High-fidelity quantum and classical control in microfabricated surface ion traps

Daniel Lobser
Sandia National Laboratories
Motivation

Quantum Information

Quantum chemistry
• Calculation of molecular potentials
• Nitrogen and Oxygen fixation, development of catalytic converters

Medicine
• Structure-based drug development

Quantum computing
• Number factorization (Shor’s algorithm)
• Search in unstructured data, searching for solutions to hard problems (Grover’s search algorithm)

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

Quantum Communication
• Securing a quantum channel

Qubit Implementations

Trapped Ions

Neutral Atoms
• Rydberg states
• Atoms in cavities

Superconducting Josephson junctions

Quantum dots
Brief Overview of Ion Trapping

**Earnshaw’s Theorem:** *Static electric fields can’t create a stable confining potential for charged particles*

---

**r.f. Paul Trap**
- Time-averaged potential is close to harmonic at the saddle point
- Off the saddle point, ions experience micromotion
- Works well for linear chains of ions
- Doesn’t support fine control of ion position or confining potential

**Segmented Paul Trap**
- Better control over confining potential
- Difficult to construct
- Doesn’t scale well

---

**Microfabricated Surface Trap**
- Consistent, well-defined electrode layout
- Microfabrication supports a lot of exotic electrode geometries
- Excellent control over potential
- Very scalable

*House, PRA 78 033402 (2008)*
Surface Ion Traps

**Benefits**
- Microfabricated traps are scalable
- They support complicated geometries
- The technology keeps improving

**Challenges**
- Proximity of ions to the trap increases heating rates
- Ions are more sensitive to small features such as dust
- Possible charging of trap due to scattered laser light

**Our Goal**
Demonstrate that microfabricated surface traps can be used for high-fidelity quantum operations
Outline

Sandia’s Surface Ion Traps

Classical Control

Quantum Control

Specialized Ion Traps
Some of Sandia’s Traps

- High Optical Access (HOA) trap
- Circulator trap
- Microwave trap
- Y-junction traps
- Stylus trap
- Localized near-field microwaves
- EPICS trap
- Ring trap
High Optical Access (HOA)

Optical access
- Excellent optical access rivaling 3D
  NA 0.25 vertical, NA 0.12 lateral

Trap strength (Typical Yb⁺)
- Radial trap frequency 2 - 5 MHz
- RF frequency 50 MHz
- Stable for long ion chains
- Low heating rates (30 q/s parallel to surface, 125 q/s perpendicular)
- >100 h observed (while running measurements)
- >5 min without cooling

70 µm ion height
Outline

Sandia’s High-Optical-Access Trap

Classical Control

Quantum Control

Specialized Ion Traps
Control of Confining Potential

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

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

\[ e_x, e_y, e_z: \text{Eigenvalues} \]

\[ \partial_{xx} \phi = e_y \sin^2(\alpha) + e_x \cos^2(\alpha) \]

\[ \partial_{xy} \phi = (e_y - e_x) \sin(\alpha) \cos(\alpha) \cos(\beta) \]

\[ \partial_{xz} \phi = (e_x - e_y) \sin(\alpha) \cos(\alpha) \sin(\beta) \]

\[ \partial_{yy} \phi = (\cos^2(\beta) - \sin^2(\beta)) \left( e_x \sin^2(\alpha) + e_y \cos^2(\alpha) \right) + e_z \sin^2(\beta) - e_z \cos^2(\beta) \]

\[ \partial_{yz} \phi = \sin(\beta) \cos(\beta) \left( -e_x \sin^2(\alpha) - e_y \cos^2(\alpha) + e_z \right) \]
Application To Complicated Electrode Geometries

- YZ basis (rotation of the radial axes) near the junction on the HOA 2.1
- XY basis (rotation in the plane of the trap) on the microwave trap with tied electrodes
The simulations accurately describe the fields and curvatures generated by the trap.

