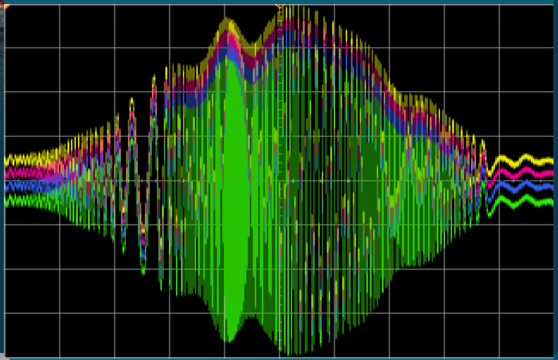
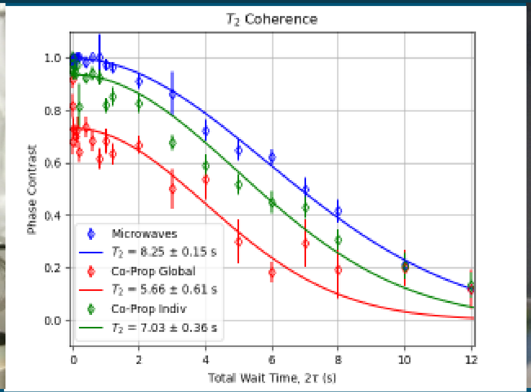
SAND2021-2716C

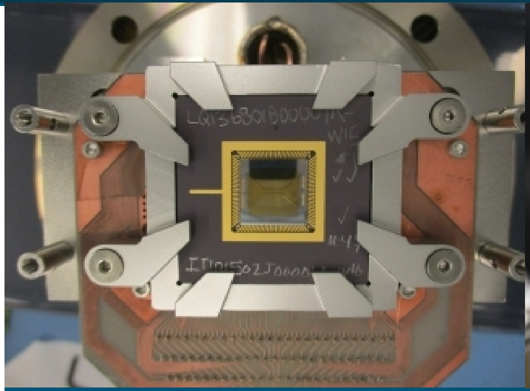
Sandia National Laboratories

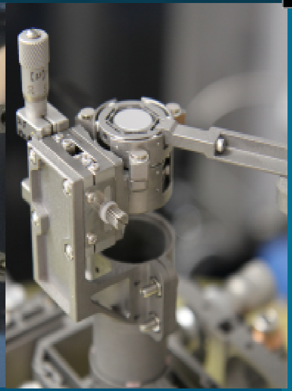
Development of the Quantum Scientific Computing Open User Testbed (QSCOUT)



QSCOUT



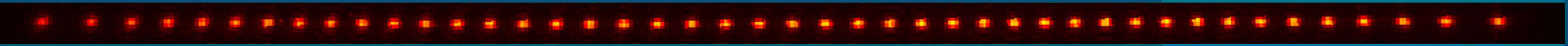




U.S. DEPARTMENT OF ENERGY
Office of Science

PRESENTED BY

Christopher G. Yale, Matthew G. Blain, Matthew N. Chow, Raymond A. Haltli, Craig W. Hogle, Andrew J. Landahl, Daniel Lobser, Jessica M. Pehr, Melissa C. Revelle, Brandon P. Ruzic, Jay W. Van Der Wall, Joshua M. Wilson, & Susan M. Clark



ENERGY NNSA

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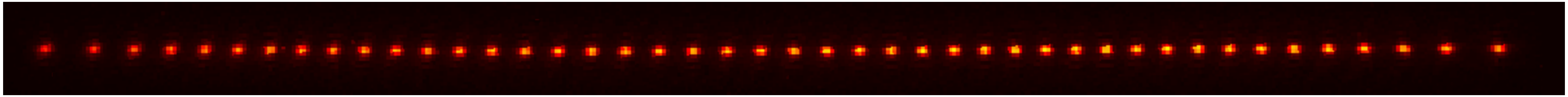
Quantum Scientific Open User Testbed (QSCOUT)



Open access ion trapping system to support scientific applications (DOE ASCR Quantum Testbed Program)

Goal

- High-fidelity operations
- Open system with fully specified operations and hardware
- Low-level access for optimal control down to gate pulses
- Open for vertical integration by users
- Phase 1 currently in progress with chains of 2-3 ions
- Introduced in phases with larger chains, improved fidelities, and greater classical control

Why Ions?

