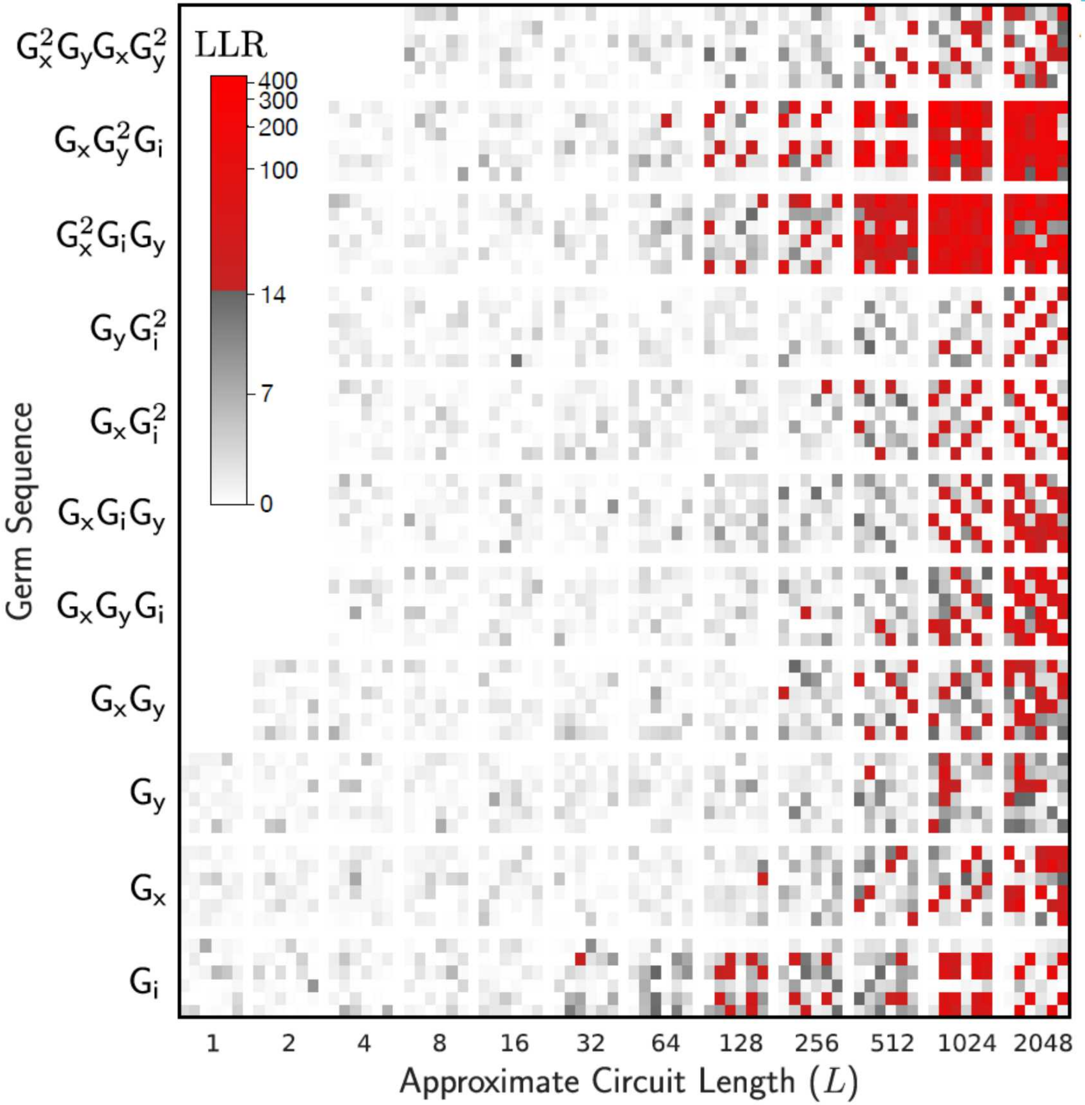
All gates are better than the fault tolerance threshold of 9.7×10^{-5}
P. Aliferis and A. W. Cross, Phys. Rev. Lett. 98, 220502 (2007).

Challenge: Model violation in GST

Assumptions are that gate actions are
- Independent of surrounding gates (context dependency)
- Independent of time (drift)



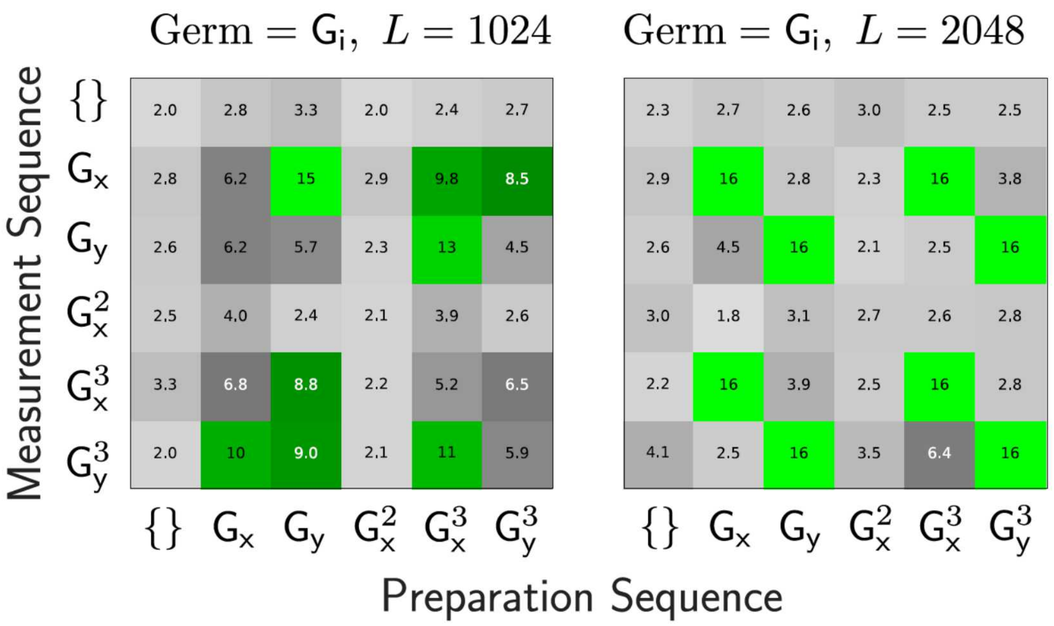
Experiments: Single-qubit microwave gates in trap with integrated microwave antenna

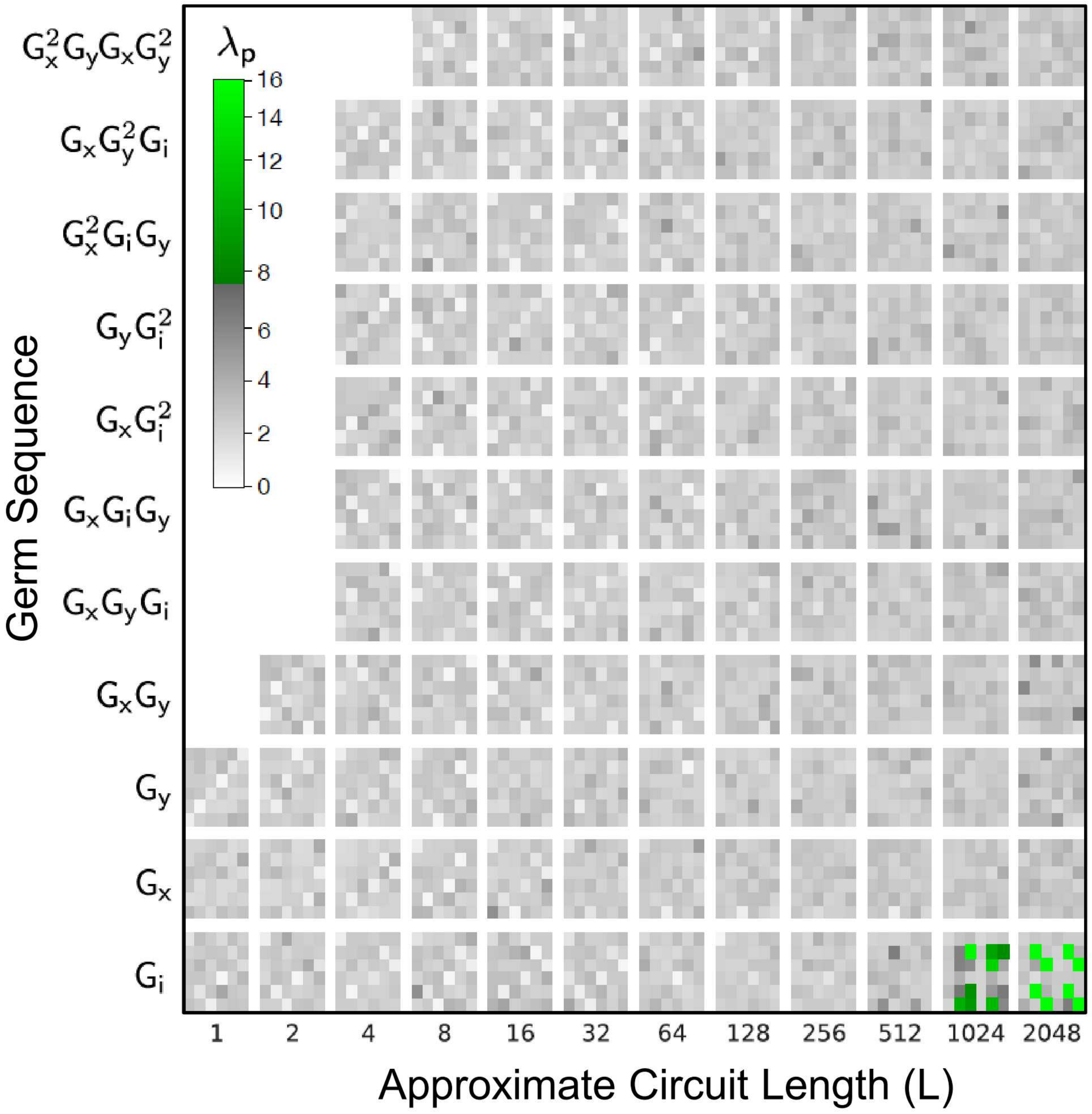


Model violation for time-independent GST estimate. (Log-likelihood ratio) global significance 5%

Is there drift?

- Time-resolved GST characterization
- Ramsey experiments show significant drift
- These sequences are candidates for further investigation

