SAND2017-15810

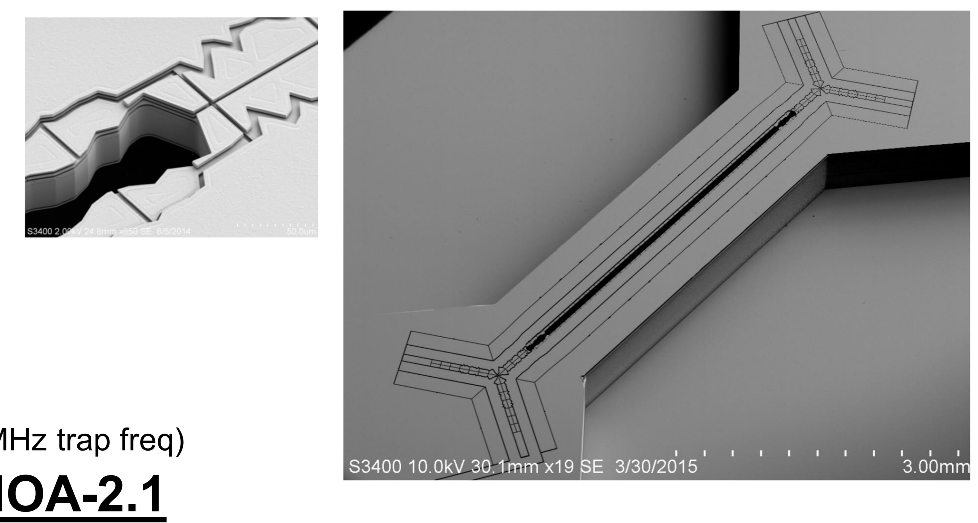
Ion Traps For Logical Qubits

Daniel Lobser, Matthew G. Blain, Raymond Haltli, Craig Hogle, Andrew Hollowell, Melissa Revelle, Daniel L. Stick, Christopher Yale, Peter Maunz

Sandia National Laboratories, Albuquerque, NM 87185

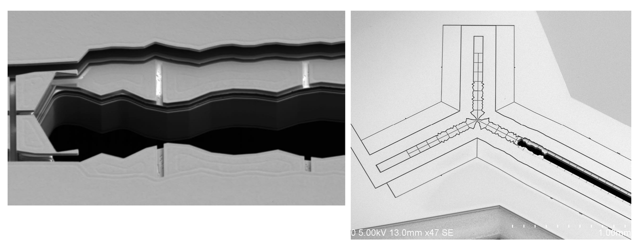
High Optical Access Trap (HOA-2)

- Excellent optical access rivaling 3D traps
  - NA 0.11 across surface
  - NA 0.25 through slot
- High trap frequencies (up to 3.2 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
  - Added aluminum wire for heating and temperature measurements



