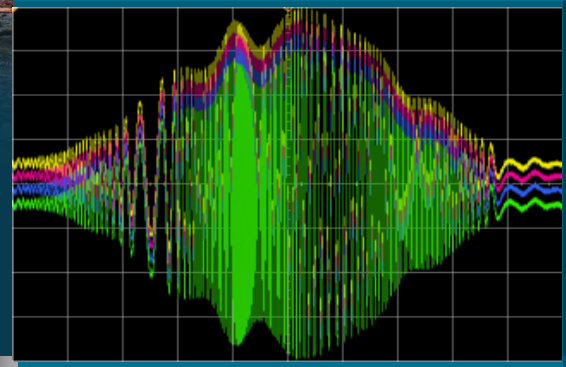
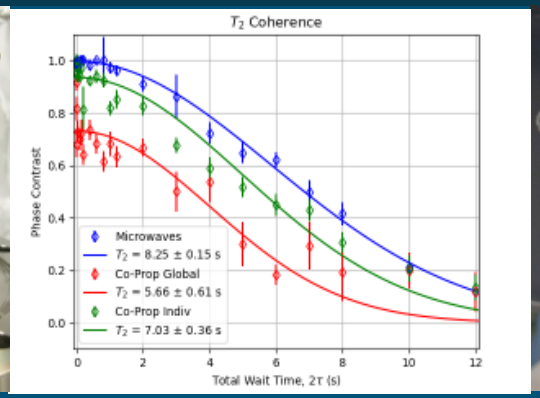
SAND2021-12934C

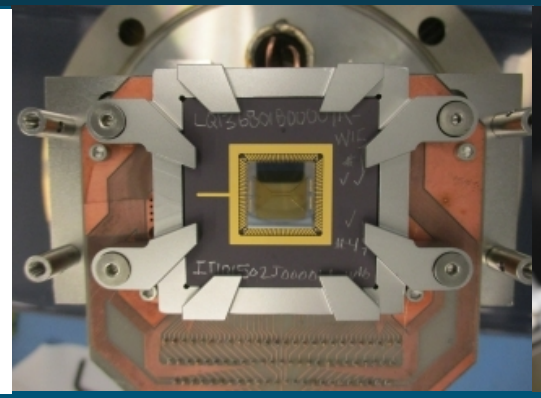
Sandia National Laboratories

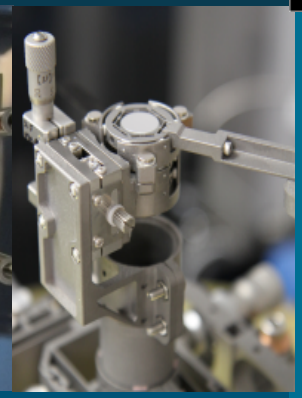


QSCOUT

An open quantum testbed based on trapped ions







U.S. DEPARTMENT OF ENERGY
Office of Science

PRESENTED BY

Christopher G. Yale

U.S. DEPARTMENT OF ENERGY NNSA

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Quantum Scientific Computing Open User Testbed (QSCOUT)

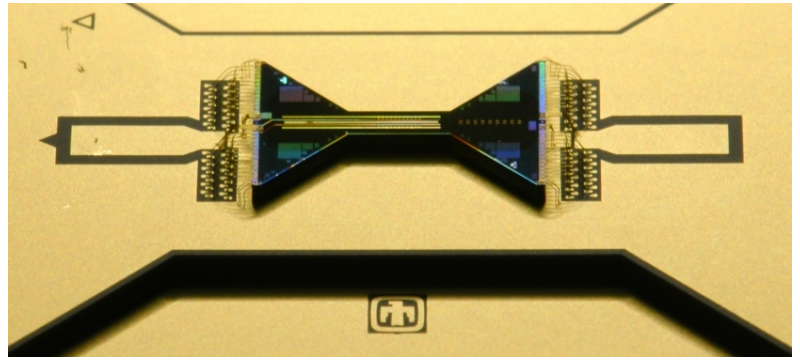
qscout.sandia.gov
qscout@sandia.gov

A quantum computing testbed based on trapped ions for the greater quantum scientific community

QSCOUT grants low-level access to quantum machines for free to researchers around the world to study their proposed research.

QSCOUT goals:

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



Tiers of accessibility: need quantum hardware available to as many people as possible

QSCOUT

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

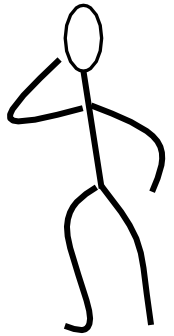
QSCOUT

Sandia National Laboratories

AQT

BERKELEY LAB

Total control, but expensive and difficult to build



Build your own

Low-level control

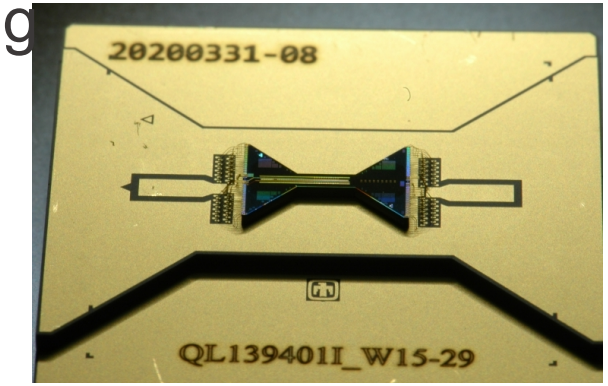
Ease of access

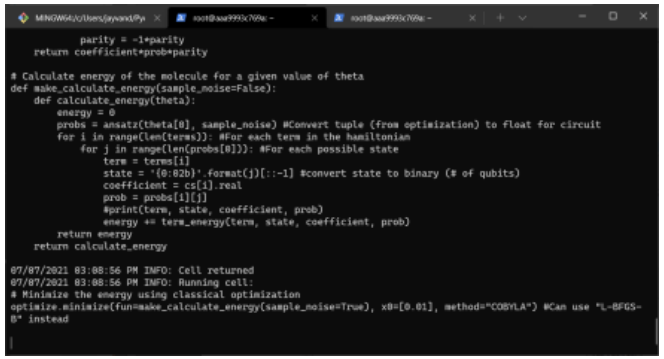
Quantum systems engineering

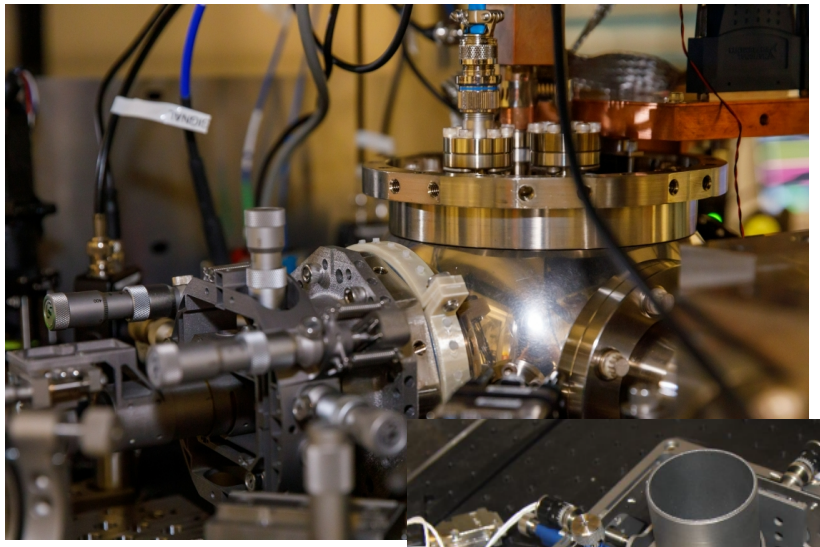
QSCOUT

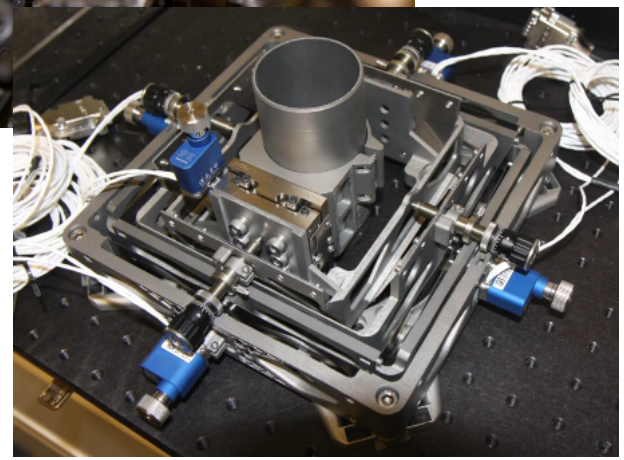
Complete quantum systems development requires:

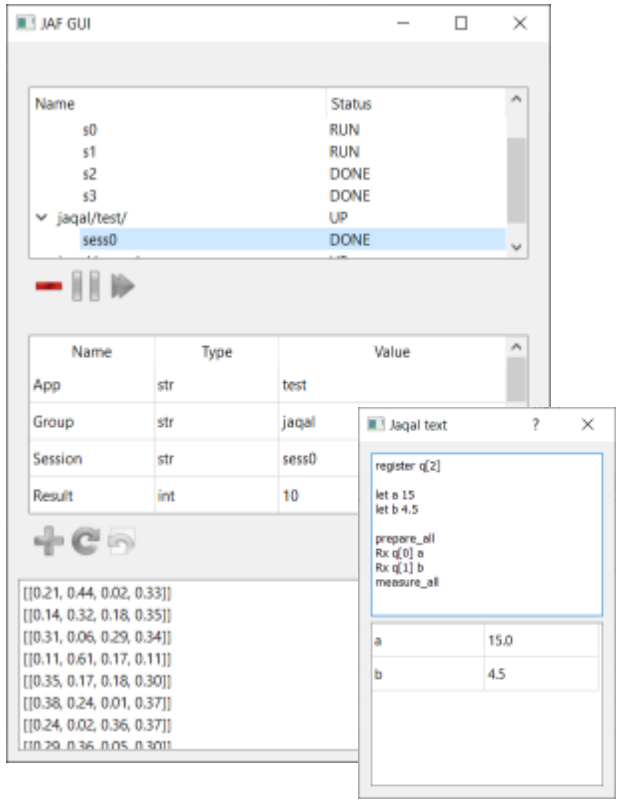
- Physicists
- Fabrication specialists
  - Electronics engineers
  - Electrical engineers
  - Materials scientists
- Mechanical engineers
- Optical engineers
- Software engineers
- And more!











