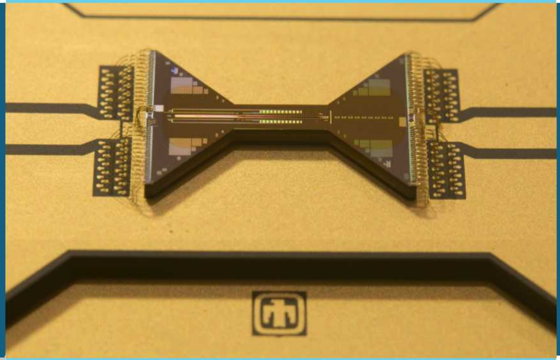
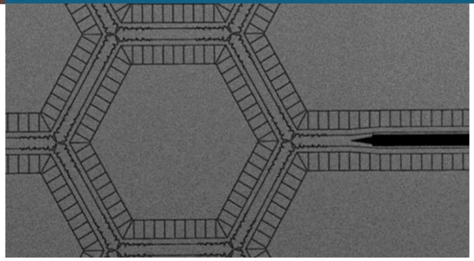
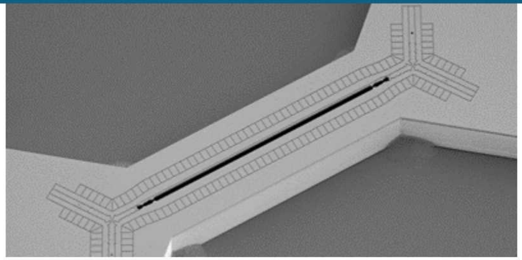
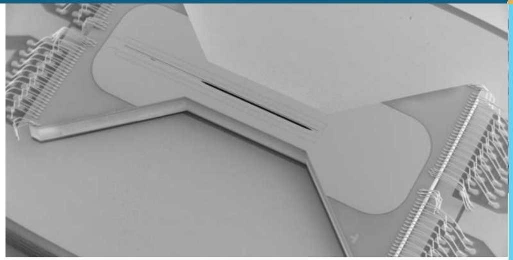
SAND2020-11183PE

Trapped Ions Experiments at Sandia National Laboratories







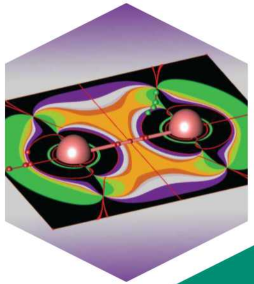


CQuiC Seminar – October 15th, 2020

Dr. Melissa Revelle

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Quantum Information

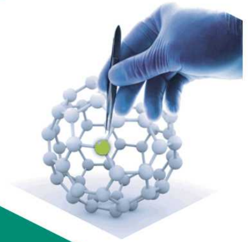


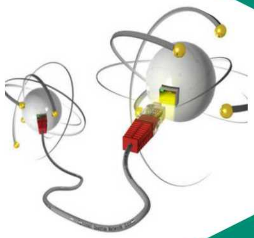
Quantum Chemistry

Calculation of molecular potentials

Medicine

Structure based drug development





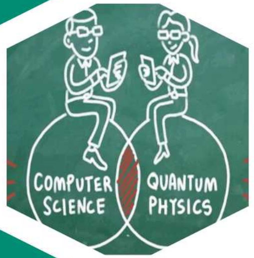
Quantum Communi-cation

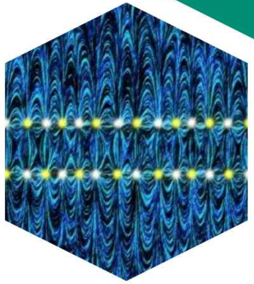
Securing a quantum channel

Quantum Computing

•Number factorization

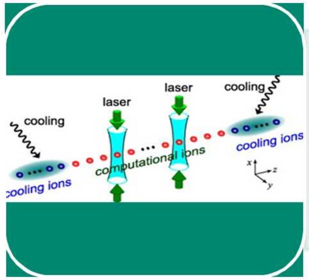
Search in unstructured data



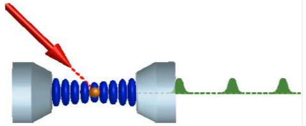


Quantum Simulation

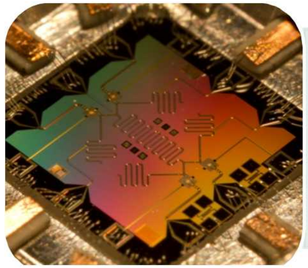
•Simulating many-body systems not possible to simulate classically.



- <u>Trapped Ions</u>
- 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)



- <u>Neutral Atoms</u>
- Rydberg states
- Atoms in cavities



- <u>Superconducting Josephson Junctions</u>
  - Devoret and Schoelkopf. "Superconducting Circuits for Quantum Information: An Outlook." *Science* 339, 1169 (2013).

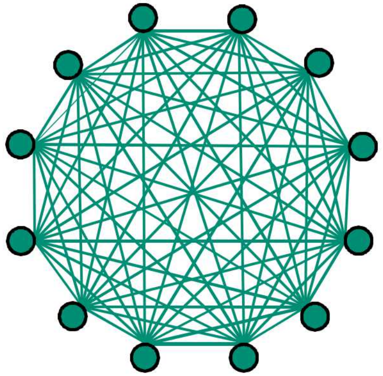
- <u>Quantum Dots</u>
  - Awschalom, et al., "Quantum Spintronics: Engineering and Manipulating Atom-Like Spins in Semiconductors." *Science* 339, 1174 (2013).

Trapped Ion Processors

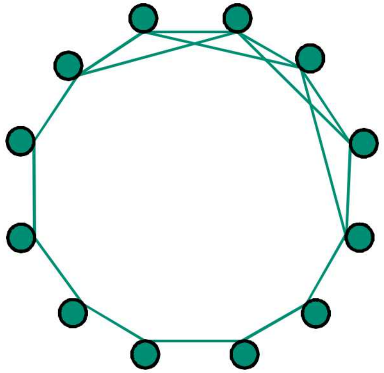
Best available qubits with history of reliability and quality

- 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

Trapped Ions:
fully connected



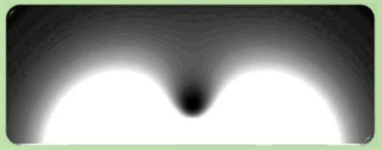
Solid State:
2D nearest neighbor coupling



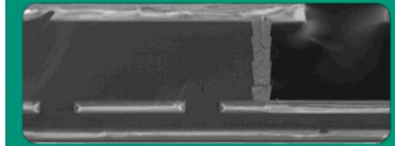
Reconfigurable in software

- 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

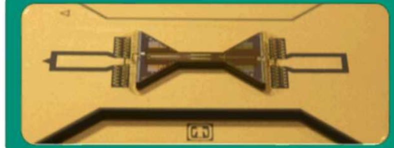
Outline



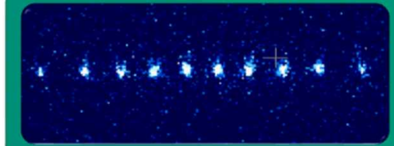
Ion Trapping



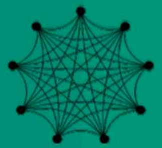
Trap Fabrication



The Phoenix/Peregrine Trap



Recent Results



QSCOUT

Earnshaw’s Theorem and Ion Trapping

Trapping requirement: A restoring force when displaced from trap center

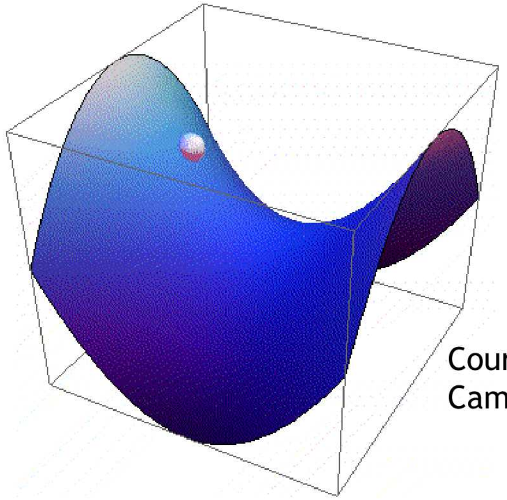
(in any direction)

Cannot use t

Field lines start/en

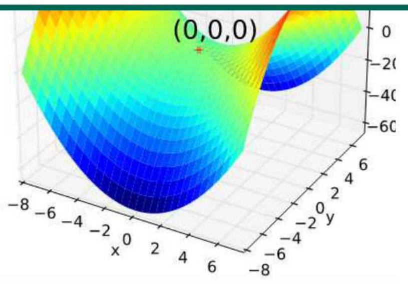
ut” and

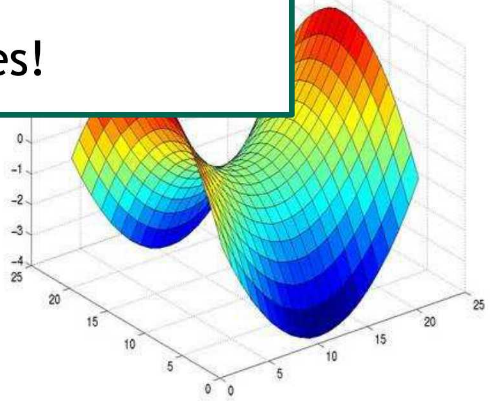
rections



Courtesy of Wes Campbell

Before ion escapes, field reverses!

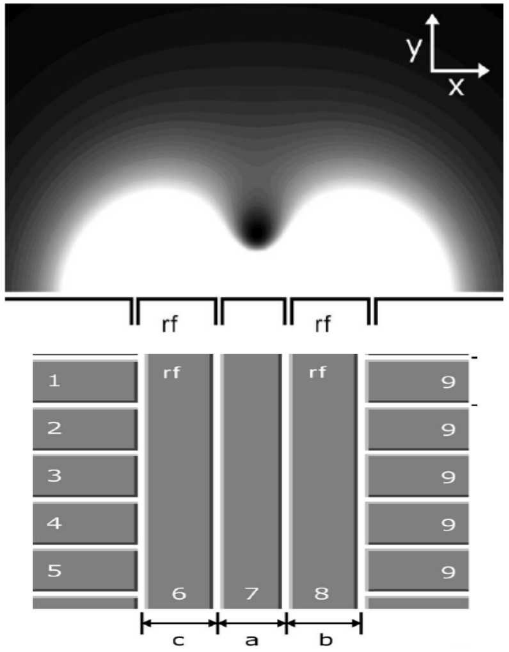




Various Trap Geometries

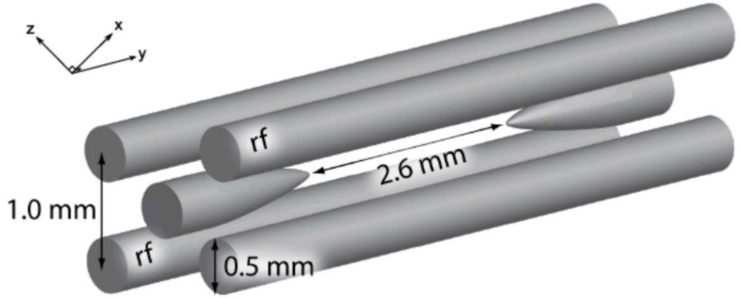
Use a combination of static and rf fields to trap ions
Various geometries possible

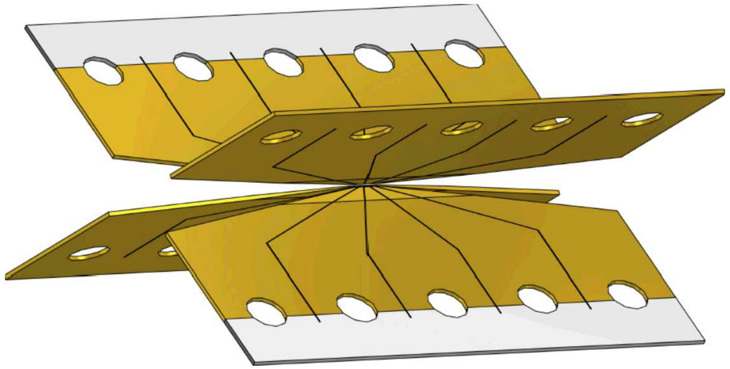
Pesudopotential well (dark area) formed along the axis of a surface trap



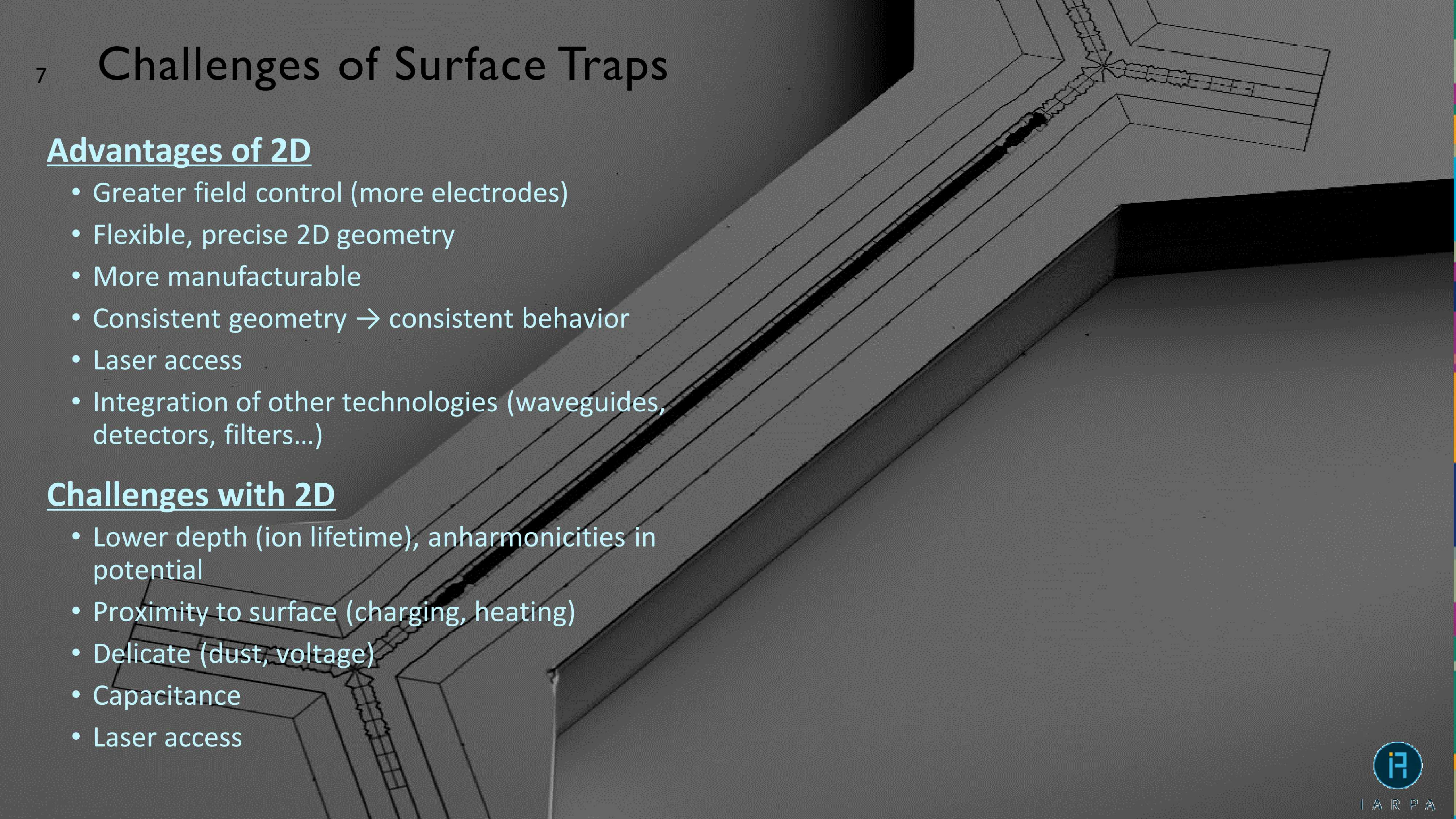
Electrodes from above

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





Challenges of Surface Traps



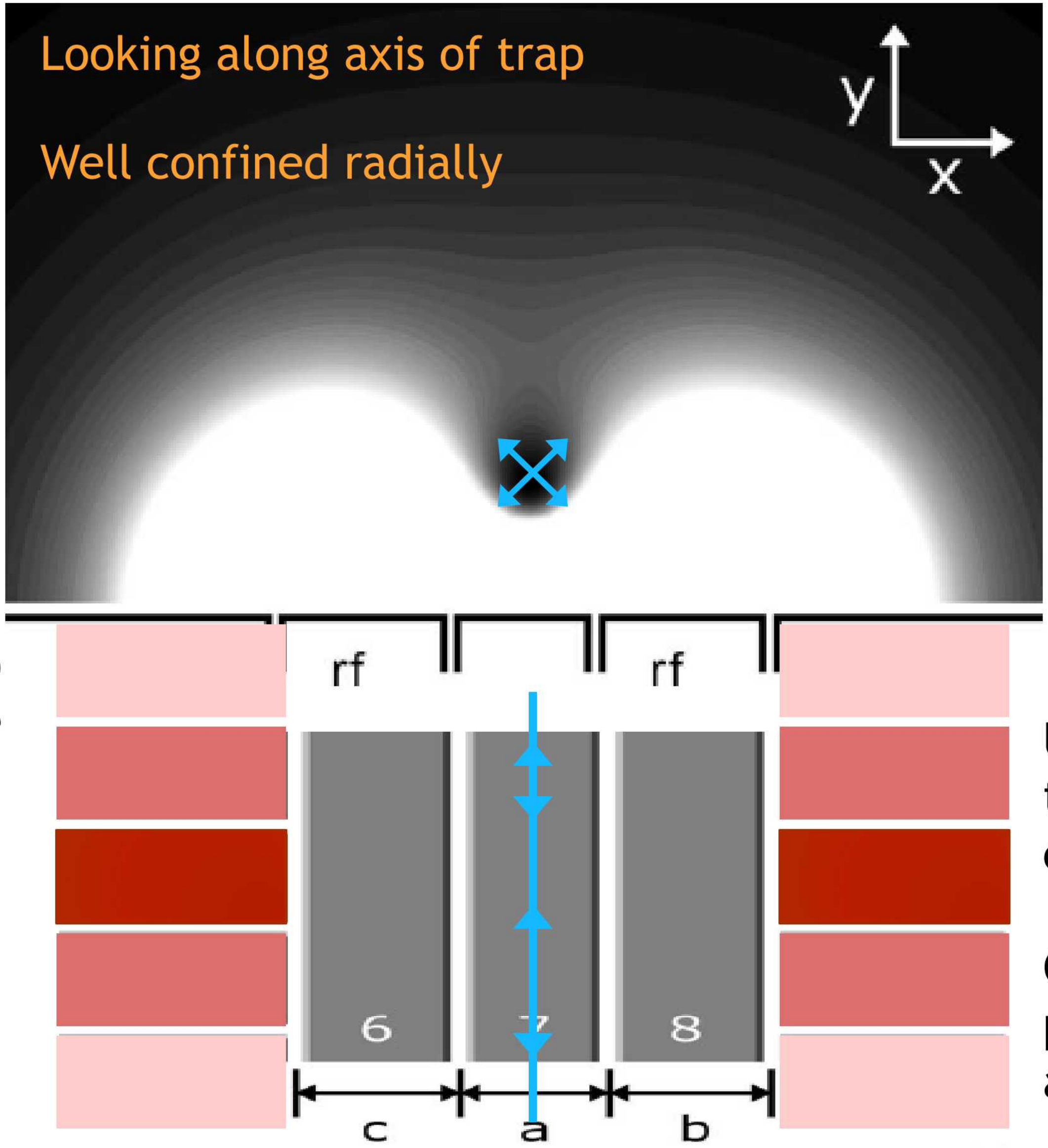
Advantages of 2D

- 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 with 2D

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

Need for DC Fields



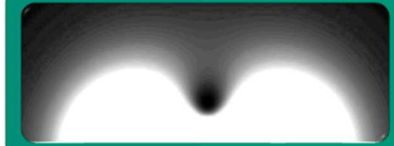
Looking at trap from above

Still free to move along axis

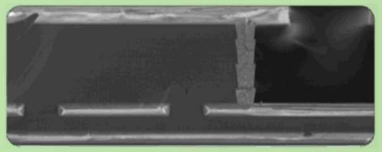
Use DC fields on the electrodes to confine

Creates a trapping potential along axis

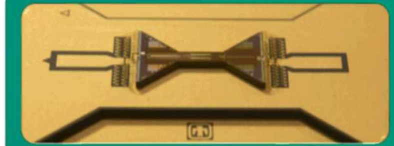
Outline



- Ion trapping



- Trap Fabrication



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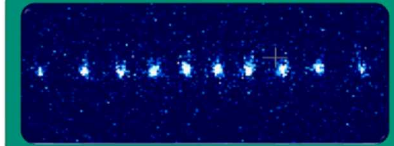
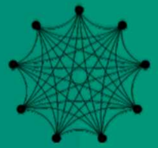


- Recent Results

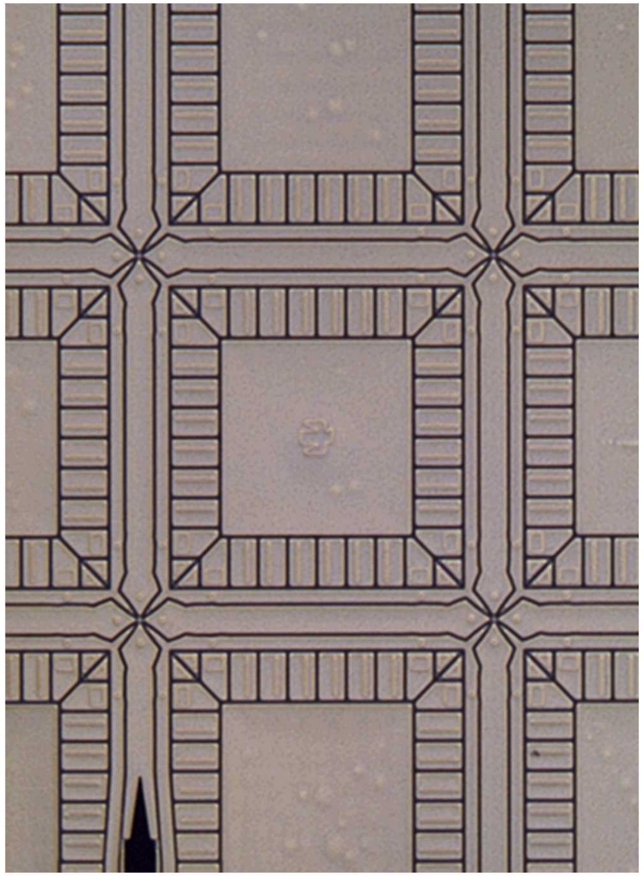


- QSCOUT

Trap Fabrication: 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



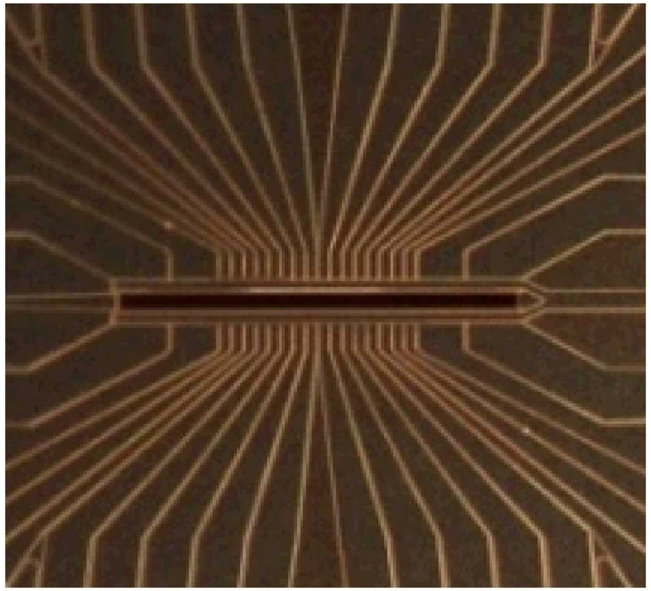
MESA facility

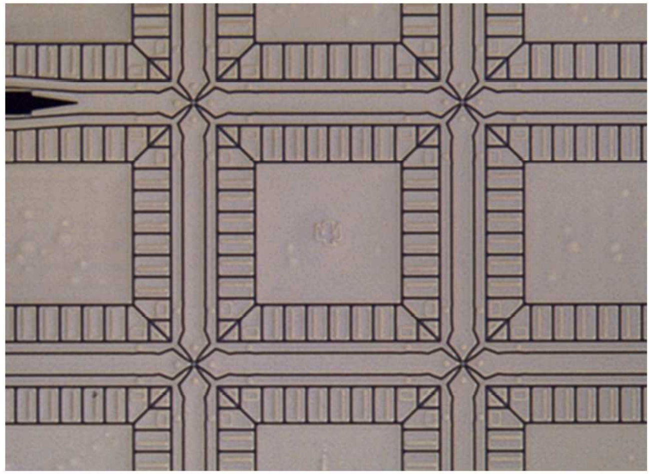
- Radiation hardened CMOS
- Leverages reliability of large batch processing
- Large feature sizes (350 nm) match well with trap requirements

Trap Fabrication: Capabilities & Requirements

Derived requirements

- Standardization (lithographically defined electrodes)
- Multi-unit production
  - ~90 devices per 8” wafer
- Multi-level lead routing for accessing interior electrodes
  - Connecting both control and RF electrodes
- Voltage breakdown >300 V @ ~50 MHz
- Overhung electrodes
- Low electric field noise (heating)
- Backside loading holes
- Trench capacitors
- High optical access (delivery and collection)





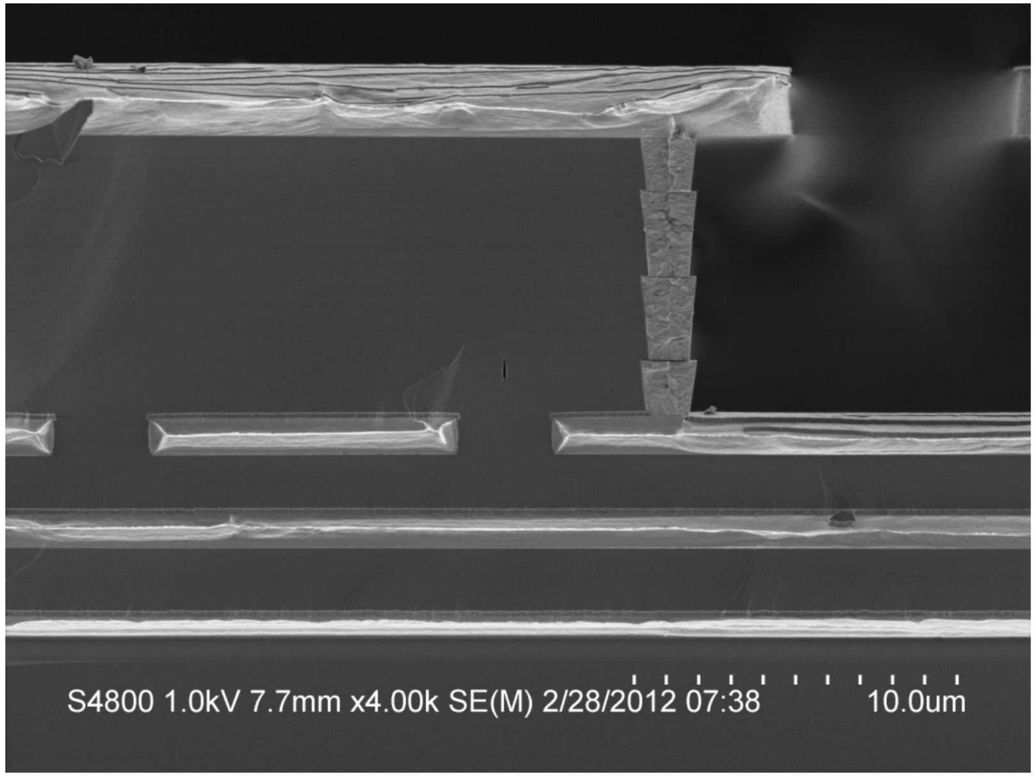
Surface Ion Trap Fabrication

Controlled Oxide Removal

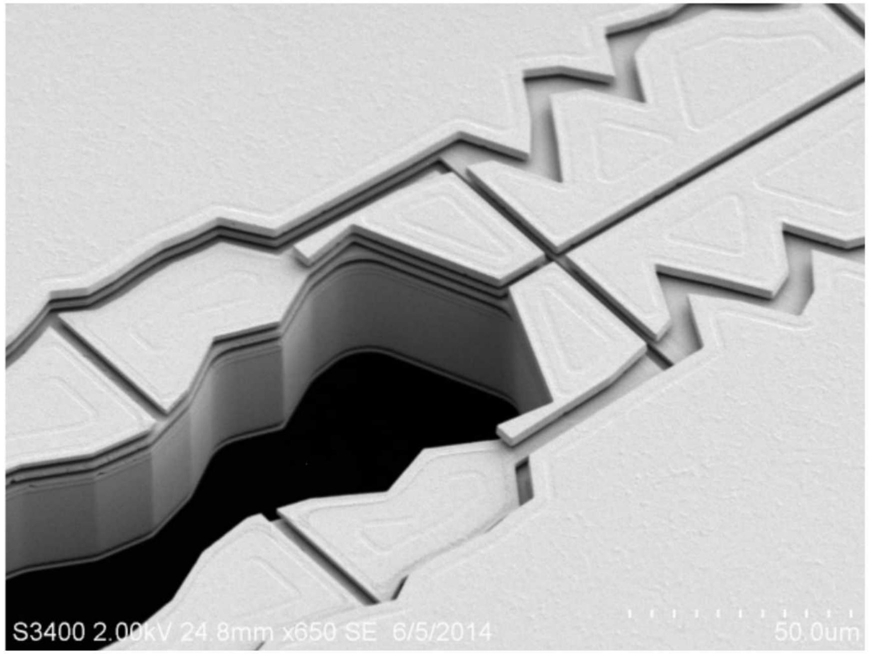
- Can create cantilevered electrodes – increased shielding from oxide to ion.