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

- Controlled rotation
- Combined rotation and translation
- Separation and merging
- Long Chains
- Compression of chains
- 3D Crystal Structures
Outline

- Sandia’s High-Optical-Access Trap
- Classical Control
- Quantum Control
- Specialized Ion Traps
The $^{171}\text{Yb}^+$ Qubit

Good clock-state qubit
Coherence time ($T_2^*$) > 3 s
The $^{171}\text{Yb}^+$ Qubit

$^2S_{1/2} \rightarrow ^2P_{3/2}$

$66 \text{ THz}$

$33 \text{ THz}$

$369 \text{ nm}$

$355 \text{ nm}$

$12.6 \text{ GHz}$

$3x \text{ Nd:YVO}_4$ (355 nm) near minimum in Differential AC Stark Shift and spontaneous emission for $^{171}\text{Yb}^+$ ($\Delta_{\text{Stark}}/\Omega_{\text{Rabi}} < 3 \times 10^{-4}$ at 355 nm)
Single-Qubit Gates

- Ions addressed via Raman transitions using a 355 nm frequency comb
- Coherent Paladin pulsed laser
  - Internal cavity is not stabilized!
  - Cavity drift leads to comb “breathing”
    → Corrected with repetition rate lock

Beam Configurations

Co-propagating
- Immune to Doppler shifts
- Not affected by timing errors and pulse overlap
- Phase insensitive

Counter-propagating
- Higher overall beam intensity at ion decreases gate times
- Need for motional addressing
- Phase sensitive

Motional Addressing
Necessary for sideband cooling to motional ground states, thermometry, two-qubit gates

Gate Primitives
- Prep
- \( \hat{I} \)
- \( \hat{X} \)
- \( \hat{Y} \)

Repetition Rate Lock
- Counter-propagating
- Bandpass select 32nd harmonic
- 3.7 GHz
- Phase detector
- Low pass
- ADC

Co-propagating
- DDS
- DDS
- freq x \( \frac{107}{32} \)
- Digital PI loop
Gate Set Tomography

Developed at Sandia
www.pygsti.info

- No calibration required
- Detailed debug information
- Detects non-Markovian noise
- Uses structured sequences to amplify all possible errors
- Efficiently measures performance characterizing fault-tolerance (diamond norm)

**Fiducials**: Used for preparing and measuring on all 6 poles of the Bloch sphere

**Germs**: Carefully chosen set of gate sequences applied repeatedly

- Desired “target” gates:
  - $G_i$: Idle (Identity)
  - $G_x$: $\pi/2$ rotation about $x$-axis
  - $G_y$: $\pi/2$ rotation about $y$-axis

- Fiducials:
  - $\{\}$
  - $G_x$
  - $G_y$
  - $G_x \cdot G_x$
  - $G_x \cdot G_x \cdot G_x$

- Germs:
  - $G_x$
  - $G_y$
  - $G_i$
  - $G_x \cdot G_y$
  - $G_x \cdot G_y \cdot G_i$
  - $G_x \cdot G_i \cdot G_y$
  - $G_x \cdot G_i \cdot G_i$
  - $G_y \cdot G_i \cdot G_i$
  - $G_y \cdot G_i \cdot G_i$
  - $G_x \cdot G_x \cdot G_i \cdot G_y$
  - $G_x \cdot G_y \cdot G_y \cdot G_i$
  - $G_x \cdot G_x \cdot G_y \cdot G_x \cdot G_y \cdot G_y$
GST: debugging microwave gates

<table>
<thead>
<tr>
<th>Gate</th>
<th>Rotn. axis</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_I$</td>
<td>0.5252</td>
<td>$-0.009$</td>
</tr>
<tr>
<td></td>
<td>0.8506</td>
<td>$-0.0244$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.001699\pi$</td>
</tr>
<tr>
<td>$G_X$</td>
<td>$-3 \times 10^{-6}$</td>
<td>$-1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-3 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-0.009$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.501308\pi$</td>
</tr>
<tr>
<td>$G_Y$</td>
<td>$-0.2474$</td>
<td>$0.0001$</td>
</tr>
<tr>
<td></td>
<td>0.9689</td>
<td>$-0.0001$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.501366\pi$</td>
</tr>
</tbody>
</table>

Experimental run:
- 17-Apr
- 2-Dec
- 9-Feb
- 2-Mar
- 30-Mar
Compensated Pulses
- BB1-type dynamical-decoupling pulses used
- Corrects pulse-length errors

“Gapless” Pulses
- Phase changed discontinuously on DDS
- Avoids finite turn-on time effects
- Removes errors caused by asynchronous pulse arrival
- Allows for continuous power stabilization

Drift Control
*(Drive Frequency)*
- Single-shot calibrations increase or decrease a control parameter by a negligible value
- Small corrections either average out or slowly accumulate
GST: debugging microwave gates