For running useful circuits, boosting capabilities at Sandia

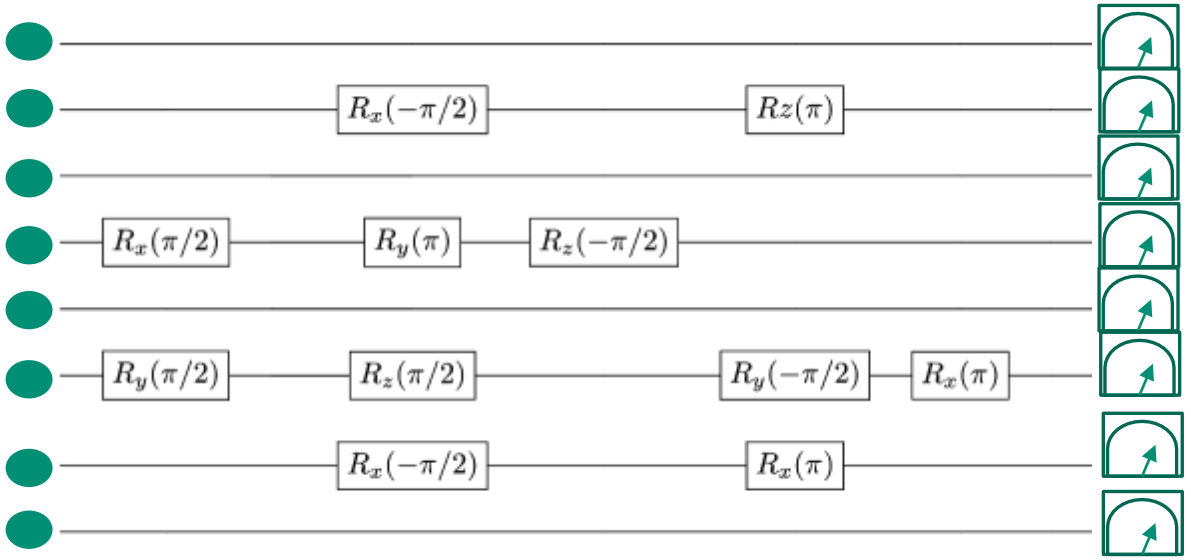
QSCOUT

Individually address ions or pairs of ions

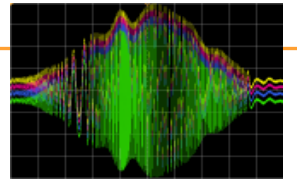
A quantum assembly language to specify gates

JAQAL

Multiple ion techniques



New hardware for advanced pulse/gate generation

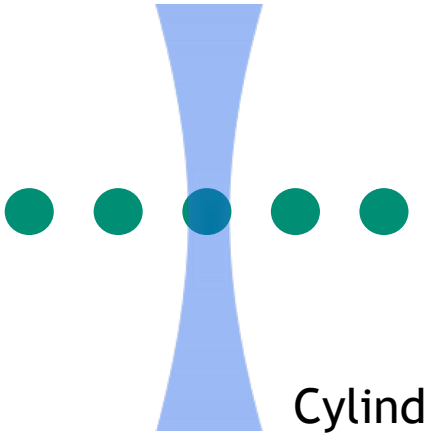


Distinguishable detection of each ion (*which* ion is in 1 or 0)

S. M. Clark, D. Lobser, M. C. Revelle, **C. G. Yale**, *et al.*, "Engineering the Quantum Scientific Computing Open User Testbed," *IEEE Transactions on Quantum Engineering* **2**, 3102832 (2021)

Individual ion addressing, non-trivial optics problem

QSCOUT



Out of AOM 80 µm

80 µm

At ion 0.8 µm

8 µm

4.5 µm

450 µm

Cylindrical lens pair

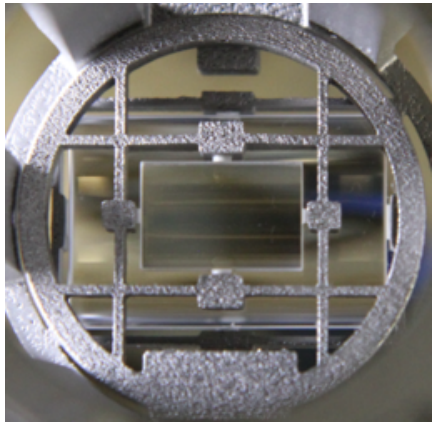
Spherical lens

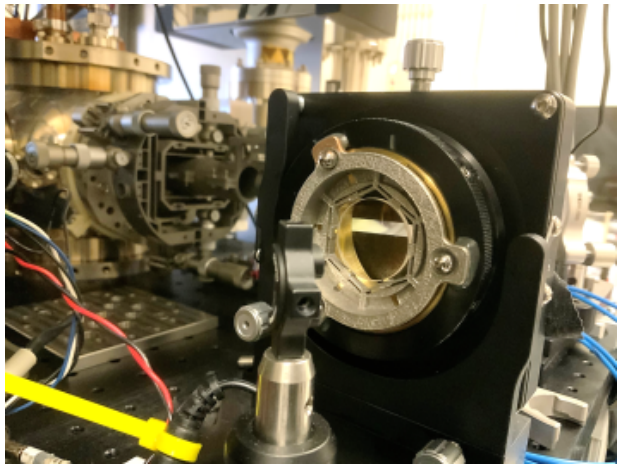
Spherical lens pair

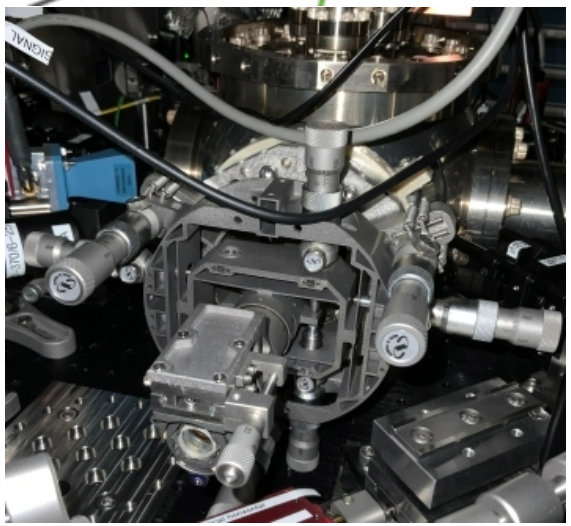
Custom imager (Photon Gear)

Side View

Top View

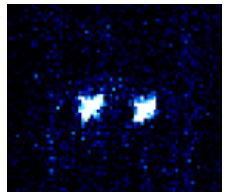






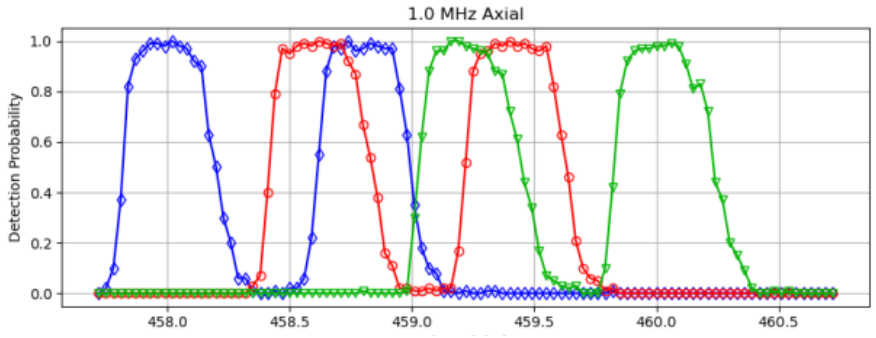
Distinguishable detection

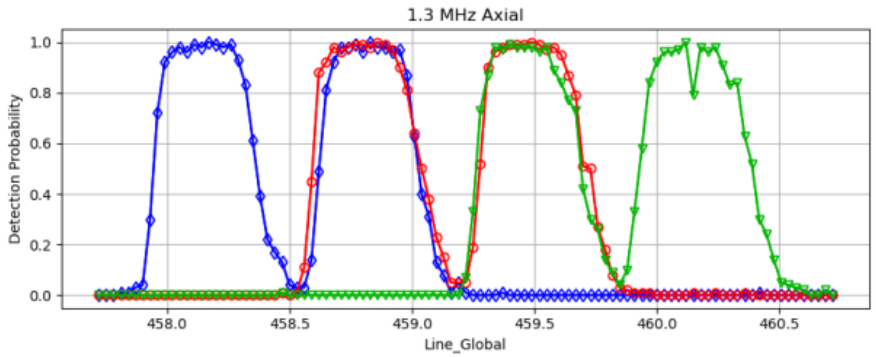
- Individual Raman Beams: 4.5 μm – fixed
- Fiber spacing: 125 μm – fixed
- Ion spacing: *variable*
  - Adjust axial terms in harmonic trapping solution:

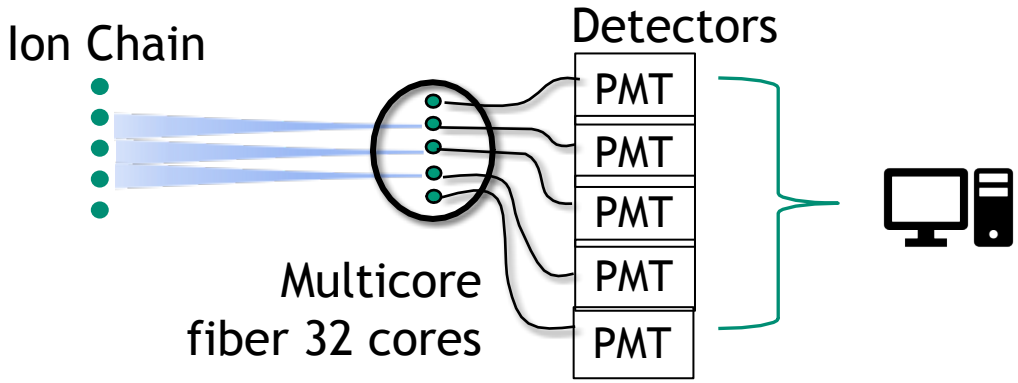


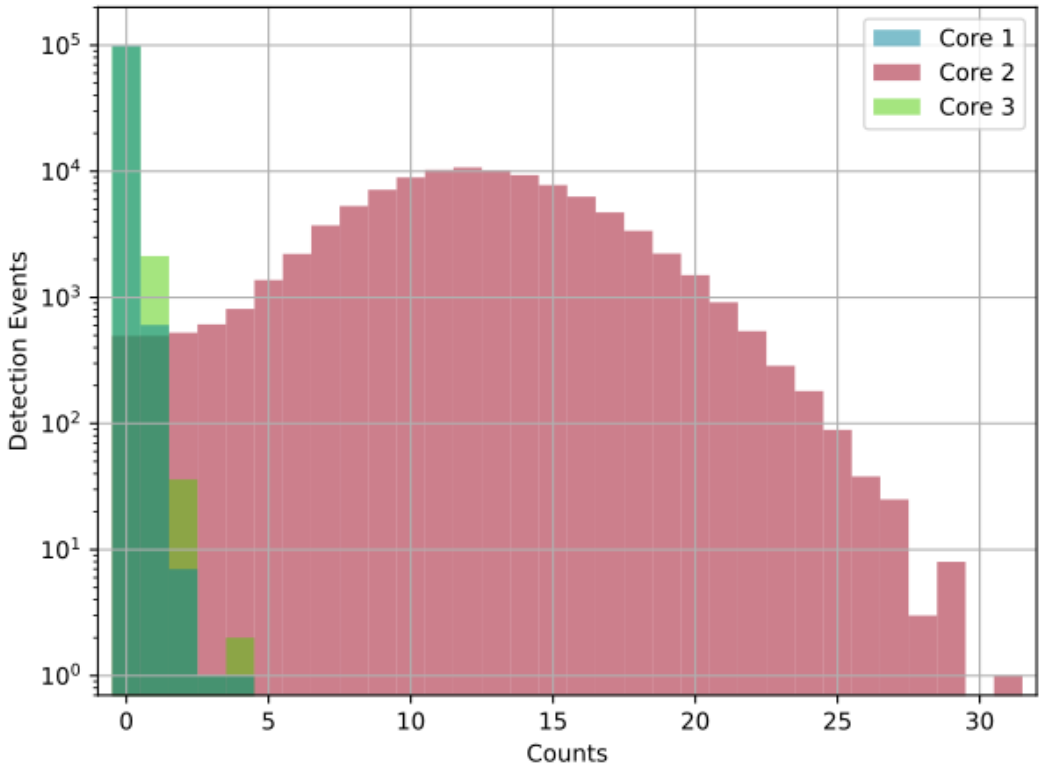
$$V(x,y,z) = \frac{m\omega_y^2 y^2}{2} + \frac{m\omega_z^2 z^2}{2} + \frac{\alpha_2 x^2}{2}$$

Increase axial term









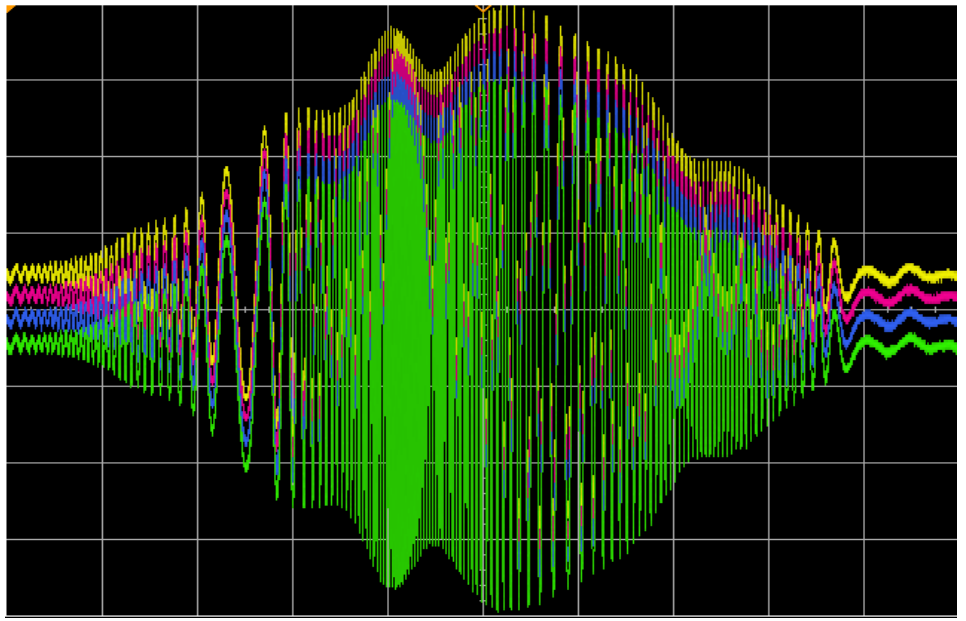
Octet: new hardware for advanced coherent pulse generation

QSCOUT

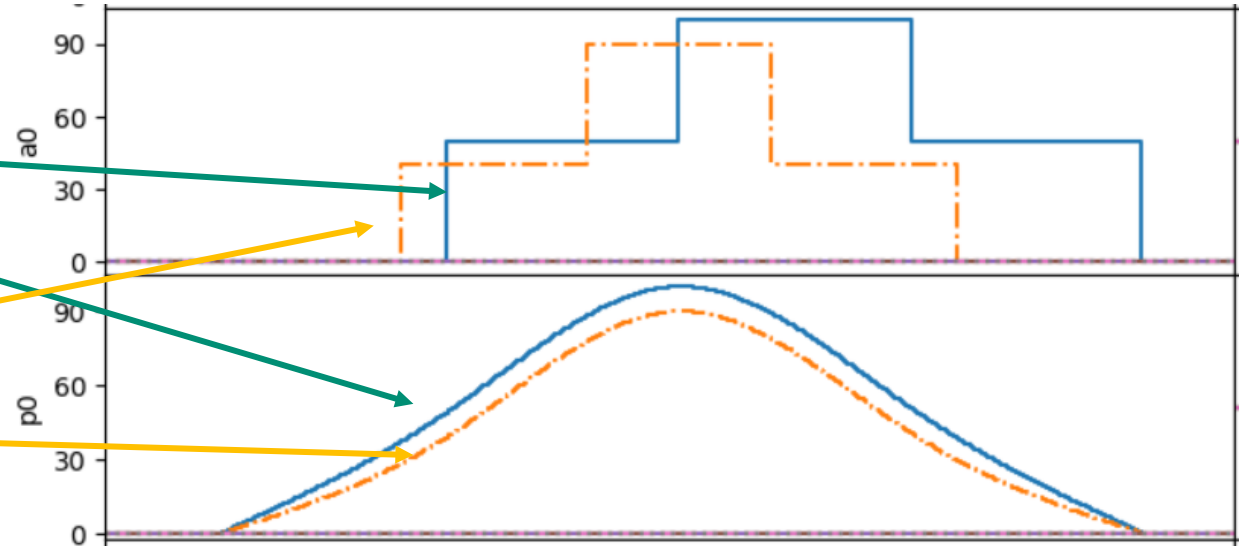
- Two tones per channel
- Coherent output synchronized between all channels
- Pulse envelopes and frequency- phase- modulation defined by splines
- Compact representation of gates for efficient streaming of circuits
- AOM Cross-talk compensation
- Z-gates performed in software
- Multi-tile sync for multiple boards

OCTET

JAQAL



```
def gate_counterprop_x(self, channel, duration_scale=1):
    return [PulseData(0, duration_scale*self.pulse_duration,
                      freq0=self.freq0,
                      freq1=self.freq1,
                      amp0=[0,50,100,50],
                      phase0=(0, 50, 100, 50, 0),
                      enable_mask=1, sync_mask=3),
            PulseData(channel, duration_scale *
self.pulse_duration,
                      freq0=self.freq0,
                      freq1=self.freq1,
                      amp0=[0,40,90,40,0],
                      phase0=(0,40,90,40,0),
                      enable_mask=2, sync_mask=3)
            ]
```



Jaqal: a new quantum programming language

QSCOUT

Jaqal

The quantum part

```
register q[2]

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

JaqalPaq:
https://gitlab.com/jaqal/jaqalpaq

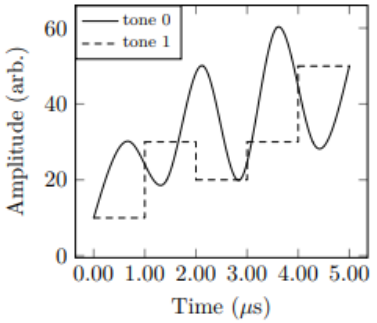
Meta programming with python, emulator, transpiliers

```
JaqalCircuitObject = parse_jaqal_file("jaqal/Sxx_circuit.jaqal")
JaqalCircuitResults = run_jaqal_circuit(JaqalCircuitObject)
print(f"Probabilities: {JaqalCircuitResults.subcircuits[0].probabil
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 *another* one?

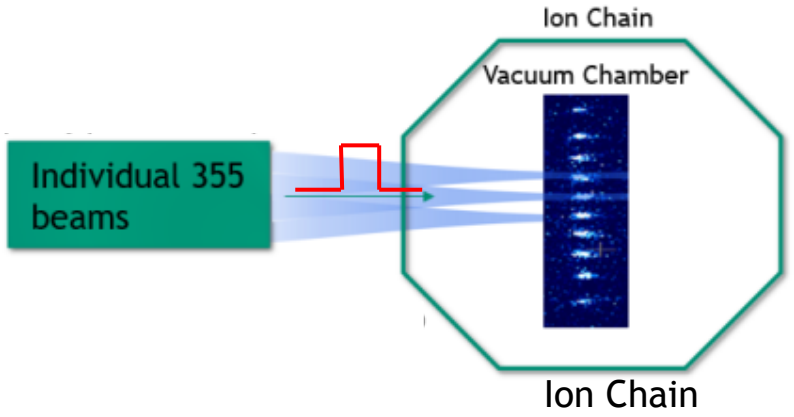
- Match needs of testbed: flexibility and control
- Specify parallel gates and loops (natural in our system)
- Other languages had operations we couldn't support, so we wanted to be upfront about it (and tailor it to track our capabilities)
- Pulse level control is intimately connected to hardware pulse generation

B. C. A. Morrison, *et al.*, "Just Another Quantum Assembly Language (Jaqal)," *2020 IEEE International Conference on Quantum Computing and Engineering (QCE)*, 402-408 (2020