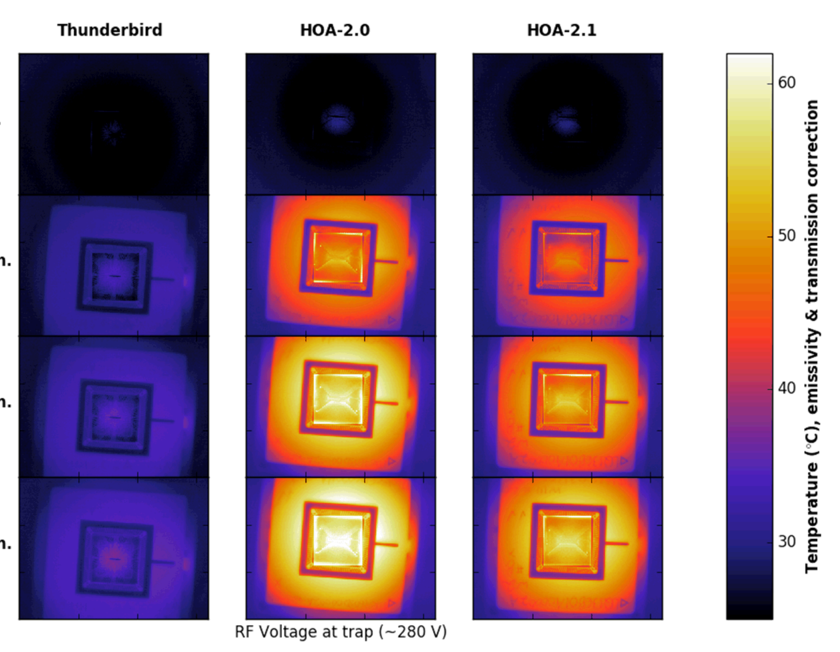
Comparison of Trap Properties

- Effect of new RF design in HOA-2.1 shows an improvement in resonant circuit Q
- Trap heating resulting from RF dissipation has been characterized
- Electrical properties have been tested at various temperatures

Improved Q and Compensation in HOA 2.1

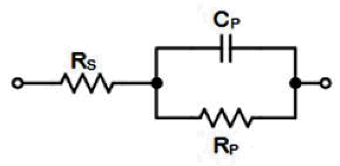
	HOA-2	HOA-2.1
resonance frequency	49.4 MHz	50.5 MHz
resonator Q	45	60
vertical adjust field	-2300 V/m	-80 V/m
lateral adjust field	-550 V/m	-30 V/m

RF induced Heating



Temperature data corrected for emissivity

Electrical Characteristics



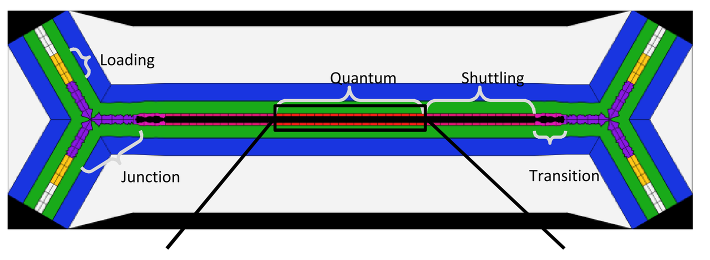
$$P_s \approx \frac{1}{2} R_s U^2 \omega^2 C_p^2$$

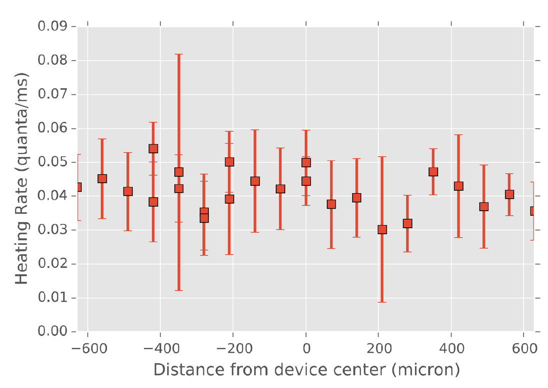
$$P_p = \frac{1}{2}\frac{\omega U^2}{R_p}$$

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
	77 K		0.7 Ω		80 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
	77 K		0.7 Ω		80 mW	
	4 K		0.5 Ω		60 mW	
Au/FS	300 K	1.93 pF	2.0 Ω	1.4 MΩ	15 mW	3.7 mW
	77 K		1.3 Ω		10 mW	
	4 K		0.8 Ω		5.9 mW	
Thunderbird	300 K	2.4 pF	0.6 Ω	1.5 MΩ	6.7 mW	3.3 mW