- Chain of $^{171}Yb^{+}$ ions
- Near-ideal SPAM
- Long coherence time / no idle errors
- Lowest demonstrated gate errors of any qubit candidate
- Low crosstalk
- All-to-all connectivity

QSCOUT JAQAL

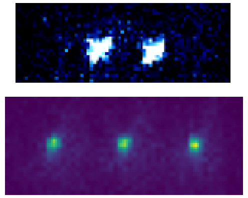
Experimental Setup and Enabling Technologies

QSCOUT

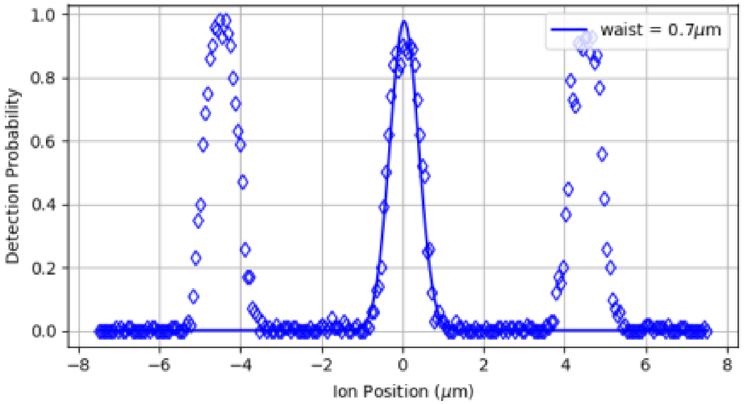
How do we move from a single ion to multiple ions, individually addressed with distinguishable detection?

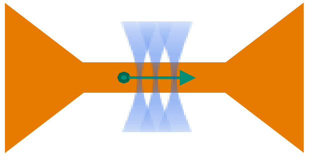
Toolbox:

- **Improve vacuum** → remove organics



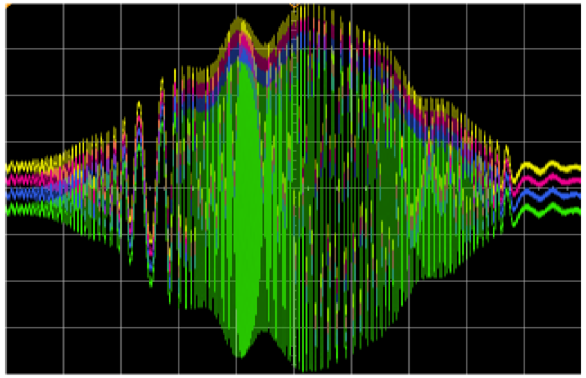
- **Individual addressing** → multi-channel AOM + interferometrically aligned mechanically stable optics



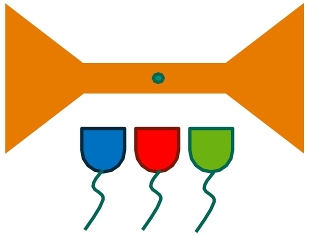


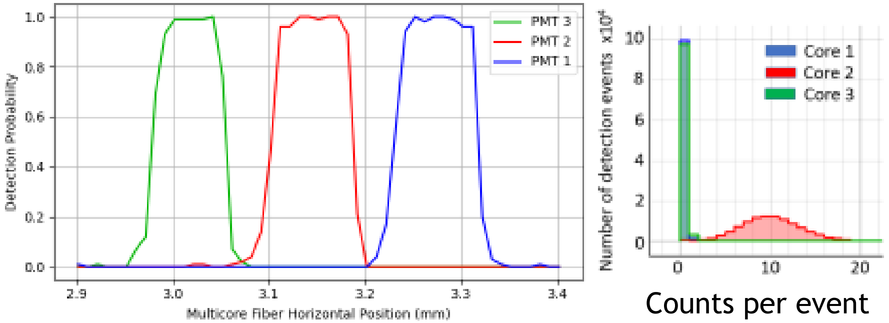
- **Pulse generation and control** → develop control hardware based on RFSoC for multi-tone, multi-channel control

