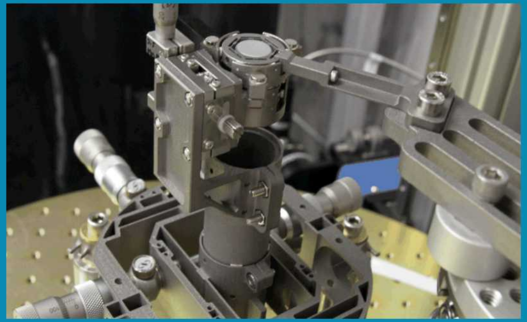
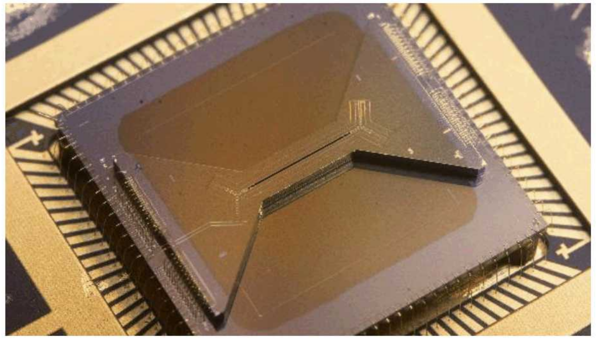
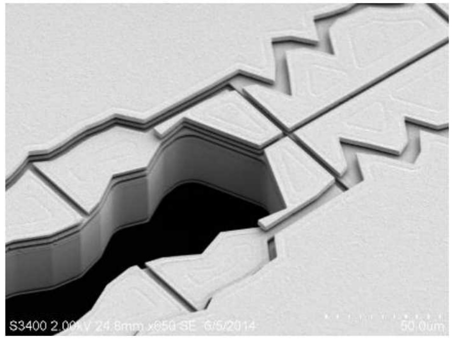
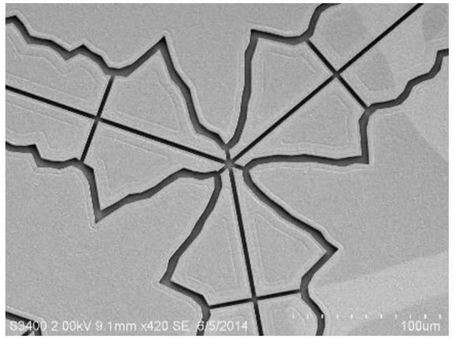
SAND2020-2599C

Logical Cooling for Noise Reduction in Analogue Quantum Simulation









Craig W. Hogle, Peter Maunz, Jaimie S. Stephens, Kevin Young, Daniel Lobser, Melissa Revelle, Christopher Yale, Jessica Pehr, Robin Blume-Kohout, Daniel Stick, Susan M. Clark

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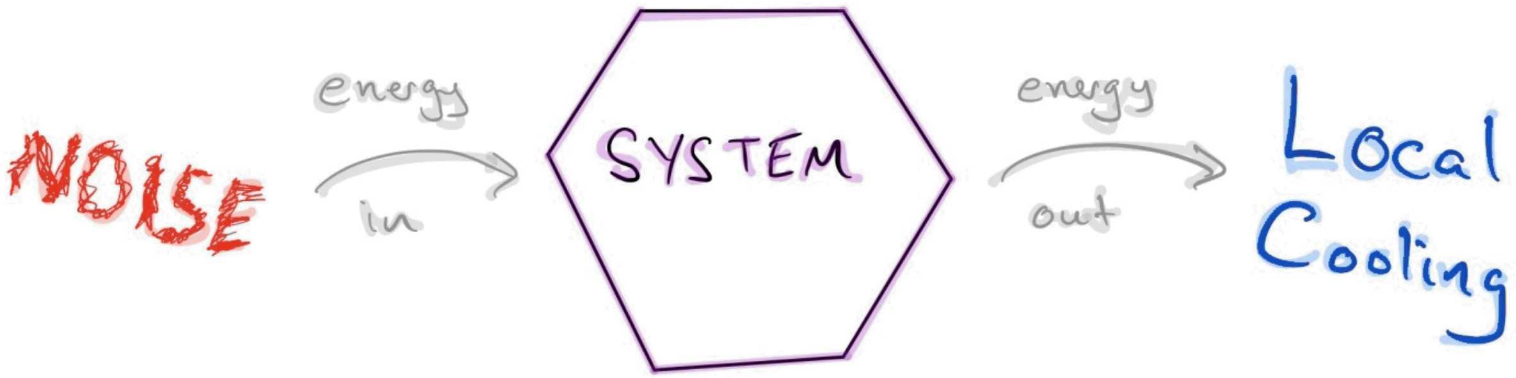
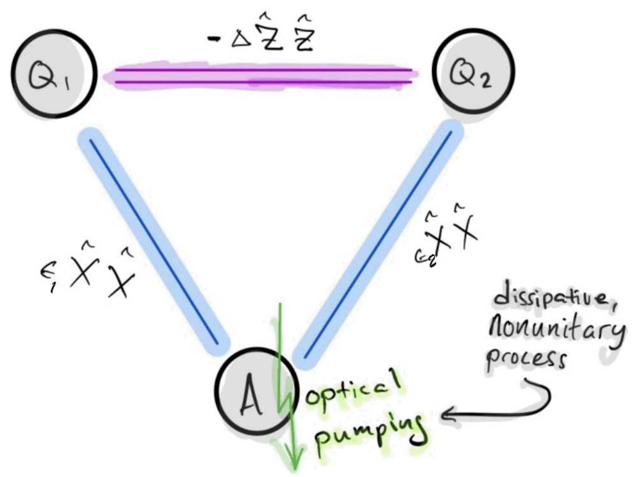
Why analogue quantum simulation?



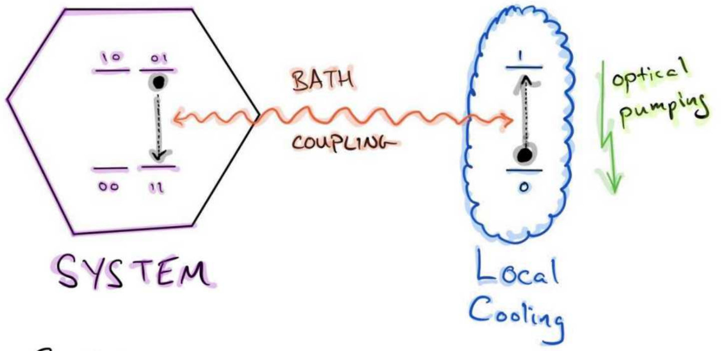
Analogue quantum simulations can teach us about fundamental quantum physics in regimes that are difficult to simulate classically

The system determines the energy landscape, we reduce errors by cooling the system to the ground state

An example system for demonstrating logical cooling

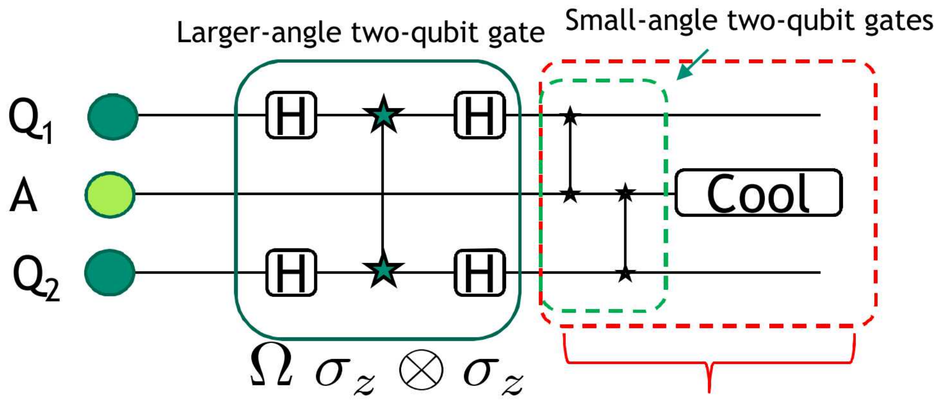


Weakly pushes data qubits to
$|00\rangle$ and $|11\rangle$



Excited system exchanges energy with cold bath, restoring the system to its ground space and effectively cooling the logical degrees of freedom

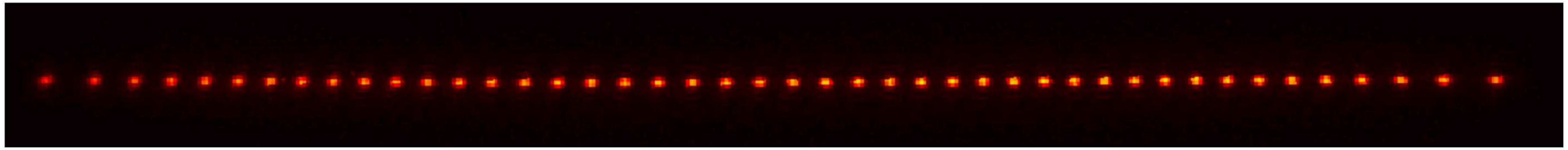
Pulse sequence for logical cooling:

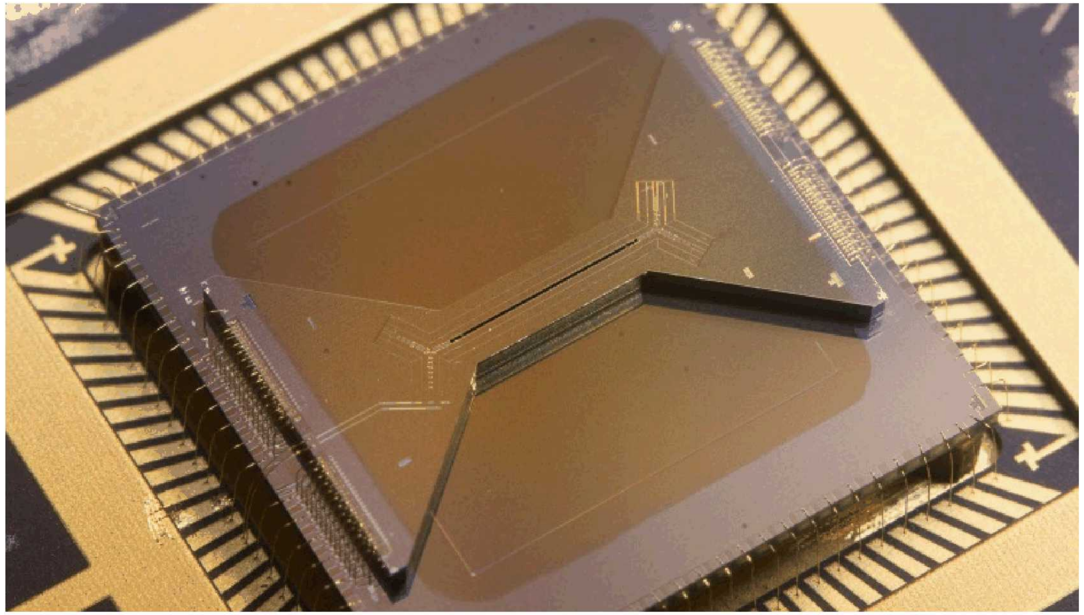


Implementation of Hamiltonian with ground states |00> and |11>

Logical cooling to pull energy out of system, thus keeping the system in |00> or |11>

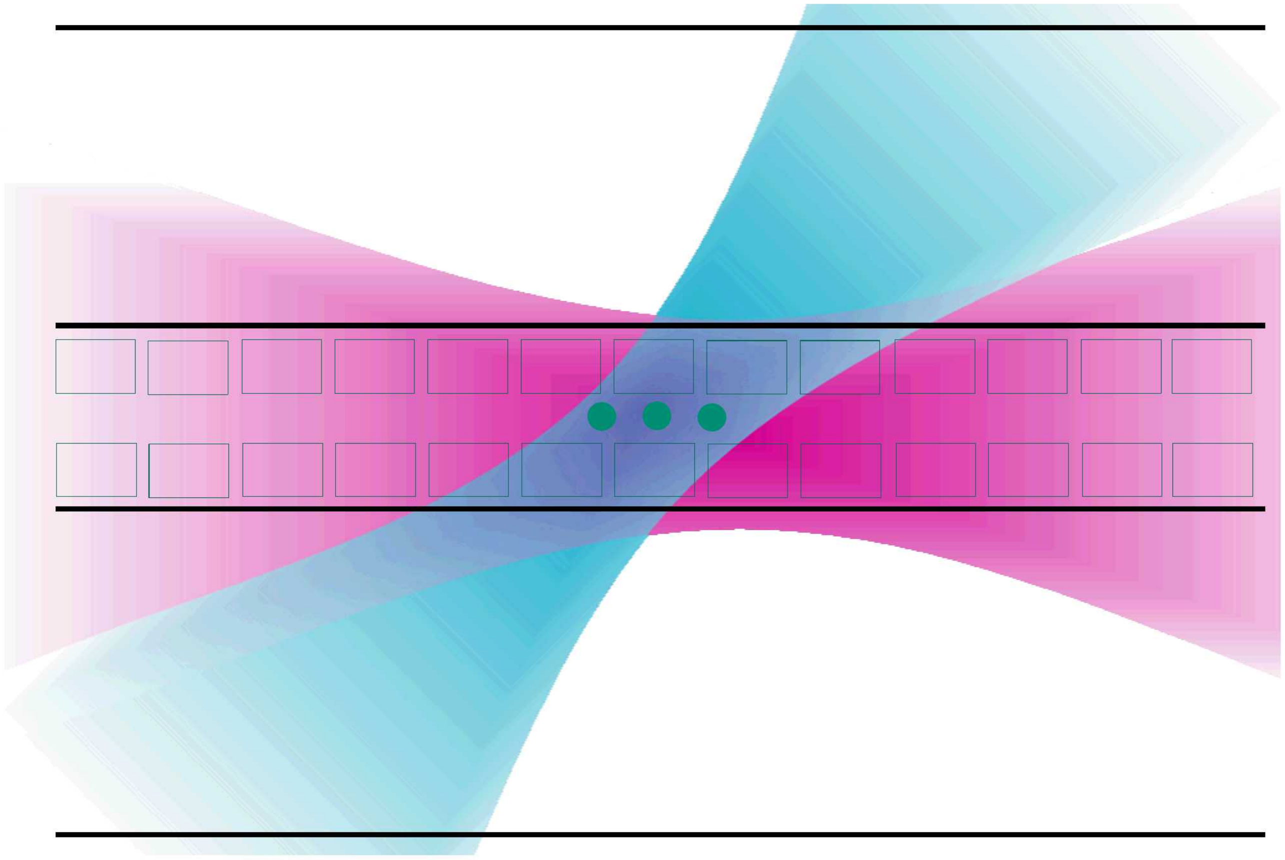
HOA2 supports long chains of ions

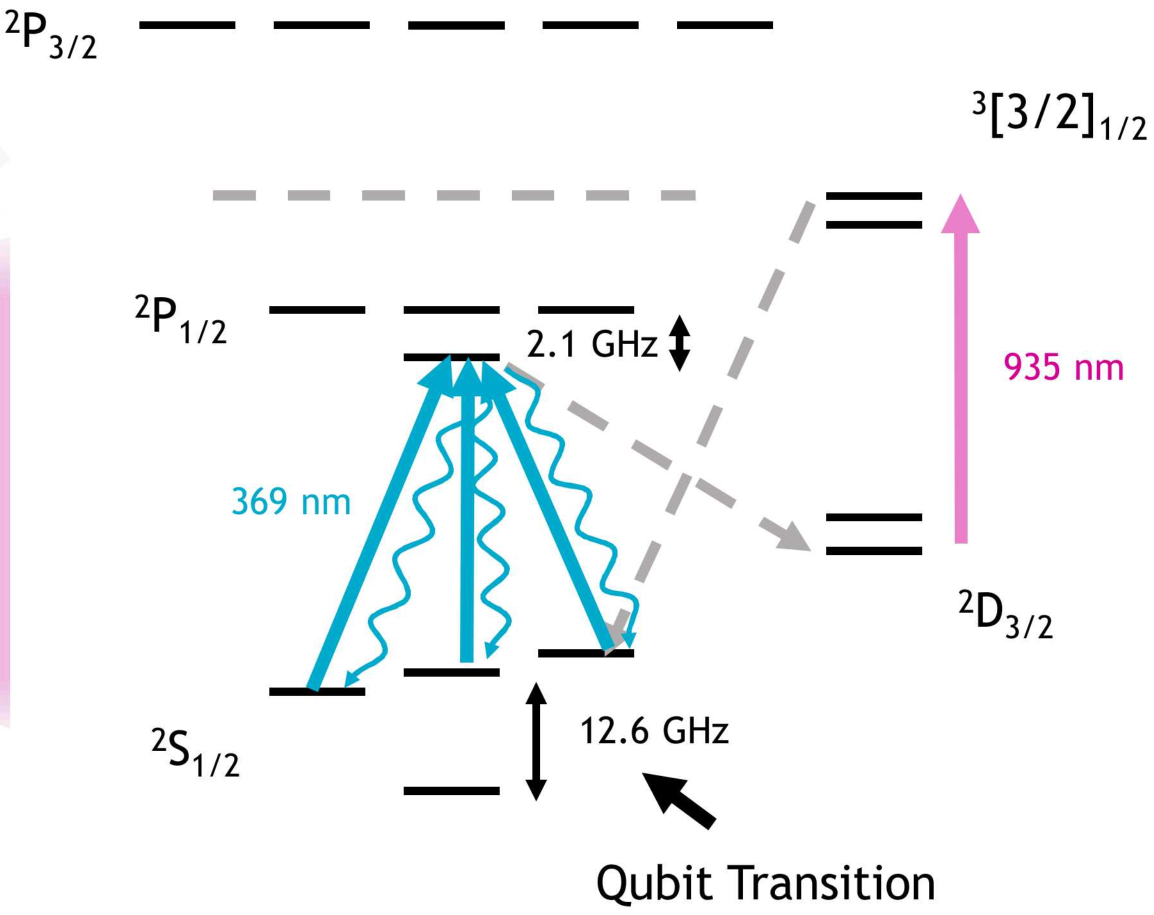




Operating voltage	**250 V amplitude, 40 MHz**
Ion height	70 μm ion height, NA 0.21 through slot, NA 0.12 skimming surface, NA > 0.6 from surface
Electrodes	144 control electrodes (94 independent)
Trap potential	3 MHz radial, 1 MHz axial (for ytterbium)
Transport	Demonstrated junction transport and controlled rotations
Ion lifetime	>100 hours demonstrated
1Q gate fidelity	99.993% (Sandia, ytterbium, microwave gates)
2Q gate fidelity	99.5% (Sandia, ytterbium, 355nm Raman lasers)