Heating Rates





Heating rate in HOA-2 is low and uniform along the length of the quantum section

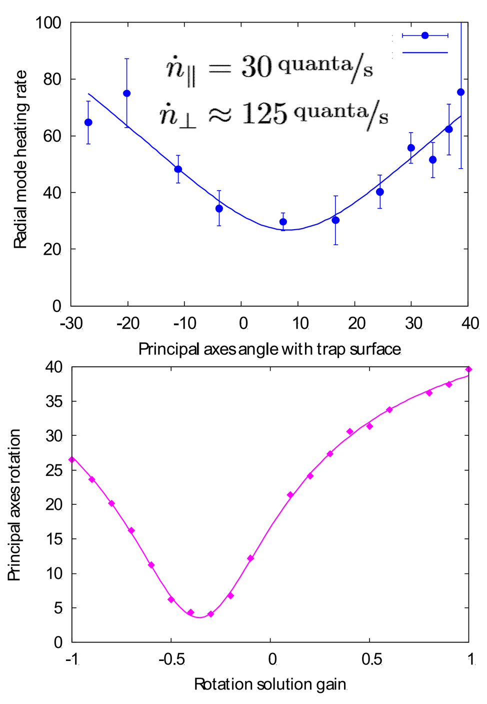
$^{171}Yb^+$, Trap frequency 2.8 MHz, r.f. 50 MHz

Heating rates as function of principal axes rotation

- Principal axes rotation measured by measuring π-times of Rabi flopping on cooled motional modes
- Minimal heating rates for motional mode parallel to trap surface $\dot{n}_\parallel$
- Without technical noise: Vertical mode has at most $\dot{n}_\perp \leq 2\dot{n}_\parallel$

(P. Schindler, et al., Phys. Rev. A **92**, 013414 (2015).

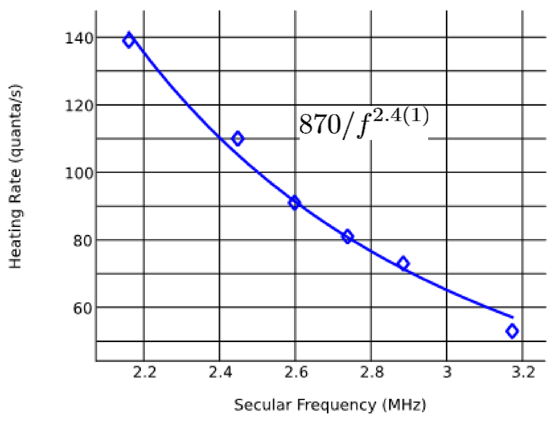
- Limited by technical noise



HOA-2.1

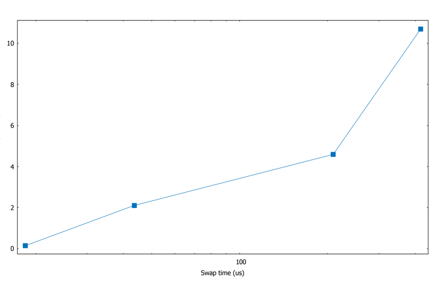
- Preliminary heating rate measurements were found to be higher in than in HOA-2.0
- Technical noise has not been ruled out
- Noise scales as 1/f^n where n = 2.4(1)

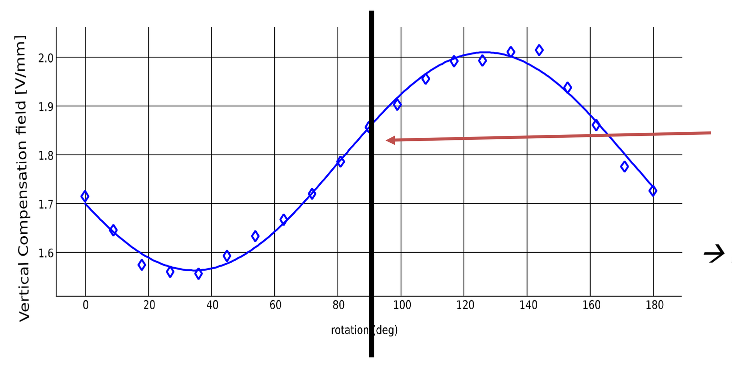
	Thunderbird	HOA-2.0	HOA-2.1
$\omega S_E(\omega)$	$200-1000\ \frac{(\mathrm{mV})^2}{\mathrm{m}^2}$	$50-140\ \frac{(\mathrm{mV})^2}{\mathrm{m}^2}$	$95-350\ \frac{(\mathrm{mV})^2}{\mathrm{m}^2}$



