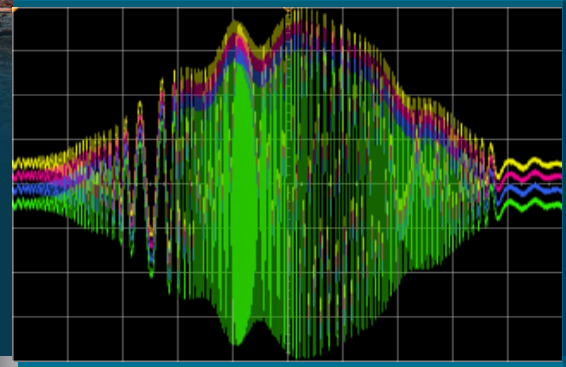
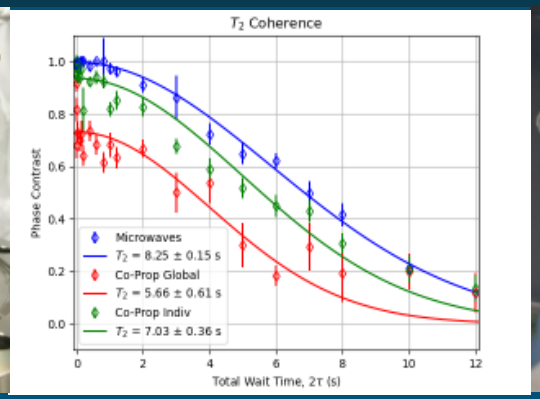
SAND2022-7071C

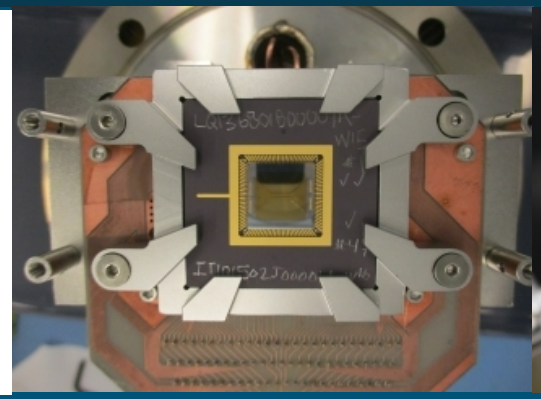
Sandia National Laboratories

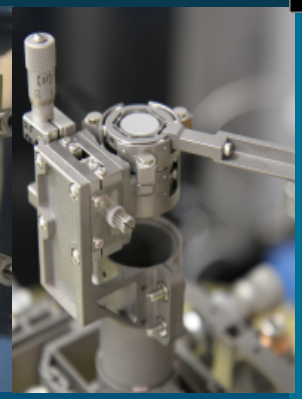


QSCOUT

The Quantum Scientific Computing Open User Testbed (QSCOUT)







U.S. DEPARTMENT OF ENERGY
Office of Science

PRESENTED BY
Melissa C. Revelle, Ashlyn D. Burch, Daniel Lobser, Christopher G. Yale, Susan M. Clark,

U.S. DEPARTMENT OF ENERGY NNSA

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Quantum Hardware needs to be accessible