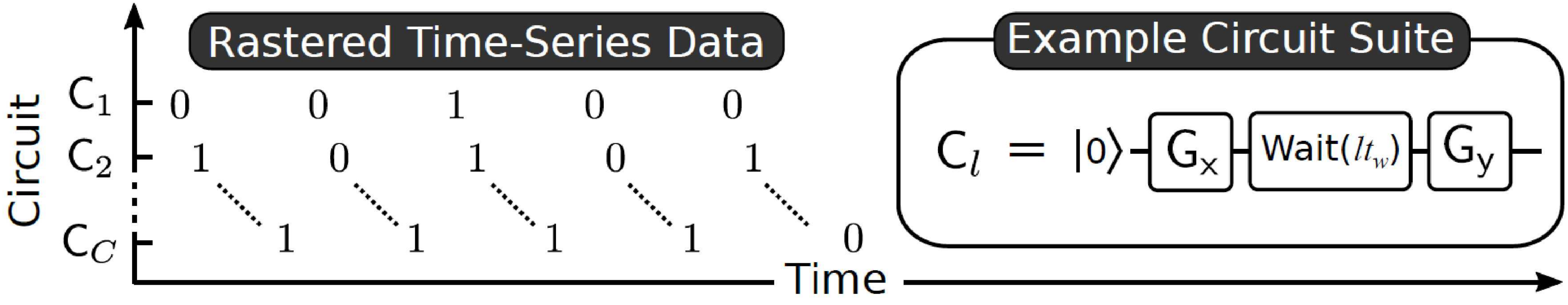


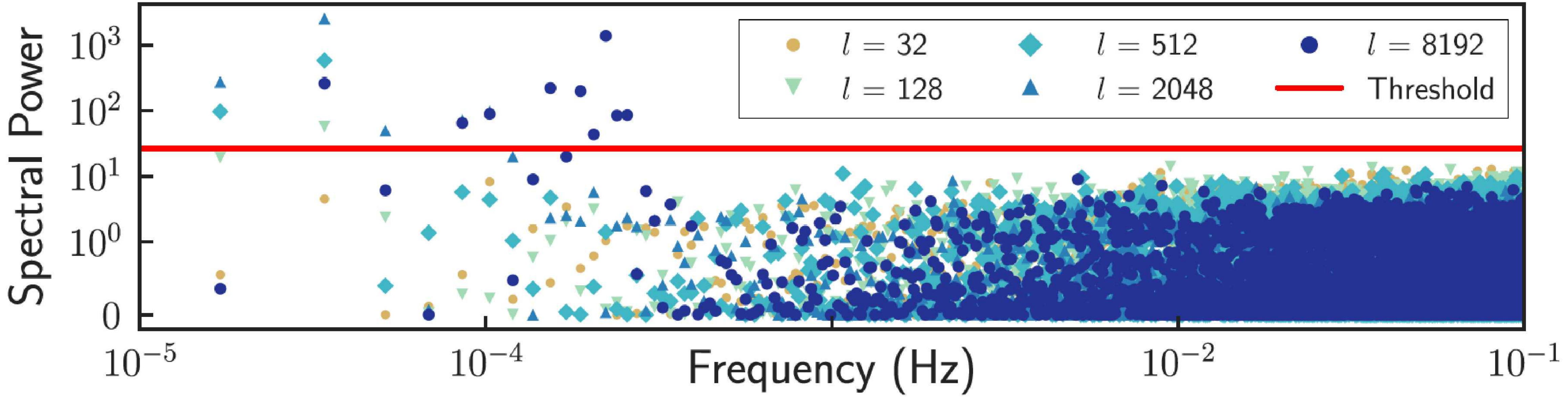


$\lambda_p = -\log_{10}(p)$ where p is the p-value of the largest power in the spectrum for that circuit

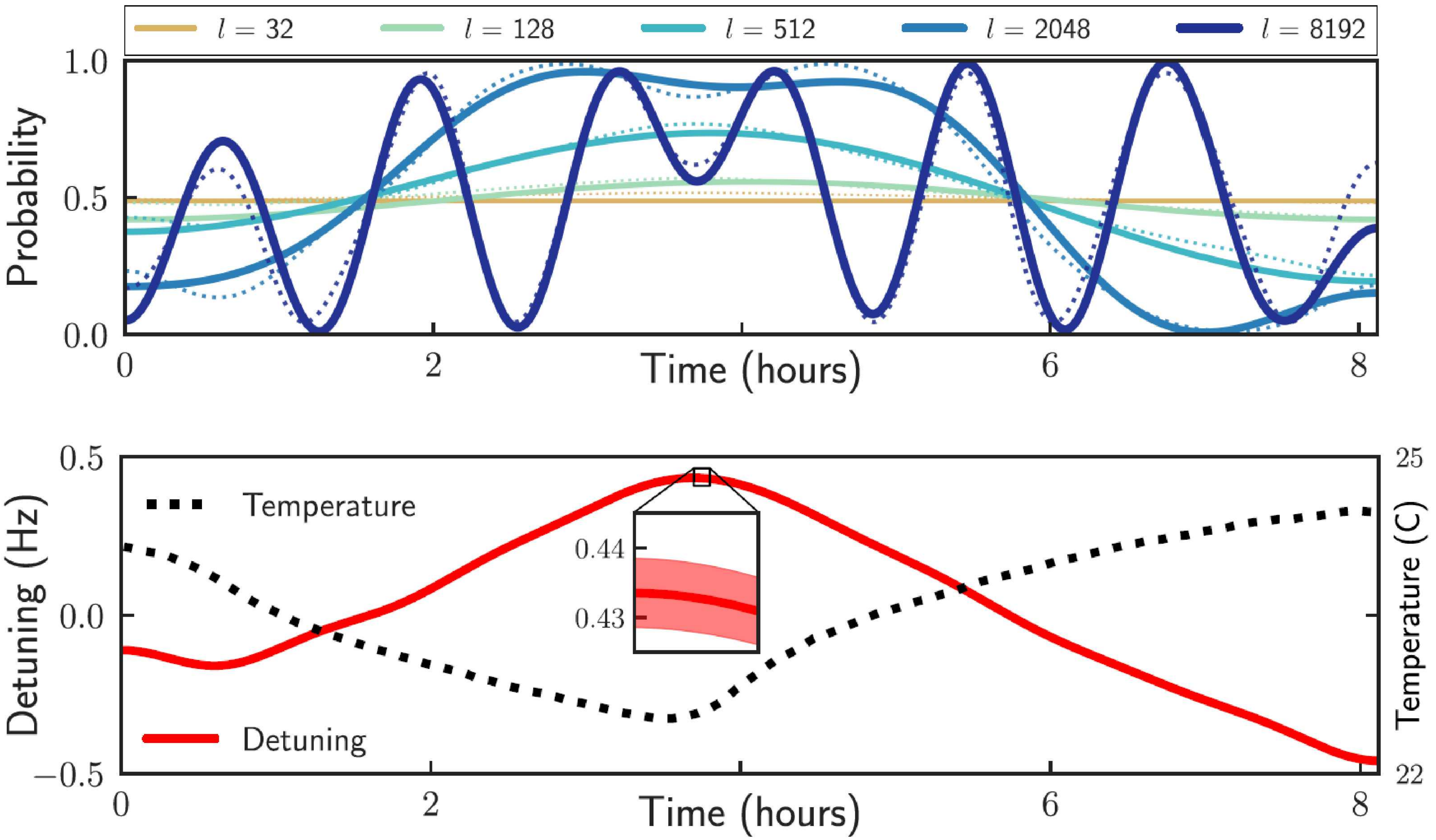
Can we measure the drift?

QSCOUT

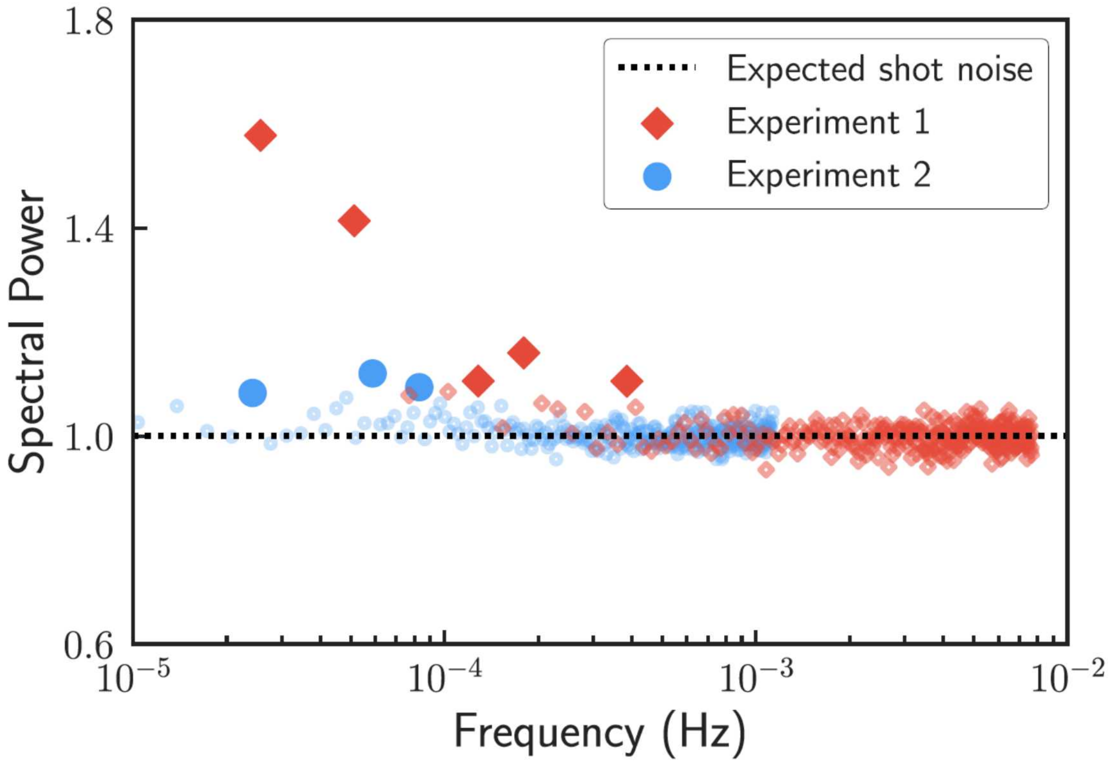


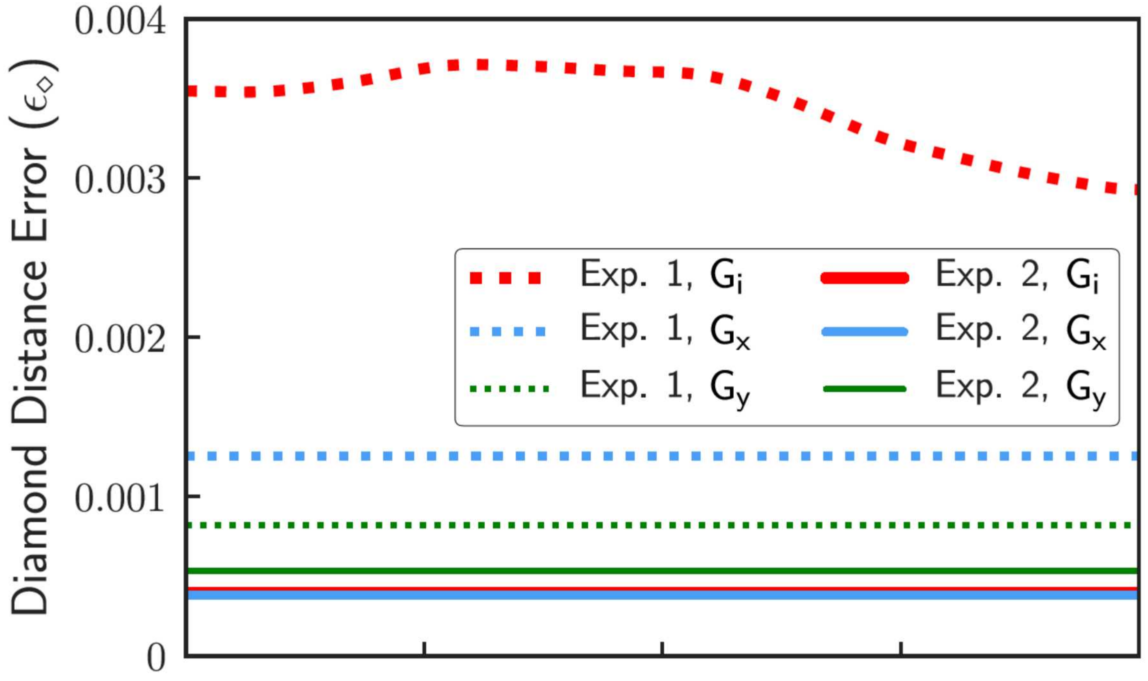


Can the drifting parameter be reconstructed?