Rotation-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



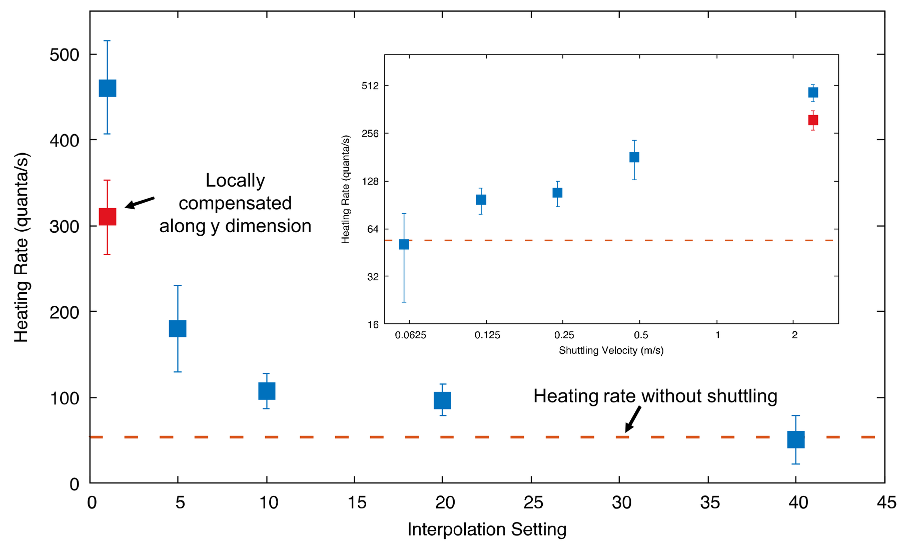


Voltages are symmetric about this line, but the Ez compensation is not!

