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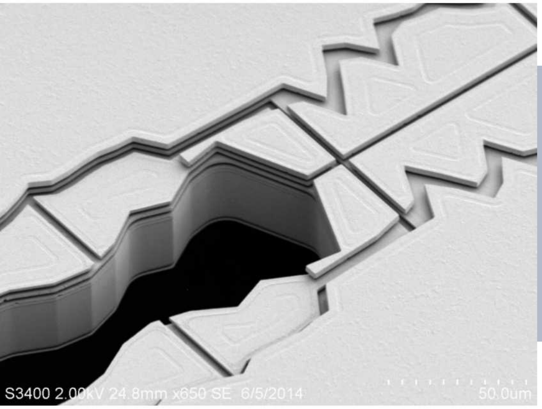

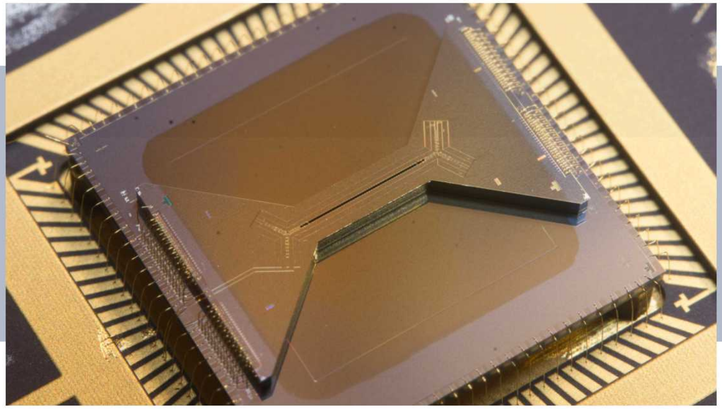
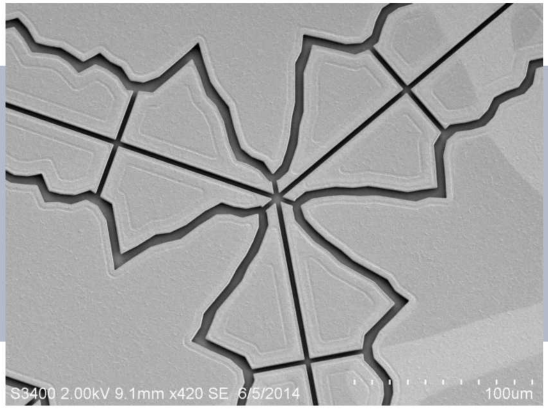

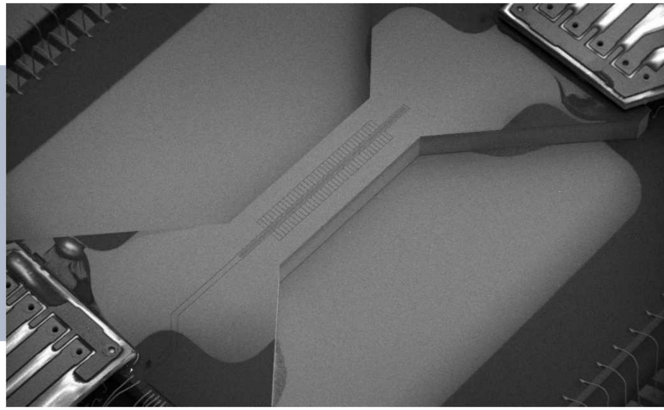

QSCOUT:

Quantum Scientific Computing Open User Testbed

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Sandia National Laboratories

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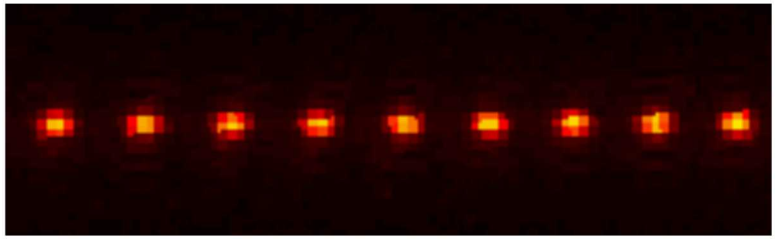
What is QSCOUT?