Multi-level Metalization

- Routing to electrode is below the surface
- Allows for more exotic trap geometries
- Island structures possible
- Uninterrupted electrodes and ground planes on the surface, can place antennae on lower layers



Holes and Slots

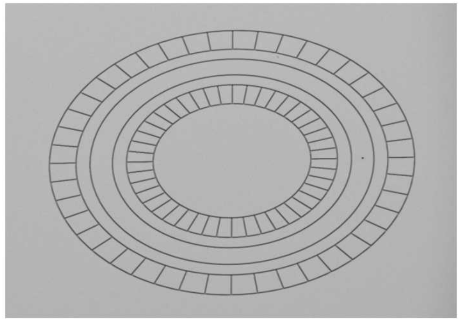


Large Cutaways

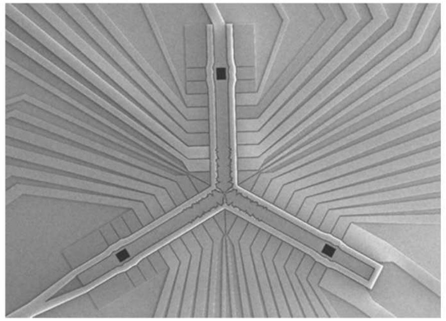
- Loading slot/holes
- Increased optical access from bow-ties shape.

Unique Designs

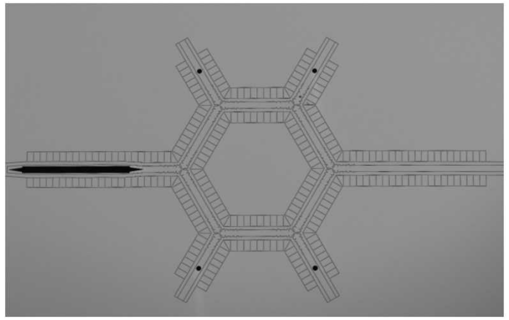
- All these capabilities combine to create unique structures all with different goals towards quantum processing



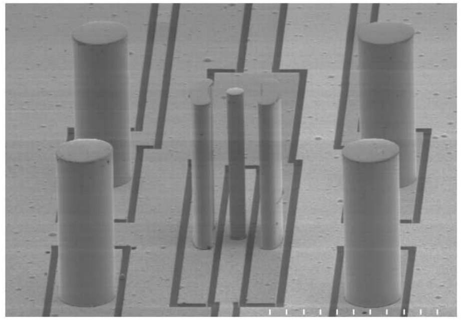
Ring Trap



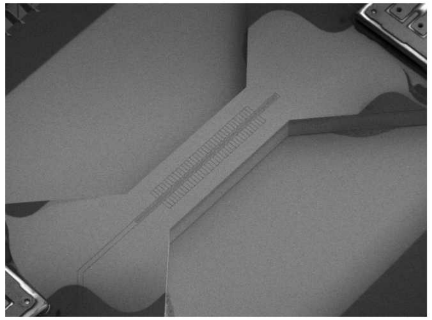
Y-junction Traps



Circulator Trap

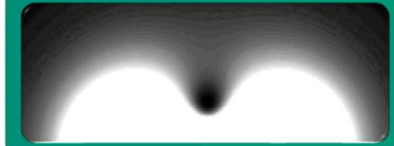


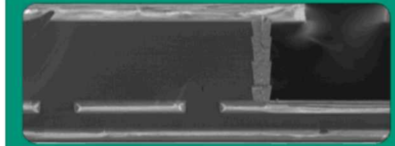
Stylus Trap

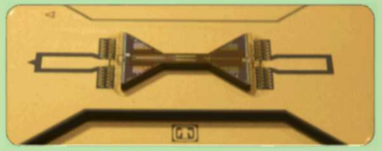


Microwave Trap

Outline


Ion trapping


Trap Fabrication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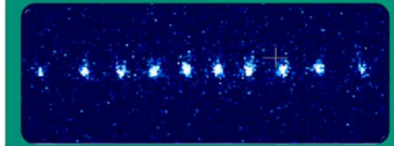
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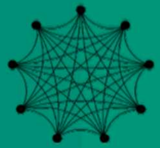
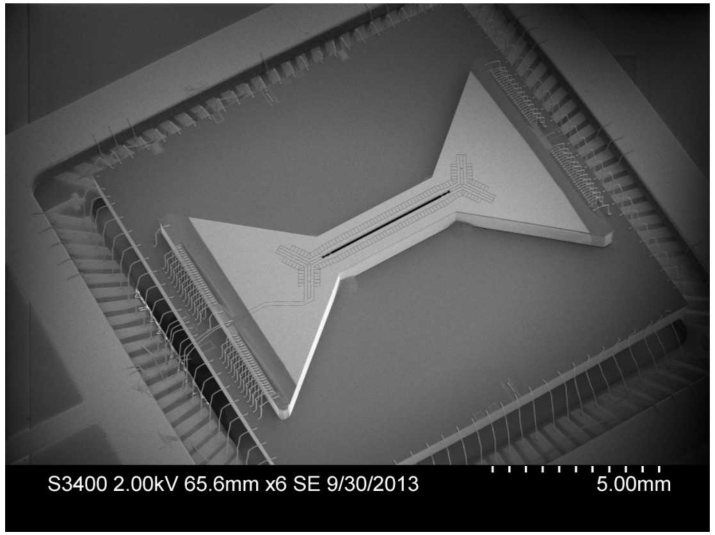
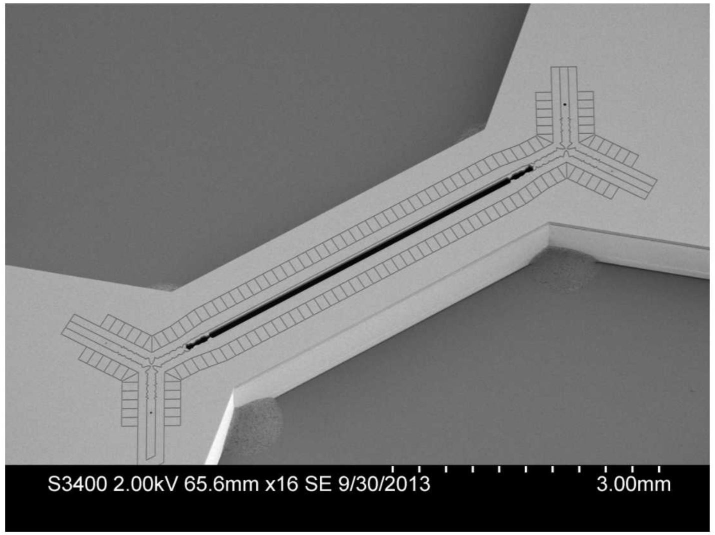
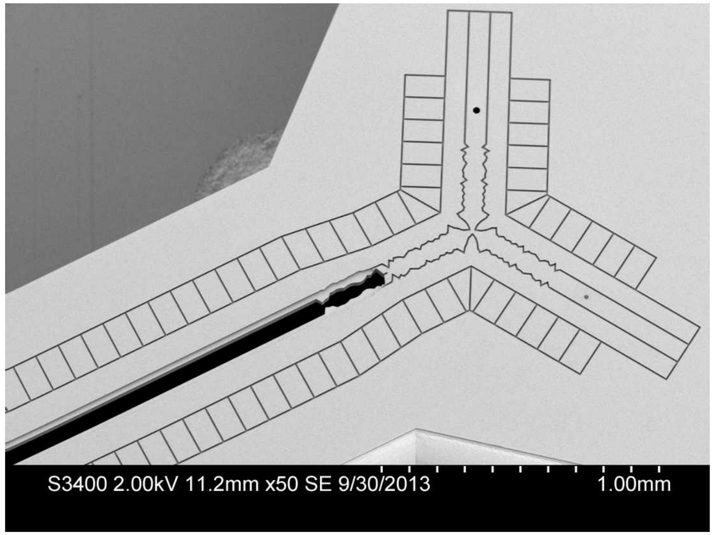
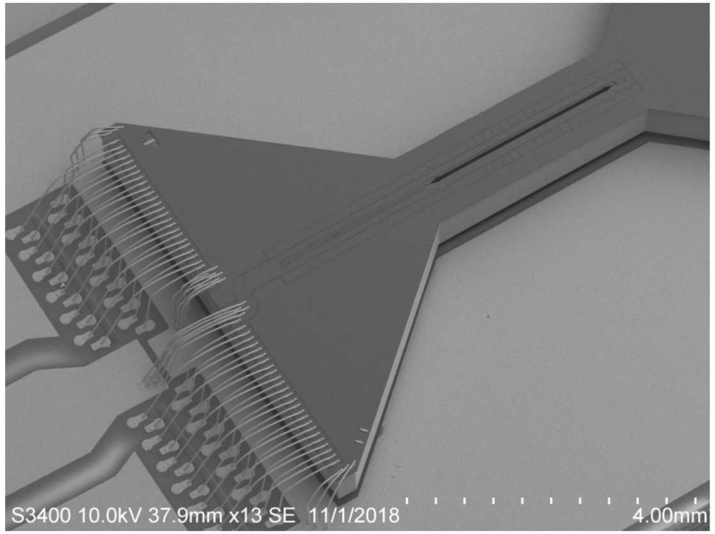

QSCOUT

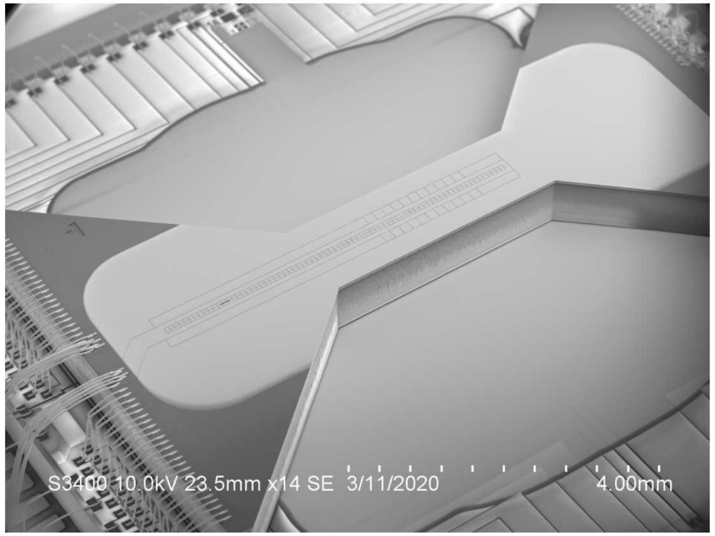
High Optical Access (HOA) – Trap Platform



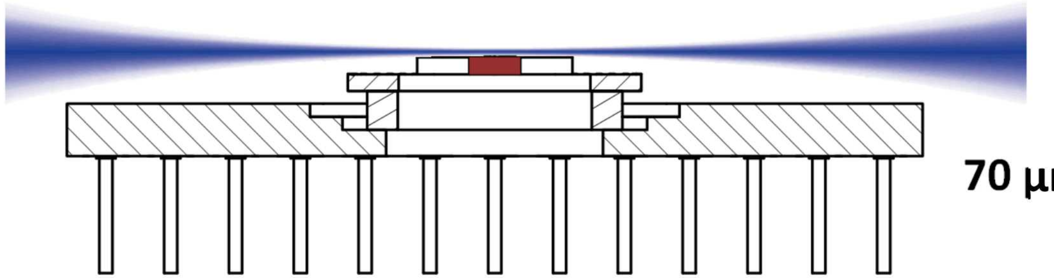




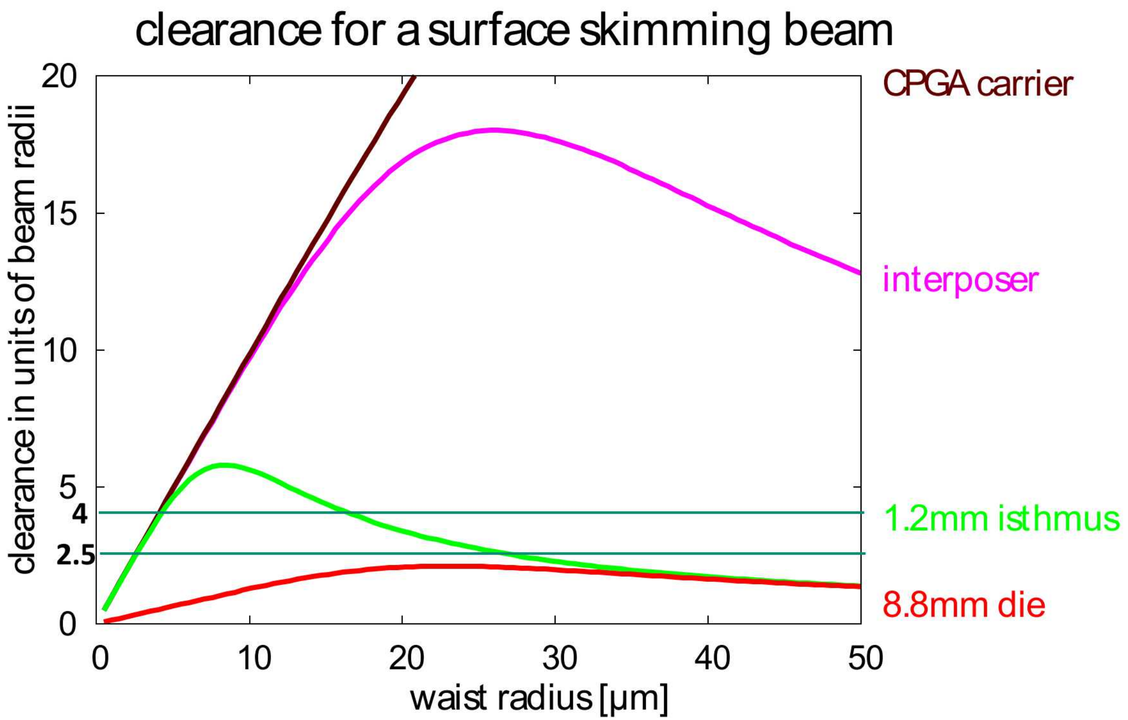




High Optical Access (HOA)



70 μm ion height



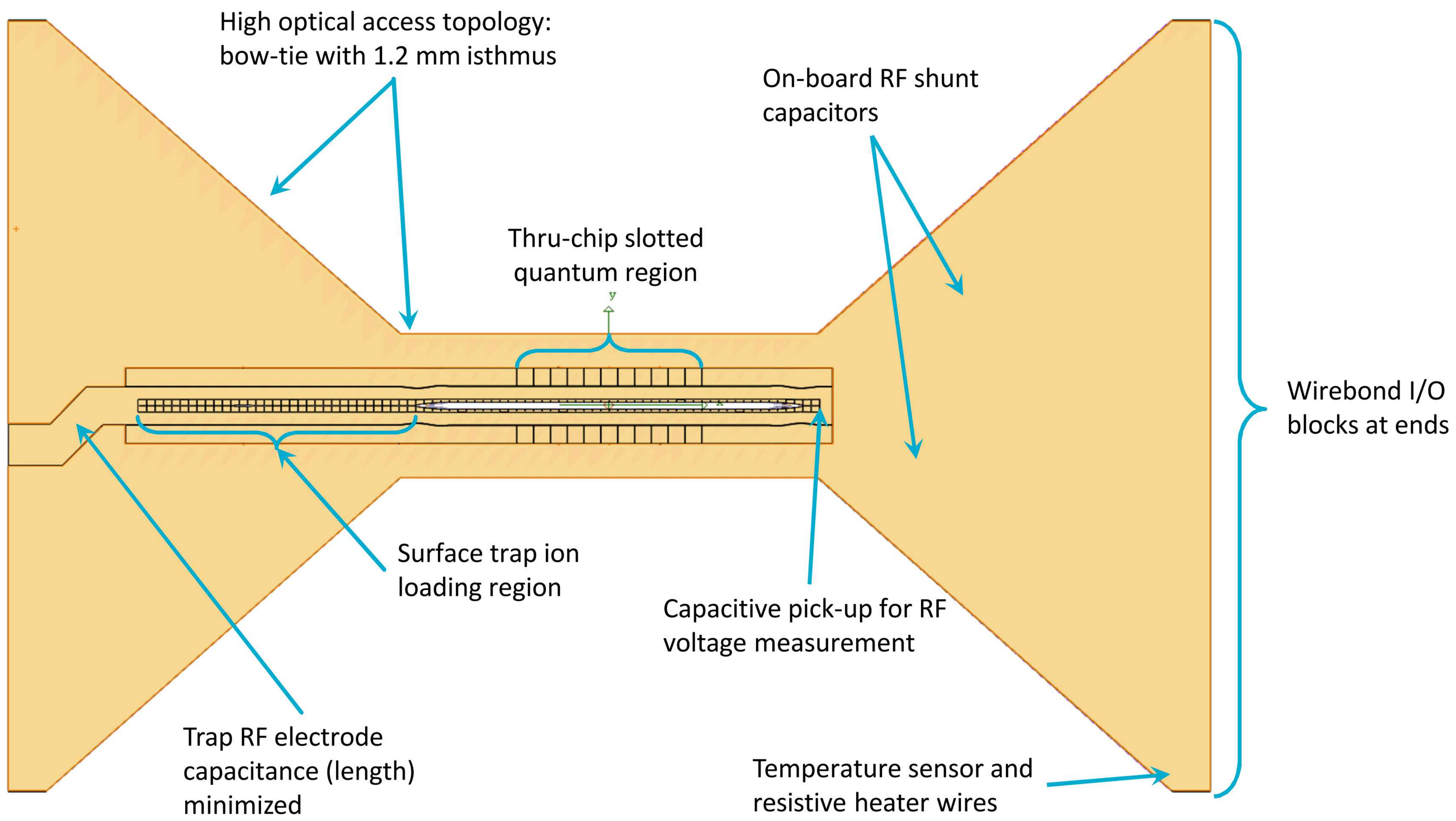
4: $<2\times10^{-14}$

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

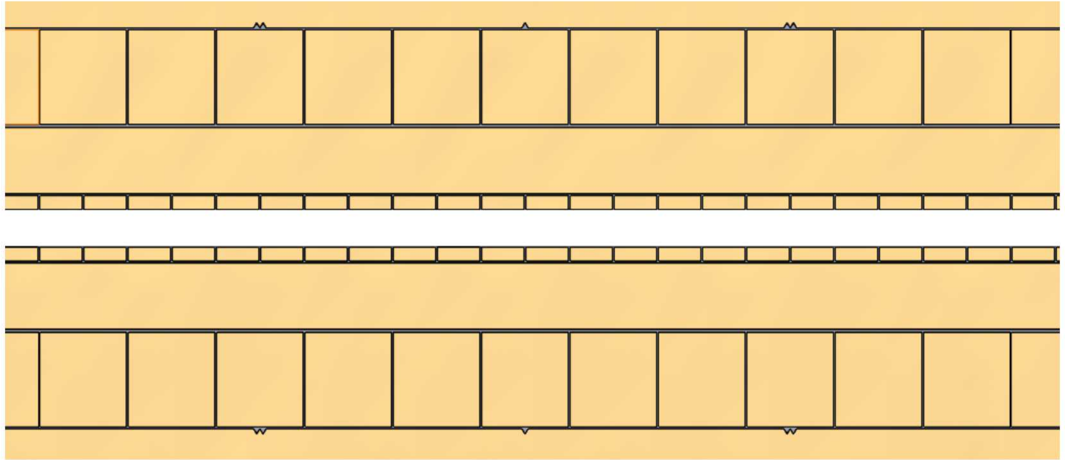
2.5: $<3\times10^{-6}$

4 μm waist is possible

Design and Features

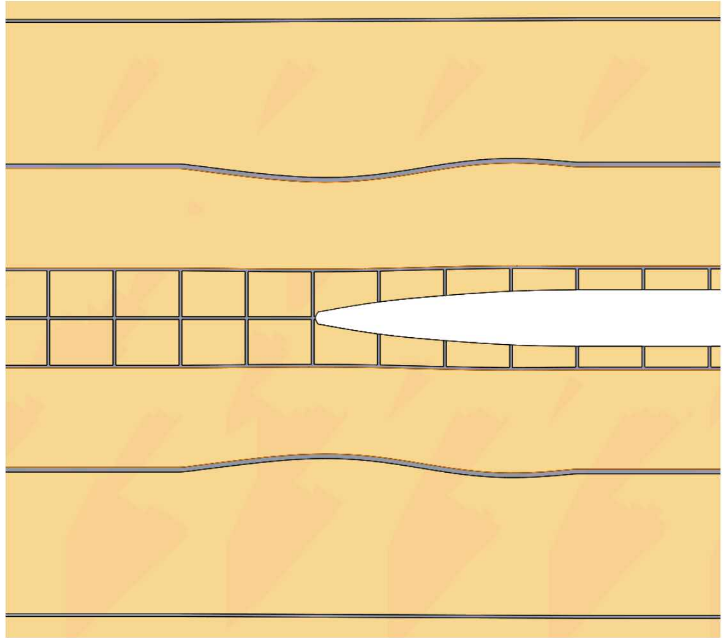


Trap Regions



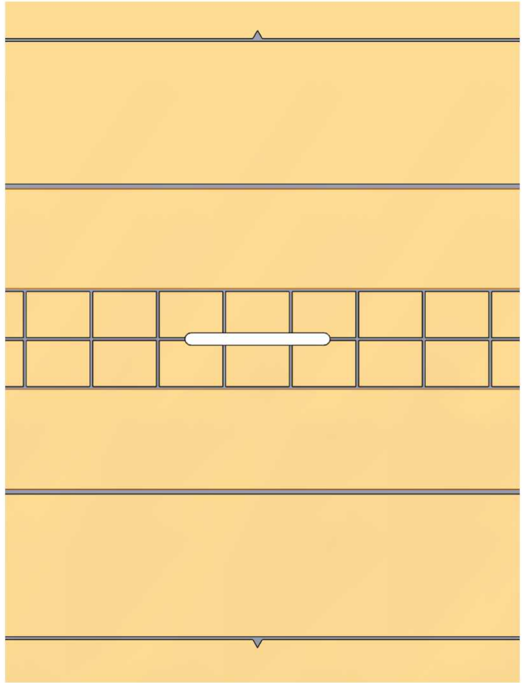
Quantum Region

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



Transition

- 9 degrees of freedom
- Low spatial frequencies

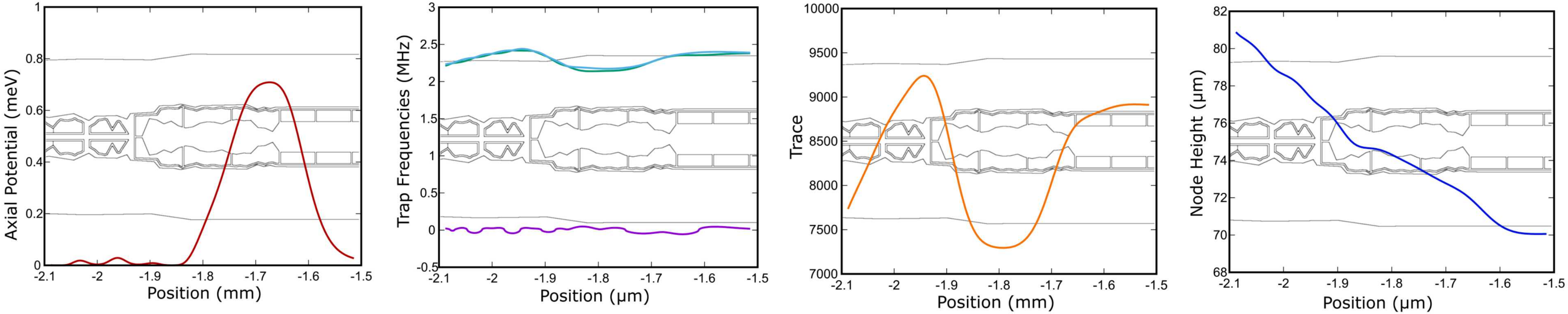


Loading Region

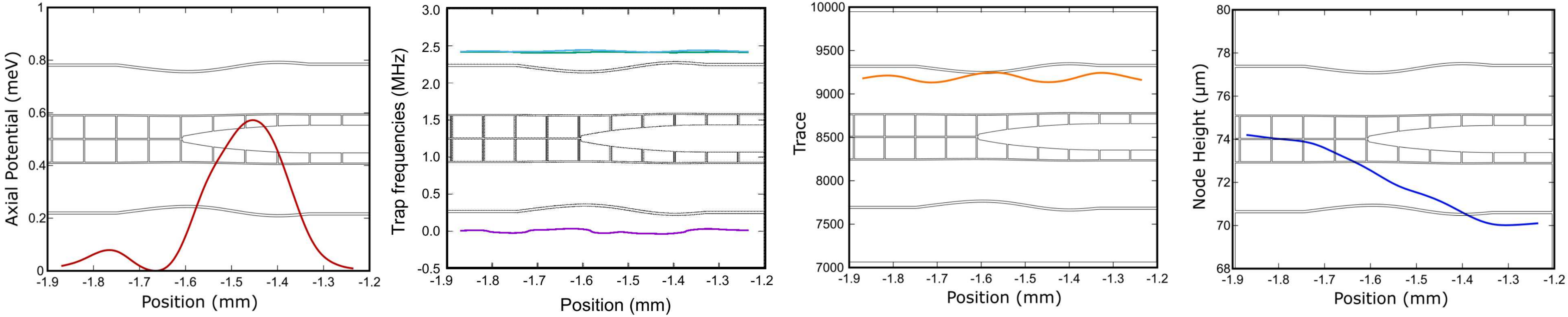
- 5 electrode pairs
- Loading slot 150µm x 13µm