QSCOUT

3 Tiers of accessibility:

Industry

Works at maximum efficiency but more difficult to study how machine works

IONQ

rigetti

IBM

Honeywell

Open Quantum Testbeds

Versatile and configurable, but less optimized for performance

QSCOUT

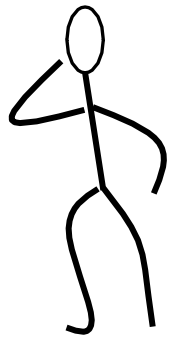
Sandia National Laboratories

AQT

BERKELEY LAB

Build your own

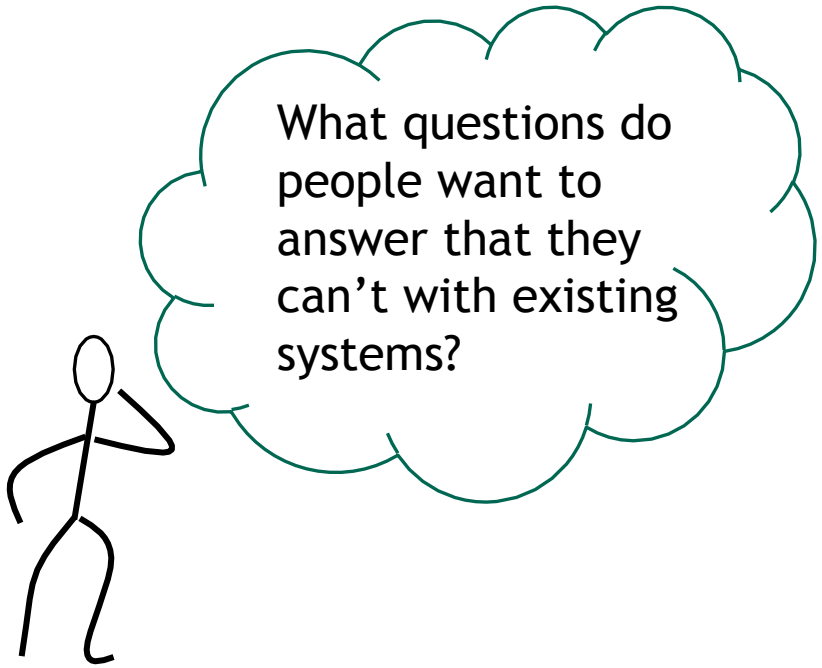
Total control, but expensive and difficult to build



Low-level control

Ease of access

QSCOUT leverages low-level access



Our goals:

- Greater understanding of how quantum machines work (and fail)
- Study new techniques for encoding and compiling quantum circuits
- Construct a roadmap for building larger, more sophisticated machines

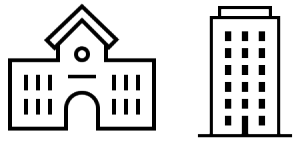
Designed to support:

- High-fidelity operations
- Gate level access
- Open for comparison and characterization of gate pulses
- Open for vertical integration by users

https://qscout.sandia.gov – Sign up for email updates!

Users are chosen via a competitive proposal process

QSCOUT



Potential users submit proposals

https://qscout.sandia.gov: for more information on how to apply

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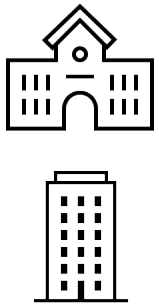
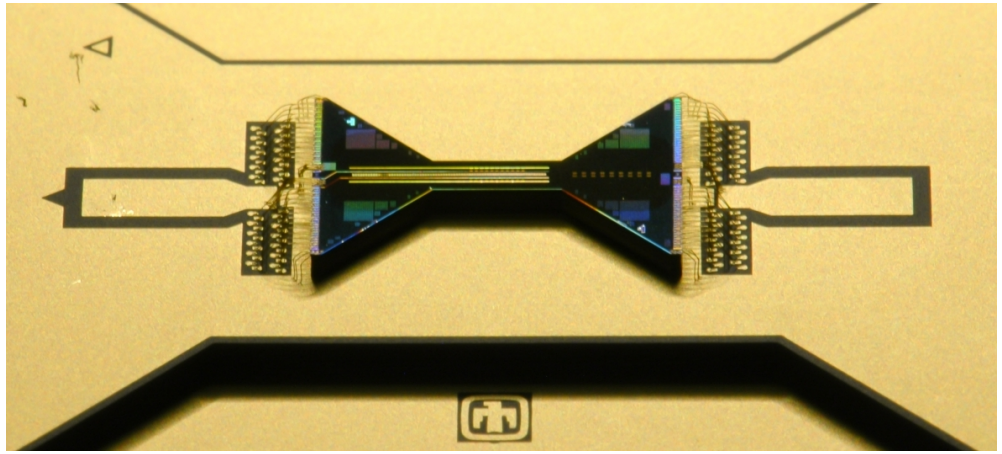
Evaluated on technical merit