→ *Result of floating M2 electrode*

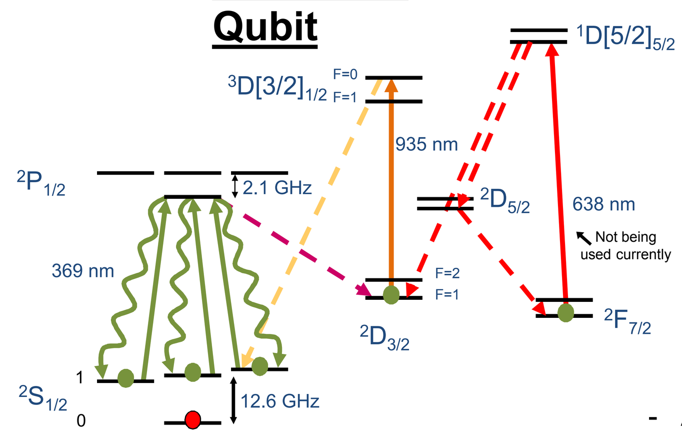
Shuttling-induced Heating

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



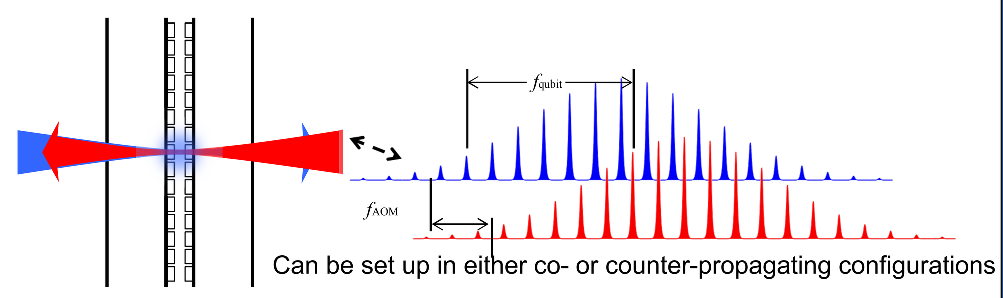
Gates

The $^{171}Yb^+$ Qubit



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

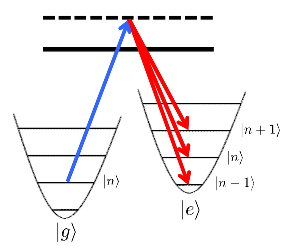
Raman Beams



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

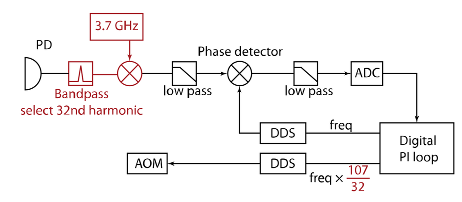
Motional State Addressing

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

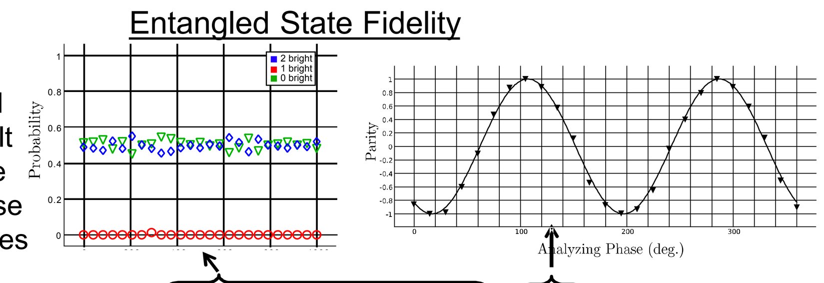
counter-propagating

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

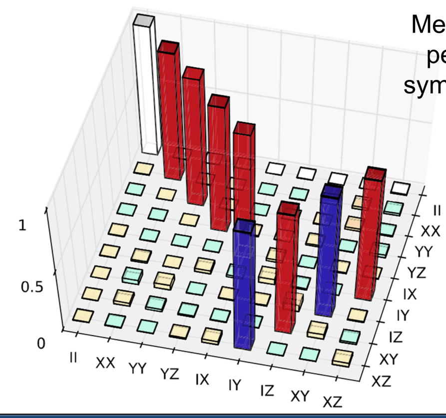
- First order Walsh compensation used
- Performed on the tilt mode parallel to the trap surface because of lower heating rates (< 8 quanta/s)