Design Improvements

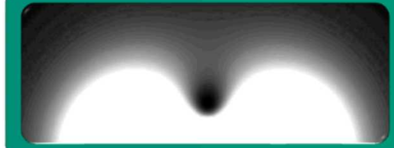
HOA - 2

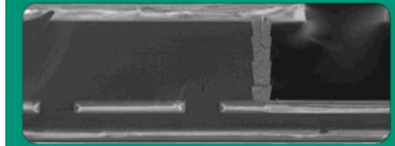


Phoenix trap



Outline


Ion trapping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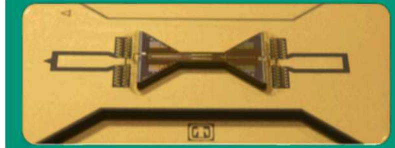
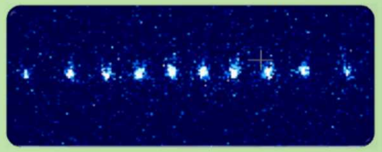
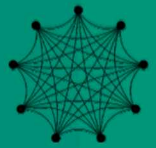
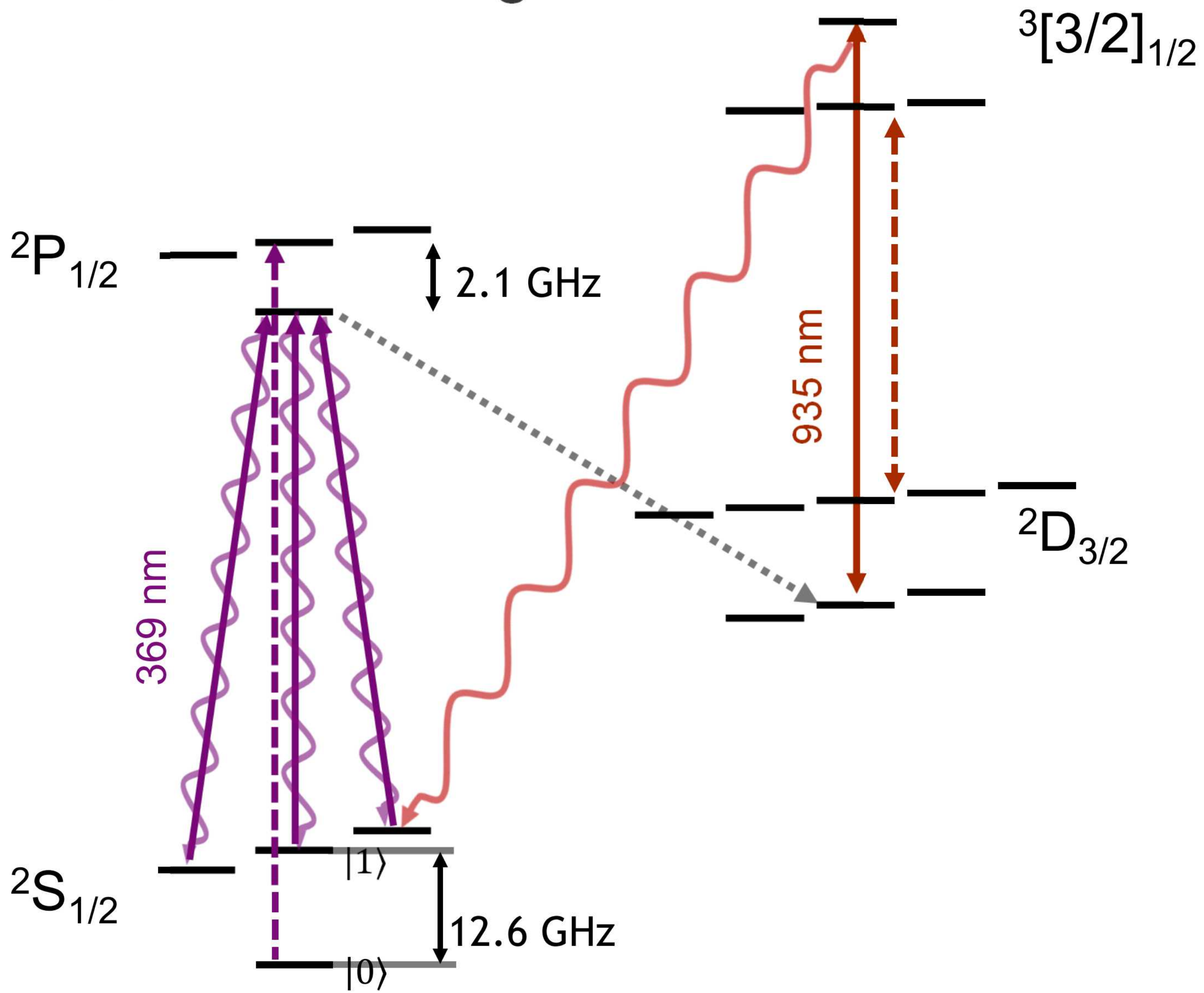

The Phoenix/Peregrine Trap


Recent Results


QSCOUT

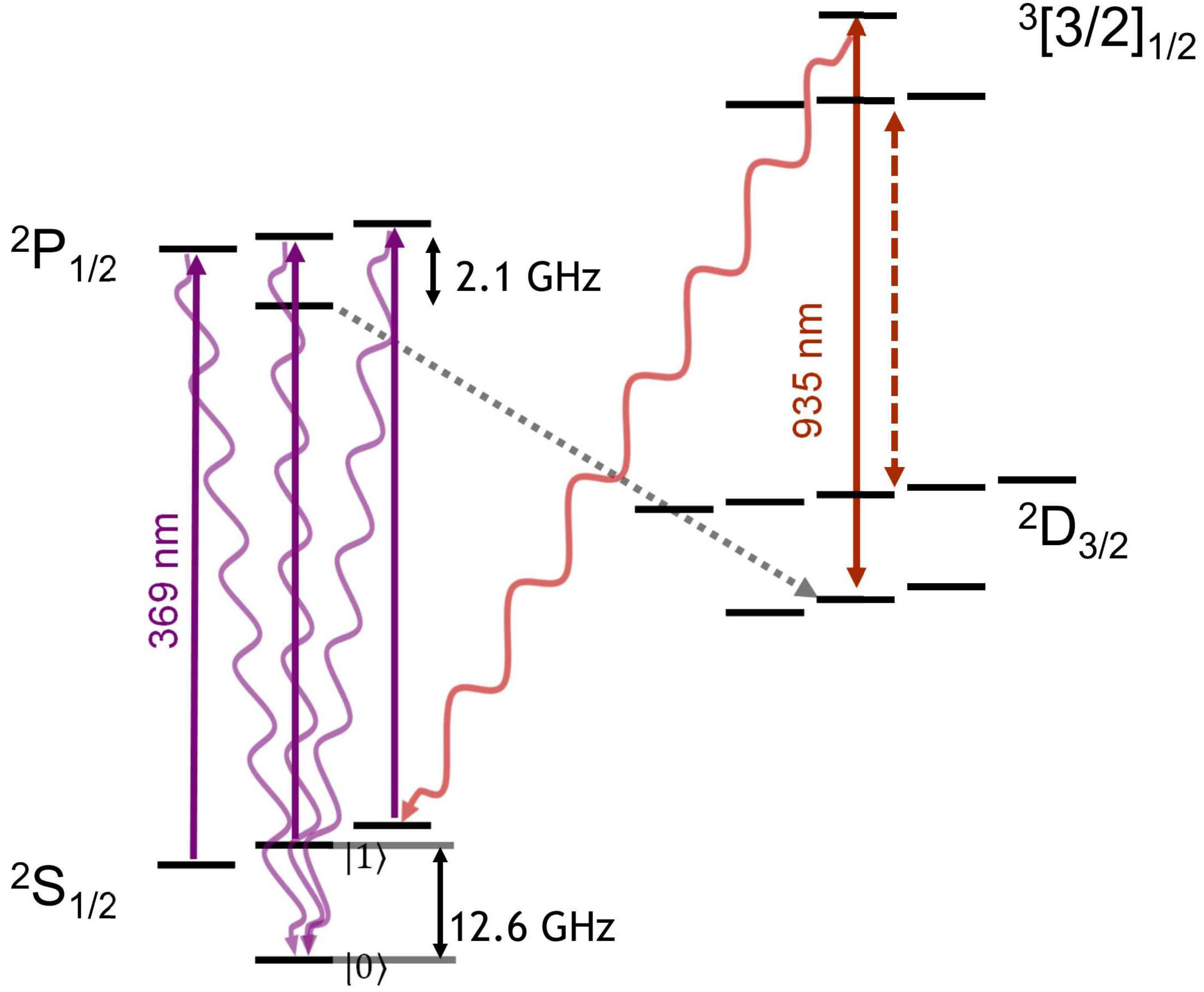
The Ytterbium Qubit – Cooling



- Clock state qubit
- Magnetic field insensitive.

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

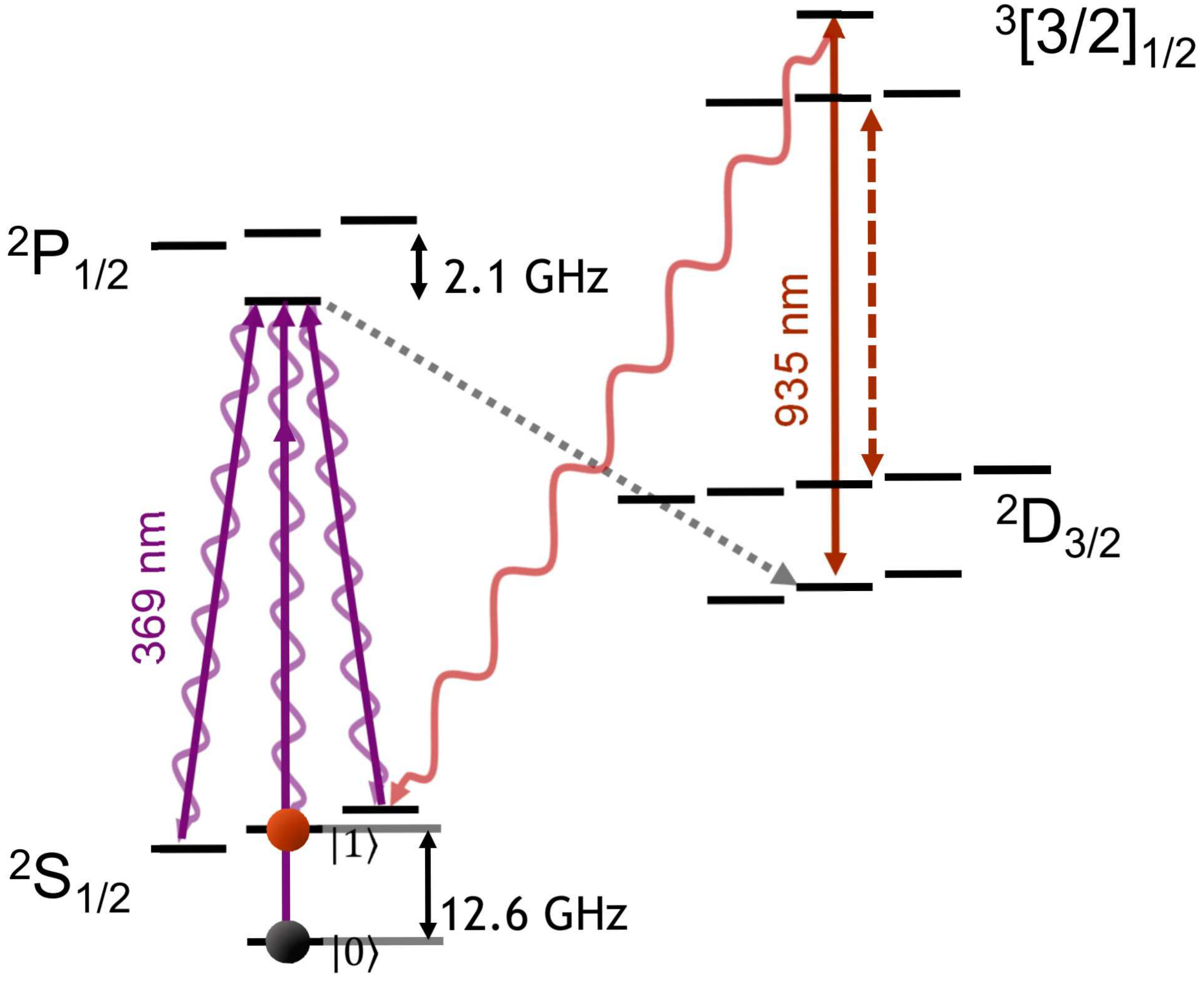
The Ytterbium Qubit – State Initialization

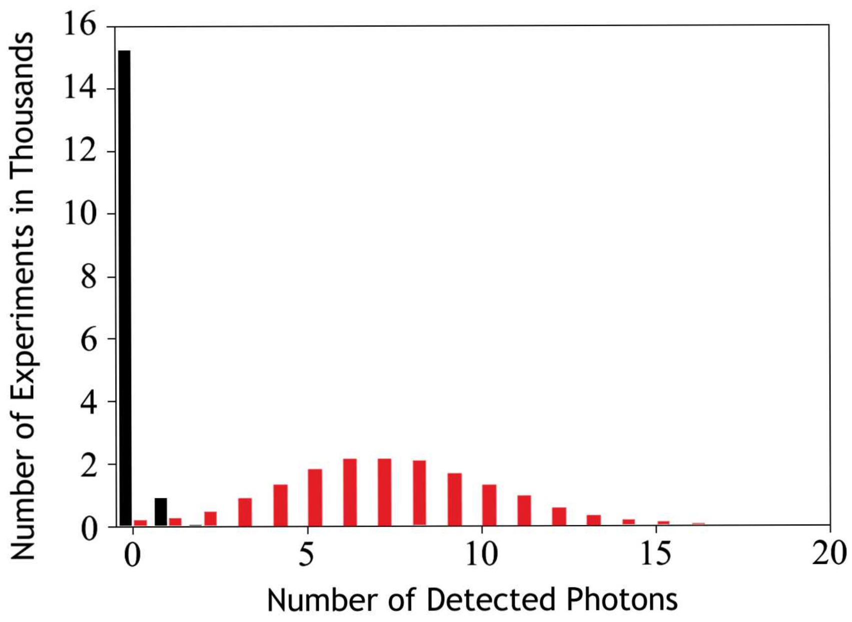


- Clock state qubit
- Magnetic field insensitive.

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

$^{171}Yb^+$ State Detection



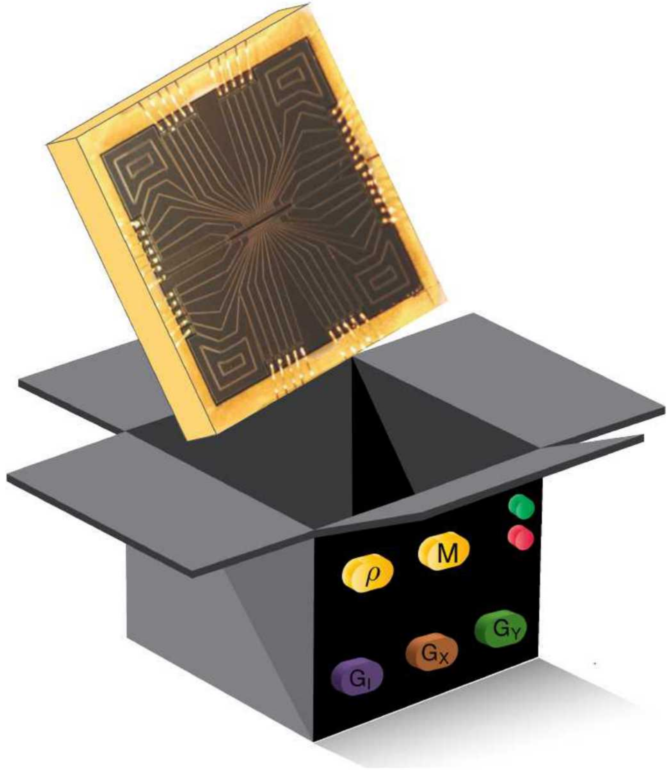


S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

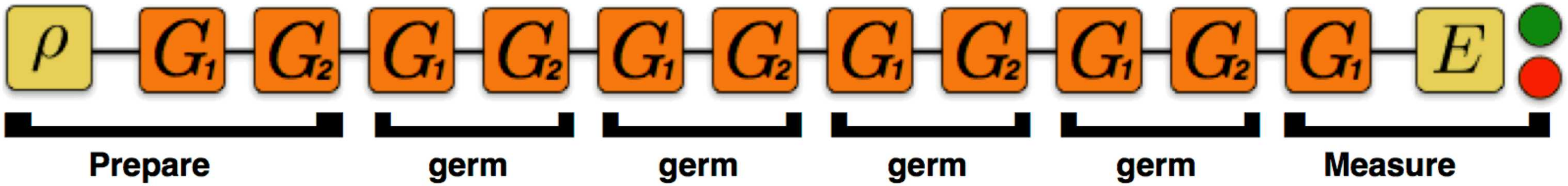
Gate Set Tomography (GST)