Current default gates

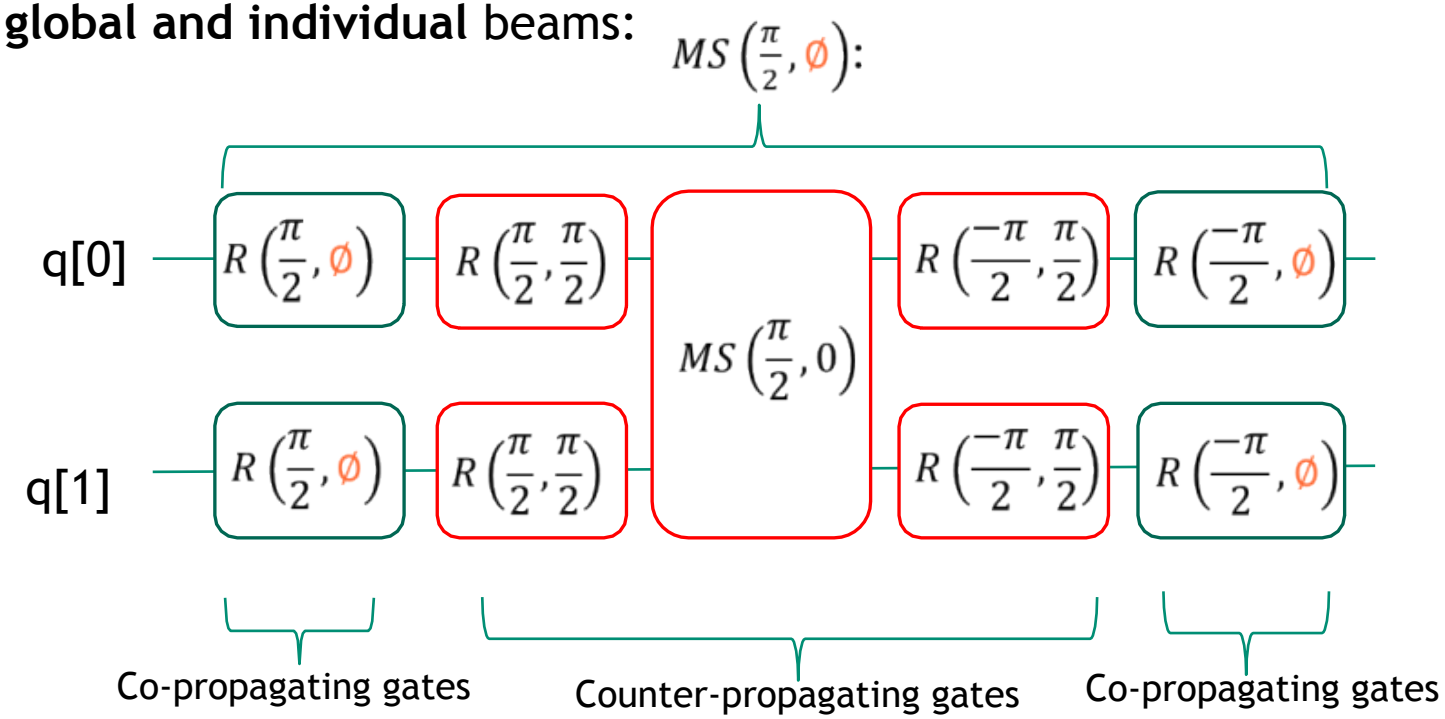
QSCOUT

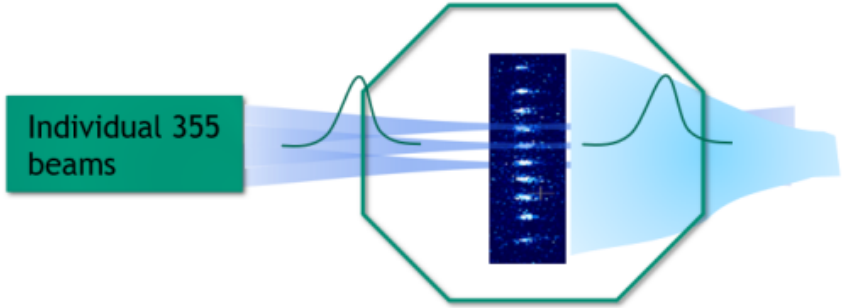
- **Idle gate**: do nothing
- **Single-qubit gate**:
  - Copropagating tones
  - ~25 us square pulse amplitude
  - Available with or without SK1 compensation

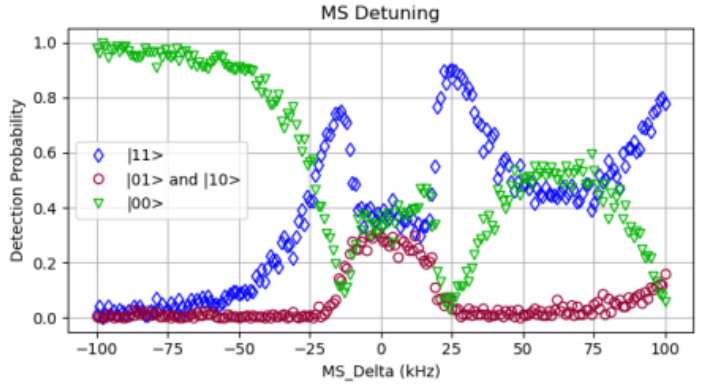


No global beam

- **Two-qubit gate**: Phase-error-corrected Mølmer-Sørensen (MS) gates with sqrt(Gaussian) envelope on **global and individual** beams:



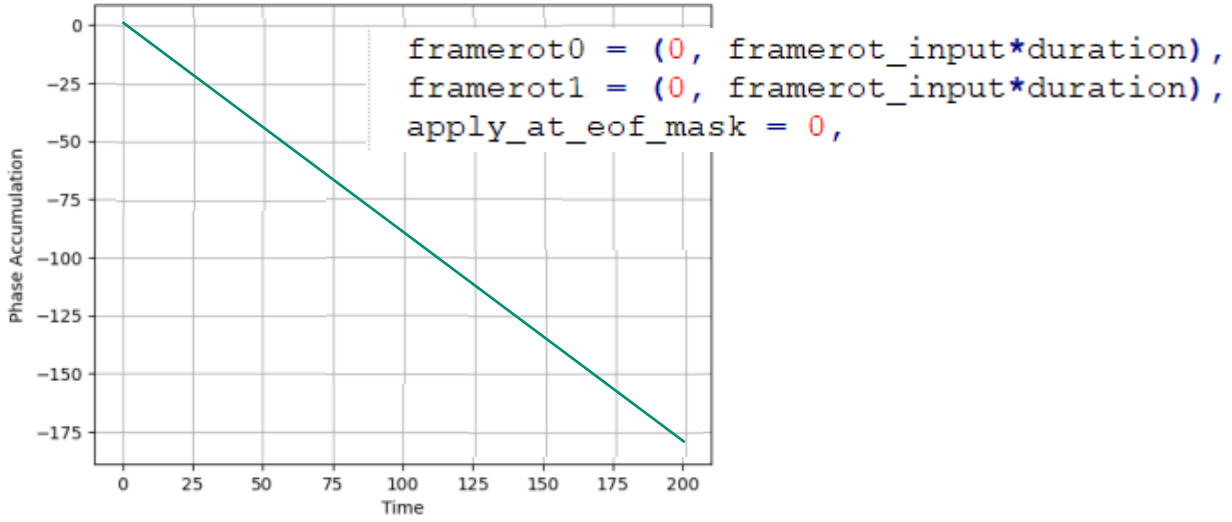




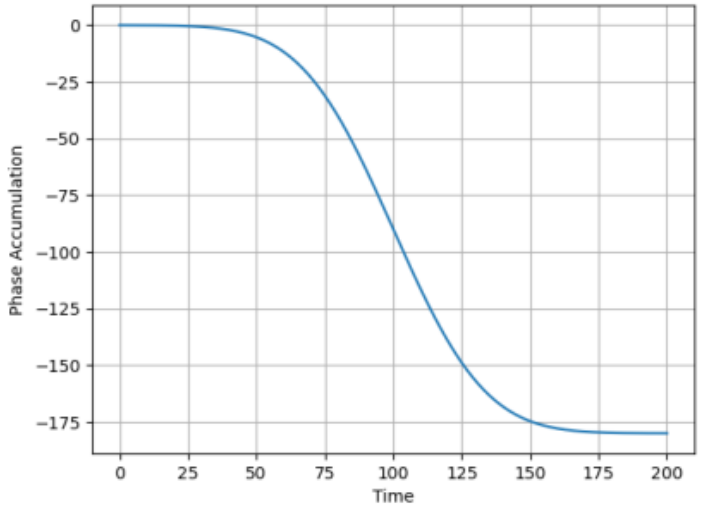
Frame rotations for AC Stark correction

QSCOUT

Linear Phase Advance for Square Pulses (Single Qubit Gates)

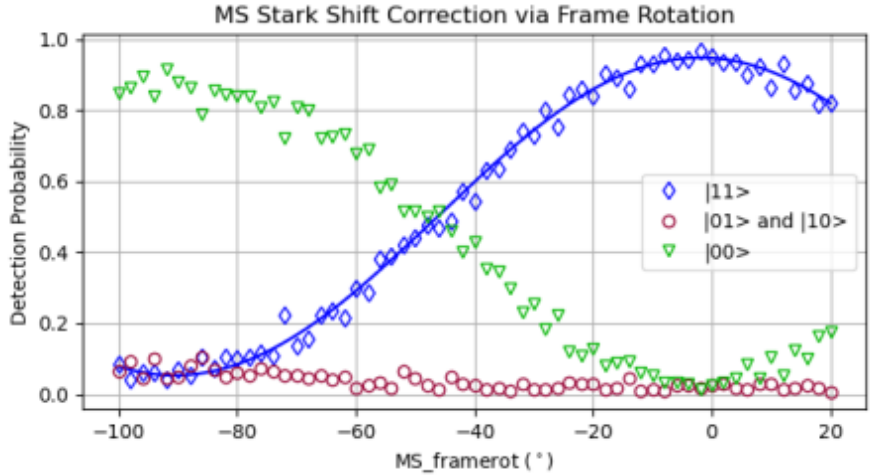


Error Function Phase Advance for Gaussian Pulses (MS Gate)



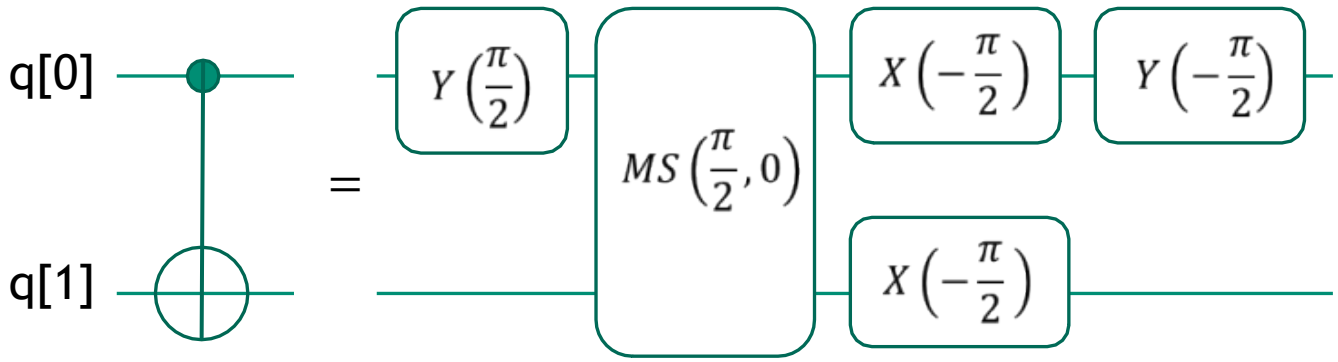
- To account for the AC Stark shift, incorporate a dynamic phase shift throughout the pulse to bring us into the Stark-shifted frame
  - Error function for Gaussian pulses
  - Linear advance for square pulses
- Calibrate MS advance with two stacked gates
- Calibrate single-qubit gates via stacking as well