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-0.009  
0.8506  
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| $G_X$ | $-3 \times 10^{-6}$  
$1$  
$-3 \times 10^{-5}$  
-0.009 | 0.501308$\pi$      |
| $G_Y$ | -0.2474  
0.0001  
0.9689  
-0.0001 | 0.501366$\pi$      |

Fixed pi/2 rotations with BB1 pulses

Fixed drift and context dependency
Single-Qubit GST Results

- Process infidelity \( \approx \) diamond norm
  - This indicates that we have gotten rid of all systematic errors

  **Below the threshold for fault-tolerant error correction!**


- 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

<table>
<thead>
<tr>
<th>Gate</th>
<th>Process Infidelity</th>
<th>1/2 ◊-Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_I )</td>
<td>( 6.9(6) \times 10^{-5} )</td>
<td>( 7.9(7) \times 10^{-5} )</td>
</tr>
<tr>
<td>( G_X )</td>
<td>( 6.1(7) \times 10^{-5} )</td>
<td>( 7.0(15) \times 10^{-5} )</td>
</tr>
<tr>
<td>( G_Y )</td>
<td>( 7.2(7) \times 10^{-5} )</td>
<td>( 8.1(15) \times 10^{-5} )</td>
</tr>
</tbody>
</table>

### Laser Gates

**co-propagating**

<table>
<thead>
<tr>
<th>Gate</th>
<th>Process Infidelity</th>
<th>1/2 ◊-Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_I )</td>
<td>( 1.17(7) \times 10^{-4} )</td>
<td>( 5.3(2) \times 10^{-4} )</td>
</tr>
<tr>
<td>( G_X )</td>
<td>( 5.0(7) \times 10^{-5} )</td>
<td>( 3(6) \times 10^{-4} )</td>
</tr>
<tr>
<td>( G_Y )</td>
<td>( 6.9(6) \times 10^{-5} )</td>
<td>( 4(9) \times 10^{-4} )</td>
</tr>
</tbody>
</table>

**counter-propagating**

<table>
<thead>
<tr>
<th>Gate</th>
<th>Process Infidelity</th>
<th>1/2 ◊-Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_I )</td>
<td>( 11.1(6) \times 10^{-4} )</td>
<td>( 22.8(1) \times 10^{-4} )</td>
</tr>
<tr>
<td>( G_X )</td>
<td>( 4.0(4) \times 10^{-4} )</td>
<td>( 13.2(6) \times 10^{-4} )</td>
</tr>
<tr>
<td>( G_Y )</td>
<td>( 4.1(4) \times 10^{-4} )</td>
<td>( 8.4(8) \times 10^{-4} )</td>
</tr>
</tbody>
</table>
Two-Qubit Gate

- Bichromatic entangling “Mølmer-Sørensen” gate
- Gate time and detuning from motional sidebands is set so that population in motionally (de-)excited states is zero corresponding to a closed loop in phase space
- Does not require ground state cooling
- Requires a number of extra calibrations
  - Rabi frequencies of red/blue detuned transitions matched
  - Ions need to be evenly illuminated
  - Phase of beat note needs to be calibrated and stable
Typical Approach: Entangled State Fidelity

- Entangled state fidelity determined by

\[ F = \frac{1}{2} \left( P(|00\rangle) + P(|11\rangle) \right) + \frac{1}{4} c \]

- Repeated application of gate
- Measure average population of entangled state

- Apply gate followed by analyzing pulse of varying phase
- Measure the resulting contrast
Two-Qubit GST

Typical Approach: **Entangled State Fidelity**

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

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

### Results

<table>
<thead>
<tr>
<th>Gate (G)</th>
<th>Process infidelity</th>
<th>(\frac{1}{2}) Diamond norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G_I)</td>
<td>(1.6 \times 10^{-3} \pm 1.6 \times 10^{-3})</td>
<td>(28 \times 10^{-3} \pm 7 \times 10^{-3})</td>
</tr>
<tr>
<td>(G_{XX})</td>
<td>(0.4 \times 10^{-3} \pm 1.0 \times 10^{-3})</td>
<td>(27 \times 10^{-3} \pm 5 \times 10^{-3})</td>
</tr>
<tr>
<td>(G_{YY})</td>
<td>(0.1 \times 10^{-3} \pm 0.9 \times 10^{-3})</td>
<td>(26 \times 10^{-3} \pm 4 \times 10^{-3})</td>
</tr>
<tr>
<td>(G_{MS})</td>
<td>(4.2 \times 10^{-3} \pm 0.6 \times 10^{-3})</td>
<td>(38 \times 10^{-3} \pm 5 \times 10^{-3})</td>
</tr>
</tbody>
</table>

