A Scalable Microfabricated Ion Trap for Quantum Information Processing

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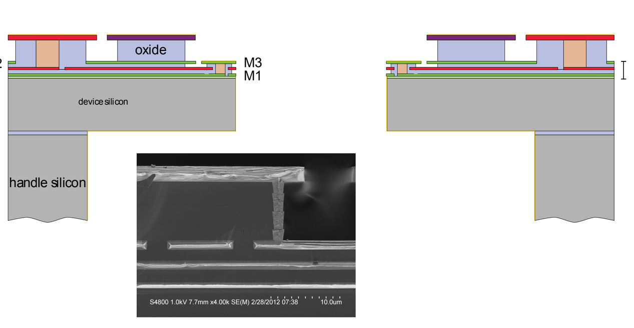
Abstract

Trapped Ion Quantum Information Processing (QIP) relies on complex microfabricated trap structures to enable scaling of the number of quantum bits [1]. Building on previous demonstrations of surface-electrode ion traps [2-4], we have designed and characterized the Sandia high-optical-access (HOA-2) microfabricated ion trap. This trap features high optical access, high trap frequencies, low heating rates, and negligible charging of dielectric trap components. We have observed trap lifetimes of more than 100h, measured trap heating rates for ytterbium of less than 40 quanta/s, and demonstrated shuttling of ions from a slotted to an above surface region and through a Y-junction. Furthermore, we summarize demonstrations of high-fidelity single and two-qubit gates realized in this trap.

[1] D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002).
[2] S. Seidelin, et al., Phys. Rev. Lett. 96, 253003 (2006).
[3] D. Stick, et al., arXiv:1008.0990 (2010).
[4] D. L. Moehring, et al., New Journal of Physics 13, 075018 (2011).

Trap Fabrication Capabilities

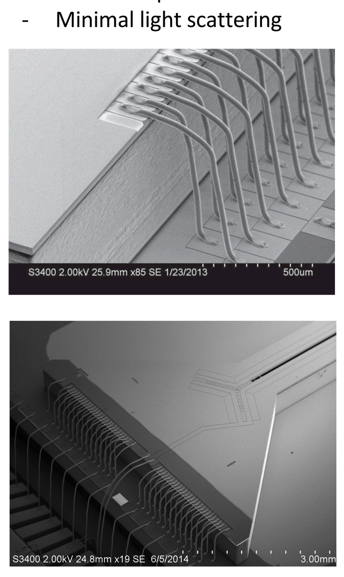
Five level metallization



DC electrodes are routed through lower metal layers allowing for:
- simplified routing as wiring can cross in different metal layers
- More complex, islanded trap structures, such as circulators and rings
- Trap layouts that are more true to models, since electrode leads don't need to be taken into account

