SAND2019-0969C

Sandia National Laboratories

QSCOUT Quantum Scientific Computing Open User Testbed

Susan M. Clark, Andrew J. Landahl, Daniel Lobser, Melissa C. Revelle, Kenneth M. Rudinger, Christopher G. Yale, and Peter Maunz

Trapped Ion Advantages

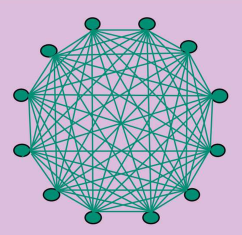
Best available qubits with history of reliability and quality

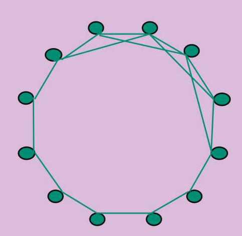
- Ions (qubits) are identical
- Near-ideal prep and measure
  - Error < 8×10^{-4} [1]
- No idle errors (long coherence times)
  - Coherence time > 15min possible[2]
- Lowest gate errors
  - Single-qubit error < 1×10^{-4} [3]
  - Two-qubit error < 1×10^{-3} [3]
- Single chain qubit registers demonstrated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

Reconfigurable in software

- Optimal for any application
- Change between quantum computer and quantum simulator is change in control
- All-to-All Connectivity
- Ideal for emulating other qubit systems

Trapped Ions: fully connected





Solid State: 2D nearest neighbor coupling

QSCOUT Approach

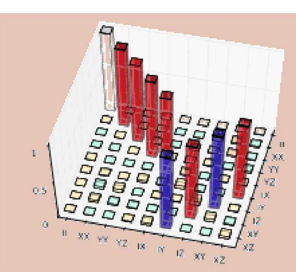
Testbed systems designed for open access to support scientific applications

- High-fidelity operations $\#gates \propto (\#qubits)^2$
- 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

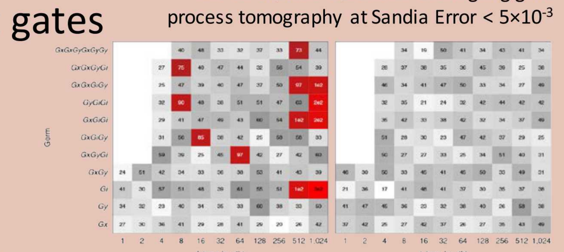
Interested? Please talk to us for access

Sandia's state of the art

- Ytterbium-171 systems
- 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



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

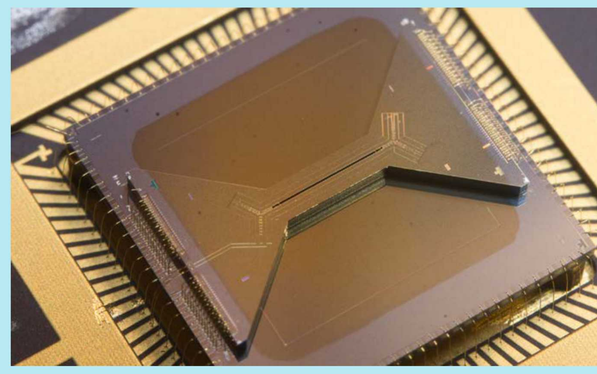


GST log-likelihood model violations In Sandia experiments before and after Improvements to reduce context-dependent errors