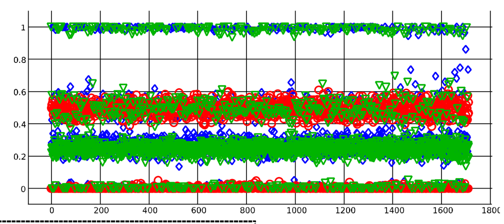


$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c \approx 0.995$$

Process Fidelity

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



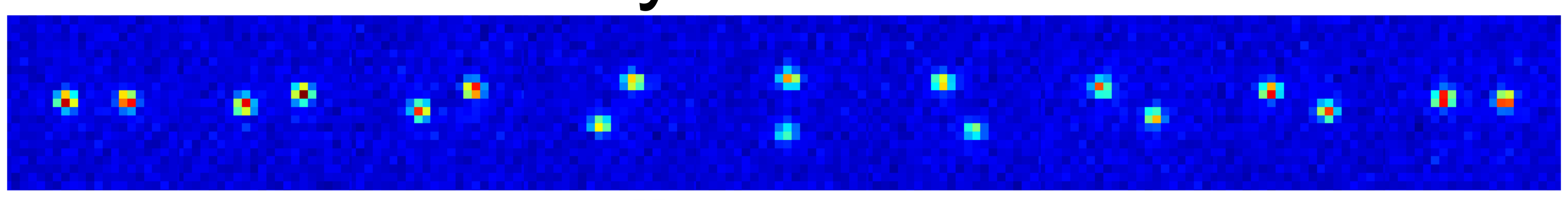


$$F_{MS} = 0.9958(6)$$

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

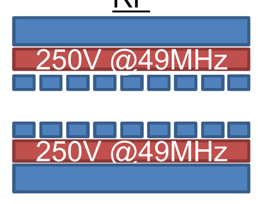
Best reported *process* fidelity of a two-qubit gate in a scalable surface trap!

Ion Crystal Rotation



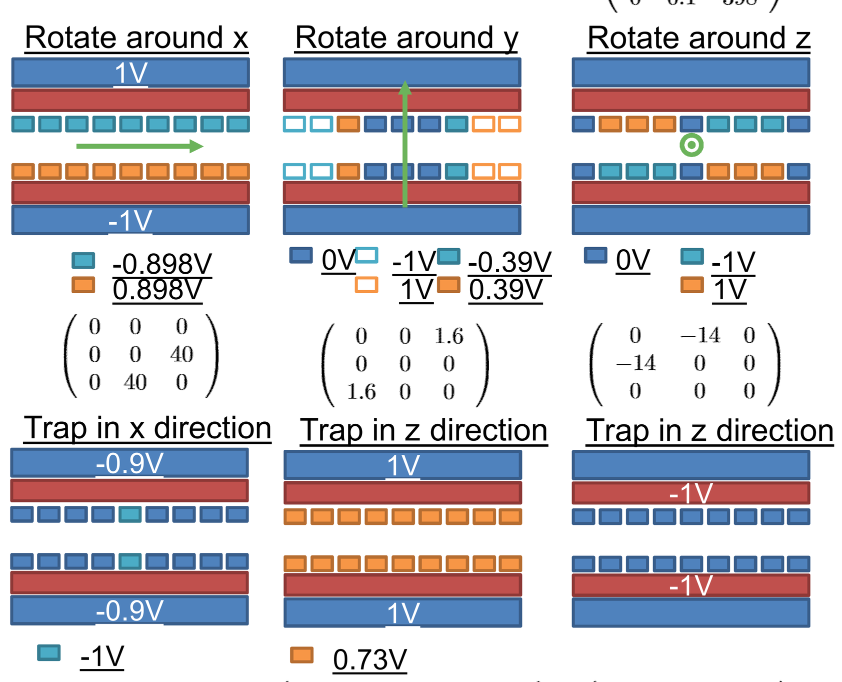
- Symmetric curvature tensor determines trap frequencies and principal axes
- Traceless for static fields
- Trace is generated by RF pseudopotential