Experimental apparatus – Trapping three ions





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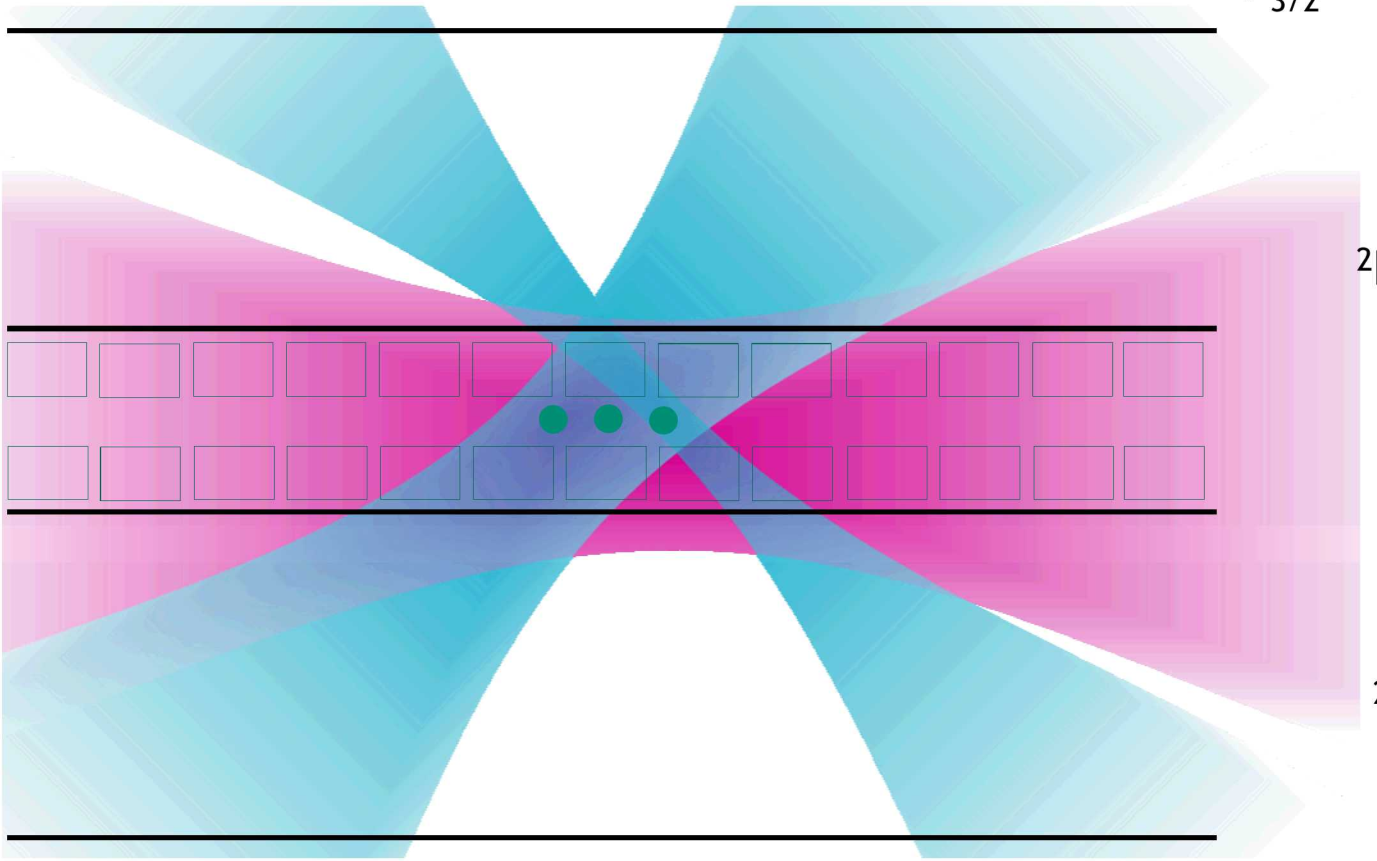

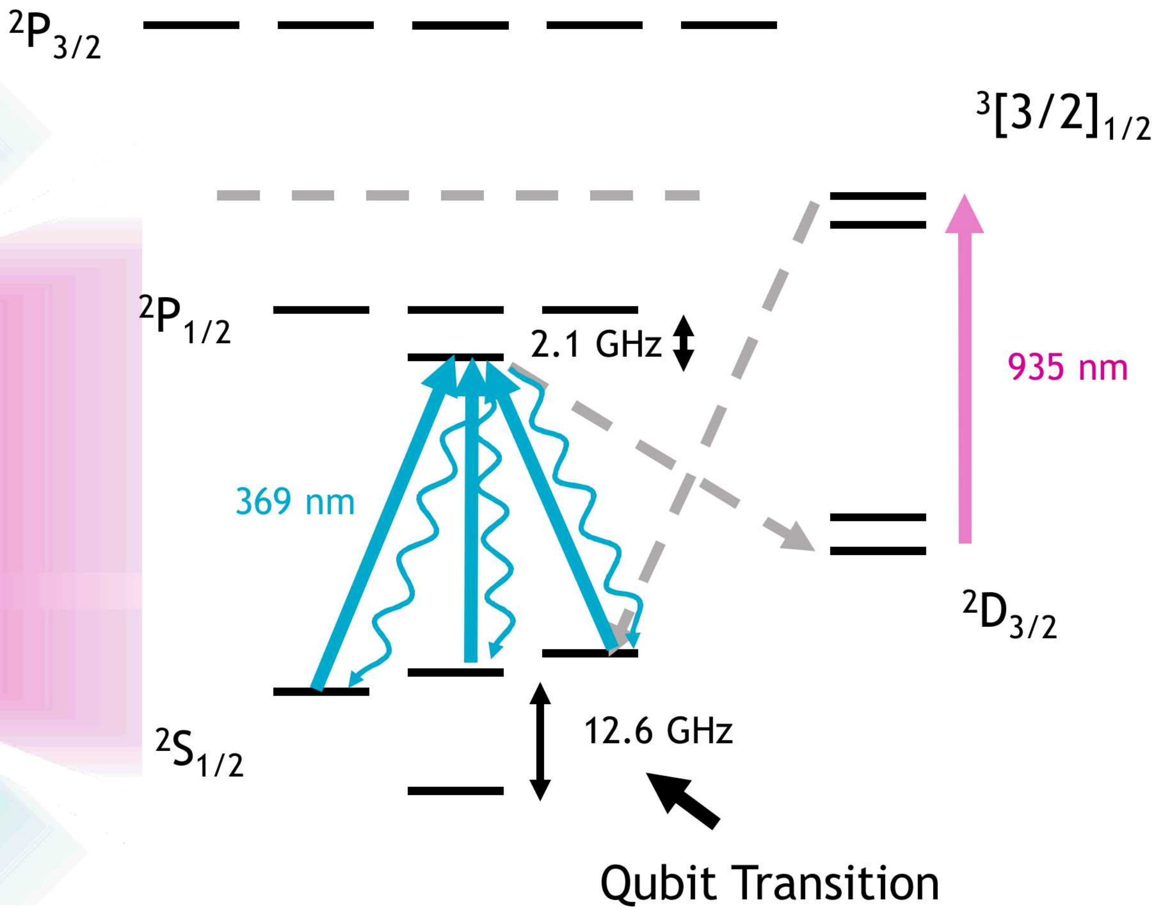

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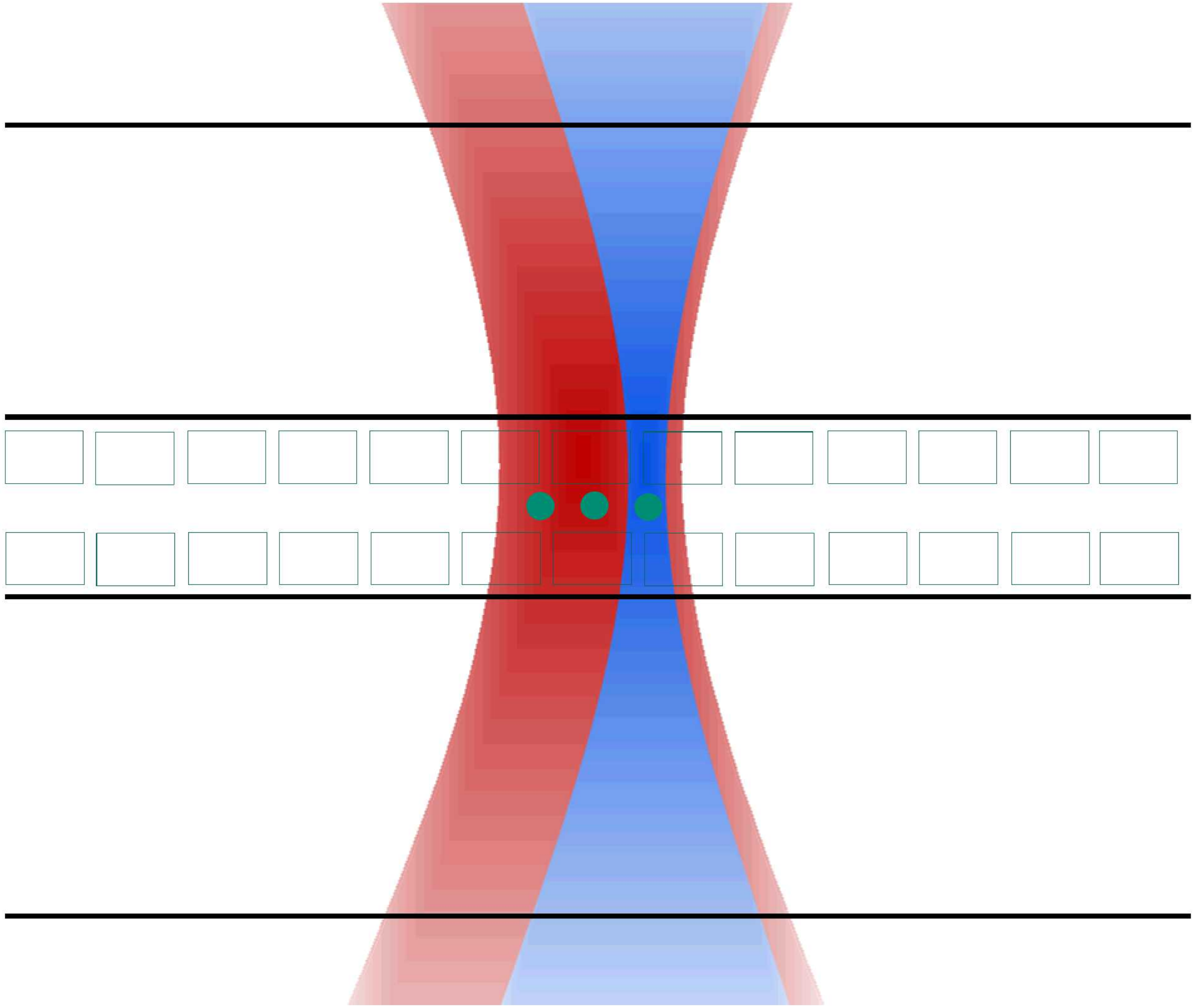

