SAND2016-10371PE

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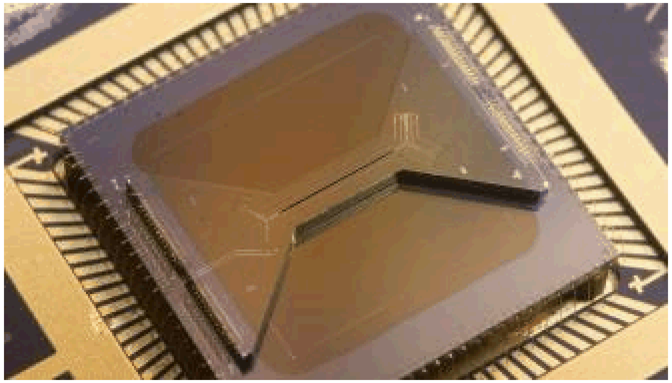

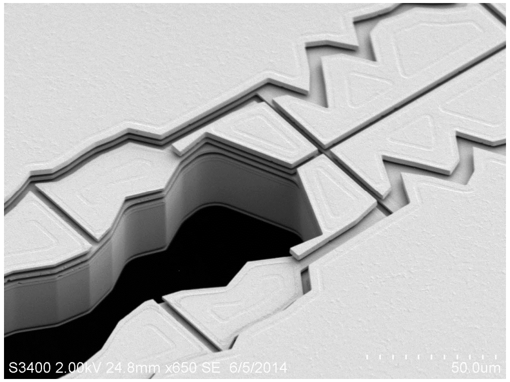

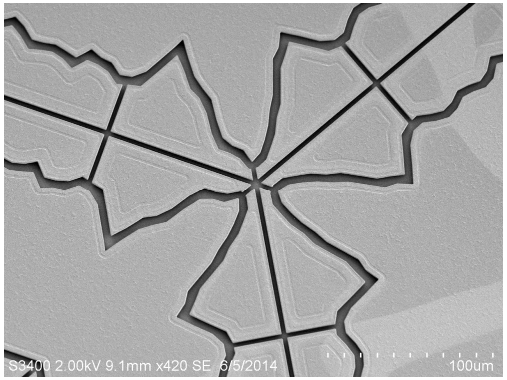

Surface ion traps for quantum computing

Dr. Daniel Stick

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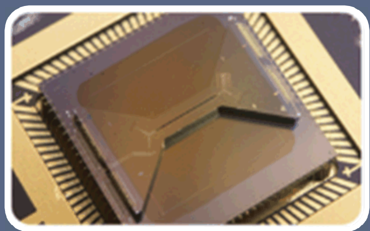
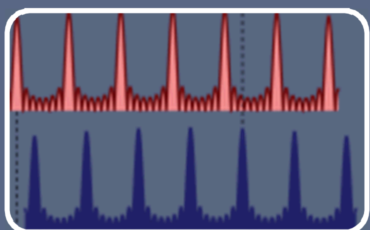
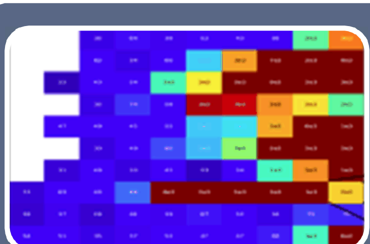
Outline



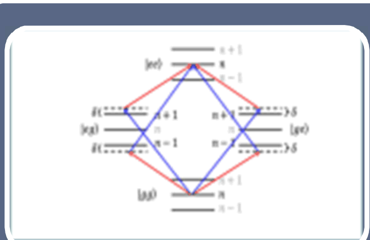
Trap features



Experimental characterization



Single qubit gates



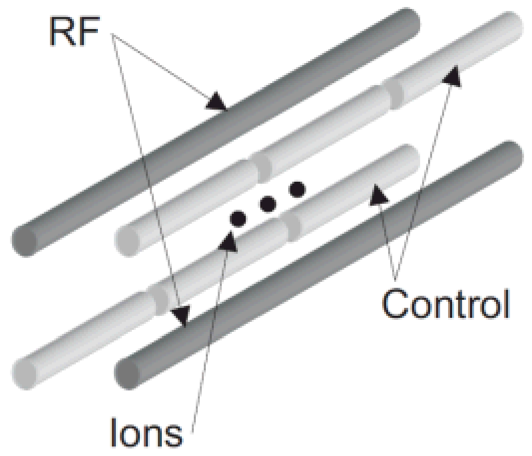
Mølmer-Sørensen two-qubit gate

Trap features

Advantages/Challenges vs 3D

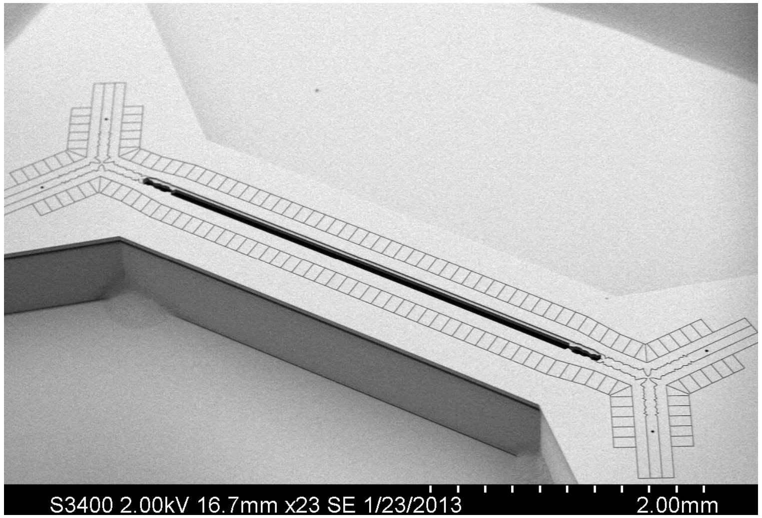
Advantages

- More manufacturable ("scalable")
- Consistent geometry -> consistent behavior
- Greater field control (more electrodes)
- 2D geometry
- Laser access
- Integration of other technologies (waveguides, detectors, filters…)



Challenges

- Low depth (ion lifetime), anharmonicities
- Proximity to surface (charging, heating)
- Delicate (dust, voltage)
- Capacitance



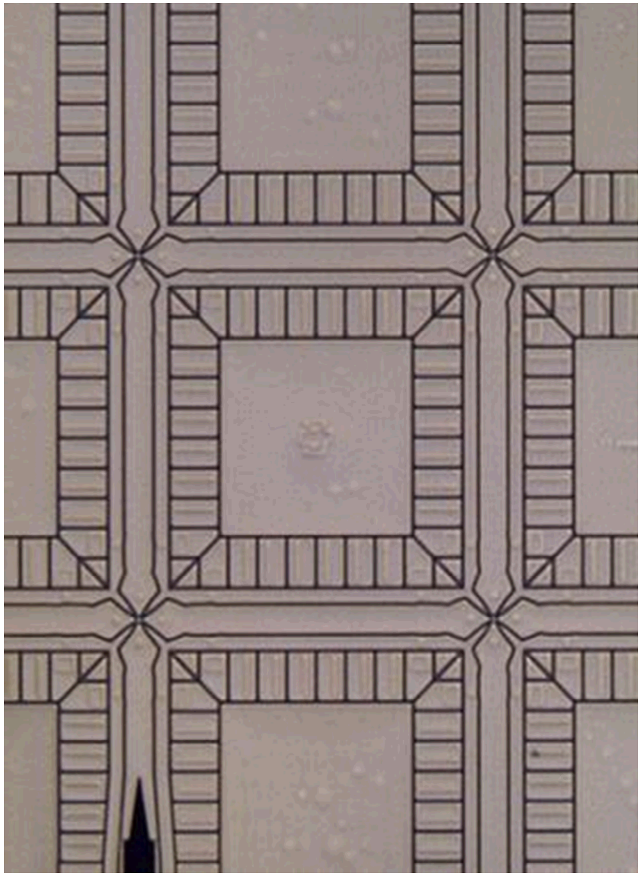
Capabilities & Requirements

Essential capabilities

- Store ions for long periods of time (hours)
- Move ions to achieve 2D connectivity
- Support high fidelity operations
- Uniform performance

Derived requirements

- Voltage breakdown >300 V @ ~50 MHz
- Backside loading hole
- Multi-level lead routing for accessing interior electrodes
- Standardization [lithographically defined electrodes]
- Overhung electrodes [evaporated metal]
- High optical access [high NA delivery and collection optics]



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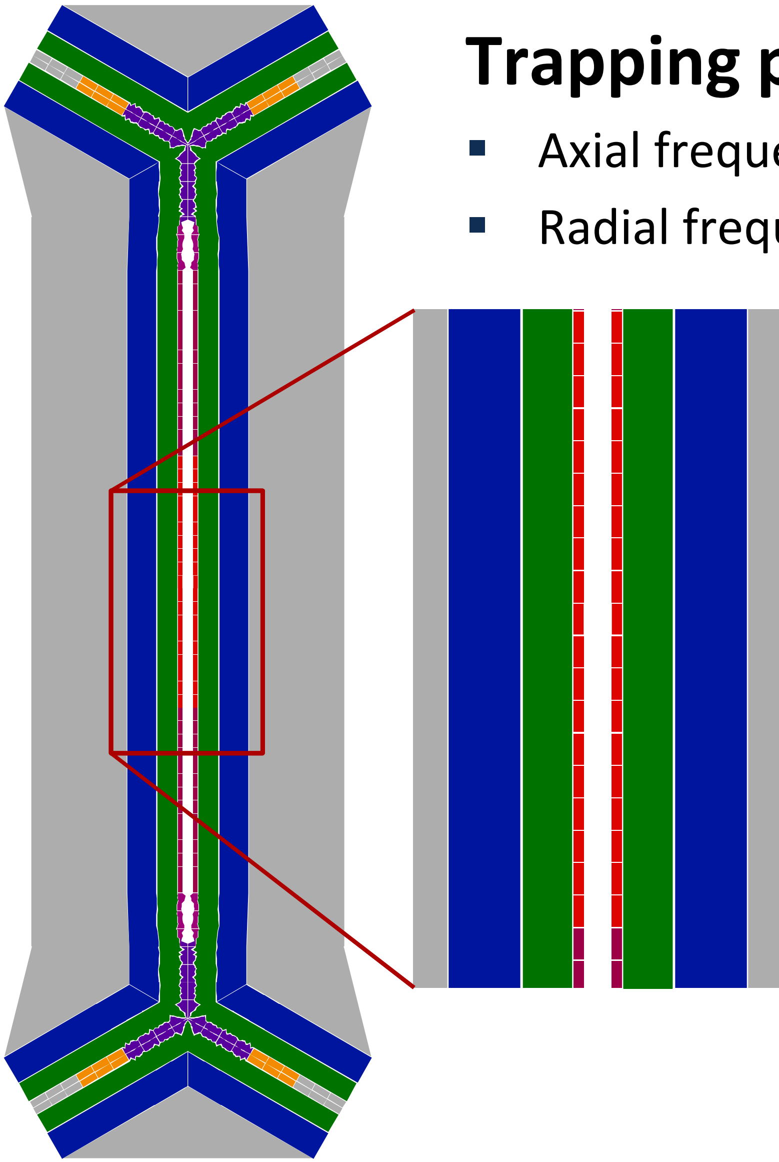
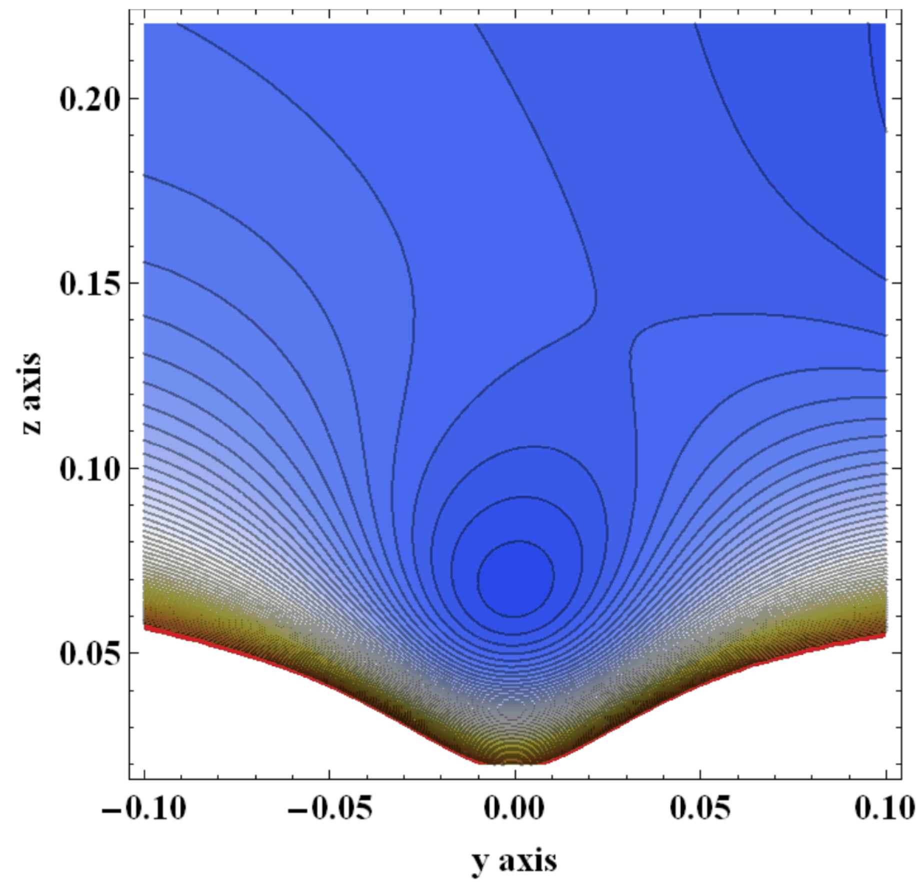
Voltage application



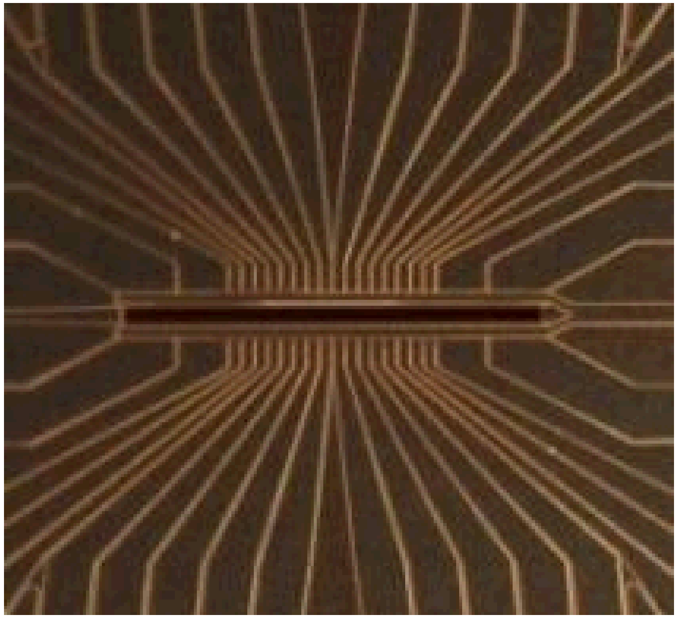
Trapping potential

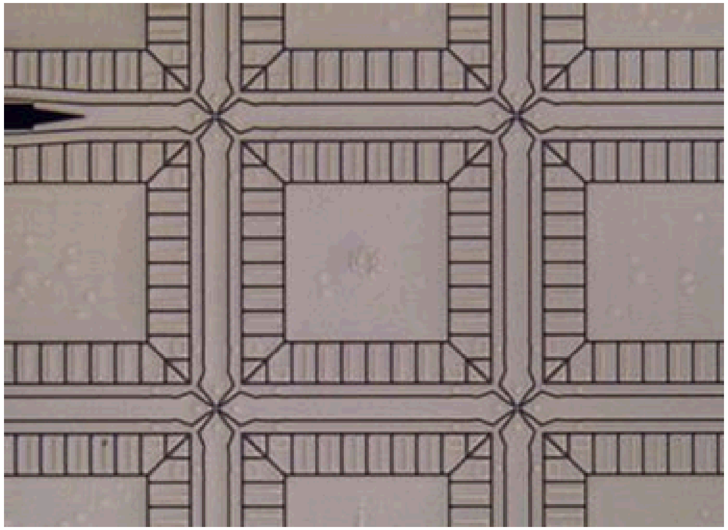
- Axial frequency: 500 kHz [<5 V]
- Radial frequency: 2.8 MHz, 3.1 MHz [250 Vrf @ 40 MHz]

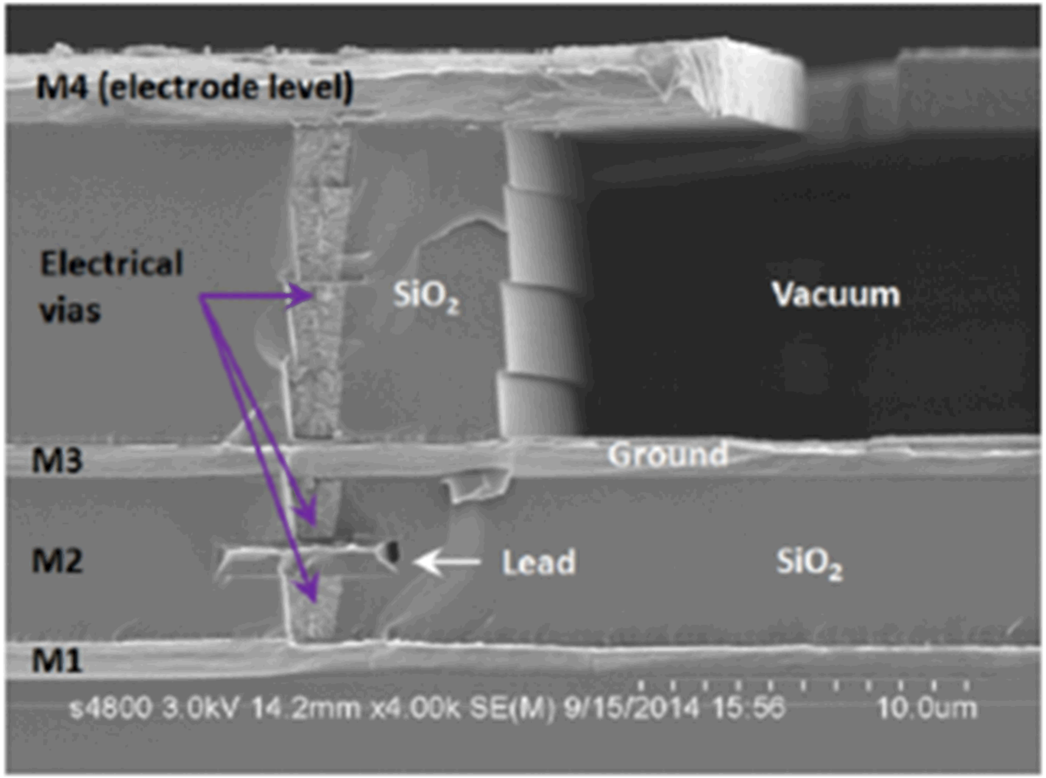


Trap features

Multi-layer metallization







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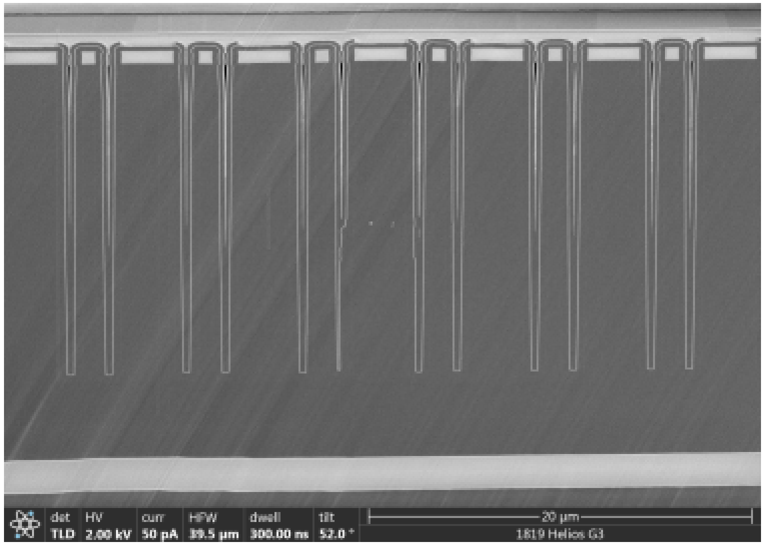
Trap features

