A high performance microfabricated surface ion trap

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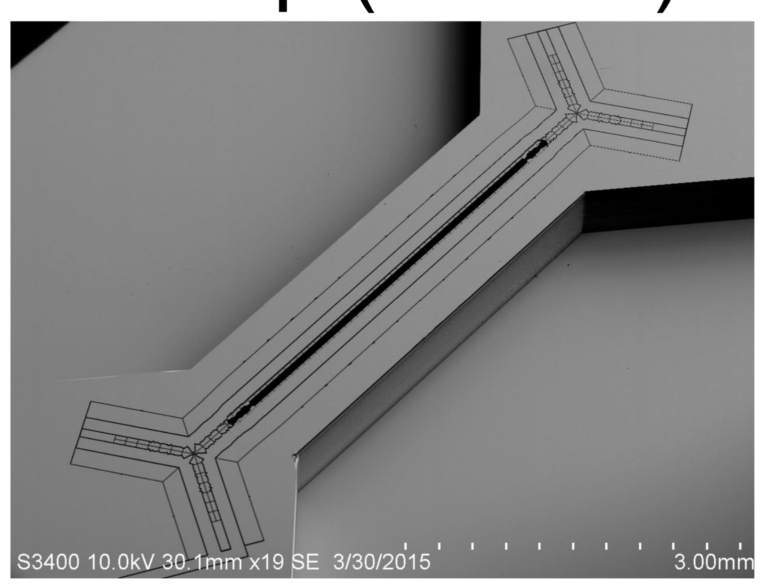
Abstract

Microfabricated surface ion traps present a natural solution to the problem of scalability in trapped ion quantum computing architectures. We address some of the chief concerns about surface ion traps by demonstrating low heating rates, long trapping times as well as other high-performance features of Sandia's high optical access (HOA-2) trap. For example, due to the HOA's specific electrode layout, we are able to rotate principal axes of the trapping potential from 0 to 2π without any change in the secular trap frequencies. We have also achieved the first single-qubit gates with a diamond norm below a rigorous fault tolerance threshold [1,2], and a two-qubit Mølmer-Sørensen gate [3] with a process fidelity of 99.58(6)%. Here we present specific details of trap capabilities, such as shuttling and ion reordering, as well as details of our high fidelity single- and two-qubit gates.

[1] R. Blume-Kohout et al. arXiv:1606.07674.
[2] P. Aliferis and J. Preskill, Phys. Rev. A 79, 012332 (2009).
[3] A. Sørensen and K. Mølmer, Phys. Rev. Lett. 82, 1971 (1999)

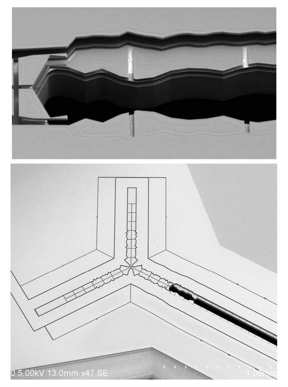
High Optical Access Trap (HOA-2)

- Excellent optical access rivaling 3D traps
  - NA 0.11 across surface
  - NA 0.25 through slot
- High trap frequencies (up to 5 MHz with Yb)
- Precise control over principal axis rotation
- Transition between slotted and un-slotted regions for 2D scalability
- Shuttling in and out of slotted area demonstrated
- Very good trap performance
  - Lifetime over 100 h in Yb while taking data
  - Lifetime > 5 m without cooling
- Low heating rates approx. 100 quanta/s (Yb, 2.5MHz trap freq)



HOA-2.1

- HOA 2.1 has been released and is undergoing initial tests
- Design features include:
  - Fixed floating M2 electrode
  - New RF trace design for reduced RF loss
  - Aluminum wire for heating and temperature measurements