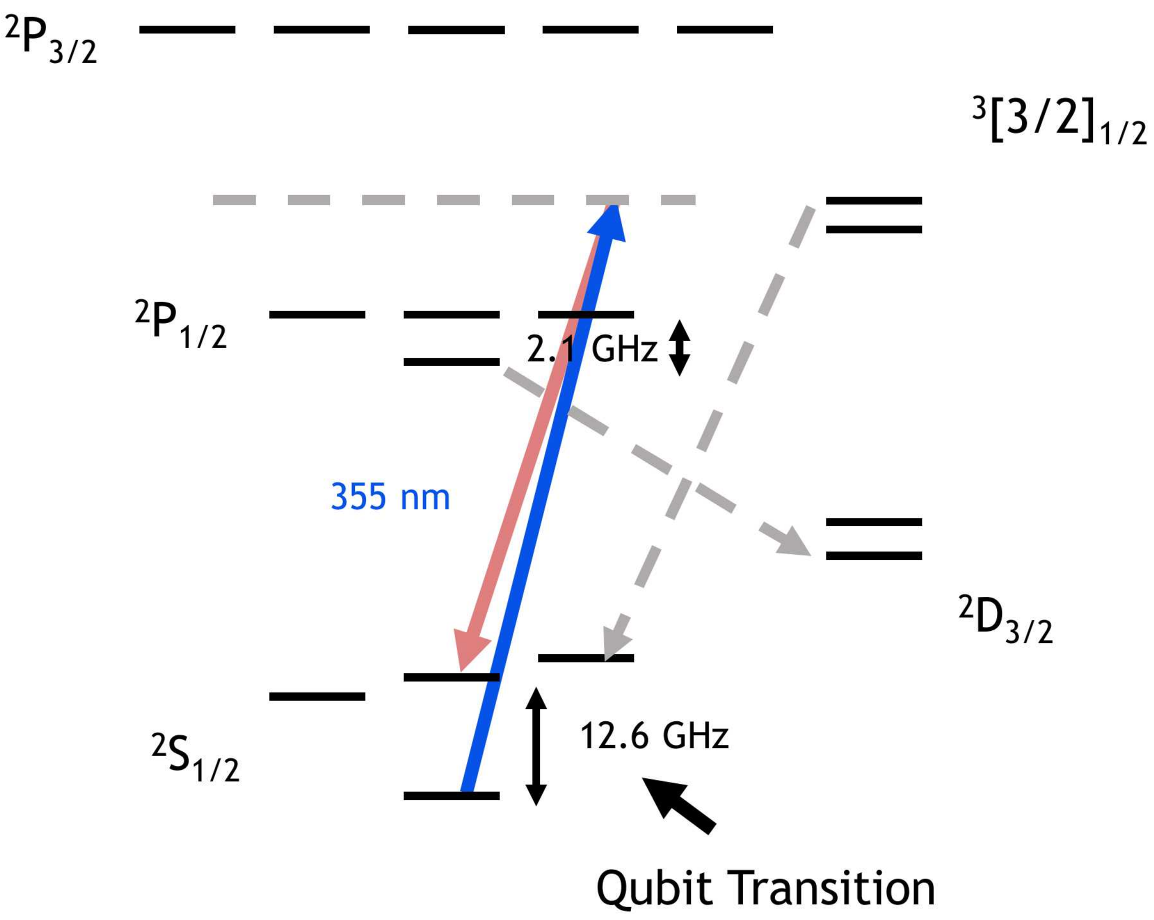

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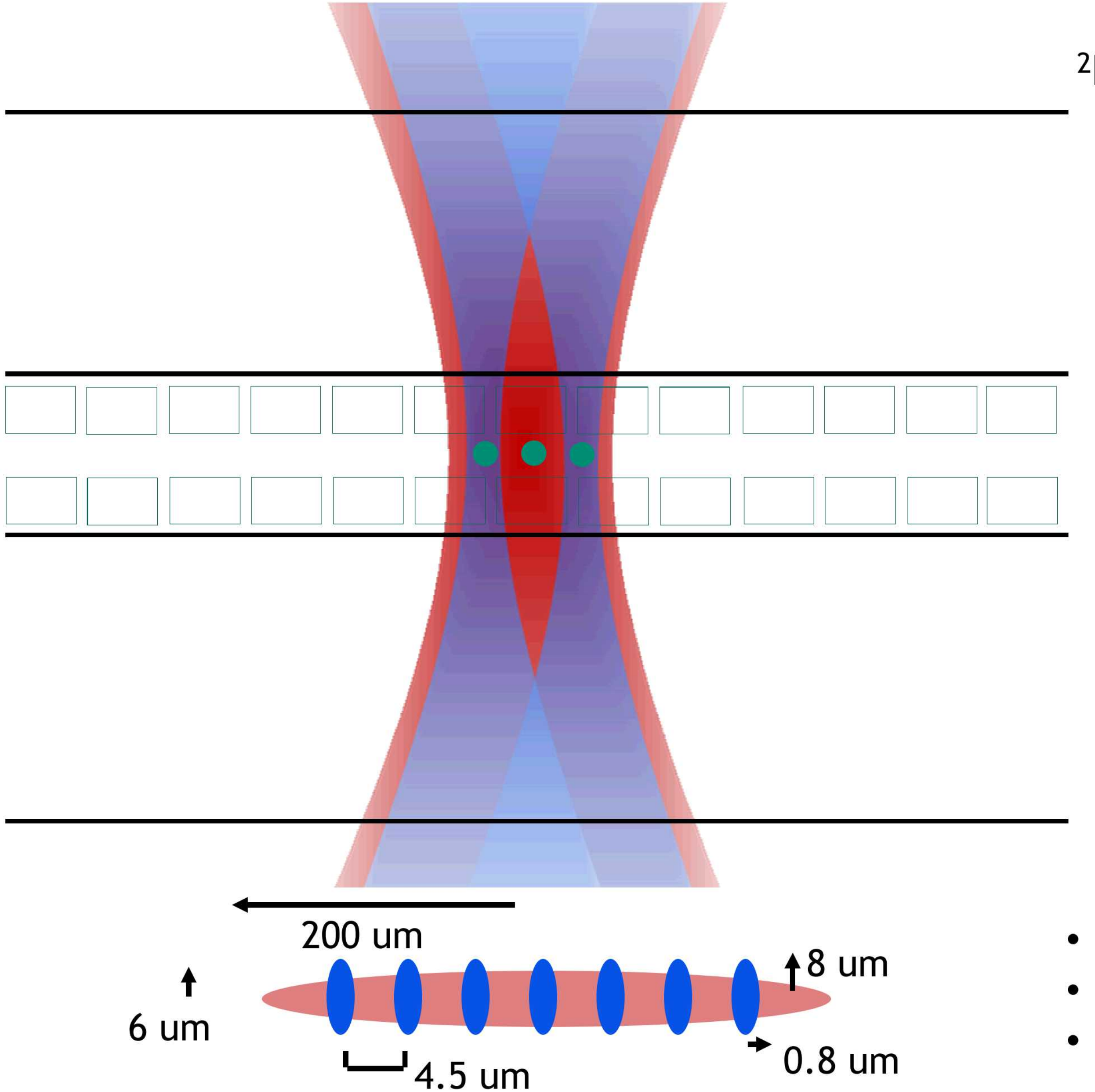
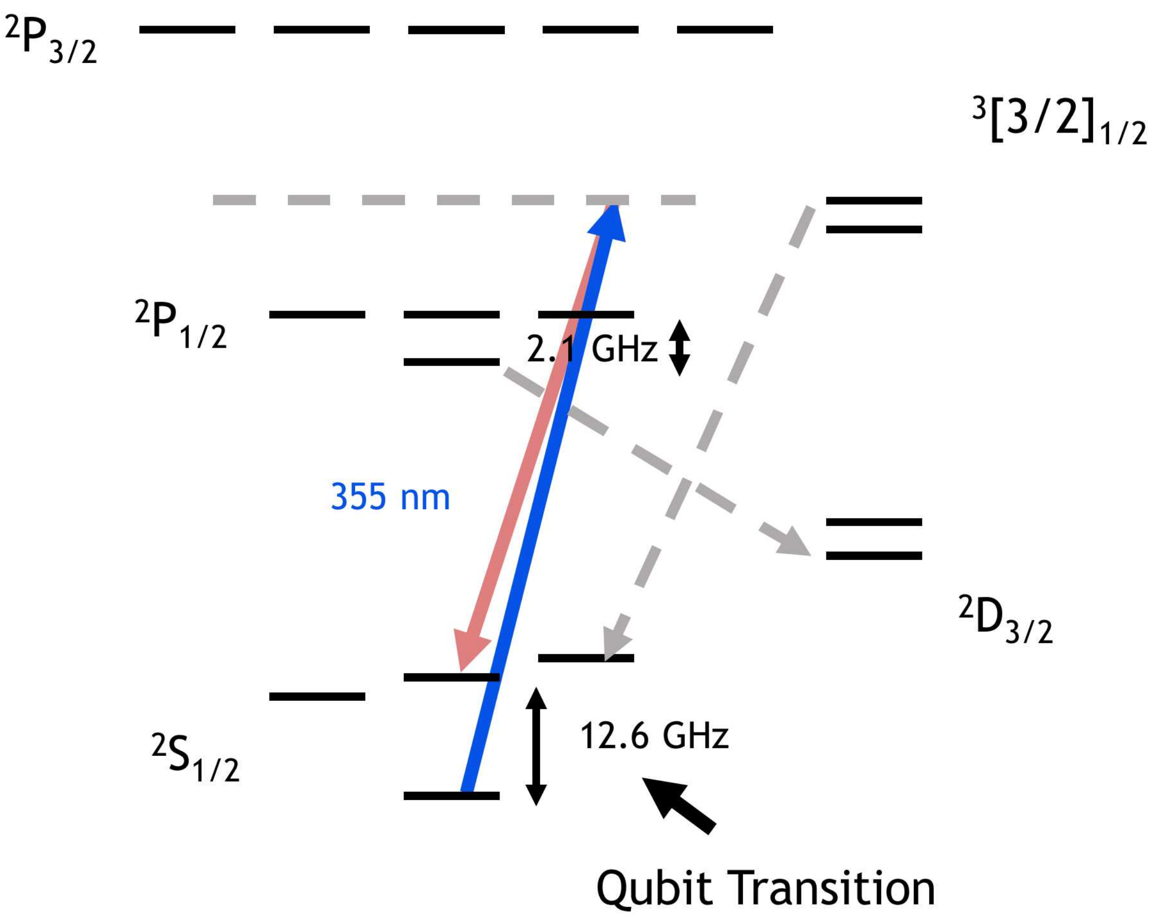


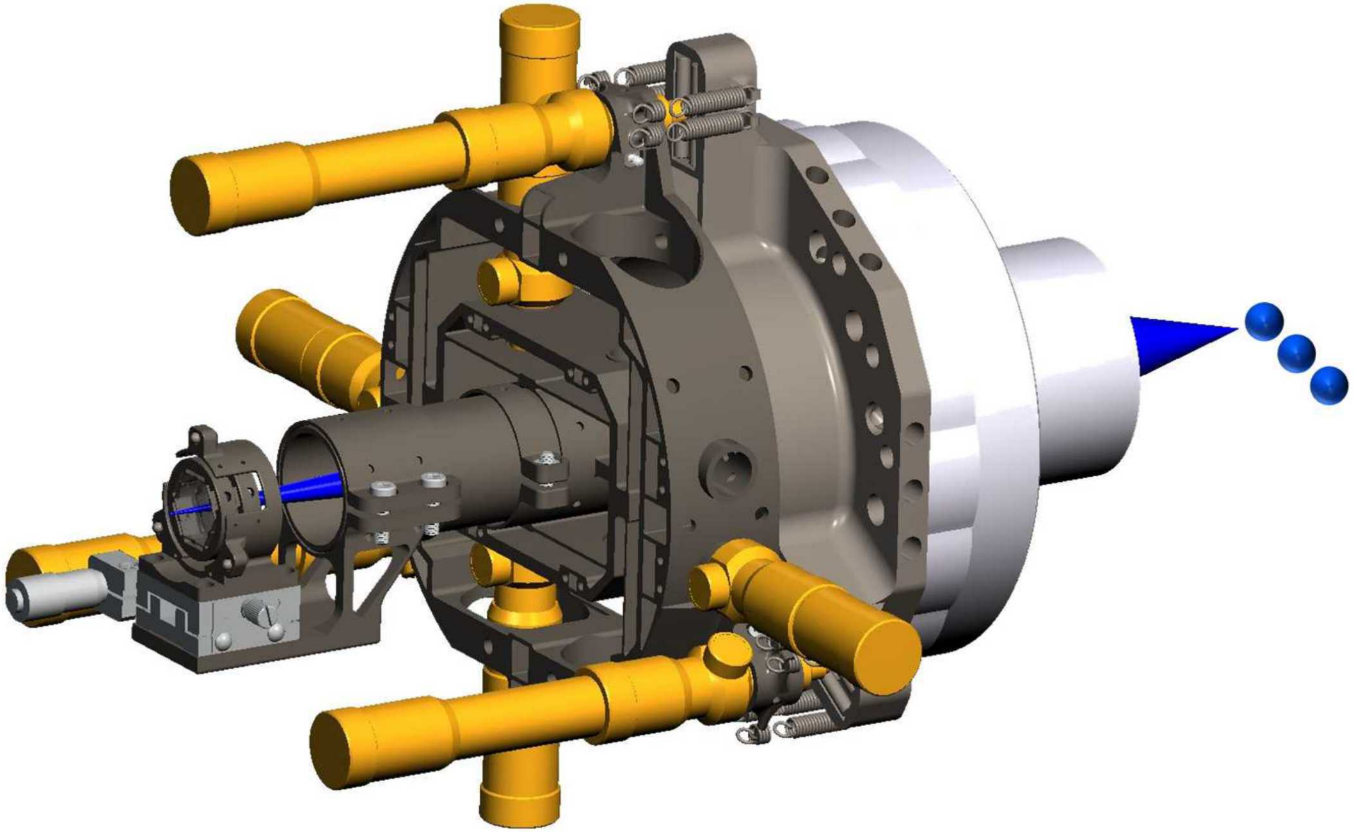


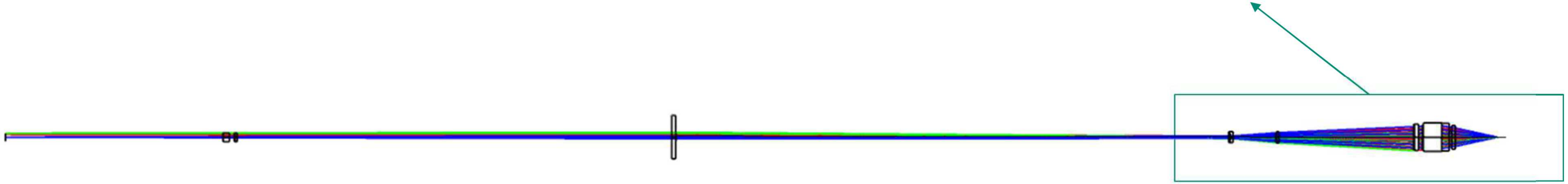
- Gates performed with microwaves or lasers
- Ions addressed with 355 nm frequency comb
- Raman beams are power stabilized

Custom imaging system is needed

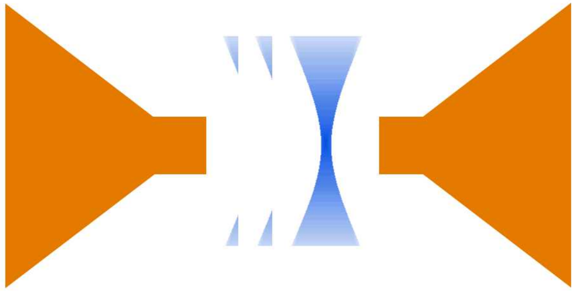
Custom design to

- Allow for the Raman laser gates specific to each ion
- Accommodate needed degrees of freedom in very cramped space
- Resilient to temperature changes
- Provide the needed mechanical stability
- Optics are interferometrically aligned and bonded during initial assembly

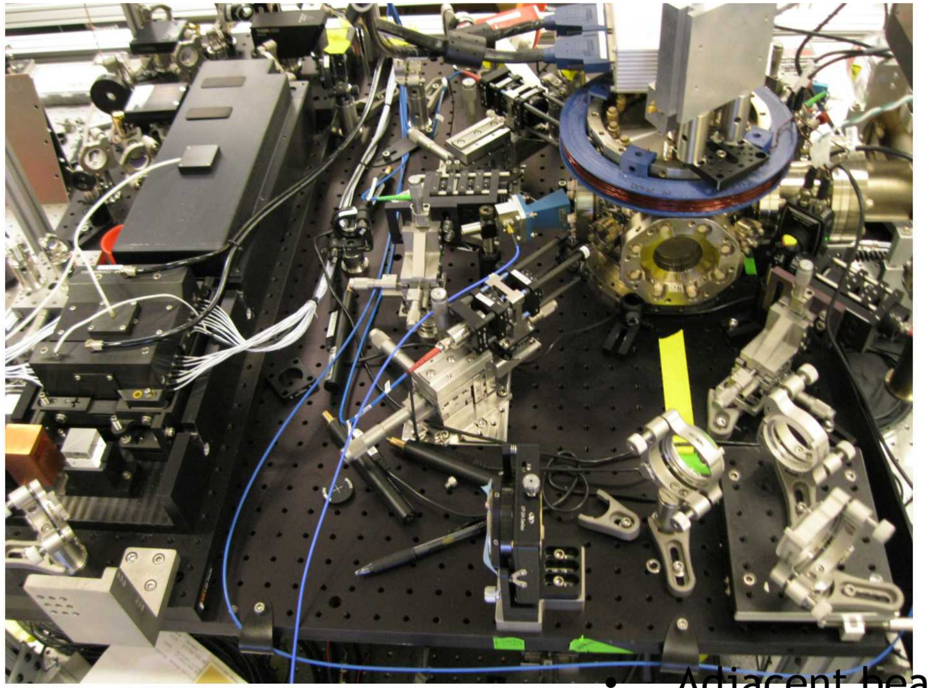


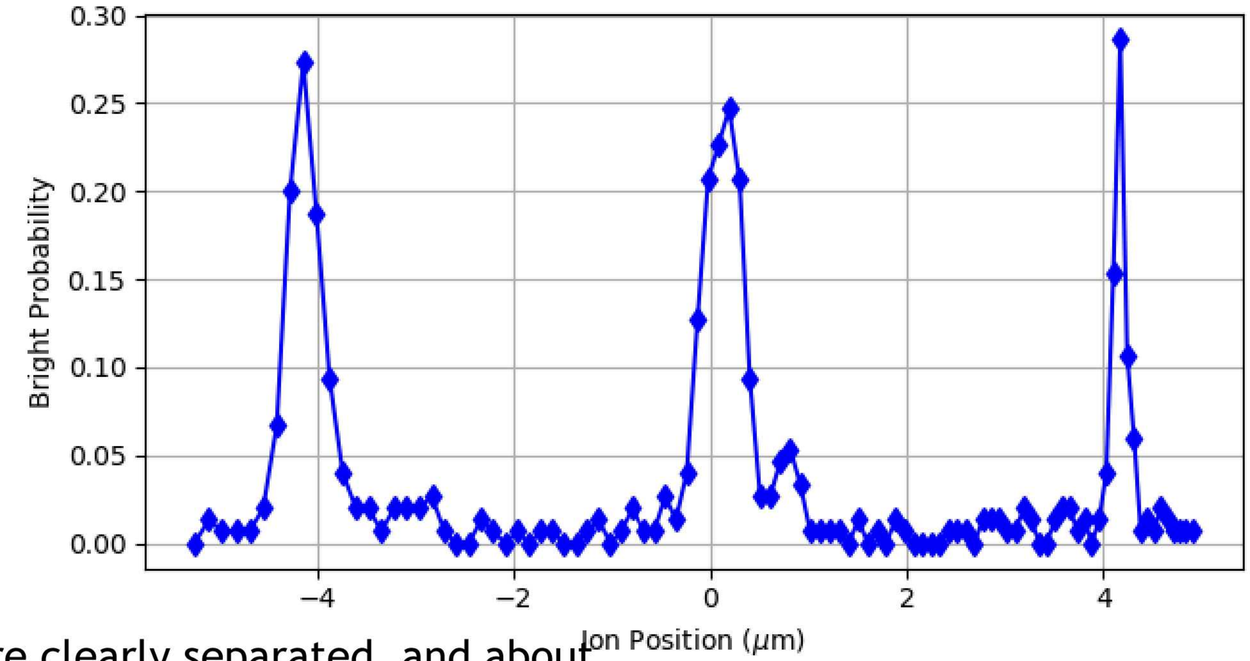


Raman laser individual addressing ion test



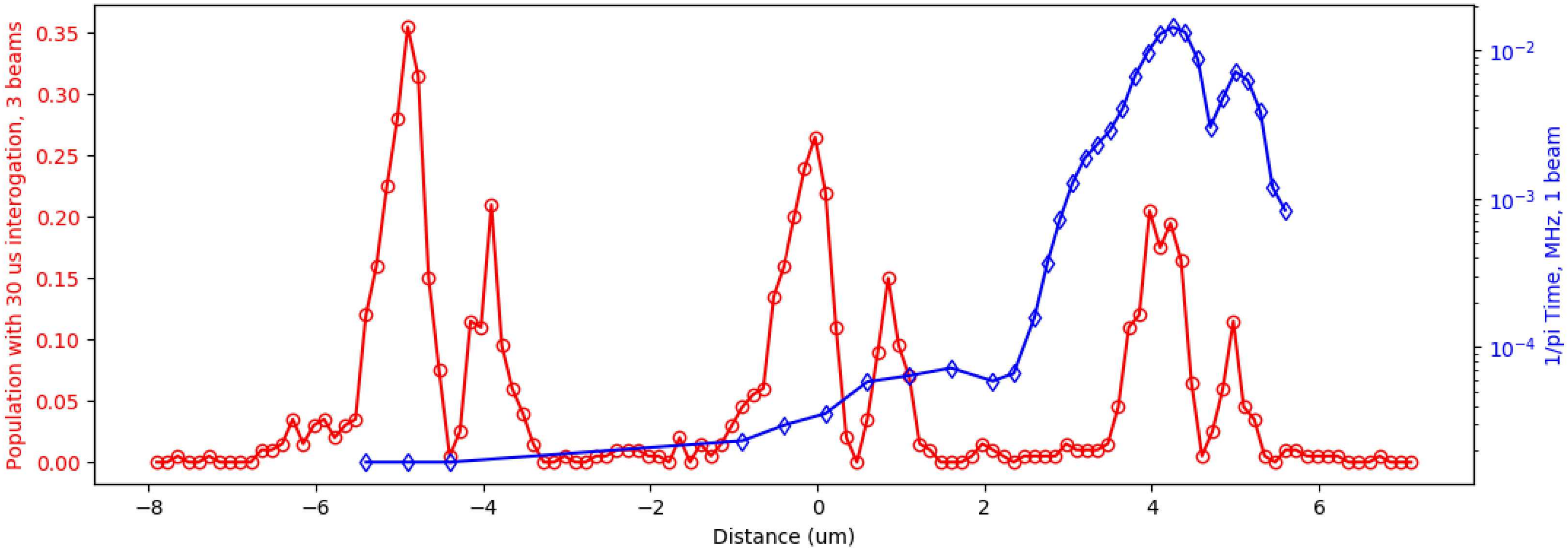
- Co-propagating Raman transitions
- Three central beams are illuminated
- A single ion is moved through the beam
- For each position the probability to flip the spin is measured



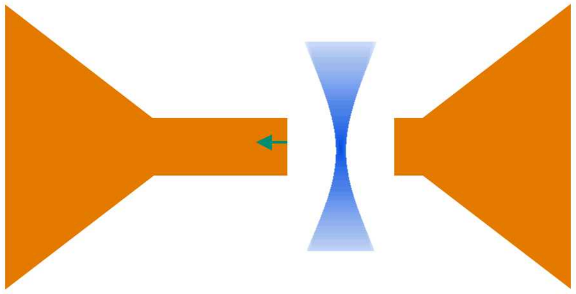


- Adjacent beams are clearly separated, and about 4.5 μm apart
- The beam waists are nearly the designed values.
- The apparent optical crosstalk is small and we are in process to fully characterize