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

\[
F_{MS} = 0.9958(6)
\]

\[
\frac{1}{2} \| G_{MS} \|_\Diamond = 0.08(1)
\]
Outline

Sandia’s High-Optical-Access Trap

Classical Control

Quantum Control

Specialized Ion Traps
Microwave Surface Trap

Benefits:
- Microwave radiation is easier to control and cheaper to implement than lasers
- Low power for Rabi oscillations
- Near field allows to generate microwave gradient fields

Challenges:
- Microwave delivery
- Dissipation, heating, thermal management
“Ideal” Two-Loop Design

- Inner current carrying loop
- Outer current carrying loop

- $B_{\text{inner}}$ and $B_{\text{outer}}$
- $B_z$ total
- $B_z$ and $dB_z/dz$ with $B=0$
- Location of null determined by geometry and ratio of currents

Two-loop concept developed at Sandia in 2012 (SAND2015-9513)
(C. Highstrete, S. M. Scott, J. D. Sterk, C. D. Nordquist, J. E. Stevens, C. P. Tigges, M. G. Blain)
Microwave trap
Rabi oscillations

- Losses between chamber and device ≈17dB
- Realized fast Rabi flopping 330ns with 15dBm at chamber, -2dBm at device
- Access to range of relevant $\pi$-times
- Will characterize gates as function of $\pi$-times.
EPICS Trap

- Integrated Superconducting Nanowire Single-Photon Detector (SNSPD) detector and reflective backplane
  - Detector developed by JPL/NIST
- SNSPD provides higher photon detection (>80% vs <30%)
- Cavity-QED provides higher photon collection efficiency
- Strong coupling regime enables qubit measurement via fast cavity transmission
- Extra rf electrodes enable alignment of rf node with cavity modes

Ion Trap Fabrication (Duke/SNL)
Nanowire Single Photon Node with cavity modes

EPICS Trap

*Concave mirror

~ 5mm

Cavity Mode

Ion

collaboration with

EPICS Trap

Sandia National Laboratories

JPL

Duke University

NIST

National Institute of Standards and Technology

U.S. Department of Commerce
Thank you

Trap design fabrication
Matthew Blain
Ed Heller
Corrie Herrmann
Becky Loviza
John Rembetski
Paul Resnick
SiFab team

Trap packaging
Ray Haltli
Drew Hollowell
Anathea Ortega
Tipp Jennings

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

RF Engineering
Christopher Nordquist
Stefan Lepkowski

GST protocols
Robin Blume-Kohout
Kenneth Rudinger
Eric Nielsen

Coming Soon:
Quantum Scientific Open User Testbed (QSCOUT)

- Quantum processor with 5 – 15 qubits
- Realized in trapped ion technology

Features
- Low single and two qubit error rates (<10^{-4}, <2 \times 10^{-2})
- All to all connectivity between qubits
- Random algorithm execution capability
- Access to all relevant low-level implementation details
- Capability to change low-level gate implementation

User support
- Exemplar programs and demonstrations
- User workshops and conferences (together with LBNL)

Availability
- Available to the DOE Scientific computing community
- First device will come online at end of 2019

Postdocs wanted!
Apply @ https://sandia.gov/careers
→ View All Jobs → Search “665253”

Questions? dlobser@sandia.gov
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**r.f. pseudopotential**

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House, PRA 78 033402 (2008)
Measuring swap fidelity

Swap yield
Quanta per swap
Swap time (us)

PMT 1
PMT 2
Mean*
- Displacing the Raman beam leads to disparate Rabi frequencies

- Contrast is improved by using PB1 compensated pulses
- 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 \( \frac{1-P(|0\rangle)+P(|1\rangle)}{2} \)

<table>
<thead>
<tr>
<th>Number of Swaps</th>
<th>PMT 1</th>
<th>PMT 2</th>
<th>Mean*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
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</tr>
<tr>
<td>3</td>
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<td>4</td>
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<td>1</td>
<td>1</td>
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<td>9</td>
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<td>1</td>
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</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