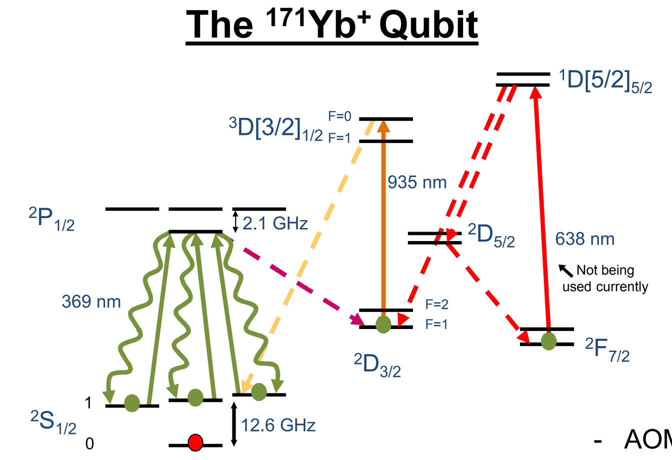


Improved Q and Compensation in HOA 2.1

	HOA-2	HOA-2.1
resonance frequency	49.4 MHz	50.5 MHz
resonator Q	45	60
vertical adjust field	-2300 V/m	-80 V/m
lateral adjust field	-550 V/m	-30 V/m

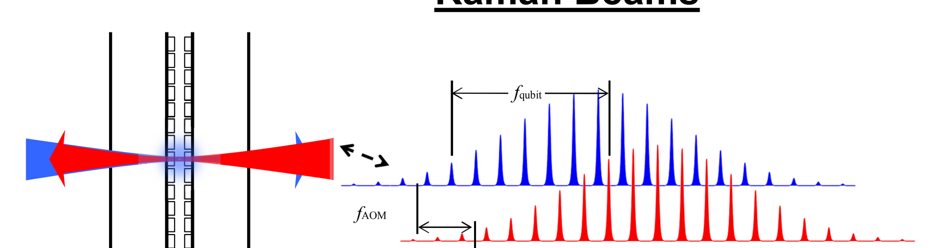
Gates

The $^{171}Yb^+$ Qubit



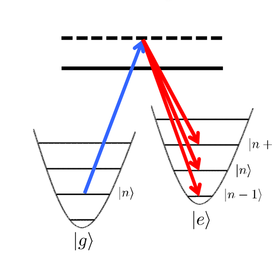
- Clock state qubit is insensitive to magnetic fields
- $T_1 > 5$ s, $T^*_2 \approx 1$ s

Raman Beams



Can be set up in either co- or counter-propagating configurations

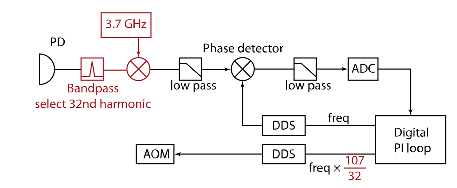
Motional State Addressing



- AOM used to fine tune frequency of Raman beams
- Can be used for sideband cooling

Comb Stabilization

- Repetition rate lock used to stabilize separation of comb teeth



Single Qubit Gates

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

Below the threshold for fault-tolerant error correction!
See P. Aliferis and A. W. Cross, Phys. Rev. Lett. 98, 220502 (2007)

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	$6.9(6) \times 10^{-5}$	$4(9) \times 10^{-4}$

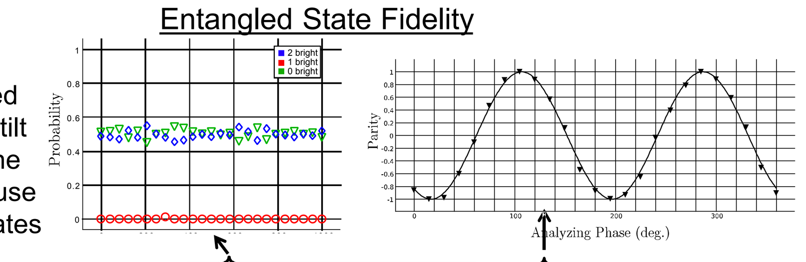
counter-propagating

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	$4.1(4) \times 10^{-4}$	$8.4(8) \times 10^{-4}$

Mølmer-Sørensen Gate

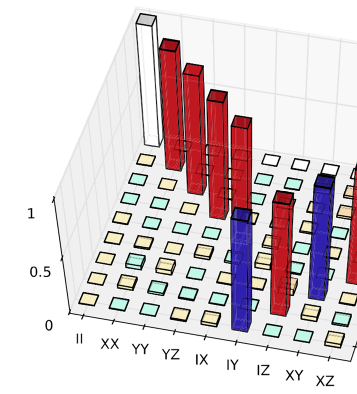
Entangled State Fidelity

- First order Walsh compensation used
- Performed on the tilt mode parallel to the trap surface because of lower heating rates (< 8 quanta/s)