Trench capacitors & Loading holes



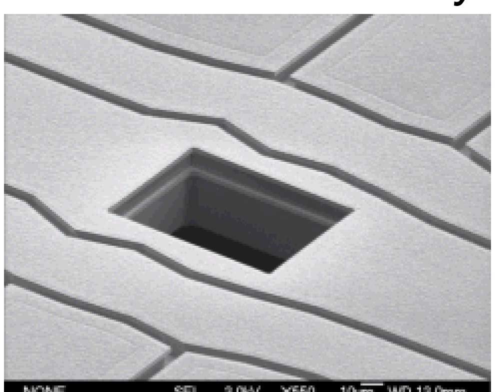
Interposer (current)

- 20V max voltage
- 1nF capacitance

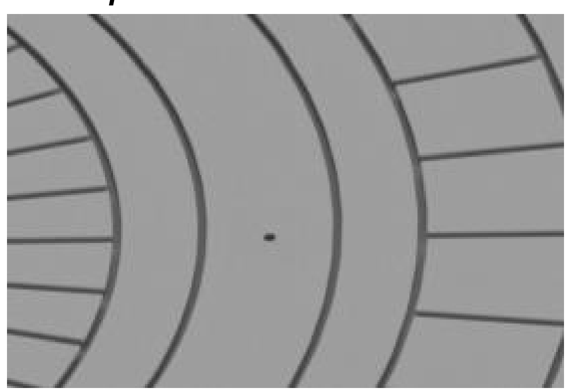
On chip (future)

- 15V max voltage
- 200pF capacitance (but low inductance)
- Up to 200 capacitors can be located within the isthmus

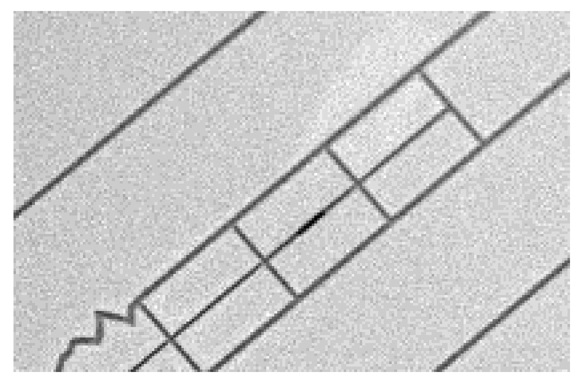
50μm×80μm
modulation necessary



10μm hole
still perturbs the field

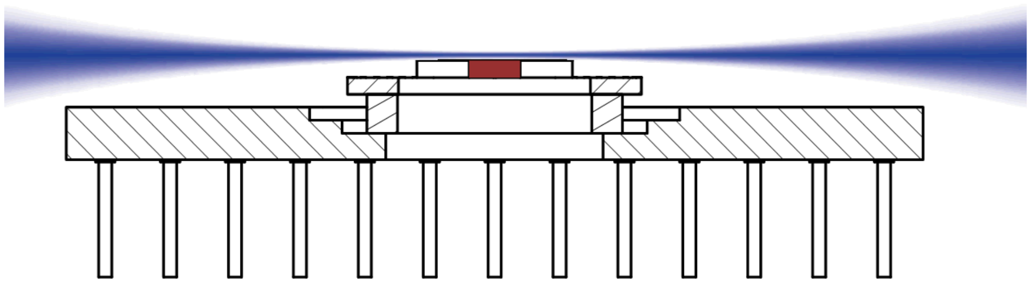


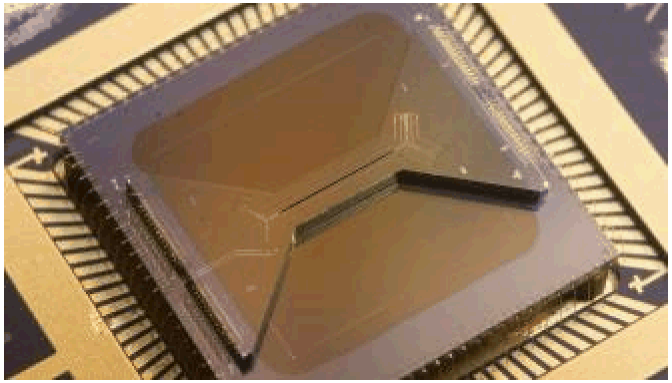
3μm×20μm



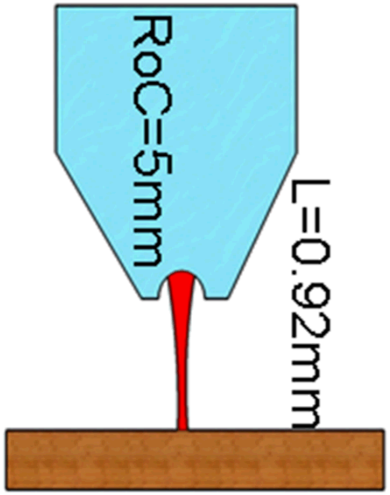
Trap features

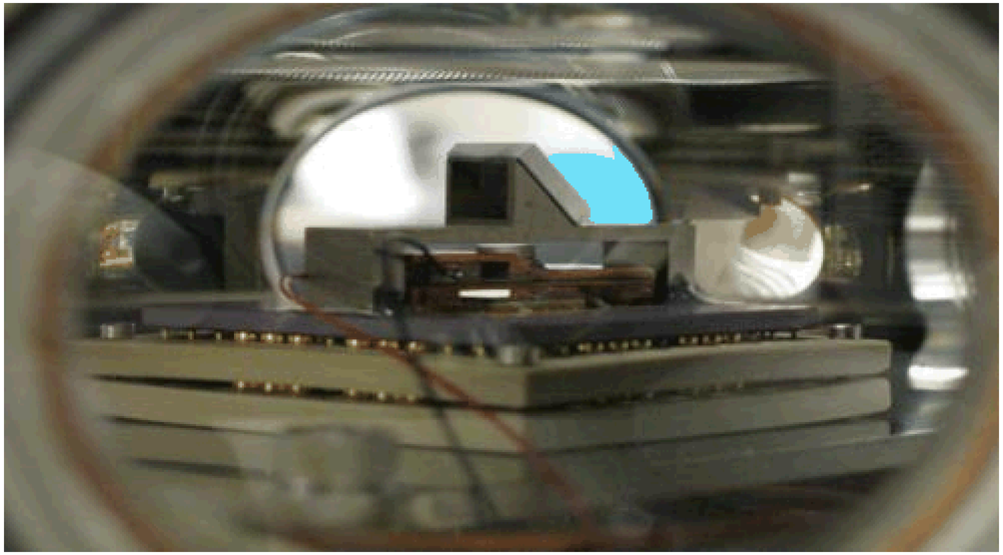
Optical access & integrated optics





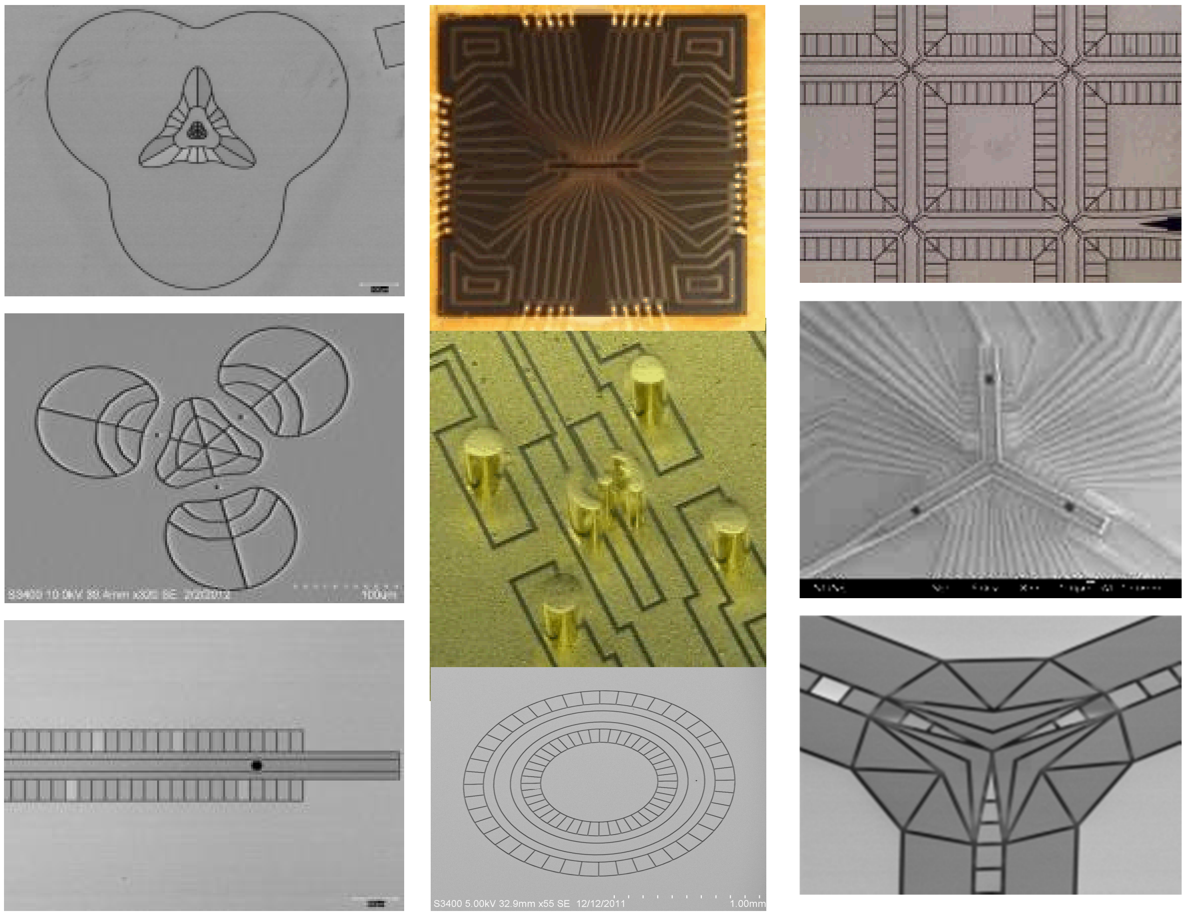
Can accommodate 4/2 um beam waist (369 nm)





Trap features

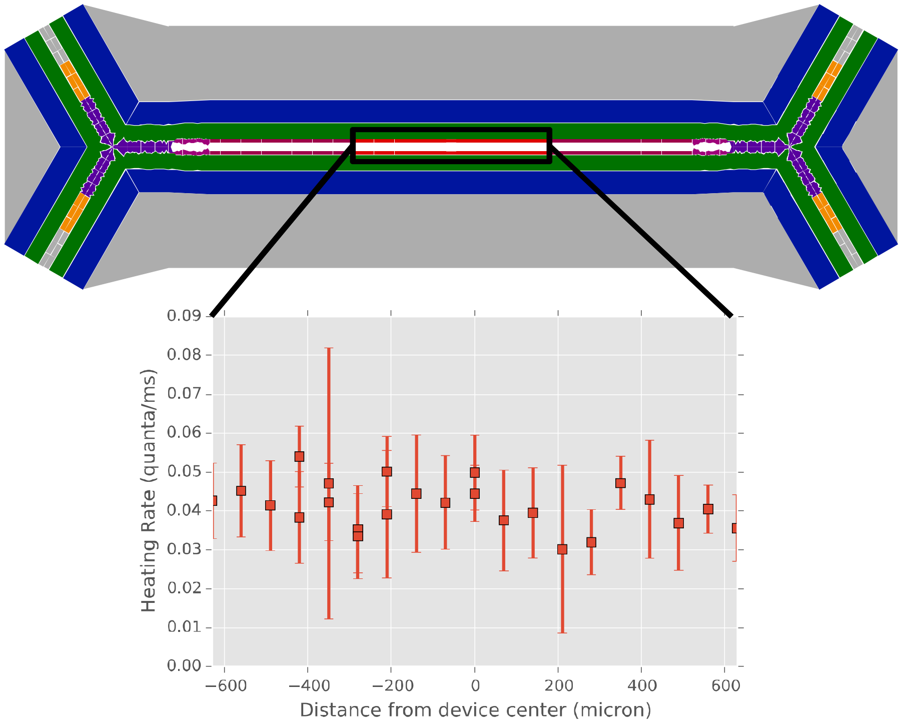
Manufacturability, uniformity

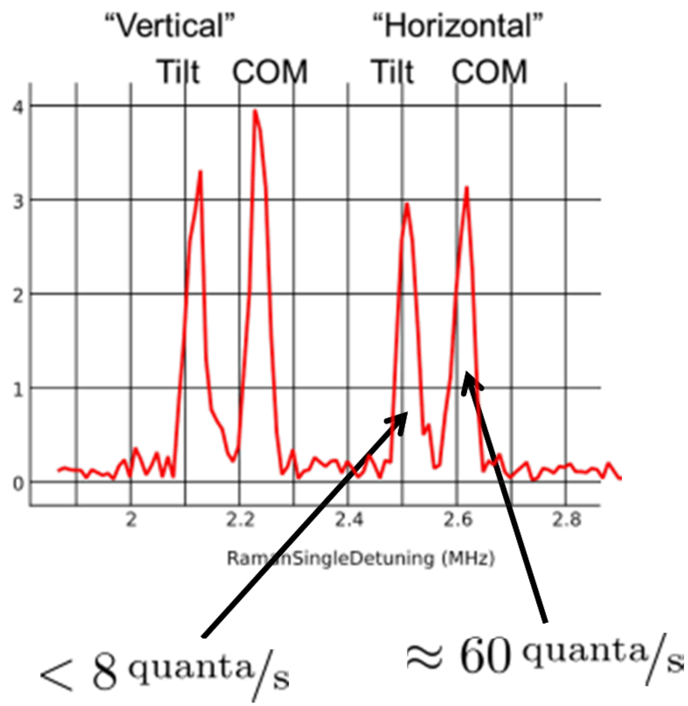


- 12 institutions, 5 countries
- >100 devices delivered
- Quantum computing
- Quantum simulations
- Quantum communication
- Surface science
- Metrology

Experimental characterization

Heating





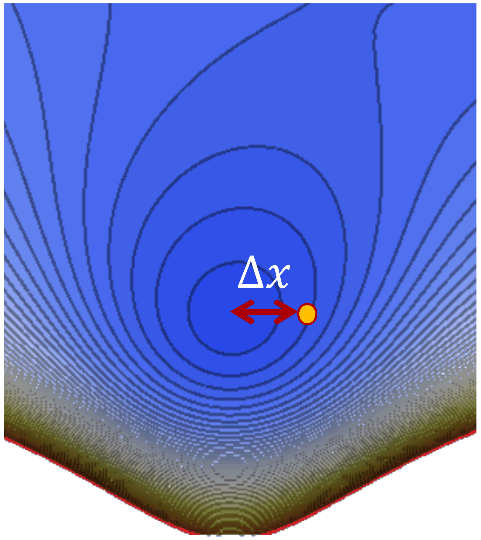
- Heating rate 40 q/s on average, $^{171}Yb^{+}$, Trap frequency 2.8 MHz, RF drive at 50 MHz
- Limited by technical noise: $\dot{n}_{\parallel} = 30\ \mathrm{quanta}/\mathrm{s}$

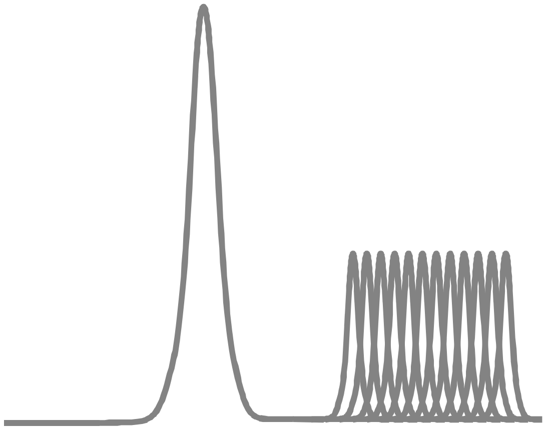
  $\dot{n}_{\perp} \approx 125\ \mathrm{quanta}/\mathrm{s}$
- Heating rate in HOA-2 is low and uniform along the length of the quantum section