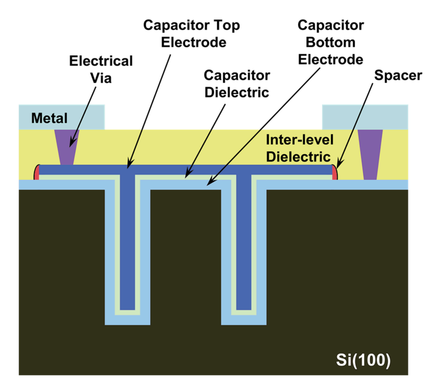
Low-profile wire bonds

- Maximal optical access
- Minimal light scattering



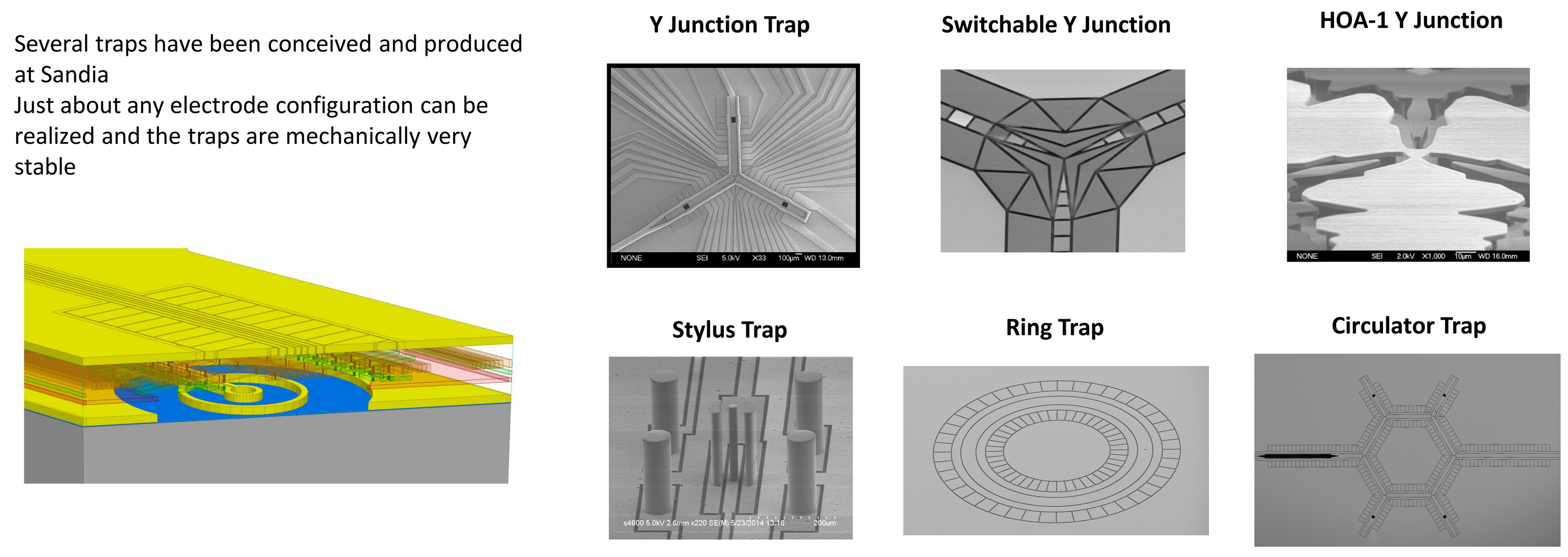
Interposer

- An interposer chip routes control voltages from the trap to the pads of the standard CPGA carrier.
- Trench capacitors are integrated directly into the interposer to reduce RF pickup



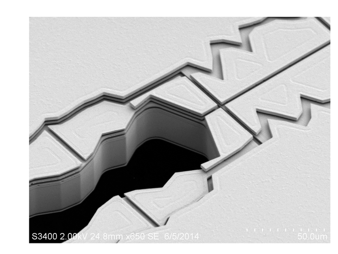
Microfabricated Traps at Sandia

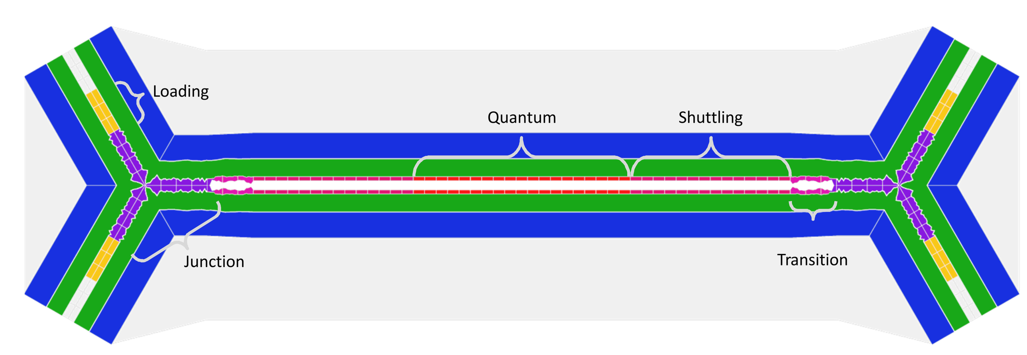
- Several traps have been conceived and produced at Sandia
- Just about any electrode configuration can be realized and the traps are mechanically very stable

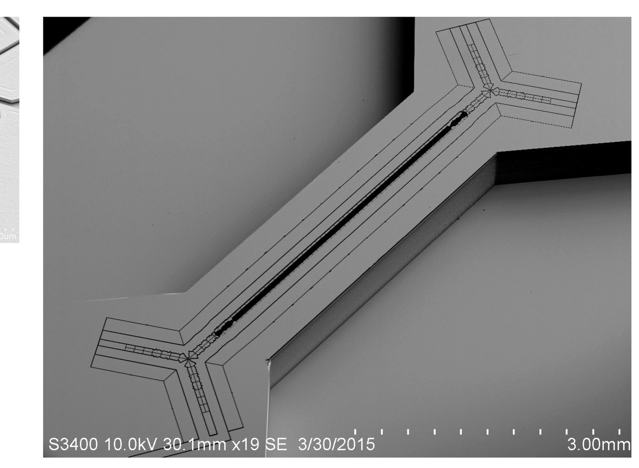


High Optical Access Trap (HOA-2)