Experimental Improvements



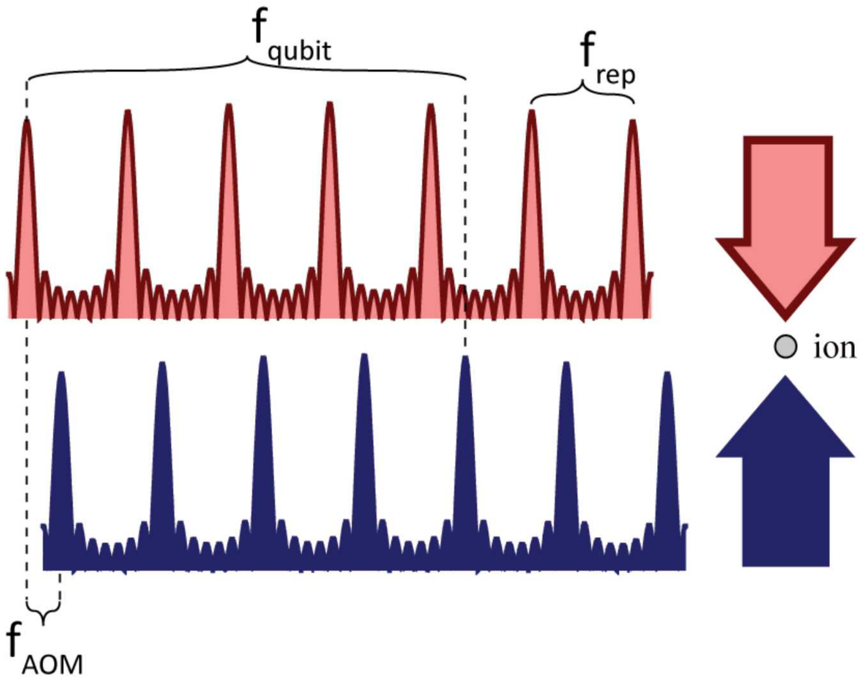


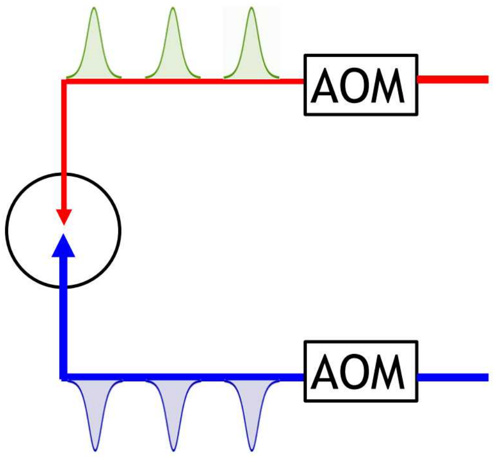
- Spectral power averaged over all sequences
- Small residual drift, cannot be assigned to specific sequences
- Reconstruction of individual sequences is below statistical significance

<u>Improvements:</u>

- Stabilized room temperature
- Incorporated drift control – feedback on transition frequency and π-time.

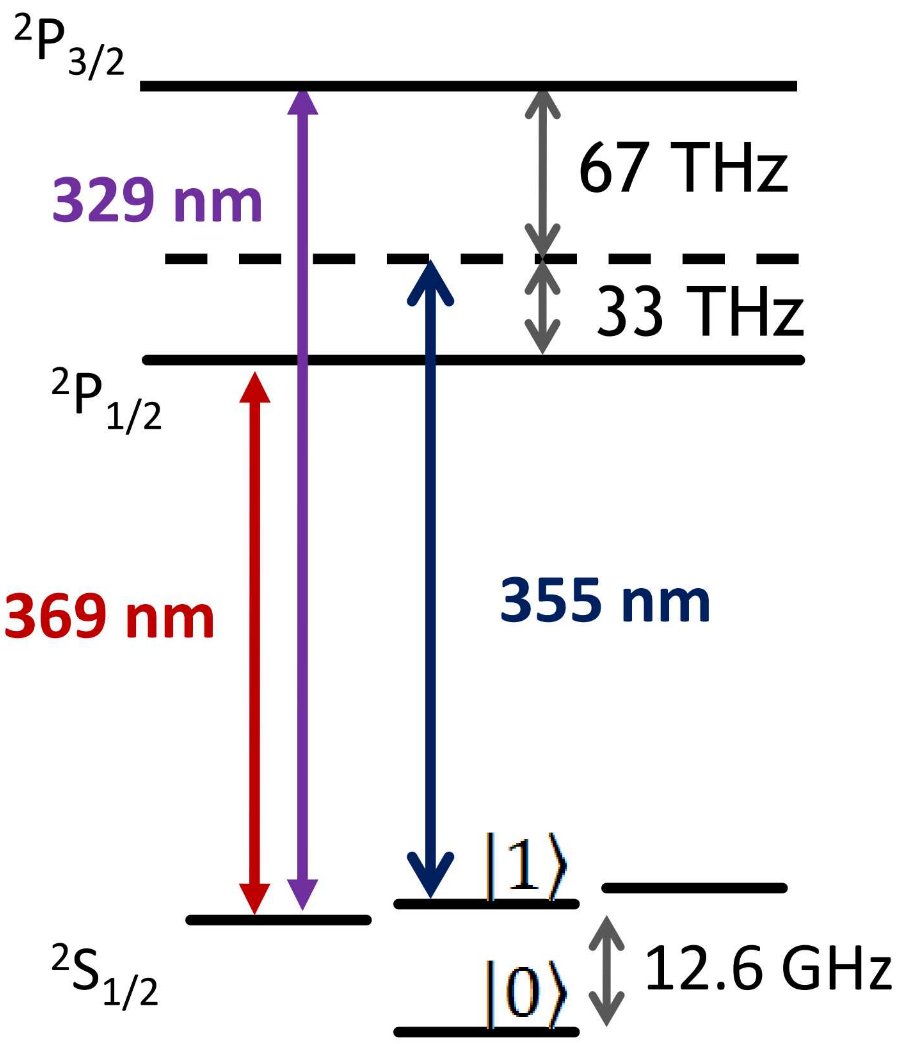
355 Raman transitions: $^{171}Yb^+$





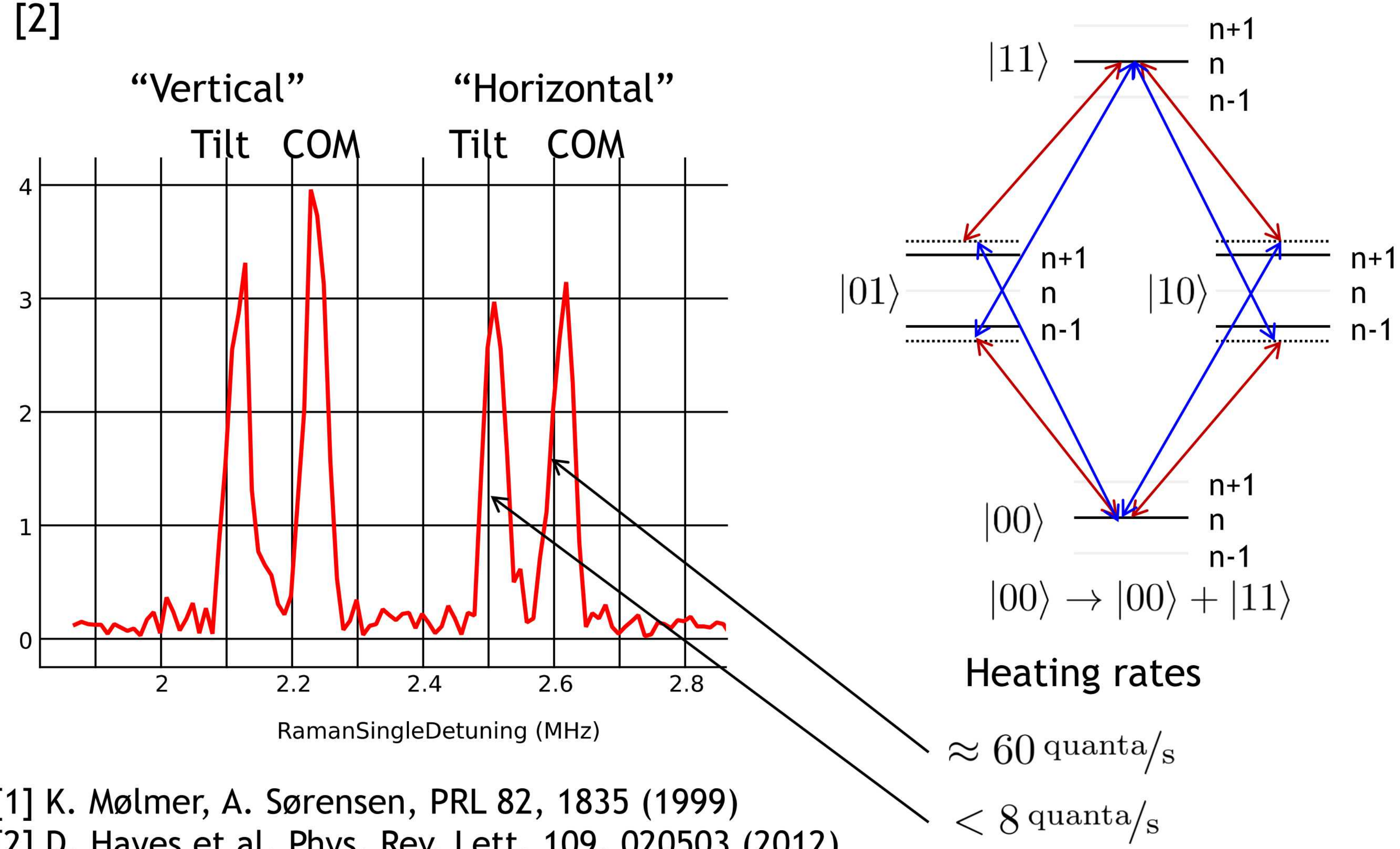
Requirement:

$$f_{qubit} = nf_{rep} \pm f_{AOM}$$



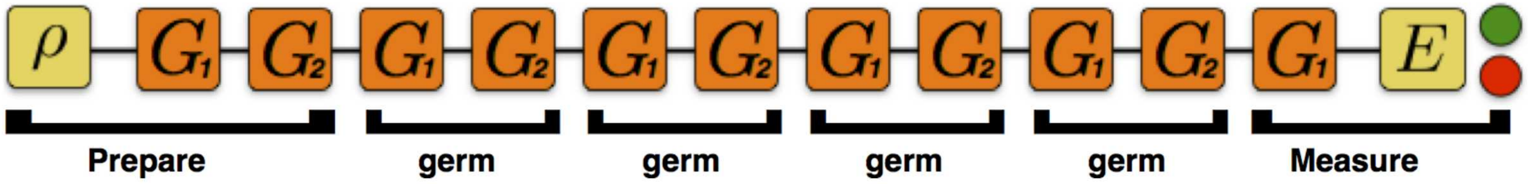
Two-qubit gate implementation

- Mølmer-Sørensen gates [1] using 355nm pulsed laser
- All two-qubit gates implemented using Walsh compensation pulses [2]



[1] K. Mølmer, A. Sørensen, PRL 82, 1835 (1999)
[2] D. Hayes et al. Phys. Rev. Lett. 109, 020503 (2012)

GST on symmetric subspace



Basic gates:

$$G_I$$
$$G_{XX} = G_X \otimes G_X$$
$$G_{YY} = G_Y \otimes G_Y$$
$$G_{MS}$$

Preparation Fiducials:

$$\{\}$$
$$G_{XX}$$
$$G_{YY}$$
$$G_{MS}$$
$$G_{XX}G_{MS}$$
$$G_{YY}G_{MS}$$

Germs:

$$G_I$$
$$G_{XX}$$
$$G_{YY}$$
$$G_{MS}$$
$$G_IG_{XX}$$
$$G_IG_{YY}$$
$$G_IG_{MS}$$
$$G_{XX}G_{YY}$$
$$G_{XX}G_{MS}$$
$$G_{YY}G_{MS}$$
$$G_IG_IG_{XX}$$
$$G_IG_IG_{YY}$$