Successful proposals are run on the machine

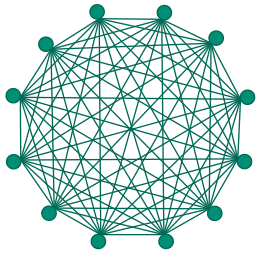


Advance the field of quantum information

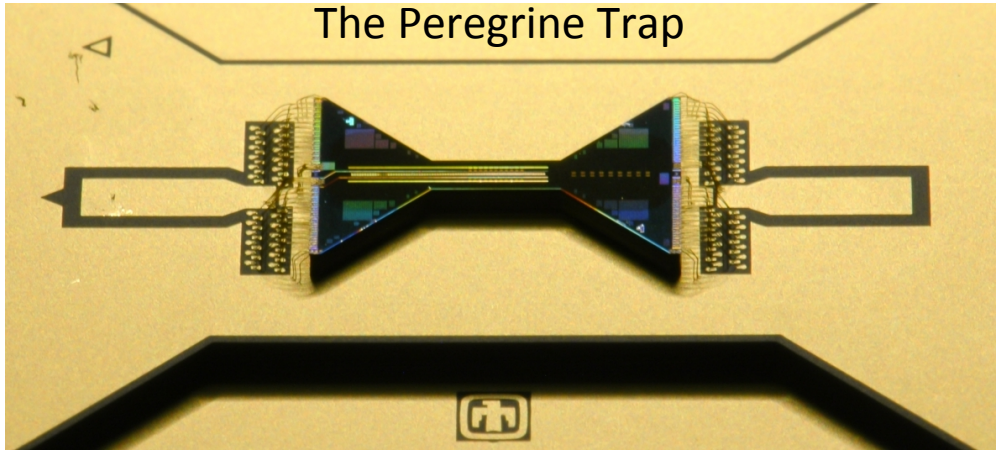
Our System, Characteristics & Benchmarks

QSCOUT

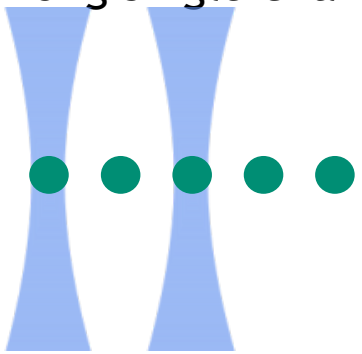
- Using long single chain of $^{171}Yb^{+}$
- Fully connected
- Ions (qubits) are identical
- Special requirements:
  - Separate beams for each ion with phase, frequency, and amplitude control
  - Ways to manage frequency crowding
  - Distinguishable detection
- Near-ideal prep and measure
  - Error $< 1 \times 10^{-2}$
- No idle errors (long coherence times)
  - Coherence time > 15min possible
- Low gate errors
  - Single-qubit error $< 7 \times 10^{-4}$
  - Two-qubit error $< 2 \times 10^{-2}$

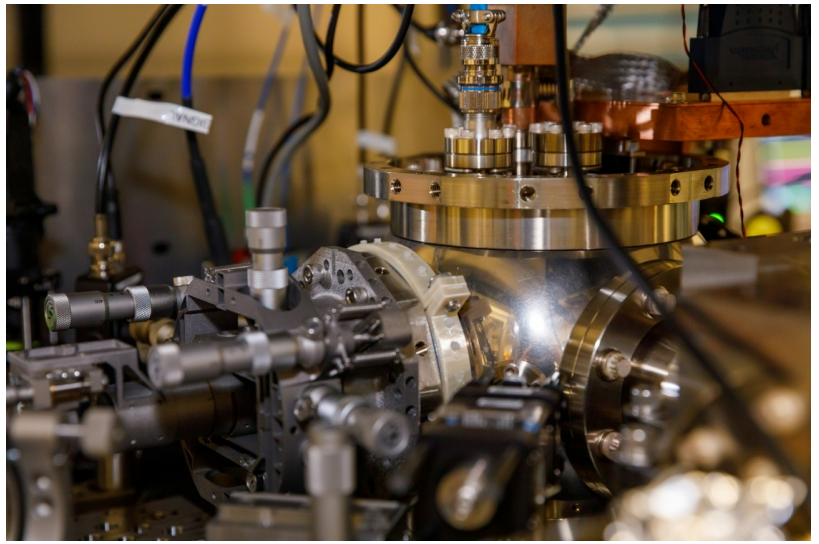


The Peregrine Trap



Long single chain





Susan M. Clark, Daniel Lobser, Melissa Revelle, Christopher G. Yale, *et al*. "Engineering the Quantum Scientific Computing Open User Testbed," in IEEE Transactions on Quantum Engineering, **2,** 1-32 (2021).