Initial optical crosstalk measurements look promising

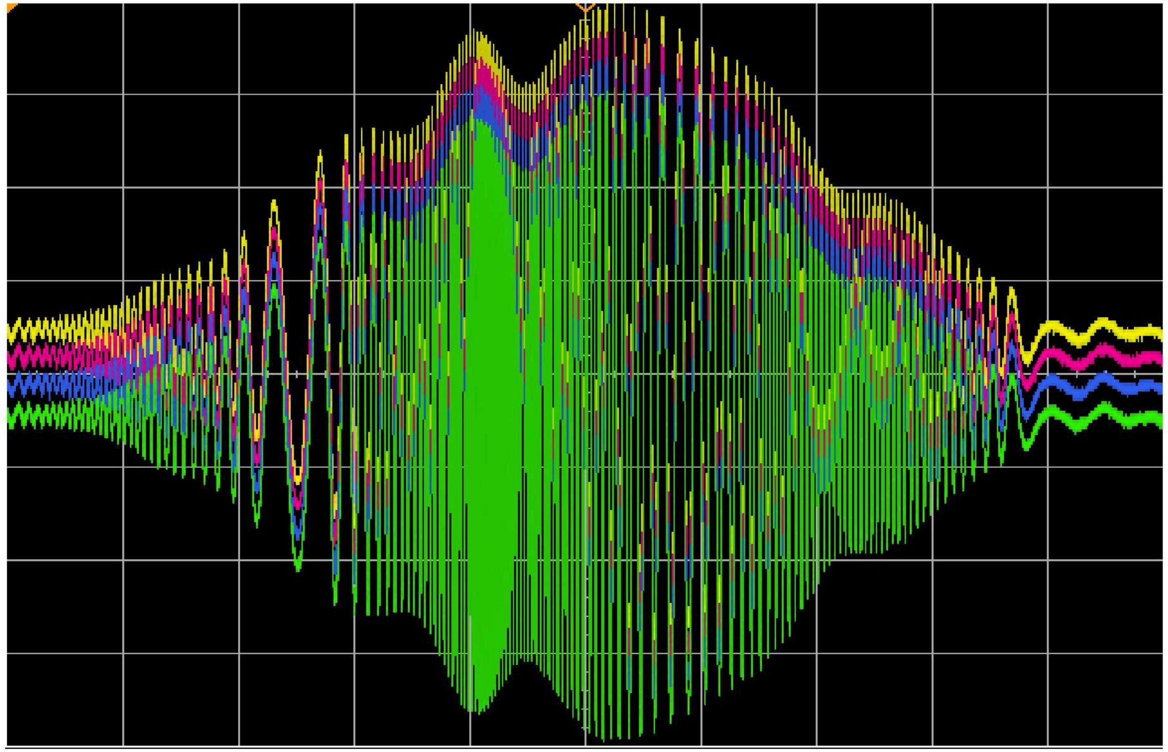


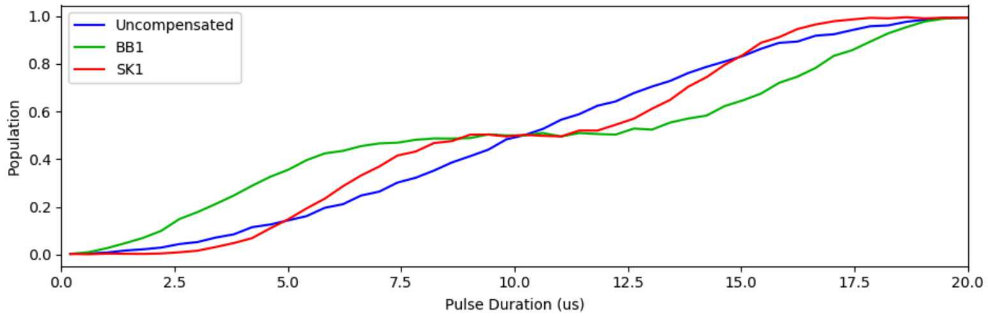
- Concern over crosstalk from Raman beams hitting neighboring ions
- Crosstalk can be optical, acoustic, or electrical
- Measured intensity as ion is scanned through multiple copropagating beams
- Observe multiple orders of magnitude suppression in driven pi time and hope to suppress this further

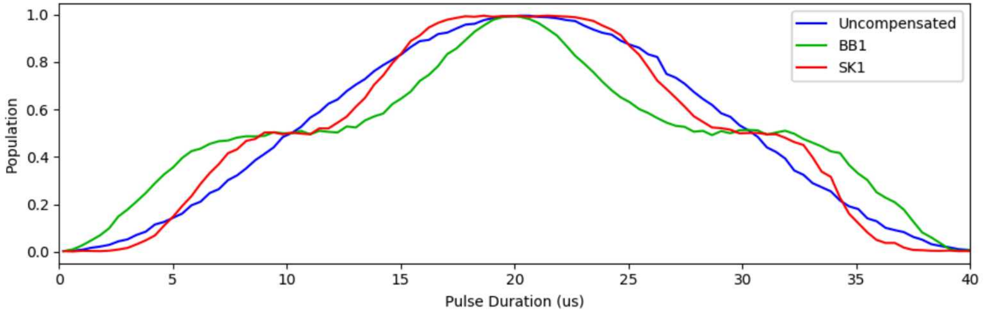


Developed custom electrons: RFSoC for coherent pulse generation

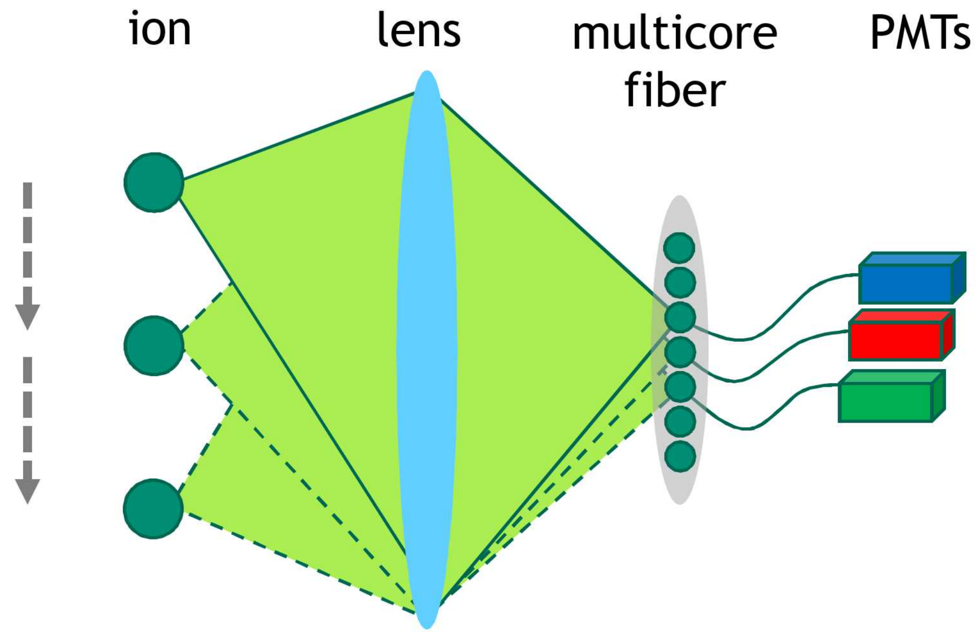
- Two tones per channel
- Coherent output synchronized between all channels
- Pulse envelopes and frequency- phase- modulation defined by splines
- Compact representation of gates for efficient streaming of circuits
- AOM Cross-talk compensation
- All data presented with Raman transitions taken with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



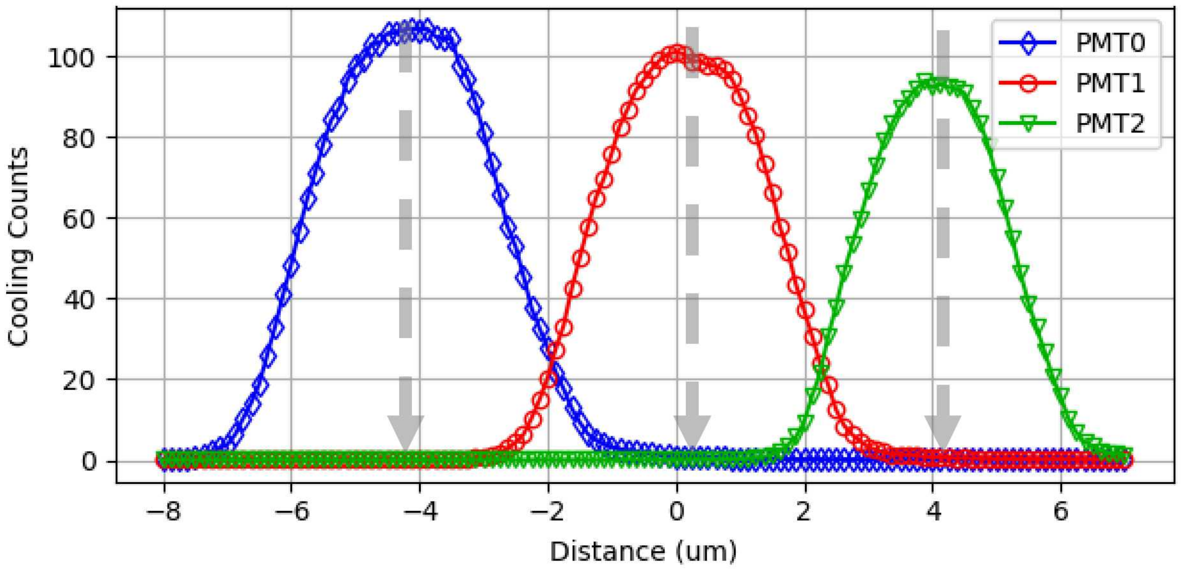




Distinguishable detection for multiple ions



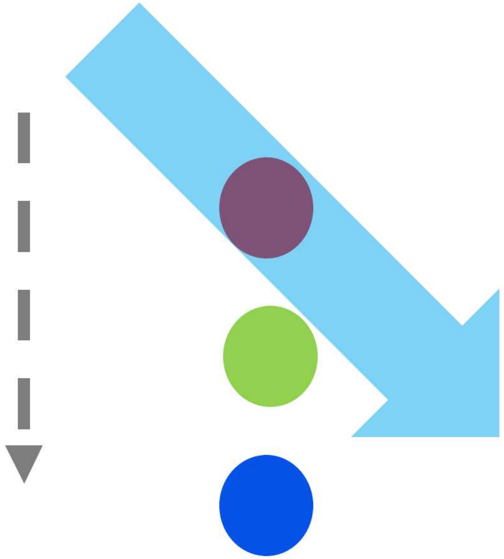
Less than 0.5% detection crosstalk (not including threshold detection) with >90% throughput measured on the PMTs

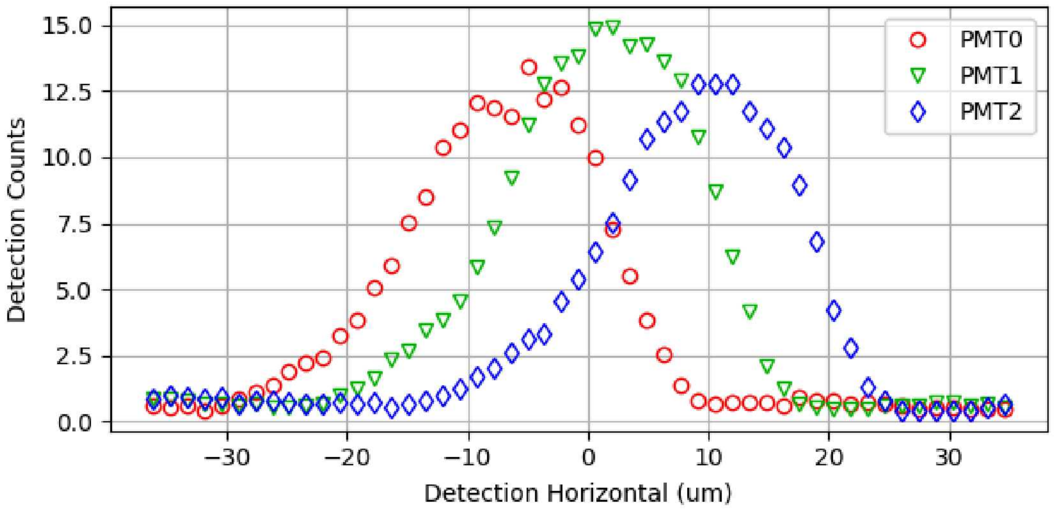


PMT 0	106.5	0.9	0.1
PMT 1	0.1	101.0	0.7
PMT 2	0.0	0.1	92.3

Progress towards individual optical pumping

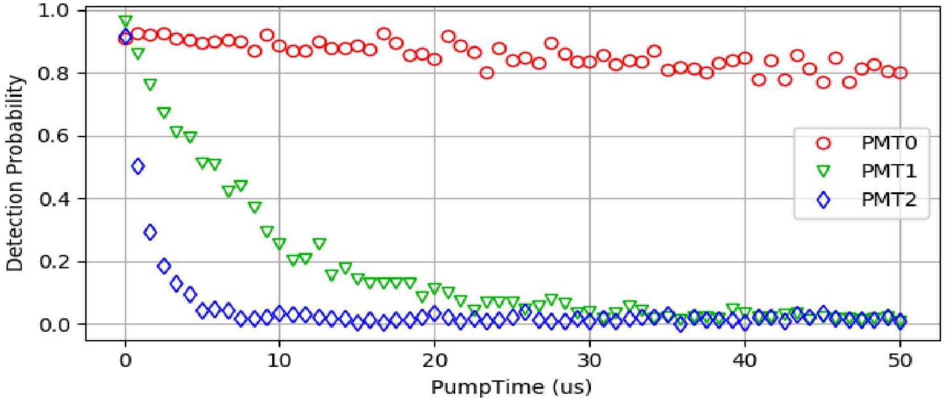
Moving detection light through three ions and looking at florescence of each ion





Ion spacing ~ 10 um, beam waist ~7 um

Observing optical pumping efficiency on each of three ions for different optical pumping beam positions (ideally only one ion is optically pumped efficiently – not the case here)



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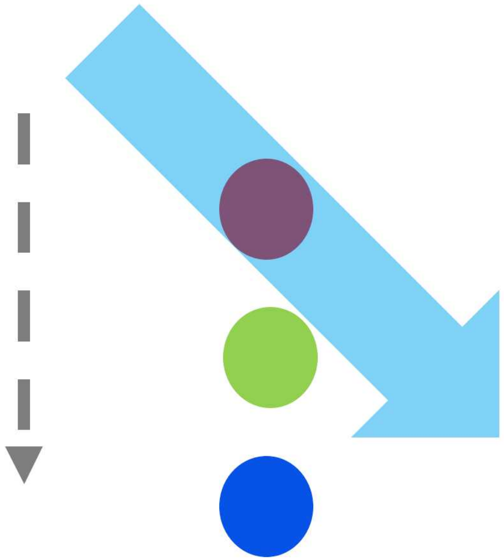

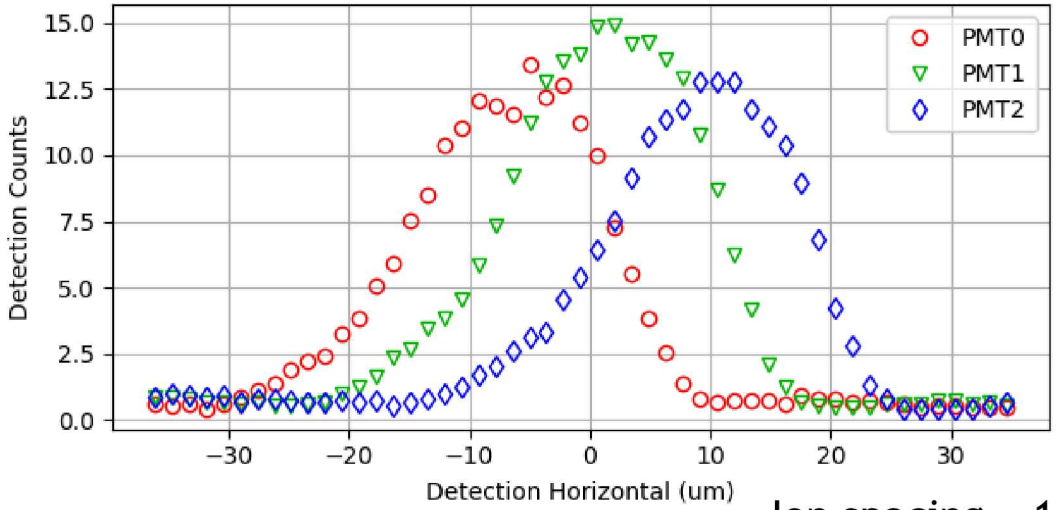

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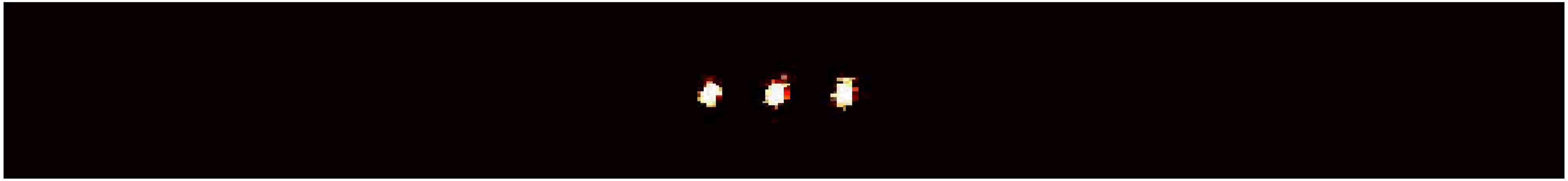
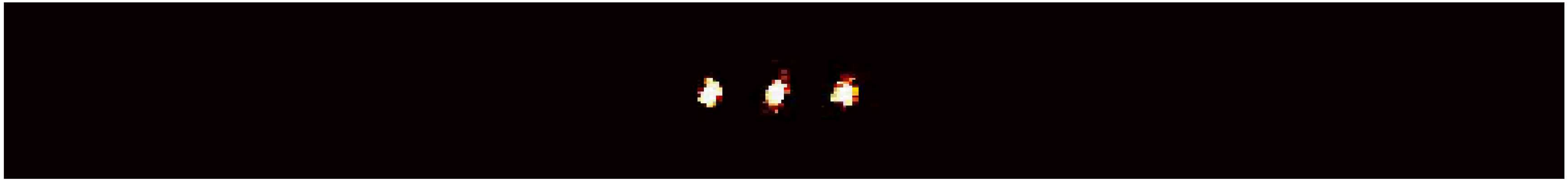


Next steps

- Implement and characterize two qubit gates
- Further minimize the overlap for our individual optical pumping
  - Look at relaxing the trap to increase spacing
- Finish characterizing the individual addressing setup
  - Improve coherence times (comparable to global addressing coherence)
  - Apply crosstalk minimization algorithms with RFSoC