Testbed systems designed for open access to support scientific applications

- High-fidelity operations
- Gate-level access
- Open system with fully specified operations and hardware
- Low-level access for optimal control down to gate pulses
- Open for comparison and characterization of gate pulses
- Open for vertical integration by users

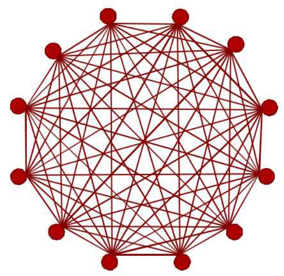
Interested? Please talk to us for access

Why Ions?

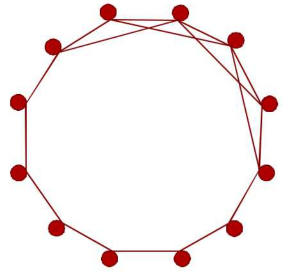
Best available qubits with history of reliability and quality

- Ions (qubits) are identical
- Near-ideal prep and measure
  - Error $< 8 \times 10^{-4}$ [1]
- No idle errors (long coherence times)
  - Coherence time > 15min possible[2]
- Lowest gate errors[3]
  - Single-qubit error $< 1 \times 10^{-4}$ [4]
  - Two-qubit error $< 1 \times 10^{-3}$ [4]
- Single chain qubit registers demonstrated[5]
- Low crosstalk

Trapped Ions:
Fully connected



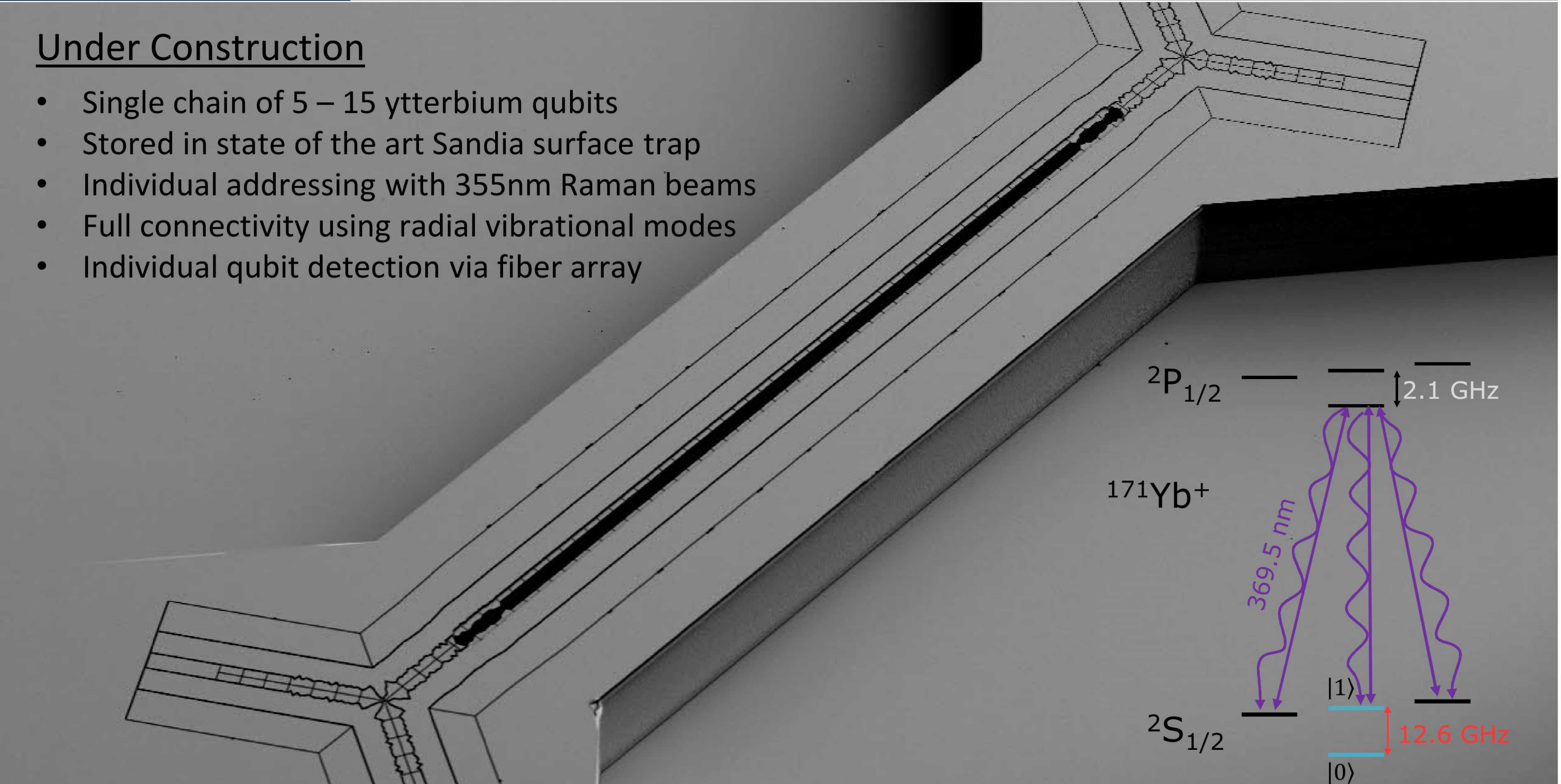
Solid State:
2D nearest neighbor coupling