OCTET



- **Distinguishable detection** → ions in separate fiber array cores



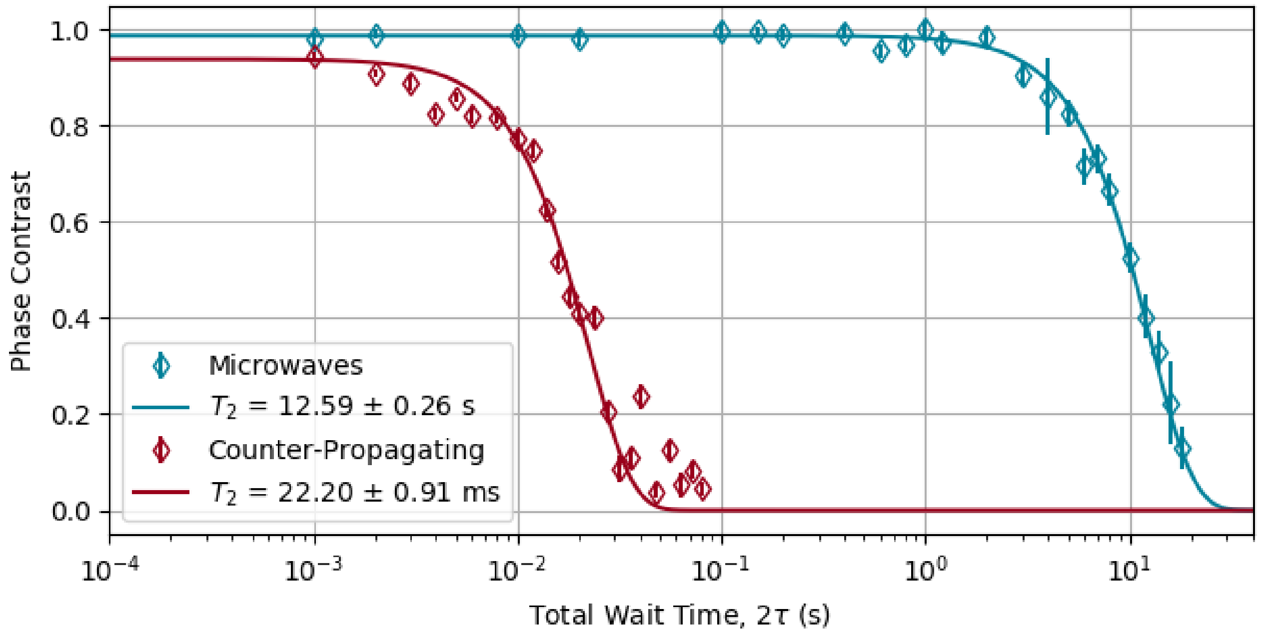


- **Put it together** → Develop a two to three ion register with all-to-all connectivity, high-fidelity single- and two-qubit gates

S. M. Clark, D. Lobser, M. C. Revelle, **C. G. Yale**, *et al.*, *in preparation*

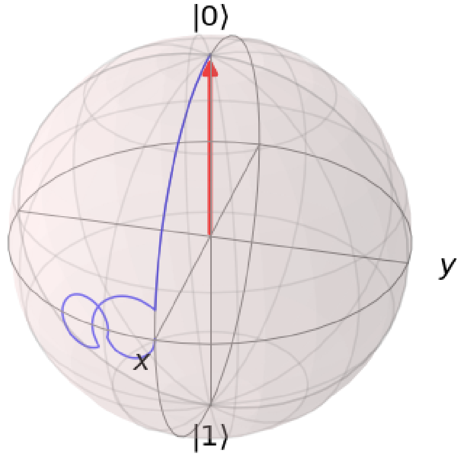
Single Ion Coherences and Fidelities

- Single-qubit gates can be driven by:
  - Global operations – act on entire chain:
    - Microwave
    - Co-propagating global Raman
  - Individual operations – act on individual ions:
    - Co-propagating individual Raman
    - Counter-propagating Raman
- Measure coherences in excess of 10 s
- Can compensate gates with BB1
- Can assess gate performance with Gate Set Tomography (GST)†



GST: BB1 Compensated Gates

Gate	Rotation Angle (rad.)	Infidelity	½ Trace Dist.	Sequence Length
Microwave - Gx	.499967π	.000039	.000178	128
Co-Prop Global - Gx	.497133π	.000656	.004688	128
Co-Prop Indiv. - Gx	.500149π	.001238	.001697	512