Thank you

RF Engineering
Christopher Nordquist
Stefan Lepkowski

Mech. Engineering
Jessica Pehr

Trap design and fabrication
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Ed Heller
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Becky Loviza
John Rembetski
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Anathea Ortega
Tipp Jennings
Andrew Hollowell

Theory
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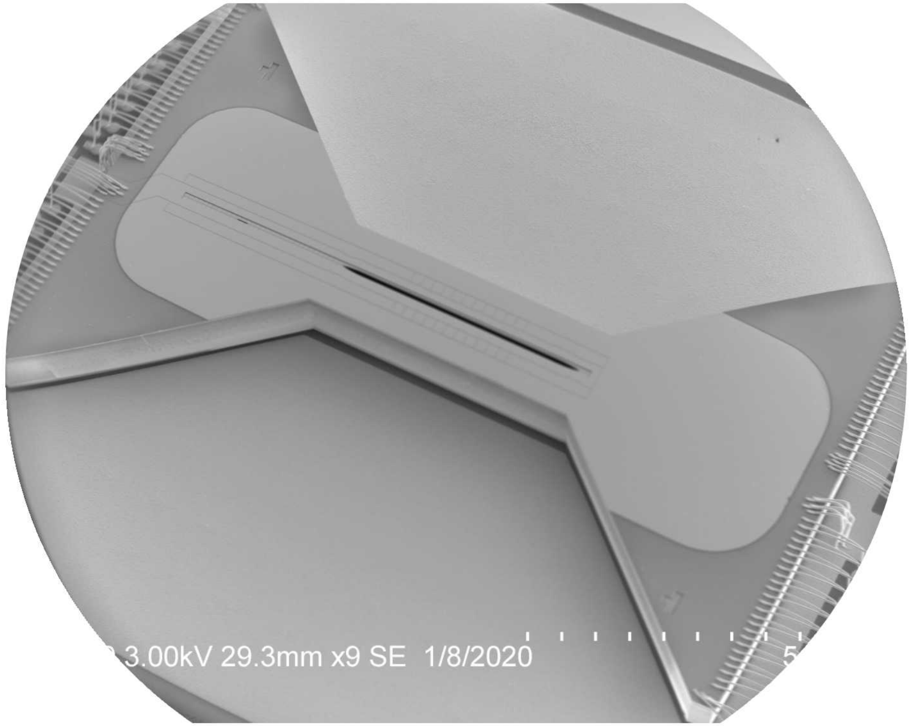
Kevin Young
Robin Blume-Kohout

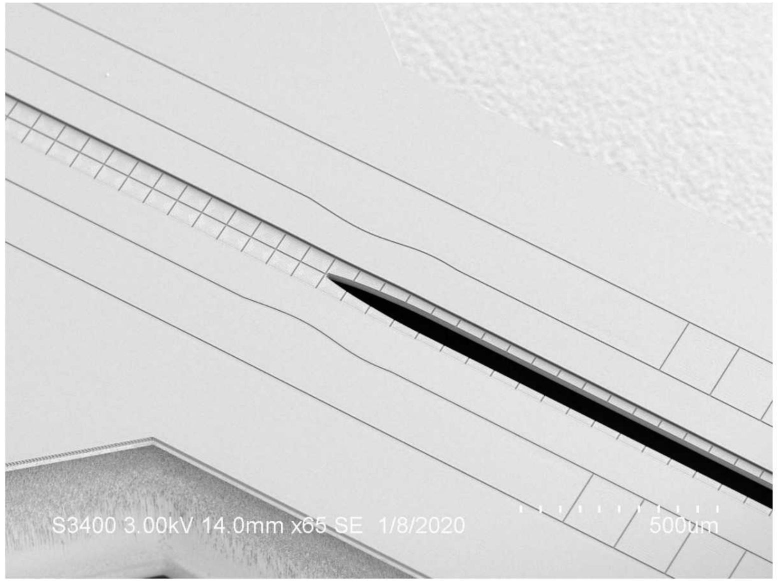
Trap design and testing
Peter Maunz
Susan Clark
Craig Hogle
Daniel Lobser
Melissa Revelle
Dan Stick
Christopher Yale