Jaqal - Custom software for user-machine interface

QSCOUT

Just Another Quantum Assembly Language

Jaqal

The quantum part

```
register q[2]

prepare_all
hadamard q[0]
cnot q[1] q[0]
measure_all
```

JaqalPaq

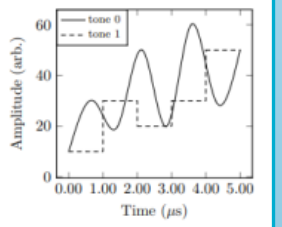
Meta programming with
python, emulator, transpiliers

```
JaqalCircuitObject = parse_jaqal_file("jaqal/Sxx_circuit.jaqal")
JaqalCircuitResults = run_jaqal_circuit(JaqalCircuitObject)
print(f"Probabilities: {JaqalCircuitResults.subcircuits[0].probability_by_str}")
JaqalProgram = generate_jaqal_program(JaqalCircuitObject)
```

JaqalPaw

Pulse level control

```
def gate_G(self, qubit):
    spline_amps = (10,30,20,50,20,60,30,50)
    discrete_amps = [10,30,20,30,50]
    return [PulseData(qubit,
                      5e-6,
                      freq0=200e6,
                      freq1=230e6,
                      amp0=spline_amps,
                      amp1=discrete_amps)]
```



There are many programming languages out there. Why Jaqal for QSCOUT?

- **Transparency**: Fully specify native gates
- **Schedulability**: Full control of sequential & parallel execution of quantum gates
- **Extensibility**: Pulse level control of laser gates (intimately tied to hardware)

Websites:
Jaqal - https://qscout.sandia.gov
JaqalPaq - https://gitlab.com/jaqal/jaqalpaq

B. C. A. Morrison, *et al.*, "Just Another Quantum Assembly Language (Jaqal)," *2020 IEEE Int. Conf. on QCE*, 402-408 (2020)

Gate Operations

QSCOUT

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 $e^{-it\sum_{i\neq k} J_{ik}\sigma_{x,j}\otimes\sigma_{x,k}}$
- Parameterize 2-qubit gate

Implementation of simulation on QSCOUT

Prepare → All the ions are pumped to $|0\rangle$

Step 1
Step 2
Step 3
Step 4
Step 5…

Single qubit and 2 qubit gates with varying angles and phases – can be different for each step

Project
Measure

Single qubit gates to measure in ZZ, XX or YY basis

JAQAL

```
projZZ{ }

projXX{
  hadamard q[0]
  hadamard q[1] }

projYY{
  <Sz q[0] | Sz q[1]>
  hadamard q[0]
  hadamard q[1] }
```