Detection Fiducials:

$$\{\}$$
$$G_{XX}$$
$$G_{YY}$$
$$G_{MS}$$
$$G_{XX}G_{MS}$$
$$G_{YY}G_{MS}$$
$$G_{XX}^3$$
$$G_{YY}^3$$
$$G_{YY}^2G_{MS}$$

Two-qubit gate characterization

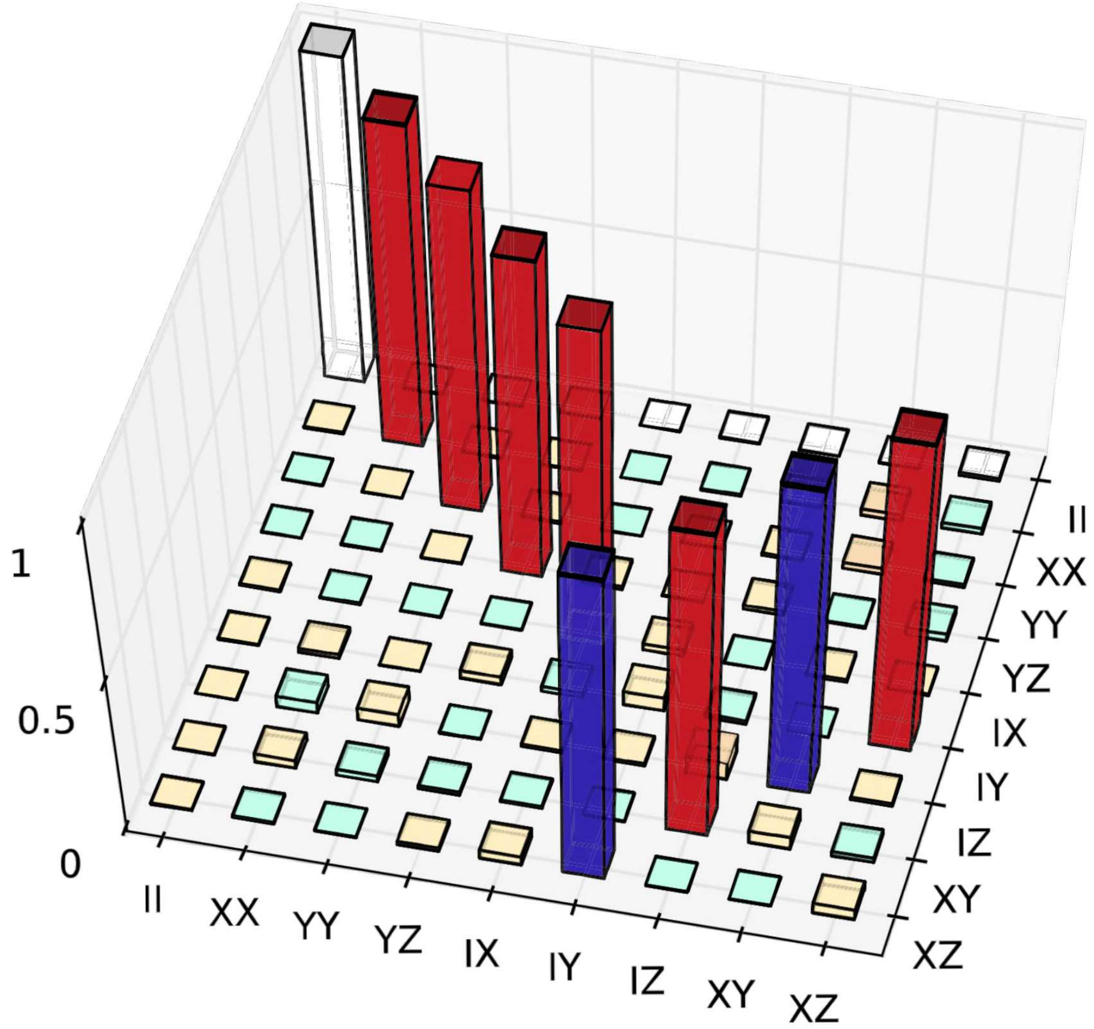
Gate	Process infidelity	$\frac{1}{2}$ Diamond norm
G_I	$1.6 \times 10^{-3} \pm 1.6 \times 10^{-3}$	$28 \times 10^{-3} \pm 7 \times 10^{-3}$
G_{XX}	$0.4 \times 10^{-3} \pm 1.0 \times 10^{-3}$	$27 \times 10^{-3} \pm 5 \times 10^{-3}$
G_{YY}	$0.1 \times 10^{-3} \pm 0.9 \times 10^{-3}$	$26 \times 10^{-3}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

The best characterized two qubit gate

By the way: It's in a scalable surface trap



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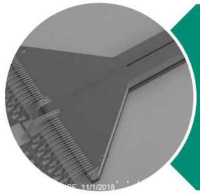
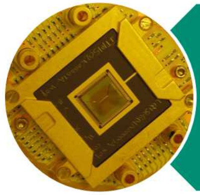


Trap fabrication capabilities



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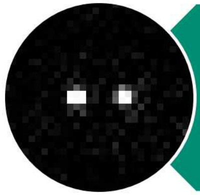

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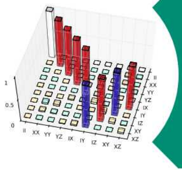
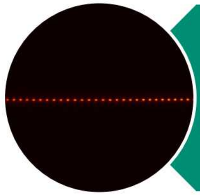


Quantum operations

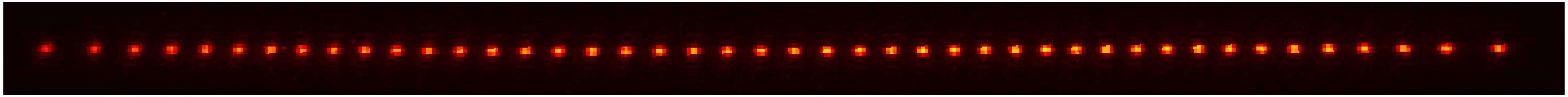
QSCOUT Quantum testbed



QSCOUT System engineering

QSCOUT DOE Quantum Testbed Laboratory

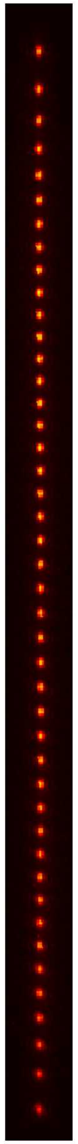
QSCOUT

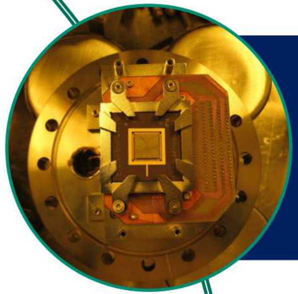


Testbed systems designed for open access to support scientific applications

- High-fidelity operations $\#gates \propto (\#qubits)^2$
- Gate-level access
- Open system with fully specified operations and hardware
- Low-level access for optimal control down to gate pulses
- Open for comparison and characterization of gate pulses
- Open for vertical integration by users