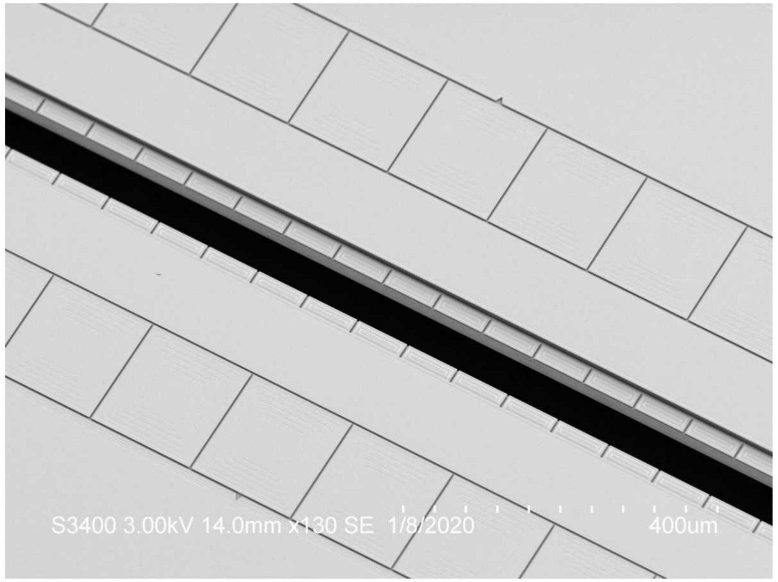
Backup slides

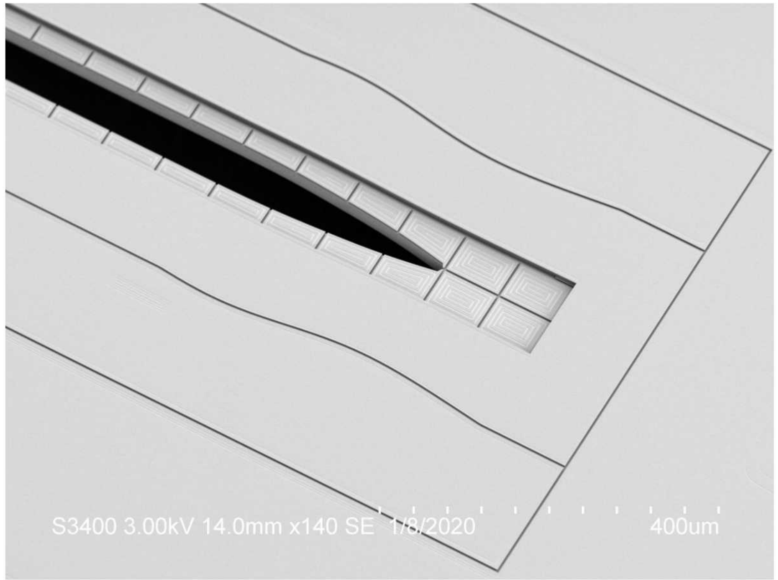
Phoenix trap

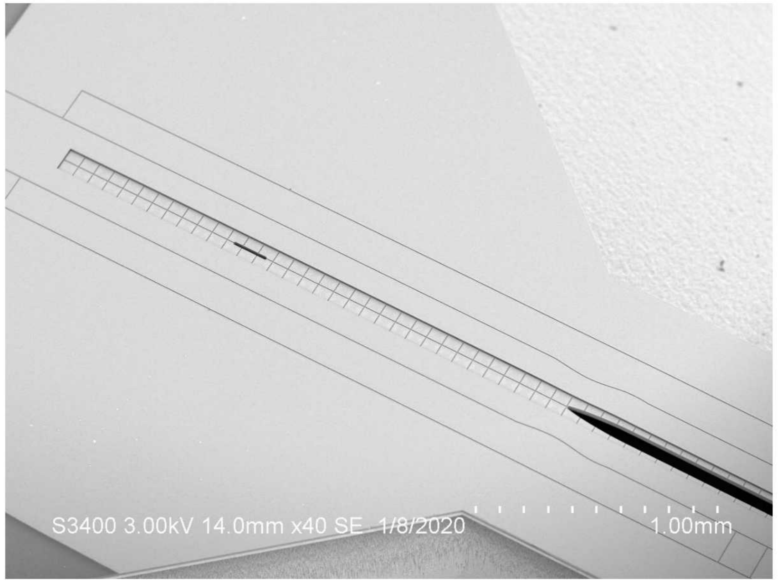


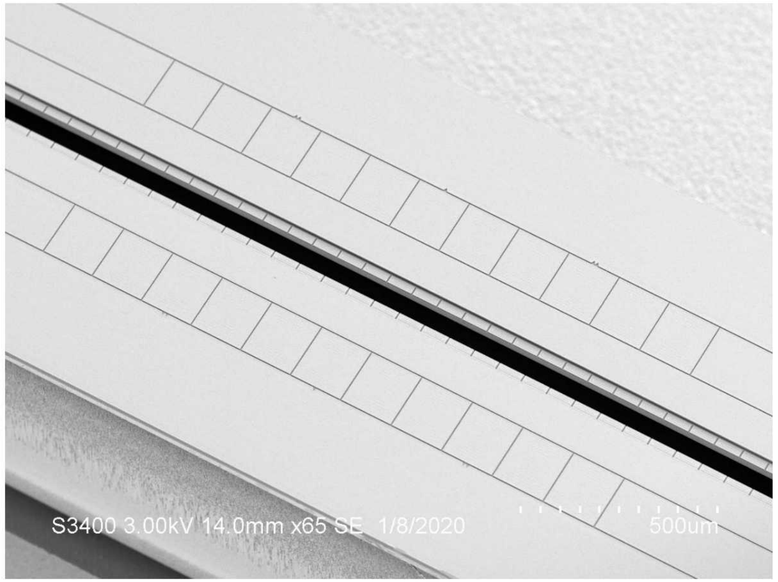
Phoenix trap

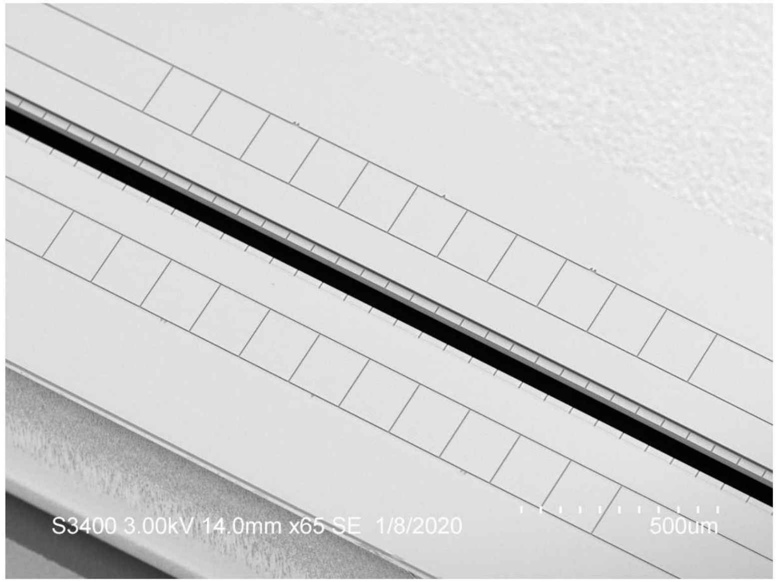




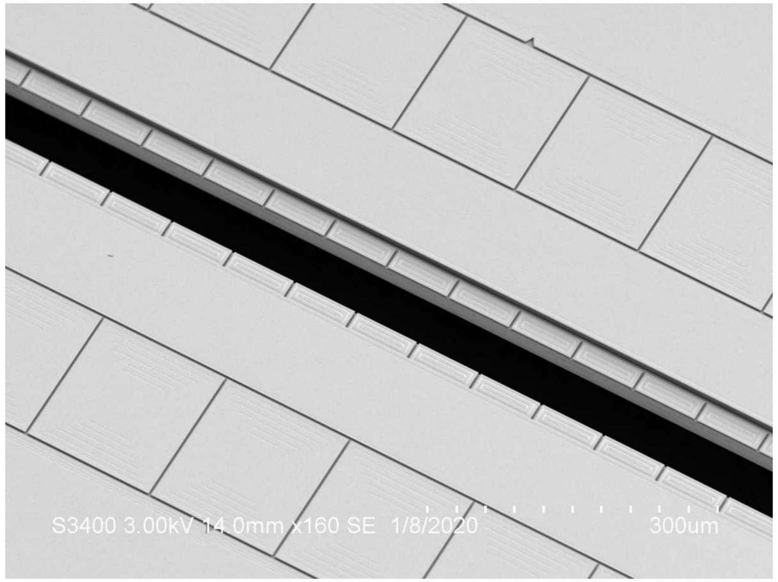








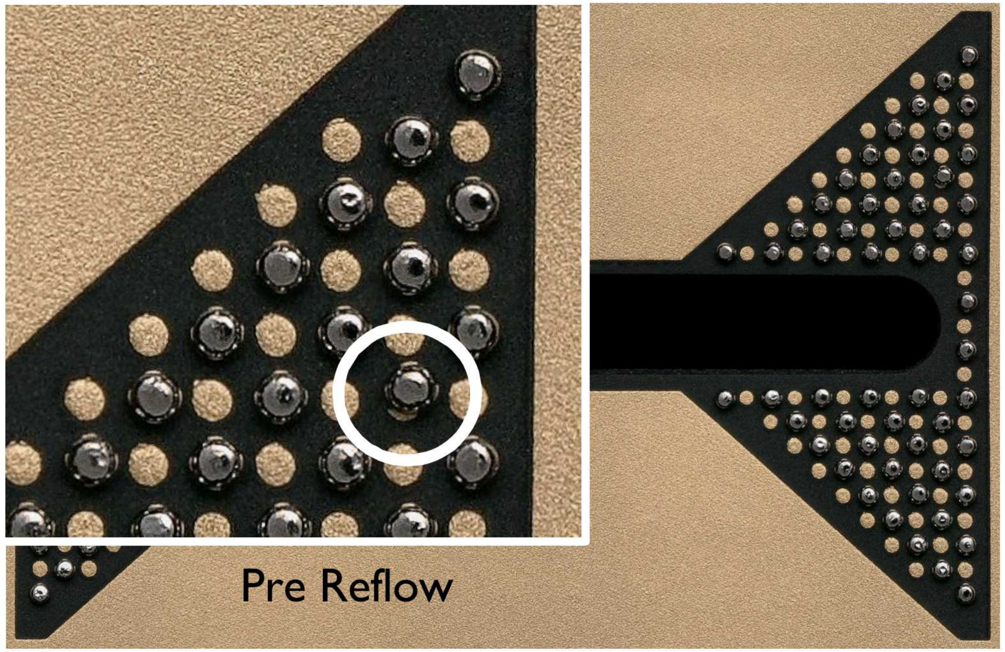
Phoenix trap

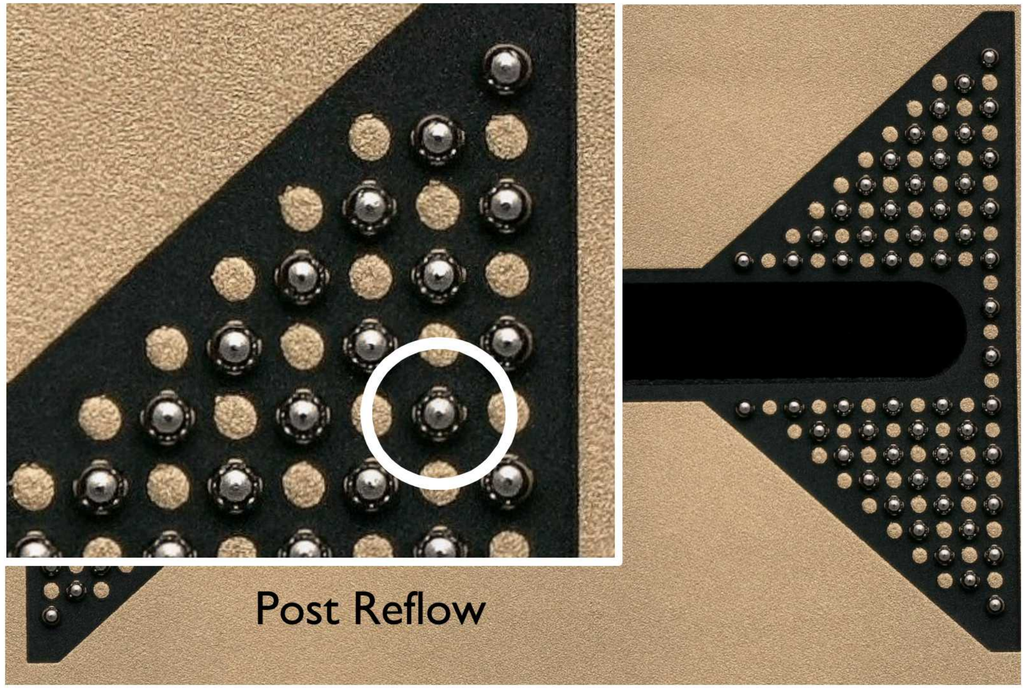


Phoenix Packaging

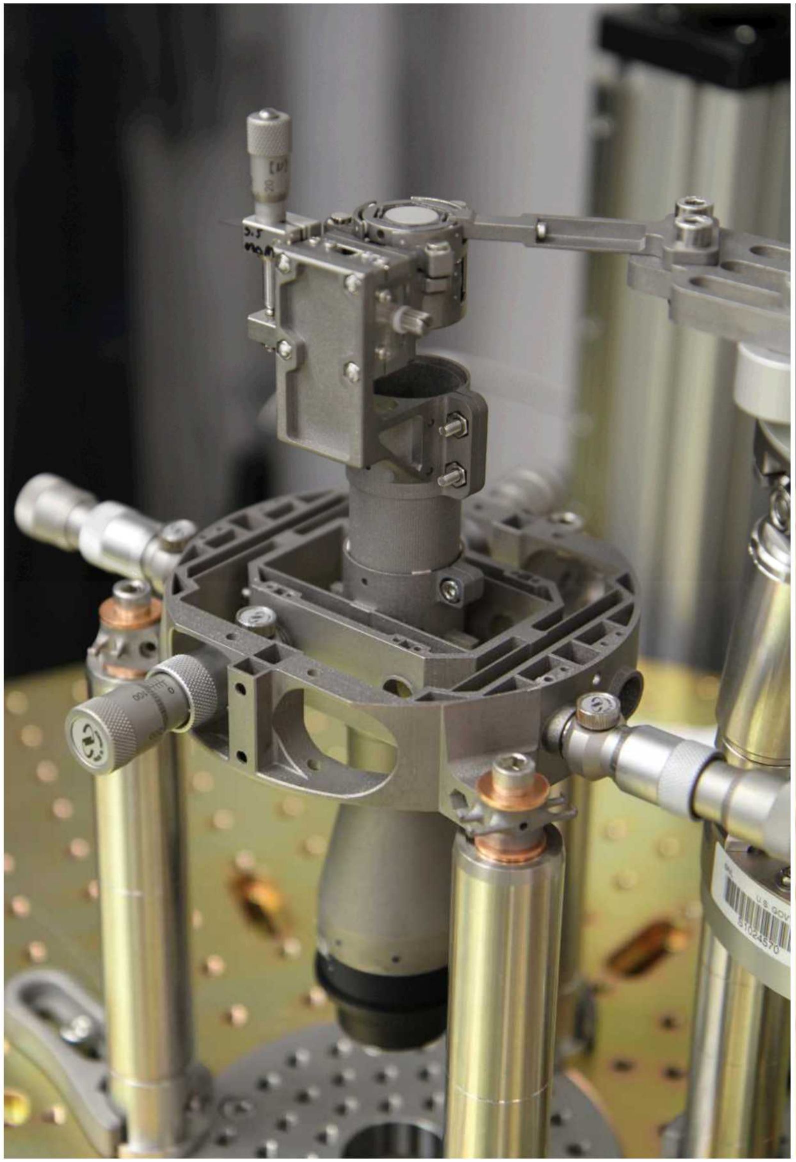
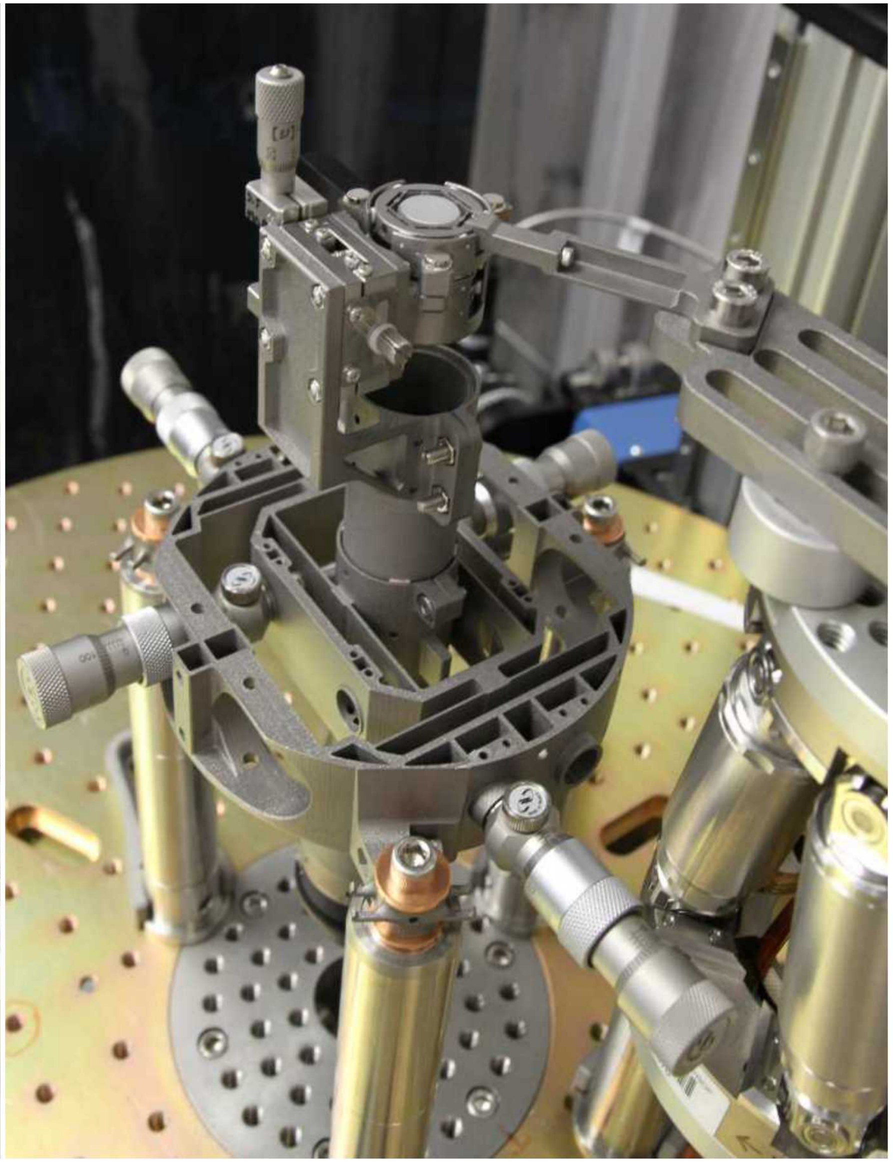
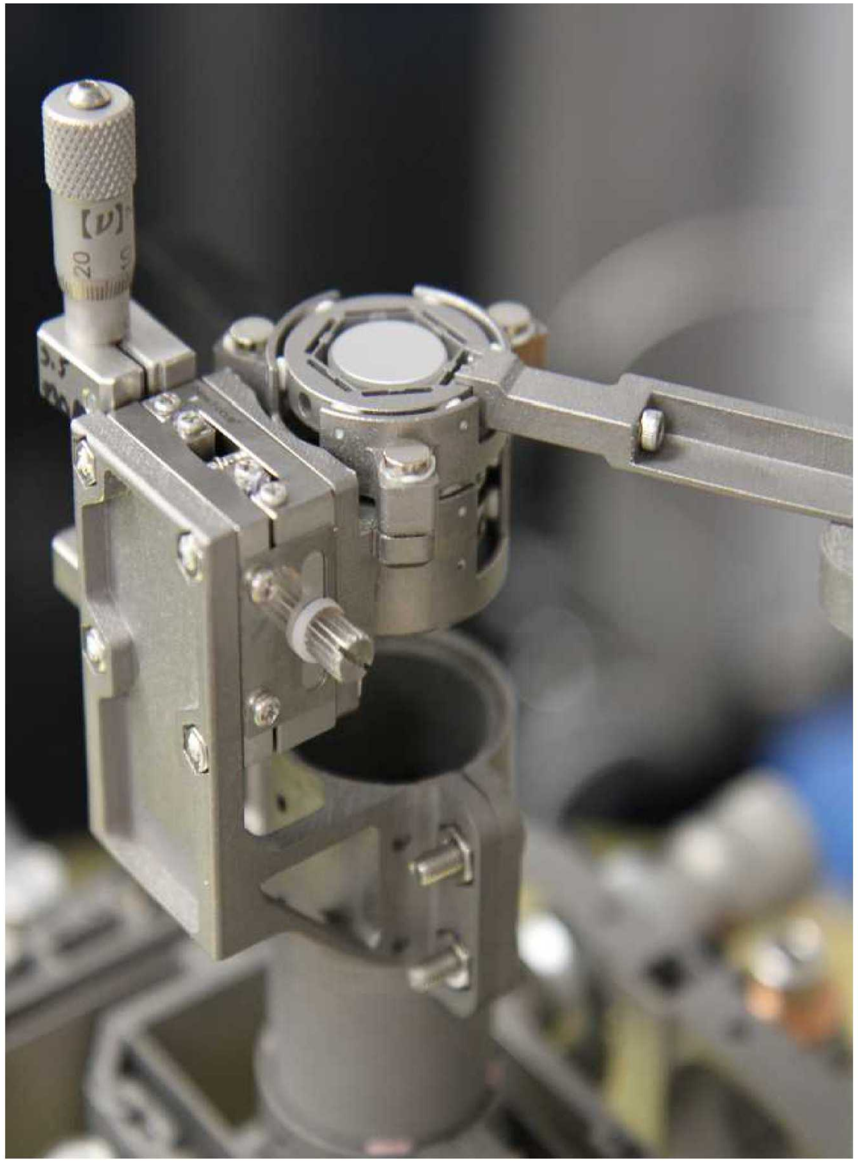
Solder Die Attach

- Removes all packaging organics from chamber
- Solder spheres laser solder “jetted” onto package surface
- Smaller solder spheres are an option
- Spheres auto-center on pads after reflow process
- To be done: shear testing, LN2 dunk and shear tests
- Smaller solder spheres and populate every pad


Pre Reflow


Post Reflow

Individual Addressing Relay Subassembly

Single-Qubit GST Results

- Process infidelity ≈ diamond norm
  - This indicates that we have gotten rid of all systematic errors

Below the threshold for fault-tolerant error correction!

See P. Aliferis and A. W. Cross, Phys. Rev. Lett. 98, 220502 (2007)

- Co-propagating gates have infidelity comparable to microwave gates, but diamond norm indicates some residual control errors

- Counter-propagating gates are noticeably worse, but are necessary for two-qubit gates
- Lower fidelity presumably results from anomalous heating and optical phase sensitivity

Microwave Gates

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	$7.2(7) \times 10^{-5}$	$8.1(15) \times 10^{-5}$

Laser Gates

co-propagating

Gate	Process Infidelity	1/2 ◊-Norm
G_I	$1.17(7) \times 10^{-4}$	$5.3(2) \times 10^{-4}$
G_X	$5.0(7) \times 10^{-5}$	$3(6) \times 10^{-4}$
G_Y	$6.9(6) \times 10^{-5}$	$4(9) \times 10^{-4}$

counter-propagating

Gate	Process Infidelity	1/2 ◊-Norm
G_I	$11.1(6) \times 10^{-4}$	$22.8(1) \times 10^{-4}$
G_X	$4.0(4) \times 10^{-4}$	$13.2(6) \times 10^{-4}$
G_Y	$4.1(4) \times 10^{-4}$	$8.4(8) \times 10^{-4}$

Two-Qubit GST

Typical Approach: Entangled State Fidelity

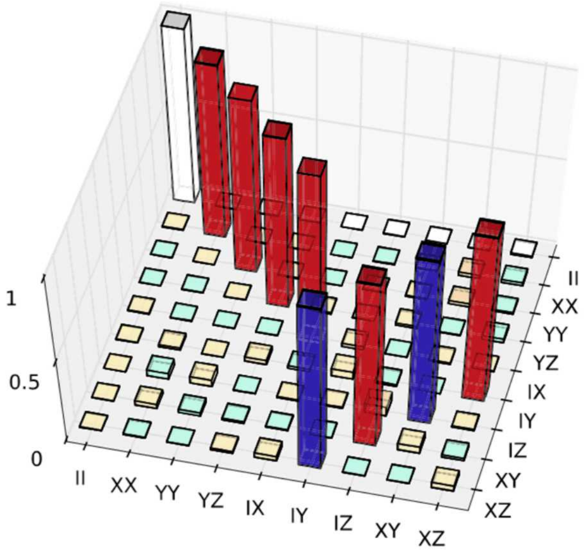
$$\mathcal{F} = \frac{1}{2}\left(P(|00\rangle) + P(|11\rangle)\right) + \frac{1}{4}c \approx 0.995$$

Two-Qubit GST

- Provides a true *process* fidelity
- Requires an extremely stable gate to take long GST measurements without constant recalibration
- Currently limited to the symmetric subspace

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

95% confidence intervals

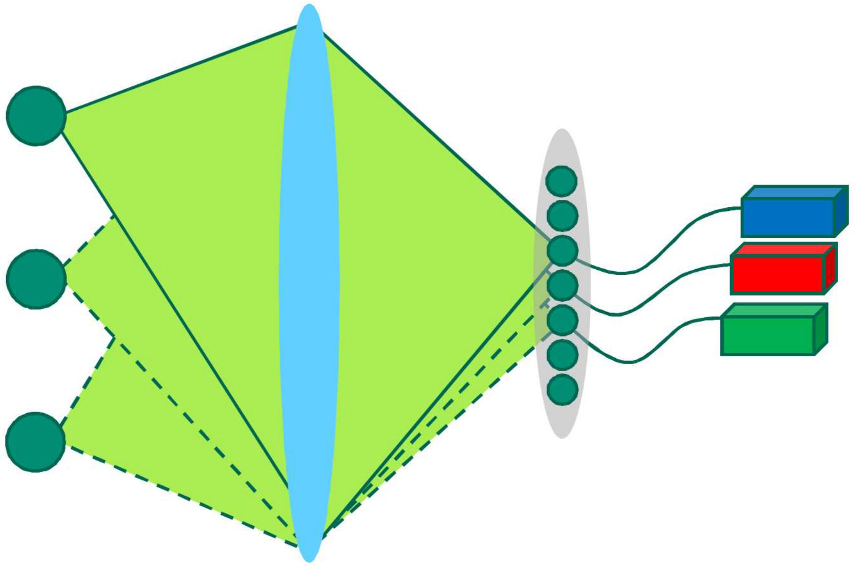


$$F_{MS} = 0.9958(6)$$

$$\frac{1}{2}||G_{MS}||_{\diamond} = 0.08(1)$$

- Much more rigorous characterization
- Gate is stable for several hours

Distinguishable Detection



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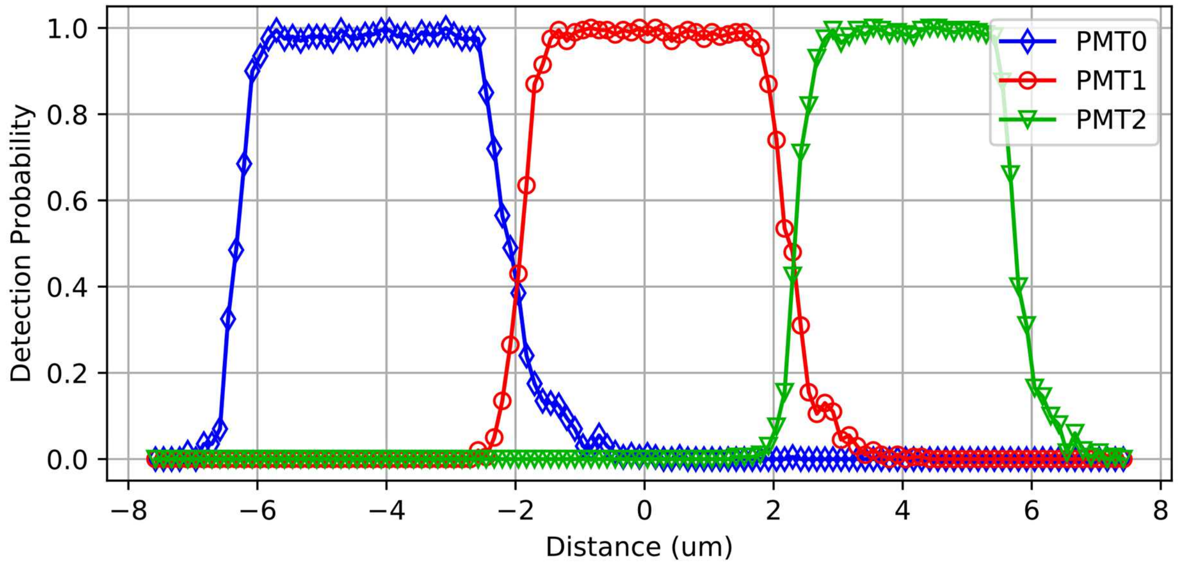
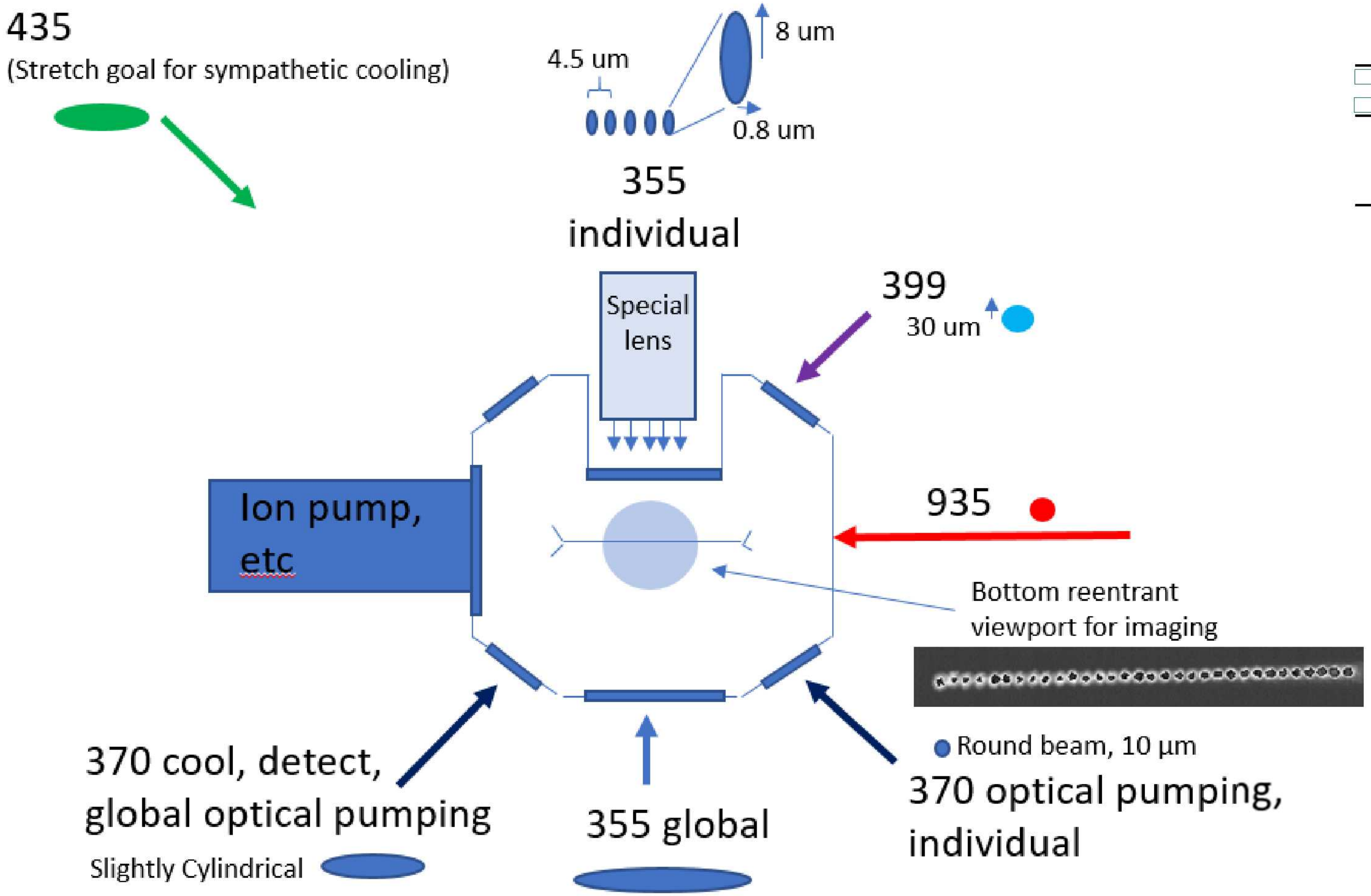
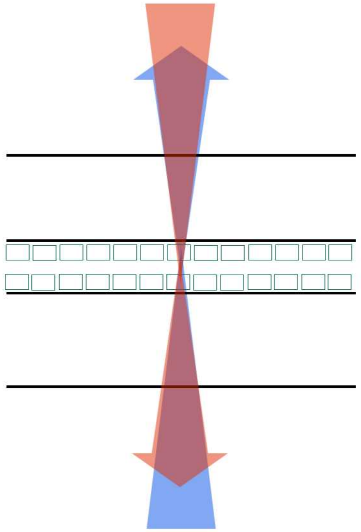