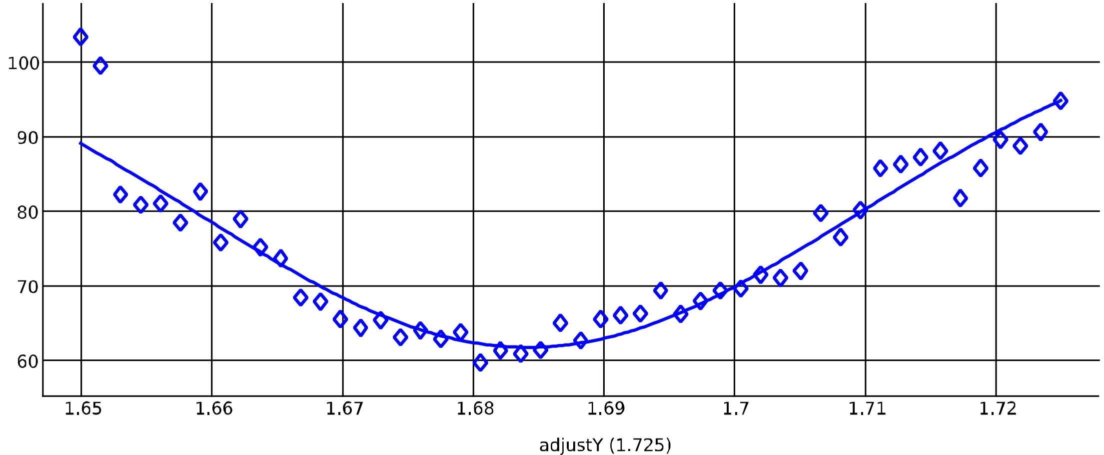
Experimental characterization

Background electric field

$$x(t) = [A\cos(\omega t) + \Delta x](1 + \frac{q}{2}\cos(\Omega t))$$



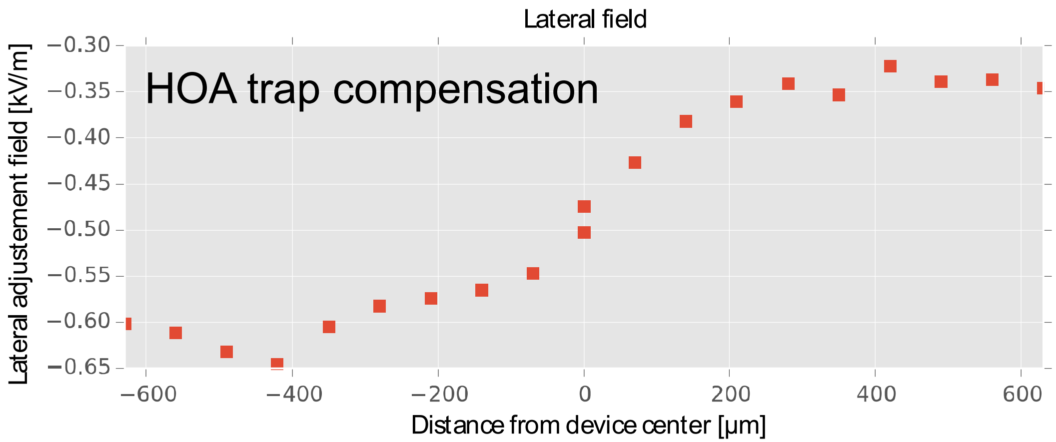




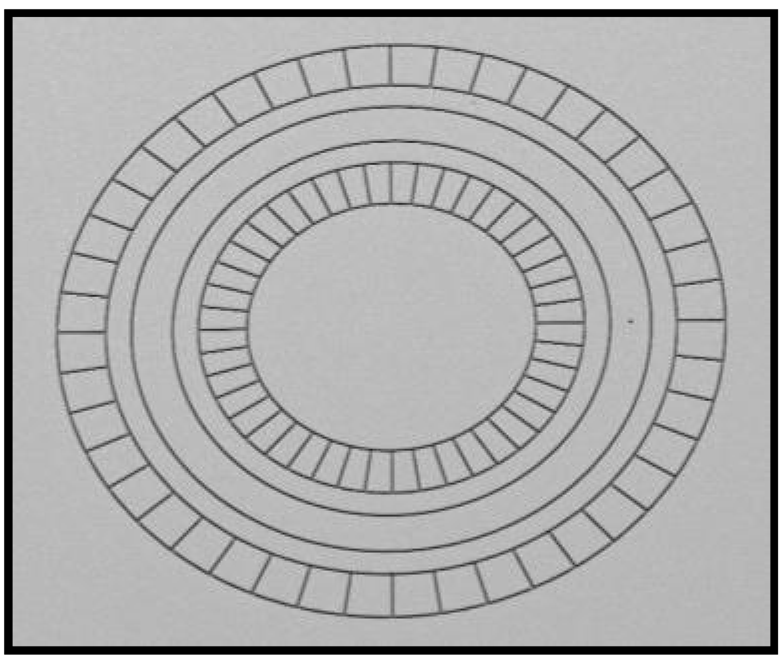
Experimental characterization

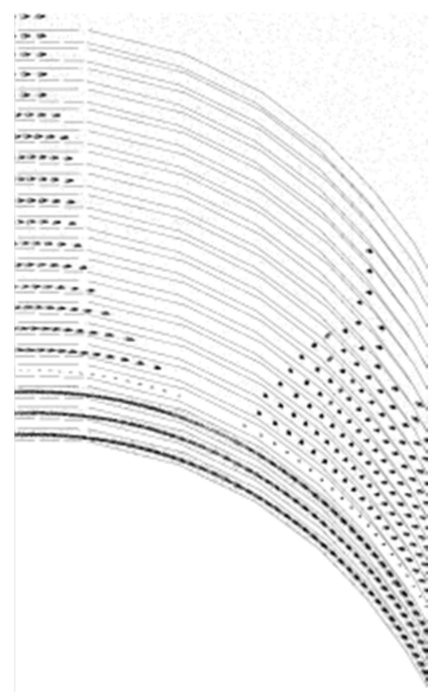
Background electric field

Linear trap



Ring trap





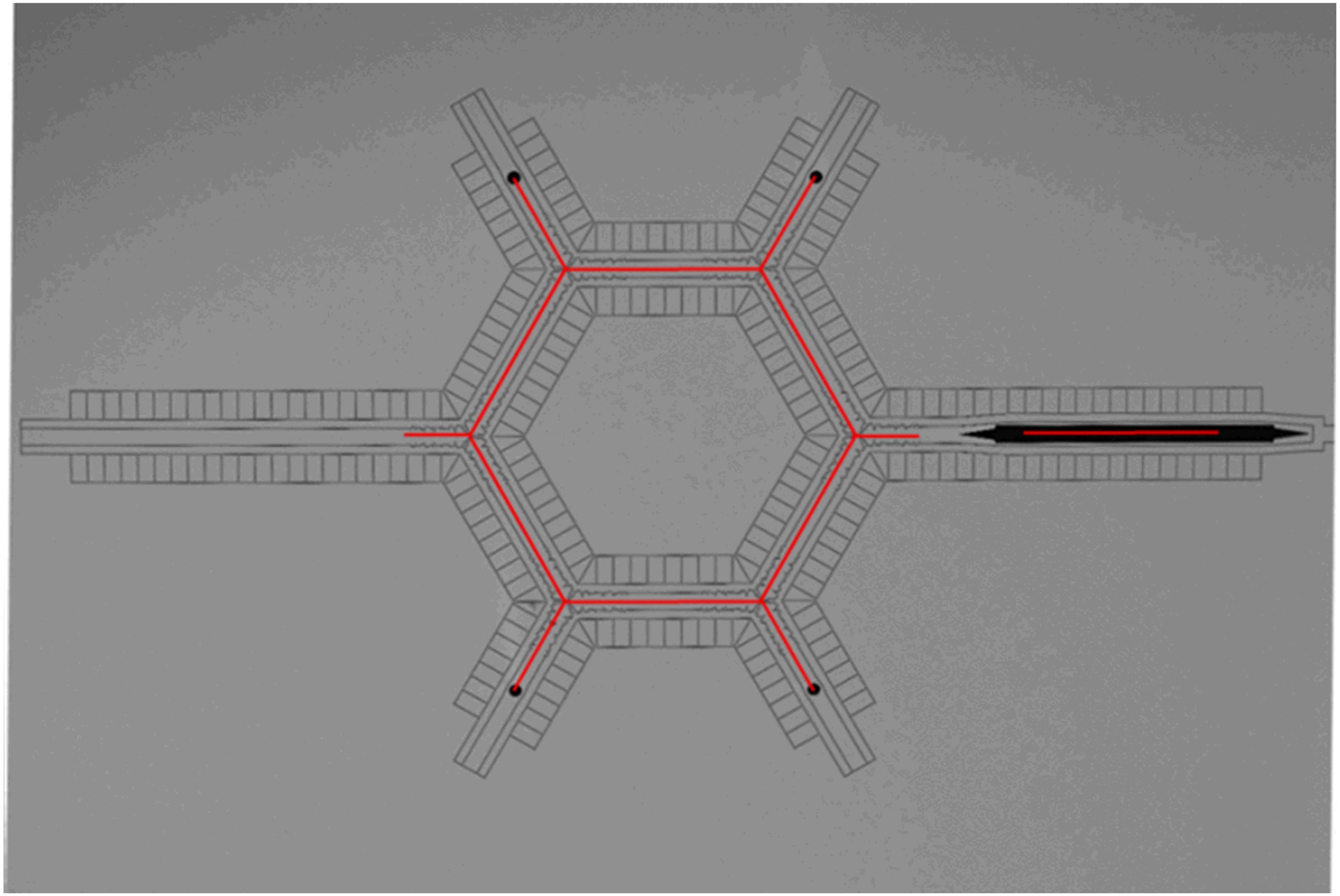
correction

0%

100%

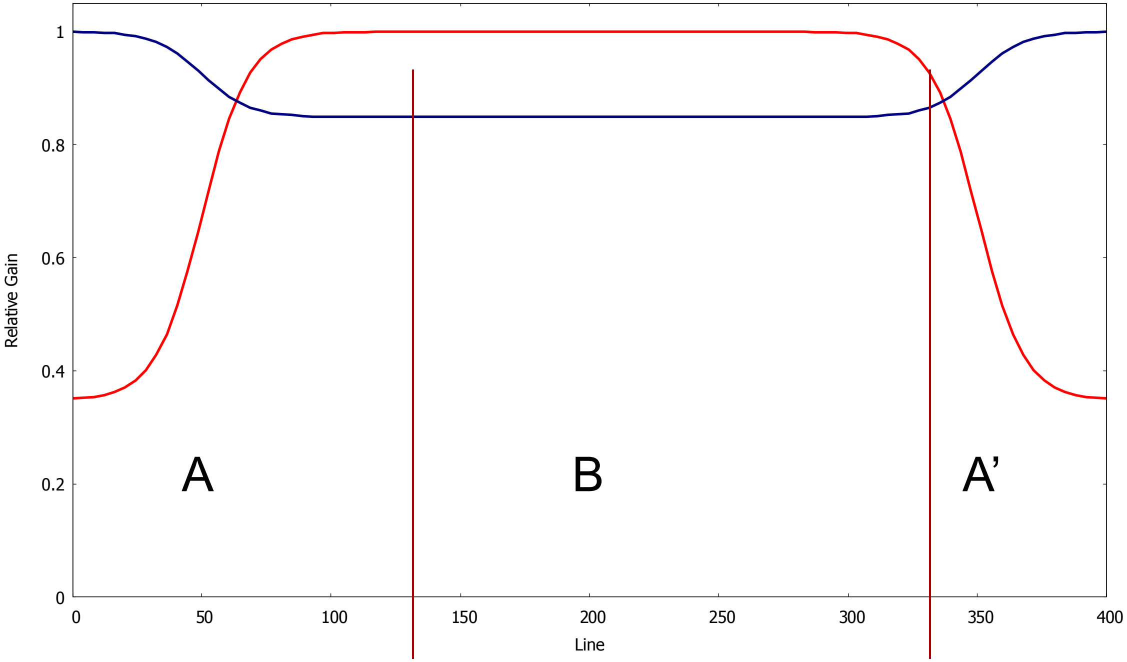
Shuttling and swapping

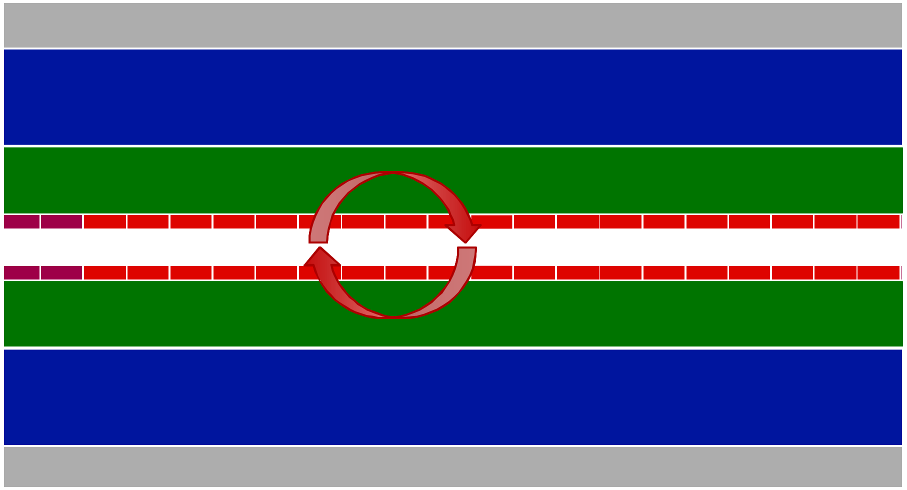
- Co-wired junction and linear sections, transported ions around device



Experimental characterization

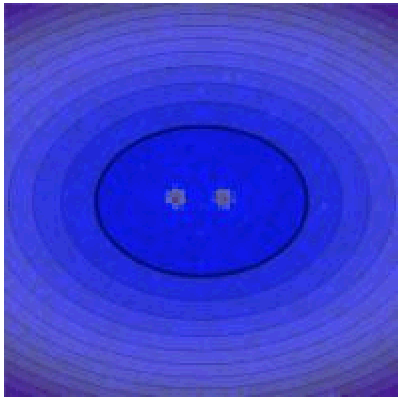
Shuttling and swapping

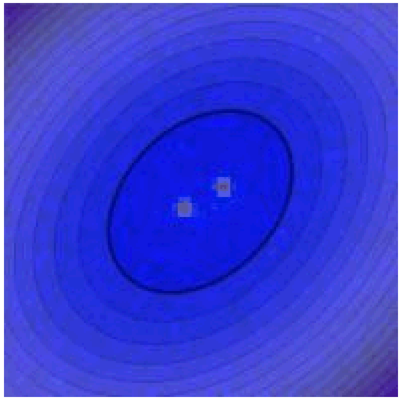




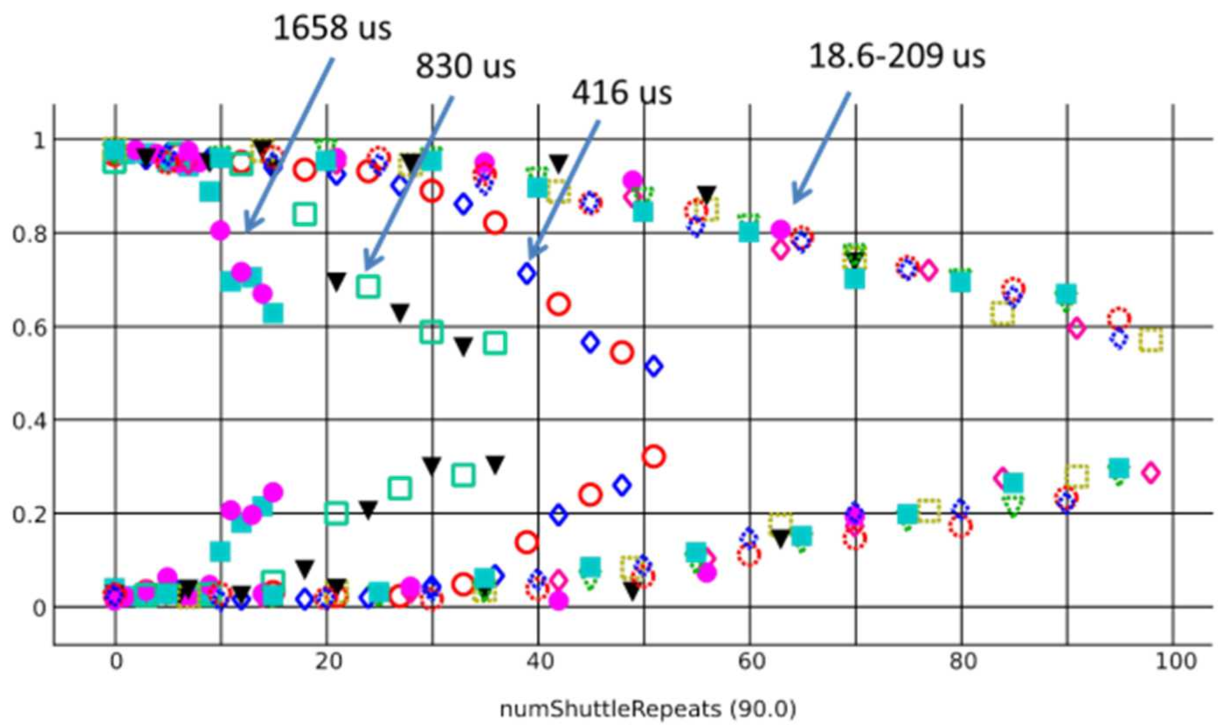
Experimental characterization

Shuttling and swapping





- Tag one ion with BB1 compensated pulse
- Measure states on separate PMT's after rotation
  - In addition to declining success probability, fluorescence drops due to motional heating
  - Success probability drops for times <18.6 us



Single qubit gates

Gate Set Tomography (GST)

- No calibration required
- Detailed debug information
- Efficiently measures performance characterizing fault-tolerance (diamond norm)
- Amplifies errors
- Detects non-Markovian noise
- Robin Blume-Kohout, SNL

Desired "target" gates:

G_i	Idle (Identity)
G_x	$\pi/2$ rotation about x-axis
G_y	$\pi/2$ rotation about y-axis

Fiducials:

$\{\}$

Gx

Gy

$Gx \cdot Gx$

$Gx \cdot Gx \cdot Gx$

$Gy \cdot Gy \cdot Gy$

Germs:

Gx

Gy

Gi

$Gx \cdot Gy$

$Gx \cdot Gy \cdot Gi$

$Gx \cdot Gi \cdot Gy$

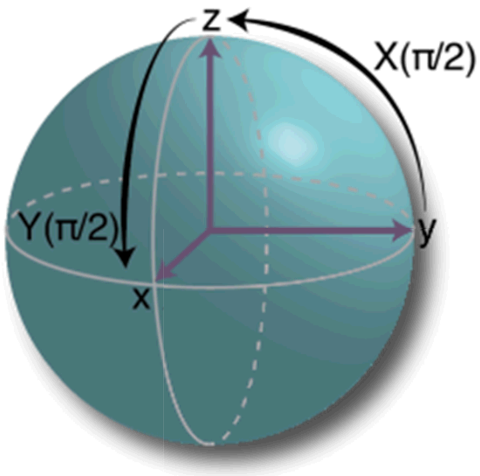
$Gx \cdot Gi \cdot Gi$

$Gy \cdot Gi \cdot Gi$

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

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

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

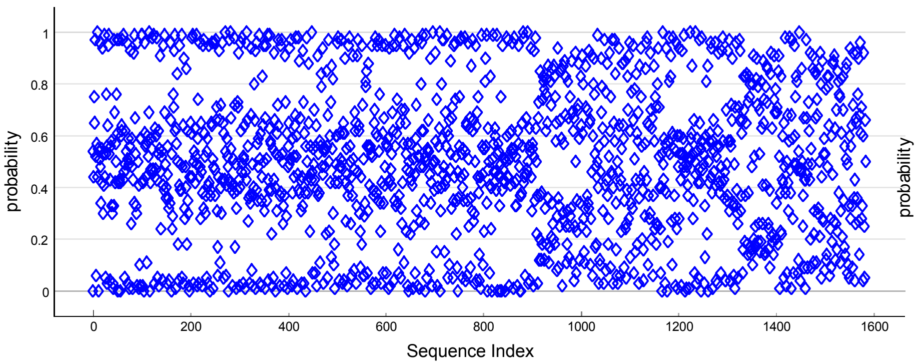


Single qubit BB1 compensated microwave gates on $^{171}Yb^{+}$

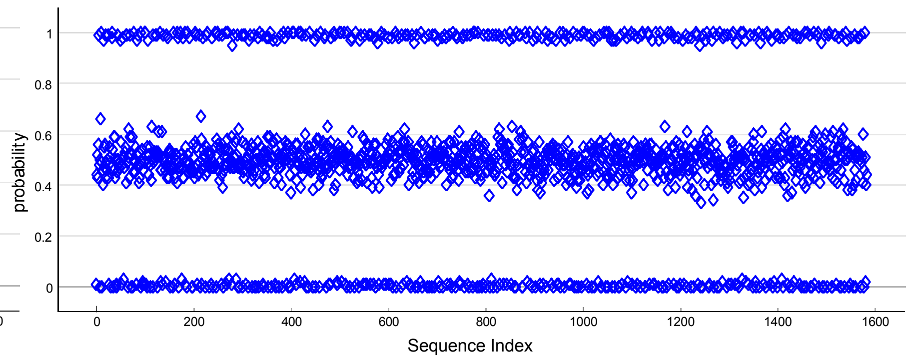
Single qubit gates

Microwave gates

Raw data poor gates

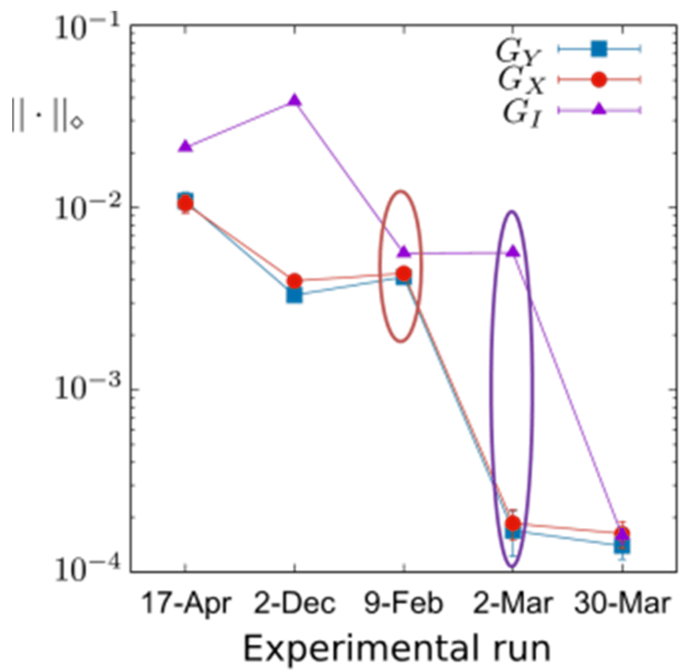


Raw data good gates



Gate	Rotn. axis	Angle
G_I	0.5252 -0.009 0.8506 -0.0244	0.001699π
G_X	-3×10^{-6} -1 -3×10^{-5} -0.009	0.501308π
G_Y	-0.2474 0.0001 0.9689 -0.0001	0.501366π

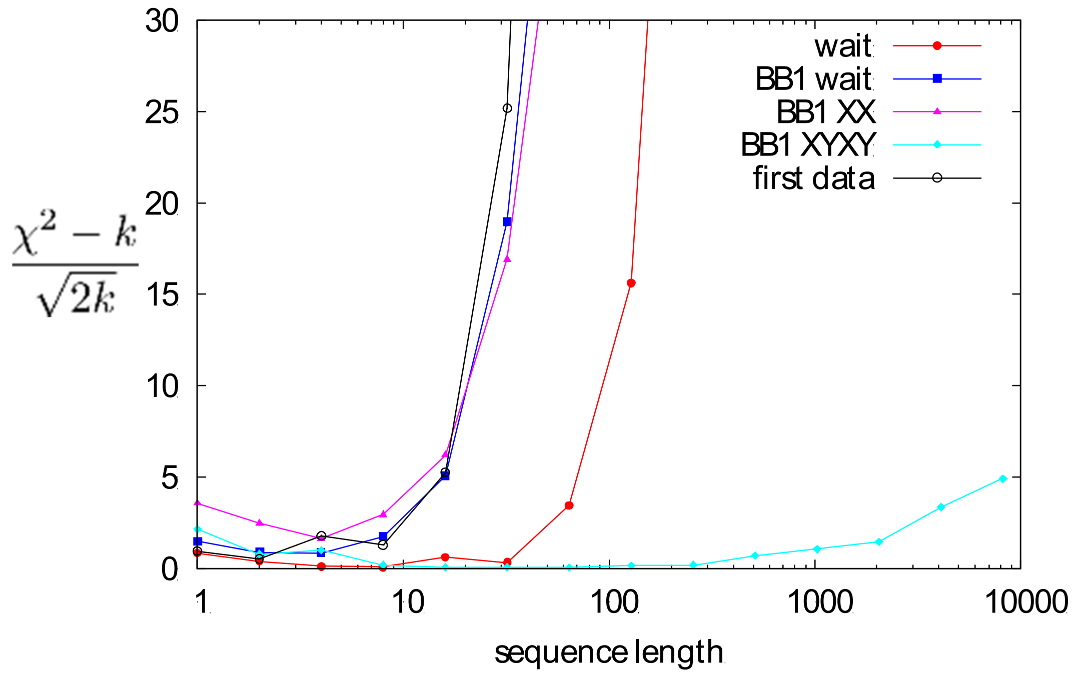
Gate	Rotn. axis	Angle
G_I	-0.0035 0.014 -0.9999 0.0006	0.001769π
G_X	-3×10^{-5} -1 1×10^{-4} 0.0006	0.500007π
G_Y	0.1104 4×10^{-5} 0.9939 0.0005	0.50001π



Single qubit gates

Markovianity violation

- BB1 decoupled microwave gates with decoupled identity have very small non-Markovian noise
- BB1 dynamically compensated pulse sequences
- Decoupling sequence for identity gate
- Drift control for π-time and qubit frequency



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

95% confidence intervals

R. Blume-Kohout, et al. arXiv:1605.07674 (2016)

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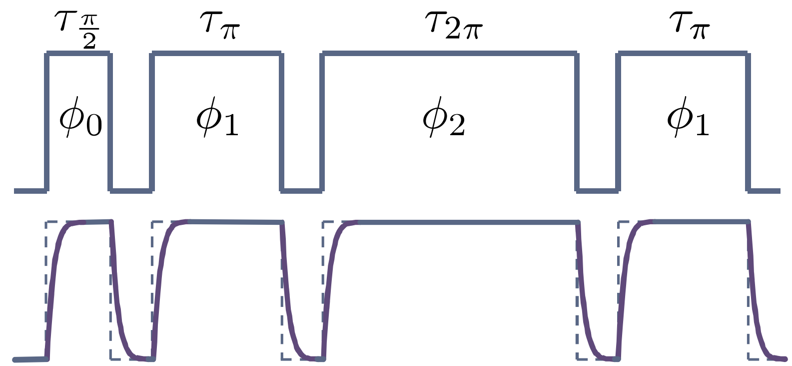
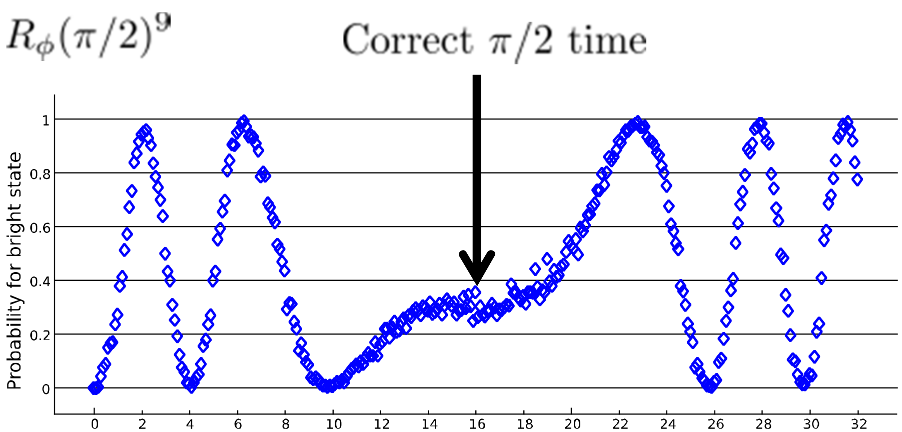
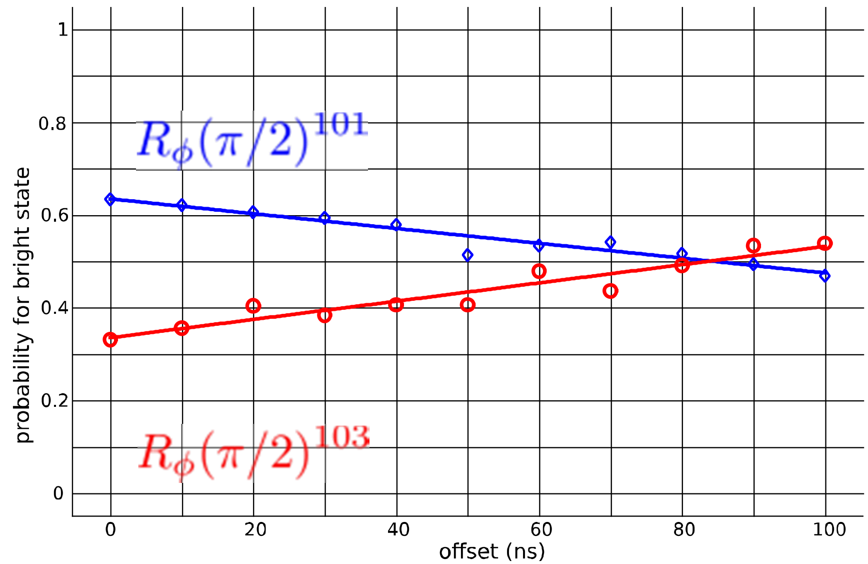
Microwave broadband pulses

BB1 compensated pulse

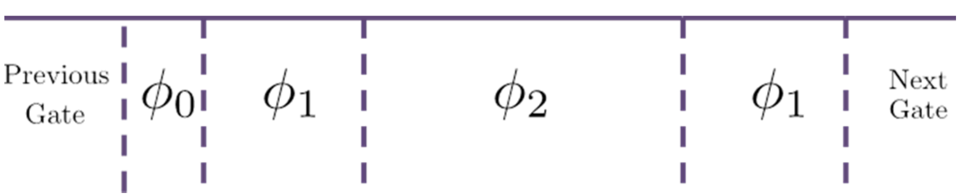
Switching artifacts







Discontinuous phase updates are used in place of gaps. Solves issues related to finite turn-on time and allows for continuous feedback on the driving field power.



Microwave error sources

- Time resolution:
  - Current time resolution is 5 ns
  - π-times are 45 μs
  - ratio: 10^{-4}
  - Possible due to broadband pulses
- Coherence time:
  - $T_2^* = 1$ s
  - longest pulse sequences 8192 : 1.66 s

GST: Raman laser results

co-propagating beam geometry

- Motion independent
- No optical phase imprinted

- BB1 dynamically compensated pulse sequences

GST results:

95% confidence intervals

	Conventional pulses		Gapless pulses	
Gate	Process Infidelity	$1/2$ $\diamond$-Norm	Process Infidelity	$1/2$ $\diamond$-Norm
G_I	$0.05(2) \times 10^{-4}$	$12(1) \times 10^{-4}$	$1.1(1) \times 10^{-4}$	$5.3(2) \times 10^{-4}$
G_X	$1.3(1) \times 10^{-4}$	$4(2) \times 10^{-4}$	$0.5(1) \times 10^{-4}$	$2(6) \times 10^{-4}$
G_Y	$1.6(4) \times 10^{-4}$	$4(3) \times 10^{-4}$	$0.7(1) \times 10^{-4}$	$4(9) \times 10^{-4}$

$$\text{Process Infidelity} < 1.2 \times 10^{-4}$$
$$1/2\,\diamond\text{-Norm} < 5.5 \times 10^{-4}$$

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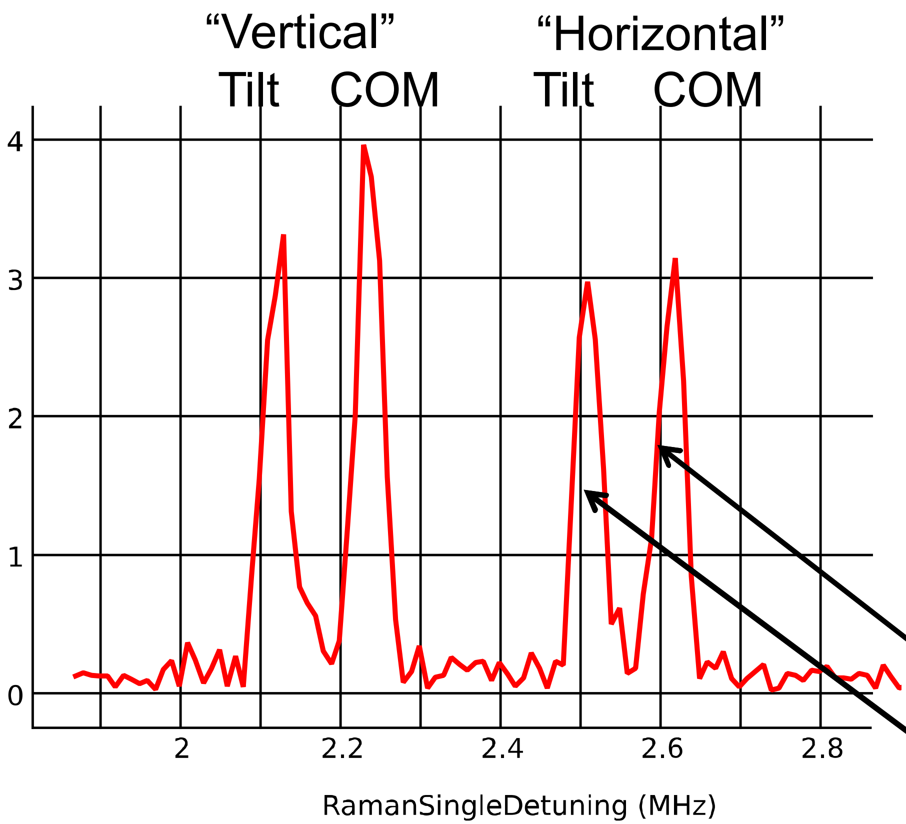
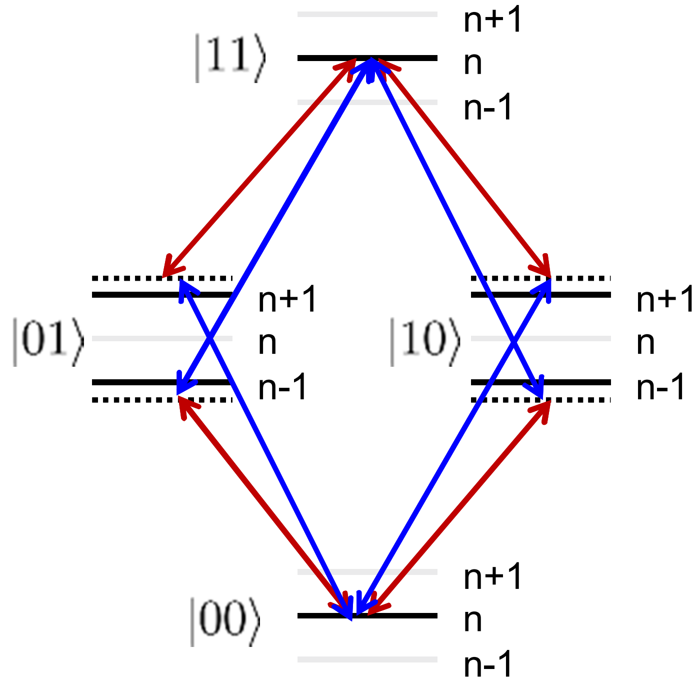
Two qubit gates

Mølmer-Sørensen gates

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





$$|00\rangle \rightarrow |00\rangle + |11\rangle$$

Heating rates

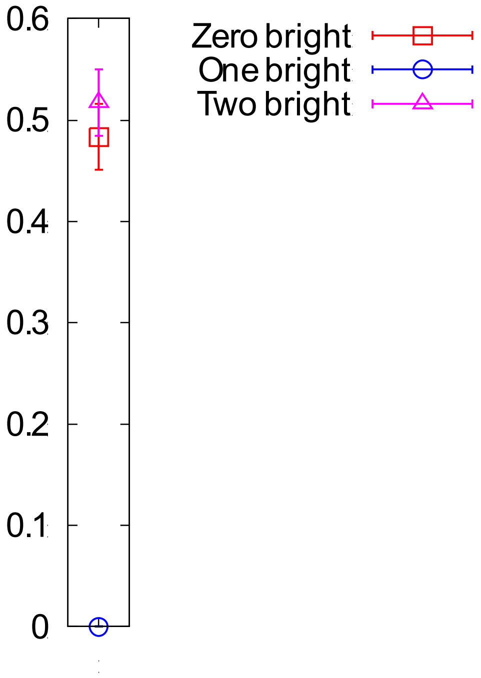
$\approx 60 \, \mathrm{quanta}/\mathrm{s}$