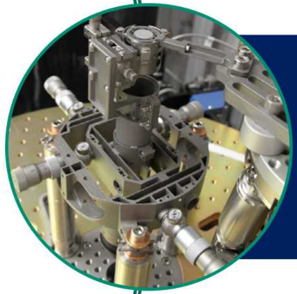
QSCOUT Systems engineering





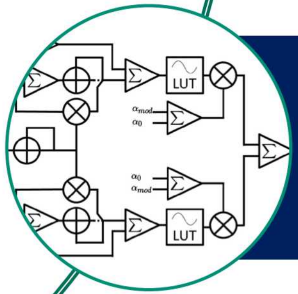
Reducing background collisions

Vacuum technology



Individual addressing

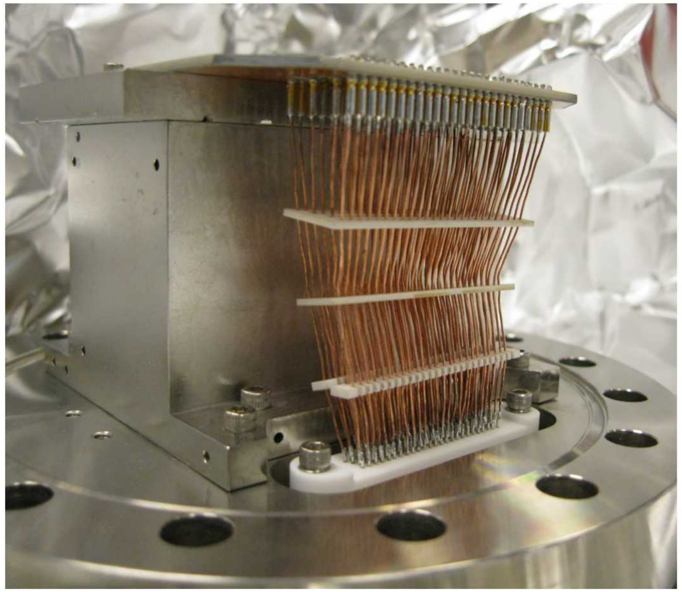
Optical and mechanical engineering



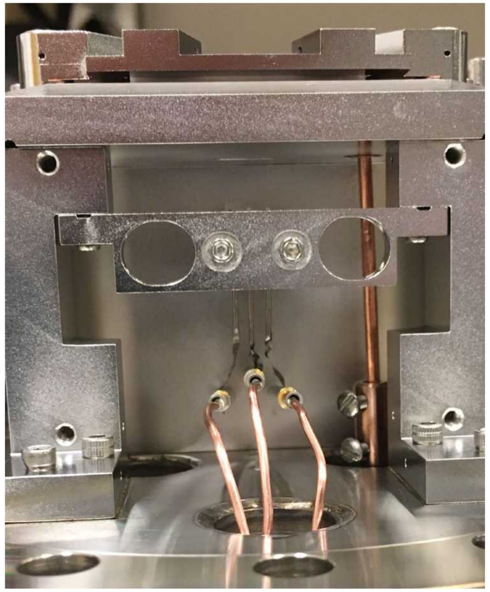
Coherent Pulse control

Electrical engineering

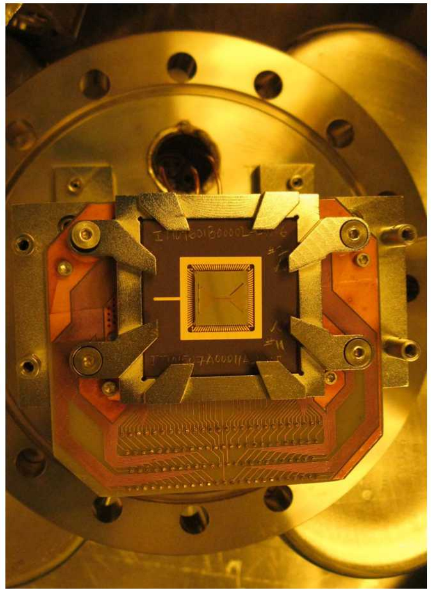
QSCOUT: Vacuum system engineering



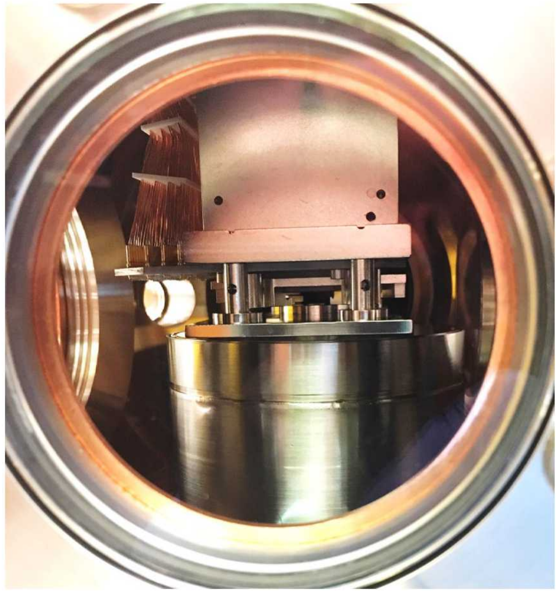
Bare copper wires with Al_2O_3 spacers



3 Yb ovens (loading slot, Peregrine loading hole, HOA loading hole)



Trap installed for final bake



Trap platform in chamber, both re-entrants visible

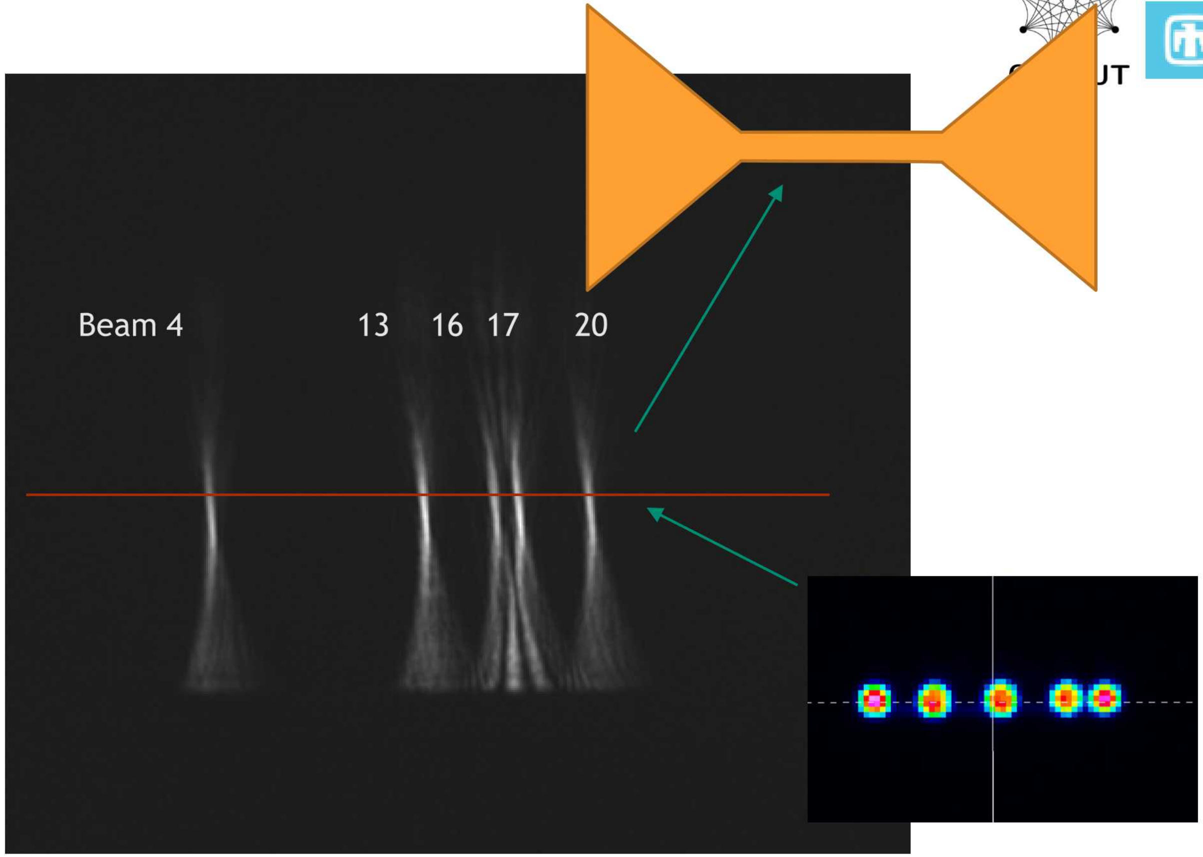
Features (hydrogen and organic mitigation):

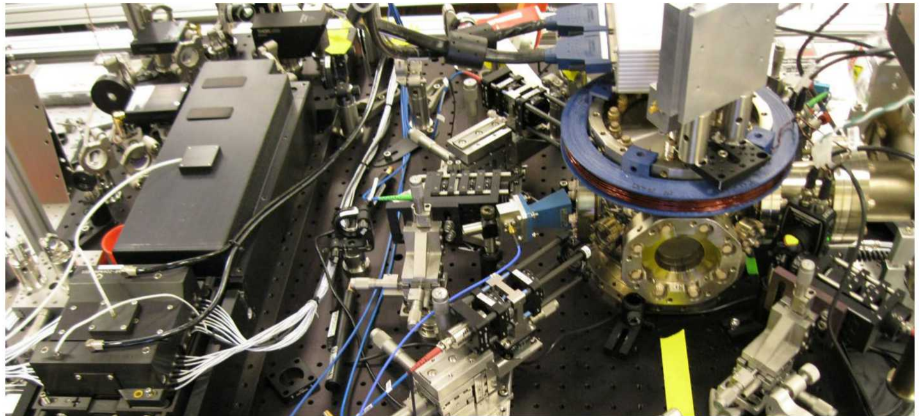
- 316L stainless steel subjected to high-temp bake process for UHV performance
- Ceramics: MACOR fuzz button spacer & Micro-D, AlN -> Al_2O_3 circuit board, Al_2O_3 wire spacers
    - Changing circuit board to Al_2O_3 allows for direct soldering of wires to board
- Bare copper wires for RF and DC voltages
- 50 L/s ion pump (previous chambers of similar form factors have used 25 L/s pumps)

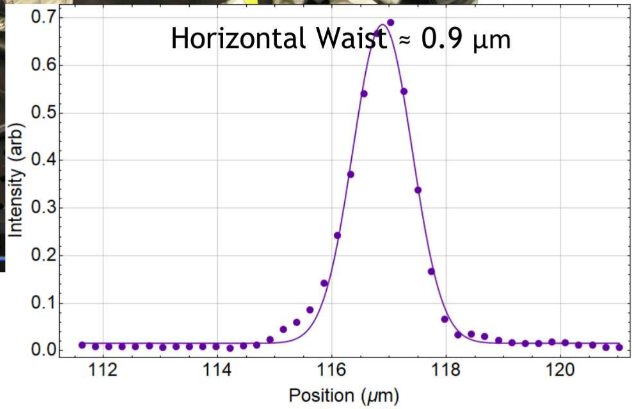
Qubit Laser – Apparatus Test

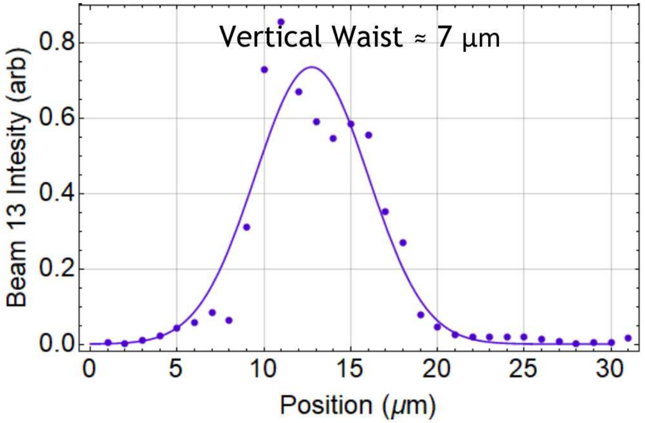
Status - Alignment Complete

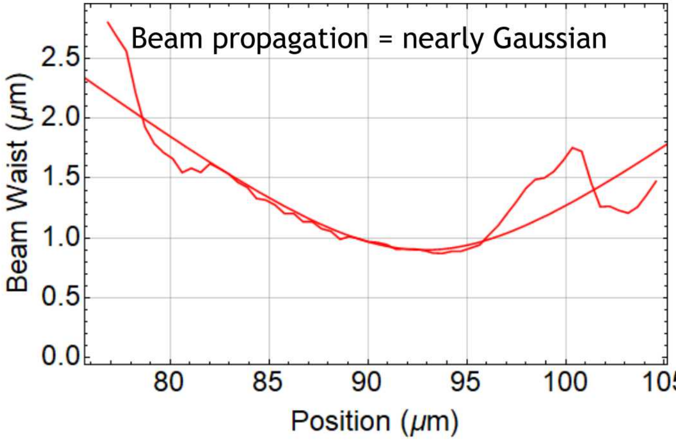
- Adjacent beams are clearly separated, and about 5 μm apart.
- The beam waists are nearly the designed values.
- The apparent optical crosstalk is small, but we need to measure using an ion.