PMT 0	0.985	0.005	0.000
PMT 1	0.000	1.000	0.005
PMT 2	0.000	0.000	0.980

Experimental apparatus





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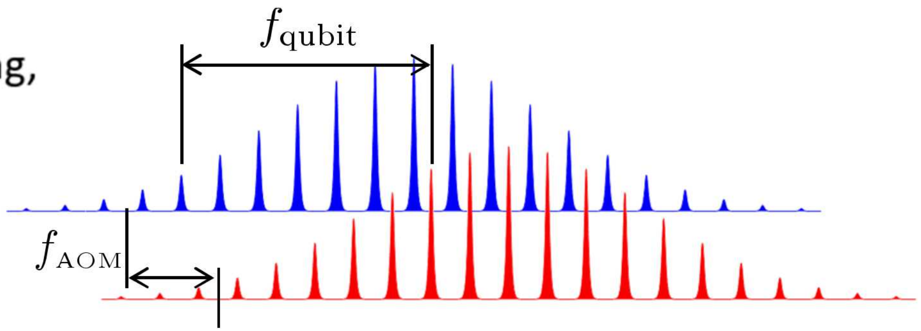
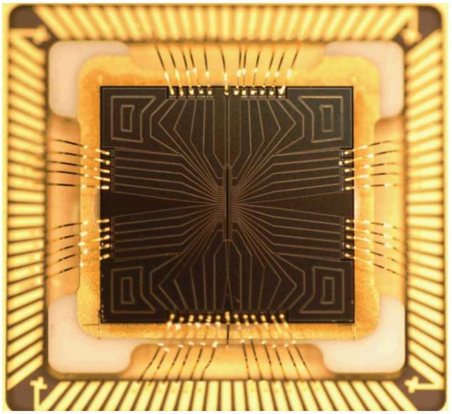


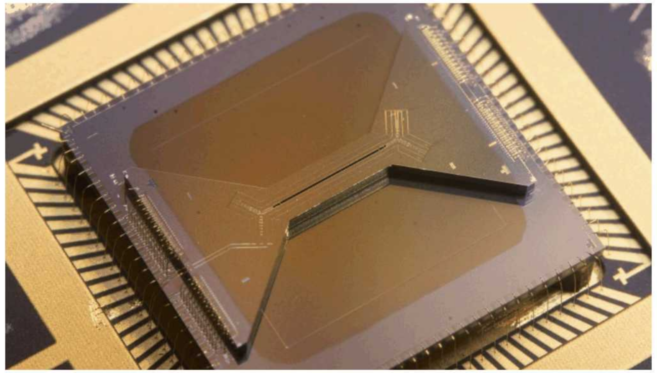
Evolving microfabricated ion traps at Sandia

Thunderbird Trap



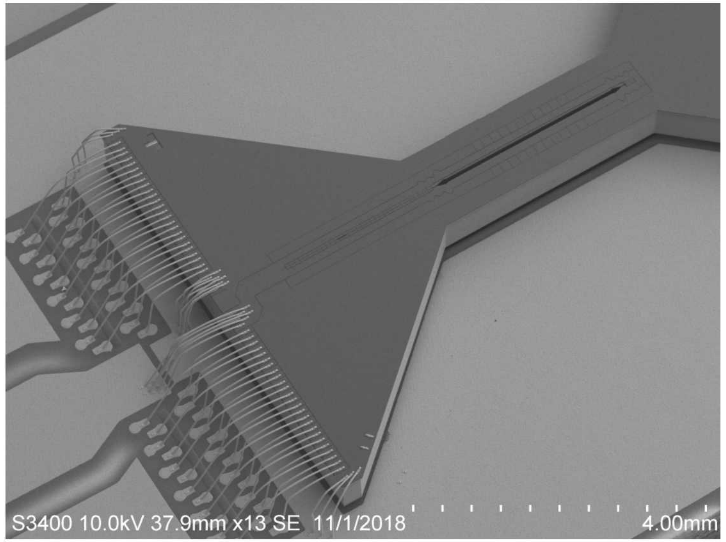
- Sandia's "claim to fame" in microfabricated traps
- 2 metal levels
- 48 I/O
- No exposed dielectric

High Optical Access Trap Platform



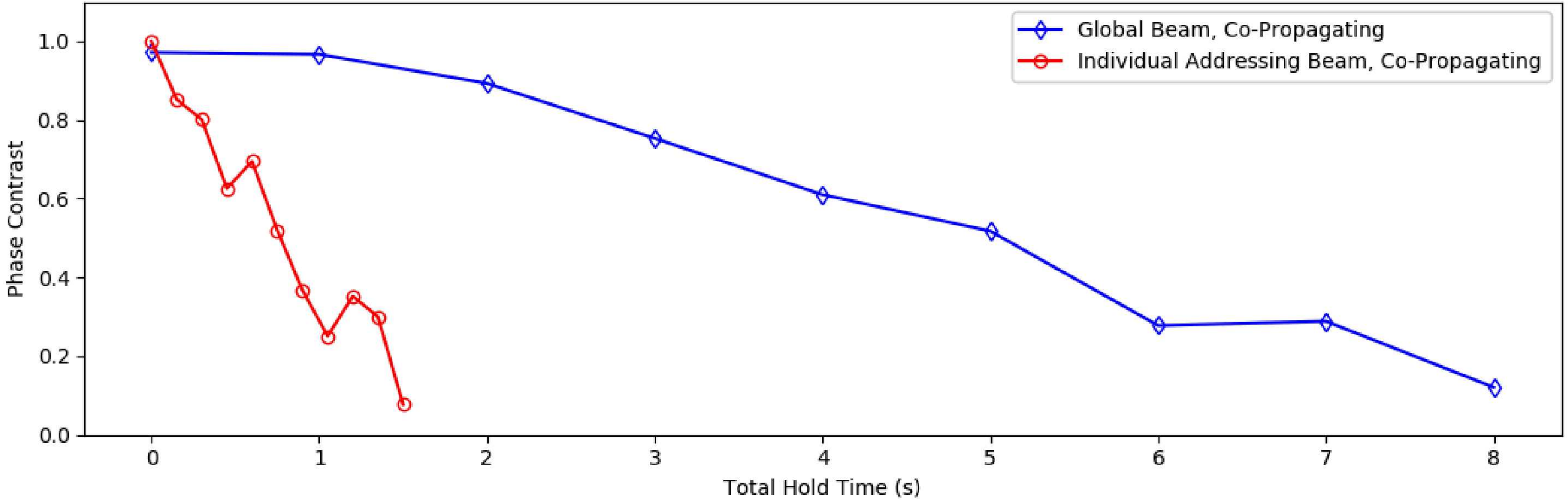
- Sandia invented the high optical access ion trap
- Realized through MEMS-like release singulation process
- 4 metal levels realized for electrical routing
- No exposed dielectric
- 94 I/O

Phoenix Trap



- Reduction of rf dissipation in device
- Additional electrode segmentation to control long ion chains
- Enable shuttling while maintaining trap characteristics
- Improve slot sidewall to enable continuous metal film
- Integrated trench capacitors on device
- Packaging with solder die attach on custom SiN ceramic package (eliminates organics)

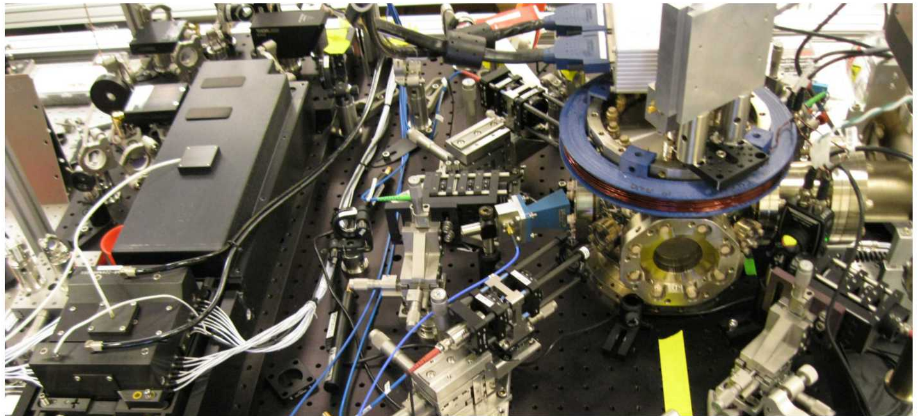
Coherence measurements test phase noise on RFSoC

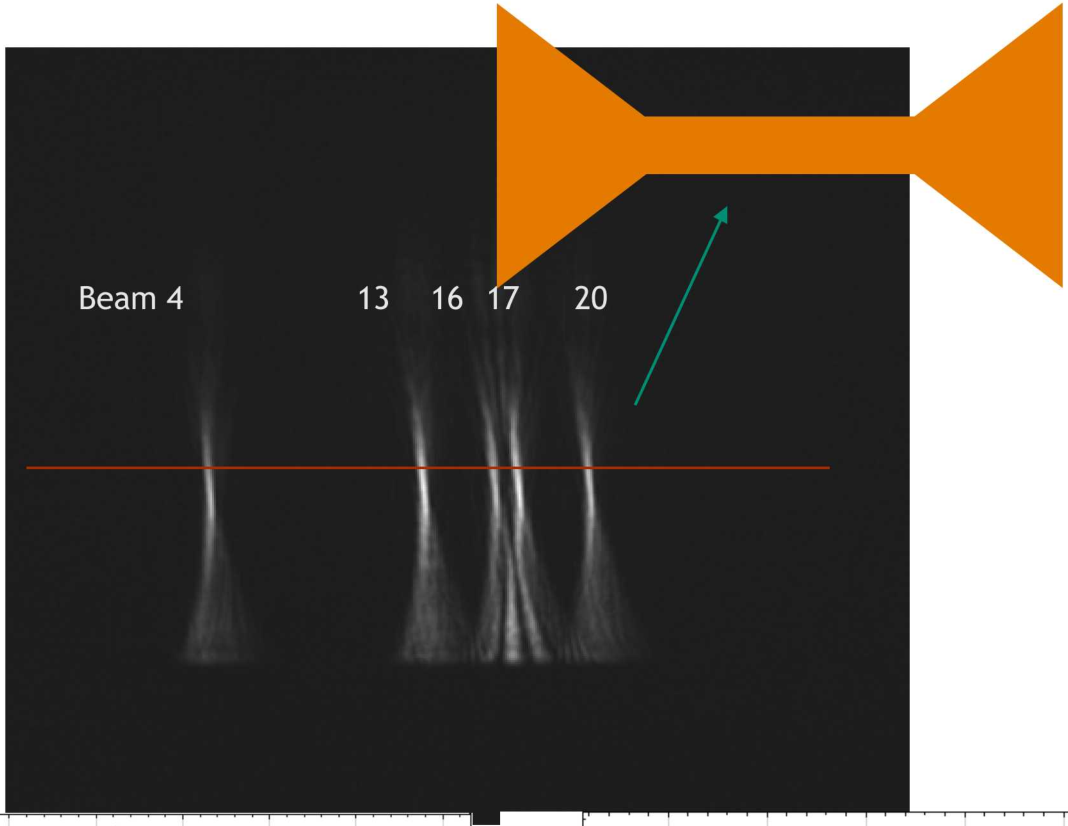


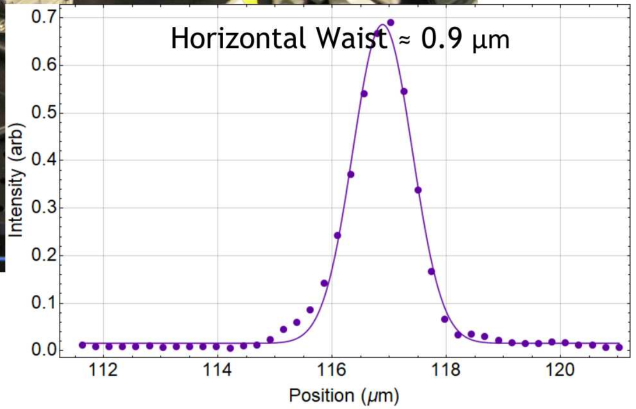
Coherence demonstrates low phase noise on the RFSoC system
System has demonstrated coherence times > 5s with both microwaves and Raman transitions

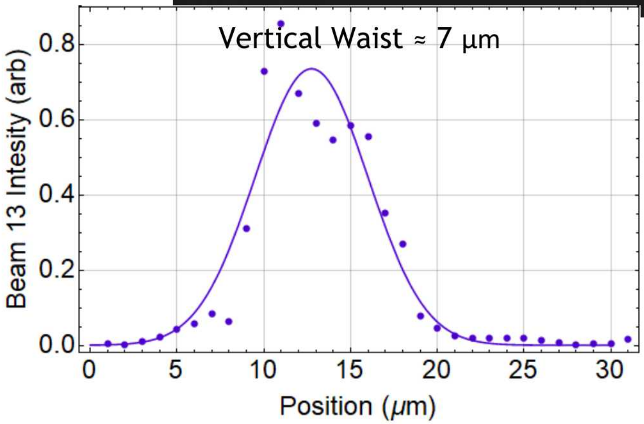
Imaging system works!

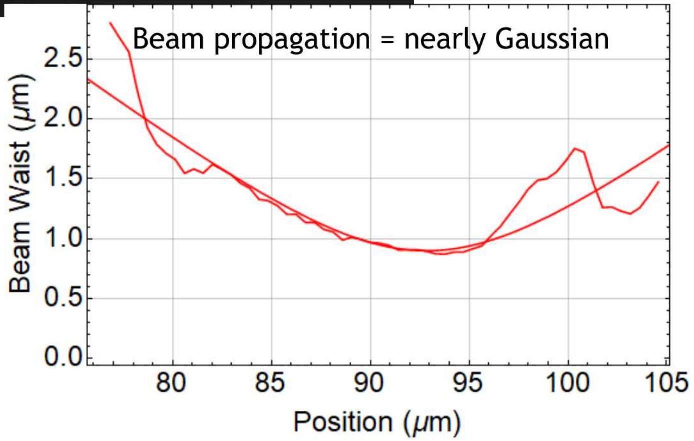
- Adjacent beams are clearly separated, and about 4.5 μm apart
- The beam waists are nearly the designed values.
- The apparent optical crosstalk is small and we are in process to fully characterize