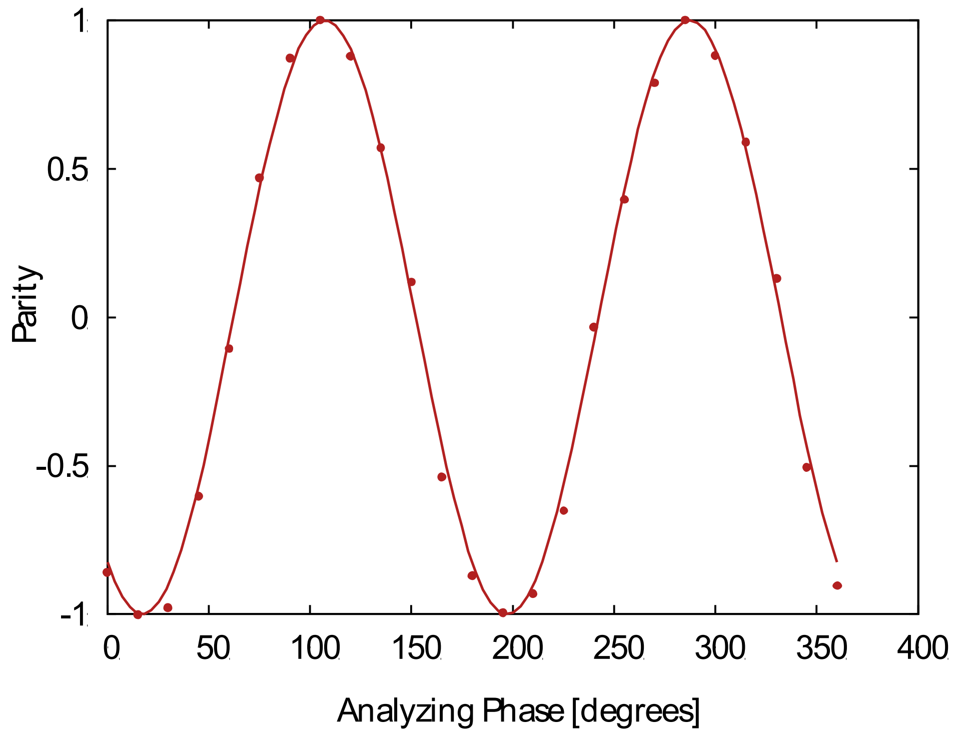
$< 8 \, \mathrm{quanta}/\mathrm{s}$

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

Fidelity measurement using parity scan

- Implemented using Walsh compensation pulses
- Optical phase sensitive





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

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Two qubit gates
GST on symmetric subspace

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_IG_{XX}

G_IG_{YY}

G_IG_{MS}

$G_{XX}G_{YY}$

$G_{XX}G_{MS}$

$G_{YY}G_{MS}$

$G_IG_IG_{XX}$

$G_IG_IG_{YY}$

Detection Fiducials:

$\{\}$

G_{XX}

G_{YY}

G_{MS}

$G_{XX}G_{MS}$

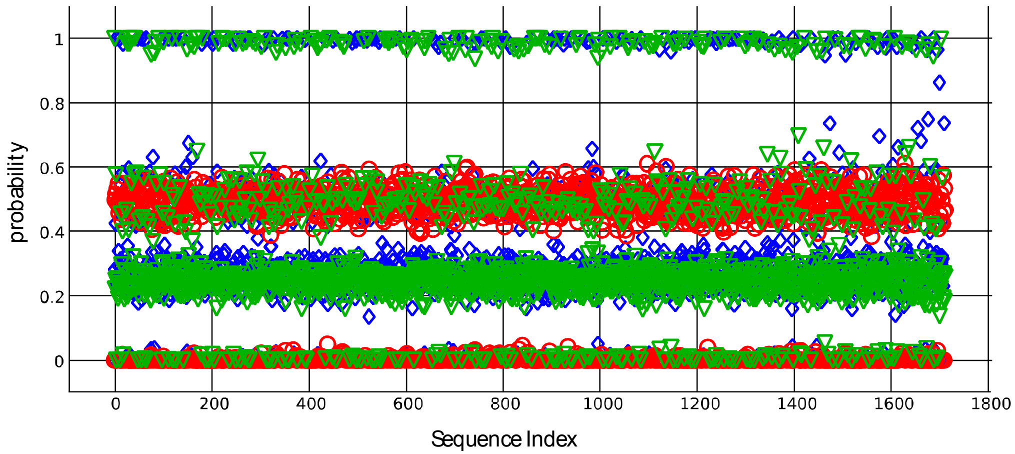
$G_{YY}G_{MS}$

G_{XX}^3

G_{YY}^3

$G_{YY}^2G_{MS}$

Two qubit gates
GST data



Zero ions bright
One ion bright
Two ions bright

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%

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Acknowledgements

Funding

CQuIC

UNM

Collaborators

MUSIQC

UNIVERSITY OF MARYLAND

GEORGIA TECH

UBC

MagiQ

Georgia Tech Research Institute
Problem. Solved.

MICHIGAN

The University of Sydney

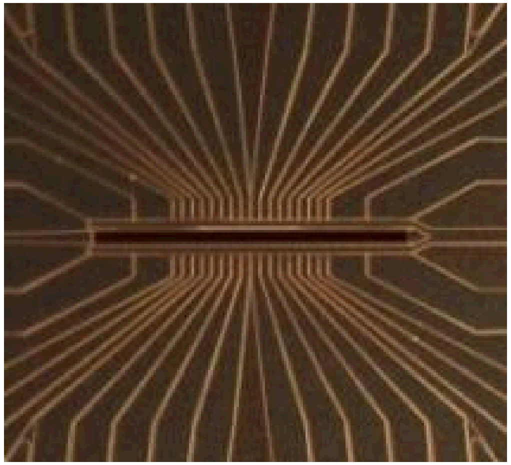
WASHINGTON

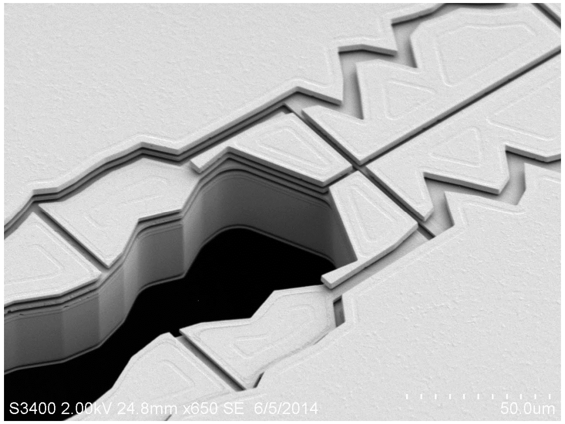
Backup

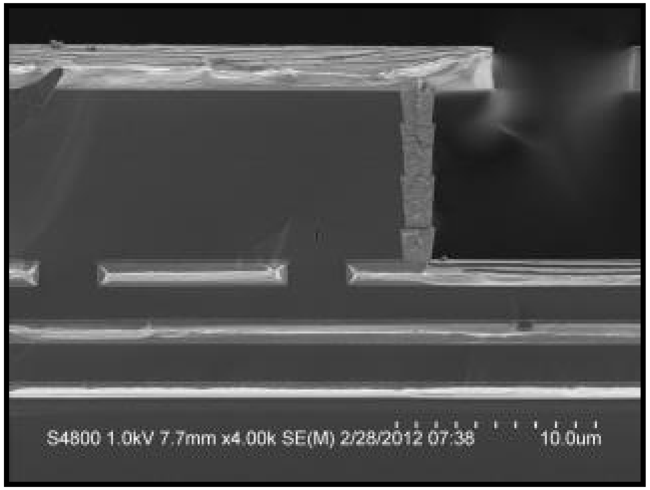
Thanks

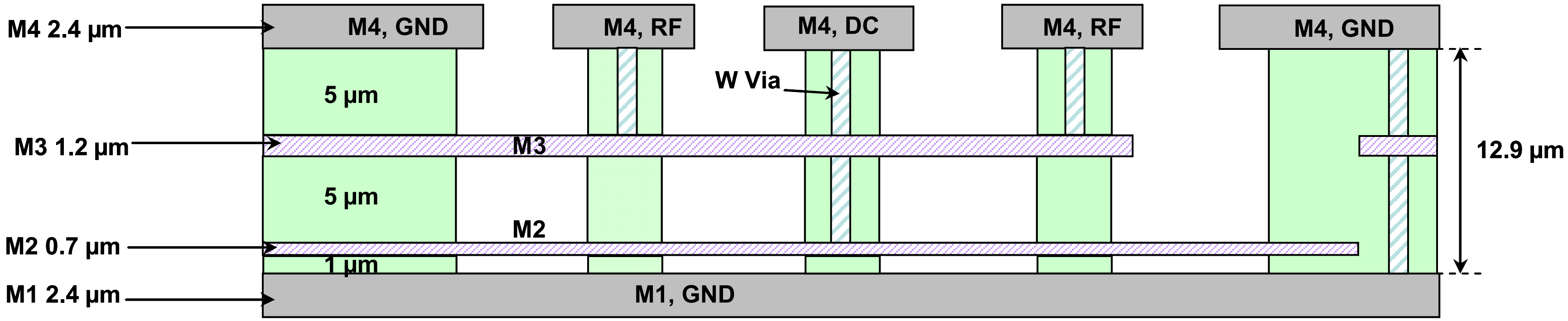
Daniel Stick, Robin Blume-Kohout, M. G. Blain, C. Clark, S. Clark, K. Fortier, R. Haltli, E. Heller, C. Hogle, A. Hollowell, D. Lobser, P. Maunz, J. Mizrahi, E. Nielsen, P. Resnick, J. Rembetski, K. Rudinger, J. D. Sterk, C. Tigges, J. Van Der Wall.

Multi-layer metalization

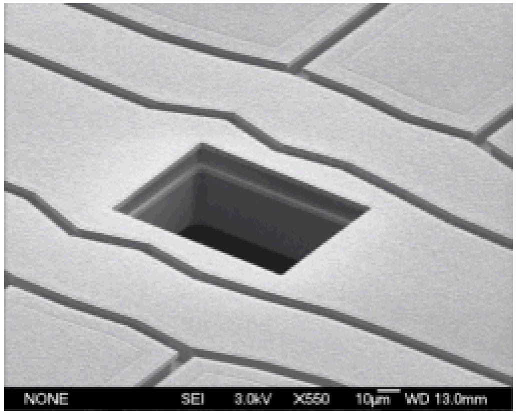




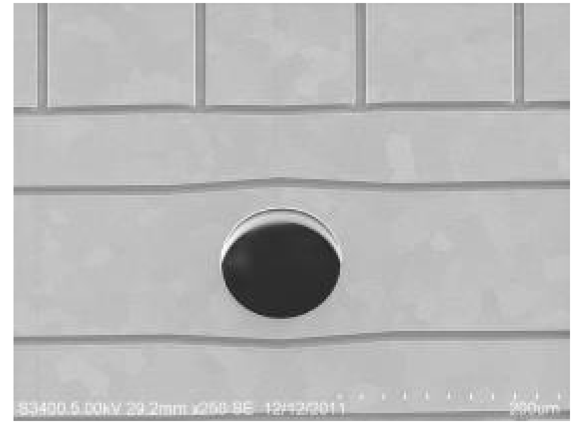




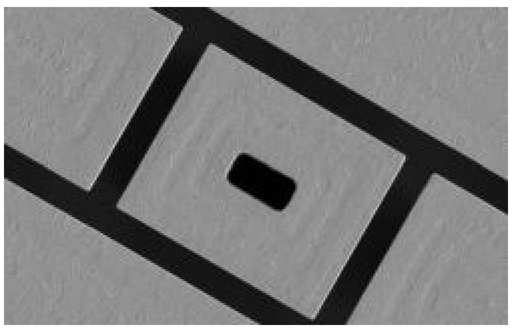
Loading holes



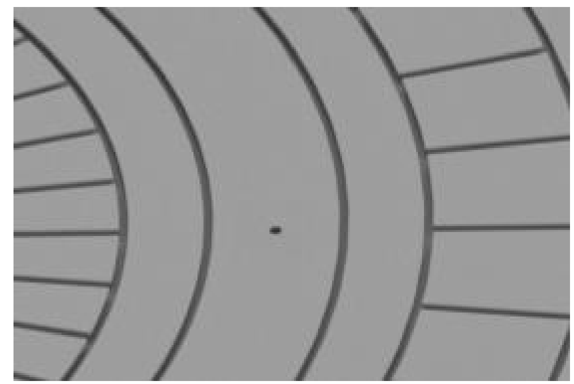
50μm×80μm
modulation necessary



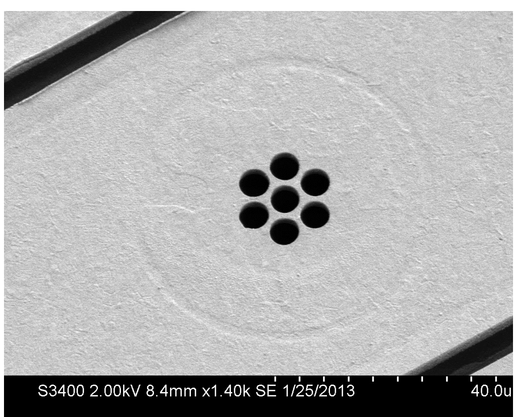
100μm diameter
modulation necessary



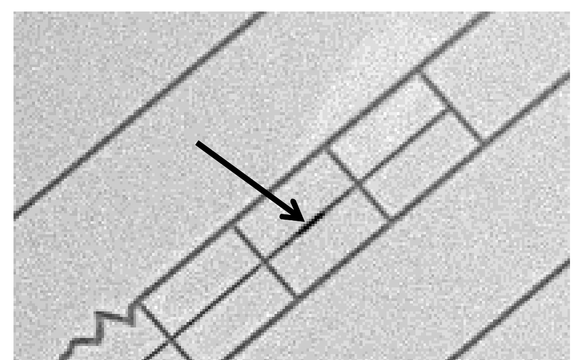
small rectangular hole
no modulation needed



10μm hole
still perturbs the field

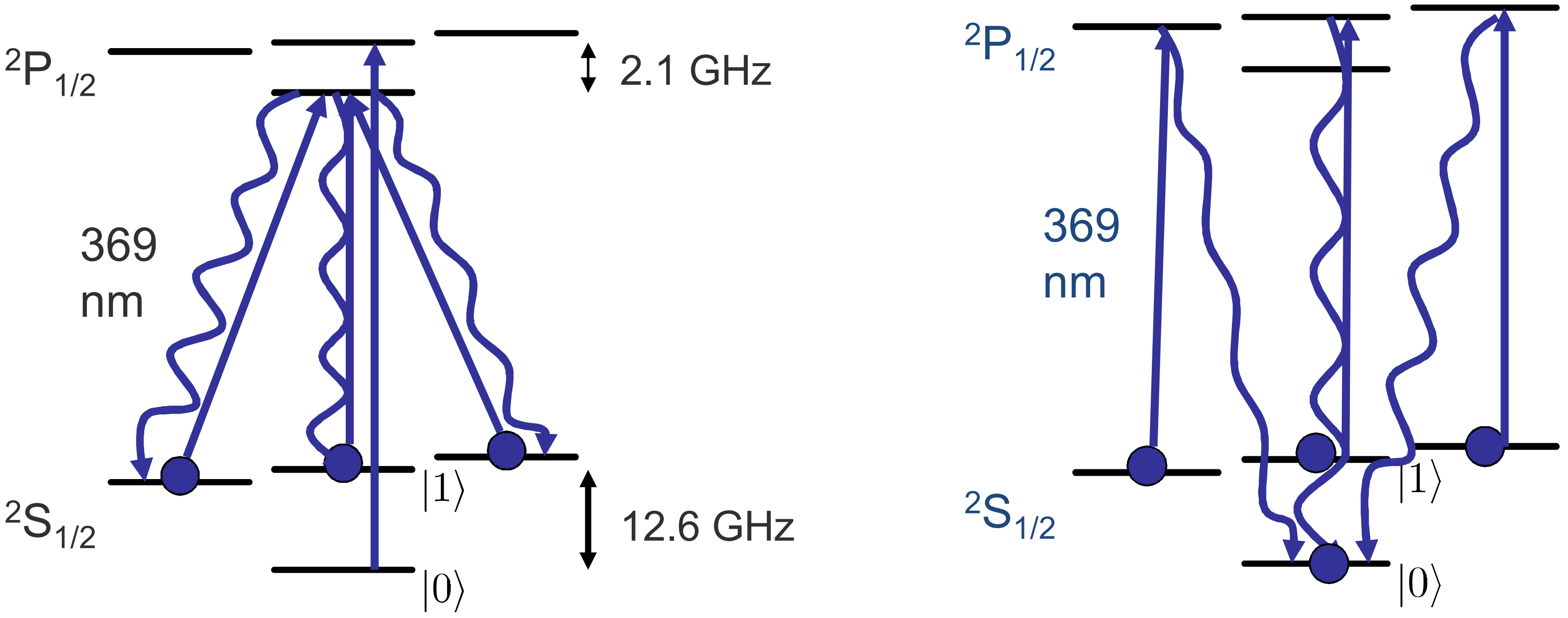


5μm holes
no modulation



3μm×20μm

Ytterbium qubit



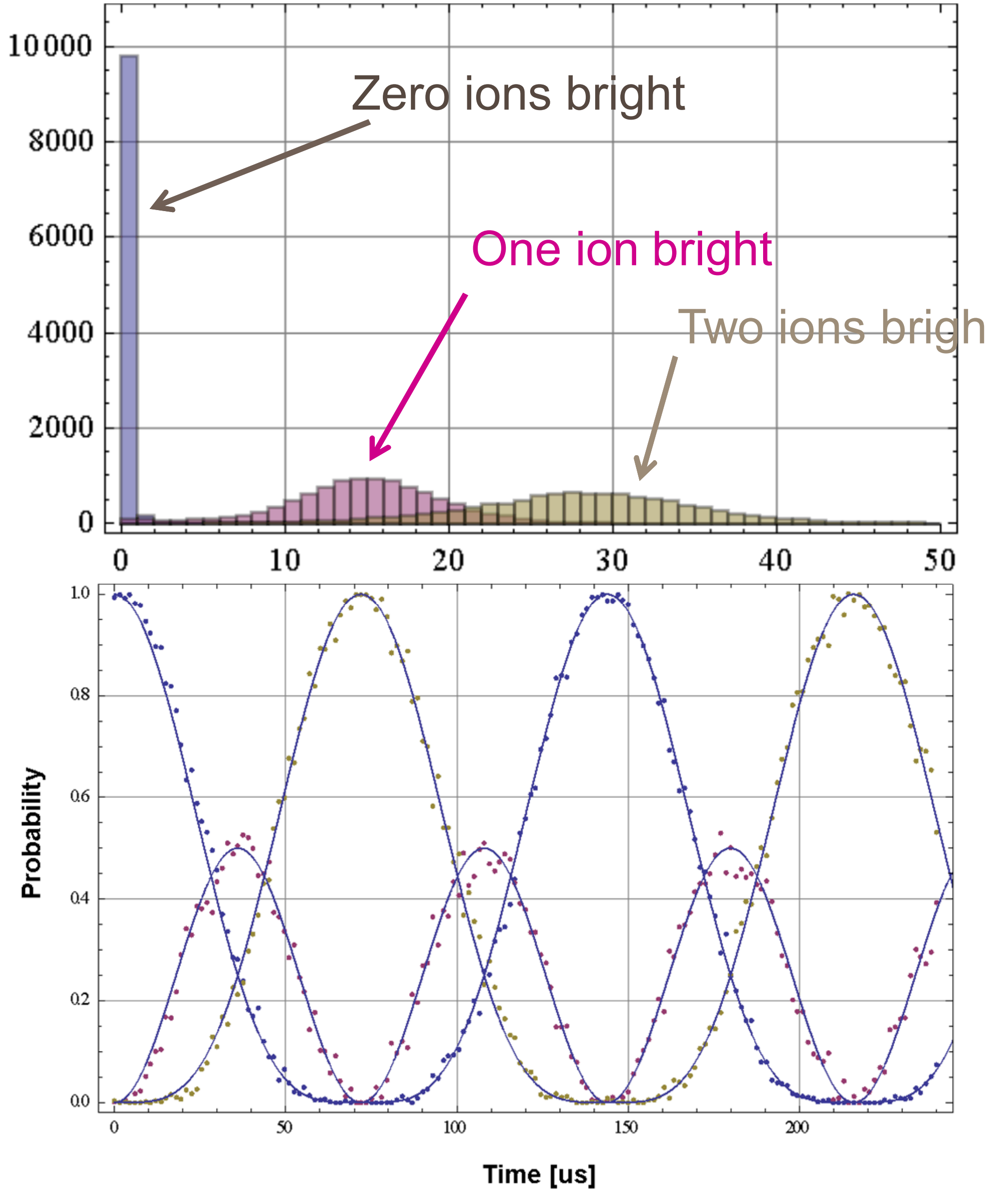
clock state qubit, magnetic field insensitive