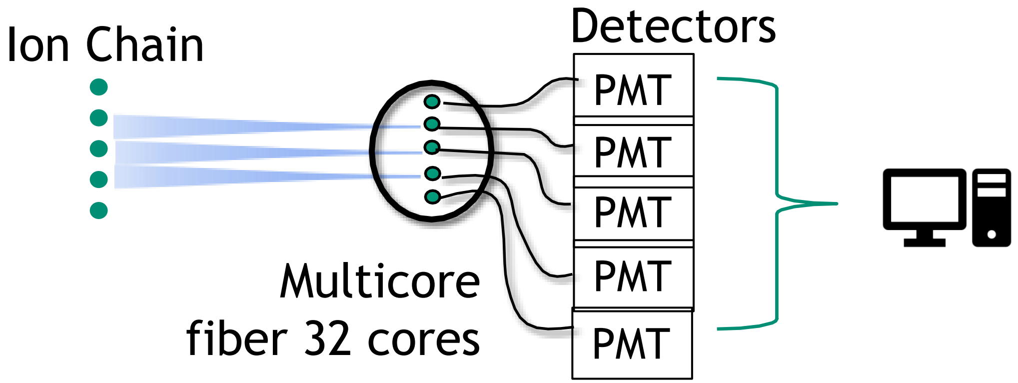
† R. Blume-Kohout, *et al.*, *Nat. Comm.* **8**, 14485 (2017)