[1] Fisk, et al. *IEEE Transact. on Ultrasonics, Ferroelectr. Freq. Cont.* **44**, no. 2 (1997): 344–54.
[2] N. M. Linke, D. Maslov, M. Roetteler, S. Debnath, C. Figgatt, K. A. Landsman, K. Wright, C. Monroe, Proc. Natl. Acad. Sci. 114, 13 (2017).
[3] Ballance, et al. *PRL* **117**, no. 6 (2016): 060504.
[4] Noek, et al. *Opt. Lett.* **38**, no. 22 (2013): 4735–38.
[5] K. Wright, et al., arXiv 1903.08181 (2019).

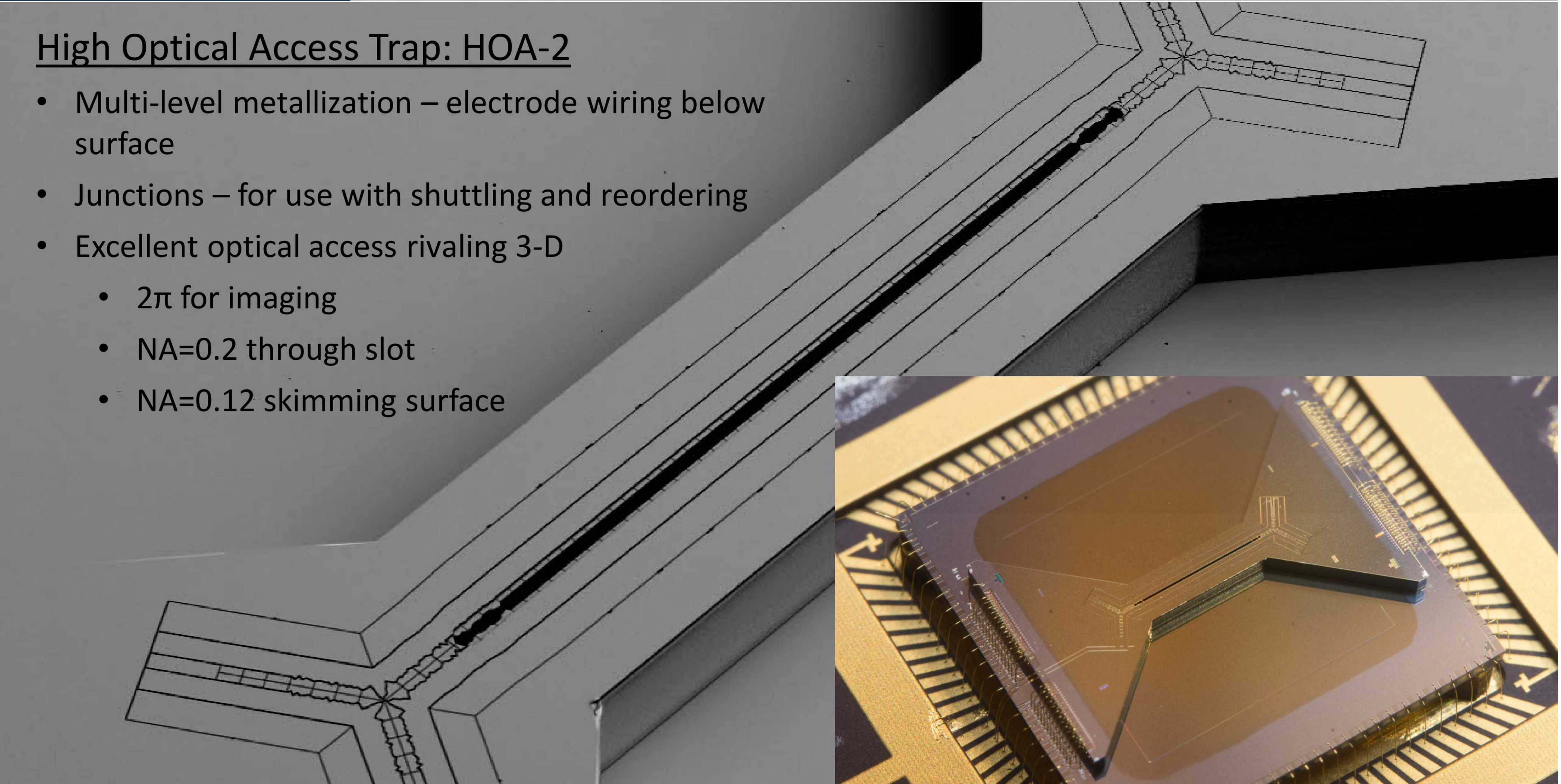
Under Construction

- Single chain of 5 – 15 ytterbium qubits
- Stored in state of the art Sandia surface trap
- Individual addressing with 355nm Raman beams
- Full connectivity using radial vibrational modes