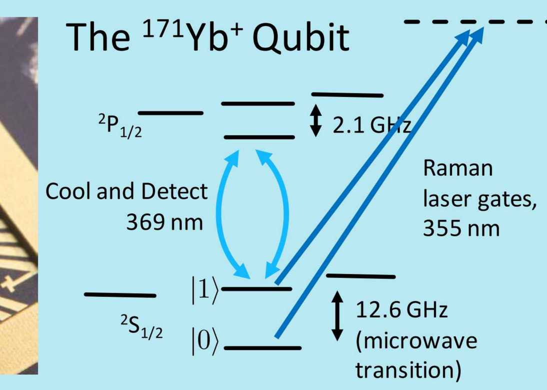
before after

Testbed 1.0

Under construction, scheduled completion October 2019

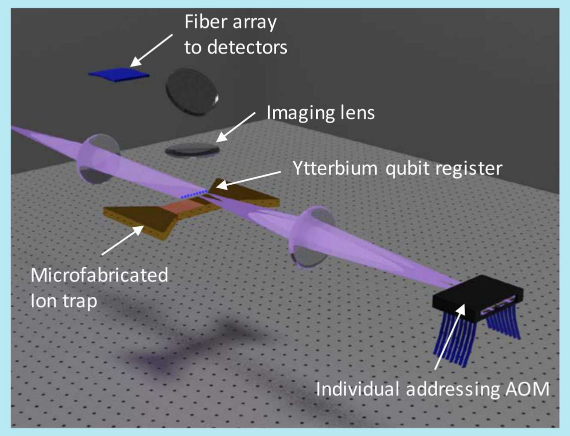


The $^{171}Yb^+$ Qubit



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

- Single chain of 5 – 15 ytterbium qubits
- Stored in Sandia surface trap
- Individual addressing with 355nm Raman beams
- Full connectivity using radial vibrational modes
- Individual qubit detection via fiber array
- Addressing and detection supports up to 32 qubits



Testbed 1.1 and 1.2 Upgrades

Scheduled for April 2021

- **Sympathetic cooling**
  - Consistent initial conditions for gates
    - Reduced context dependent errors
    - Improved system duty cycle
- **Reduced gate errors**

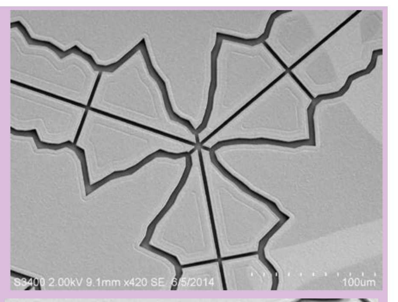
Scheduled for November 2022

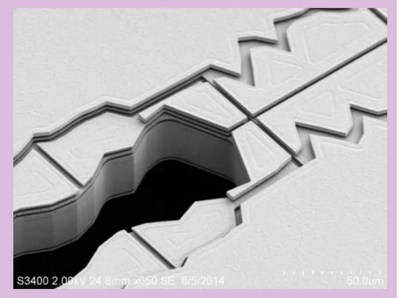
More qubits

- While keeping error rates consistent $\#gates \propto (\#qubits)^2$

Multi chain operations

- Scaling to larger number of qubits
- Use of Quantum CCD approach to scaling[4]





Available 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)

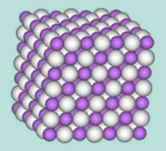
Pulse-level control

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

Support for vertical integration

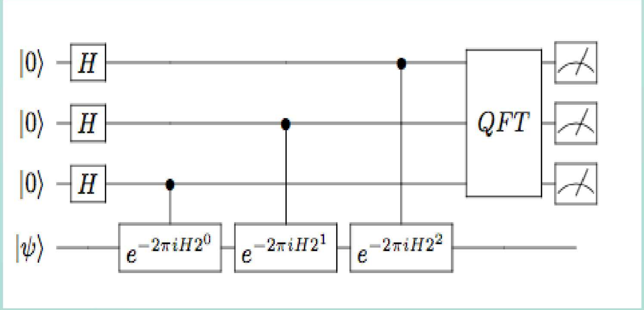
- For NISQ processors vertical resource optimization across layers from algorithm to device is essential to achieve the best possible results
- QSCOUT will support vertical integration and optimization and provide users with the necessary access to realize the integration even beyond instruction set architecture.

QSCOUT Workflow



Lithium Hydride Example

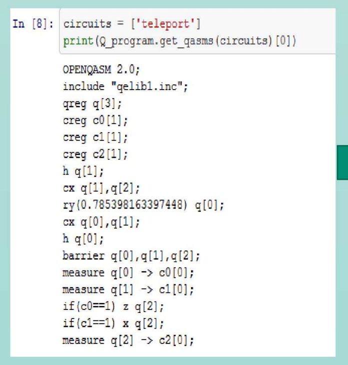
Textbook Digital Quantum Simulation Circuit