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

State detection for two ions

- Too much overlap between histograms of 1 and 2 bright ions

- Fit sums of experimentally measured 0, 1 and 2 ion bright histograms to determine probabilities of ensemble



Demonstration:

- Two trapped ions undergoing global Rabi oscillations

- Is described using one fit parameter: the π-time

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HOA-2 heating rates

Heating rates as function of principal axes rotation

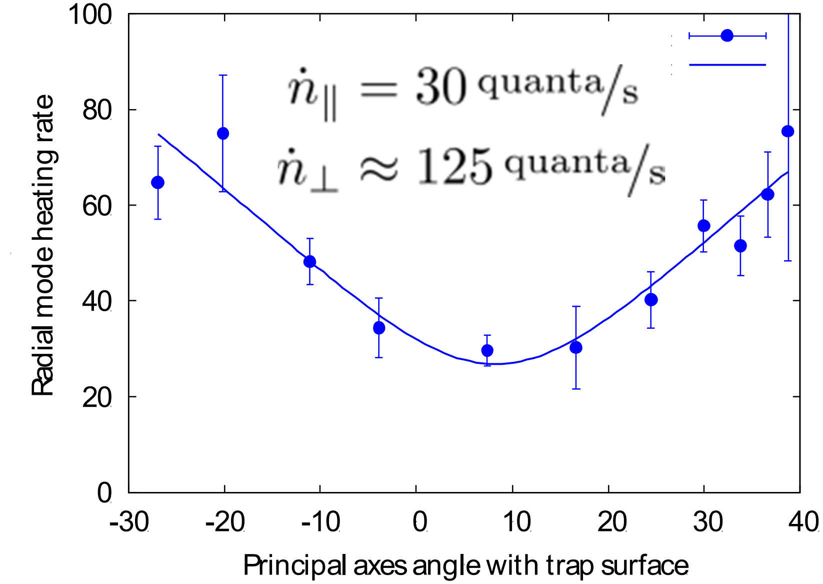
- Principal axes rotation measured by measuring π-times of Rabi flopping on cooled motional modes

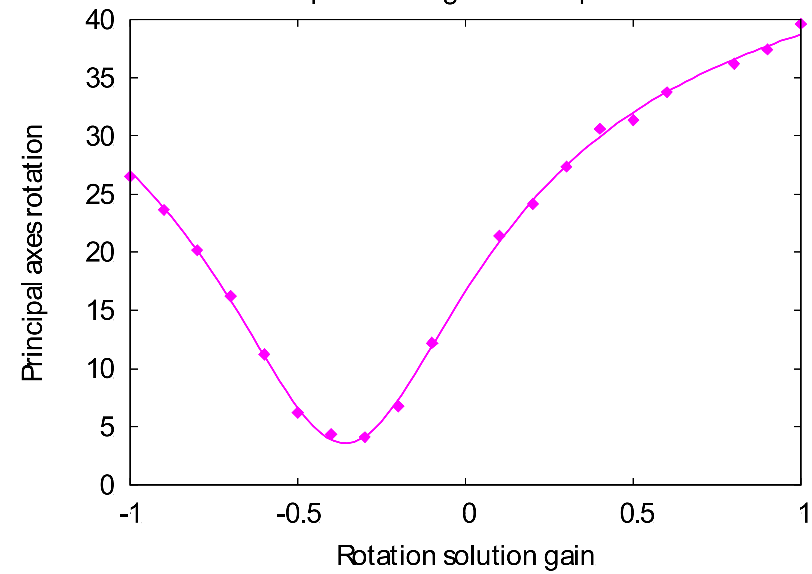
- Minimal heating rates for motional mode parallel to trap surface $\dot{n}_{\|}$

- Without technical noise: Vertical mode has at most $\dot{n}_{\perp} \leq 2\dot{n}_{\|}$
(P. Schindler, et al., Phys. Rev. A **92**, 013414 (2015).

- Limited by technical noise

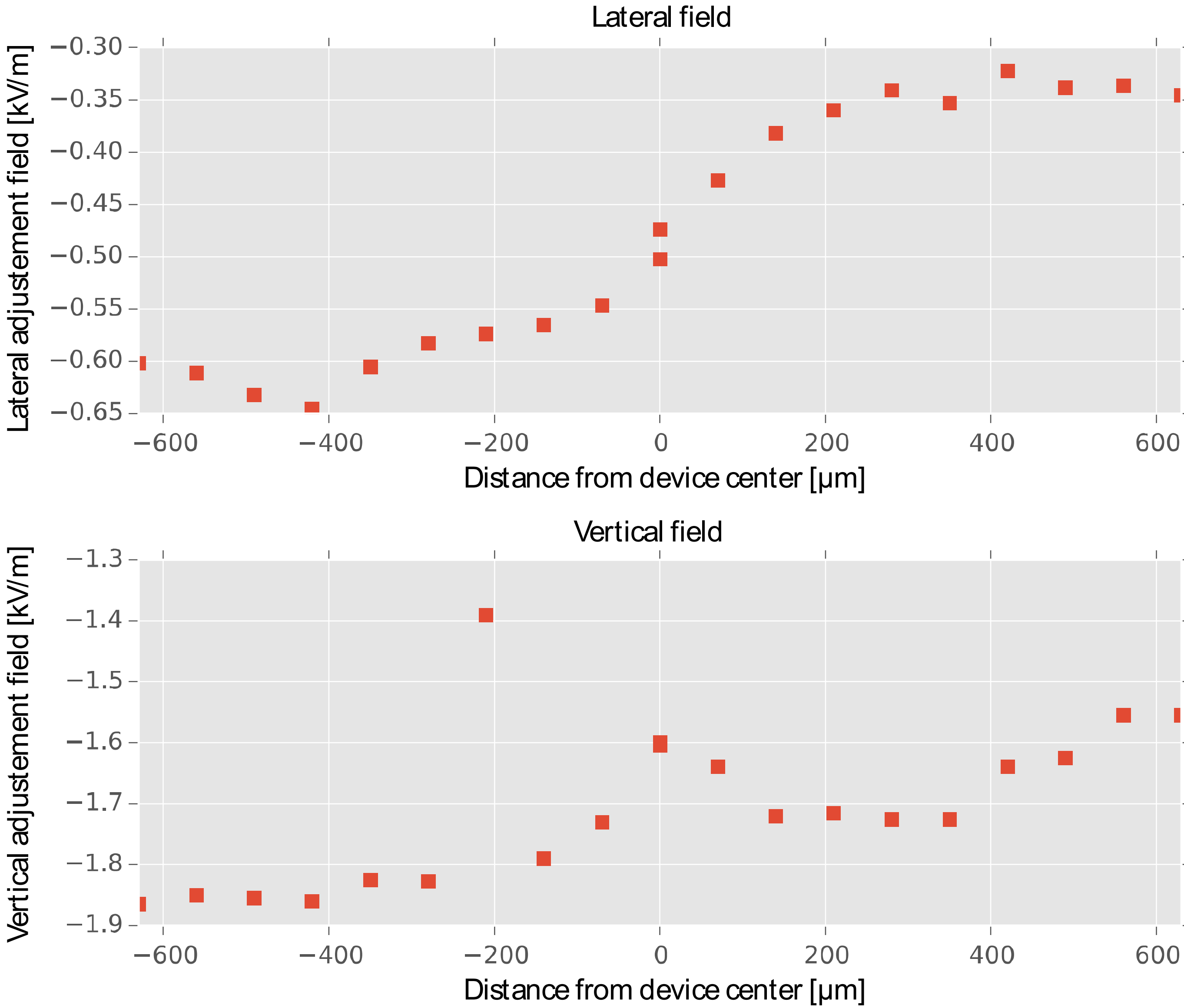
$^{171}Yb^{+}$, Trap frequency 2.8 MHz, r.f. 50 MHz



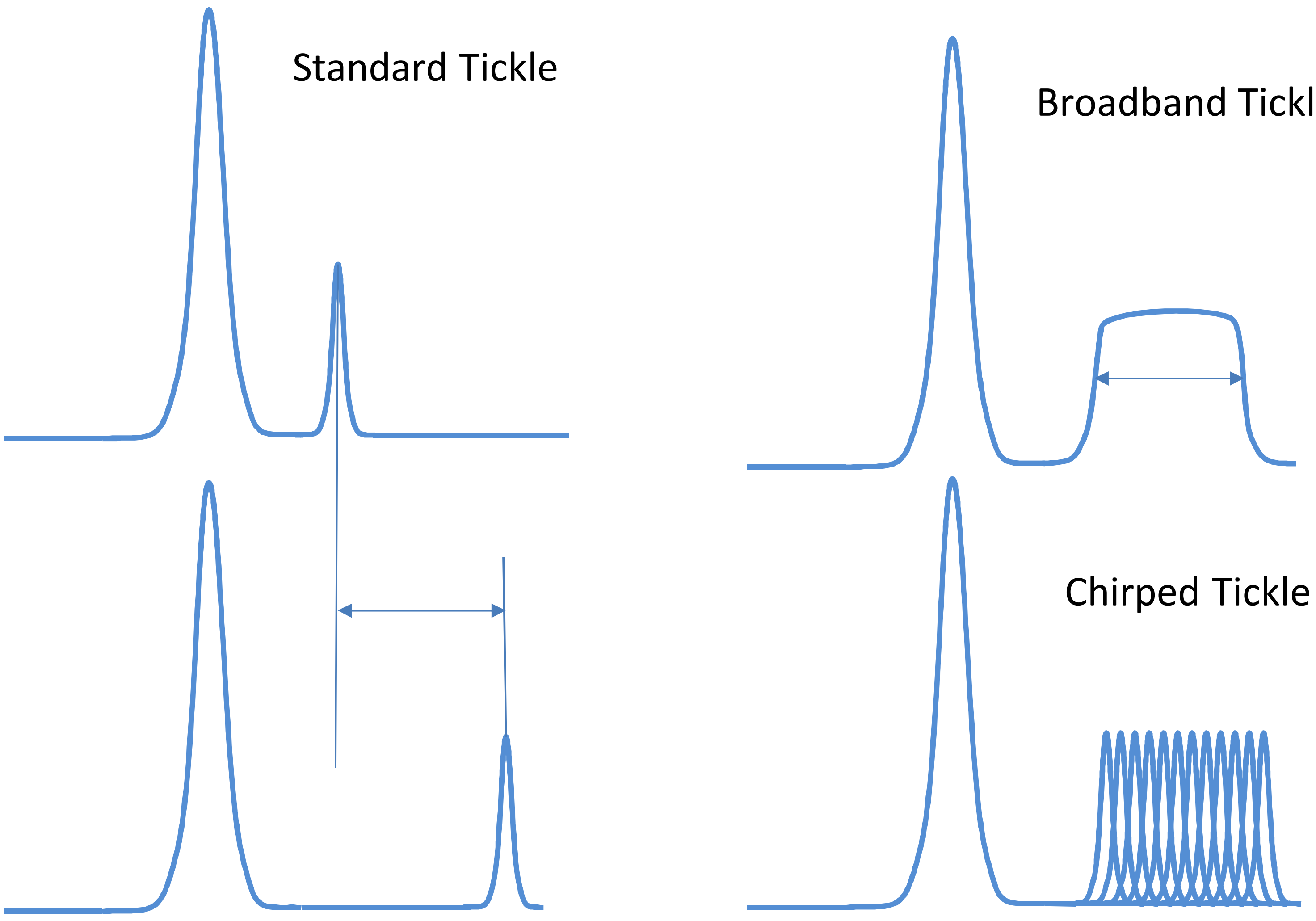


Compensation Q-section

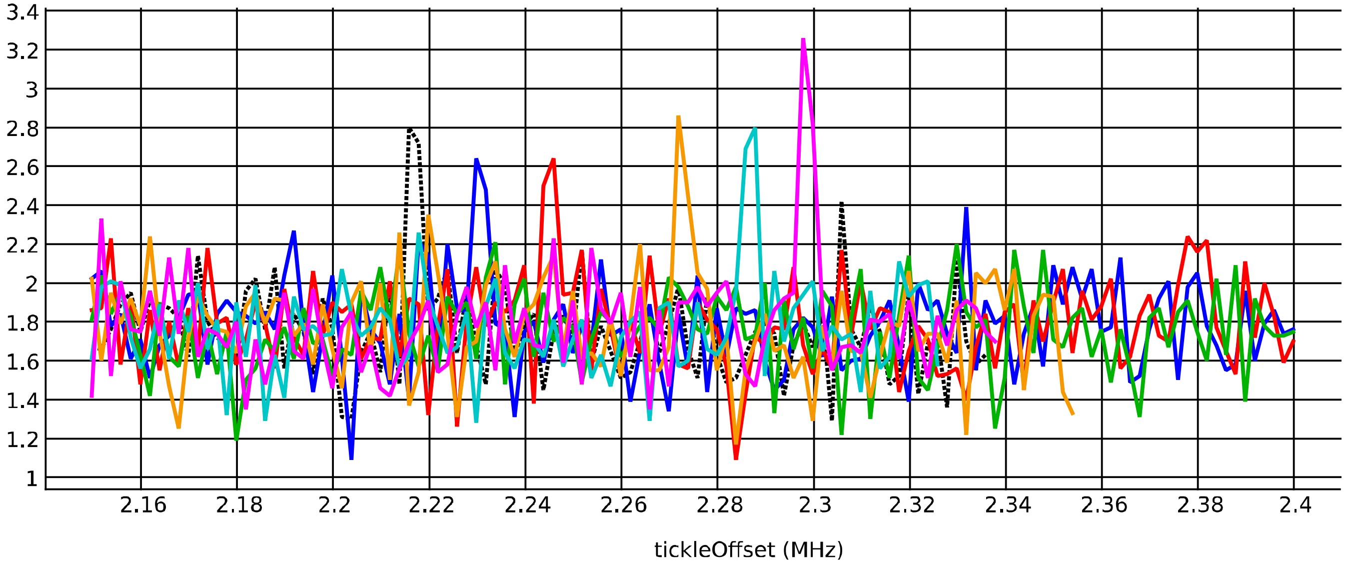
Compensation field varies slowly along linear quantum section of the trap