- Individual qubit detection via fiber array



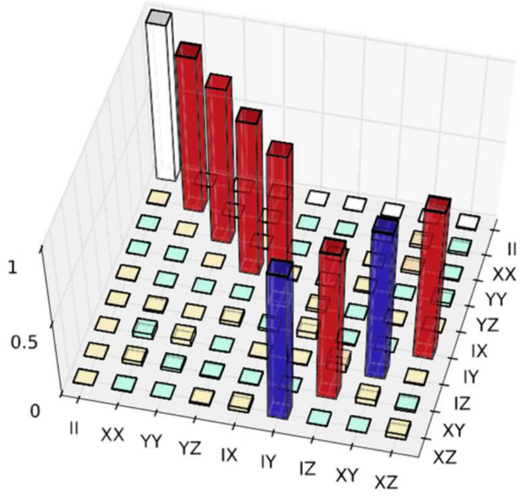
High Optical Access Trap: HOA-2

- Multi-level metallization – electrode wiring below surface
- Junctions – for use with shuttling and reordering
- Excellent optical access rivaling 3-D
  - 2π for imaging
  - NA=0.2 through slot
  - NA=0.12 skimming surface

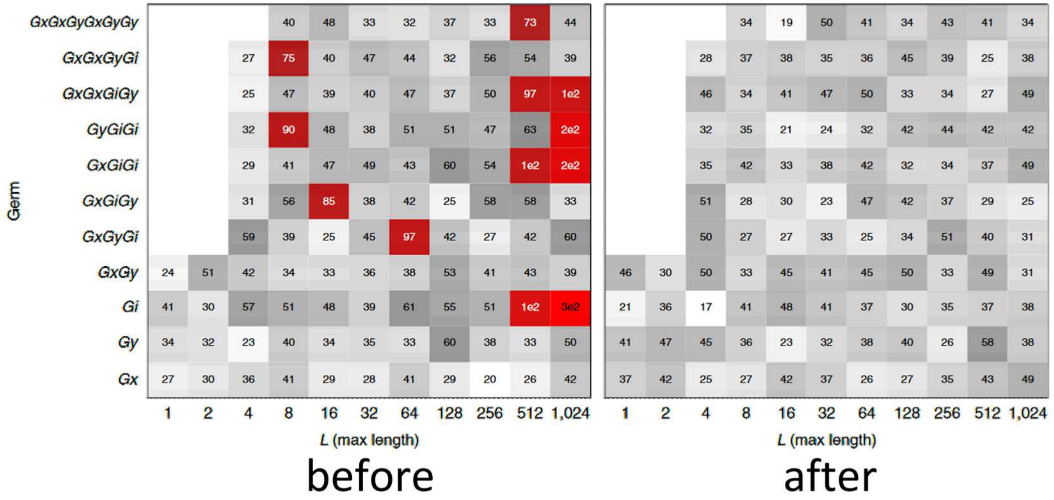


High Fidelity Gate Operations

- Single qubit gate errors < 1×10^{-4} (GST)
- Low drift and context-dependent errors
- Two qubit gate errors < 5×10^{-3}
- Understand errors: Single qubit gates reach coherence time limits
- Use GST to improve context-dependent errors