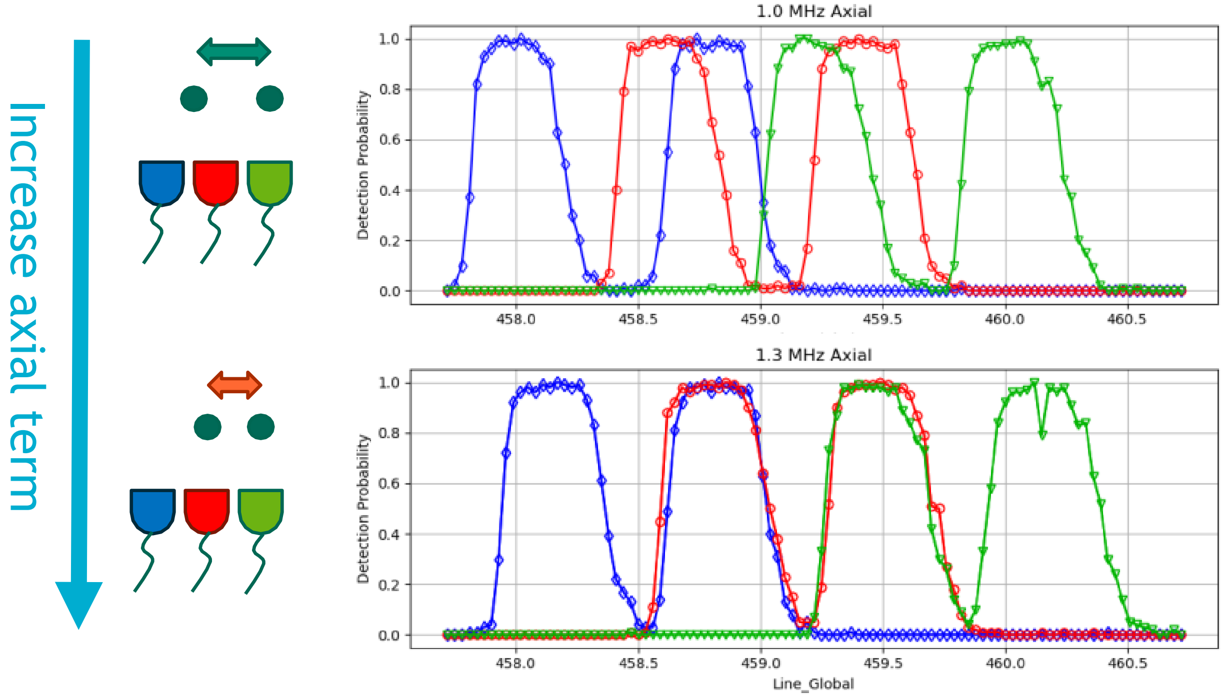
All single qubit gates > 99.5% fidelity

Moving to Two Ions: Aligning Fibers, Ions, and Beams

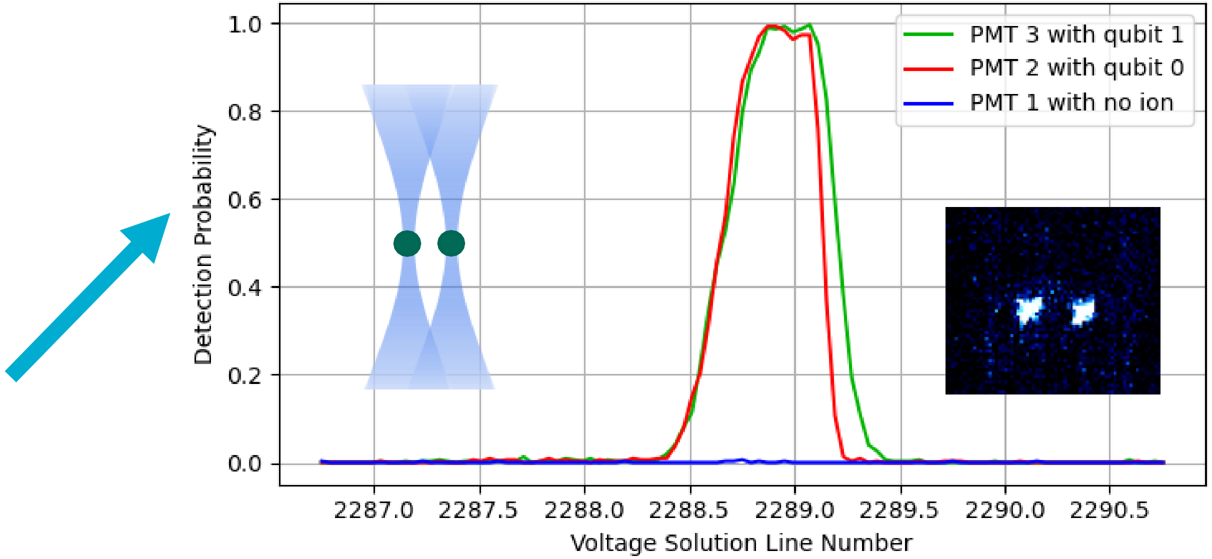
- Individual Raman Beams: 4.5 μm – fixed
- Fiber spacing: 125 μm – fixed
- Ion spacing: *variable*
  - Adjust axial terms in harmonic trapping solution:

$$V(x,y,z) = \frac{m\omega_y^2 y^2}{2} + \frac{m\omega_z^2 z^2}{2} + \frac{\alpha_2 x^2}{2}$$