6.2 us vs 10.3 us

Number of Swaps

Number of Swaps
**Derived requirements**

- Standardization (lithographically defined electrodes)
- Multi-unit production
- Multi-level lead routing for accessing interior 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)

**Diagram**

- Undercut and gold coated to reduce dielectric in line of sight of ion
- Multi-level routing
- View from above
- 60 μm
- Top layer electrodes
- Inner electrodes
- Device silicon
- Handle silicon
- Oxide
High Optical Access (HOA)
Shuttling Solutions

- Same method can be used along entire trap

Solution for Ex field in increments of 5 um

Ion Position

Electrode Number
Shuttling Solutions

- Generate basis solutions for each point

Advantages:
- Solution are orthogonal
- Full parametric control over trap parameters at each point during shuttling
- Optimization techniques, such as machine learning or search algorithms, can be used to dynamically change basis amplitudes for improved shuttling
- Shuttling primitives can easily be decoupled, for example crystal rotation or linear shuttling at any position in the trap
• Trap frequencies are stable to within 16 kHz over the course of linear shuttling.
• Shuttling in linear section over 140µm, 5 repeats
• Optimization performed with a Nelder-Mead type simplex algorithm

• 12 degrees of freedom for x, y, z offset fields

• First attempts at optimization demonstrate nearly a factor of 2 in heating rate during shuttling
Microwave trap properties

- $^{171}\text{Yb}^+$
- ion height 29 μm
- rf frequency 87 MHz
- trap frequency 6 MHz
Two-qubit gate implementation

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

[[Image: Diagram of qubit states and heating rates.]]

Heating rates

\[ \approx 60 \text{ quanta/s} \]

\[ < 8 \text{ quanta/s} \]

[1] K. Mølmer, A. Sørensen, PRL 82, 1835 (1999)
Basic gates:

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

Preparation Fiducials:

\{ \}
\[ G_{XX} \]
\[ G_{YY} \]
\[ G_{MS} \]
\[ G_{XX}G_{MS} \]
\[ G_{YY}G_{MS} \]

Germs:

\[ G_I \]
\[ G_{XX} \]
\[ G_{YY} \]
\[ G_{MS} \]
\[ G_I G_{XX} \]
\[ G_I G_{YY} \]
\[ G_I G_{MS} \]
\[ G_{XX}G_{YY} \]
\[ G_{XX}G_{MS} \]
\[ G_{YY}G_{MS} \]
\[ G_I G_{XX}G_{MS} \]
\[ G_I G_{YY}G_{MS} \]

Detection Fiducials:

\{ \}
\[ G_{XX} \]
\[ G_{YY} \]
\[ G_{MS} \]
\[ G_{XX}G_{MS} \]
\[ G_{YY}G_{MS} \]
\[ G_{XX}^3 \]
\[ G_{YY}^3 \]
\[ G_{XX}^2G_{MS} \]
\[ G_{YY}^2G_{MS} \]
Scaling trapped ion systems

Quantum charge coupled device


MUSIQC scaling (scaling beyond a single chip using remote entanglement)

The Ytterbium Qubit

$^2S_{1/2} \rightarrow ^2P_{1/2}$

369 nm

2.1 GHz

Doppler Cooling

12.6 GHz

clock state qubit, magnetic field insensitive.

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

clock state qubit, magnetic field insensitive.

S. Olmschenk et al., PRA 76, 052314 (2007)
$^{171}\text{Yb}^+$ state detection

\begin{align*}
\end{align*}

$^{2}\text{P}_{1/2}$

$^{2}\text{S}_{1/2}$

$|0\rangle$

$|1\rangle$

2.1 GHz

12.6 GHz

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

- Best fidelity between 20µs and 200µs
- Failure probability increases with number of swaps (heating)
Heating rates as function of principal axes rotation

- Principal axes rotation measured by measuring $\pi$-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 $\dot{n}_\perp \leq 2\dot{n}_\parallel$
  

- Limited by technical noise

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

Radial mode heating rate vs. Principal axes angle with trap surface

Rotation solution gain vs. Principal axes rotation

$\dot{n}_\parallel = 30$ quanta/s

$\dot{n}_\perp \approx 125$ quanta/s
Compression of ion chains

lifetime

15 min

1.5 hours

> 16 hours
Linear chain melting
Slightly buckled chain stability
Ramping up buckling
Ion “braid” stability