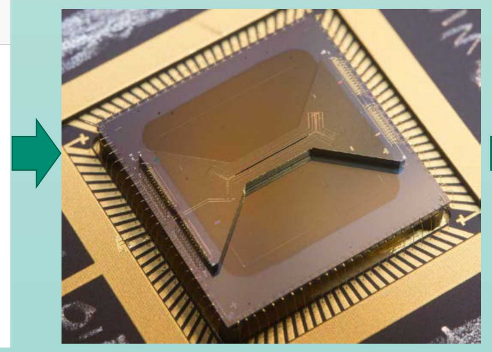


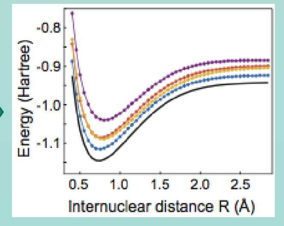
QSCOUT code/microcode

Implement on Hardware

Results





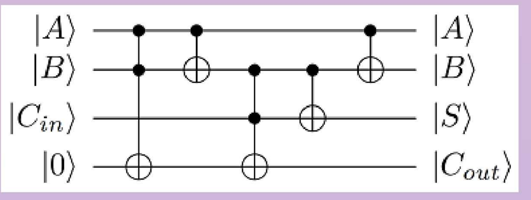


Exemplars and Training

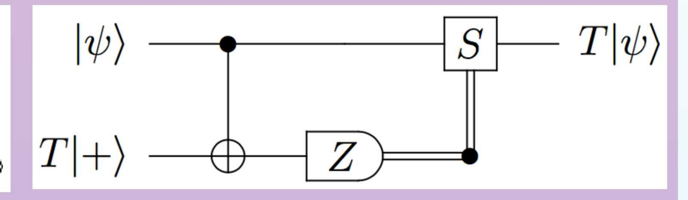
Training by example

- Will highlight system features by demonstrating their use.
- Annual workshops will showcase exemplar programs.
- User documentation for exemplars will be provided.

System Feature	Exemplar Programs
High-fidelity gates	Quantum Ripple Carry Adder
Small-angle gates	Quantum Chemistry Simulator
All-to-all connectivity	Solid-State NISQ-Device Emulators
Classical Feedback	Quantum Gate Teleporter
…	…



1 + 1 on a Quantum Computer



Quantum Gate Teleportation

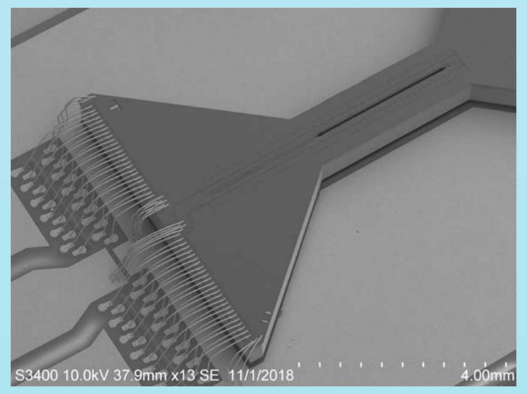
Testbed 2.0 Plans

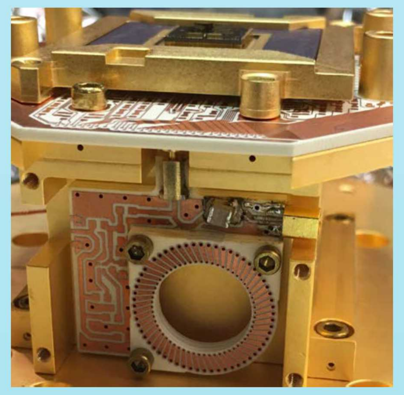
Challenges of Testbed 1:

- Anomalous heating of ions in the trap
  - Limits gate fidelity and leads to context-dependent errors
- Residual background gas collisions
  - Limit chain lifetime and system duty cycle

Trapping at Cryogenic (4K) temperatures as mitigation:

- Heating rates can be reduced up to 100x
- Better vacuum conditions and lower energy collisions





References:

[1] Fisk, et al. "Accurate Measurement of the 12.6 GHz 'Clock' Transition in Trapped $^{171}Yb^+$ Ions." *IEEE Transact. on Ultrasonics, Ferroelectr. Freq. Cont.* **44**, no. 2 (March 1997): 344–54.

[2] Ballance, et al. "High-Fidelity Quantum Logic Gates Using Trapped-Ion Hyperfine Qubits." *PRL* **117**, no. 6 (August 4, 2016): 060504.

[3] Noek, et al. "High Speed, High Fidelity Detection of an Atomic Hyperfine Qubit." *Optics Letters* **38**, no. 22 (November 15, 2013): 4735–38.

[4]

[5]

[6]

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND No. ____________

U.S. DEPARTMENT OF ENERGY Office of Science