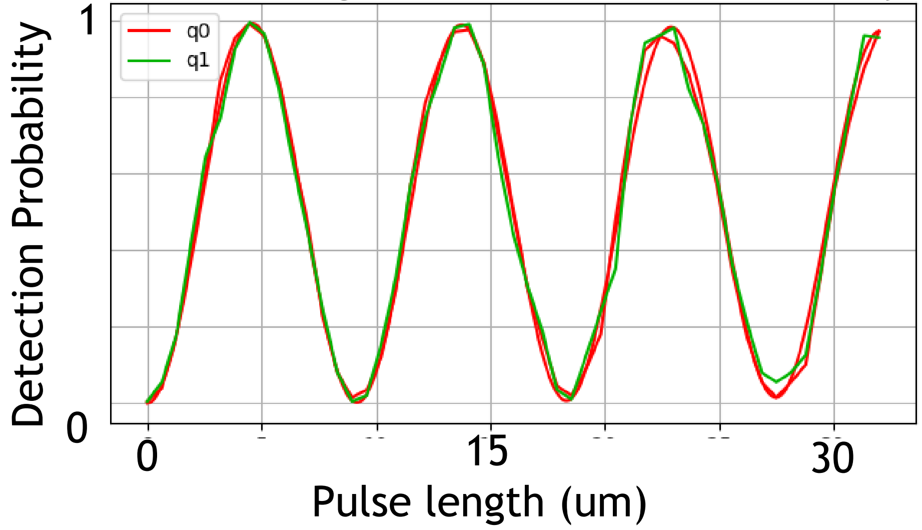


Moving two ions through two beams in the fibers

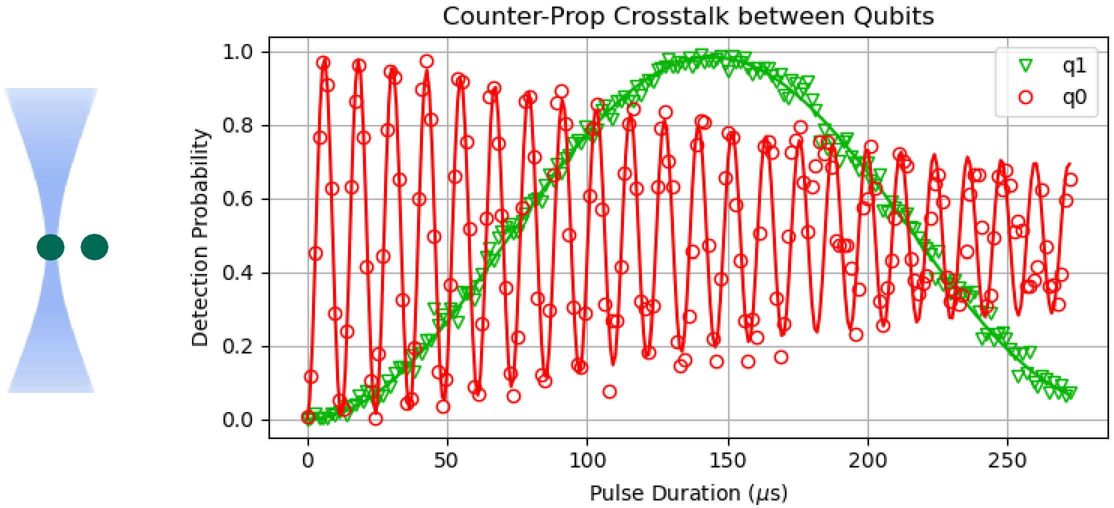


Single-Qubit Gates on Two Ions

Addressing two ions simultaneously