- Excellent optical access rivaling 3D traps
  - NA 0.11 across surface
  - NA 0.25 through slot
- High trap frequencies (up to 2.6 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



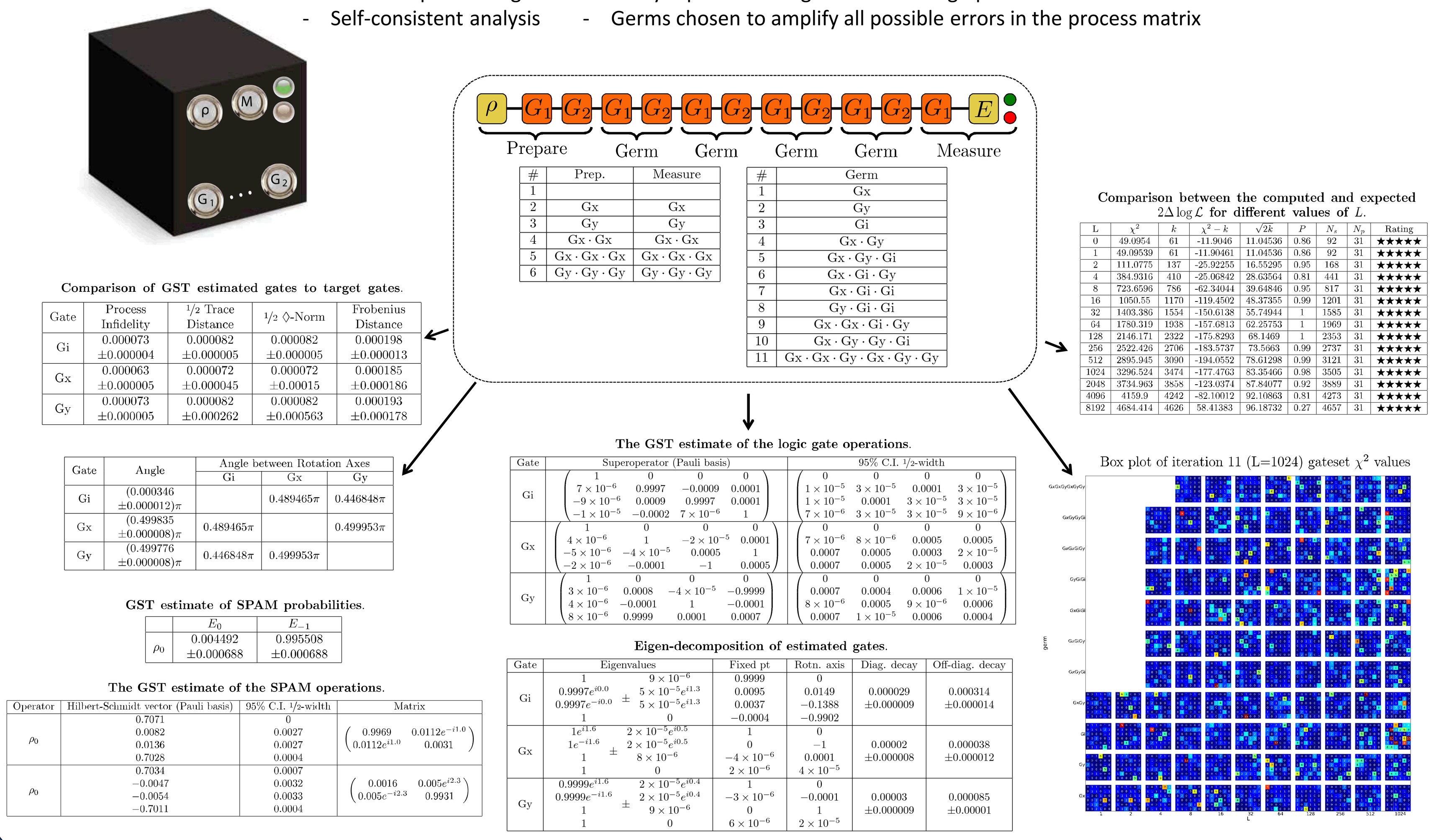




- Very good trap performance
  - Lifetime over 100 h in Yb while taking data
  - Lifetime > 5 m without cooling
- Low heating rates approx. 100 quanta/s