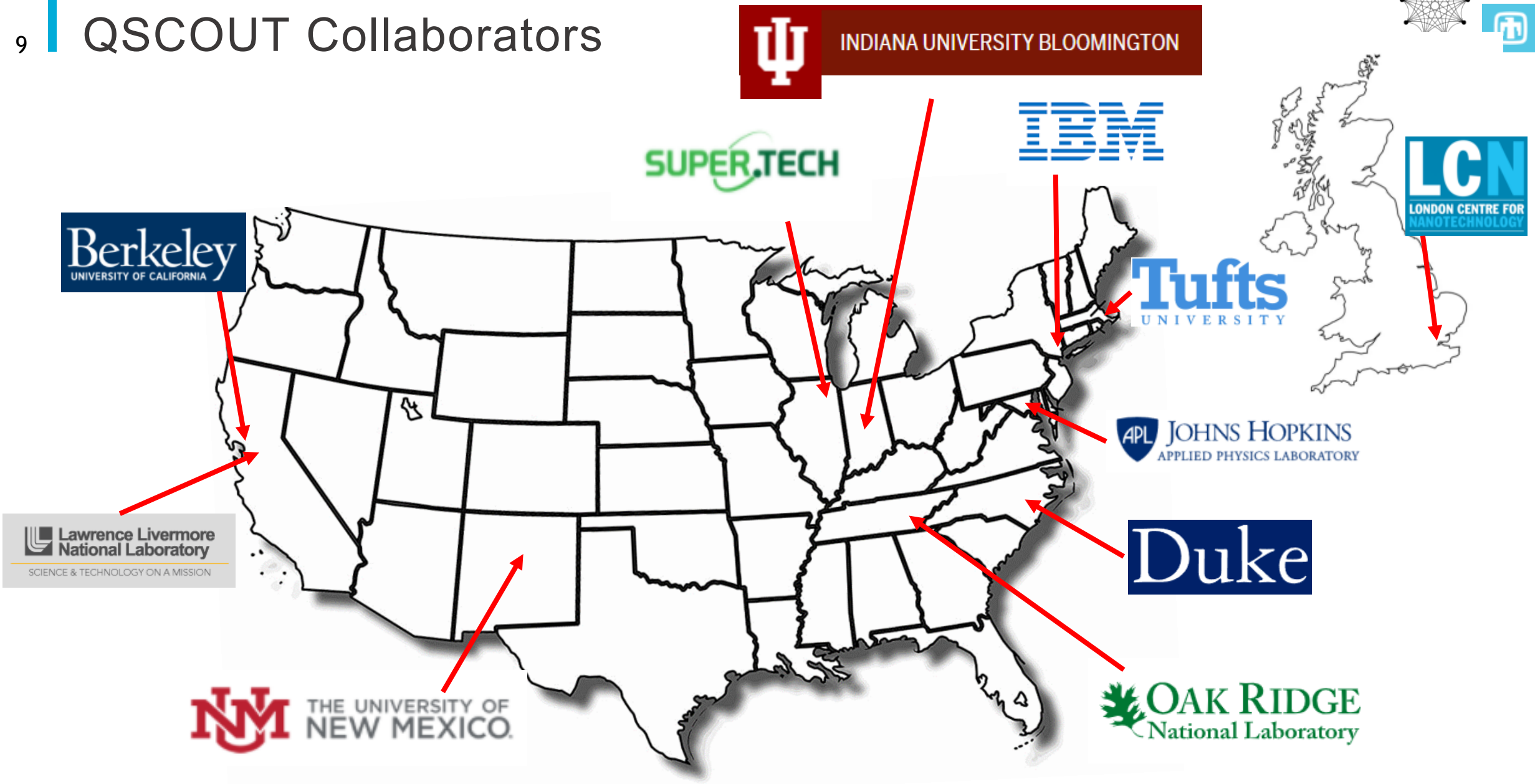
JAQAL

```
<Rz q[0] ntheta7_1 | Rz q[1] ntheta10_1 >
<Ry q[0] ntheta8_1 | Ry q[1] ntheta11_1 >
<Rz q[0] theta9_1 | Rz q[1] theta12_1 >
<Ry q[0] theta8_1 | Ry q[1] theta11_1 >
<Rz q[0] theta7_1 | Rz q[1] theta10_1 >
<Rx q[0] npi_2 | Rx q[1] npi_2>
MS q[0] q[1] pi_2 ntheta15_1
<Rx q[0] pi_2 | Rx q[1] pi_2>
MS q[0] q[1] pi_2 ntheta14_1
MS q[0] q[1] 0 ntheta13_1
<Rz q[0] ntheta1_1 | Rz q[1] ntheta4_1 >
<Ry q[0] ntheta2_1 | Ry q[1] ntheta5_1 >
<Rz q[0] theta3_1 | Rz q[1] theta6_1 >
<Ry q[0] theta2_1 | Ry q[1] theta5_1 >
<Rz q[0] theta1_1 | Rz q[1] theta4_1 >
```

- Use resonant light to determine final state of the ions.
- Each ion is detected in a different fiber core = distinguishable detection

Example with Trotterization
(Breaking the Hamiltonian into discrete time steps)