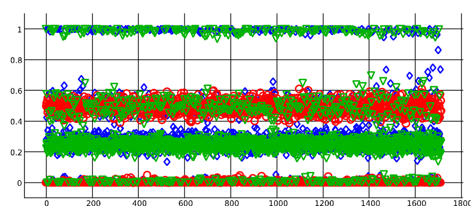


$$\mathcal{F} = \frac{1}{2}\left(P(|00\rangle) + P(|11\rangle)\right) + \frac{1}{4}c \approx 0.995$$

Process Fidelity



Measured with GST performed on the symmetric subspace: II, XX, YY, M

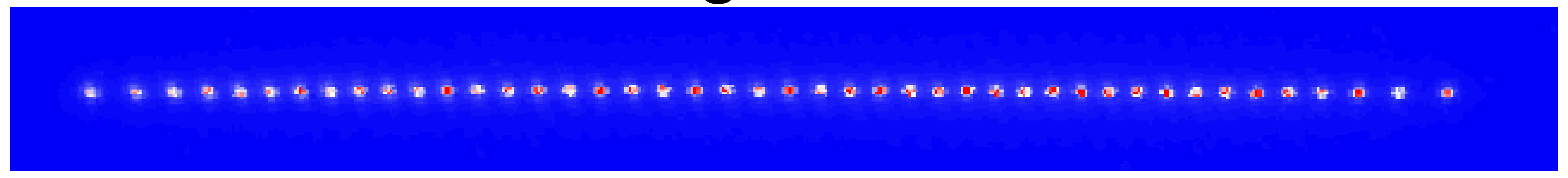


$$F_{MS} = 0.9958(6)$$

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

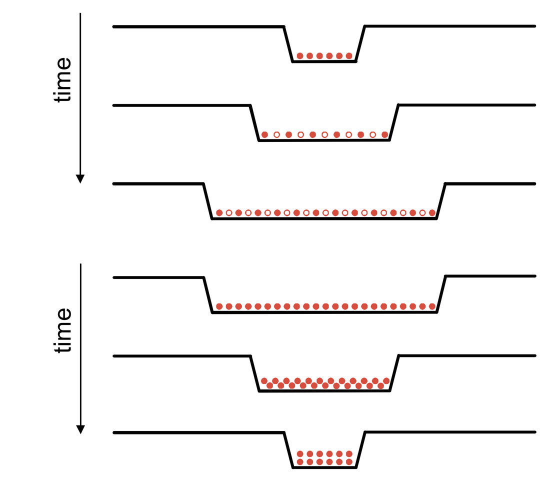
Best reported *process* fidelity of a two-qubit gate in a scalable surface trap!