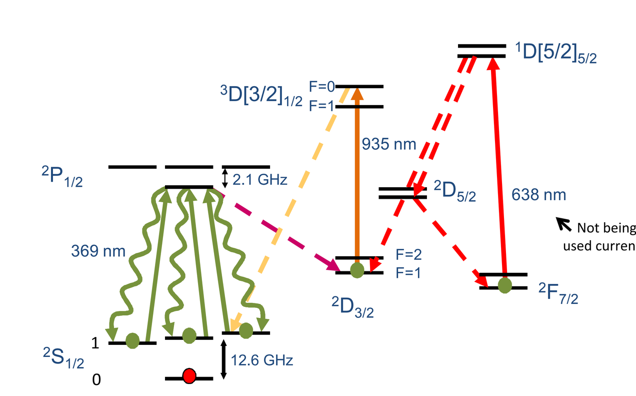
Gate Set Tomography

- No assumptions on gates
- Self-consistent analysis
- Many repetitions on gates enables high precision
- Germs chosen to amplify all possible errors in the process matrix



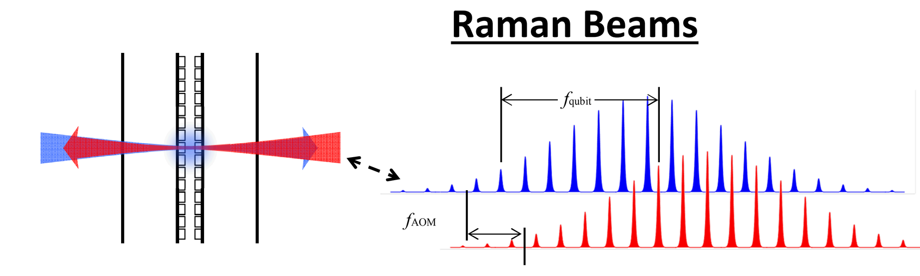
Single-Qubit Gates

The $^{171}Yb^+$ Qubit



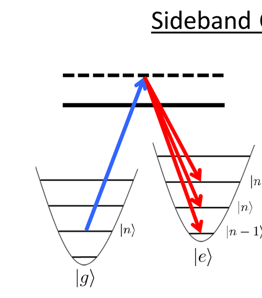
- Clock state qubit is insensitive to magnetic fields
- Trapping time >100 hours with continuous measurements >5 m without cooling
- $T_1 > 5$ s, $T_2^* = 1$ s

Raman Beams



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

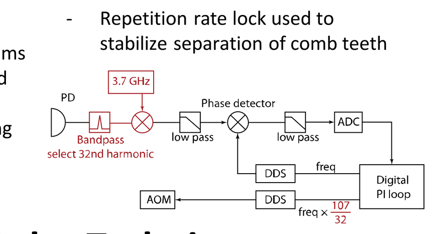
Sideband Cooling



- AOM used to fine tune frequency of Raman beams
- Can be used for sideband cooling
- Also allows for addressing of motional states