Stack two MS gates to find ideal phase advance



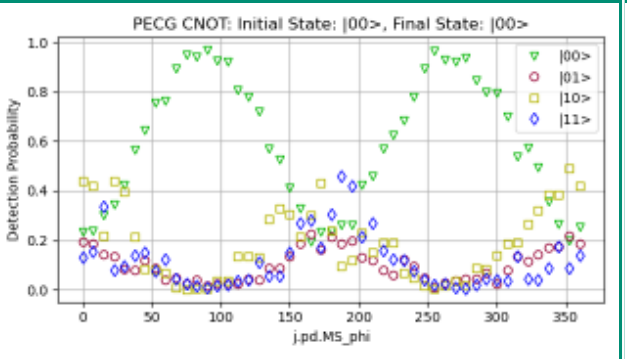
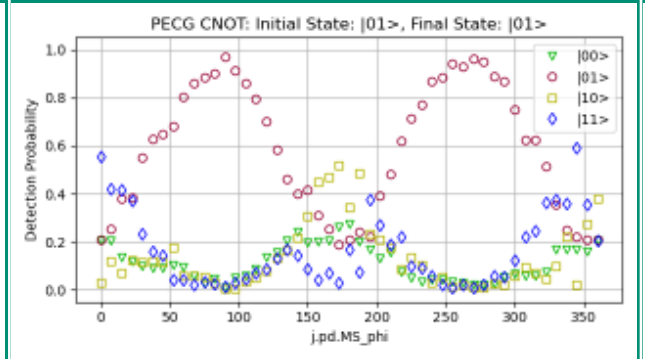
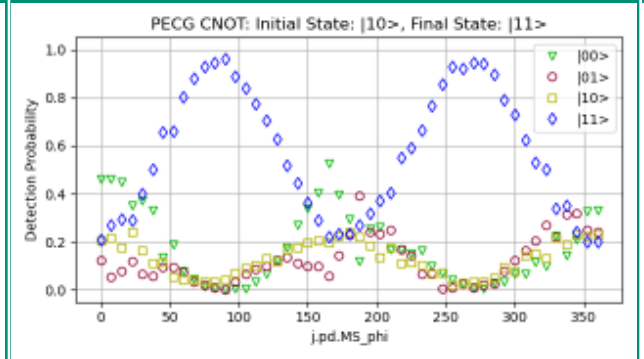
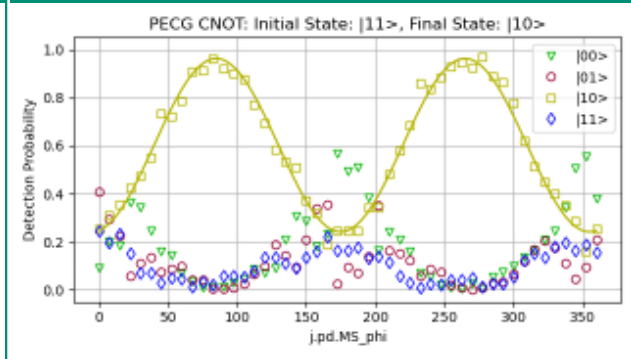

```
framerot0=tuple(self.erf(7,self.MS_framerot,freqwidth=300e3, total_duration=4e-6)),
framerot1=tuple(self.erf(7,self.MS_framerot,freqwidth=300e3, total_duration=4e-6)),
apply_at_eof_mask=0,
```

Controlled-NOT (CNOT) for phase relationship



Input	Output
|00>	|00>
|01>	|01>
|10>	|11>
|11>	|10>

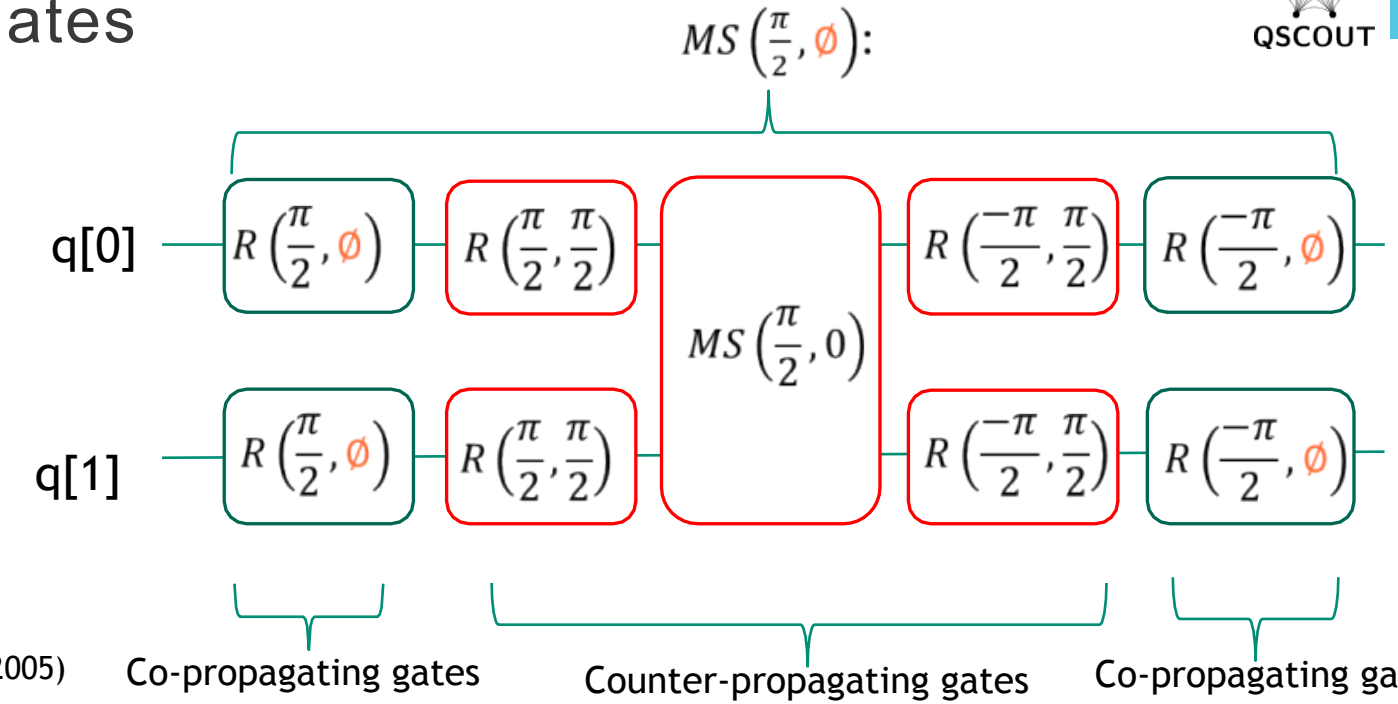
- We noticed a number of our users were calling for a CNOT gate
- As such, it became our first non-standard gate developed in the system
- It grew into a standard calibration routine to determine phase relationships between 1- and 2-qubit gates

Initial State: |00>	|01>	|10>	|11>
			
Final State: |00>	|01>	|11>	|10>

Phase-error-corrected MS gates

QSCOUT

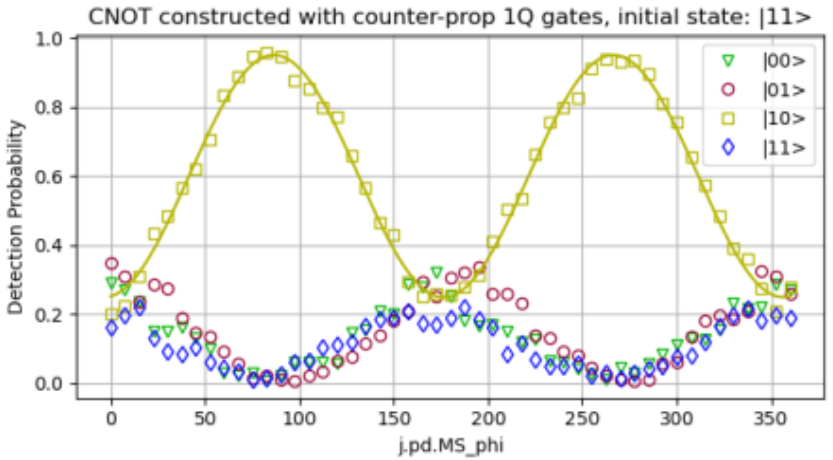
- Goal: Allow for use of co-propagating single qubit gates and MS gates without phase drifts/discrepancies
- Approach: Transform XX interaction into a ZZ interaction via counter-propagating gates†, and then back into an XX interaction via co-propagating gates
- "Sandwiching" the MS gate creates a "basis transformation"



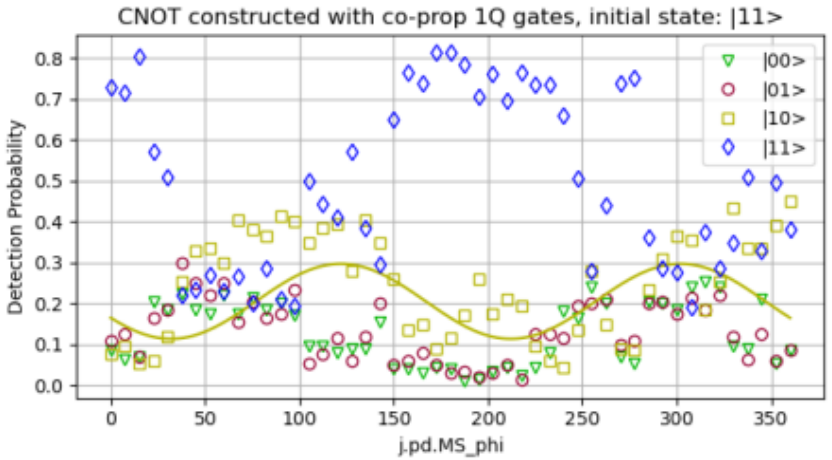
† P. J. Lee, *et al*. J. Opt. B: Quantum Semiclass. Opt. **7**, S371-S383 (2005)