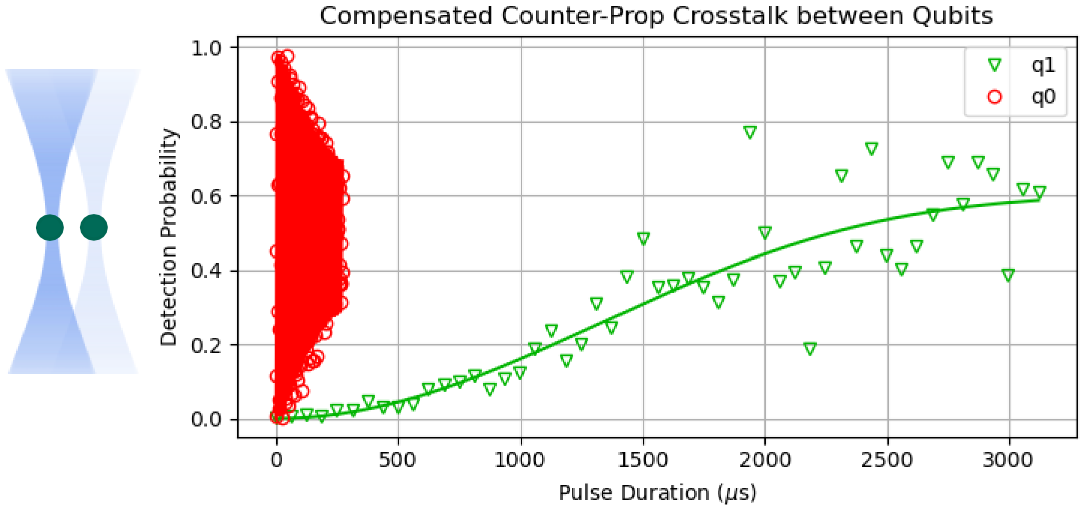


Qubit 0, π-time = 6 μs



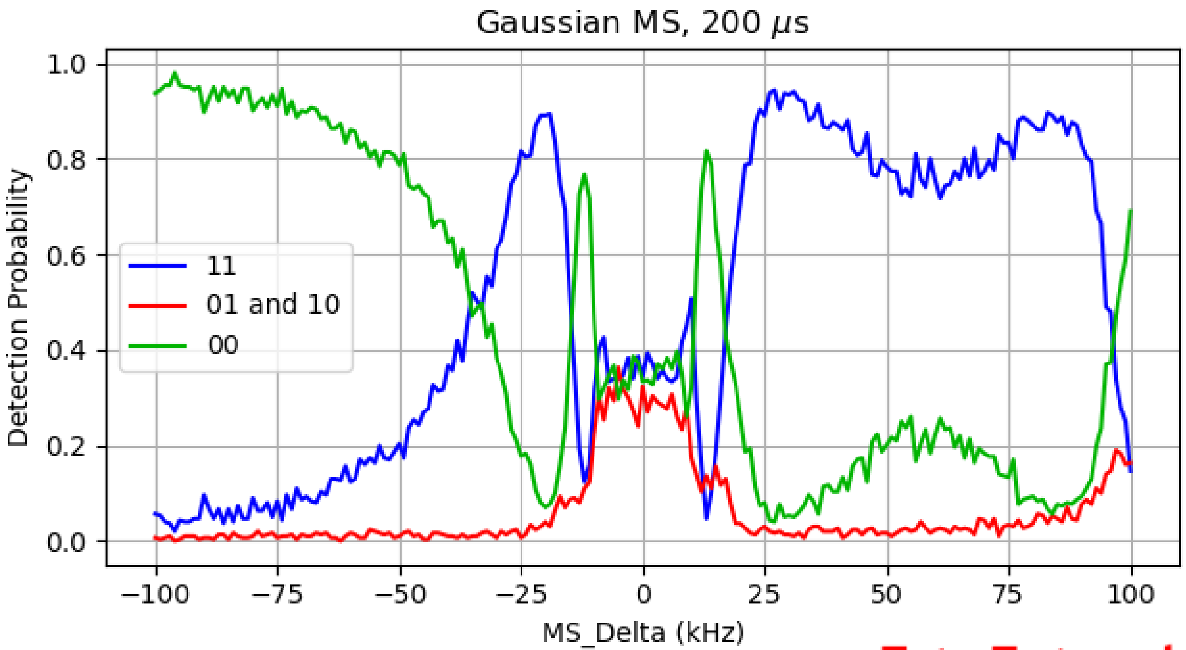
Qubit 1, π-time = 150 μs (4%)

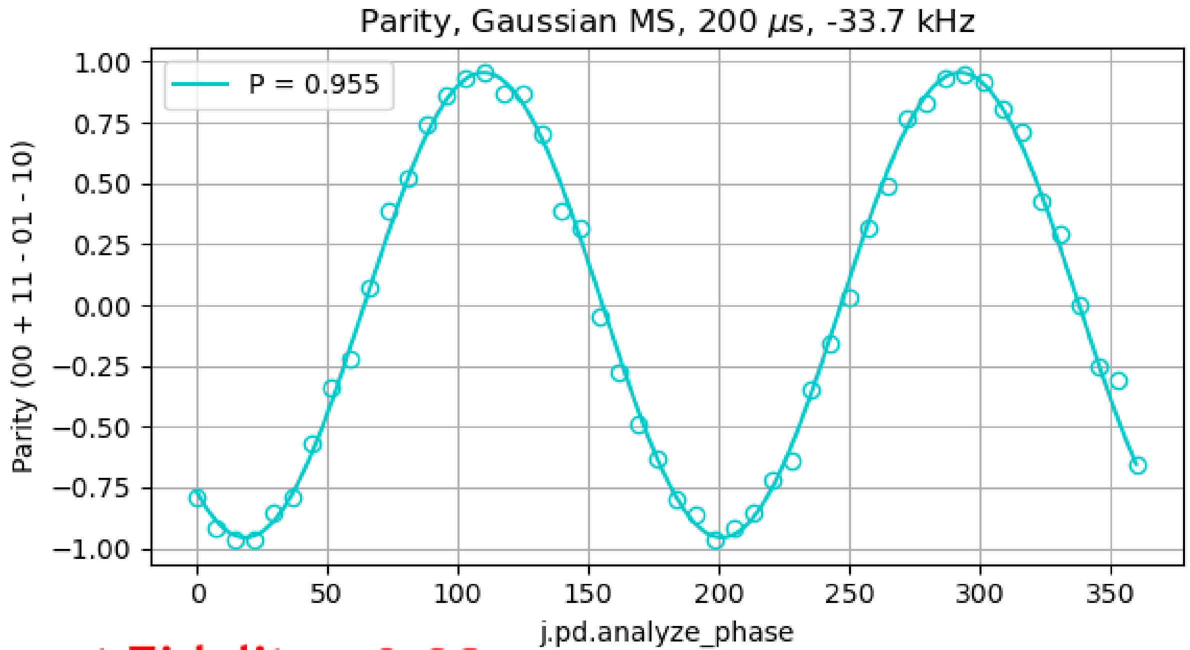
Qubit 1, crosstalk compensated π-time = 3000 μs (0.2%)