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

Advantages
- 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

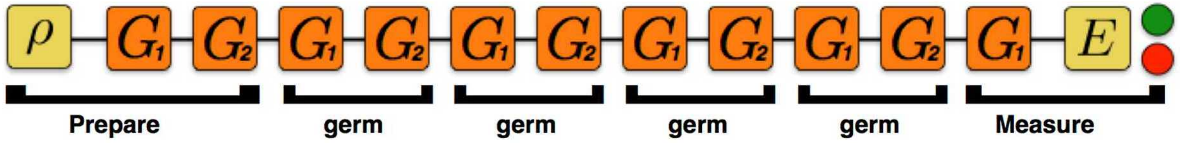


Developed at Sandia by QCVV team



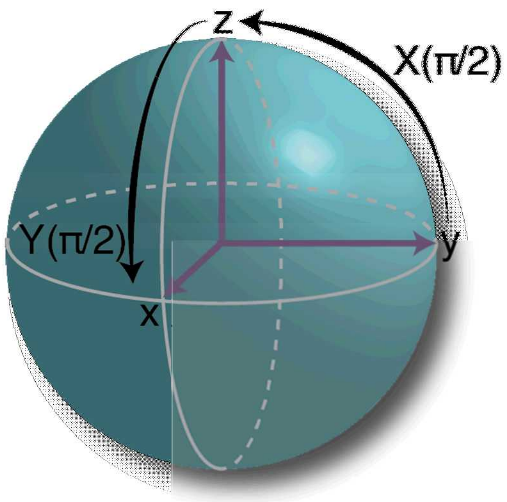
GST sequences

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



Approximately prepare 6 points on Bloch sphere

Fiducials

$\{\}$

Gx

Gy

$Gx \cdot Gx$

$Gx \cdot Gx \cdot Gx$

$Gy \cdot Gy \cdot Gy$

G

Gx

Gy

Gi

$Gx \cdot Gy$

$Gx \cdot Gy \cdot Gi$

$Gx \cdot Gi \cdot Gy$

$Gx \cdot Gi \cdot Gi$

$Gy \cdot Gi \cdot Gi$

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

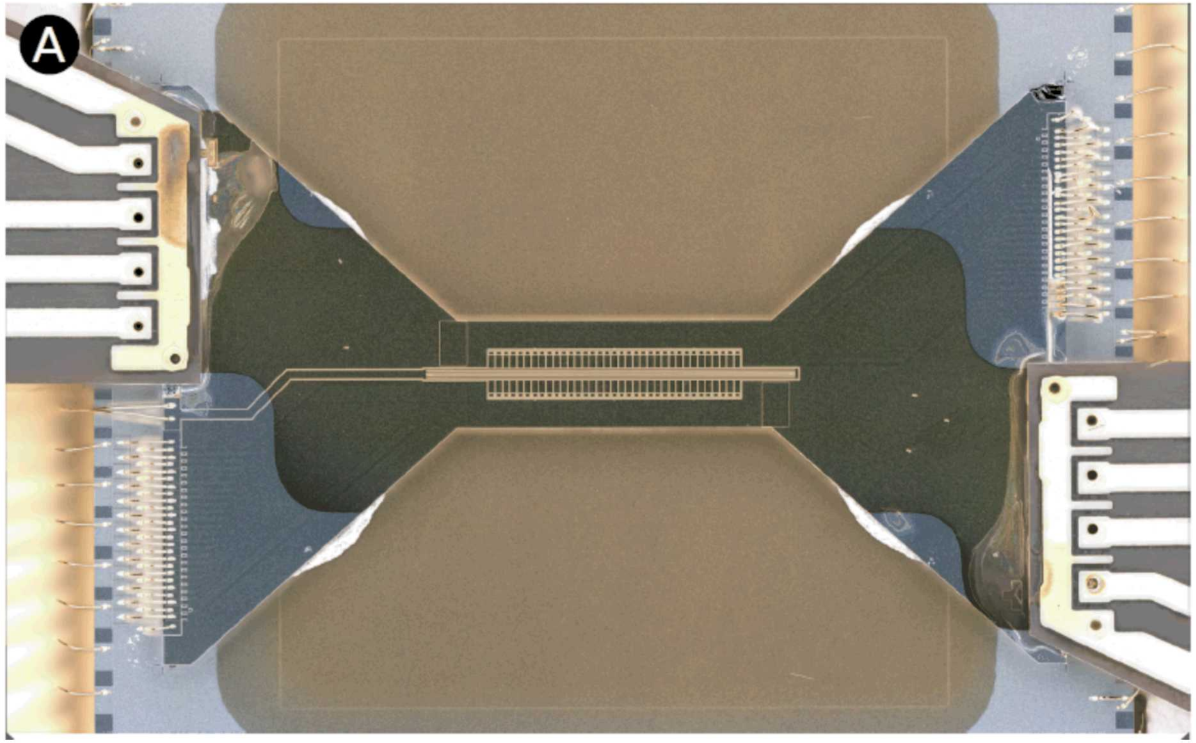
$Gx \cdot Gy \cdot Gy \cdot Gi$

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

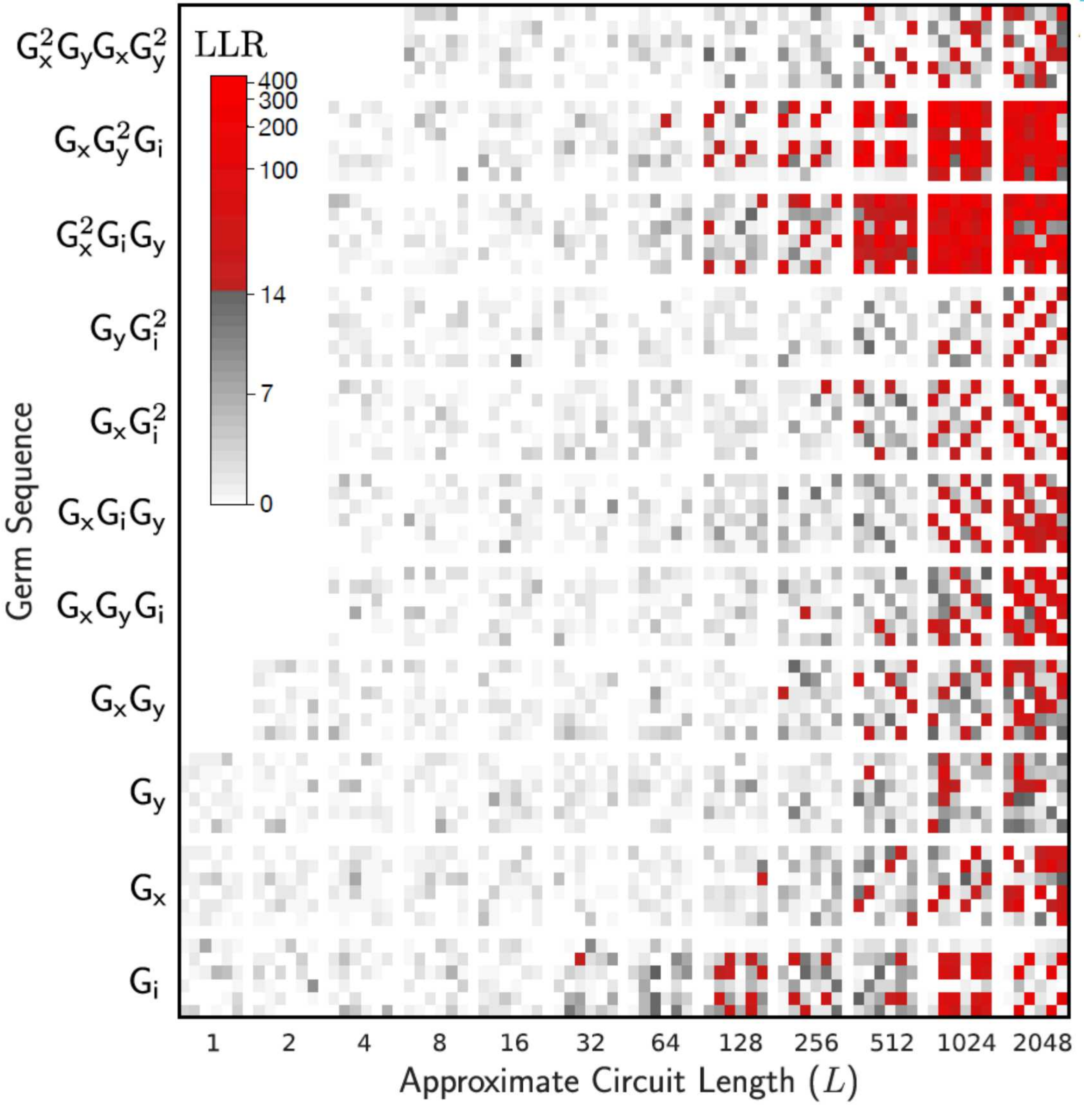
Challenge: Model violation in GST

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%

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

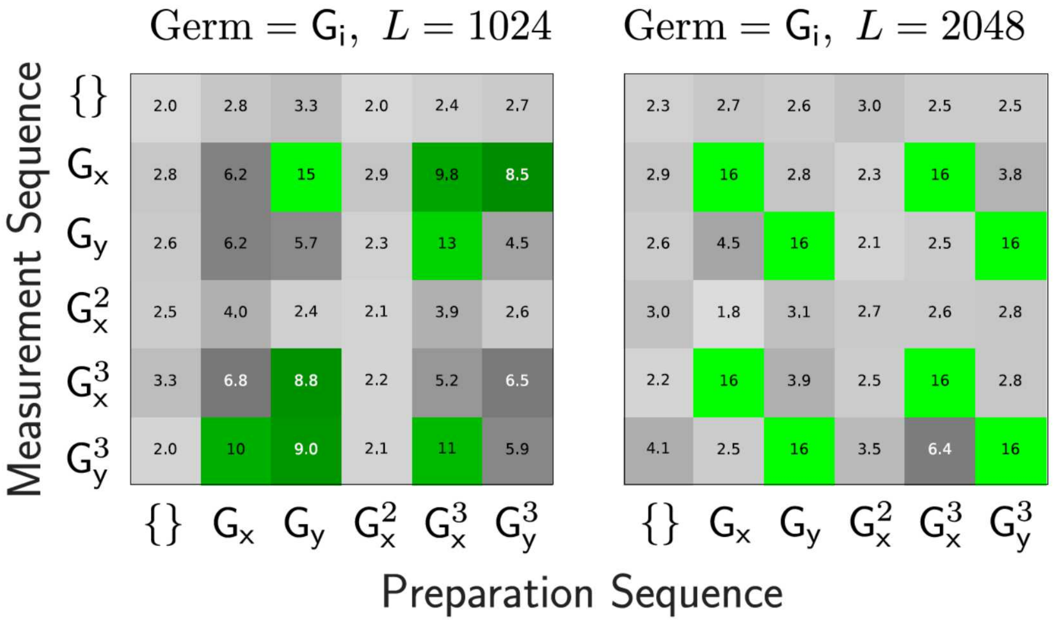
95% confidence intervals

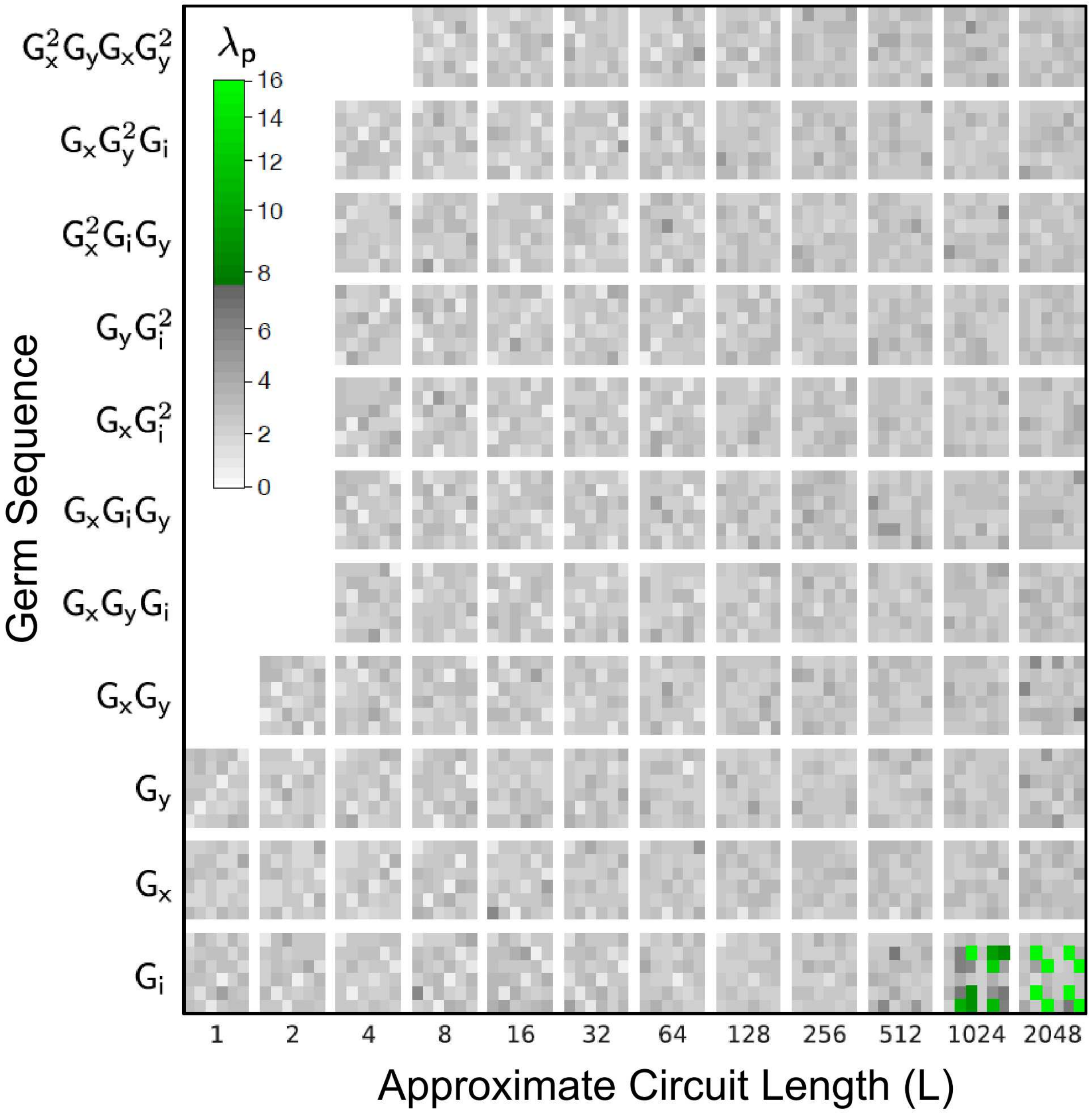
Gate	Process Infidelity	$1/2$ ◇-Norm
G_I	$6.9(6) \times 10^{-5}$	$7.9(7) \times 10^{-5}$
G_X	$6.1(7) \times 10^{-5}$	$7.0(15) \times 10^{-5}$
G_Y	$7.2(7) \times 10^{-5}$	$8.1(15) \times 10^{-5}$

All gates are better than the fault tolerance threshold of
P. Aliferis and A. W. Cross, Phys. Rev. Lett. 98, 220502 (2007).

Drift?

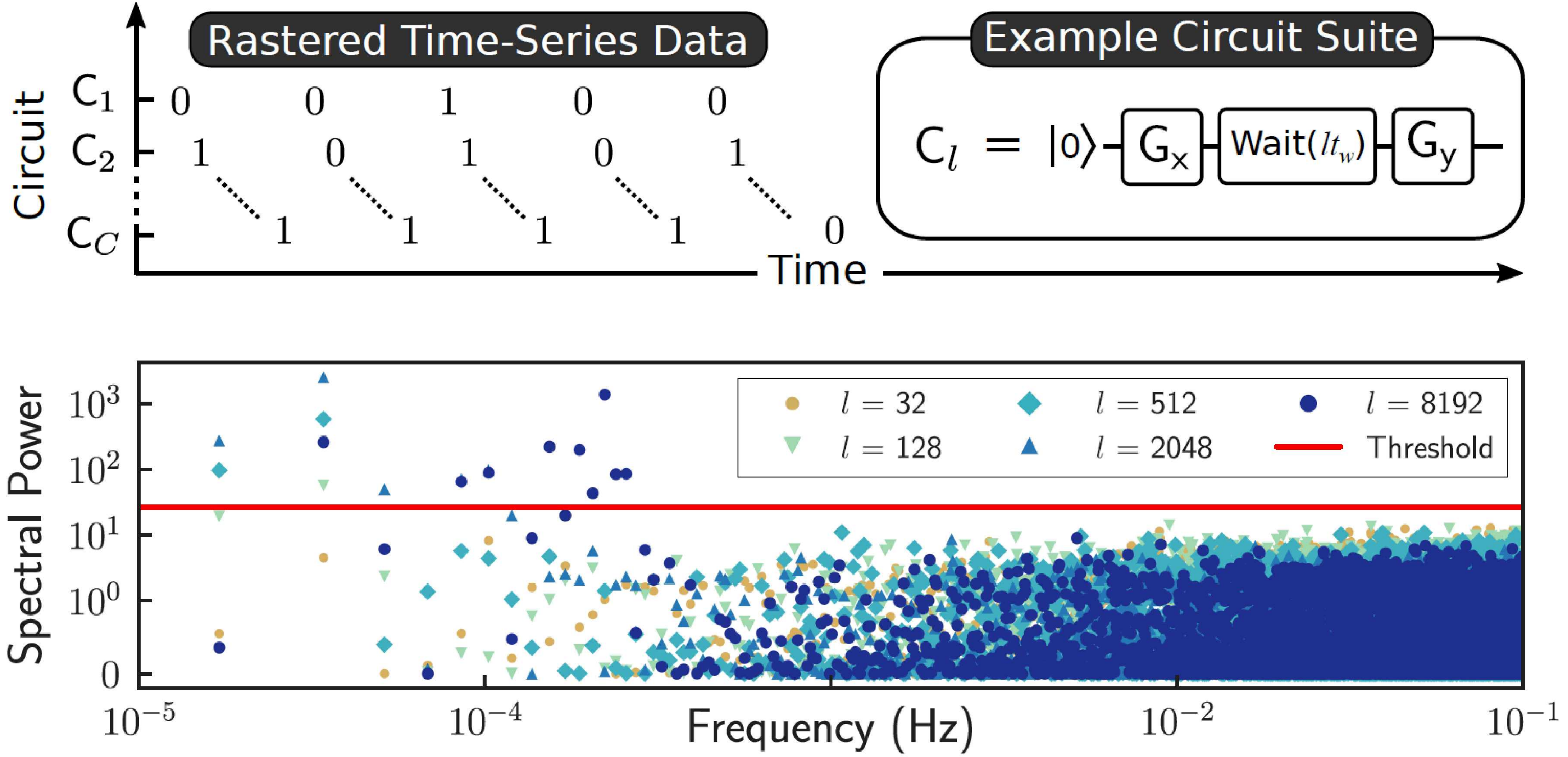
- Time-resolved GST characterization
- Ramsey experiments show significant drift
- These sequences are candidates for further investigation





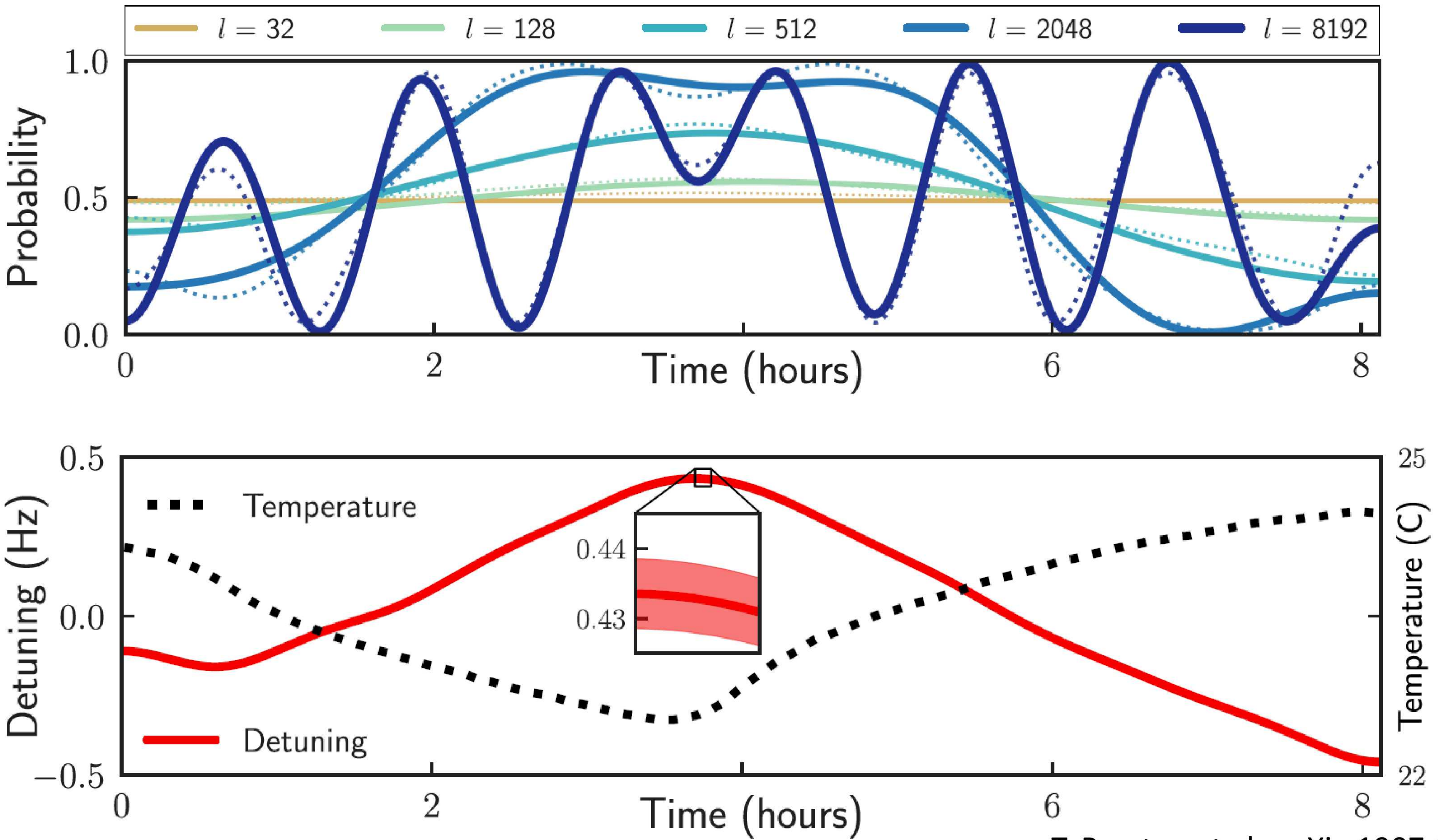
$\lambda_p = -\log_{10}(p)$ where p is the p-value of the largest power in the spectrum for that circuit

Can we measure the drift?



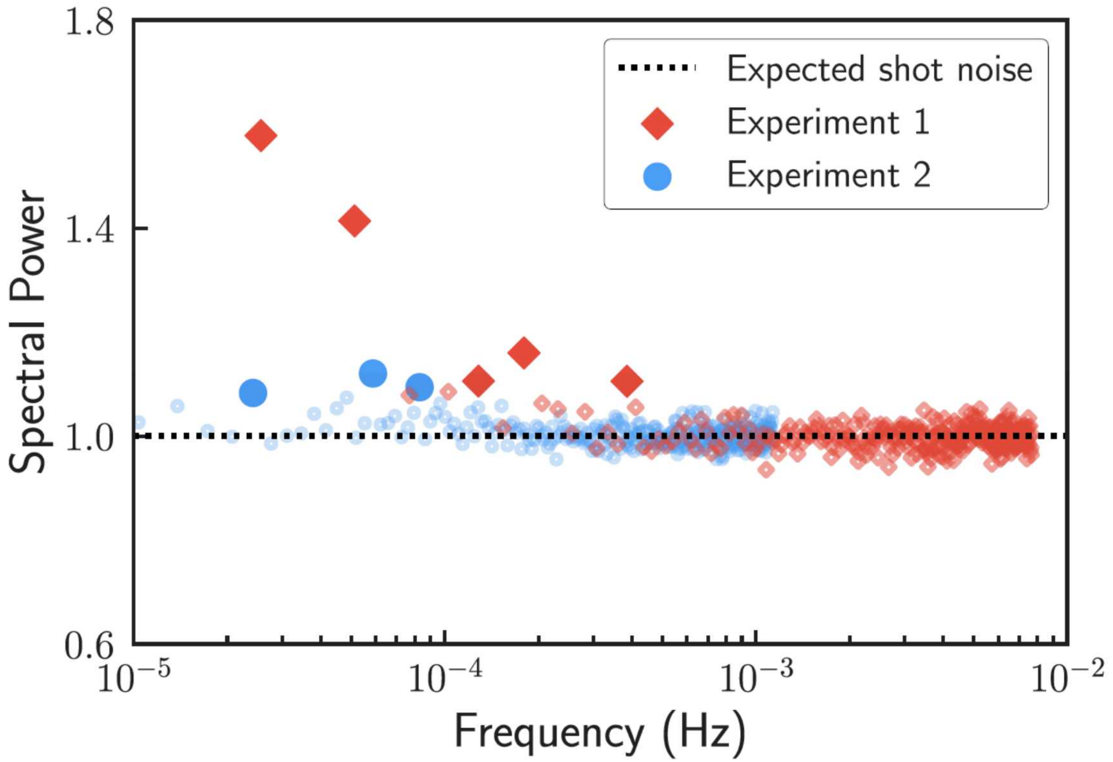
T. Proctor, et al., arXiv:1907.13608 (2019).

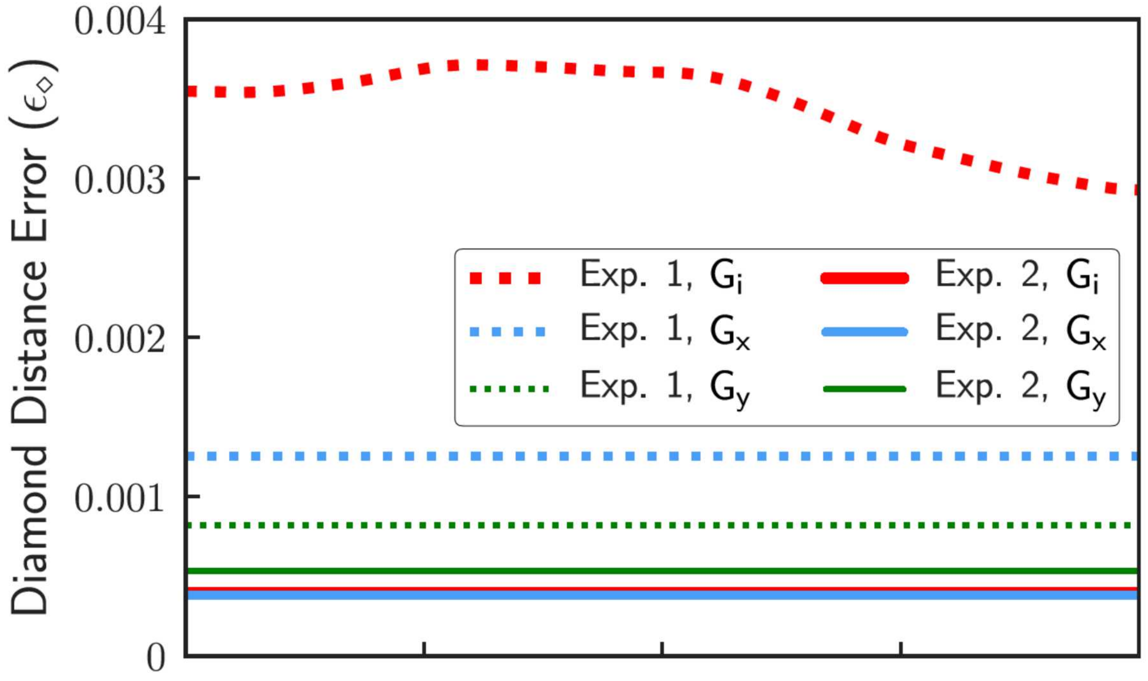
Can the drifting parameter be reconstructed?



T. Proctor, et al., arXiv:1907.13608 (2019).

Experimental Improvements





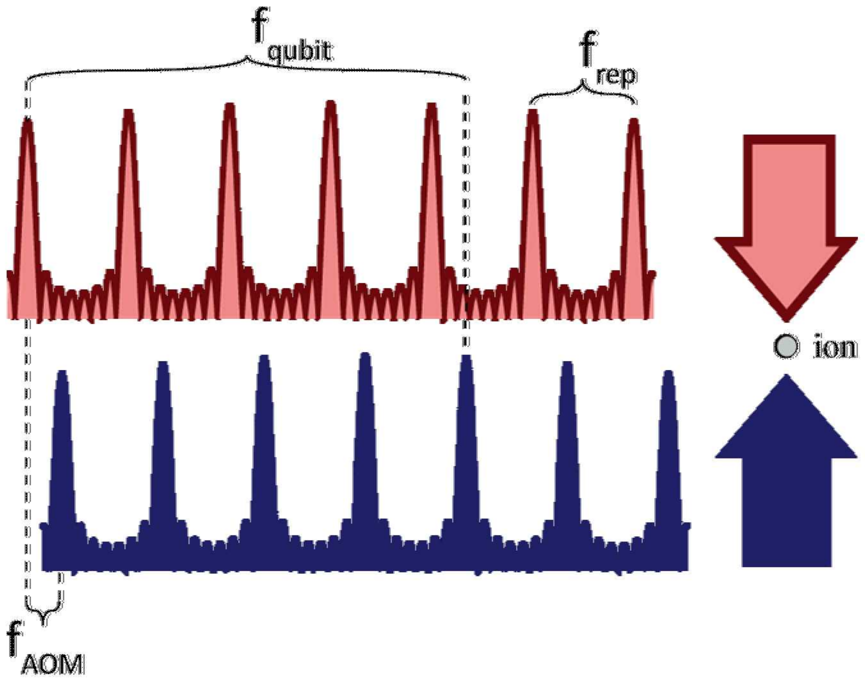
- Spectral power averaged over all sequences
- Small residual drift, cannot be assigned to specific sequences
- Reconstruction of individual sequences is below statistical significance

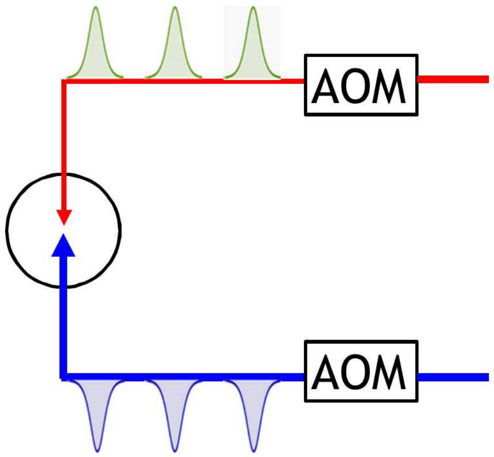
<u>Improvements:</u>

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

T. Proctor, et al., arXiv:1907.13608 (2019).

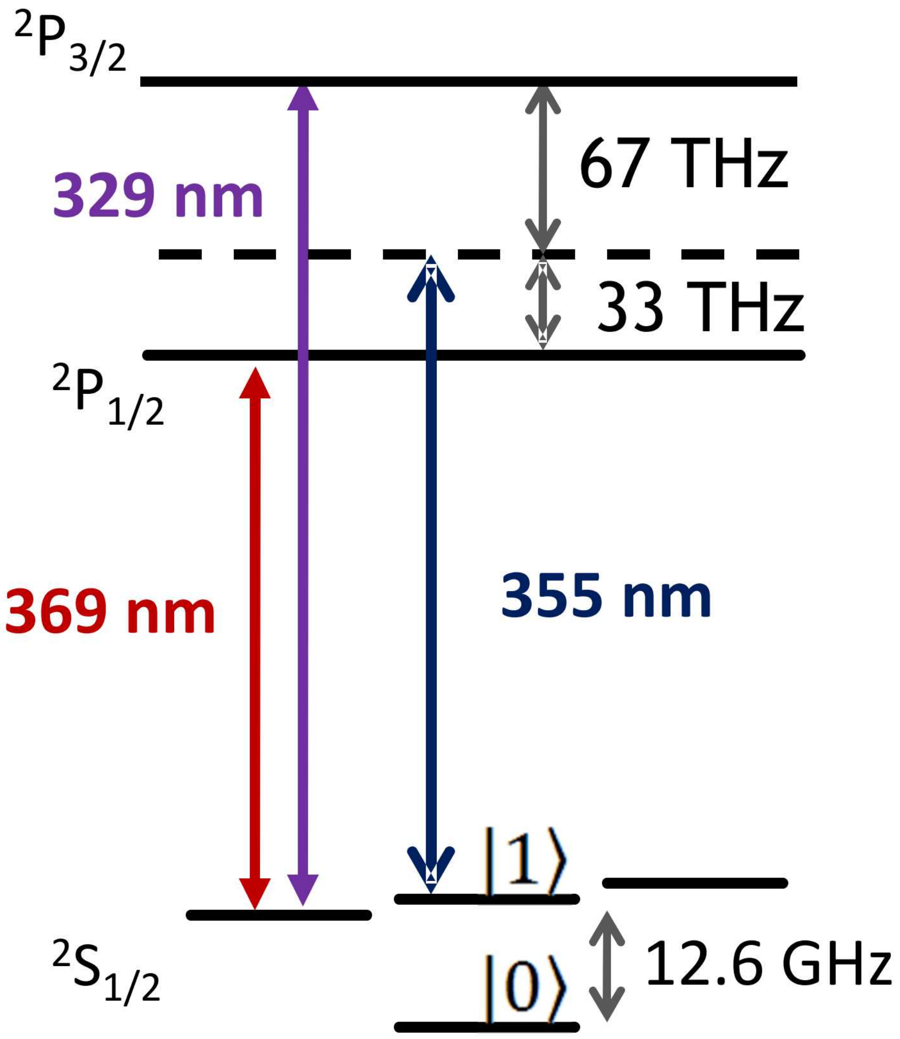
355 Raman Transitions: $^{171}Yb^+$





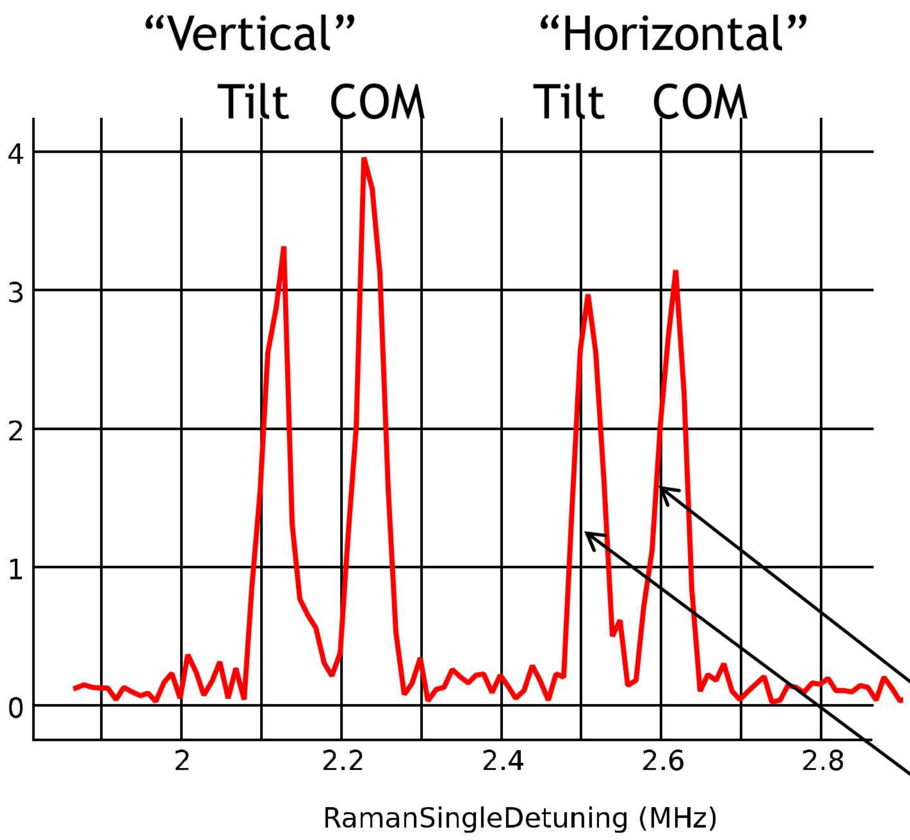
Requirement:

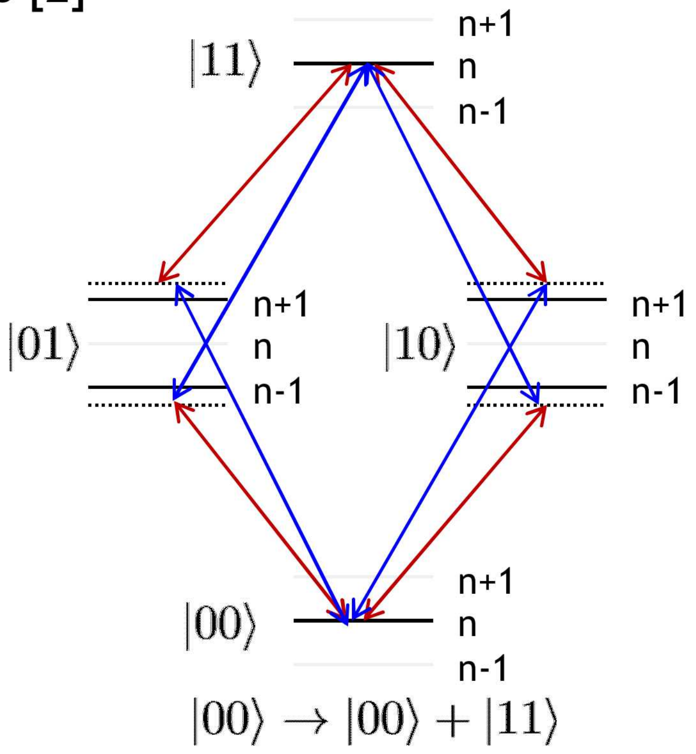
$$f_{qubit} = nf_{rep} \pm f_{AOM}$$



Two-Qubit Gate Implementation

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





Heating rates on HOA-2.0

$\approx 60\ \mathrm{quanta}/\mathrm{s}$

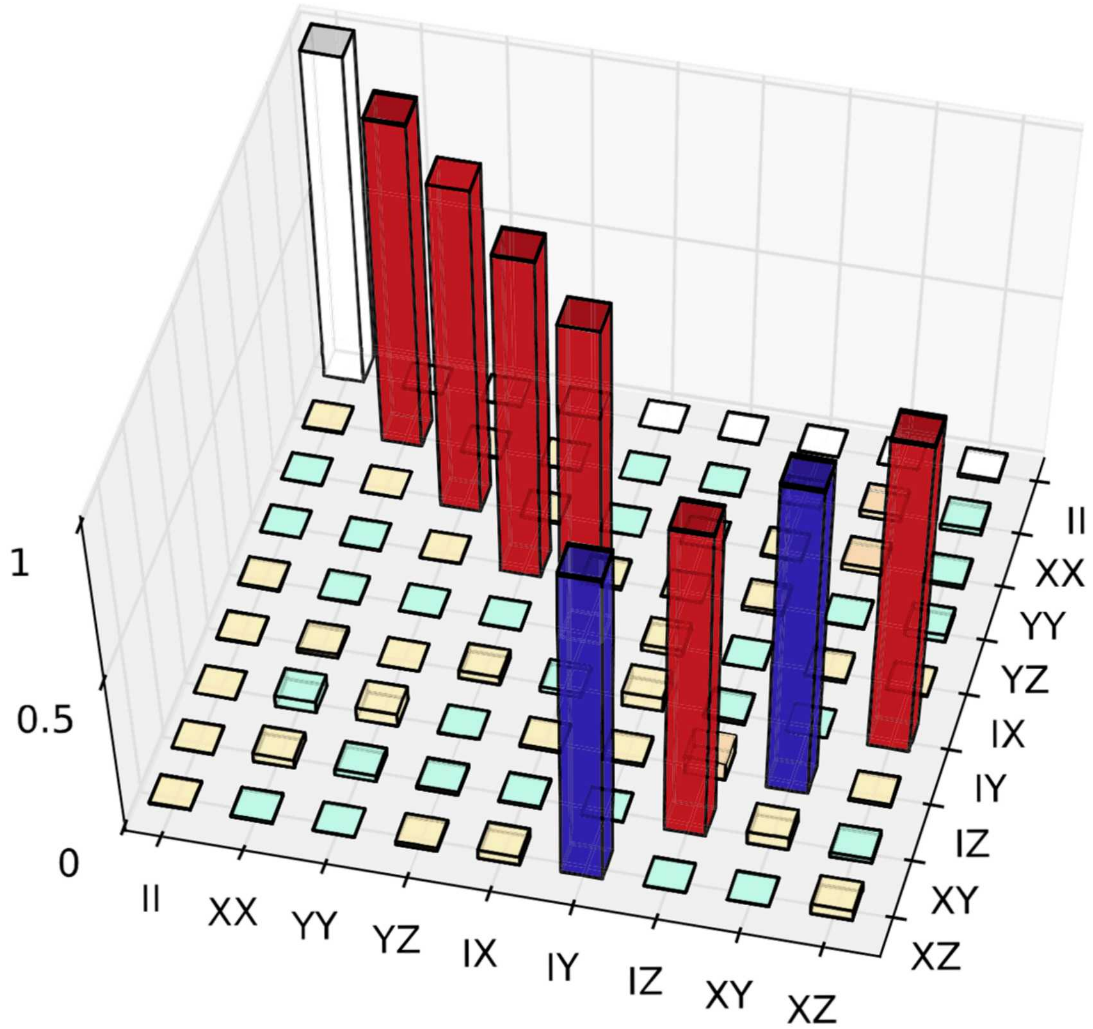
$< 8\ \mathrm{quanta}/\mathrm{s}$

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

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

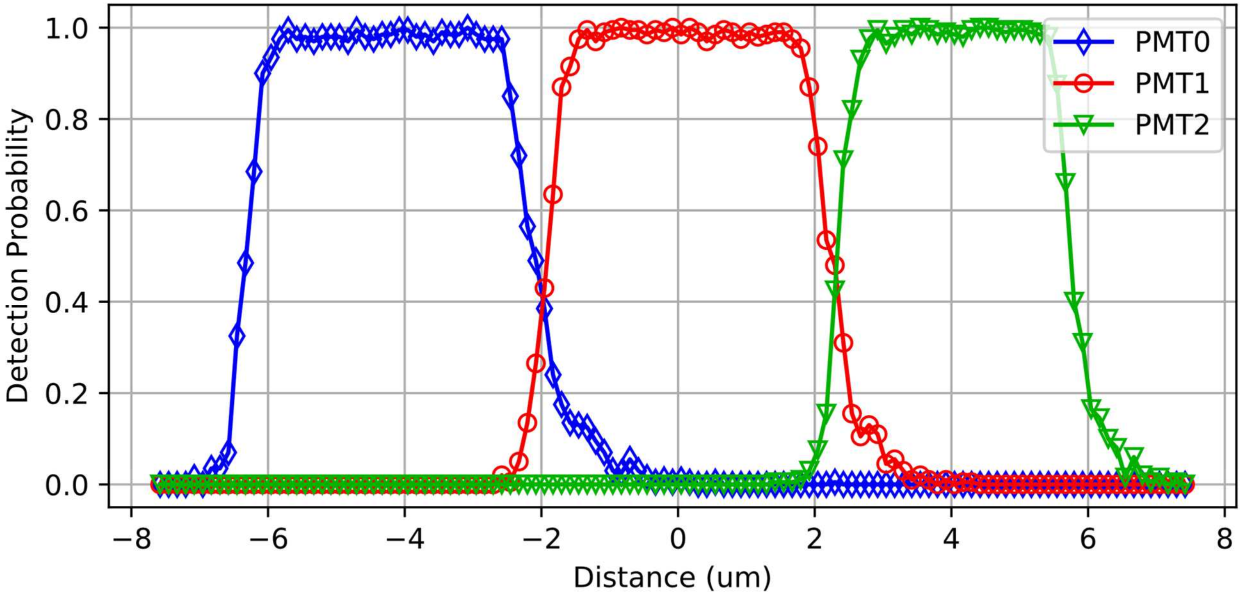


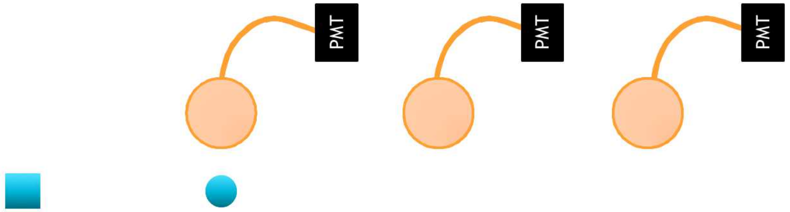
Process fidelity of two-qubit Mølmer-Sørensen gate > 99.5%

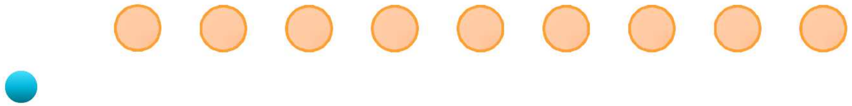
By the way: It’s in a scalable surface trap

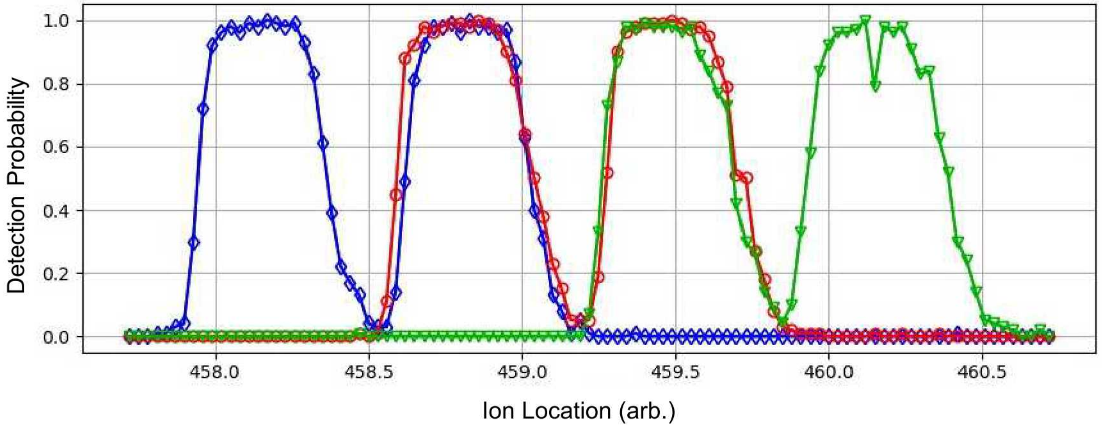
Distinguishable Detection

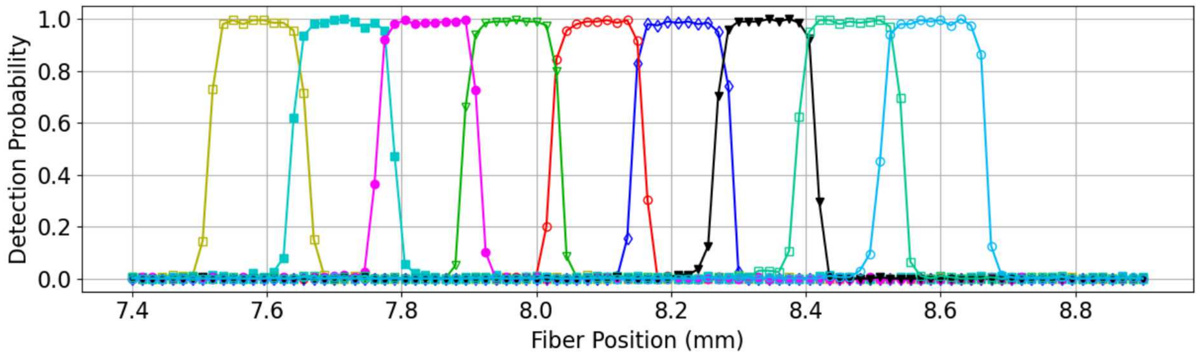
- Fiber array allows for individual detection of each ion with >90% throughput measured to the PMTs
- Measured <0.5% detection crosstalk (not maximized for specific chain performance)
- Scalable to longer chains, currently operating with up to 9 ions





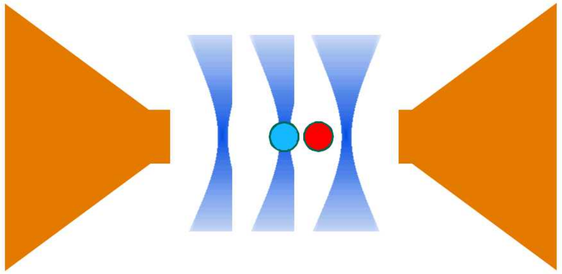


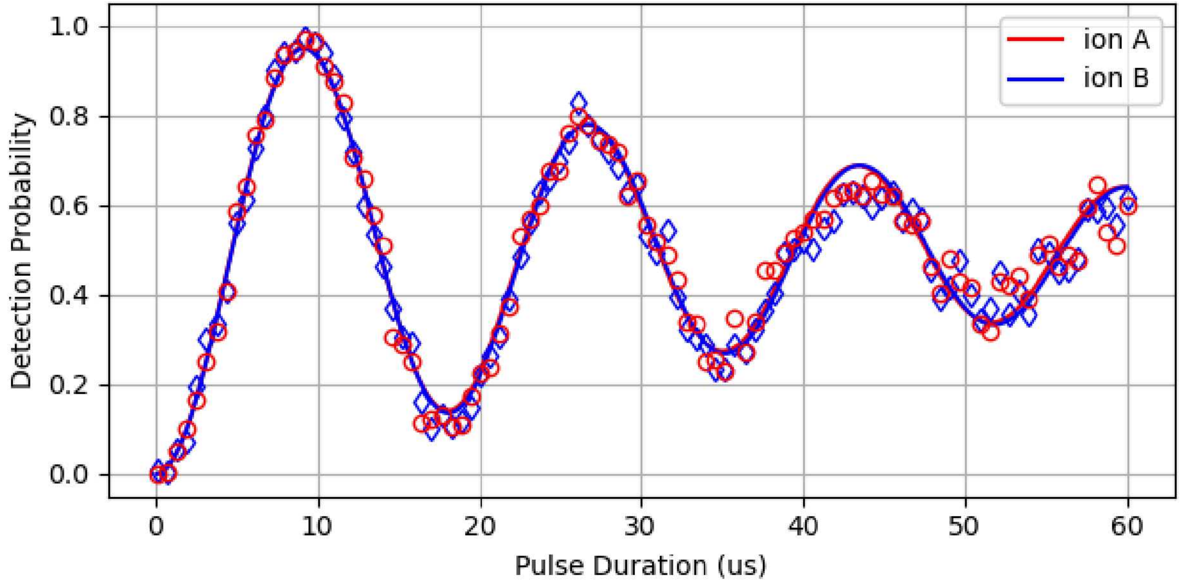


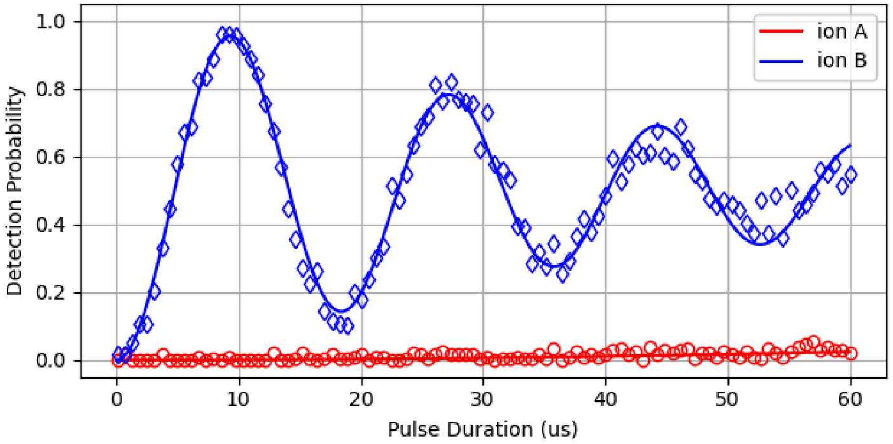


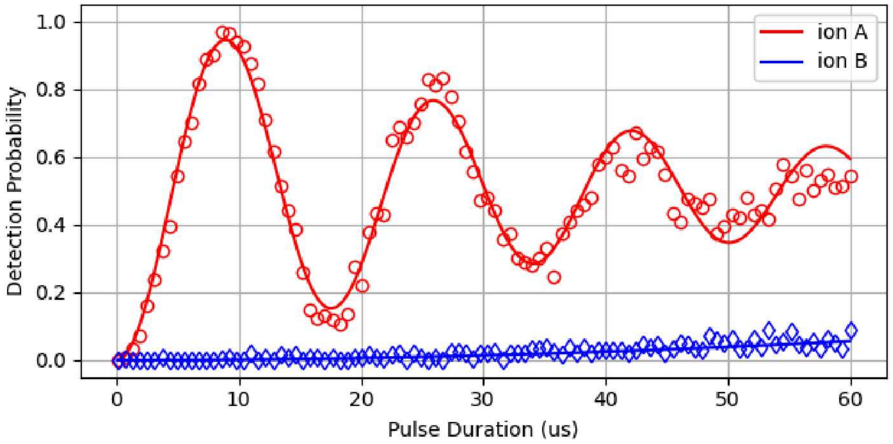
Individual Addressing

- Initial testing of single qubit gates on ions with neighboring channels
- Able to align ions to individual addressing beams and then align fiber to ions
- Tests performed without the crosstalk minimization protocols

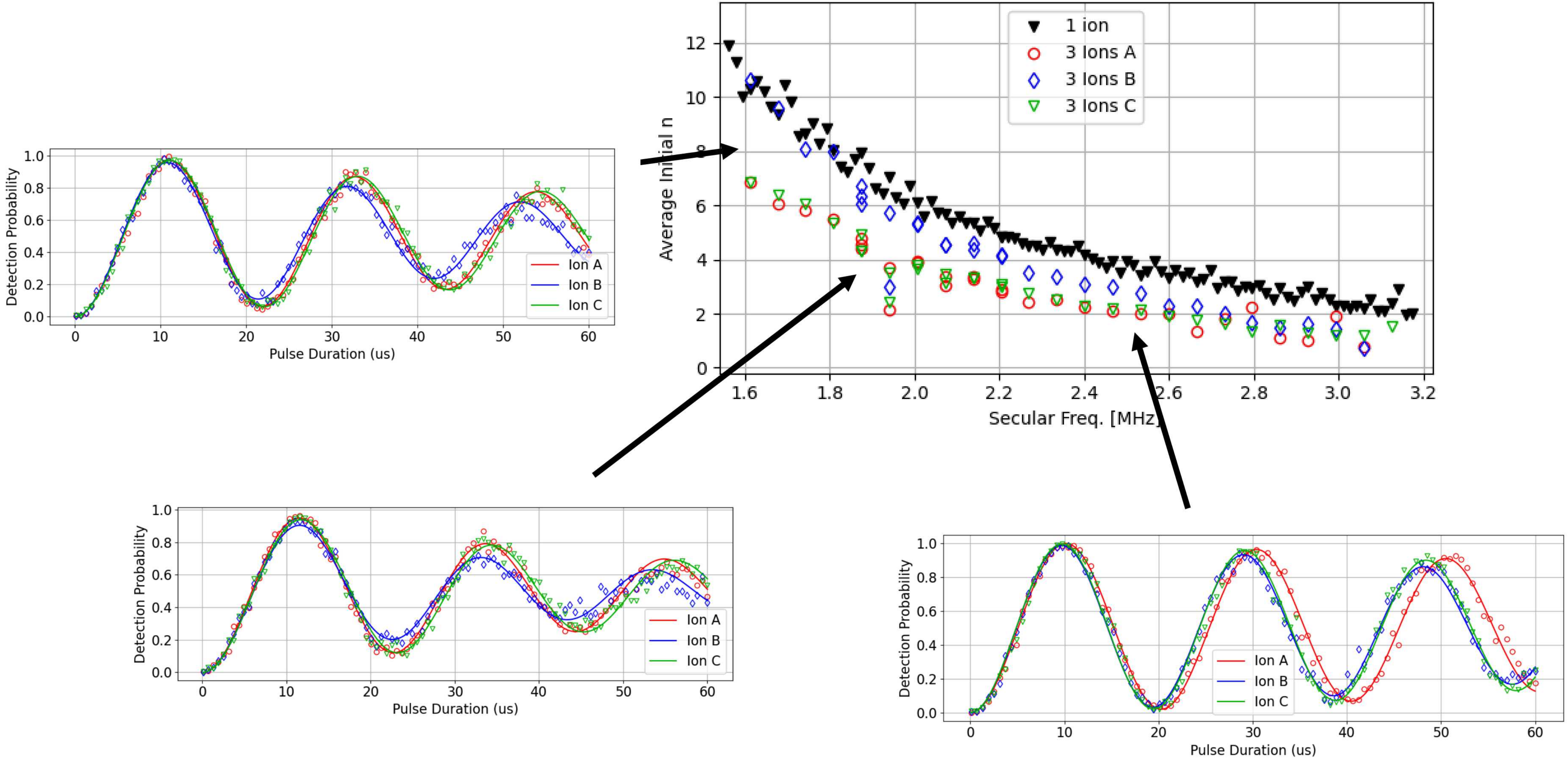




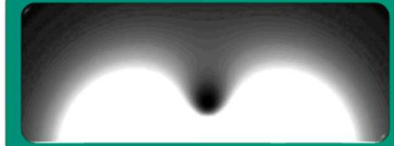


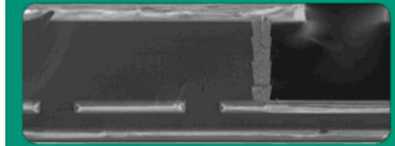


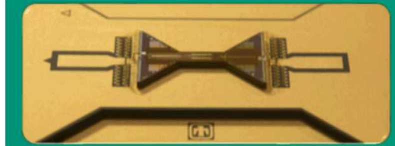
Chain Temperature Measurements

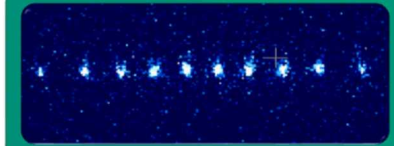


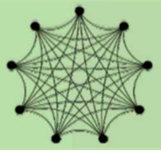
Outline


Ion trapping

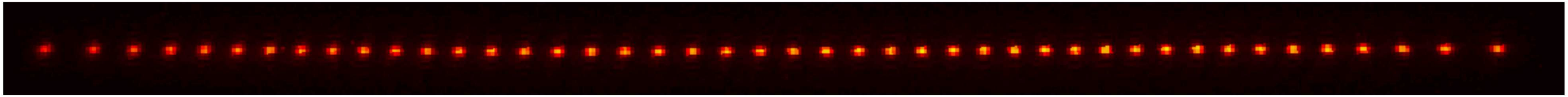

Trap Fabrication


The Phoenix/Peregrine Trap


Recent Results


QSCOUT

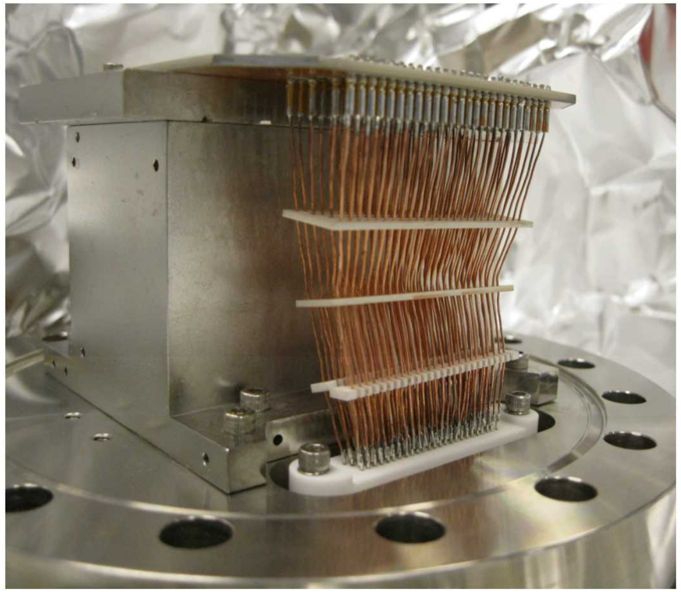
QSCOUT DOE Quantum Testbed Laboratory



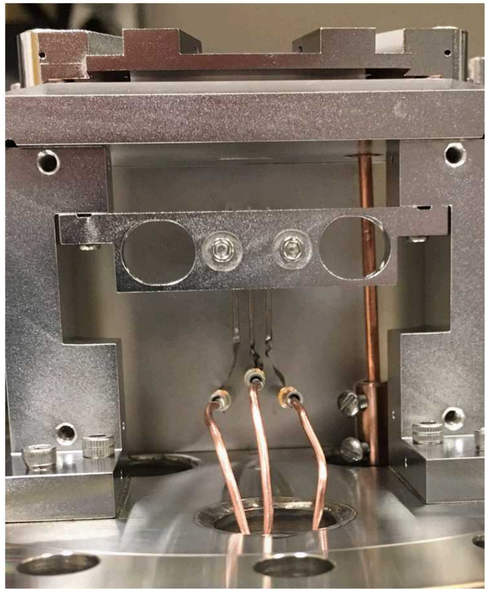
Testbed systems designed for open access to support scientific applications