QSCOUT Collaborators

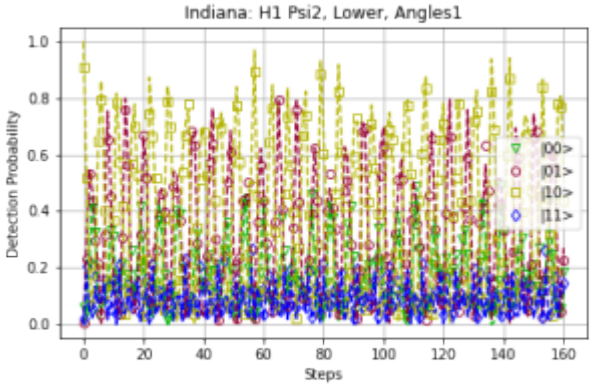


How have users interacted with low-level access?

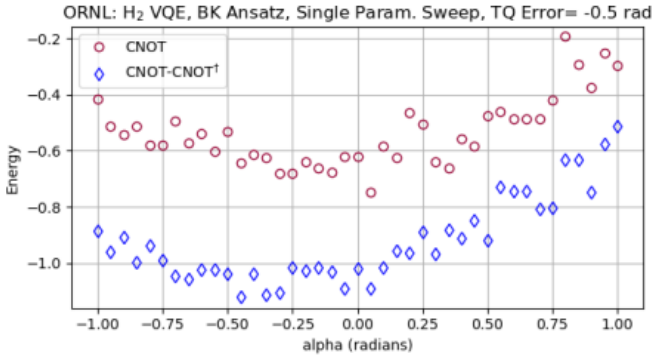
QSCOUT

INDIANA UNIVERSITY BLOOMINGTON

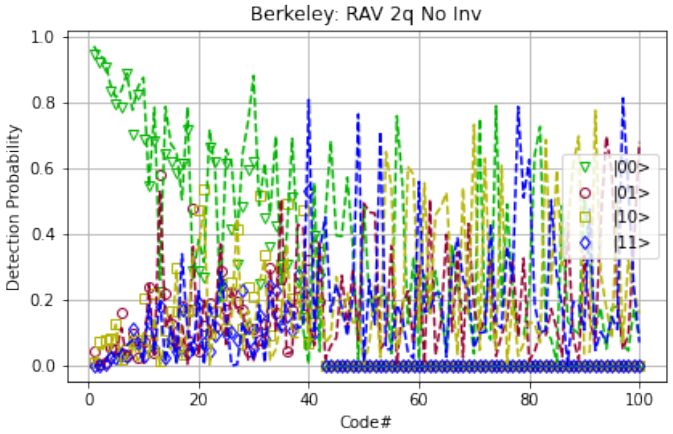
Used composite CNOT gates, which were added to our calibration routine.



OAK RIDGE National Laboratory



We were able to purposefully introduce noise and miscalibration to test robustness

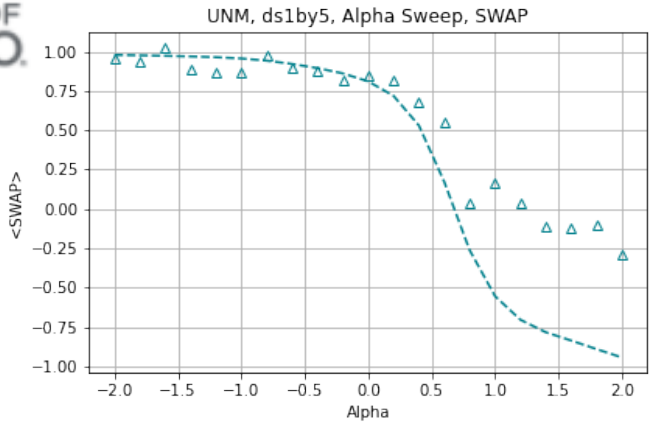


Berkeley UNIVERSITY OF CALIFORNIA

Analog benchmarking > 1000 unique gates (axes and angles)