CNOT Phase Scans:

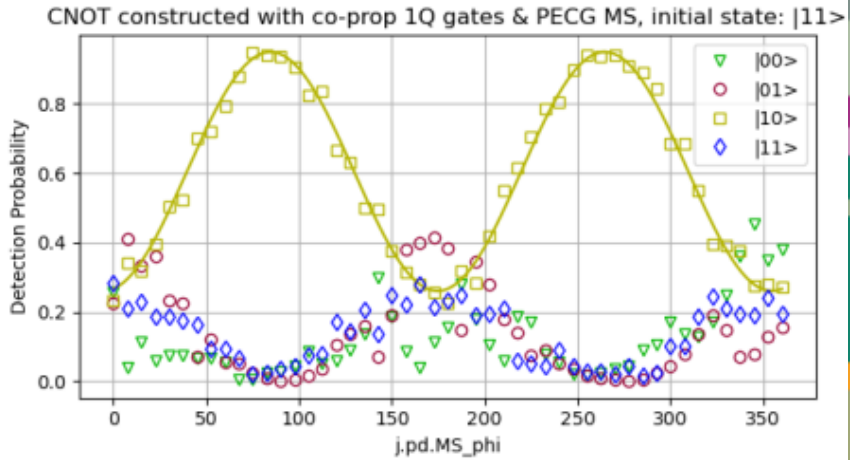
MS Gate with counter-prop 1Q gates



MS gate with co-prop 1Q gates



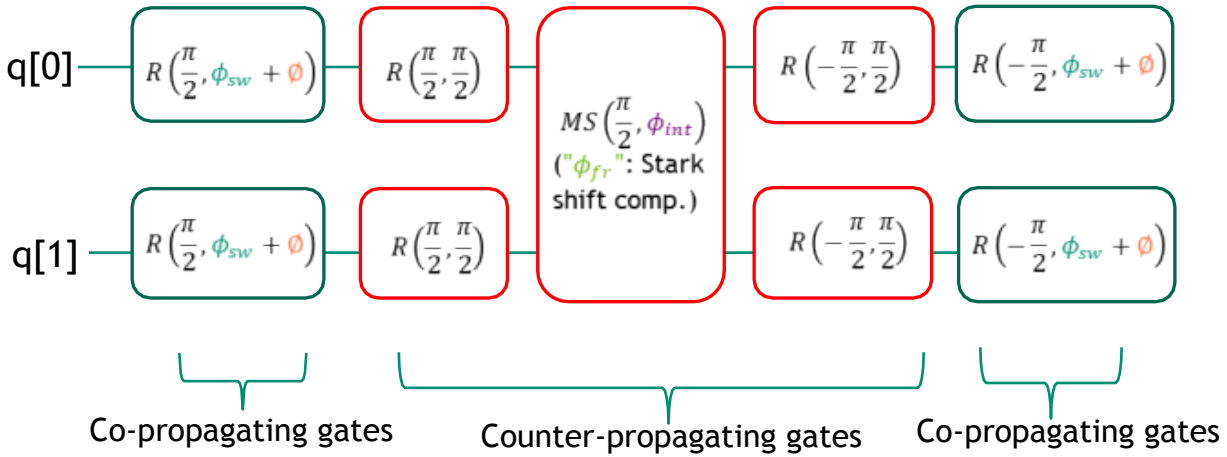
PEC MS gate with co-prop 1Q gates



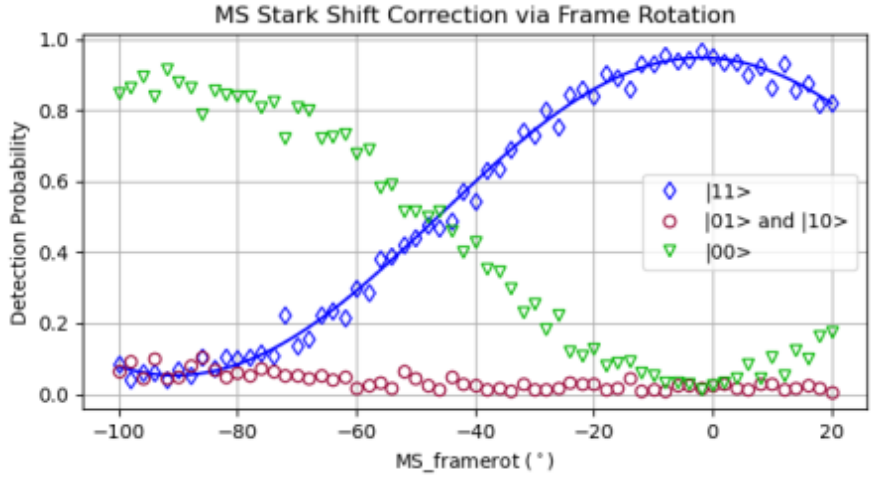
Putting it all together: phase calibration routine for 2-qubit gate

How do we calibrate our two qubit gates to play nice with the other gates?

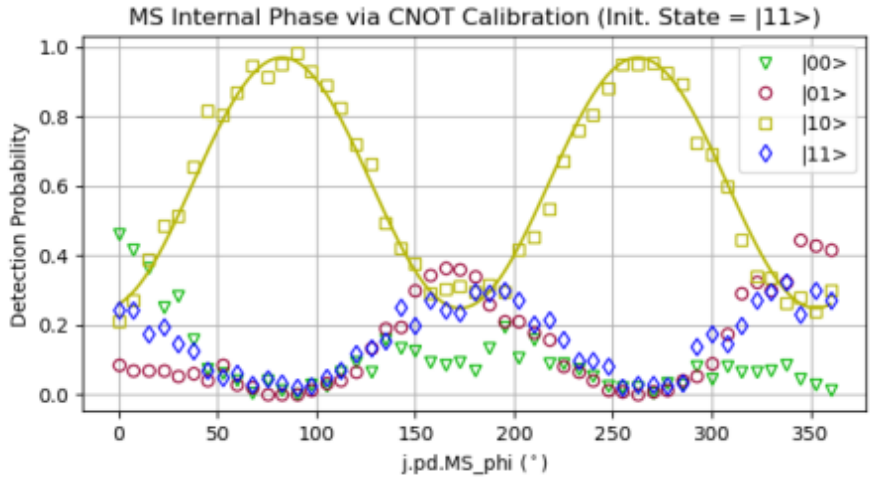
$MS\left(\frac{\pi}{2}, \emptyset\right)$:



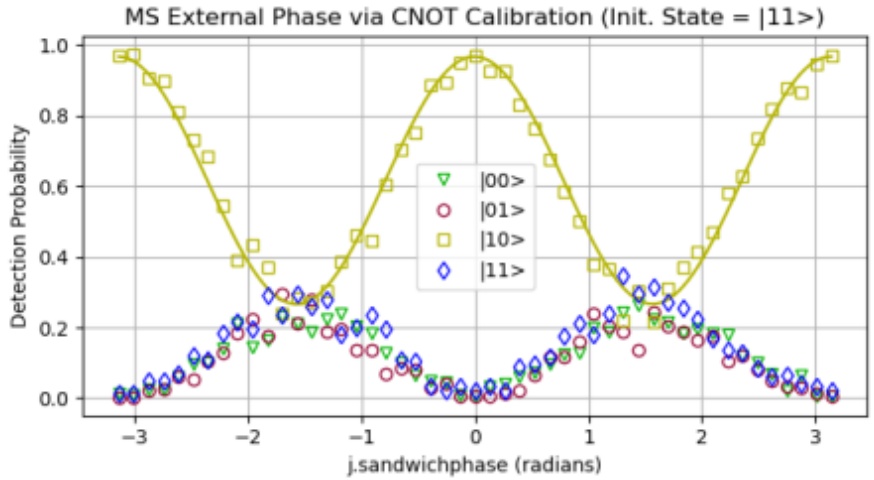
"ϕ_{fr}": Frame rotation to account for AC Stark shift



ϕ_{int}: Internal phase relation of MS Raman legs



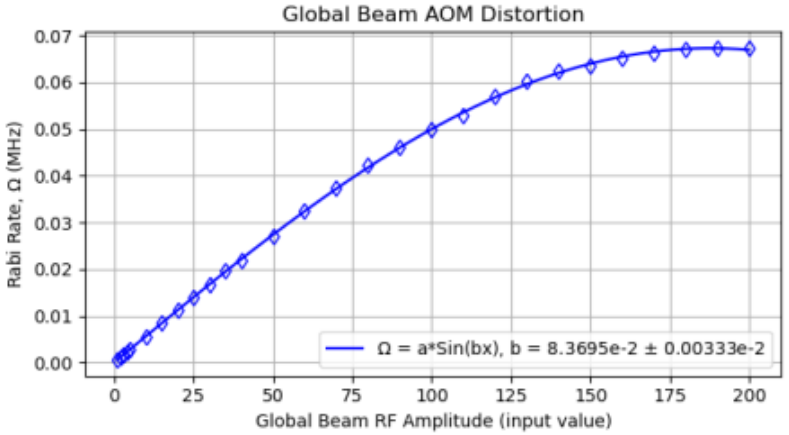
ϕ_{sw}: External phase relation to co-prop gates

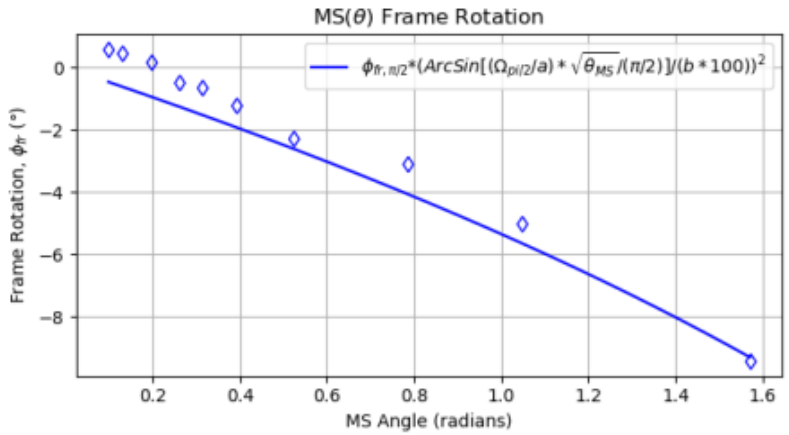


Arbitrary-angle MS gate (MS(θ))

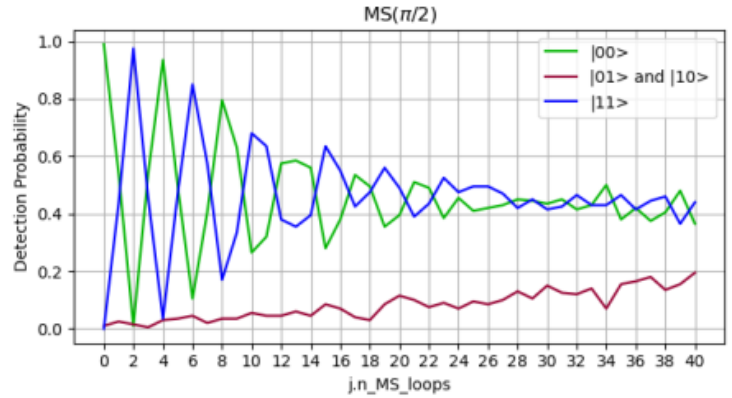
- Set MS gate angular enclosure by adjusting the global beam power
- Calibrate distortion in the global beam AOM (and similarly the frame rotation)
- Loops of a specific input angle help to determine the actual area enclosed by a single gate
- Smaller MS gate angles appear to have more “coherence” than larger angles -> amplitude fluctuations?