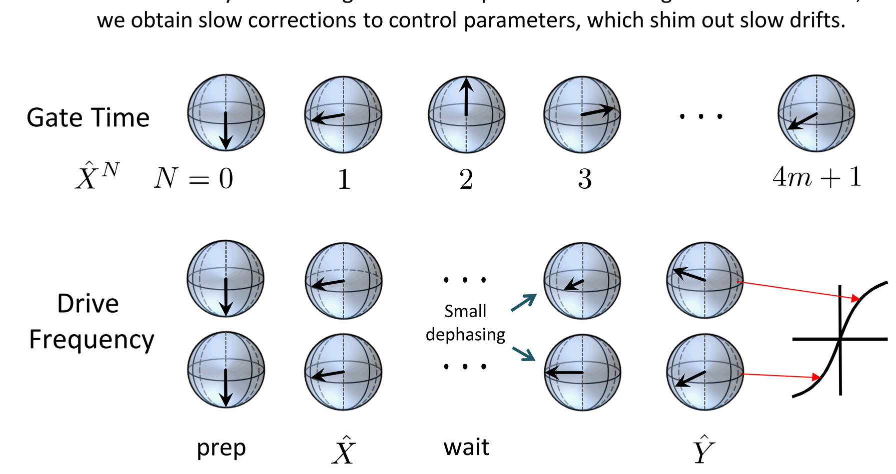
Comb Stabilization

- Repetition rate lock used to stabilize separation of comb teeth

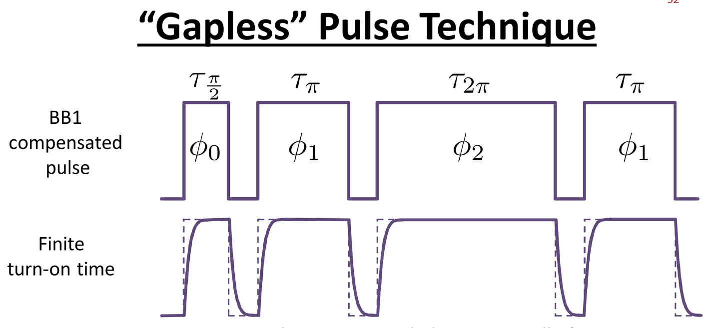


Drift Control

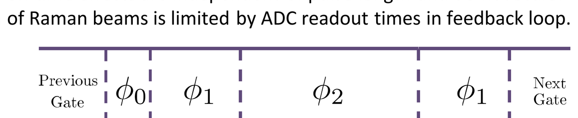
Regular recalibration of control parameters is time-consuming and ideally intermittent. By interleaving individual experiments with single-shot calibrations, we obtain slow corrections to control parameters, which shim out slow drifts.



"Gapless" Pulse Technique

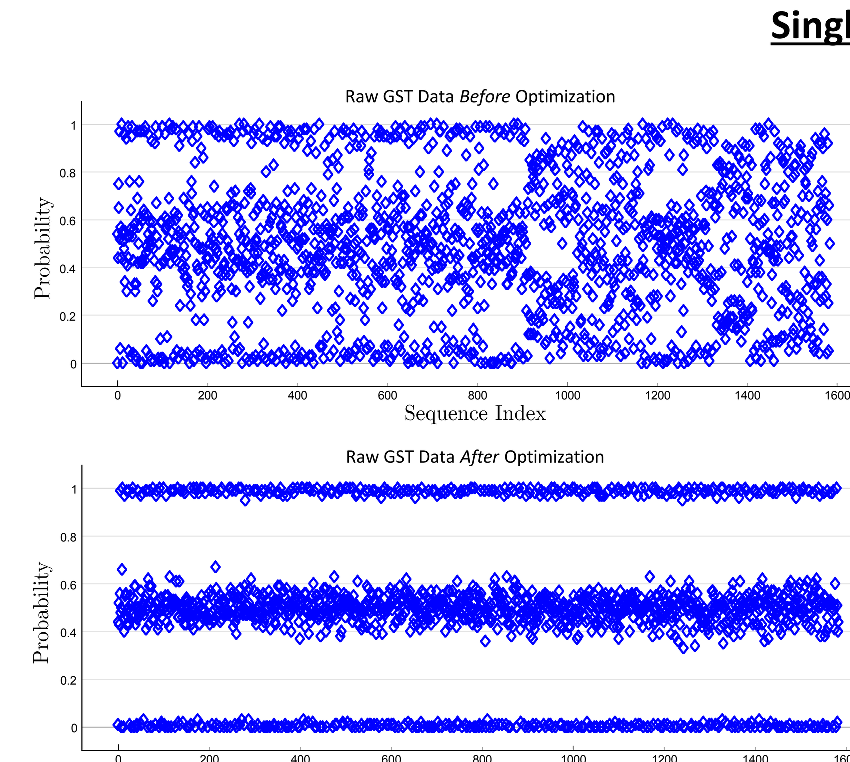


BB1 compensation assumes variations in pulse area are scaled proportionally for extra compensation pulses. Finite turn on-time effects are independent of pulse length and do not scale! Power stabilization of Raman beams is limited by ADC readout times in feedback loop.



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.