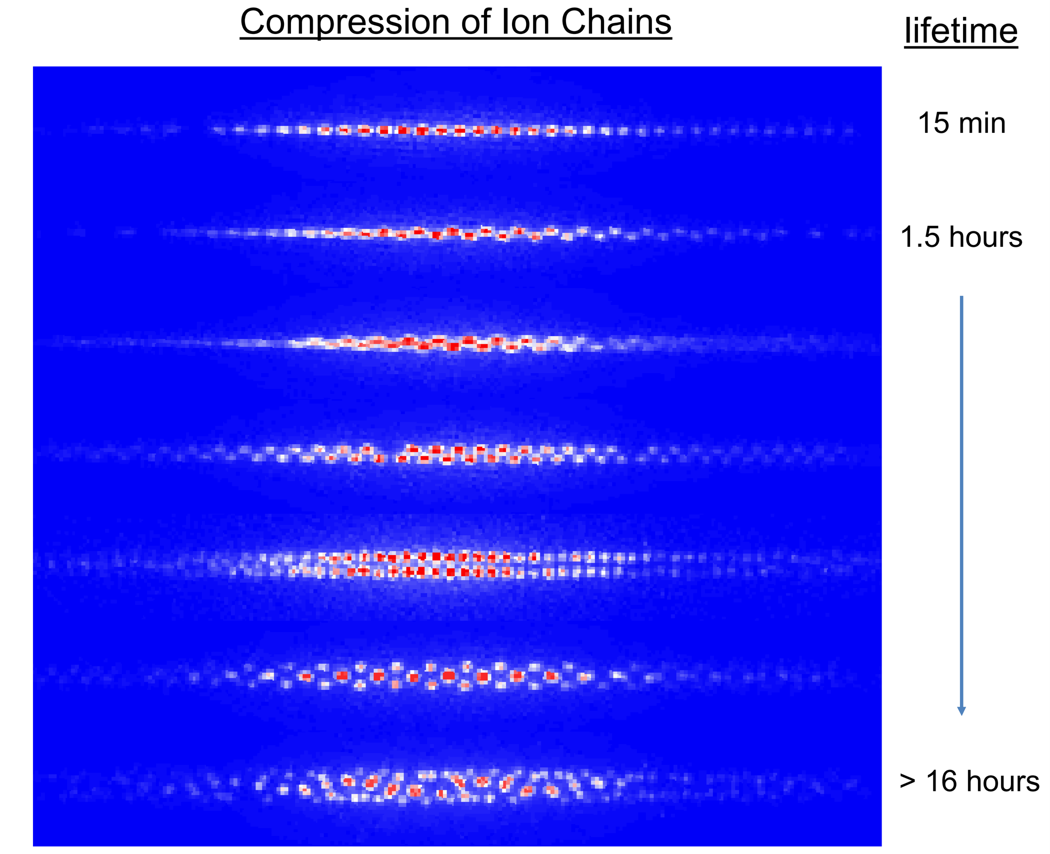
Long Chains



- The HOA supports chains containing several hundred ions
- Long chains are loaded by slowly widening a box potential during loading
- Box potential can be subsequently compressed to create buckled or non-trivial ion crystal structures
- Lifetime improves for highly buckled chains

Compression of Ion Chains



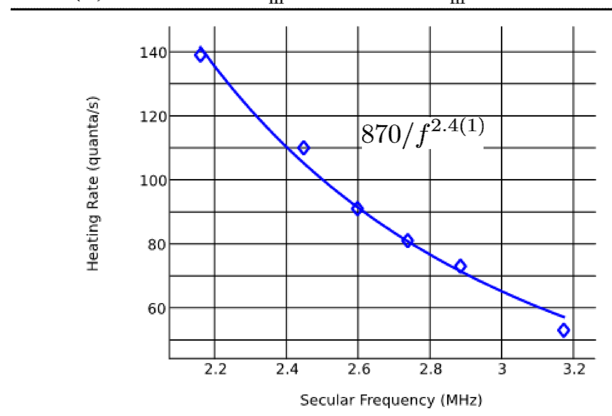


Heating Rates

HOA-2.1

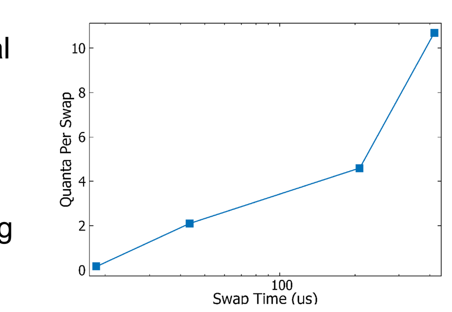
- Preliminary heating rate measurements were found to be higher in than in HOA-2.0
- Technical noise has not been ruled out
- Noise scales as 1/f^n where n = 2.4(1)

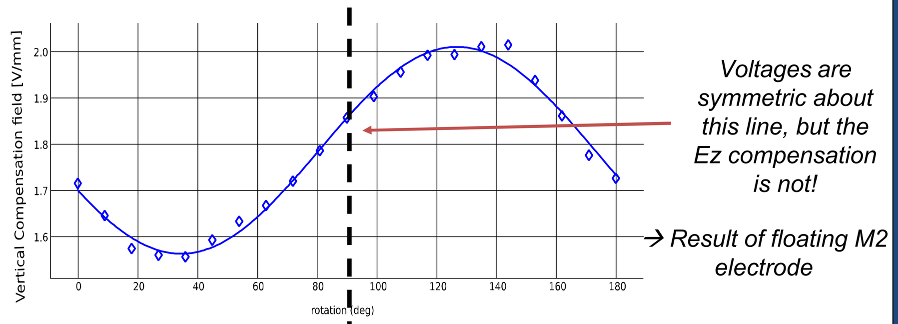
	Thunderbird	HOA-2.0	HOA-2.1
$\omega S_E(\omega)$	$200 - 1000\ \frac{(\mathrm{mV})^2}{\mathrm{m}^2}$	$50 - 140\ \frac{(\mathrm{mV})^2}{\mathrm{m}^2}$	$95 - 350\ \frac{(\mathrm{mV})^2}{\mathrm{m}^2}$