- High-fidelity operations $\#gates \propto (\#qubits)^2$
- Distinguishable detection
- Individual addressing for qubit operations
- 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

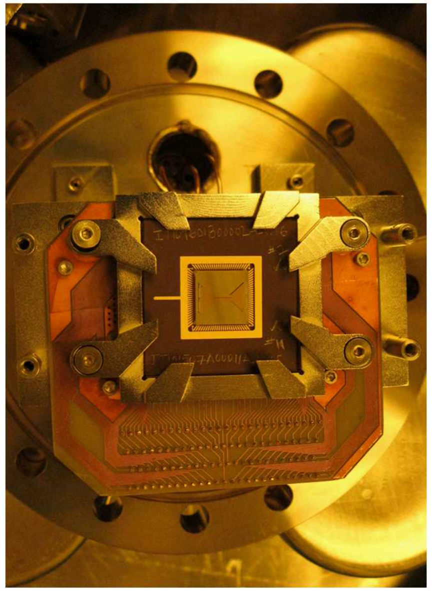
QSCOUT: Vacuum System Engineering



Bare copper wires with Al_2O_3 spacers



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



Trap installed for final bake

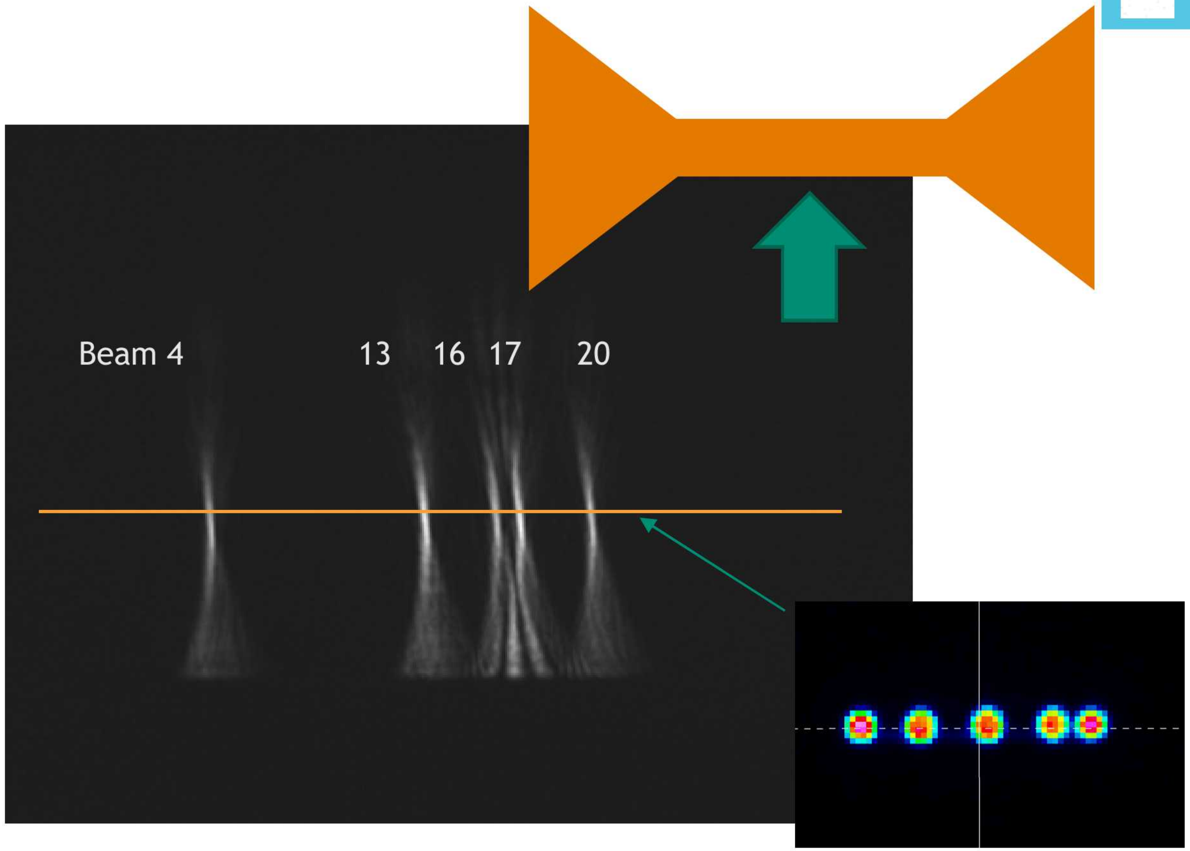
Trap platform in chamber, both re-entrants visible

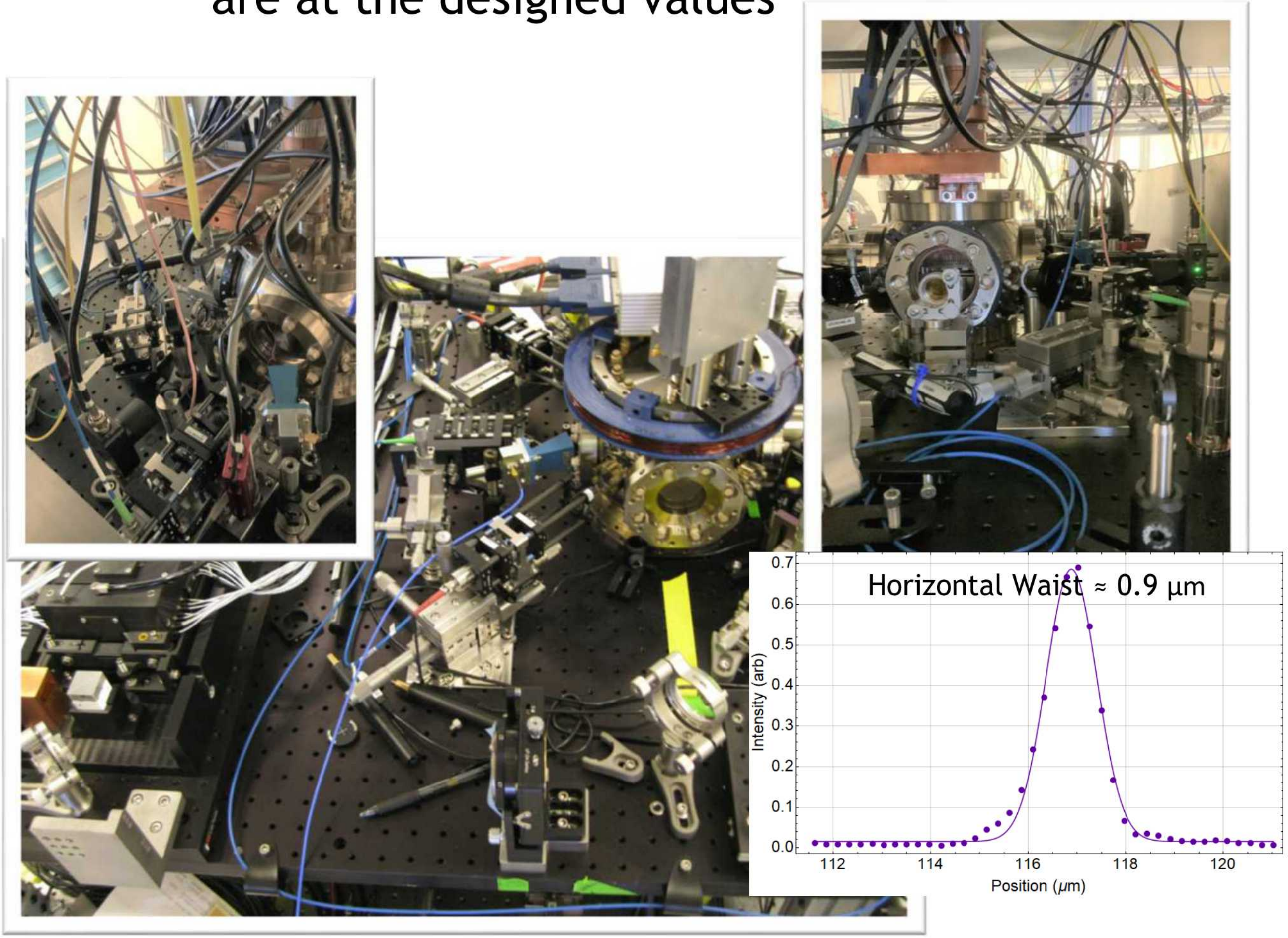
Features (hydrogen and organic mitigation):

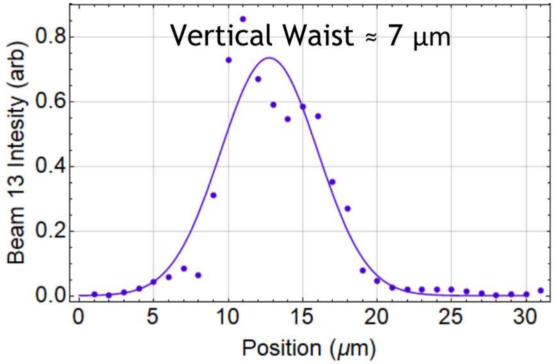
- 316L stainless steel subjected to high-temp bake process for UHV performance
- Ceramics: MACOR fuzz button spacer & Micro-D, AlN -> Al_2O_3 circuit board, Al_2O_3 wire spacers
    - Changing circuit board to Al_2O_3 allows for direct soldering of wires to board
- Bare copper wires for RF and DC voltages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

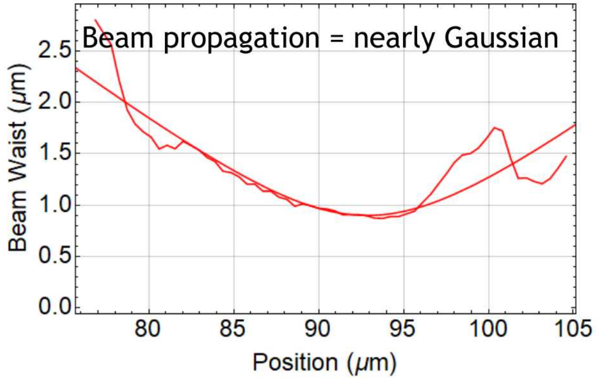
Multichannel AOM imaging

- Reimaging of the Harris 32 channel AOM
- Adjacent beams are clearly separated, and about **4.5 µm apart**
- The beam waists, horizontal and vertical, are at the designed values

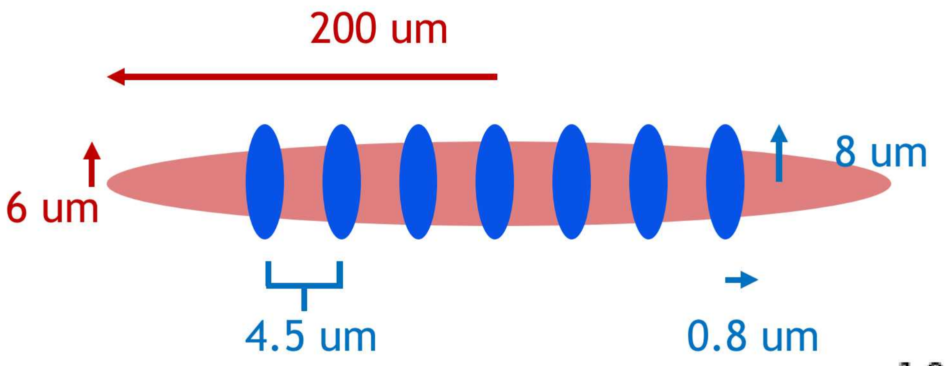


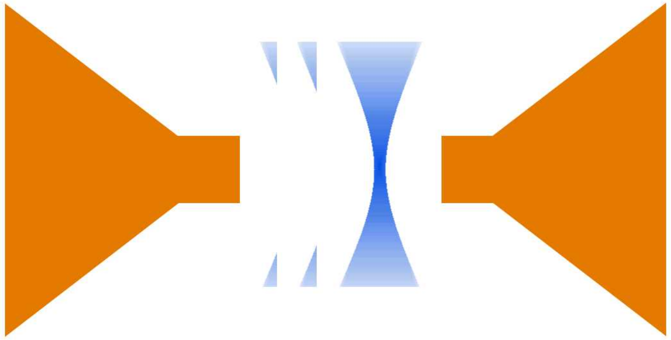


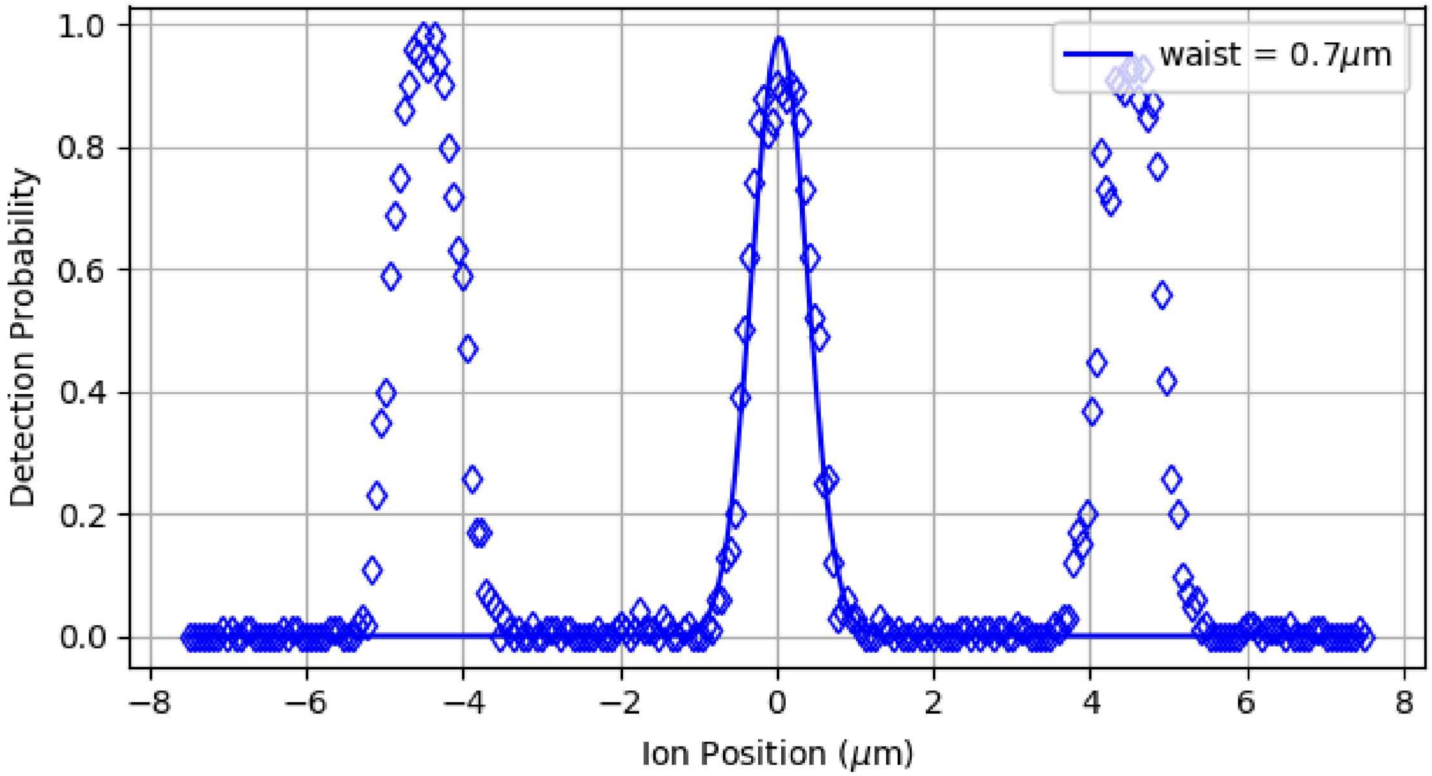




Individual Addressing of Ions

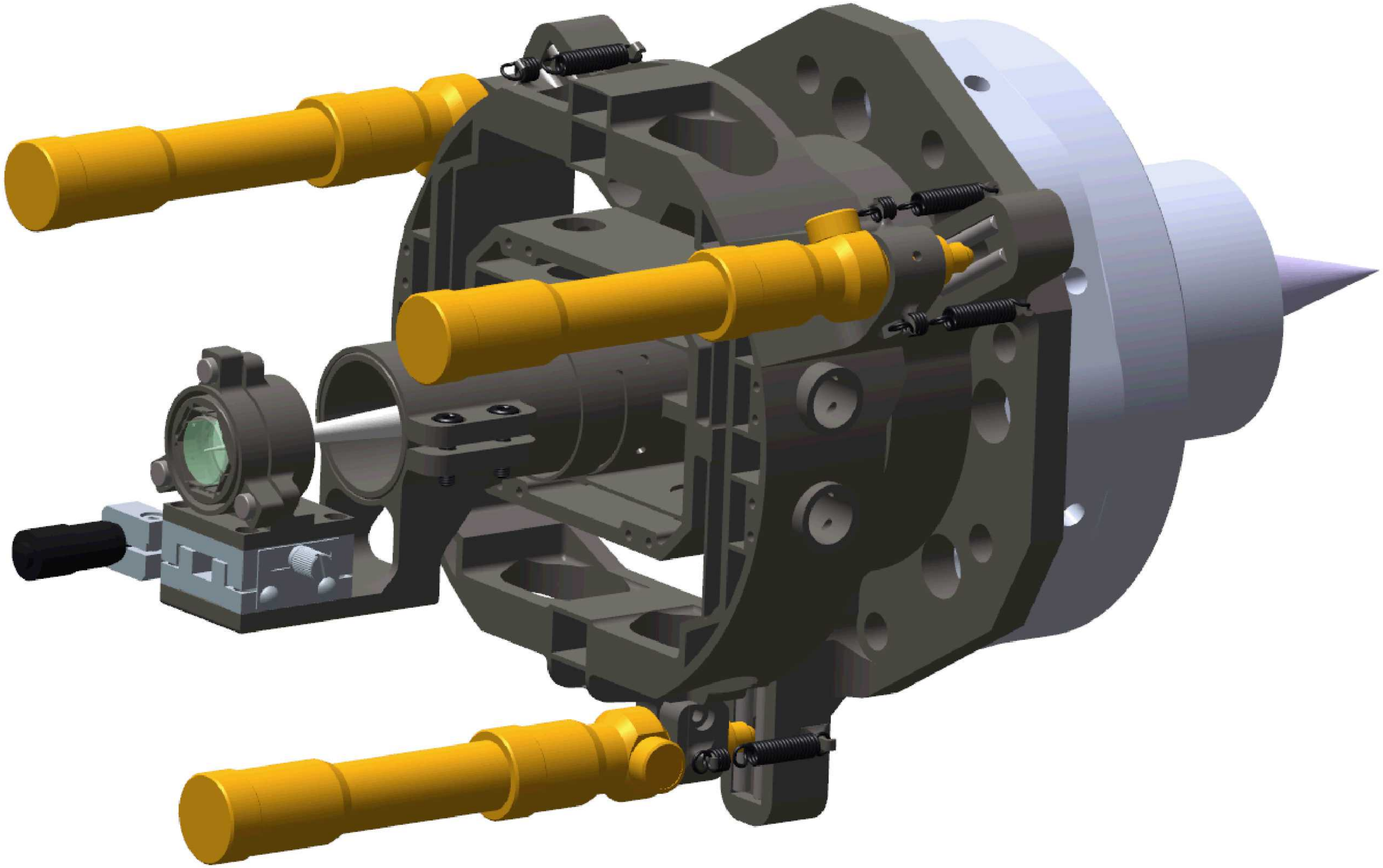


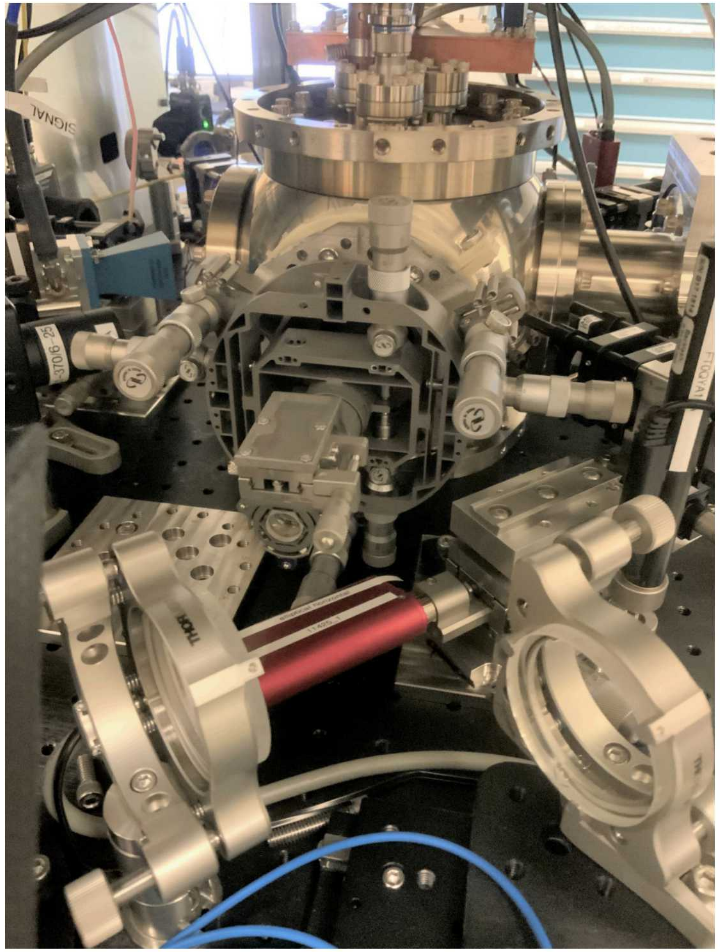




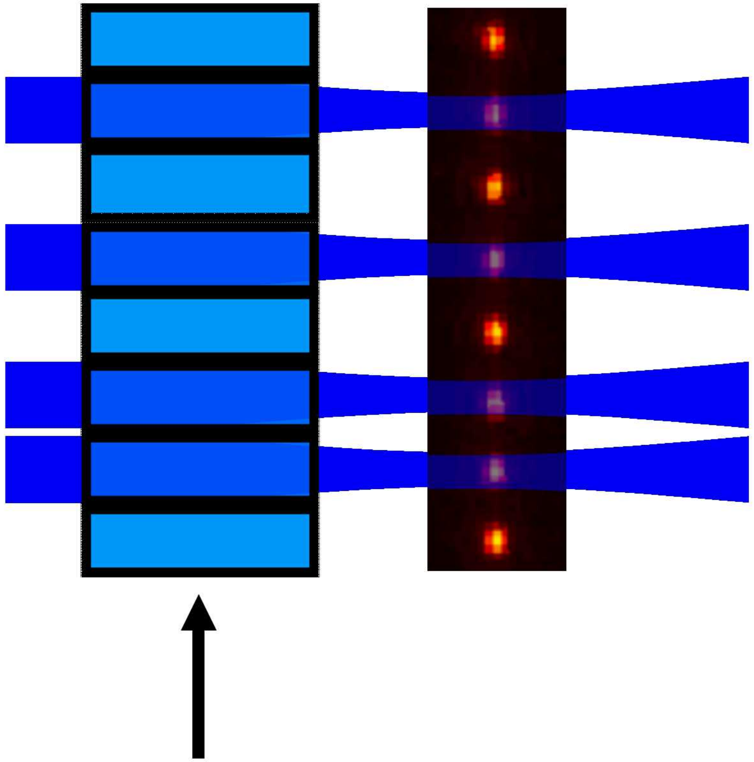
- Distinct Raman beams individually address ions
  - Adjacent beams ~4.5 μm separation
  - Elliptical beam waists match closely to design
  - Global Raman beam to allow for co- and counter-propagating gates