THE UNIVERSITY OF NEW MEXICO

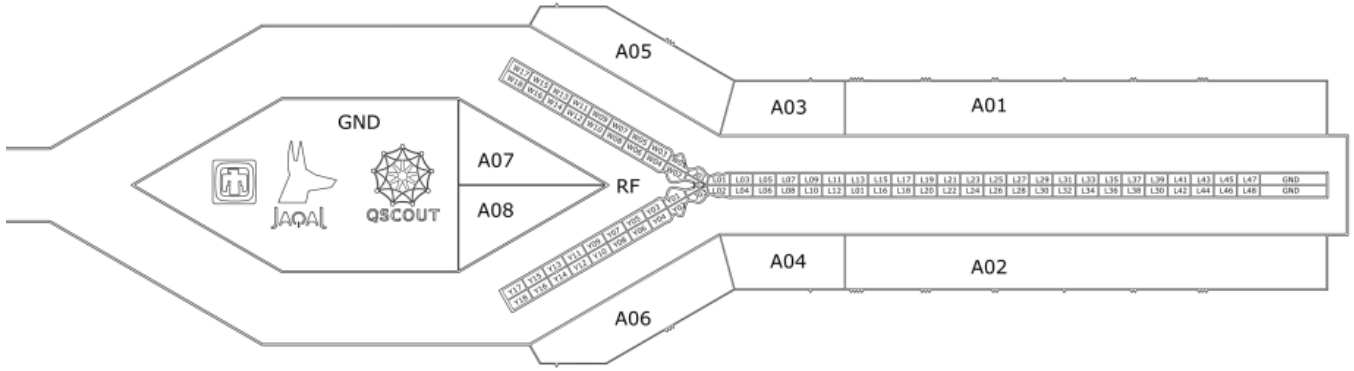
Used variable “small-angle” gates to test different amounts of Trotterization



Key QSCOUT Experimental Features

- Some features were developed during the first round to support our users
  - We expect this to continue in the coming rounds
- Users work closely with the QSCOUT experimental team to develop calibrations and gates as needed
  - Regular feedback from both QSCOUT and the users is encouraged to maximize the experience
- Able to add functionality at the experimental level – such as error injection
  - Single-qubit demonstration: intentional errors to verify model
    - Rabi rate, ε errors
    - Phase, φ errors
  - VQE demonstration: intentional errors to reveal hidden inverse construction robustness
    - Under-rotation errors
    - Ion temperature
- Currently expanding the number of ions
- Coming soon:
  - Even more ions
  - Cryo
  - Mid-circuit measurements