Swap-Induced Heating

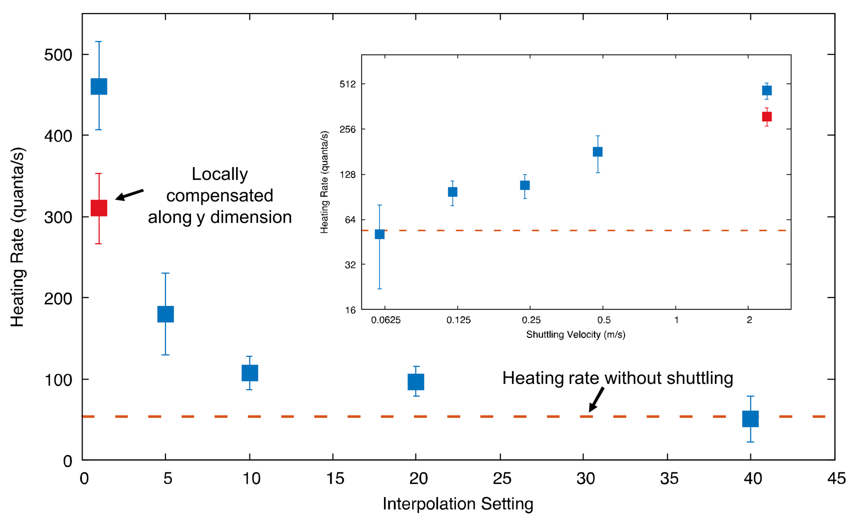
- Heating induced by the crystal swap was found to be minimally 0.16 quanta/swap.
- These results were limited by vertical field compensation effects imposed by the floating M2 electrode in the HOA-2.0



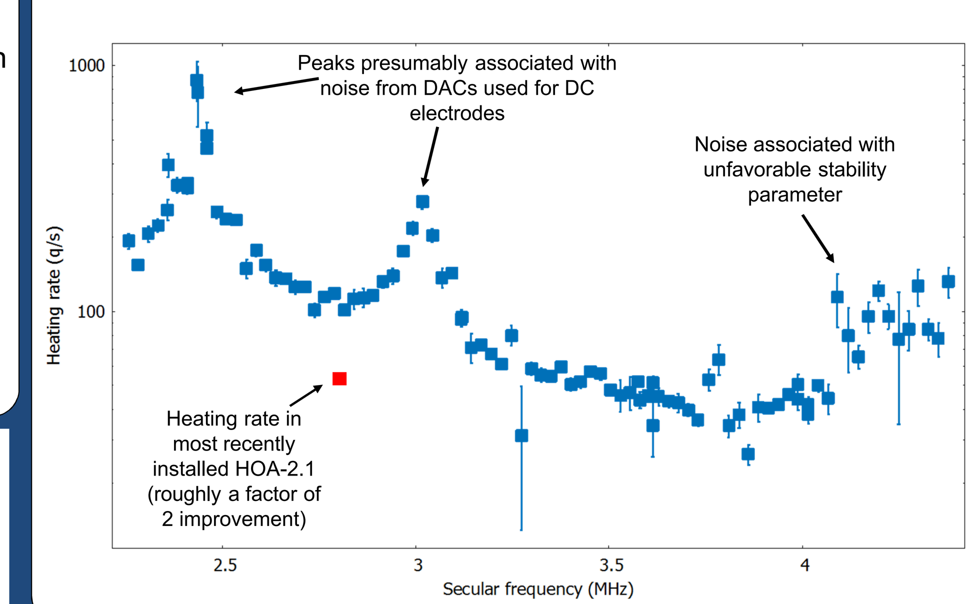


Shuttling-induced Heating

- Interpolating shuttling solutions increases shuttling time but provides a smoother and more adiabatic transfer
- Shuttling induced heating increases dramatically as adiabaticity is broken
- Improvements have been observed by locally compensating fields along shuttling path