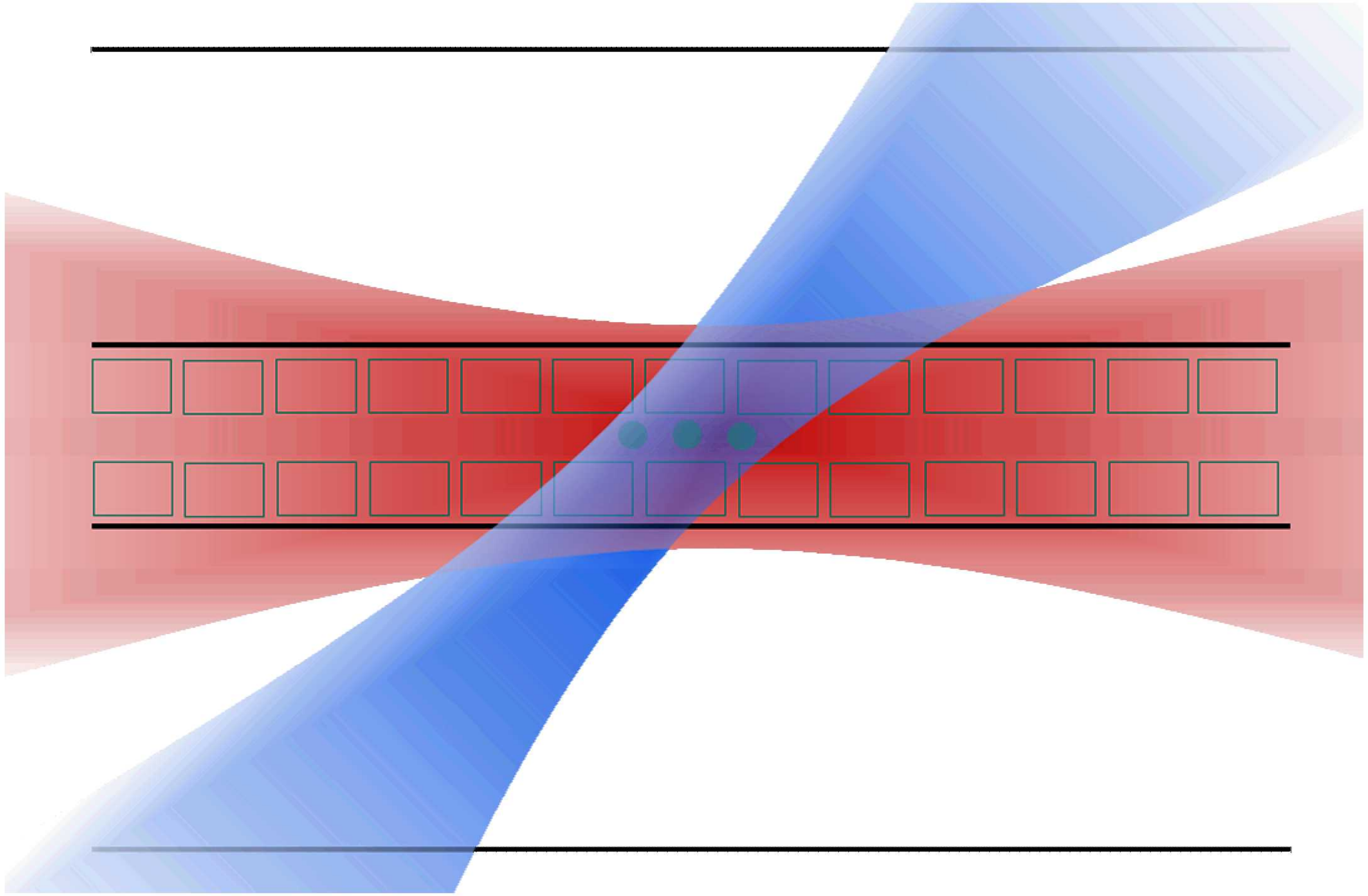


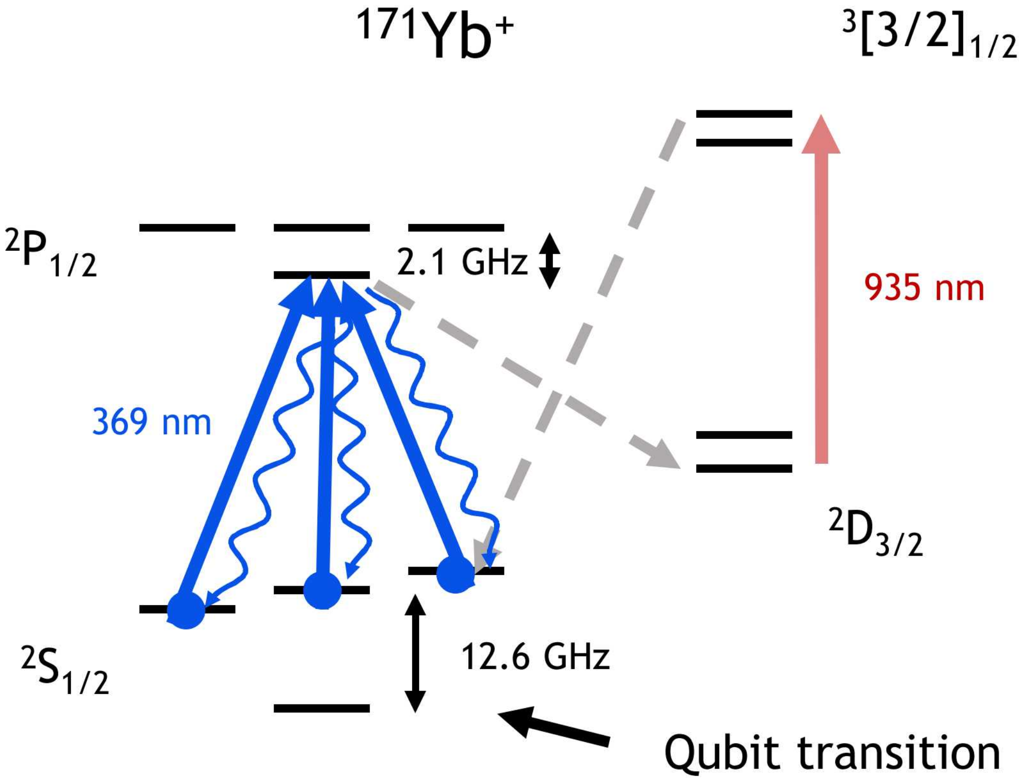




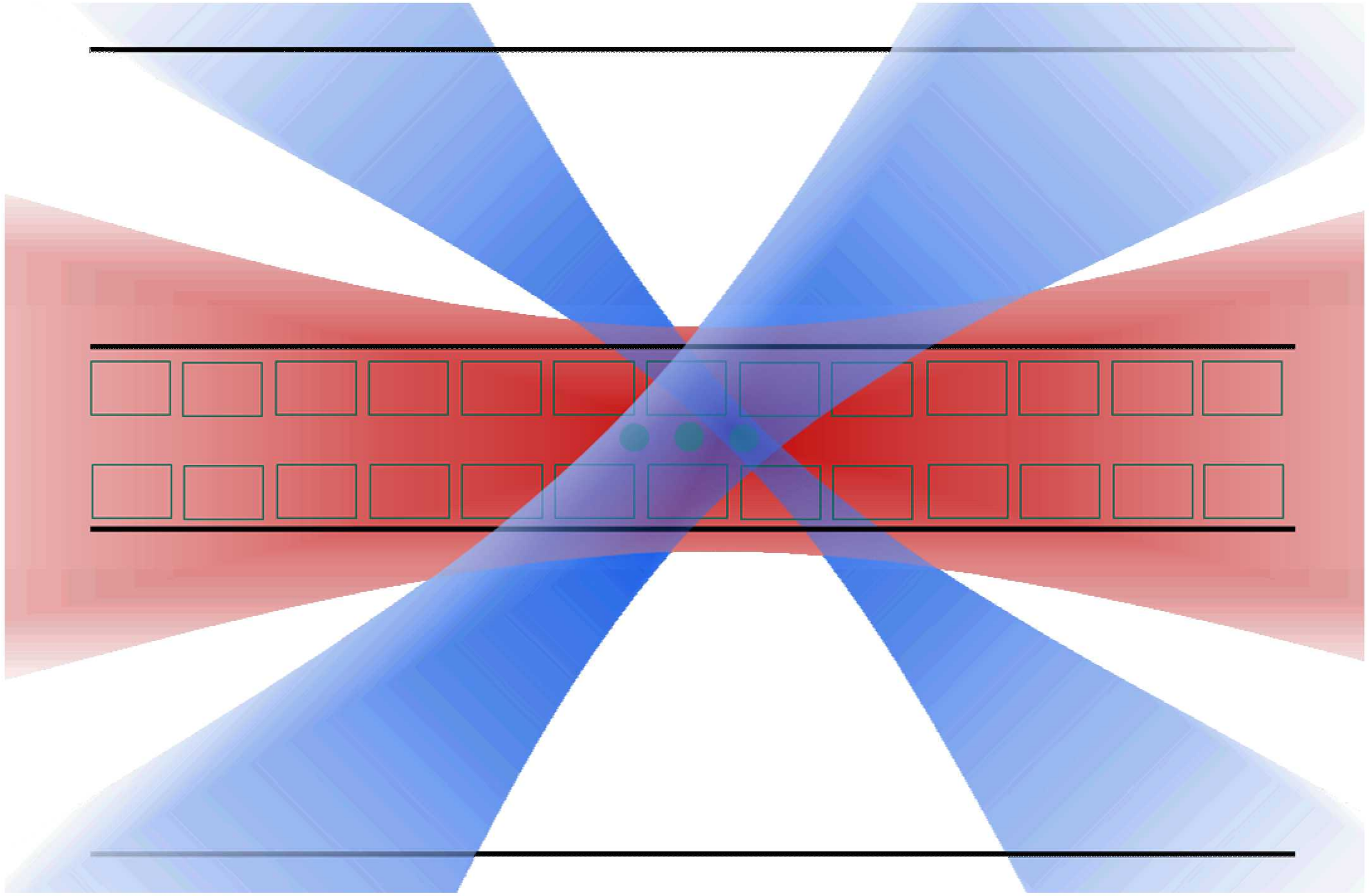


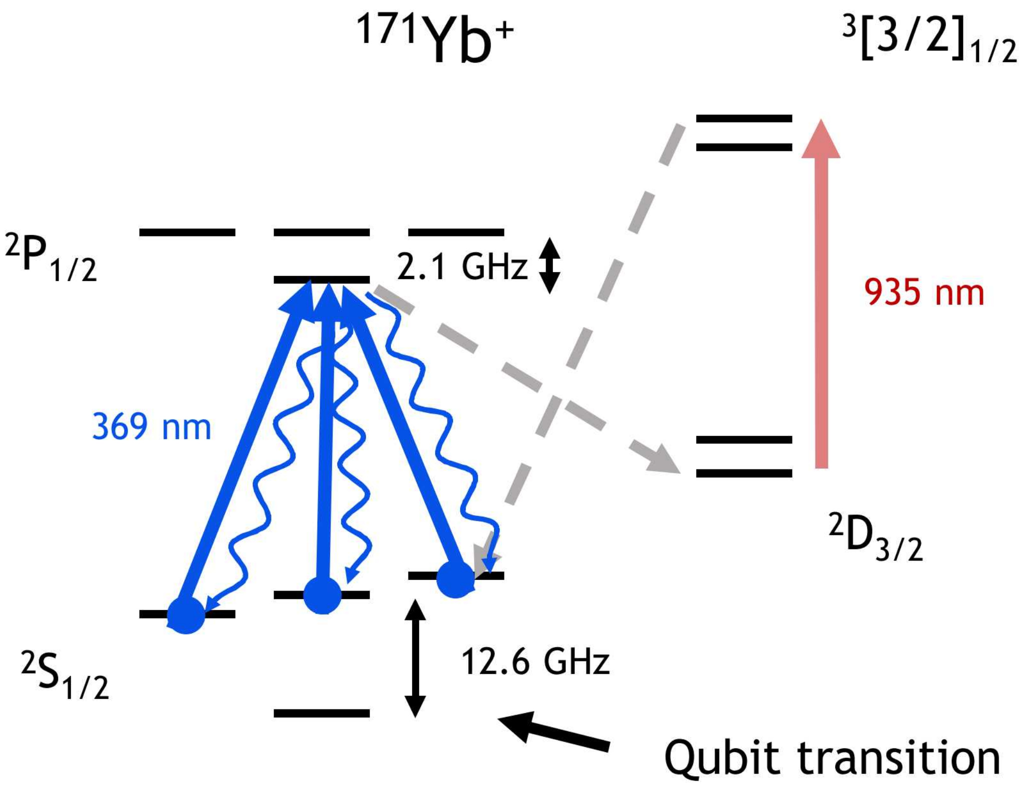
Experimental apparatus – Trapping three ions



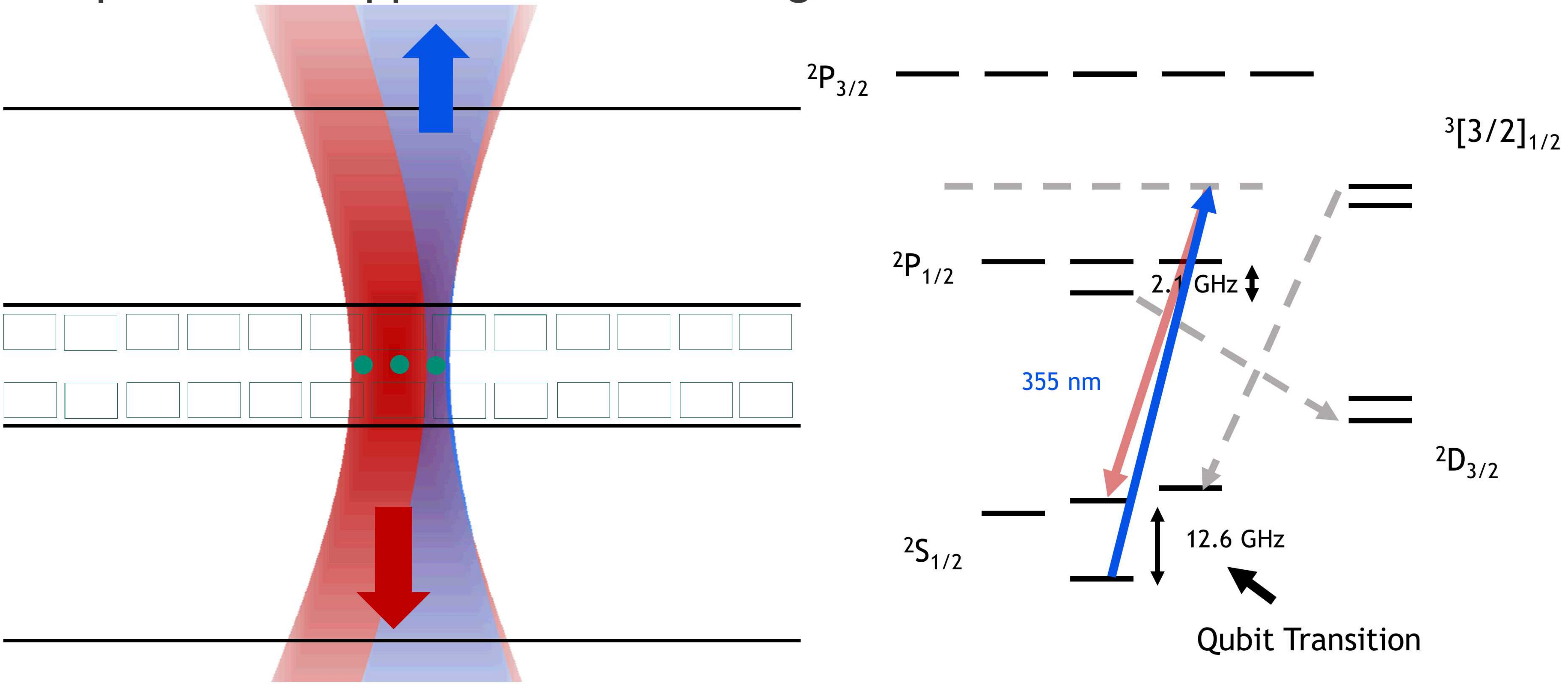


Experimental apparatus – Trapping three ions

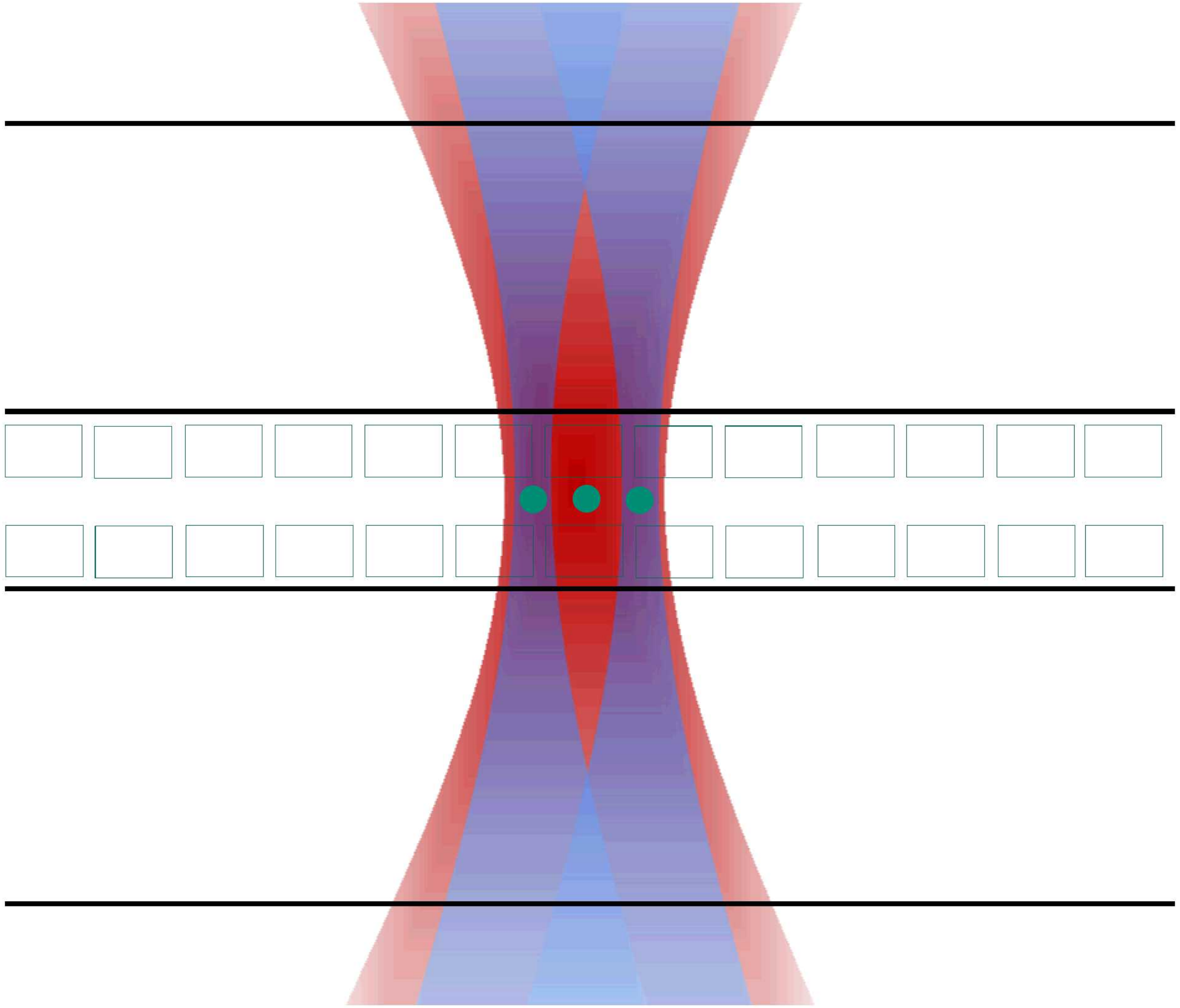


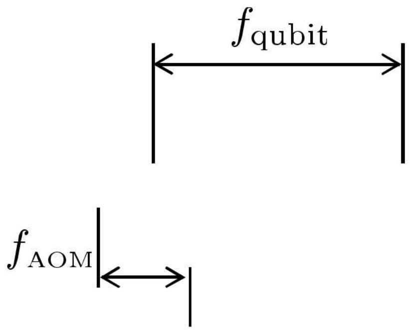


Experimental apparatus – two ion gates



Experimental apparatus – Individual addressing with Raman beams





- Gates performed with microwaves or lasers
- Ions addressed with 355 nm frequency comb
- Raman beams are power stabilized