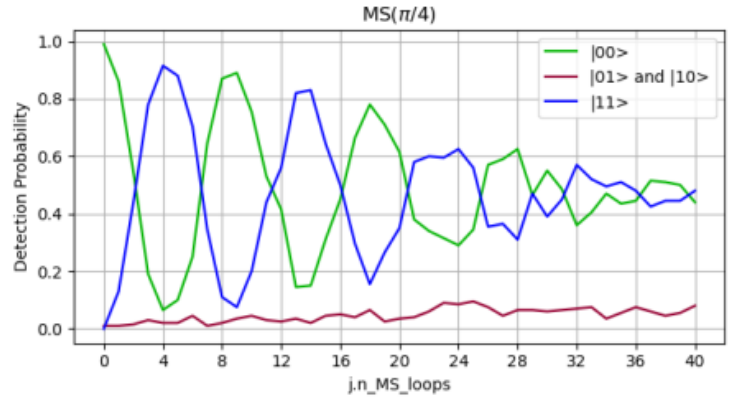
Global Beam Calibrations (Distortion and AC Stark shift)

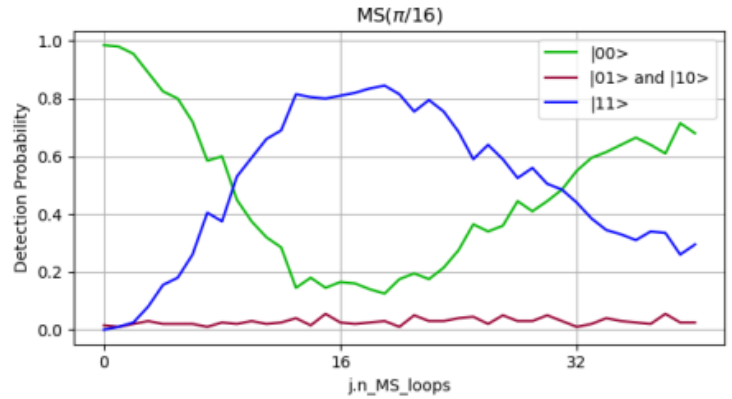




MS Loops

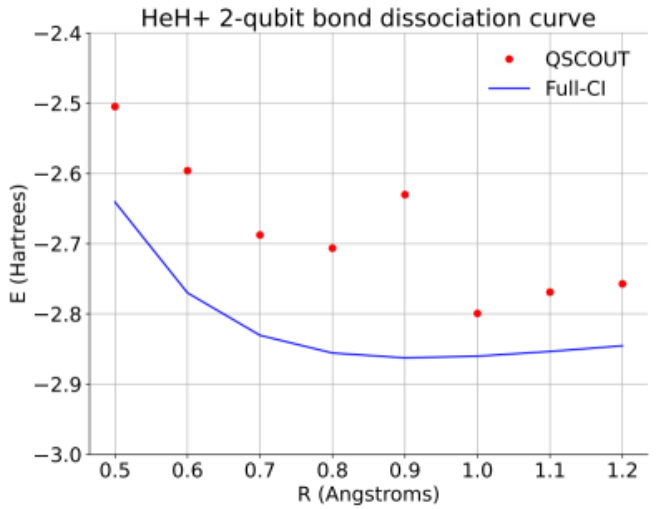




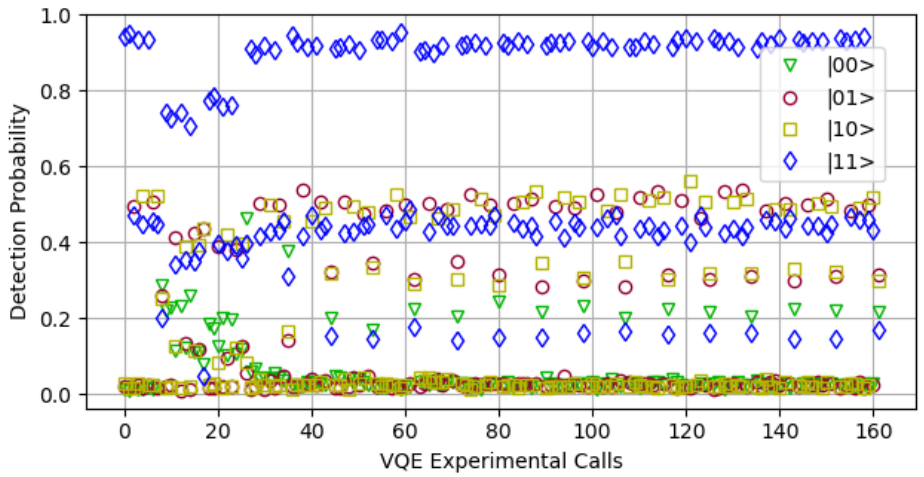


Example algorithm: HeH+ variational quantum eigensolver (V

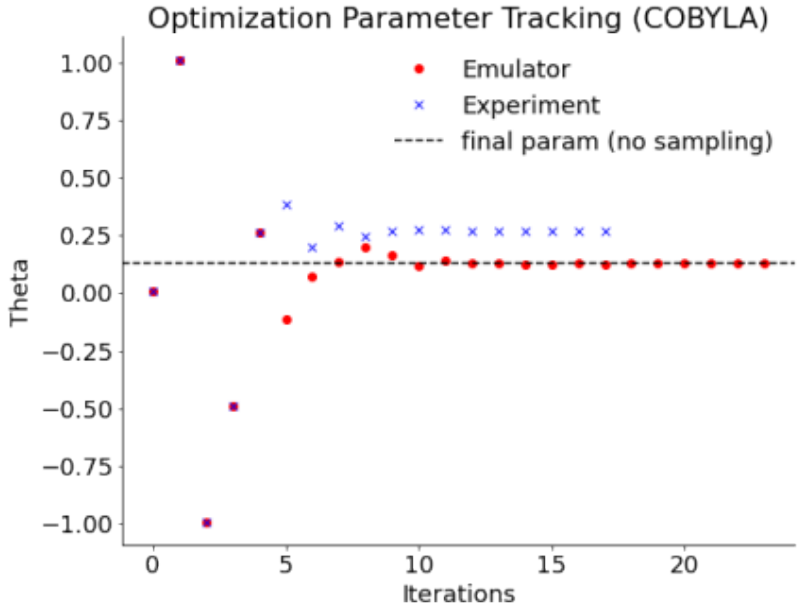
- One example algorithm run on the system is VQE for HeH+
  - Exemplar code can be found on https://qscout.sandia.gov

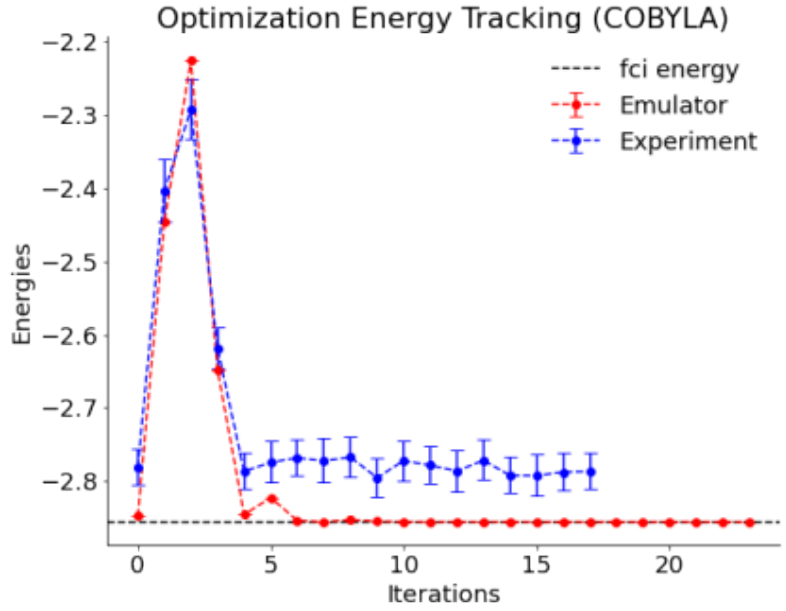



```
prepare_all
Px q[0]
Px q[1]
MS q[1] q[0] 0 pi2
Rz q[1] theta
MS q[1] q[0] 0 npi2
measure_all
```



- Initial attempt with counter-prop 1Q -gates (above) gave 5% error from expectation
- Further attempts with co-prop 1Q-gates and PEC MS gates (right) have halved that error
- Examined one bond length, r = 0.8Å and followed optimizer iterations





**In collaboration with Oliver Maupin and Peter Love, Tufts University*

QSCOUT user base

- Our users come from a variety of institutions – universities, national labs, private corporations, and start-ups

Round 1

THE UNIVERSITY OF NEW MEXICO

INDIANA UNIVERSITY BLOOMINGTON

OAK RIDGE National Laboratory

Berkeley UNIVERSITY OF CALIFORNIA

Round 2

JOHNS HOPKINS APPLIED PHYSICS LABORATORY

IBM

SUPER.TECH

LCN LONDON CENTRE FOR NANOTECHNOLOGY

Lawrence Livermore National Laboratory
SCIENCE & TECHNOLOGY ON A MISSION

INDIANA UNIVERSITY BLOOMINGTON

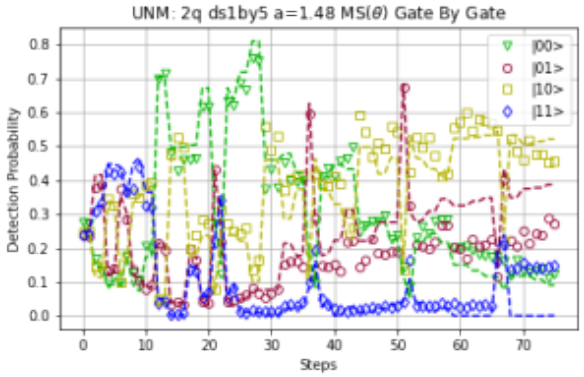
Round 1 users

- First round of user code began Spring 2021 (even before our two-qubit gates were up and running)
- Combination of benchmarking, simulation, and gate optimizations
- System development directly tied to user input