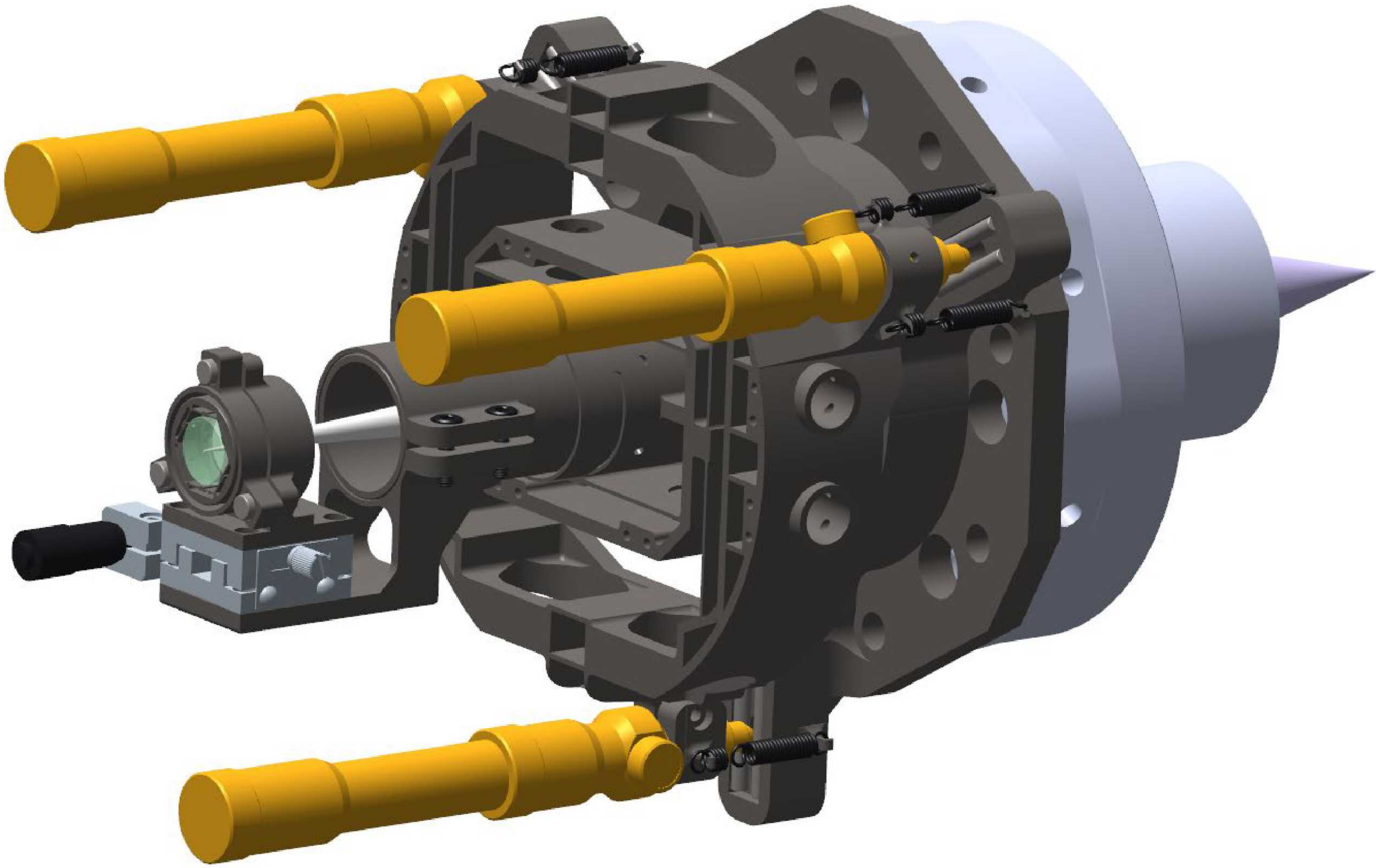






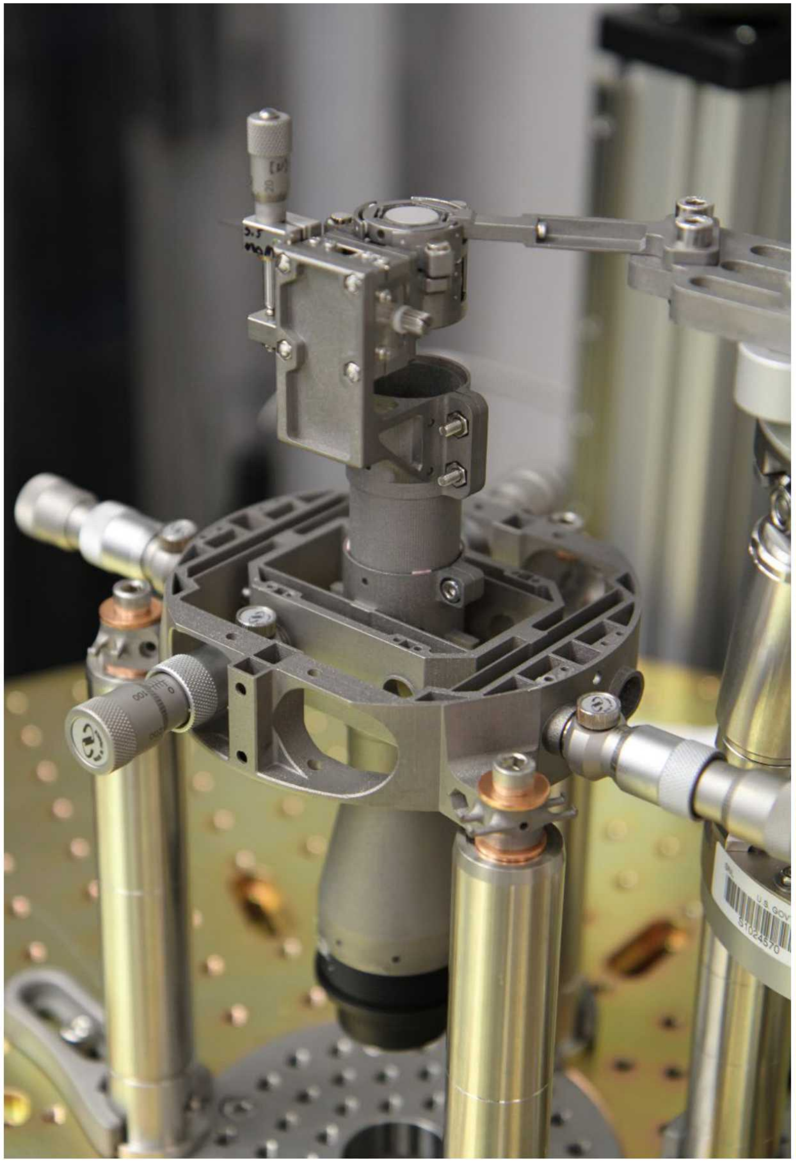


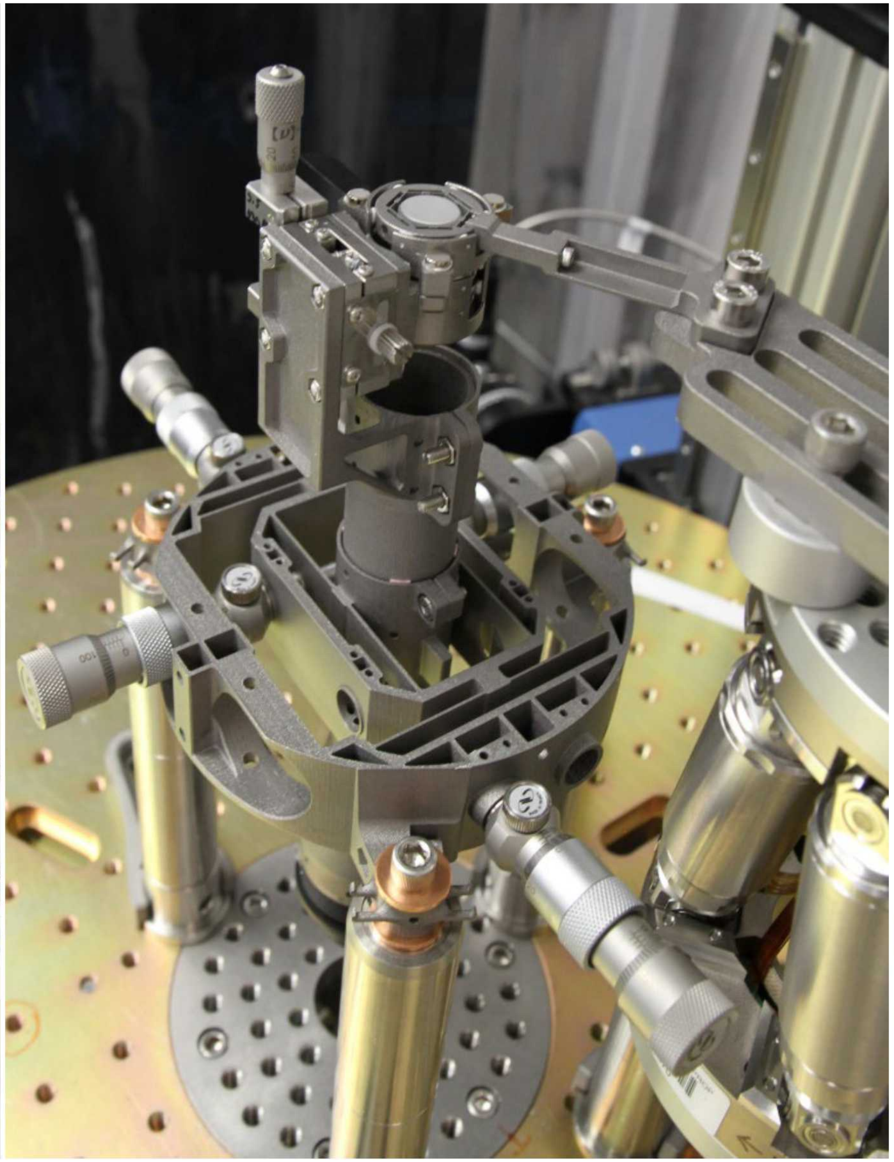
Individual Addressing Relay Subassembly

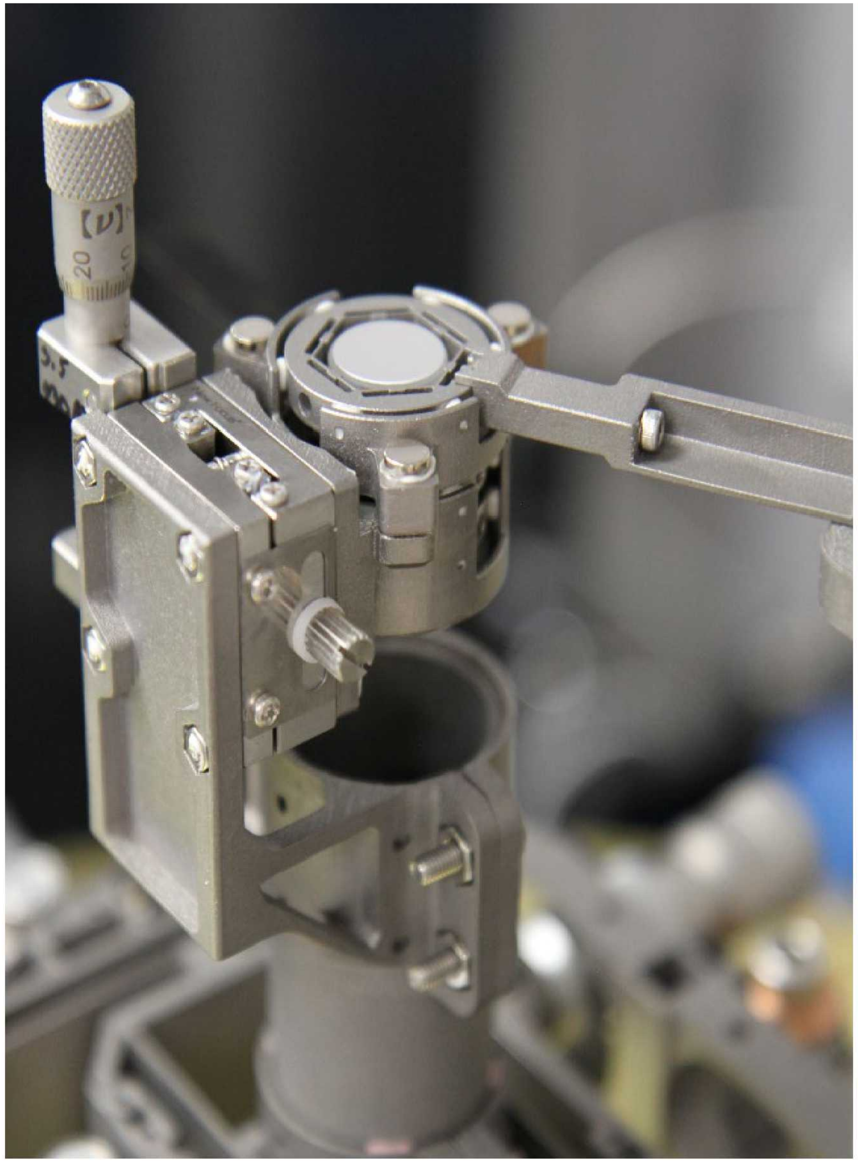


Individual Addressing Relay Subassembly

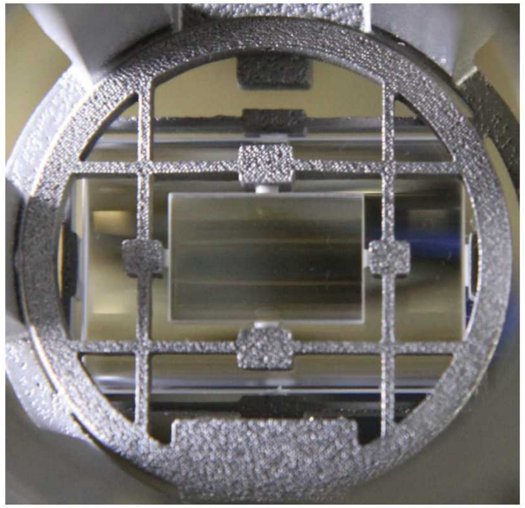
QSCOUT

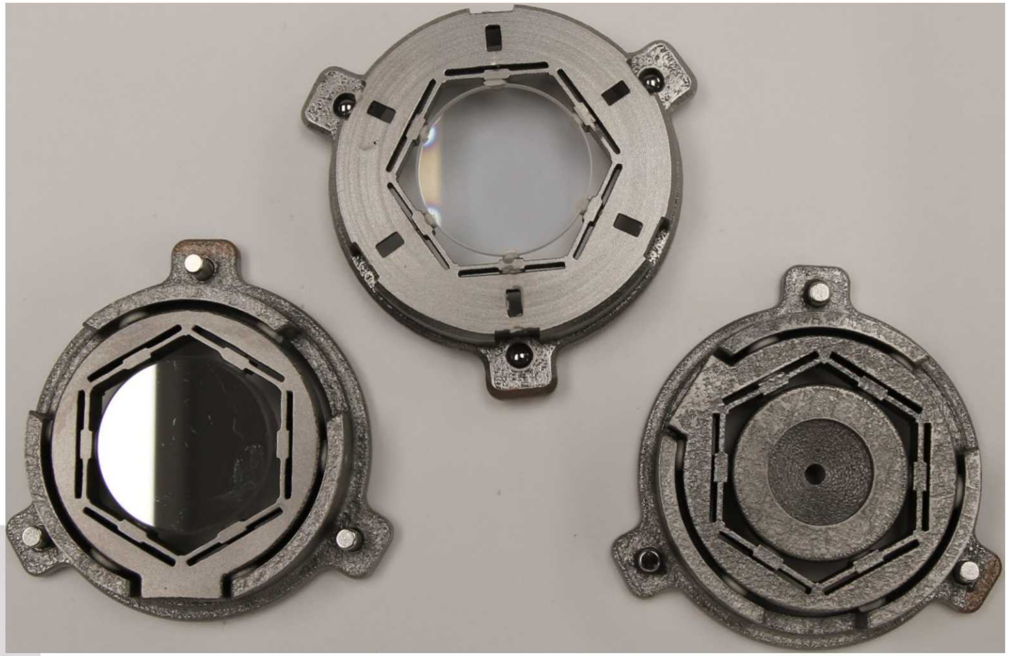


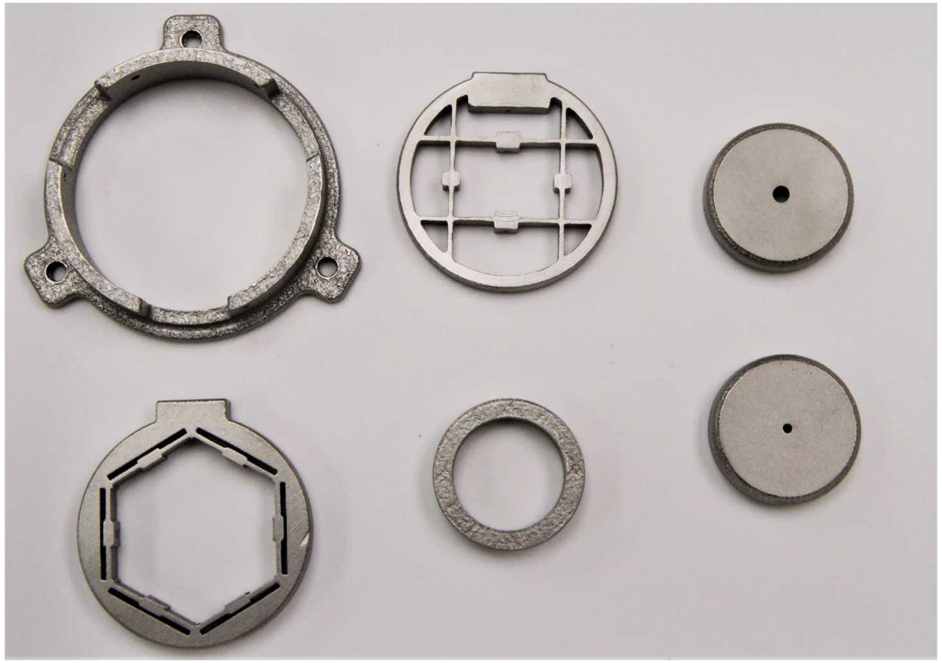




Flexture mounts for active alignment

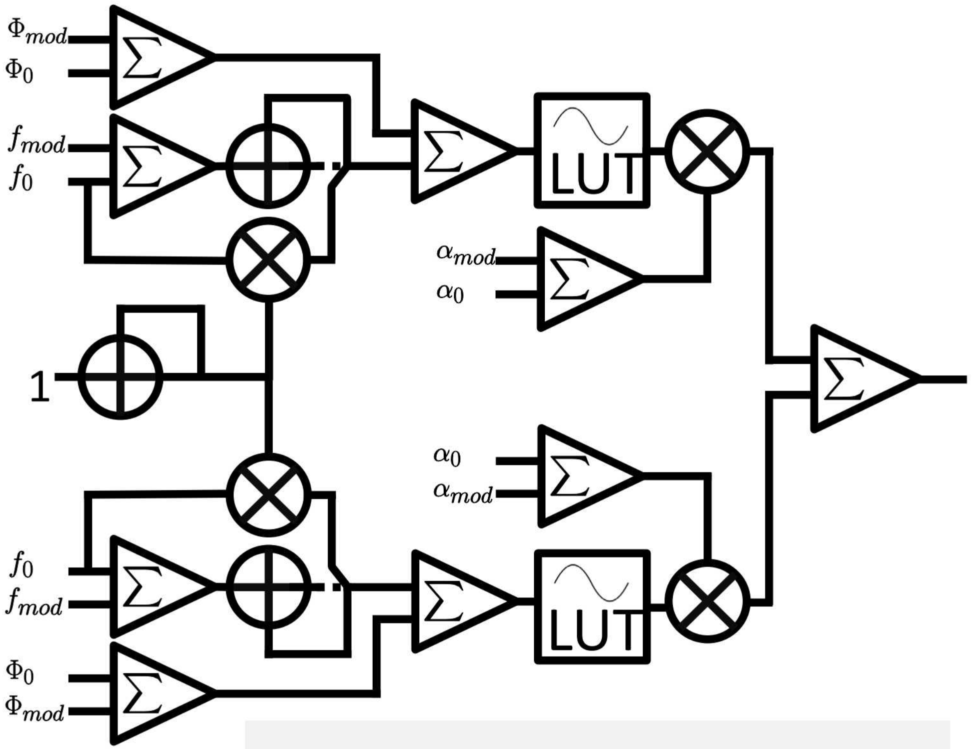




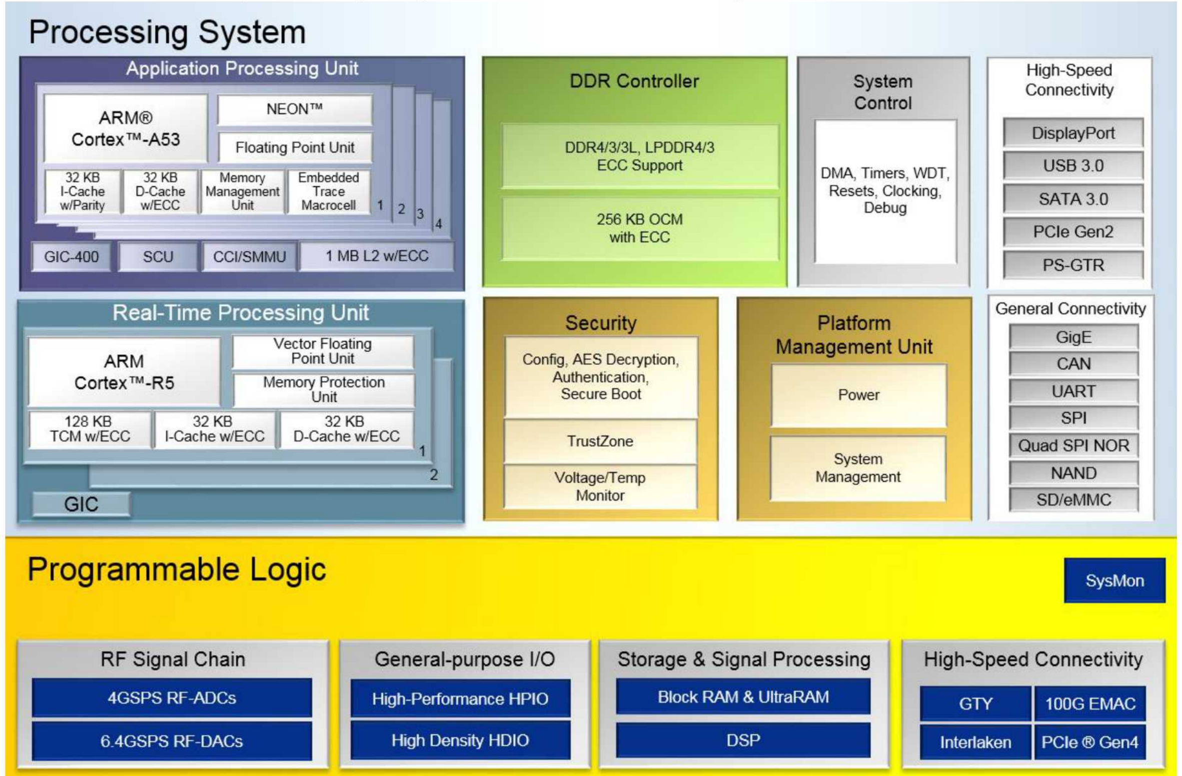


RFSoC for coherent pulse generation