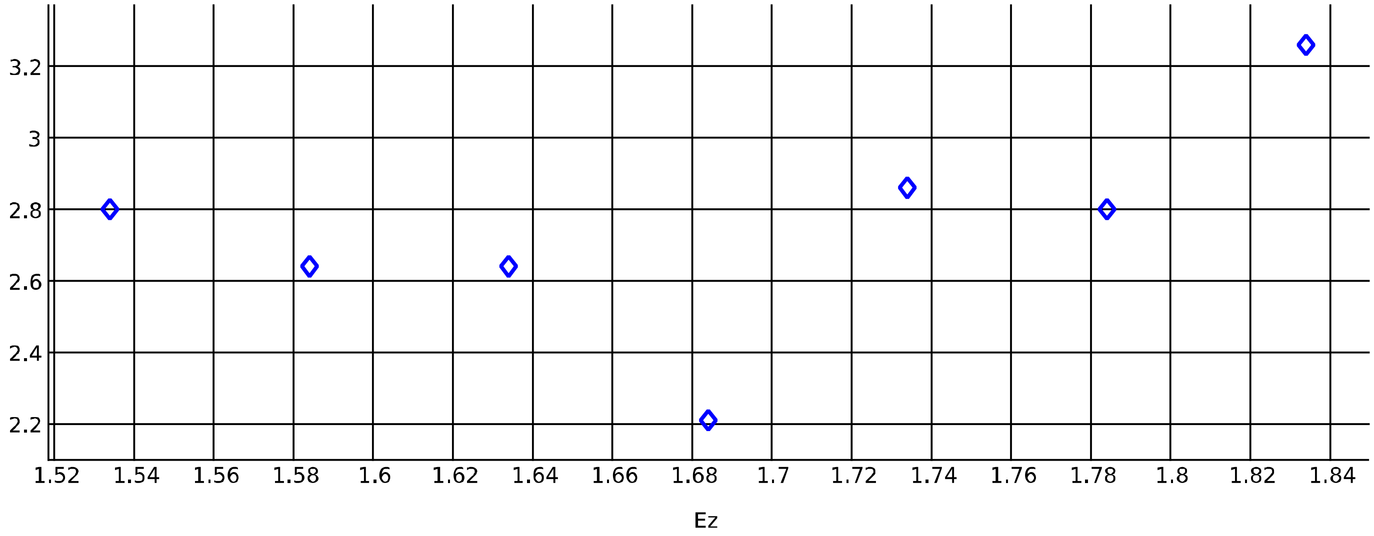


Vertical Micromotion Compensation

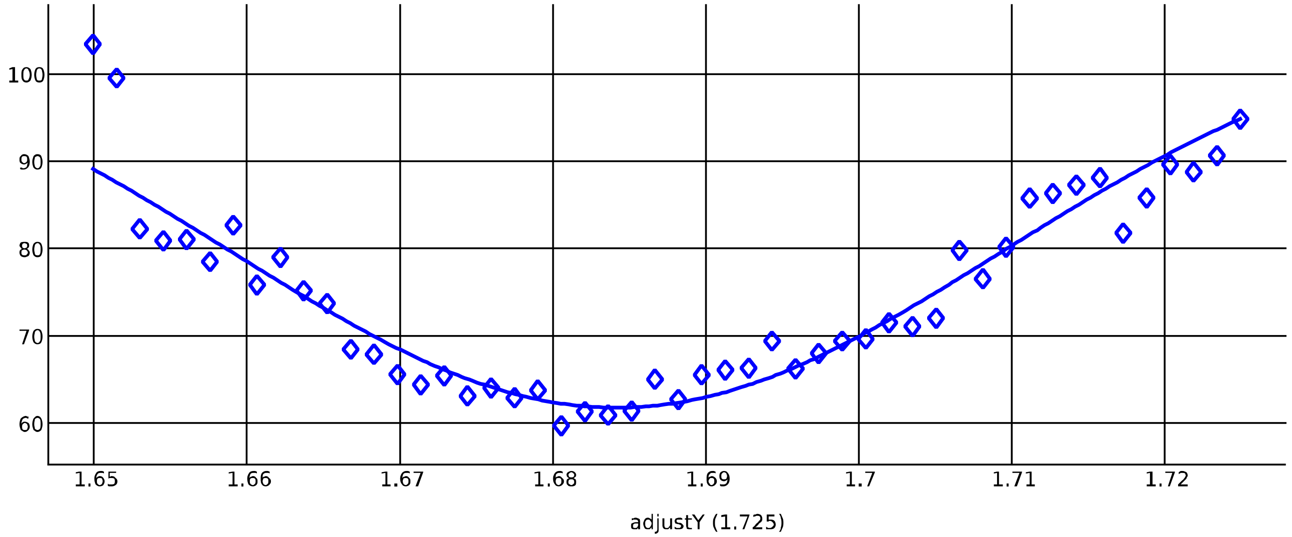


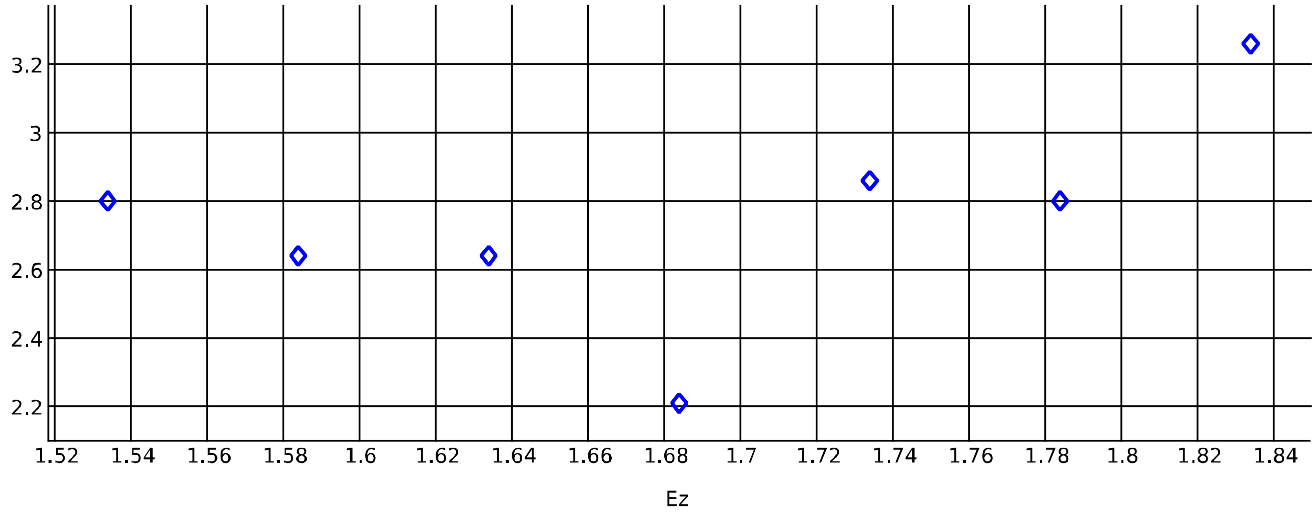
Standard Tickle Scan



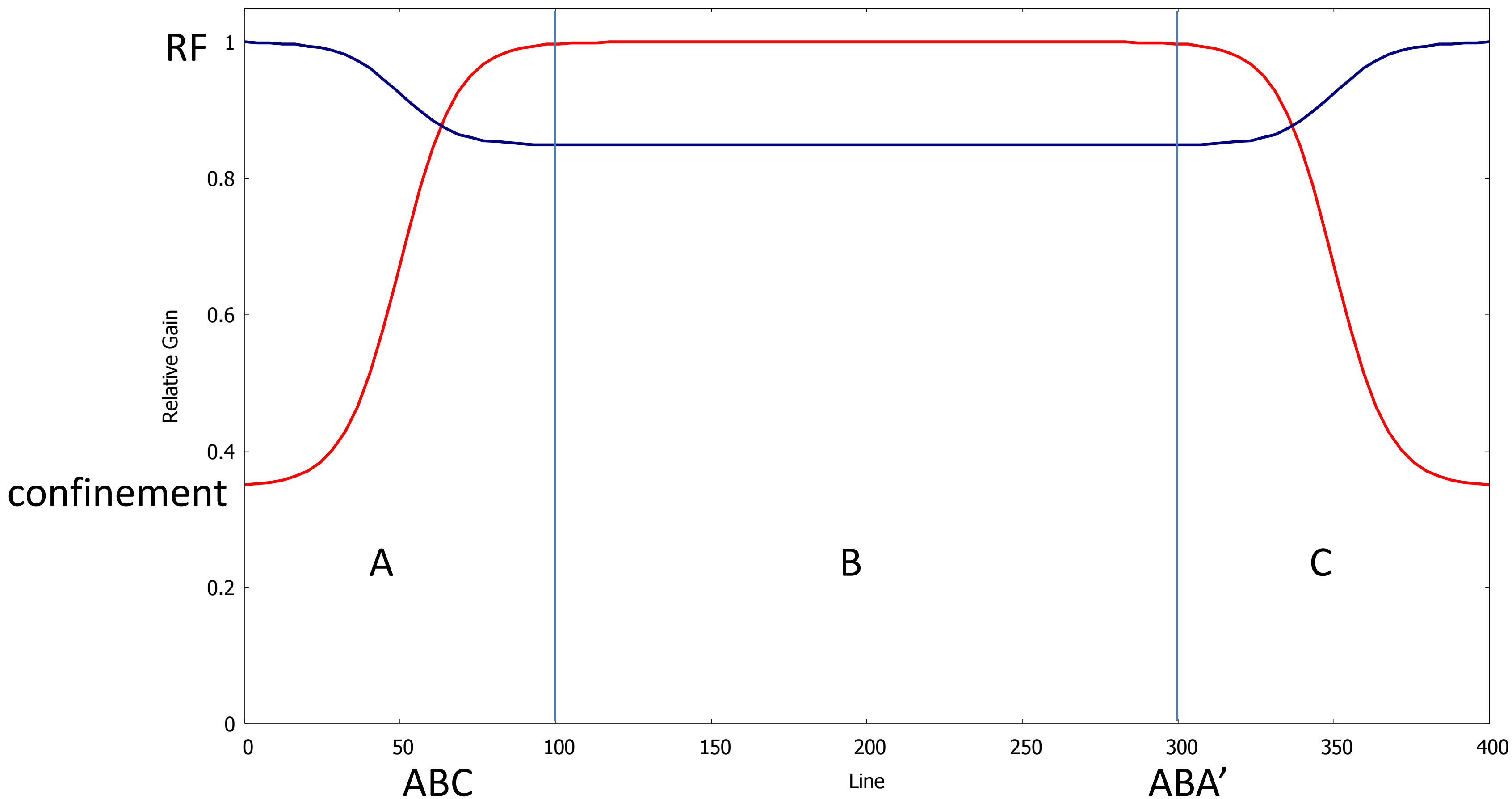


Chirped vs Standard Tickle





Rotation Solution with RF and axial confinement ramp

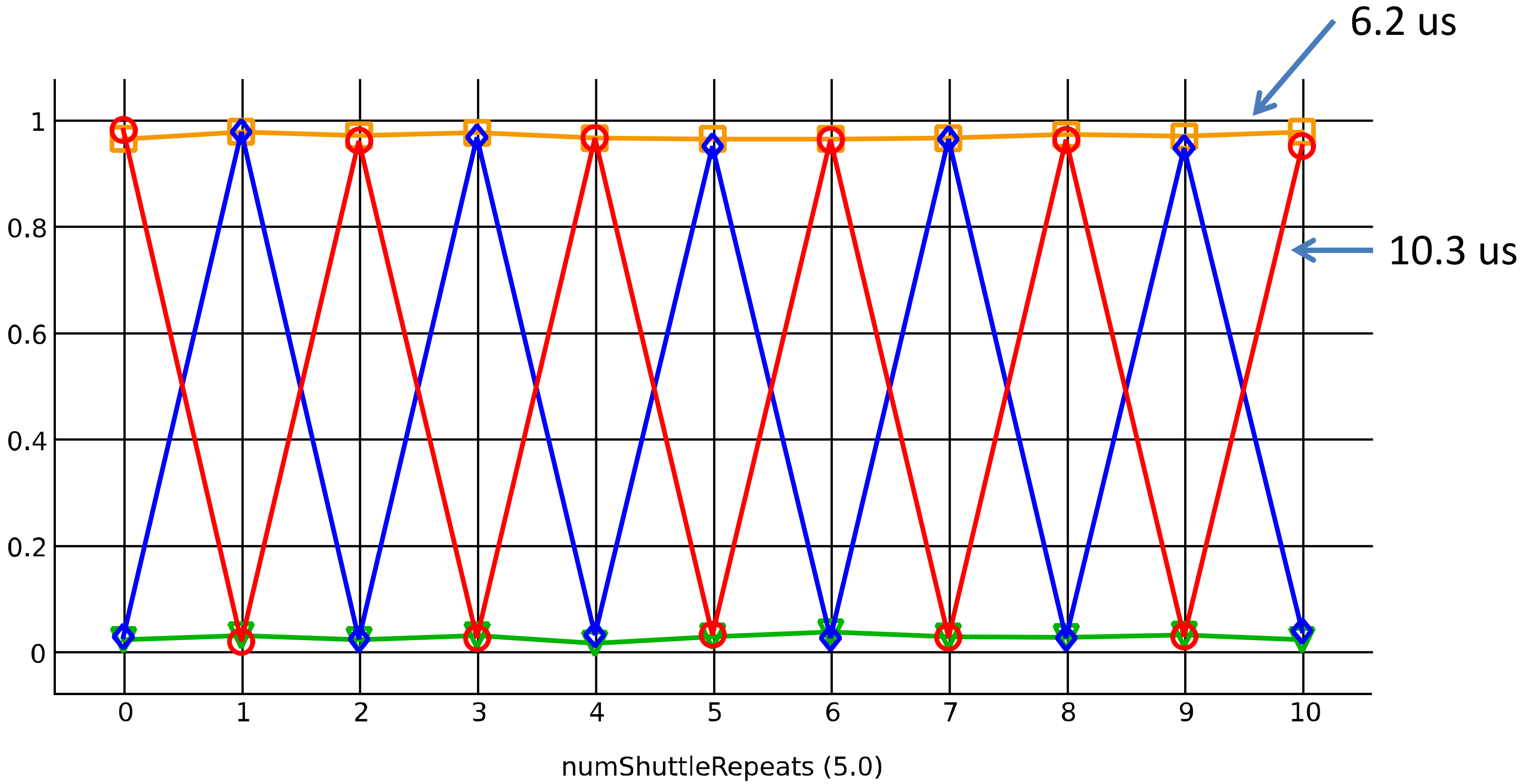


ABC
ABB'A'
ABB'BC
…

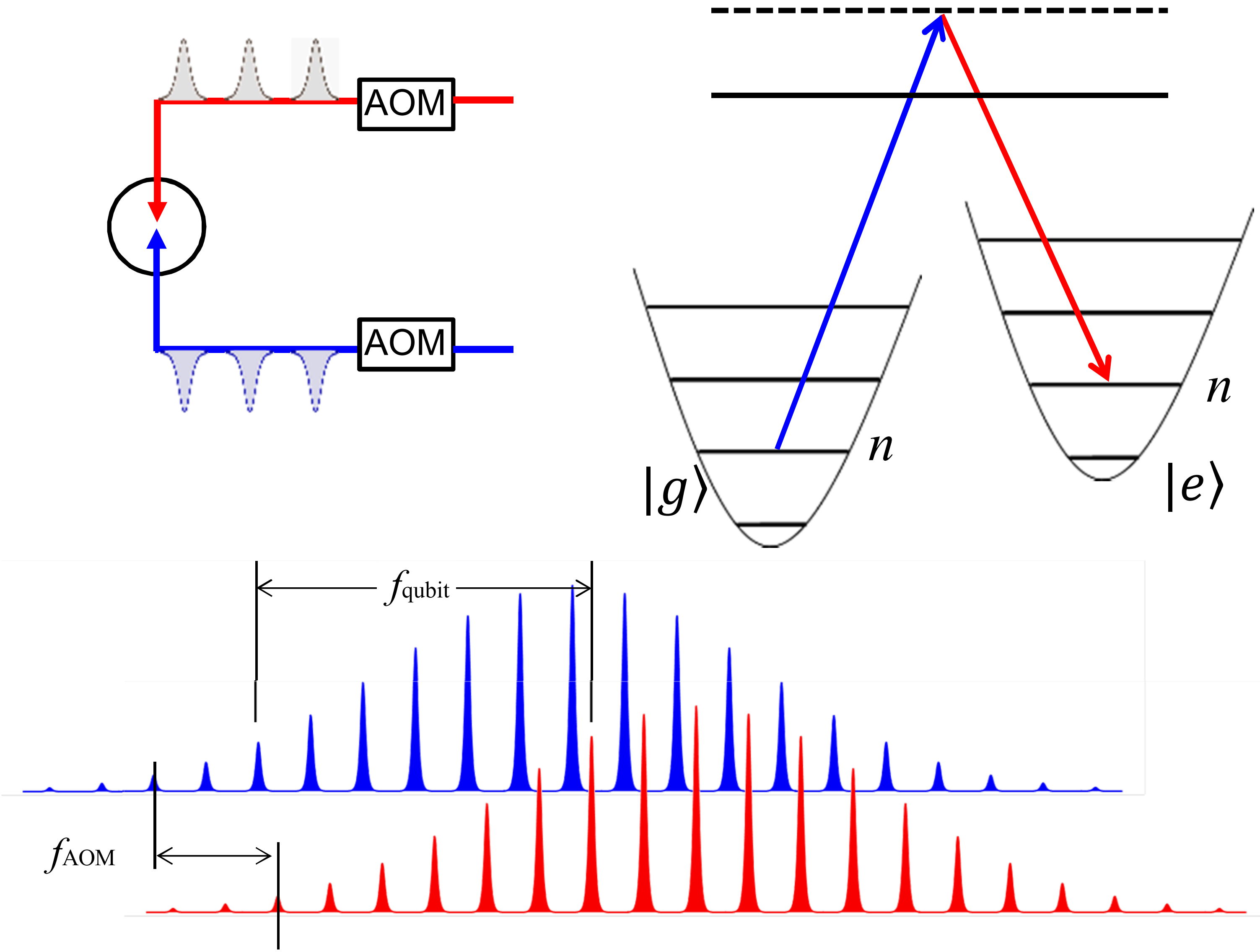
or

ABA'
ABBA'
ABBBA
…

Breakdown of swap



Pulsed laser Raman transitions



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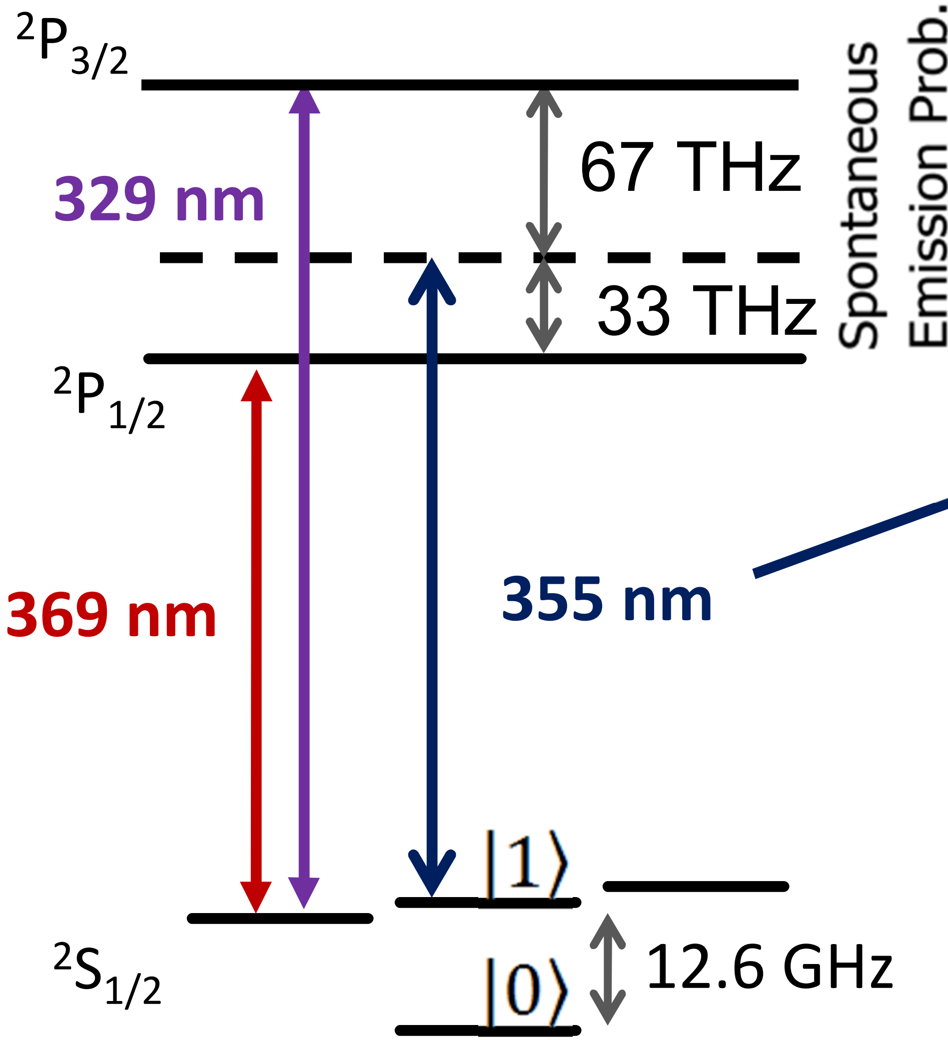
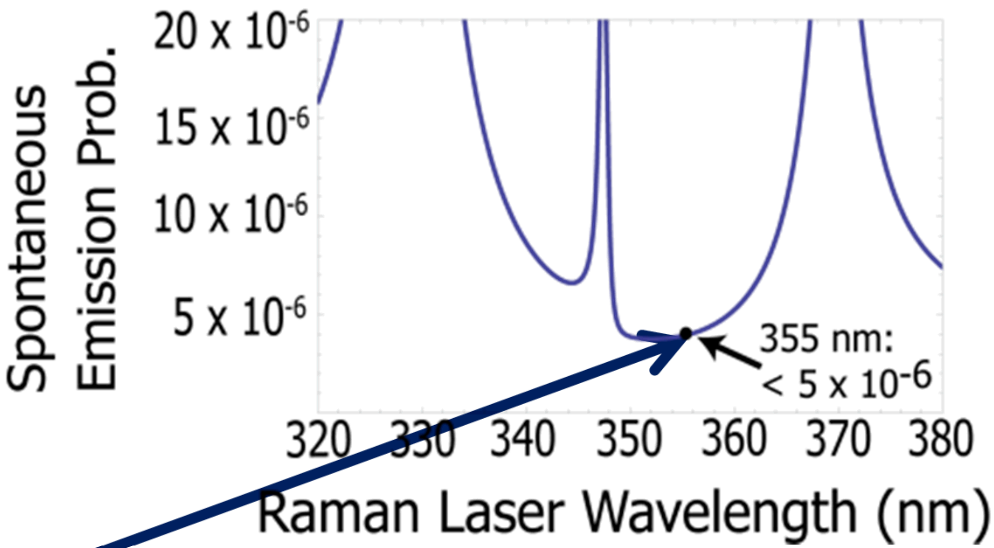
355 Raman transitions: $^{171}Yb^{+}$