THE UNIVERSITY OF NEW MEXICO

Tameem Albash
Elizabeth Crosson
Milad Marvian
Namitha Pradeep

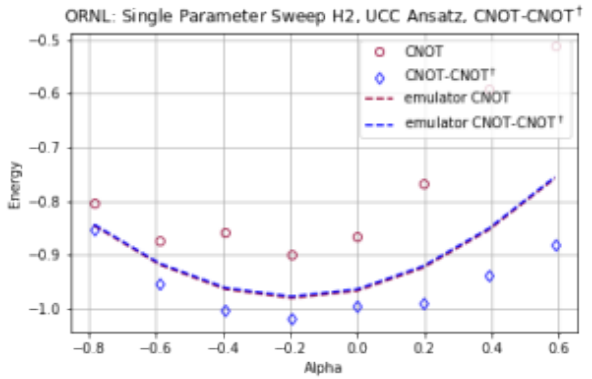
Digital simulation of non-stoquastic Hamiltonians



OAK RIDGE National Laboratory

Raphael Poozer
& the MIQASA team

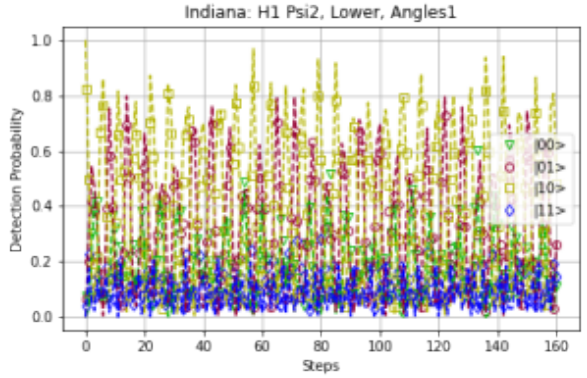
Connecting low level characterization metrics to higher level algorithmic performance with a tractably small simulation



INDIANA UNIVERSITY BLOOMINGTON

Philip Richerme
Debadrita Saha
Amr Sabry
Sam Norrell
Srinivasan Iyengar

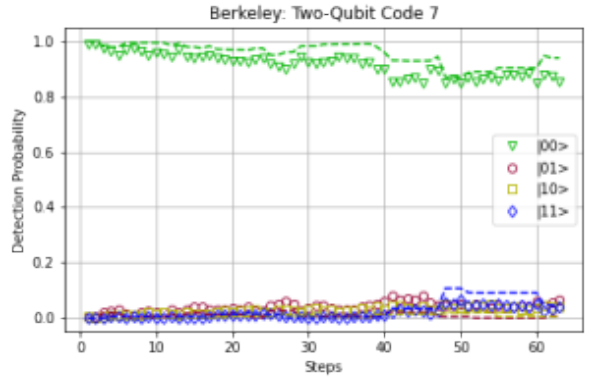
Simulating the quantum dynamics of proton-coupled electron transport problems in quantum chemistry



Berkeley UNIVERSITY OF CALIFORNIA

Ryan Shaffer
Hang Ren
Hartmut Haffner

Assessing the Performance of the Randomized Analog Verification protocol for gate-based devices



Round 2 users

- Second round of user code slated to begin shortly along with first round users
- Combination of benchmarking, simulation, gate optimizations, & **pulse-level control**
- Once again system development will follow along with our users

Characterization and optimal control of time-correlated amplitude control noise

Native gate optimizations and performance benchmarking

Simulating quantum evolution of infinite systems using tensor networks

Using control pulse engineering to improve the effective fidelity of ion trap quantum computers

Quantum volume benchmarking

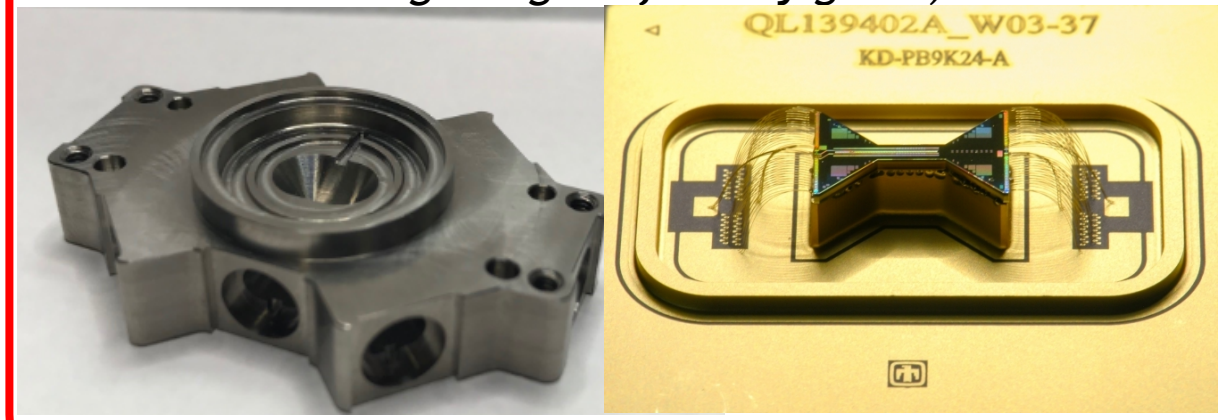
Simulating quantum chemical nuclear dynamics problems

Future upgrades: more ions, partial measurements

QSCOUT

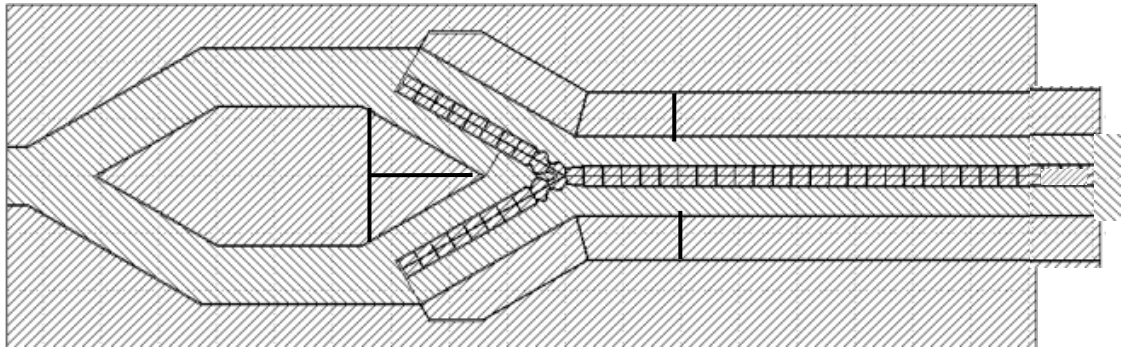
QSCOUT 1.0 (current)	QSCOUT 1.1 (10 ion goal) 9/2021	QSCOUT 2.0 (cryo) 7/2022	QSCOUT 1.2 (Partial meas.) 11/2022	Beyond QSCOUT >9/2023
2-3 ions	3-11 ions	>10 ions	>10 ions Partial measurements	32 ion machine

Cryo, *under development*
(better ion lifetime,
less ion heating = higher fidelity gates)



Cold Quanta

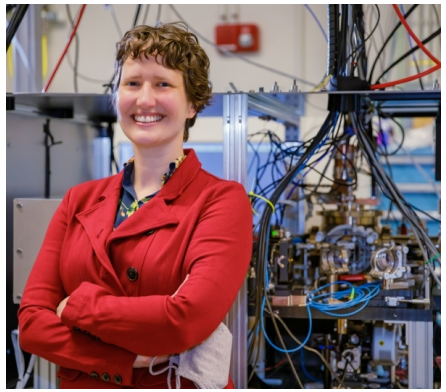
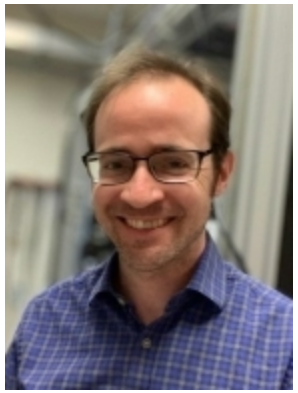
New trap design for re-ordering ions,
enables mid-circuit measurements



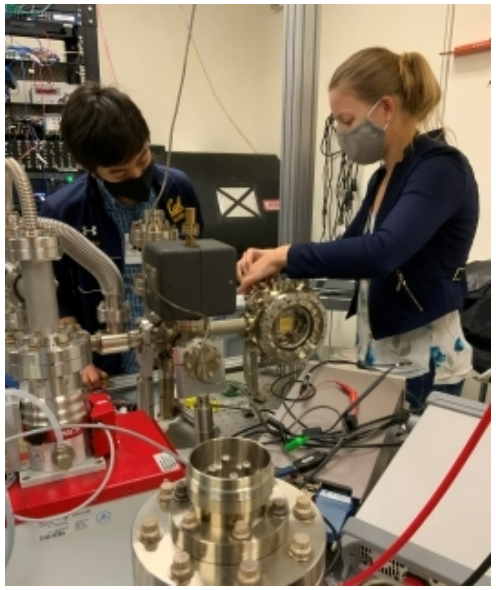
QSCOUT Team

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

QSCOUT Experimental Team



Experimental Team
Susan Clark, PI
Christopher Yale
Dan Lobser
Melissa Revelle
Matt Chow
Ashlyn Burch
Craig Hogle
Megan Ivory
Peter Maunz
Dan Stick
Andrew Van Horn
Josh Wilson

Mechanical & Optical Engineering
Brad Salzbrenner
Madelyn Kosednar
Jessica Pehr
Ted Winrow
Bill Sweatt
Dave Bossert

Theory & Software Team
Andrew Landahl
Ben Morrison
Tim Proctor
Kenny Rudinger
Antonio Russo
Brandon Ruzic
Jay Van Der Wall
Josh Goldberg
Kevin Young
Collin Epstein

Trap Fabrication and Packaging
Matt Blain
Ed Heller
Jason Dominguez
Chris Nordquist
Ray Haltli
Tipp Jennings
Ben Thurston
Corrie Sadler
Becky Loviza
John Rembetski
Eric Ou
Matt Delaney

Collaborators
Ken Brown, Duke
Peter Love, Tufts
Oliver Maupin, Tufts