Technical Noise

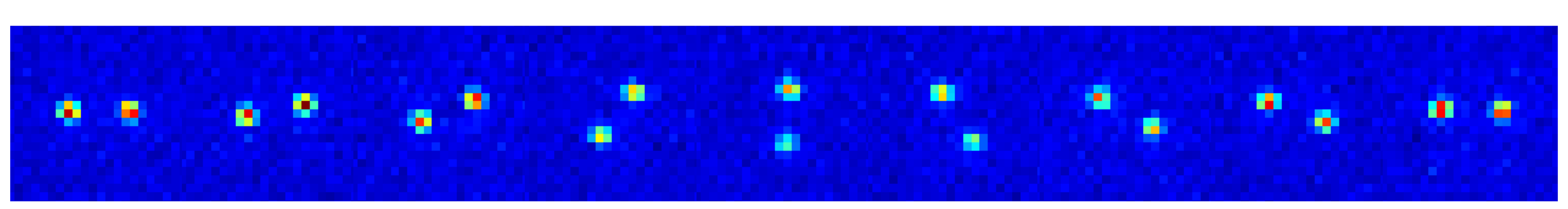


- A closer look at heating rate vs trap frequency reveals resonances where increased heating rate is observed.
- Resonances are most likely caused by noise discovered on the DACs used to apply voltages to DC trap electrodes.
- Instability above 4 MHz expected to be a result of the high ratio of secular to RF frequency

Precise Control Over Principal Axes

- Accurate control over trap curvature is imperative for developing optimal voltage solutions used for shuttling, separation and merging and other operations necessary for more complicated algorithms
- Comparison with simulations allows for data-driven design decisions that provide insight into improvements for future trap designs

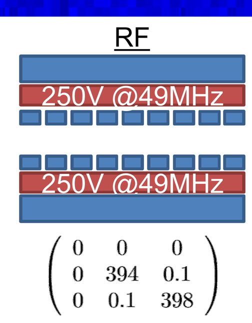
Ion Crystal Rotation



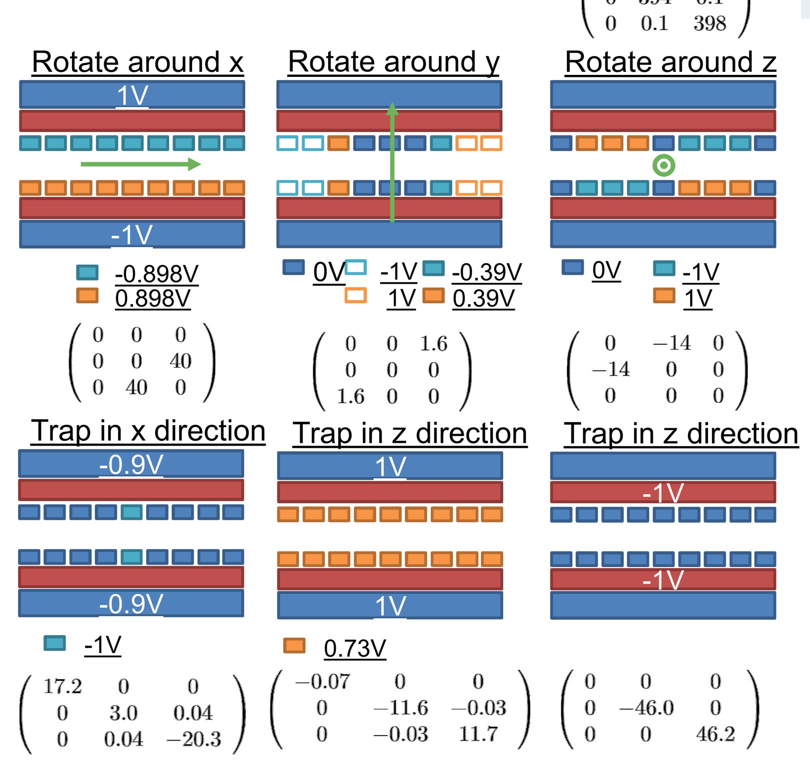
- Accurate control of the rotation of the radial modes can be generated with the same model
- Simulated solutions agree very well with data