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



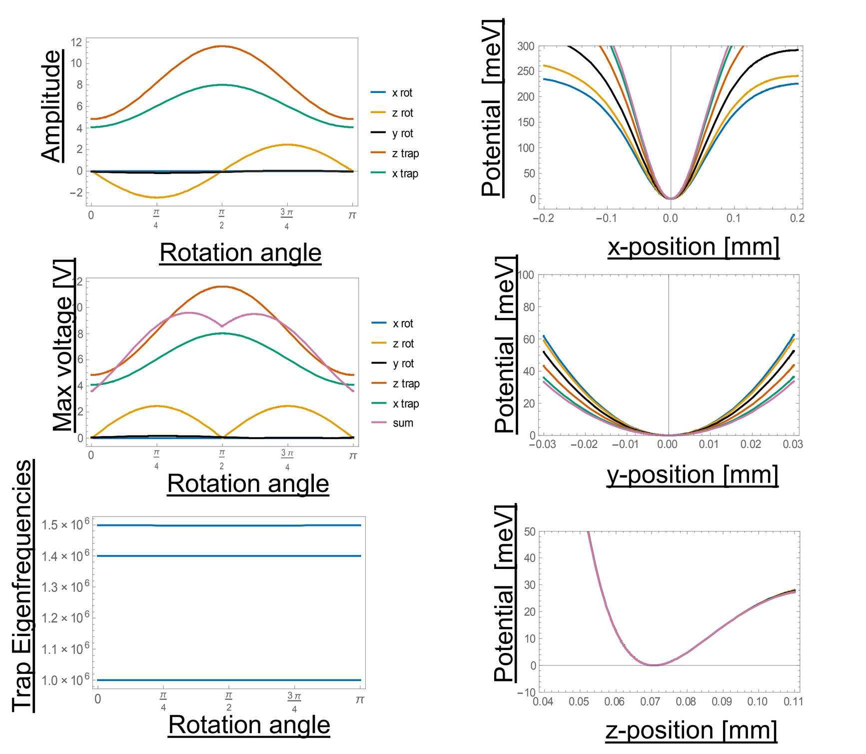
$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 394 & 0.1 \\ 0 & 0.1 & 398 \end{pmatrix}$$

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



$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 40 \\ 0 & 40 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 1.6 \\ 0 & 0 & 0 \\ 1.6 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & -14 & 0 \\ -14 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

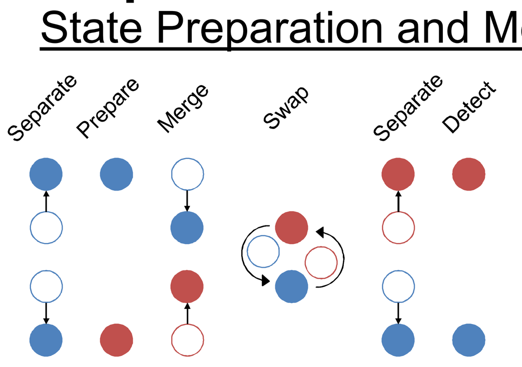
$$\begin{pmatrix} 17.2 & 0 & 0 \\ 0 & 3.0 & 0.04 \\ 0 & 0.04 & -20.3 \end{pmatrix} \quad \begin{pmatrix} -0.07 & 0 & 0 \\ 0 & -11.6 & -0.03 \\ 0 & -0.03 & 11.7 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & -46.0 & 0 \\ 0 & 0 & 46.2 \end{pmatrix}$$



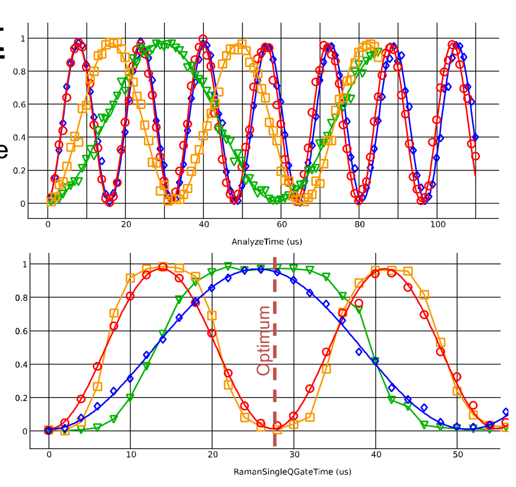
Swap Characterization

State Preparation and Measurement

- Current setup does not support individual addressing
- We prepare ions in the |01> state by separating the ions slightly and applying pi and 2pi rotations to the ions 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



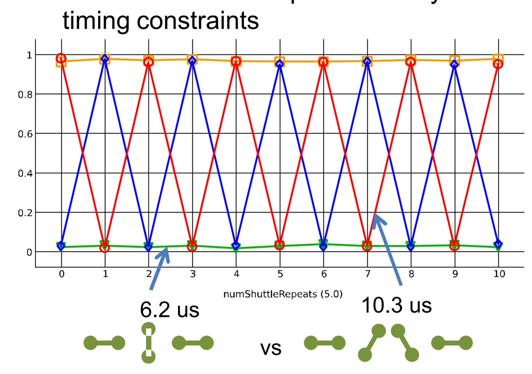
- Displacing the Raman beam leads to disparate Rabi frequencies
- Contrast is improved by using PB1 compensated pulses