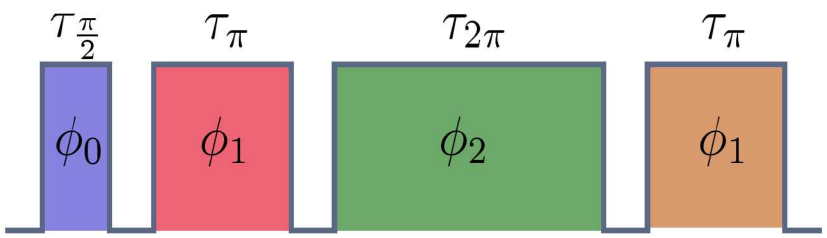
GST of Mølmer-Sørensen entangling gate process tomography at Sandia Error < 5×10^{-3}

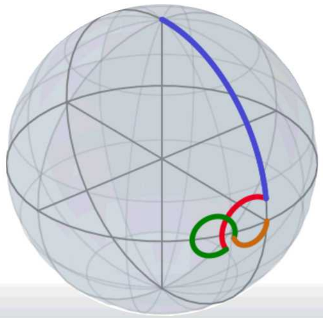


Error Mitigation

Compensated Pulses

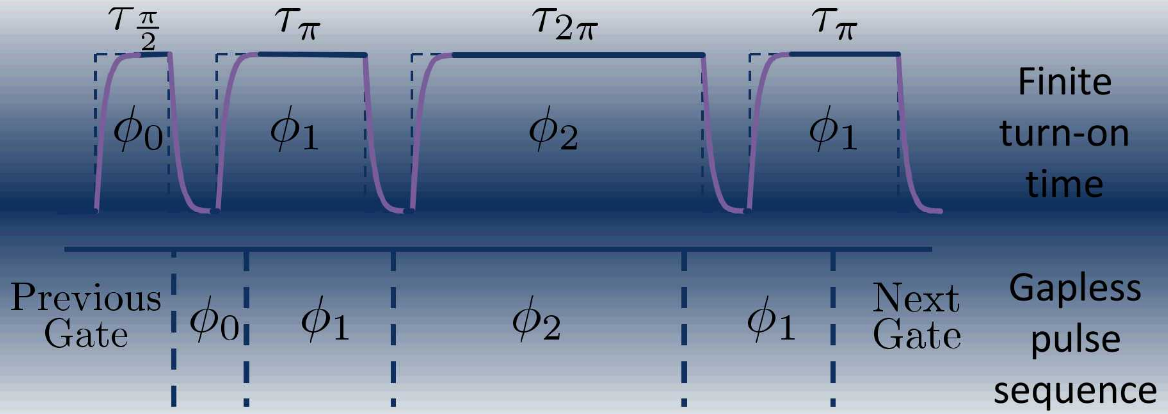
- BB1-type dynamical-decoupling pulses used
- Corrects pulse-length errors





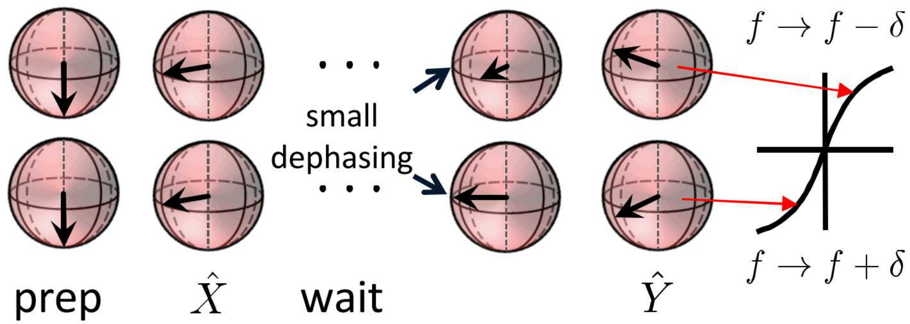
"Gapless" Pulses

- 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

- Single-shot calibrations increase or decrease a control parameter by a negligible value
- Small corrections either average out or slowly accumulate