- Gates run in parallel or serialized
- Crosstalk between gates on qubits
  - Non-driven nearest neighbor: ~2-4% driving from nearest neighbor
  - Serial vs. Parallel: ~5% difference in π-time
- Crosstalk compensation through **Octet**: amplitude-, phase-, and delay-control on tones from nearest and next-nearest neighboring qubits
- Simultaneous GST – see B33.00003 (Kevin Young)

Driving a Two-Qubit Gate





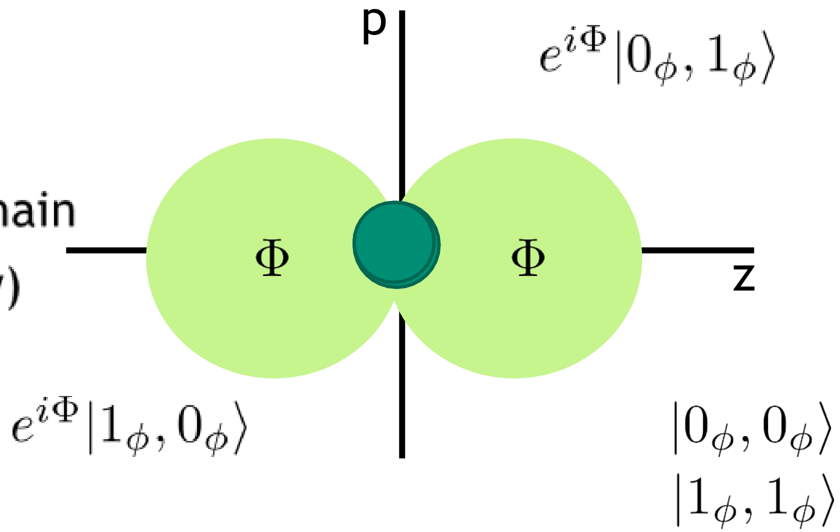
Est. Entanglement Fidelity ~0.98

Mølmer-Sørensen Entangling Gate

- $|00\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$
- Based on closing geometric phase loops
- Acts as a bus through common vibrational modes of entire ion chain
- Pick your favorite two qubits for the gate (all-to-all connectivity)

Implementing with Octet

- Gaussian pulse shaping drastically improved our two-qubit gate performance



Capabilities and Testbed Availability

- **QSCOUT will be operational in stages**
  - Stage 1, Testbed 1.0: Currently in progress
    - Running user algorithms on two ions and building up to three ions
    - Single qubit gates: >99.5% fidelity
    - Two-qubit Mølmer-Sørensen gates between any pair: 98% fidelity
    - Gate-level access and pulse-level access to realize custom gates
  - Future stages:
    - Longer chains, partial measurements, improved fidelities
    - Cryogenic system: longer-lived chains, less heating
- **Stage 2 call for proposals coming soon!**
  - Determining how many qubits available
  - Submit a short QSCOUT collaboration proposal, reviewed externally – join mailing list – email *qscout@sandia.gov*
  - QSCOUT programmed with JAQAL (Just Another Quantum Assembly Language) – more @ *qscout.sandia.gov* (arXiv:2003.09382, 2008.08042)

Visit qscout.sandia.gov for more details!

Stage 1 User Teams:

Berkeley UNIVERSITY OF CALIFORNIA

Randomized analog verification

IBM

Quantum volume benchmarking

INDIANA UNIVERSITY BLOOMINGTON

Proton-coupled electron transport

THE UNIVERSITY OF NEW MEXICO

Non-stoquastic Hamiltonians

OAK RIDGE National Laboratory

Connecting low level metrics to algorithmic performance via small simulation