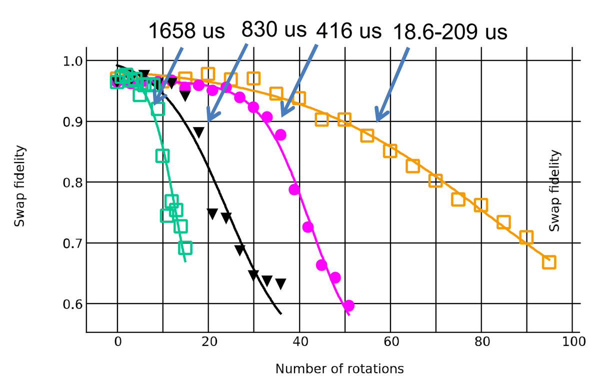
Swap Breakdown

Velocity Upper Bound

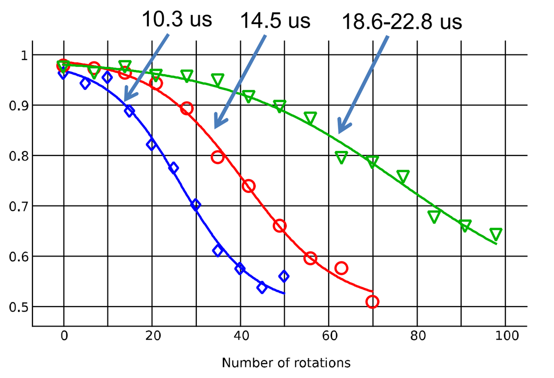
- The absolute upper bound on velocity for a successful swap is limited by timing constraints



Low Velocity Limit

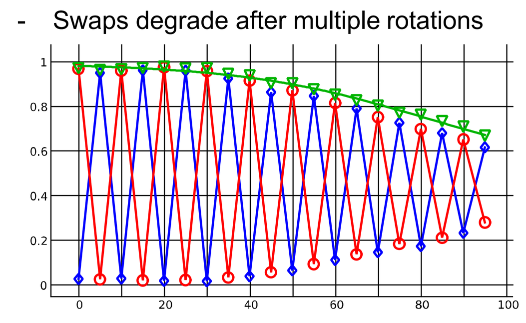


High Velocity Limit

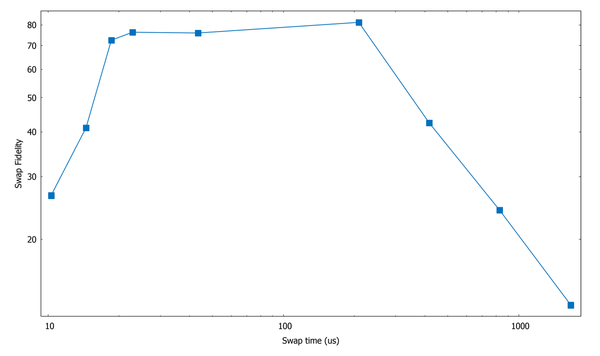


Eventual Decay

- Swaps degrade after multiple rotations



- Swap yield is stable over a large range of velocities from 18.6 to 209 us
- High velocity swaps breakdown presumably because of rotation-induced heating
- Low velocity swaps breakdown presumably because of prolonged exposure to micromotion



This work was supported by the Intelligence Advanced Research Projects Activity (IARPA) and Sandia's Laboratory Directed Research and Development (LDRD) Program. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

U.S. DEPARTMENT OF ENERGY

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

National Nuclear Security Administration