Individual Addressing Relay Subassembly

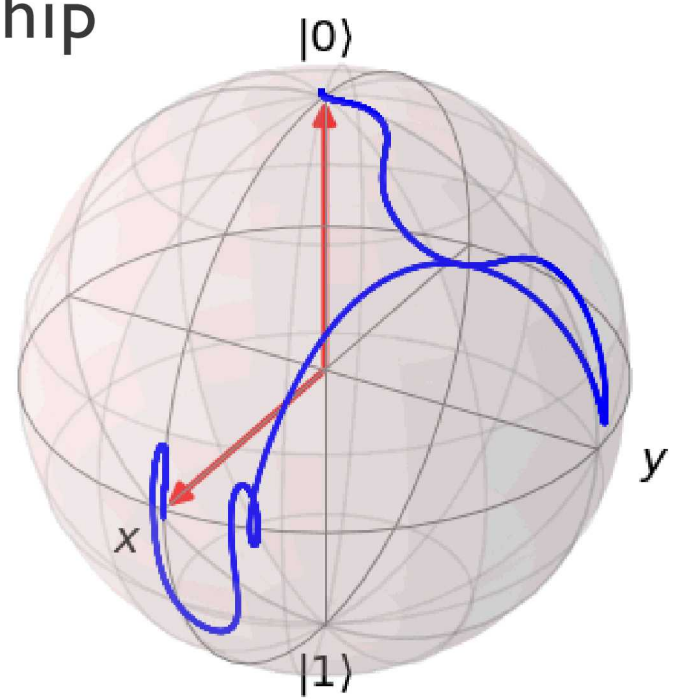


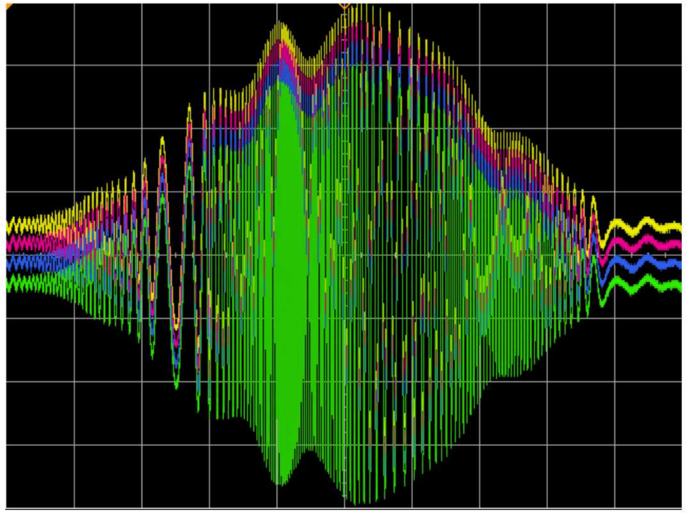


RFSoC - Radio-Frequency System on a Chip



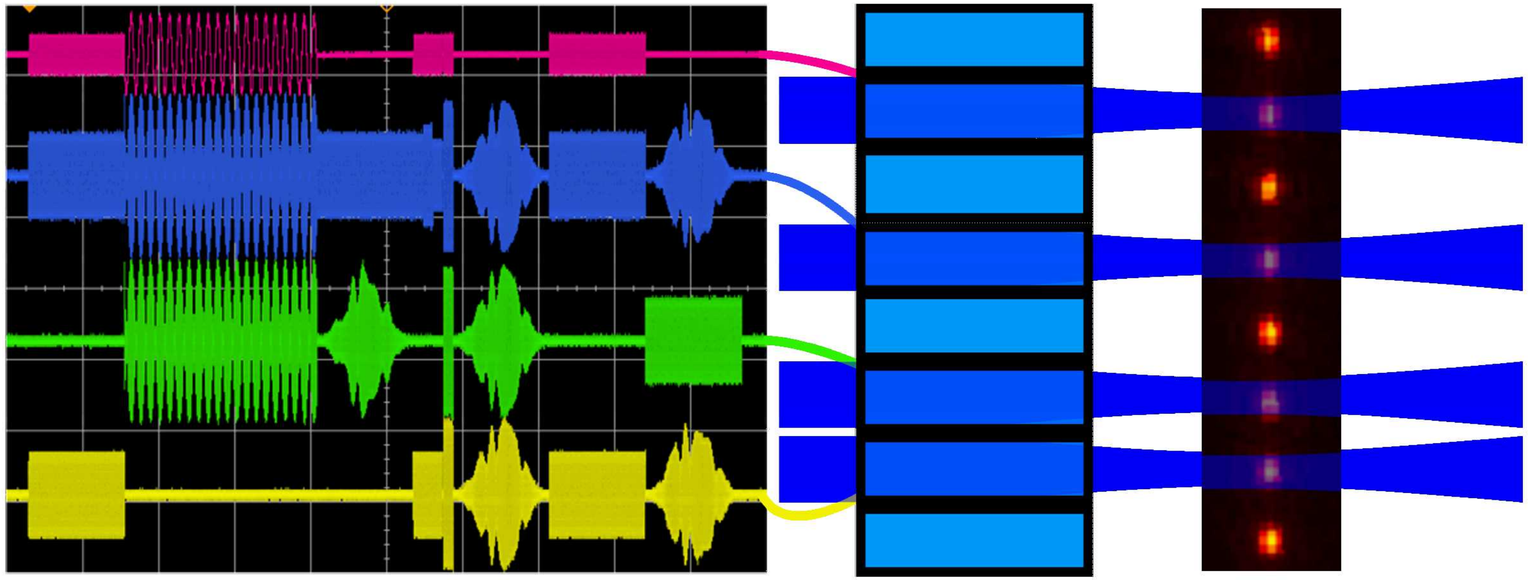
Acousto-Optic Modulators





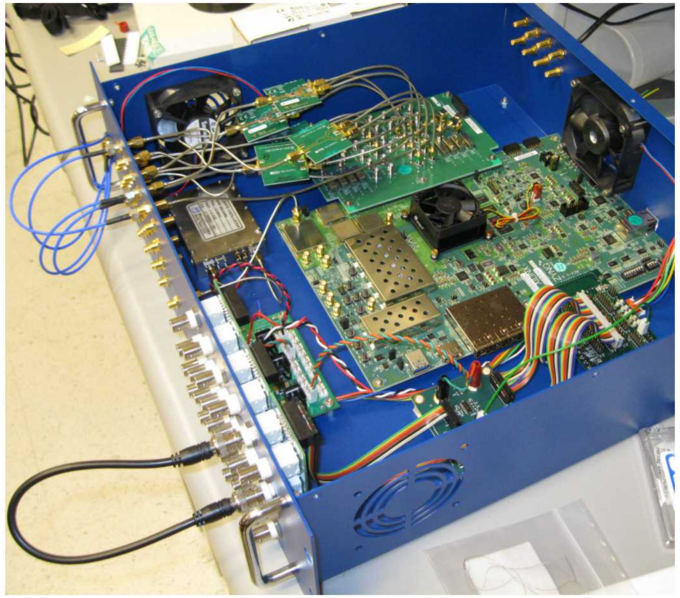
RFSoC

Acousto-Optic Modulators



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

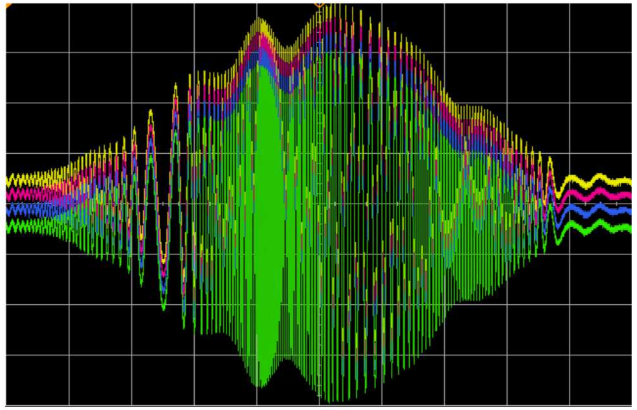


Compact gate scheduling with Jaqal
"Just another quantum assembly language"

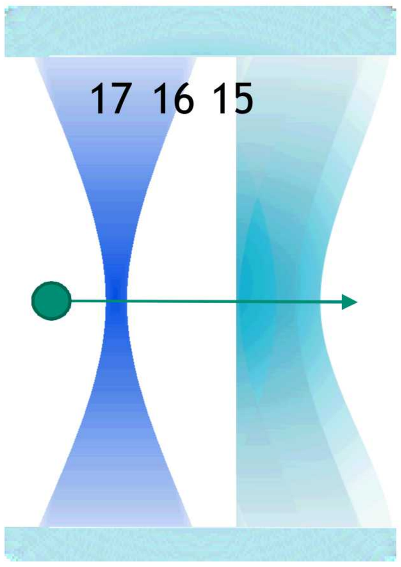
```
from PulseDefinitions.CustomPulses usepulses *

register q[8]

< Gmod q[1] | Gmod q[2] | Gmod q[3] | Gmod q[4] >
```

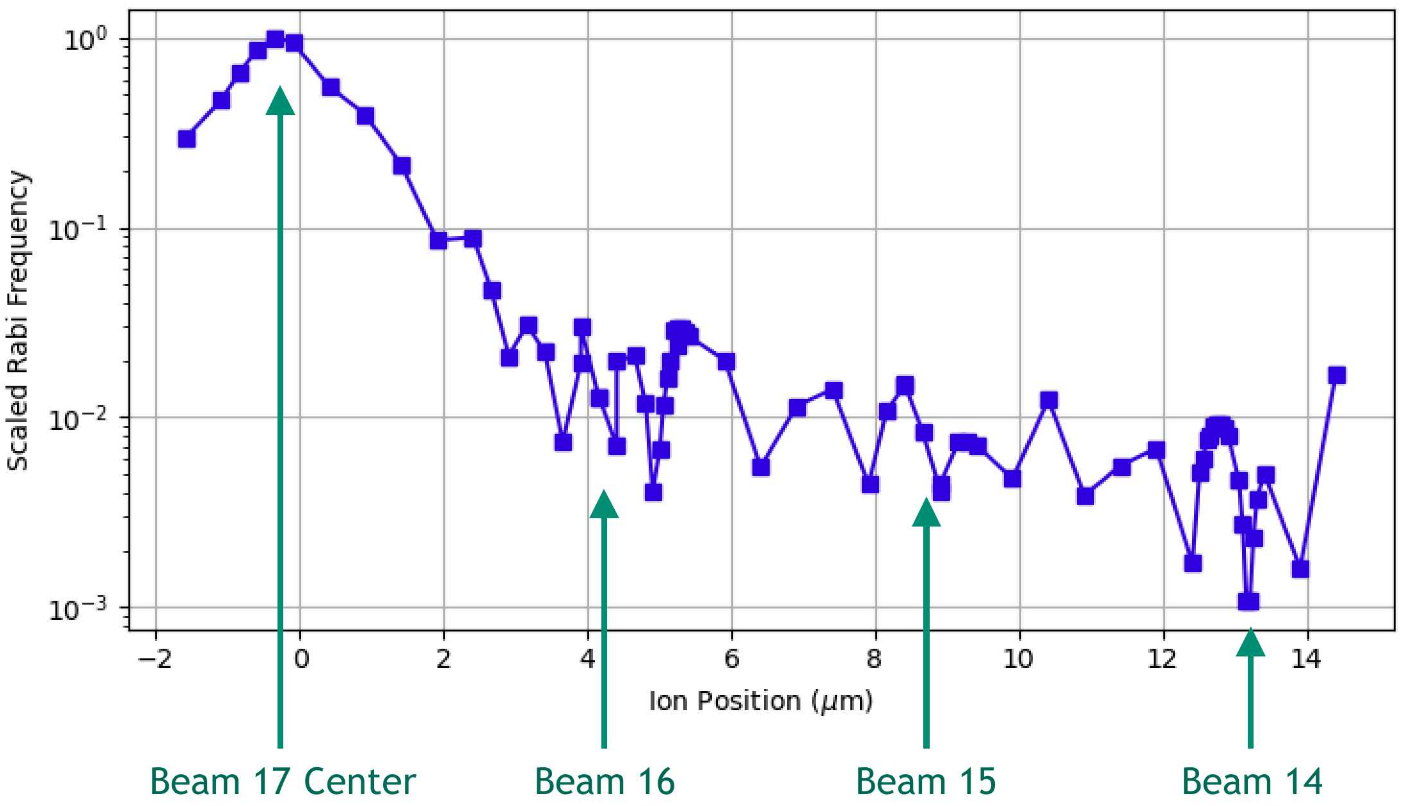
Custom gate definitions at the pulse level with JaqalPaw
"Jaqal Pulses and Waveforms"

```
def gate_Gmod(self, qubit):
    fmod = self.frequency_mod_parameters(qubit)
    #    = [220.242e6, 190.52e6, 250.2e6, ... ]
    amod = self.amplitude_mod_parameters(qubit)
    #    = [0, 5, 7, 35, 32, 48, 40, 50,  ... ]
    return [PulseData(qubit,
                      self.calibrated_duration,
                      freq0=self.aom_center_frequency,
                      freq1=Spline(fmod),
                      amp0=Spline(amod),
                      amp1=Spline(amod),
                      fb_enable_mask=0b10,
                      sync_mask=0b11)]
```



Inherent Crosstalk

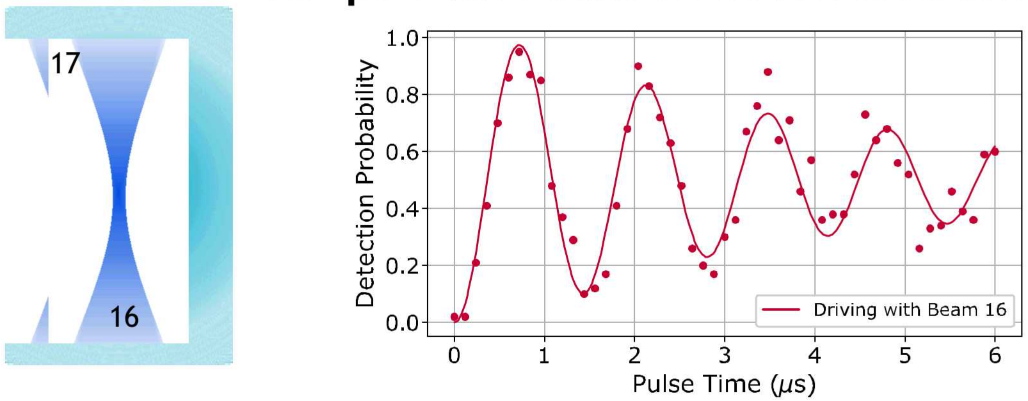




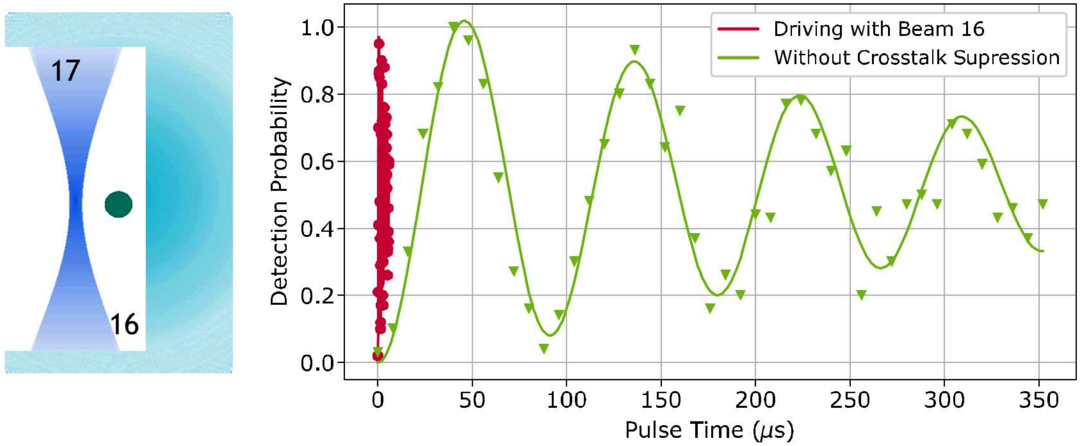
- The effect of performing gates in proximity to an idle ion must be reduced to maintain high fidelity in multi-ion chains
- Using the counter-propagating beams, we measure the crosstalk on adjacent ion locations. Crosstalk < .03 at nearest neighbor site.
- Beam 17 used to probe, all other individual beams are off.

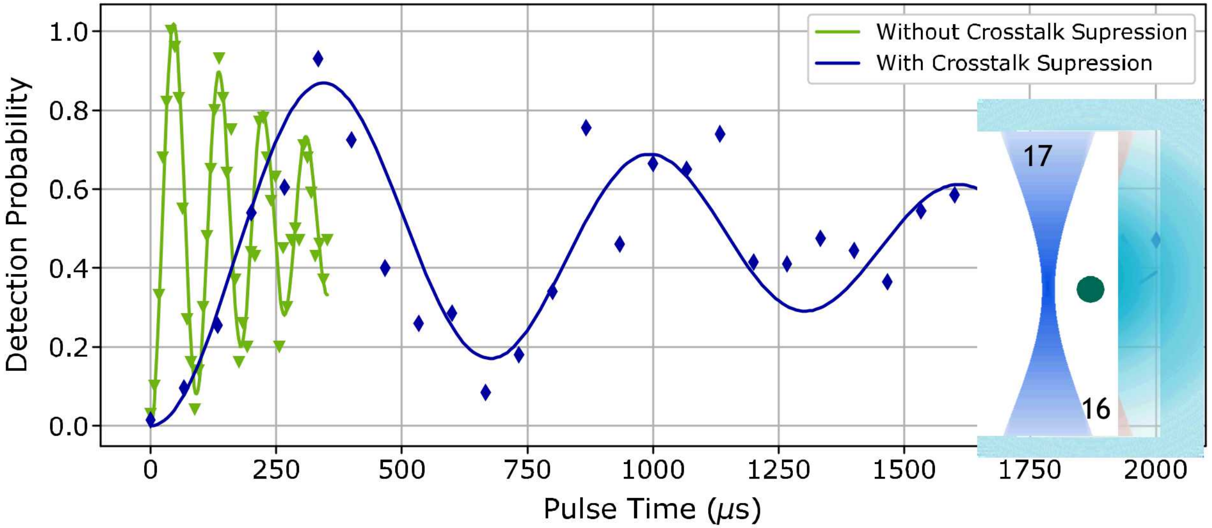
Crosstalk Suppression – Less than 0.23%

- By applying the correct cancellation tone, we can reduce the measured crosstalk
- π-time = **0.8 μs** with beam on at ion location



- The measured π-time due to light on the neighboring site ≈ **45 μs**

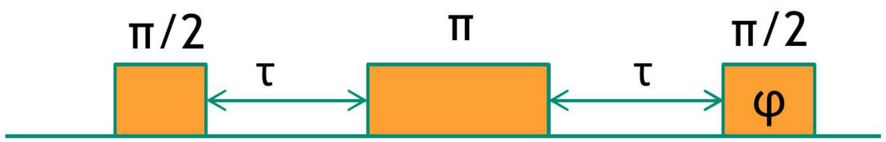


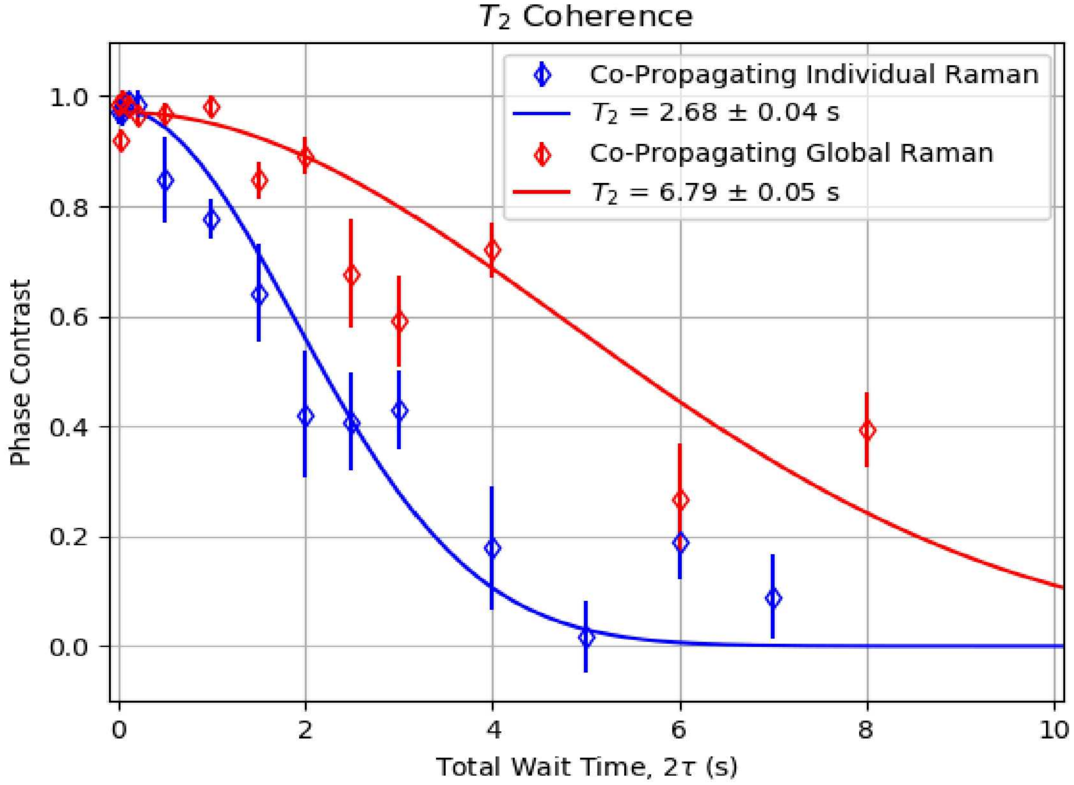


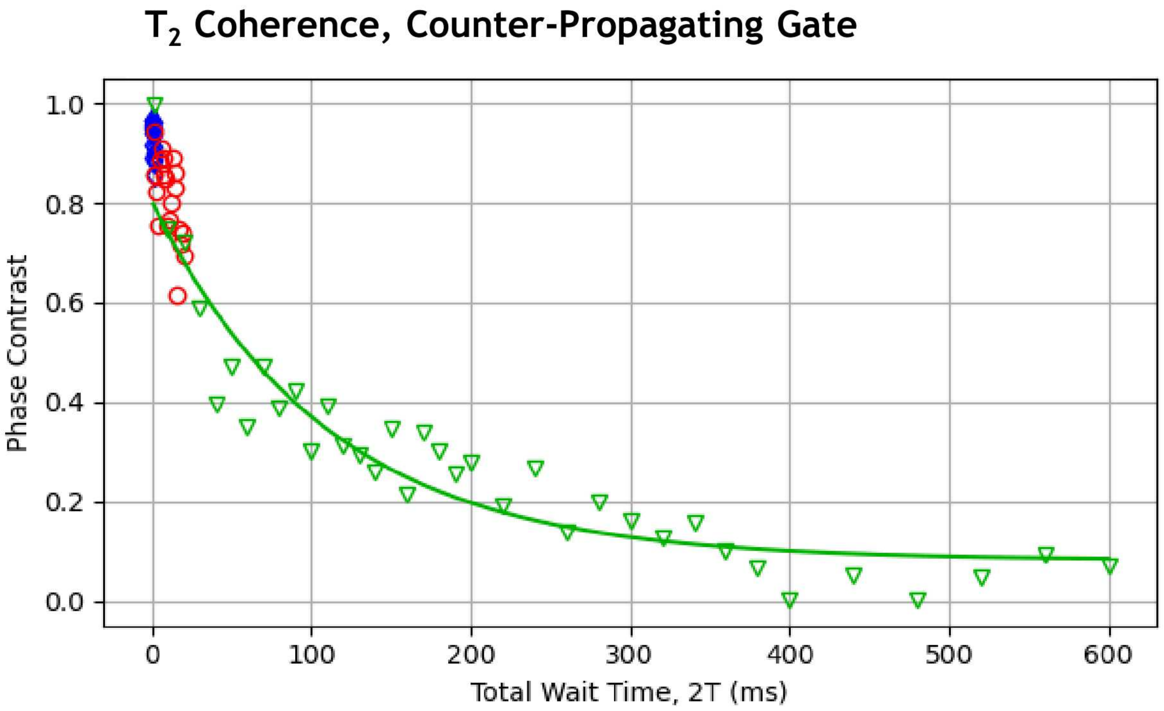
- π-time > **350 μs** with cancellation tone
- With preliminary optimization, the crosstalk reduces to <0.0023 when a cancelling tone is applied at the ion location, a 26dB suppression
- This measurement is performed without ground state cooling, n ≈ 4.

355 Coherence Times

- Co-propagating transition = not sensitive to motion
- Counter-propagating transition = sensitive to motion
- Coherence time:
  - Global: T_2 ~ 6.8 s
  - Individual: T_2 ~ 2.7 s - likely limited by the ion's stability in the beam
  - Counter-propagating: T_2 ~ 100 ms

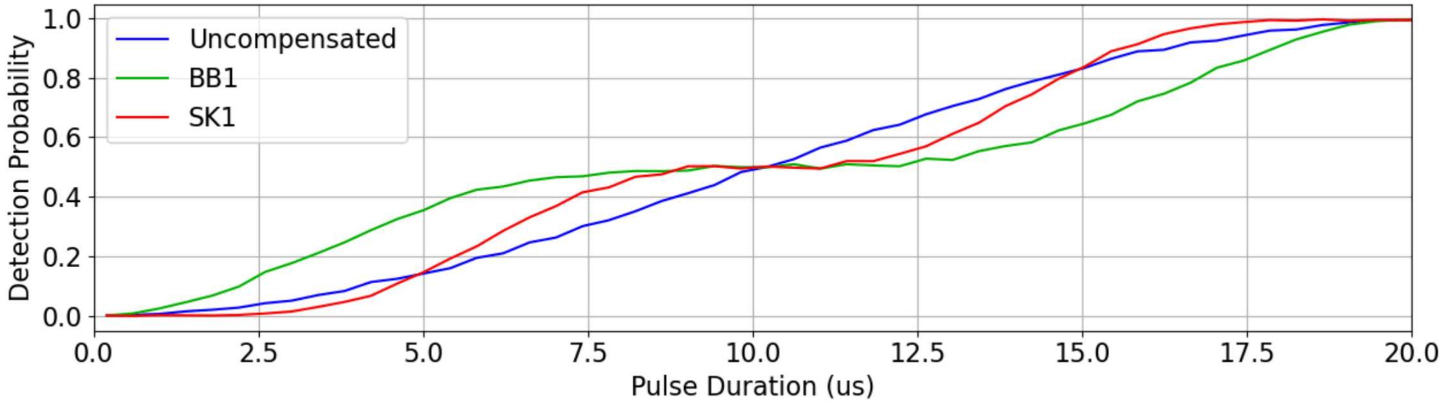


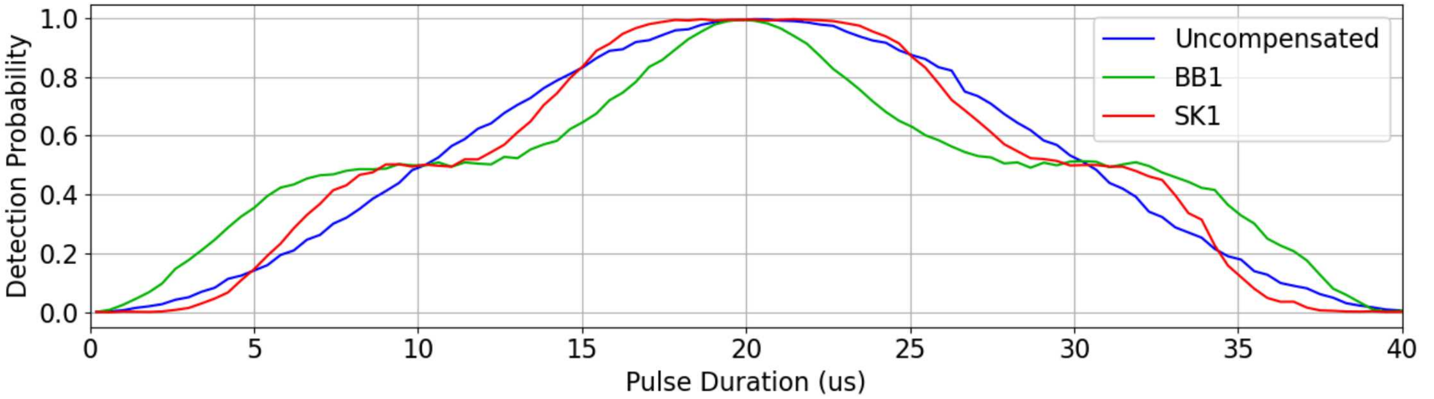




Dynamically Compensated Gates Using RFSoC

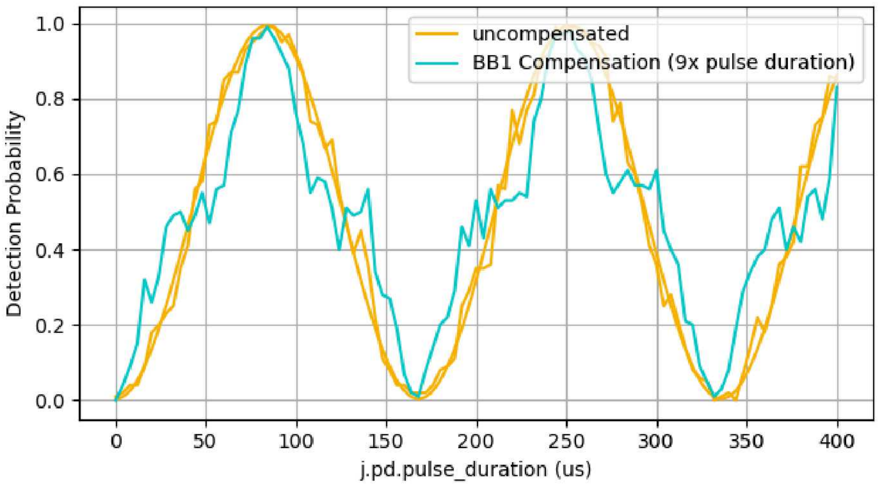
- Pulse envelopes and frequency- phase- modulation defined by splines
- Compact representation of gates for efficient streaming of circuits
- Increased control for improved gate fidelities