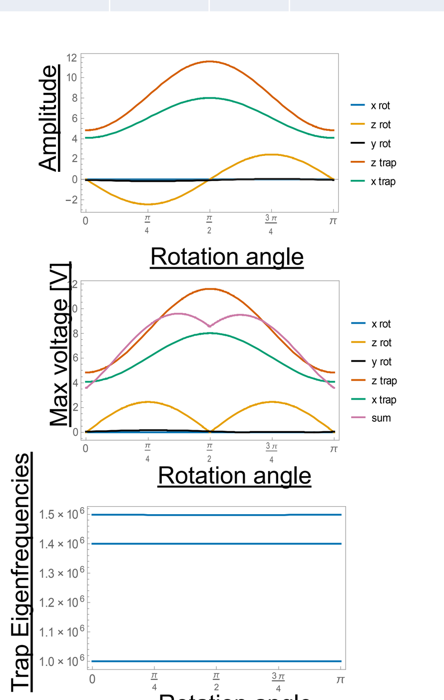
- Symmetric curvature tensor determines trap frequencies and principal axes
- Traceless for static fields, trace generated by RF pseudopotential

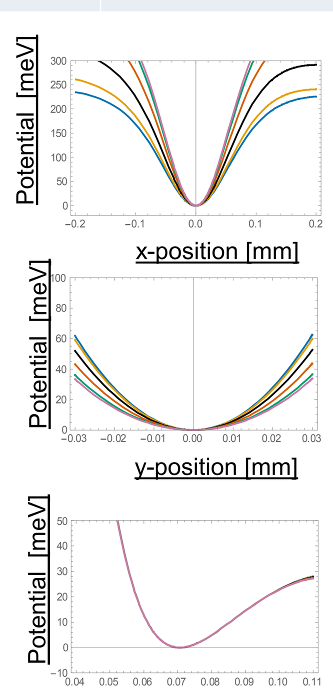
$$\begin{pmatrix} \frac{\partial\phi}{\partial x \partial x} & \frac{\partial\phi}{\partial x \partial y} & \frac{\partial\phi}{\partial x \partial z} \\ \frac{\partial\phi}{\partial y \partial x} & \frac{\partial\phi}{\partial y \partial y} & \frac{\partial\phi}{\partial y \partial z} \\ \frac{\partial\phi}{\partial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



Voltage Budget	Chain length	Min ratio	Calcium	Ytterbium
±10V	2	1.32	2.1, 2.95, 3.15 MHz	1.0, 1.4, 1.5 MHz
±30V	2	1.32	3.5, 5.1, 5.5 MHz	1.79, 2.5, 2.6 MHz
±10V	3	1.87	1.46, 2.78, 2.92 MHz	0.7, 1.34, 1.42 MHz
±30V	3	1.87	2.5, 4.8, 5.0 MHz	1.22, 2.33, 2.45 MHz