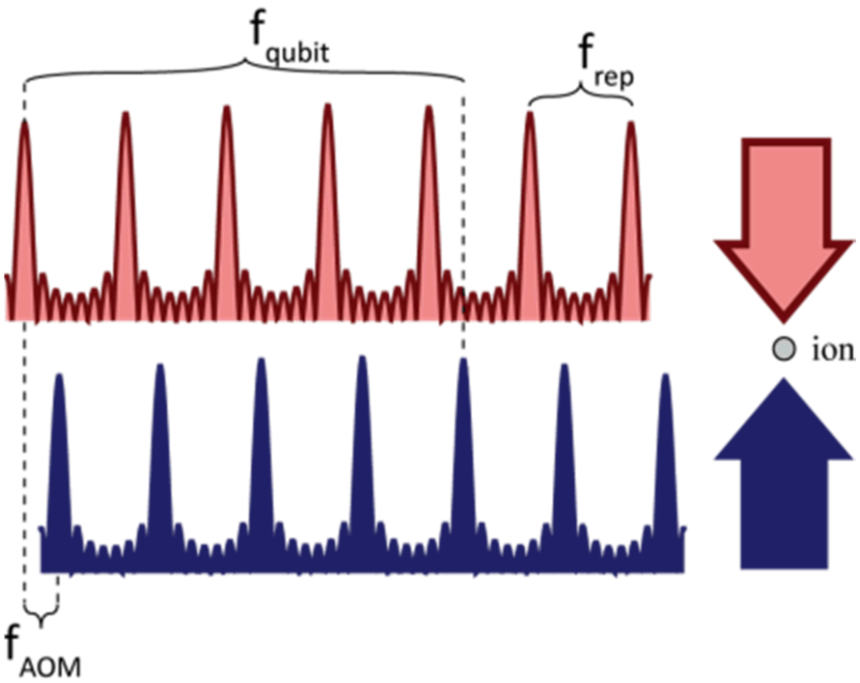




3x Nd:YVO_4 (355 nm) near minimum in Differential AC Stark Shift and spontaneous emission for $^{171}Yb^{+}$ ($\Delta_{Stark}/\Omega_{Rabi} < 3 \times 10^{-4}$ at 355 nm)

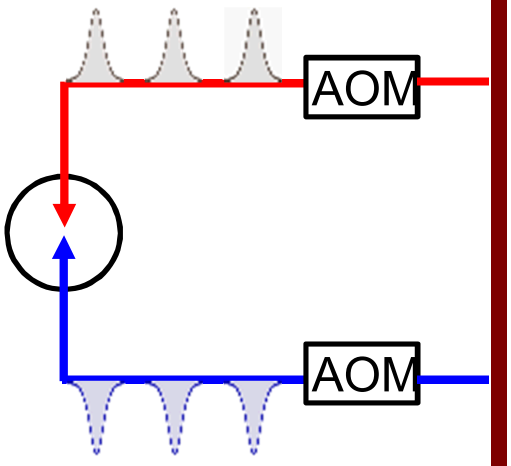
Pulsed laser Raman transitions

- Couple to ions using 355nm frequency comb
- Beat note created by repetition rate and AOM shift
- Get large splitting for free

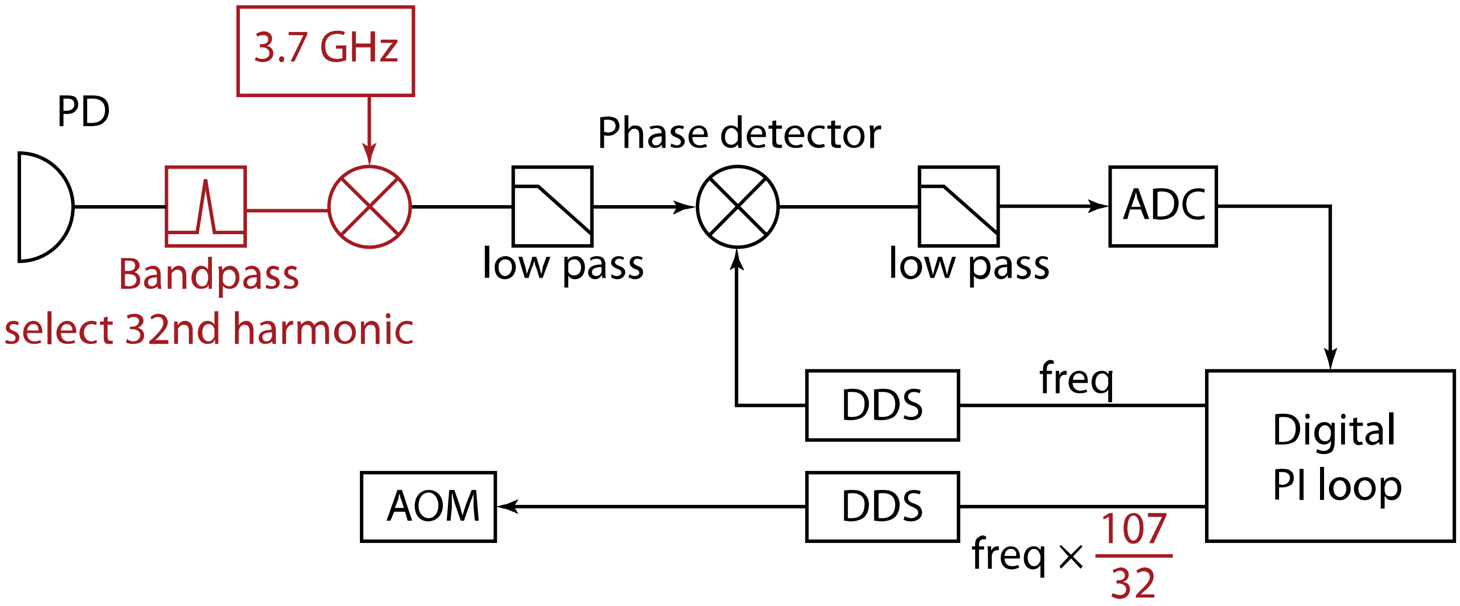


Requirement:

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



Stabilizing the beatnote frequency



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

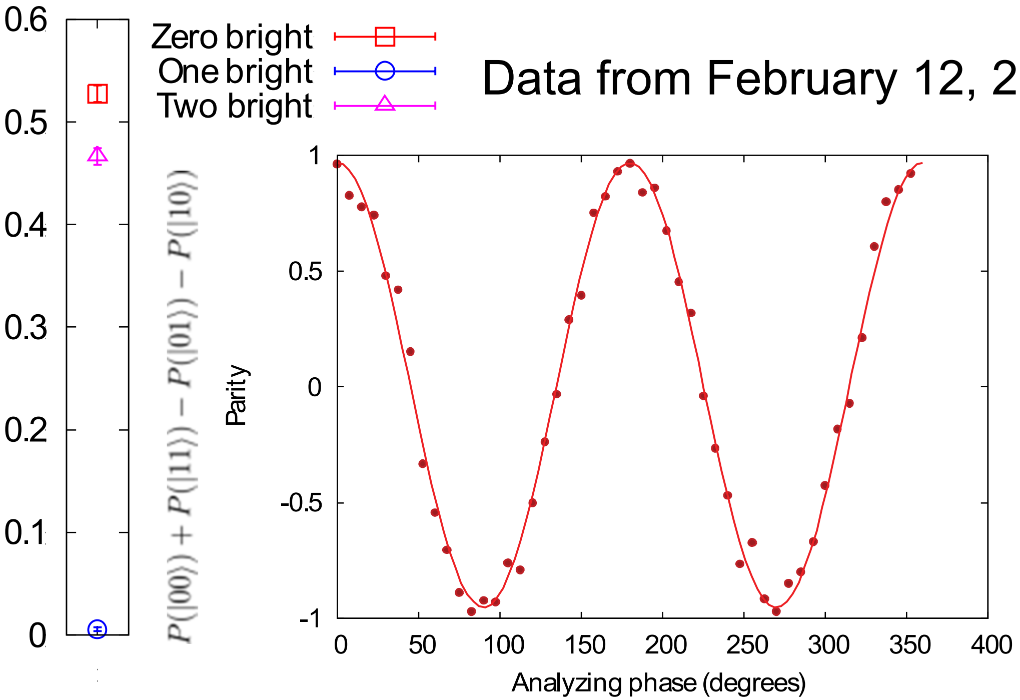
95% confidence intervals

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

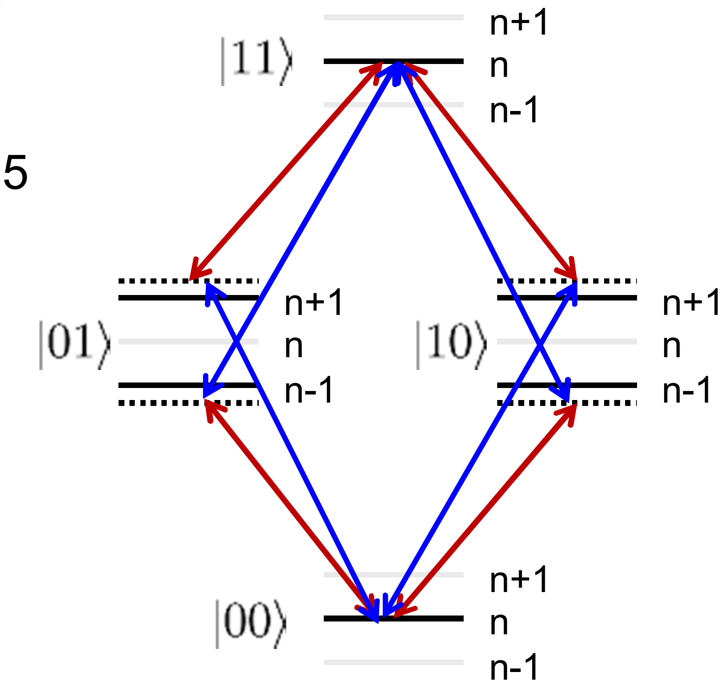
All gates are better than the fault tolerance threshold of 9.7×10^{-5}
P. Aliferis and A. W. Cross, Phys. Rev. Lett. 98, 220502 (2007).

Two-qubit gate implementation

- Implemented using Walsh compensation pulses
- Optical phase sensitive



Data from February 12, 2015



$$|00\rangle \rightarrow |00\rangle + |11\rangle$$

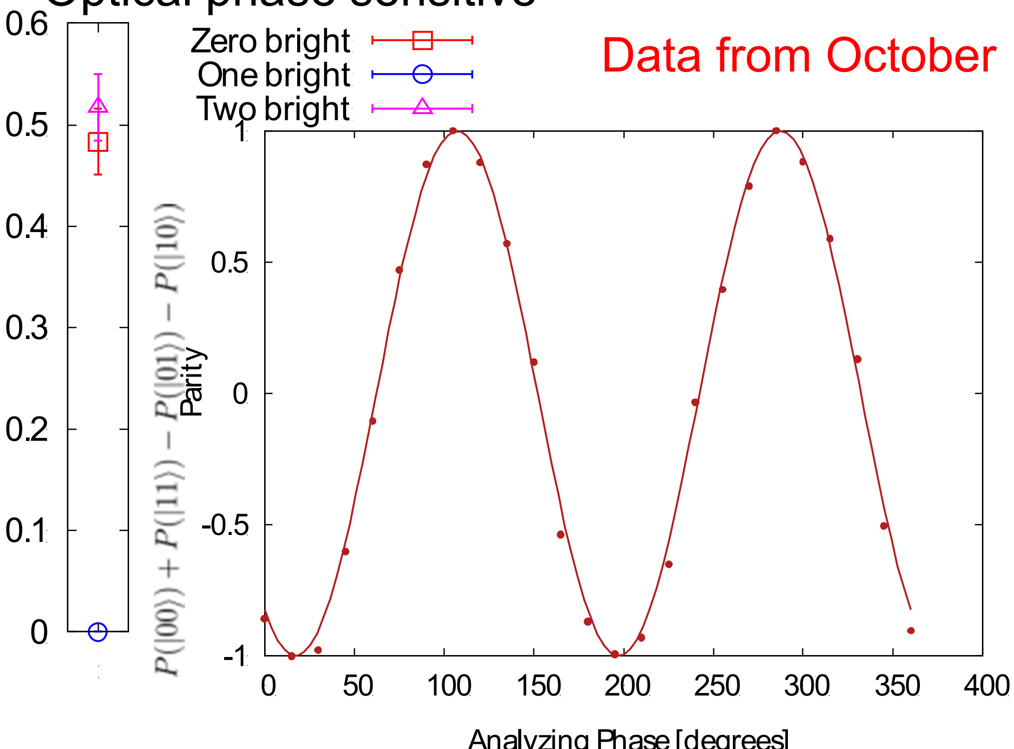
$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c = 0.977$$

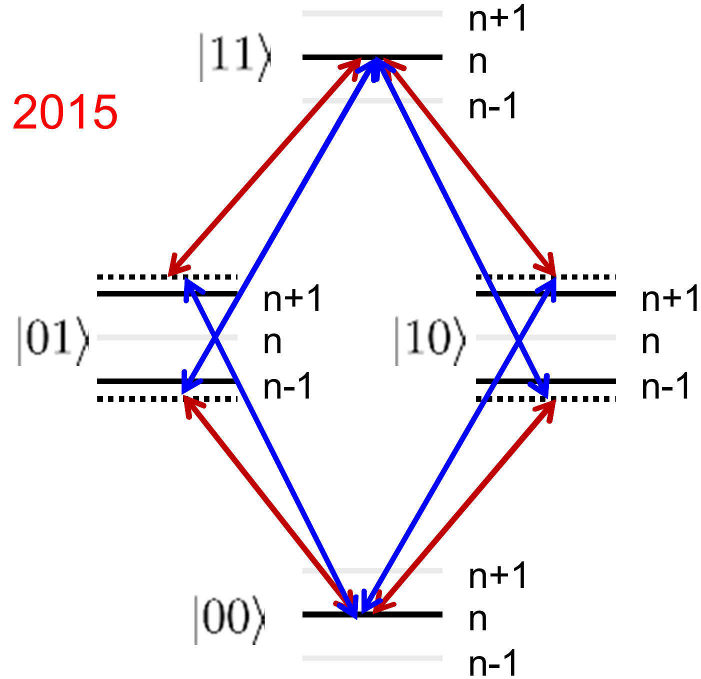
Data from February 12, 2015

Two-qubit gate implementation

- Implemented using Walsh compensation pulses
- Optical phase sensitive

Data from October 10, 2015





$$|00\rangle \rightarrow |00\rangle + |11\rangle$$

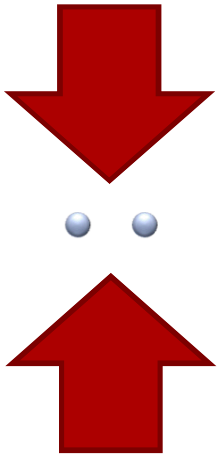
$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c = 0.977$$

Data from February 12, 2015

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

Data from October 10, 2015

Process fidelity of two-qubit gate



Currently:

- Two ions in single trap well
- No individual addressing

- Ideally all operations are symmetric
- Only symmetric subspace of two-qubit Hilbert space is accessible

Solution:
Perform GST on symmetric subspace of two-qubit Hilbert space

Fundamental gates:

$$G_I$$

$$G_{XX} = G_X \otimes G_X$$

$$G_{YY} = G_Y \otimes G_Y$$

$$G_{MS}$$

9 Preparation Fiducials
12 Germs
6 Measurement Fiducials:

GST debugging of the setup

GST characterizes the implemented processes and helps identify problems
$X_{\pi/2}$ and $Y_{\pi/2}$ gates implemented using BB1 pulse sequence

4/17: Markovianity violation
- Improve passive stability
- Add drift control of π-times

12/2: Improved X and Y gates, identity is worst
- Decoupled identity using $X_\pi W_{1.25\pi} -X_\pi W_{1.25\pi}$
- Switched to HOA-2 trap

2/9: Gates improved, systematic over-rotation detected
- Improve calibration of BB1 pulses
- Drift control of qubit frequency

3/2: X and Y gates are good, identity is still worst
- Implement identity as $X_\pi Y_\pi X_\pi Y_\pi$

3/30: Process fidelity of all gates $<6\times10^{-5}$