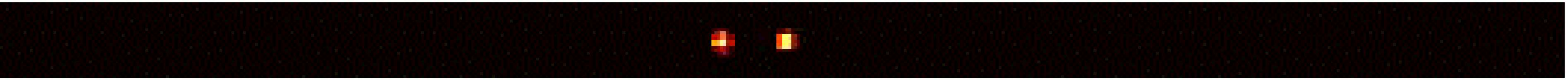


Capabilities

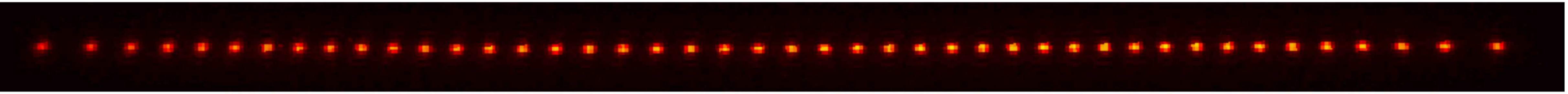
Ion Transport

- Principle axis rotation – no change in trap frequencies

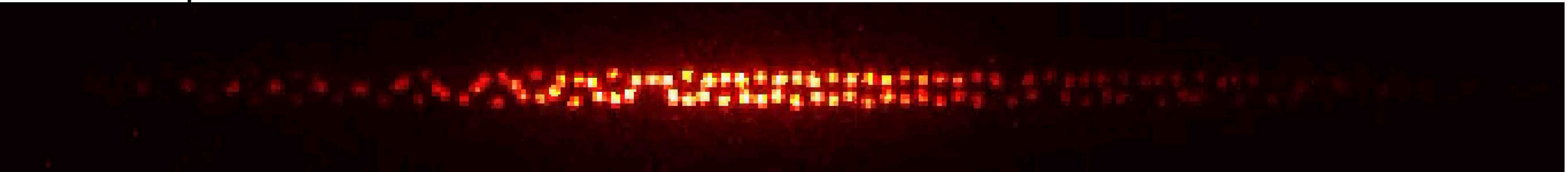
- Separation and merging



- Long chains



- Compression of chains



Gate Operations

Gate-level control

Single qubit gates (direct, or dynamically decoupled)

- $R_\phi(\theta),\ X_{\pi/2},\ Y_{\pi/2},\ Z_\phi,\ H,\ T$
- Z-rotations via per qubit phase offset tracking

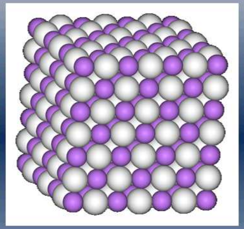
Two-qubit gates

- $MS(\theta,\phi) = e^{-i\frac{\theta}{2}(\cos(\phi)\sigma_x + \sin(\phi)\sigma_y)^{\otimes 2}}$
- Mølmer–Sørensen gates between all pairs of ions (fully connected)
- CNOT, CPHASE (implemented via MS)

Pulse-level control

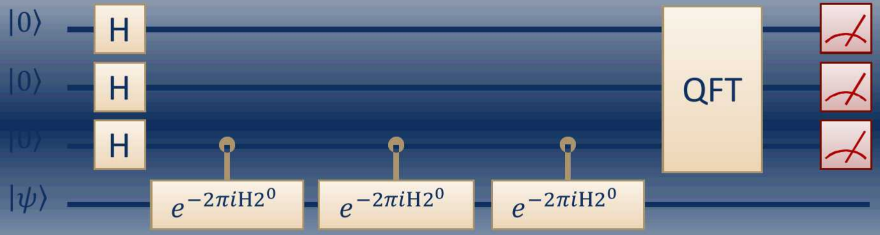
- Mølmer–Sørensen $\sigma_x \otimes \sigma_x$ interaction with optimal control
- Could be combined with Ising interaction $e^{-it\sum_{i\neq k} J_{ik}\sigma_{x,j}\otimes\sigma_{x,k}}$