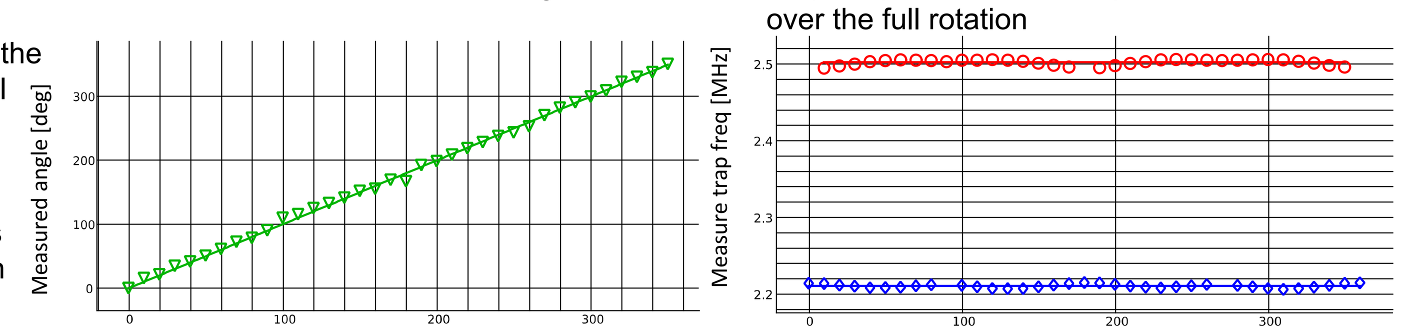






Rotation About The Trap Axis

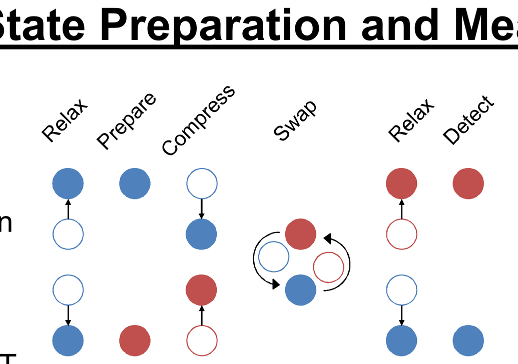
- Continuous rotation over the full range achieved
- Trap frequencies and compensation fields stable over the full rotation



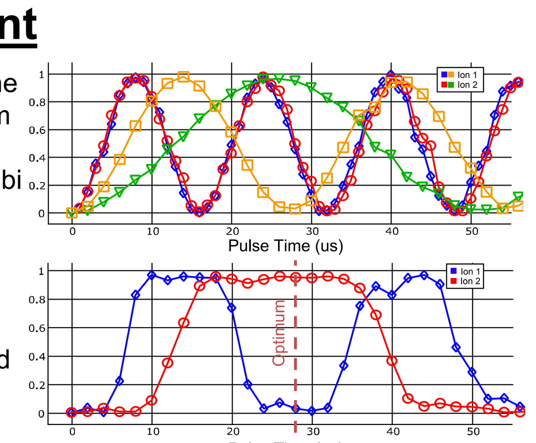
Swap Characterization

State Preparation and Measurement

- We prepare ions in the |01> state by separating the ions slightly and applying π and 2π with a single pulse
- State preparation and detection fidelities are improved by separating the ions slightly, which also gives a cleaner readout on the segmented PMT

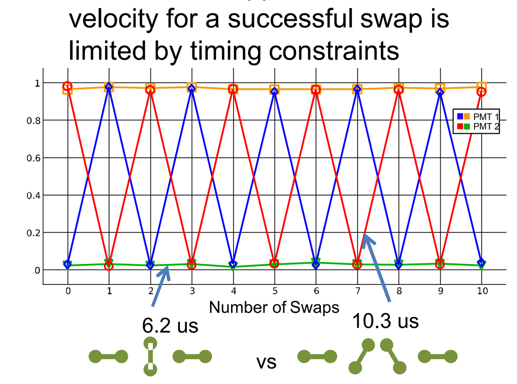


- Displacing the Raman beam leads to disparate Rabi frequencies
- Contrast is improved by using PB1 compensated pulses

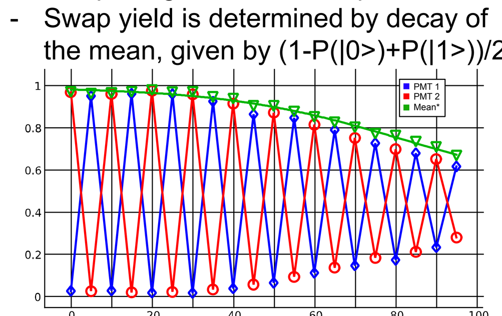


Swap Breakdown

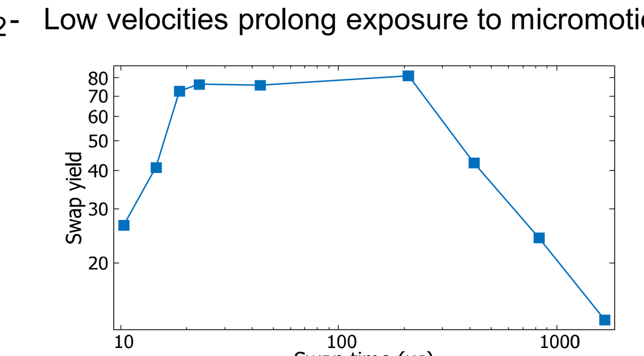
- The absolute upper bound on velocity for a successful swap is limited by timing constraints



- Swaps degrade after multiple rotations
- Swap yield is determined by decay of the mean, given by (1-P(|0>)+P(|1>))/2



- High velocities lead to rotation-induced heating
- Low velocities prolong exposure to micromotion



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