Single-Qubit GST



- Careful optimization of gates provides the necessary foundation for scaling to N qubits.
- GST not only gives an extremely accurate characterization of our gates, which can be used for debugging
- Laser-based single-qubit gates optimized to a level that rivals results from standard traps
- First reliable measurements of the diamond norm, which are approaching the fault-tolerance threshold

Evolution of Gates During Debugging

Experimental Parameters				Infidelity ($\times 10^{-4}$)		1/2 $\Diamond$ Norm ($\times 10^{-4}$)	
Beam Orientation	Drift Control	Compensated Gates	Gapless	Gi	max(Gx,Gy)	Gi	max(Gx,Gy)
$\Rightarrow$				0.16	10.73	13.2	48.6
$\Rightarrow$	✓			0.13	7.2	12.5	44.5
$\Rightarrow$		Gi, Gx, Gy		16.2	1.63	269	5.0
$\Rightarrow$	✓	Gi, Gx, Gy		10.5	2.0	15.5	5.1
$\Rightarrow$	✓	Gx, Gy		0.05	1.6	12.5	4.4
$\Rightarrow$	✓	Gi, Gx, Gy	✓	1.17	0.69	5.3	4.0
$\rightleftharpoons$		Gi, Gx, Gy	✓	11.1	4.1	22.8	13.2
$\rightleftharpoons$		Gx, Gy	✓*	0.89	5.8	8.8	15.3

Table 1: Summary of laser-based gates. Beam orientations are indicated by $\Rightarrow$ for co-propagating Raman beams and $\rightleftharpoons$ for counter-propagating Raman beams. Gapless pulses all use power-stabilized Raman beams. The gapless measurement with uncompensated I gates, marked by ✓*, is not strictly gapless, but the only gaps occur during the wait I gates.

While our laser-based gates have significantly improved, they are still dominated by coherent errors as evidenced by the diamond norm. These gates can be compared to our best microwave-based gates, which were optimized using the same GST approach.

Microwave Gates

Gate	Process Infidelity	1/2 $\Diamond$-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	$7.2(7) \times 10^{-5}$	$8.1(15) \times 10^{-5}$

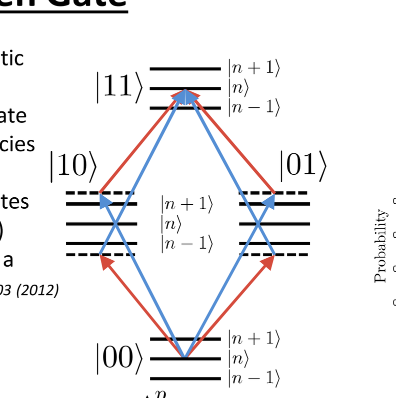
Below the threshold for fault-tolerant error correction!

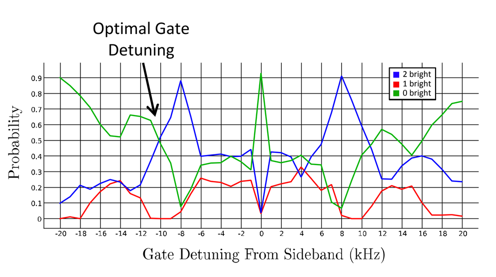
See P. Aliferis and A. W. Cross, Phys. Rev. Lett. 98, 220502 (2007)

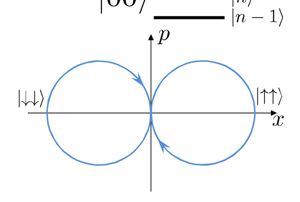
Two-Qubit Gate

Mølmer-Sørensen Gate

- Entangling gate that takes advantage of bichromatic fields and does not require ground state cooling
- Requires a number of extra calibrations such as gate detuning and phase, and to balance Rabi frequencies along all transitions used in the gate
- We use the tilt mode because of lower heating rates (<8 quanta/s vs ≈ 60 quanta/s for the COM mode)
- Gates are 200 μs long and are compensated with a first order Walsh function *see D. Hayes et al, PRL 109, 020503 (2012)*