New Y-Trap - Out of Fab

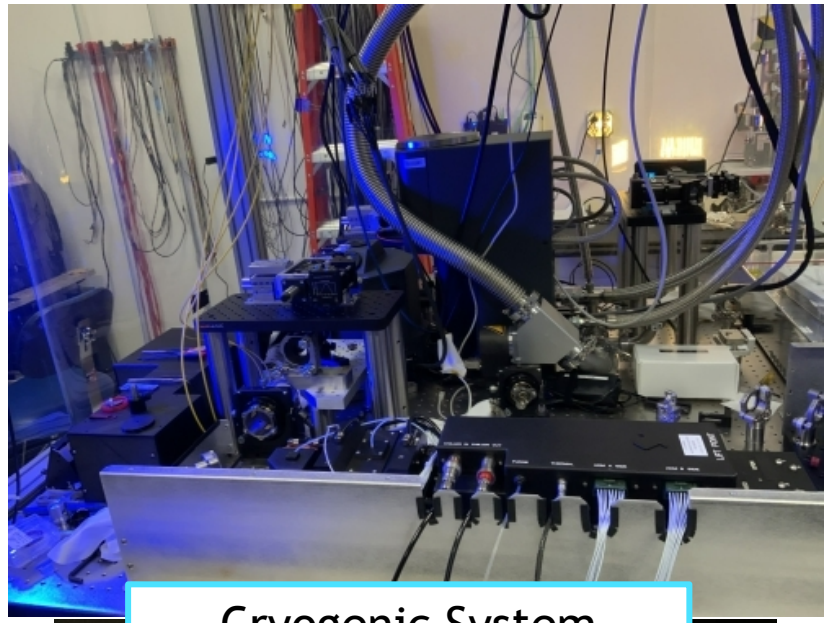


Websites & timelines of note

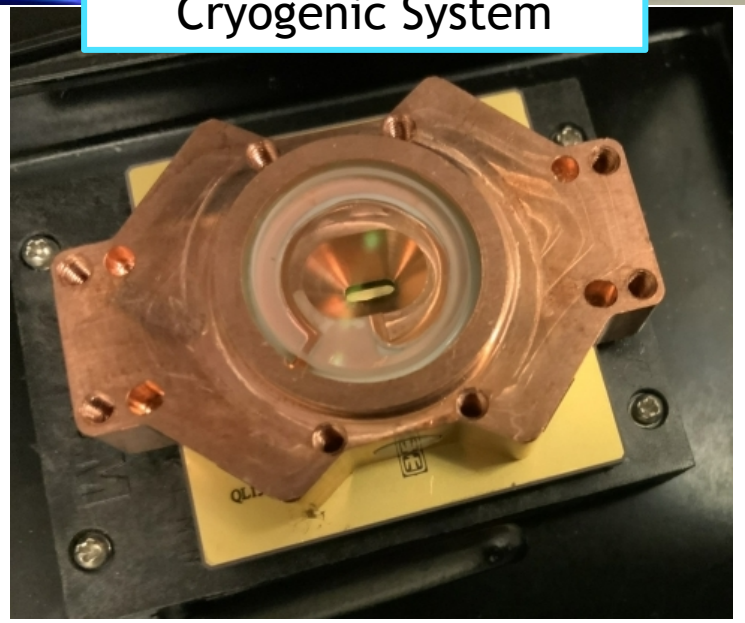
For more information on QSCOUT or Jaqal: https://qscout.sandia.gov
Email us to be added to the mailing list: qscout@sandia.gov
To download JaqalPaq: https://gitlab.com/jaqal/jaqalpaq

The QSCOUT manual: Susan M. Clark, Daniel Lobser, Melissa Revelle, Christopher G. Yale, *et al*. "Engineering the Quantum Scientific Computing Open User Testbed," in IEEE Transactions on Quantum Engineering, **2,** 1-32 (2021).

This Summer, the call for proposals on the cryo system – notifications will be sent to the mailing list
Winter – proposals for mid-circuit measurements



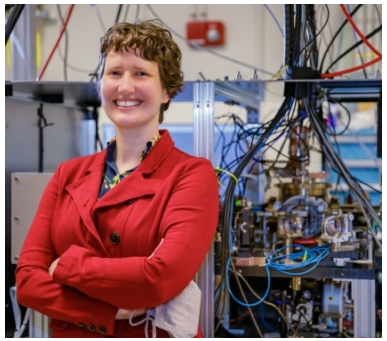
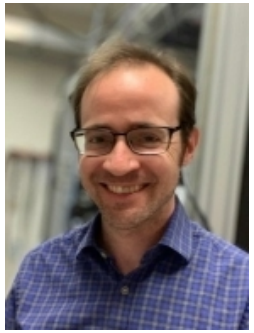
Cryogenic System



Current QSCOUT Team

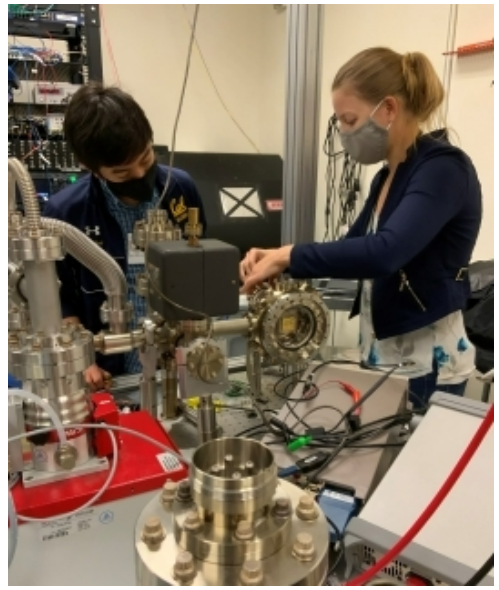
Email: qscout@sandia.gov (mailing list) **Web:** https://qscout.sandia.gov **Jaqal:** https://gitlab.com/jaqal/jaqalpaq

QSCOUT Experimental Team







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