Workflow



Lithium Hydride Example

Textbook Digital Quantum Simulation Circuit

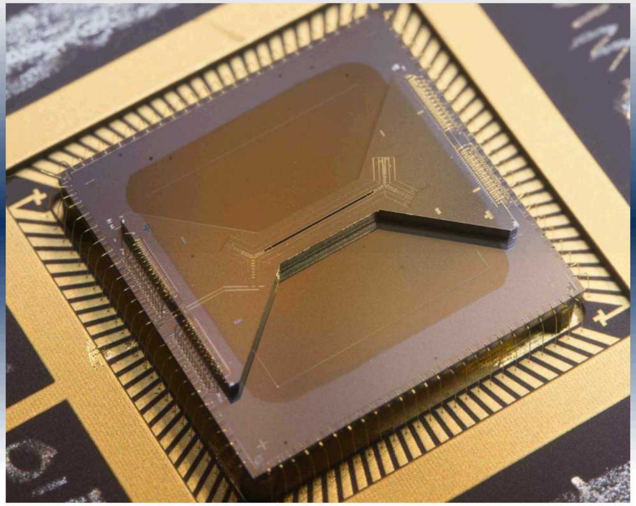


QSCOUT code/microcode

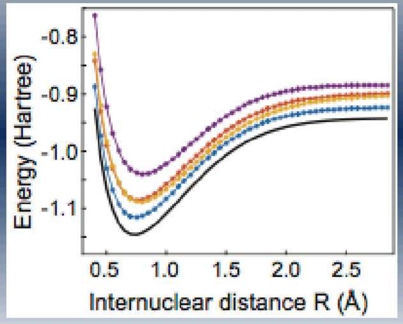
```
In [8]: circuits = ['teleport']
        print(Q_program.get_qasms(circuits)[0])

        OPENQASM 2.0;
        include "qelib1.inc";
        qreg q[3];
        creg c0[1];
        creg c1[1];
        creg c2[1];
        h q[1];
        cx q[1],q[2];
        ry(0.785398163397448) q[0];
        cx q[0],q[1];
        h q[0];
        barrier q[0],q[1],q[2];
        measure q[0] -> c0[0];
        measure q[1] -> c1[0];
        if(c0==1) z q[2];
        if(c1==1) x q[2];
        measure q[2] -> c2[0];
```

Implement on Hardware



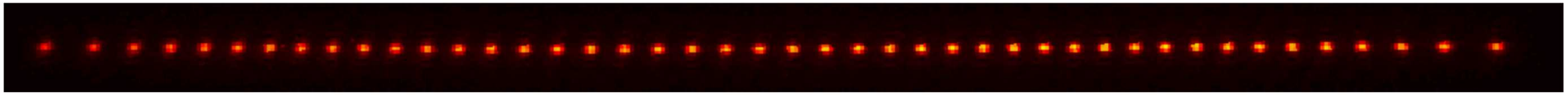
Results



Conclusion

Testbed 1.0

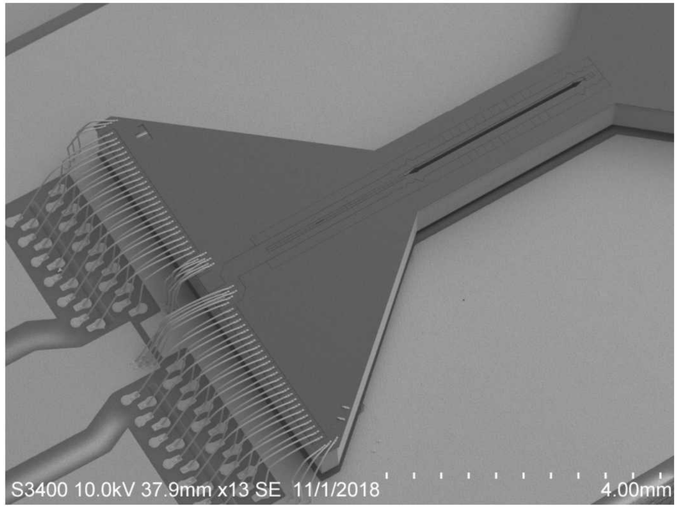
- Phase 1 planned to be complete by the end of 2019
- 5-15 individually addressable qubits available for quantum simulation



Contact for inquires about access to Qscout:
Melissa Revelle – mrevell@sandia.gov
Peter Maunz – pmaunz@sandia.gov

Future Upgrades

- Phoenix Trap
- Sympathetic cooling
- Reduced gate errors
- More qubits



Testbed 2.0

- Trapping at Cryogenic temperatures