- Two tones per channel
- Coherent output synchronized between all channels
- Pulse envelopes and frequency- phase- modulation defined by splines
- Compact representation of gates for efficient streaming of circuits
- AOM Cross-talk compensation



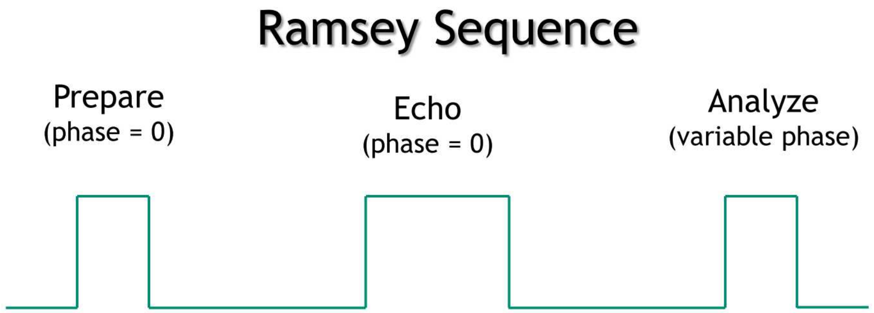
Radio-Frequency System on a Chip



Microwave Coherence Time Measurement

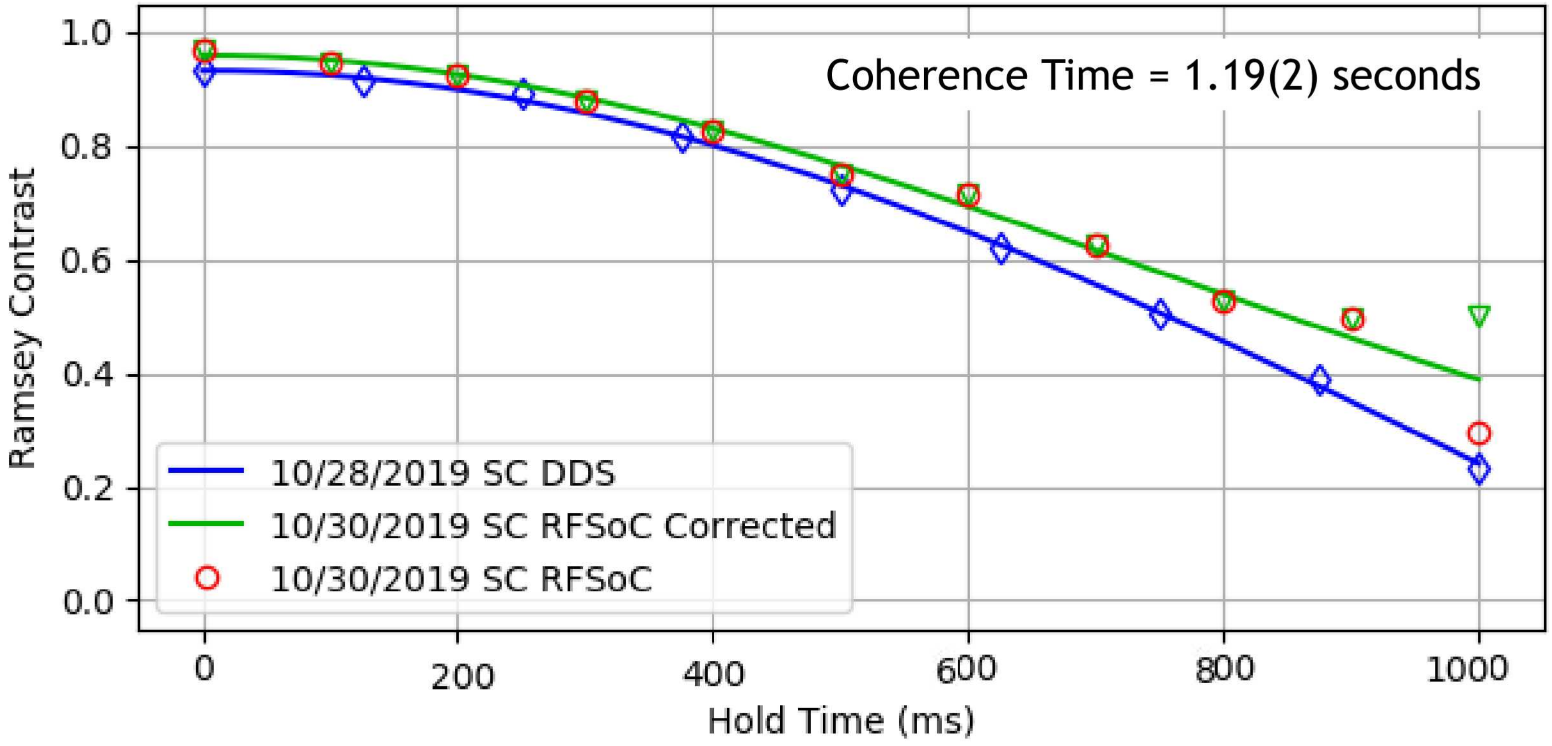
QSCOUT

- Completed FPGA logic design and server software
- 8 channels, 818 MHz data rate, up-sampled to 6.5GHz
- Integrated beat-note lock for pulsed laser



First test:

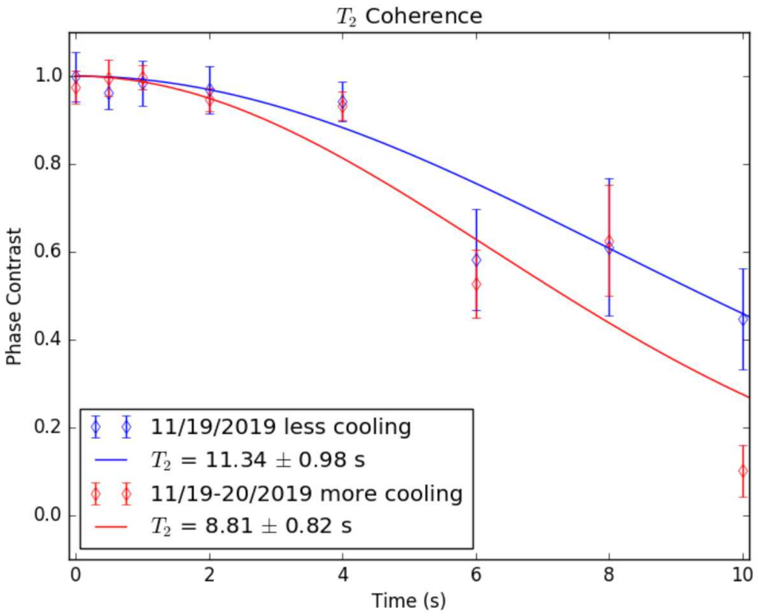
- Coherence time comparison between RFSoC system and legacy DDS based system
- Measured on legacy ion system
- Measured coherence time of 1.19s slightly better than legacy system
- Limited by experimental setup

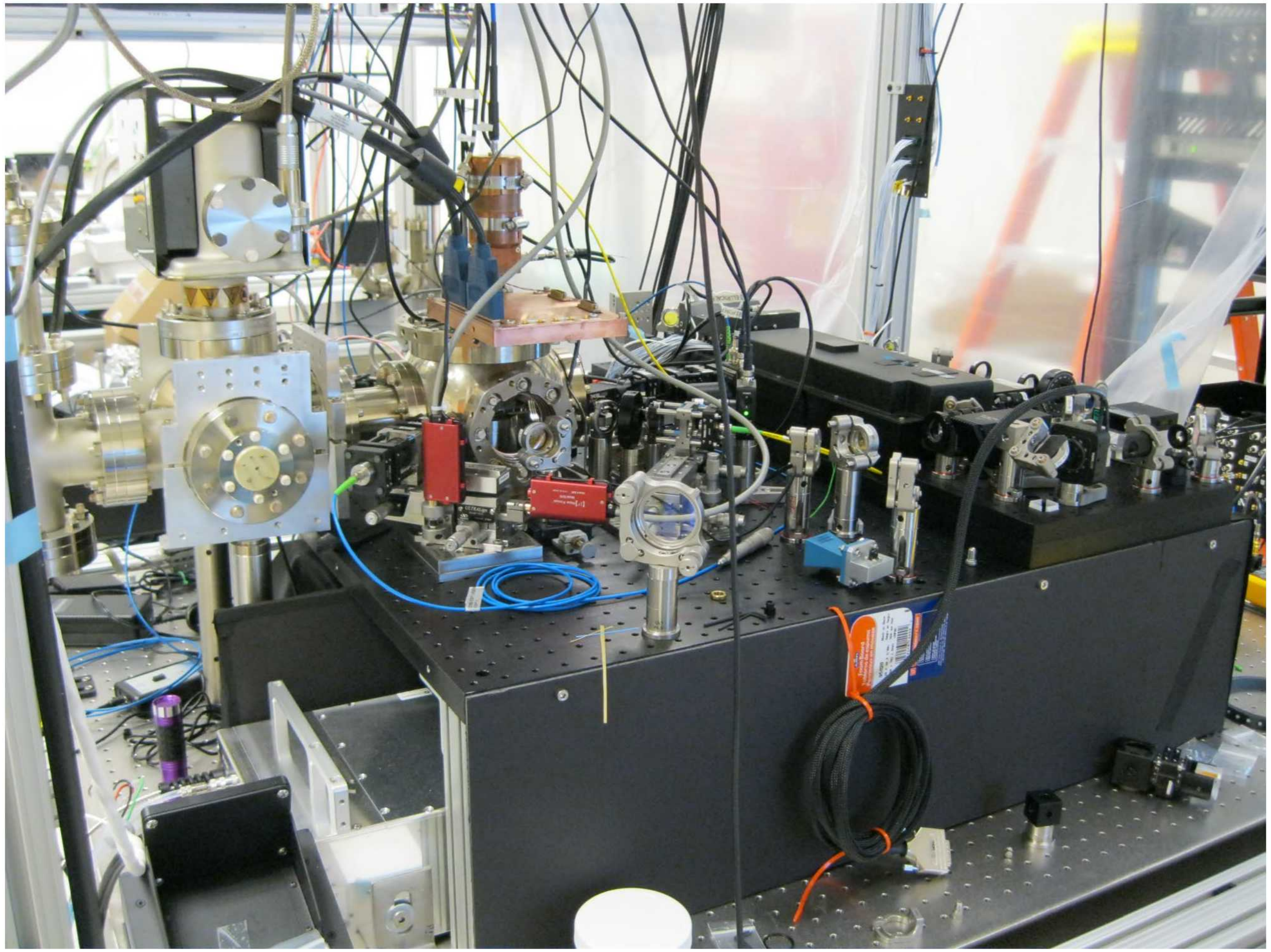


QSCOUT system currently being assembled

QSCOUT

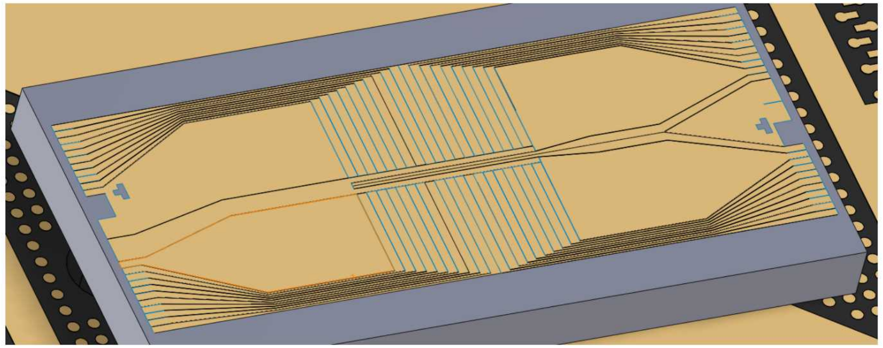
- Trapped ions
- Vacuum pressure seems very promising (will measure background collisions using W-potential)
- State preparation and detection established
- Coherence time (single echo pulse) >8s

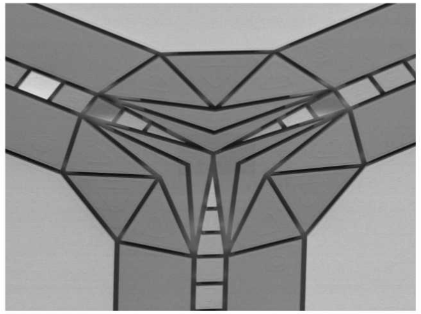


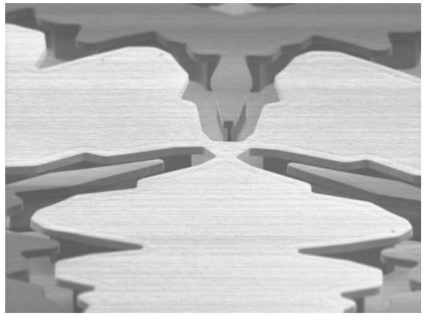


Outlook: Trap design fabrication and integration

- Ion heating @ cryogenic temperatures
- Ion transport and quantum register reconfiguration
- Junction design and operation
- Charging of traps leading to ion shifts
- Simplification of trap fabrication
- Integration of optics and electronics







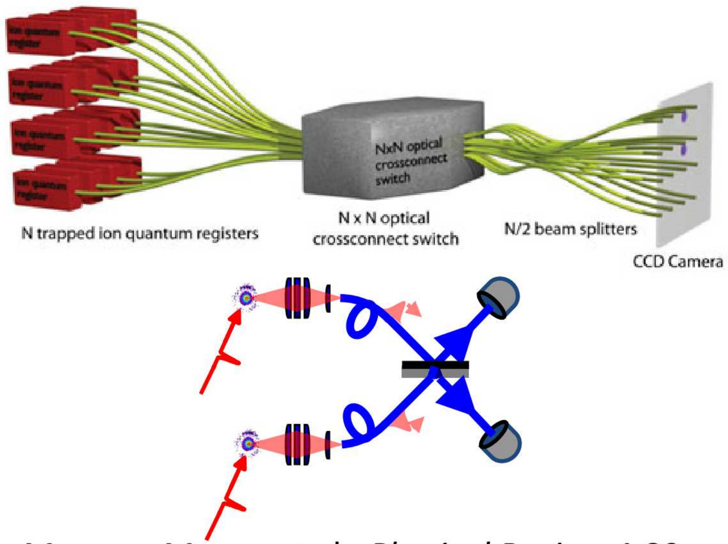
Outlook: Scaling

- Photonic interconnect to scale beyond a single trap chip
- Integration of an optical cavity with microfabricated traps
  - For UV light, cavity finesse much lower than in infrared
  - Dielectric mirrors of cavities subject to charging
  - Possibility: Use infrared transitions to meta-stable states for entanglement and transfer quantum state to hyperfine qubit

New gate technologies:

- Ultra-fast gates
  - Use short pulse train from pulsed laser
- Rydberg gates
  - Use Rydberg states as demonstrated in neutral atoms and recently in trapped ions

Distributed quantum networks with ions as memories



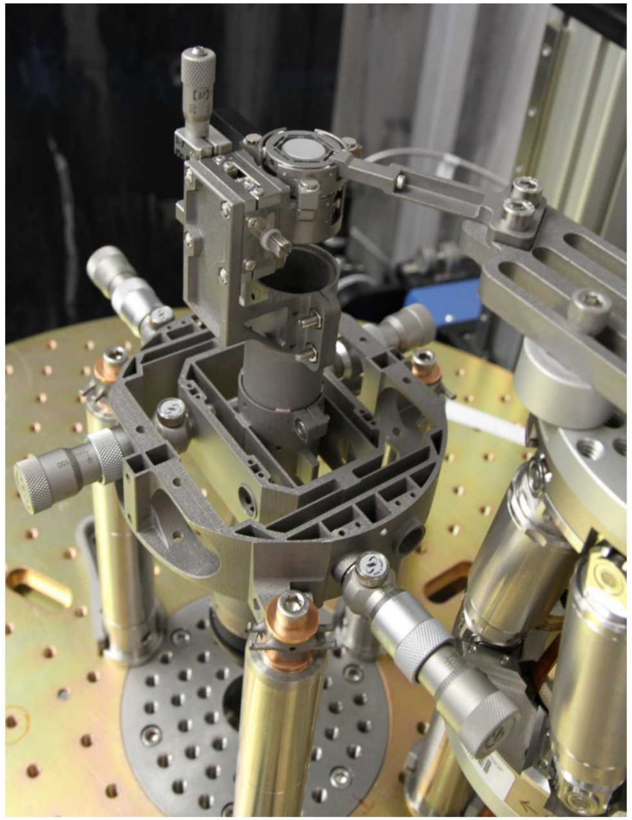
Monroe, Maunz et al., *Physical Review A* 89, 022317 (2014).

Outlook: Systems engineering

- Vacuum Technology

- Mechanical Engineering

- Electrical Engineering



Thanks

Trap design and fabrication

Matthew Blain
Jason Dominguez
Ed Heller
Corrie Herrmann
Becky Loviza
John Rembetski
Paul Resnick
SiFab team

Mechanical Engineering

Jessica Pehr
Zachary Kreiner

Trap packaging

Ray Haltli
Andrew Hollowell
Anathea Ortega
Tipp Jennings

Theory

Setso Metodi
Brandon Ruzic

Drift detection

Tim Proctor
Kevin Young

Trap design and testing

Peter Maunz
Craig Hogle
Daniel Lobser
Melissa Revelle
Dan Stick
Christopher Yale

RF Engineering

Christopher Nordquist
Stefan Lepkowski