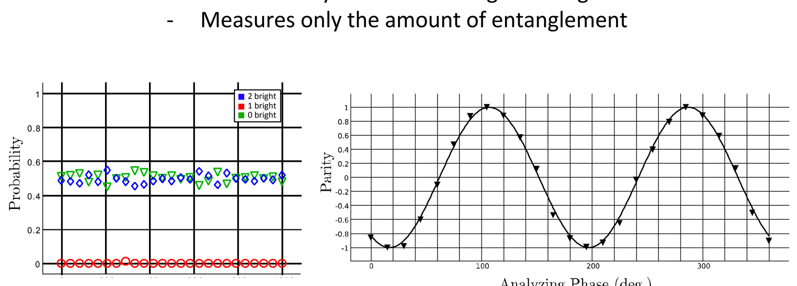






Entangled State Fidelity

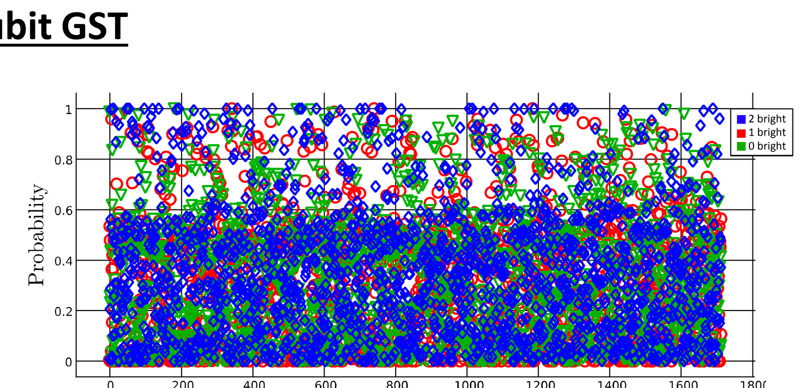
- Standard way of characterizing the MS gate
- Measures only the amount of entanglement



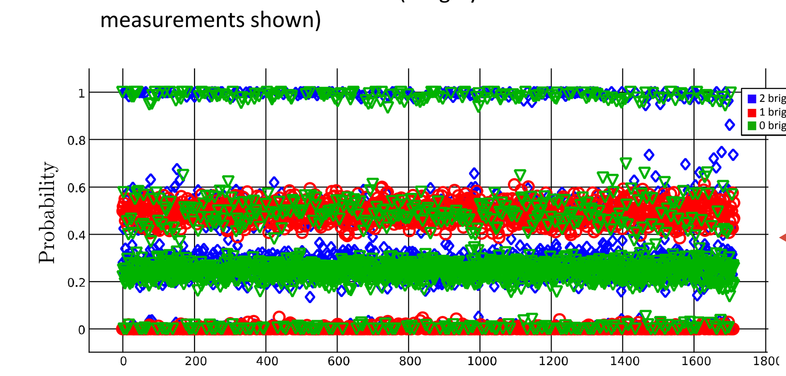
$$\mathcal{F} = \frac{1}{2}\left(P(|00\rangle) + P(|11\rangle)\right) + \frac{1}{4}c \approx 0.995$$

Two-Qubit GST

- Provides a *process* fidelity instead of just the entangled state fidelity
- Much more rigorous than entangled state fidelity measurements typically used for benchmarking the MS gate
- Currently limited to the symmetric subspace due to lack of individual addressing
- Requires an extremely stable MS gate to take long GST measurements without constant recalibration (roughly 4 hours for the measurements shown)



Good entangled state fidelity, *bad* process fidelity



Good entangled state fidelity, *good* process fidelity

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

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

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

Conclusions

- Demonstrated performance of a Sandia microfabricated trap that rivals performance of macroscopic traps, showing that surface traps are ready for cutting edge QIP
- Various experimental improvements and new techniques used to improve our gates
- Best characterized gates in a surface ion trap
- Reliable determination of the diamond norm afforded by GST
- Laser-based single-qubit gates approaching the fault-tolerance threshold
- Best two-qubit gate in a surface ion trap
- System stable for several hours allowing us to take long sets of data

Microwave Gates

Gate	Process Infidelity	1/2 $\Diamond$-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

Gate	Process Infidelity	1/2 $\Diamond$-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	$6.9(6) \times 10^{-5}$	$4(9) \times 10^{-4}$

Two-Qubit Gate

Gate	Process Infidelity	1/2 $\Diamond$-Norm
G_{MS}	$4.2(6) \times 10^{-3}$	$3.8(5) \times 10^{-2}$

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