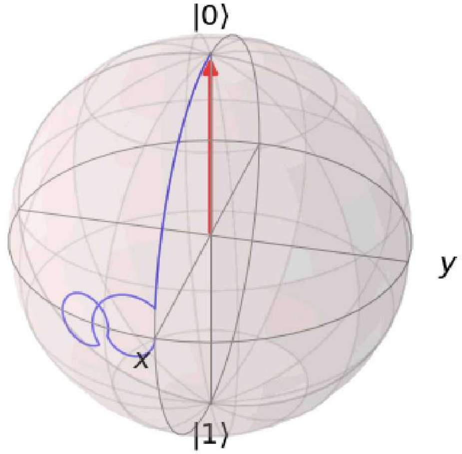


BB1 Compensated Gates and Gate Set Tomography

BB1 Compensation

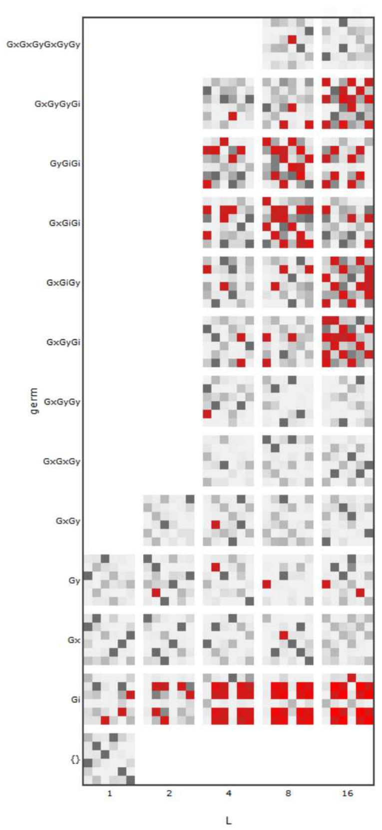


- BB1 gates implemented for μwave, co-prop global, and co-prop individual
- GST implemented for BB1 gates

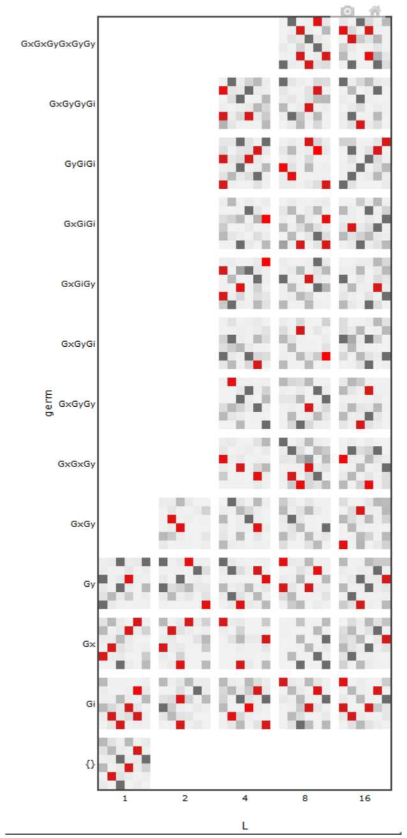


Testing out variety of compensated I gates

i = Wait



i = $\pi_X\pi_Y\pi_X\pi_Y$



Gate	°	° v. Gi	Infidelity	½ Trace Dist.
Gi	.0469π	--	.005599	.073724
Gx	.4990π	.5003π	.000087	.0016
Gy	.4988π	.5021π	.000145	.00196

Gate	°	° v. Gi	Infidelity	½ Trace Dist.
Gi	.0005π	--	.00019	.000817
Gx	.5000π	.4354π	.00004	.001003
Gy	.4996π	.5306π	.000001	.001151

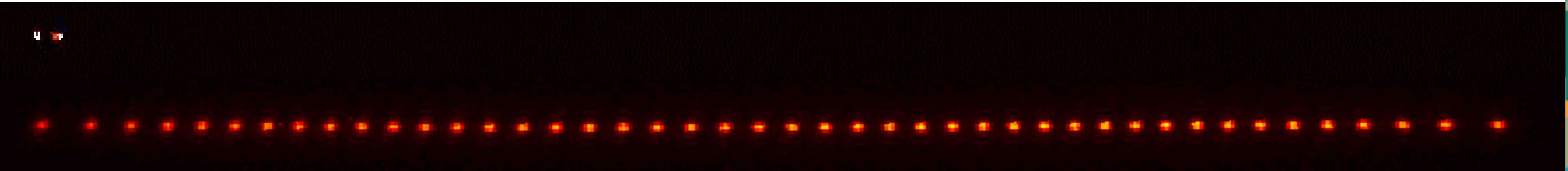
Outlook

Currently

- Developing the QSCOUT testbed and beginning first phase of user defined research
- Releasing next generation Phoenix and Peregrine devices for use in quantum processing

Next Steps

- Ion shuttling and position control
- High fidelity quantum operations
- Charging of traps leading to ion shifts



Thank you - Current Team

Trap design and fabrication

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Corrie Sadler
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John Rembetski
Jason Dominguez

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Jessica Pehr

Software

Jay Van Der Wall

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Tipp Jennings
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Setso Metodi
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Stefan Lepkowski

Optical Engineering

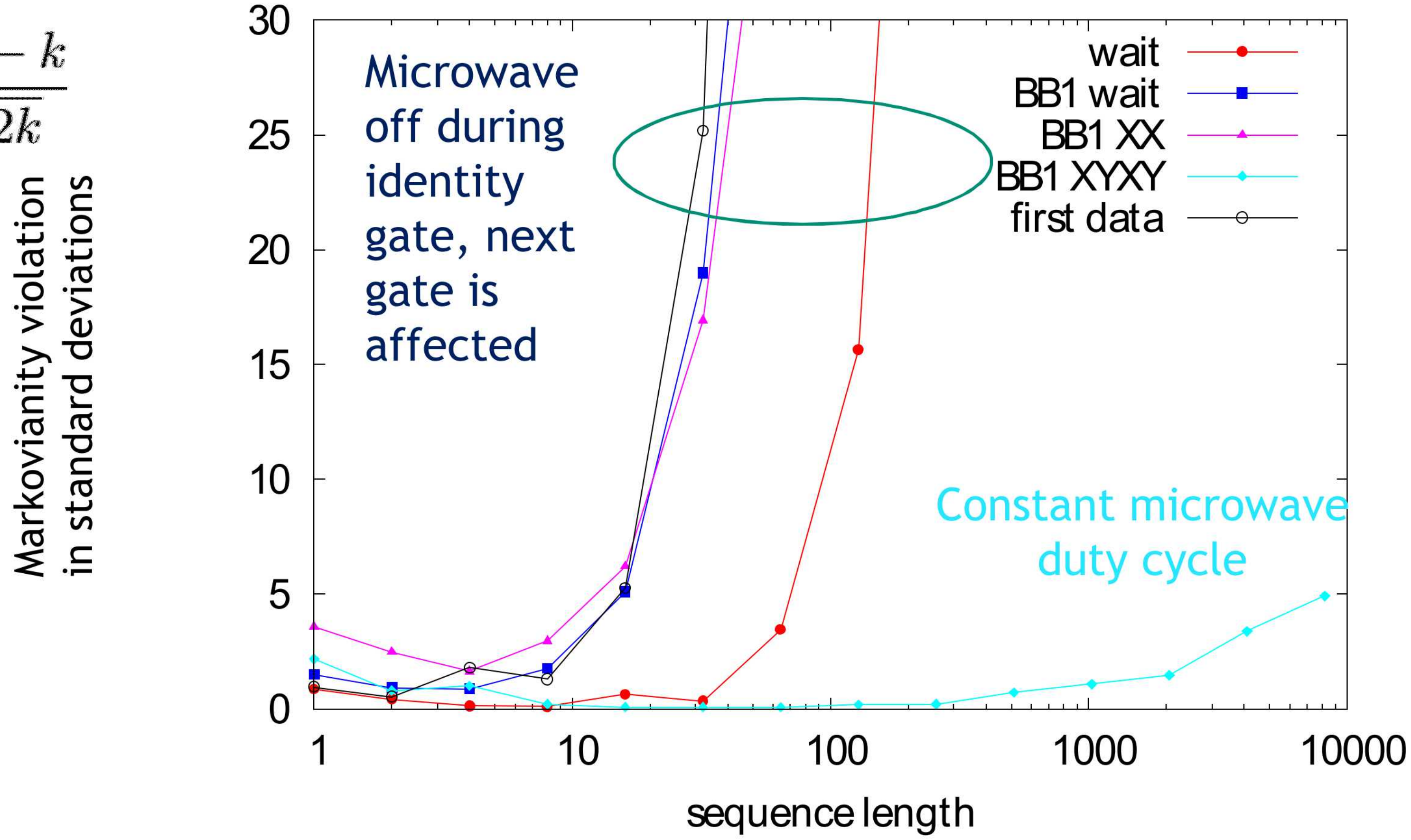
William Sweatt

Back-up Slides

GST model violation

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

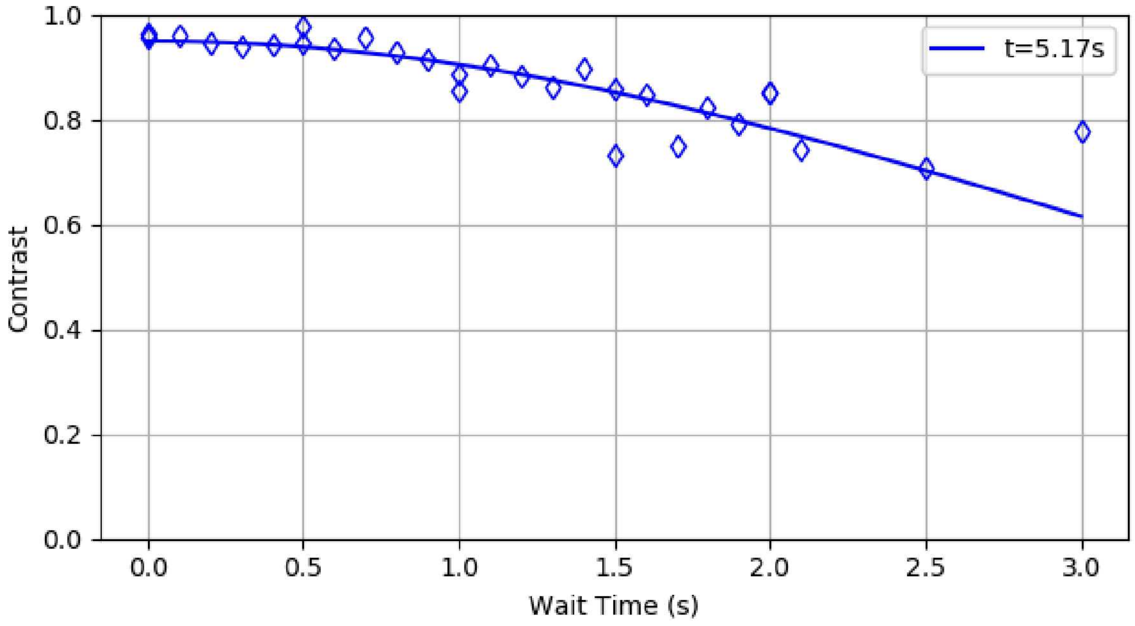
$$\frac{\chi^2 - k}{\sqrt{2k}}$$

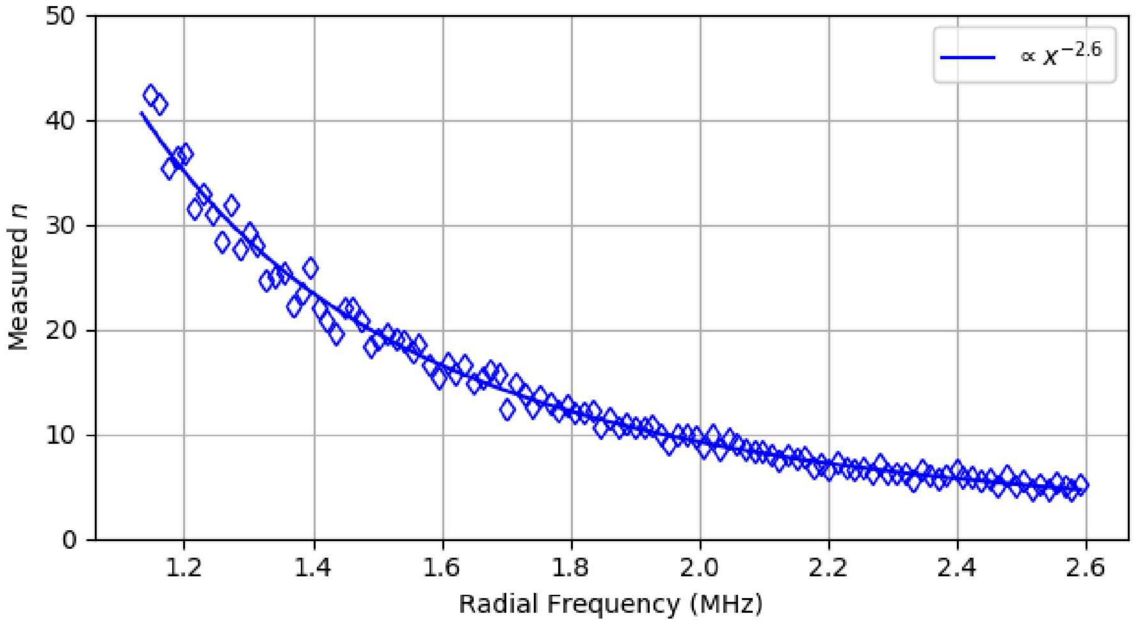


BB1 decoupled gates with decoupled identity have very small non-Markovian noise

Preliminary Heating Rate

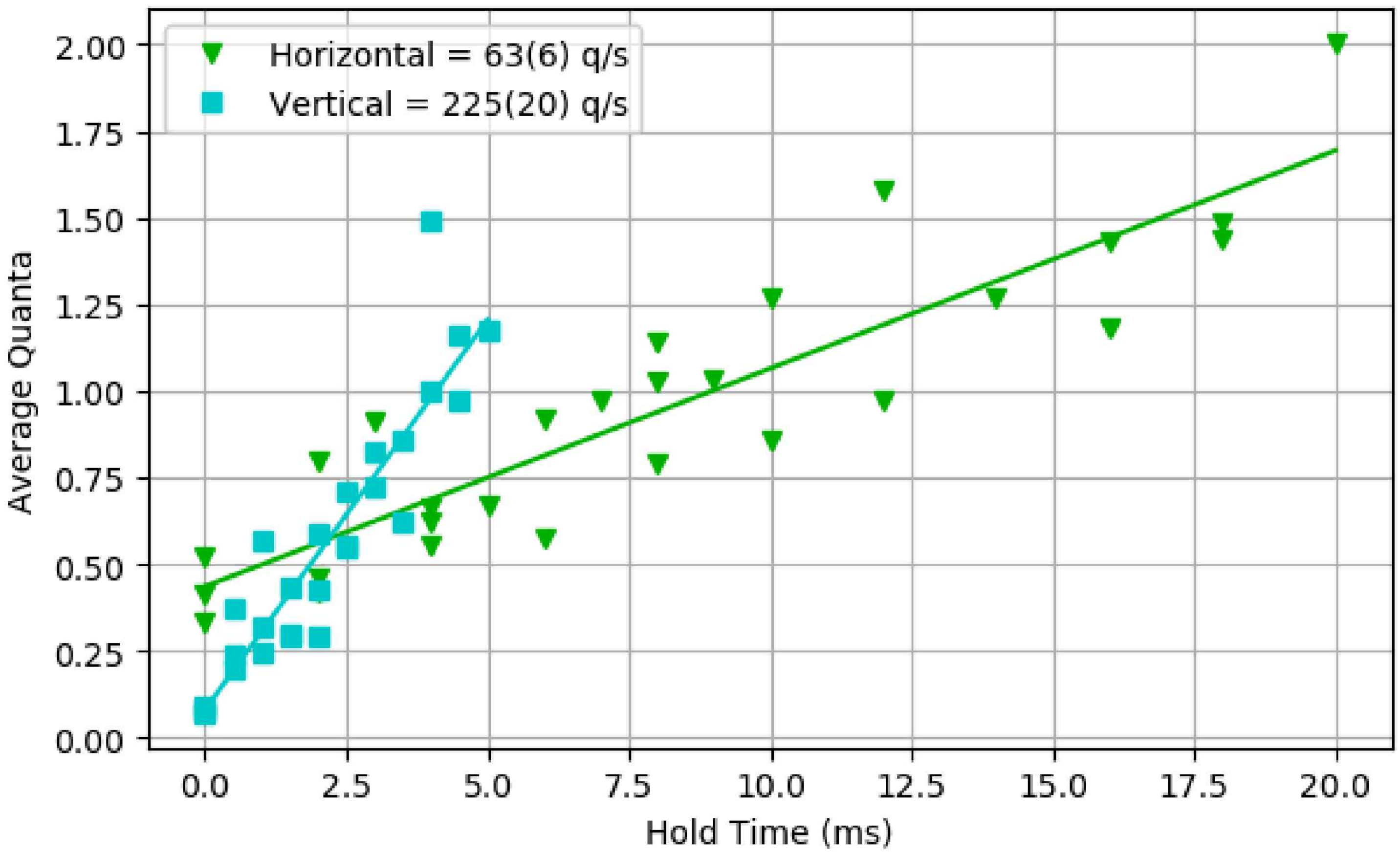
- We measure microwave coherence times > 5s – should not be device limited
- Using Raman beams, the initial ion temperature is measured as a function of rf power.
    - Freq$^{-2.6}$ scaling
- Initial n < 4 for frequencies > 2.6 MHz





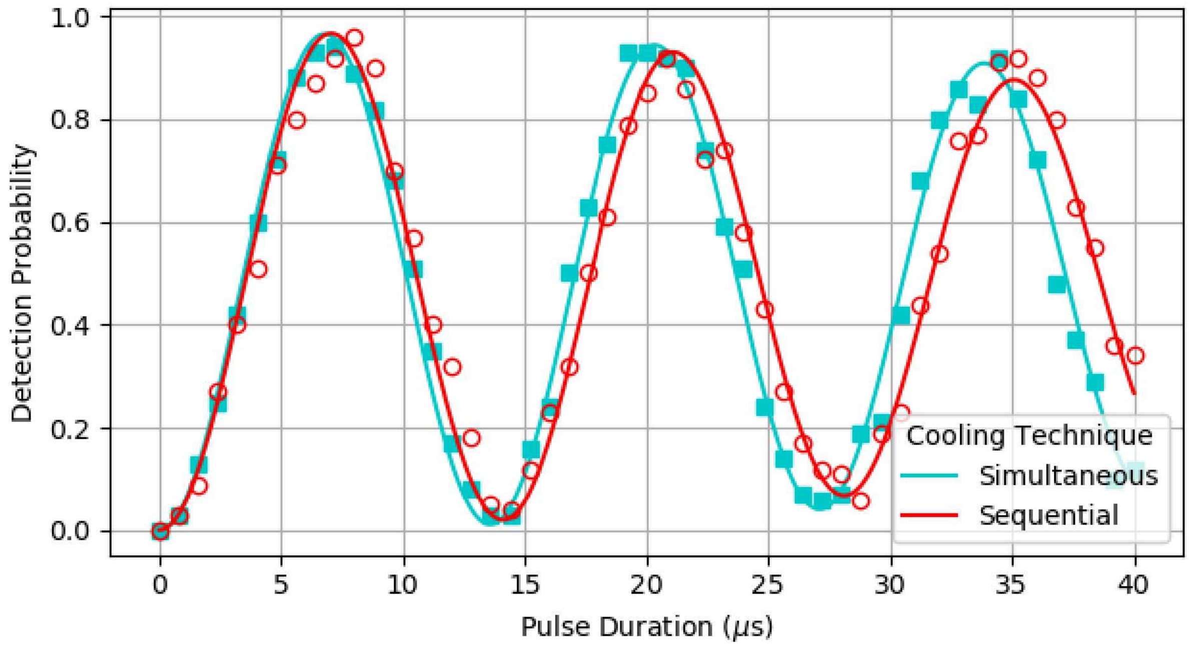
Preliminary Heating Rate

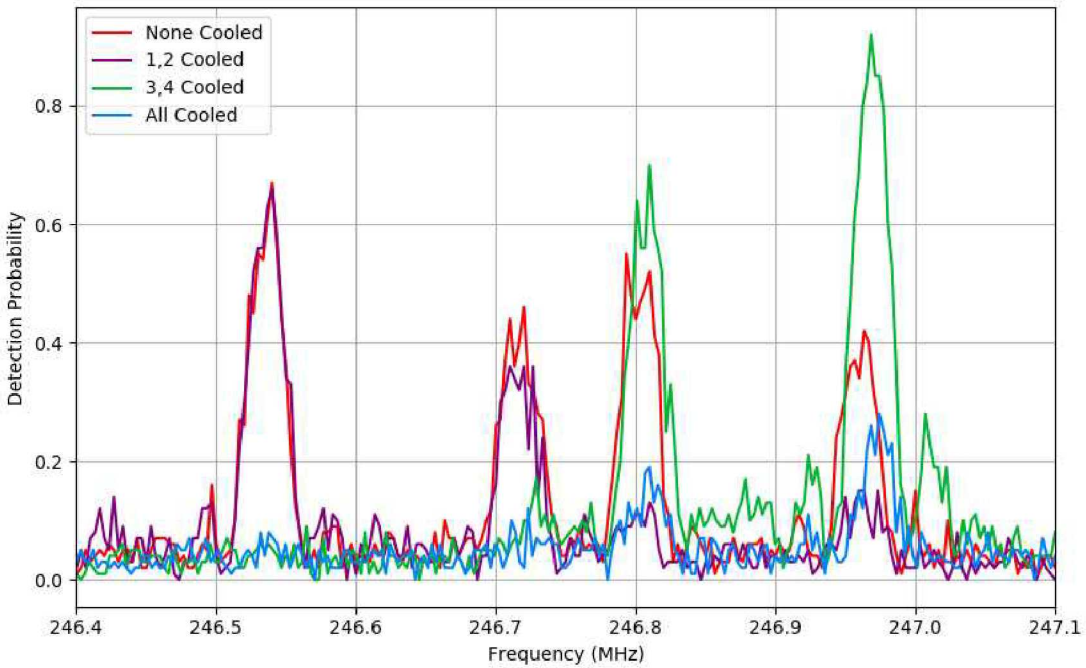
- Initial heating rates at 2.5 MHz on Phoenix trap
- Peregrine < 600 q/s – likely limited by measurement technique



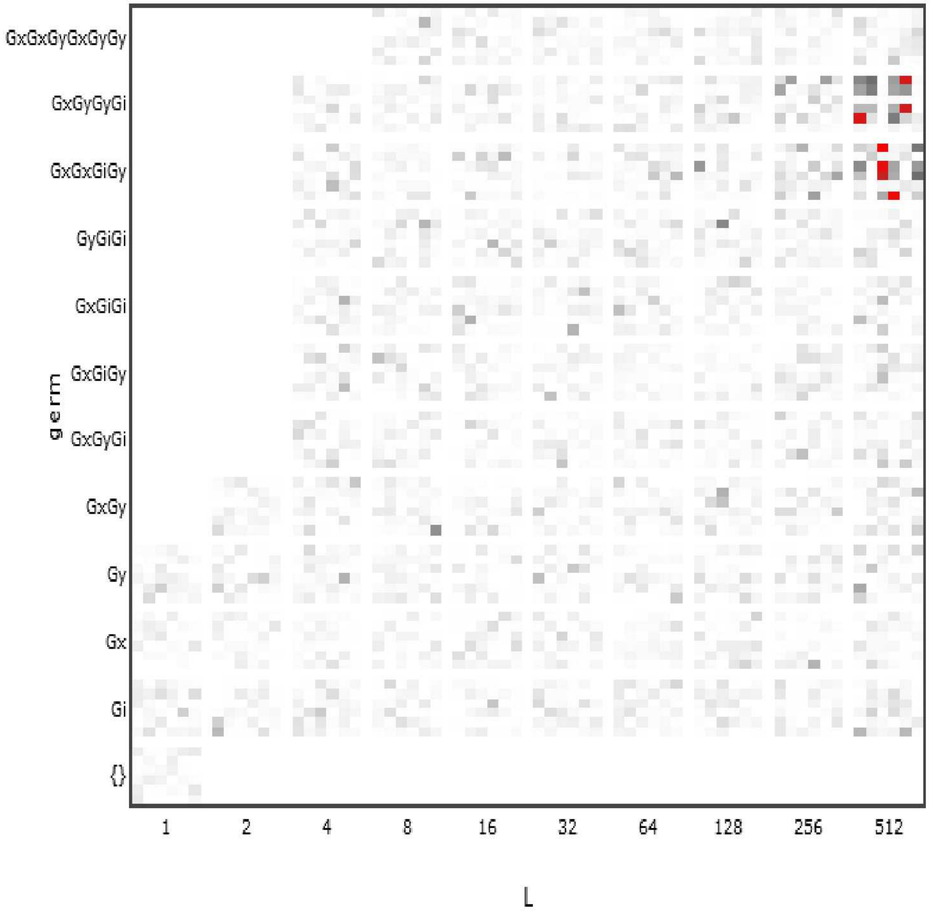
Simultaneous Sideband Cooling

- Leveraging the RFSoC – we can apply cooling tones for 2 radial modes simultaneously.
- Typically, we interleave cooling on mode 1 and mode 2. Takes about 2.6 ms.
- By applying the tones simultaneously, we decrease the number of cycles. Average time = 1.75 ms
- Extended to 4 modes by interleaving the simultaneous cooling loops. n < 0.5





GST model violation



- 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

- Identifying problems due to context dependency and drift