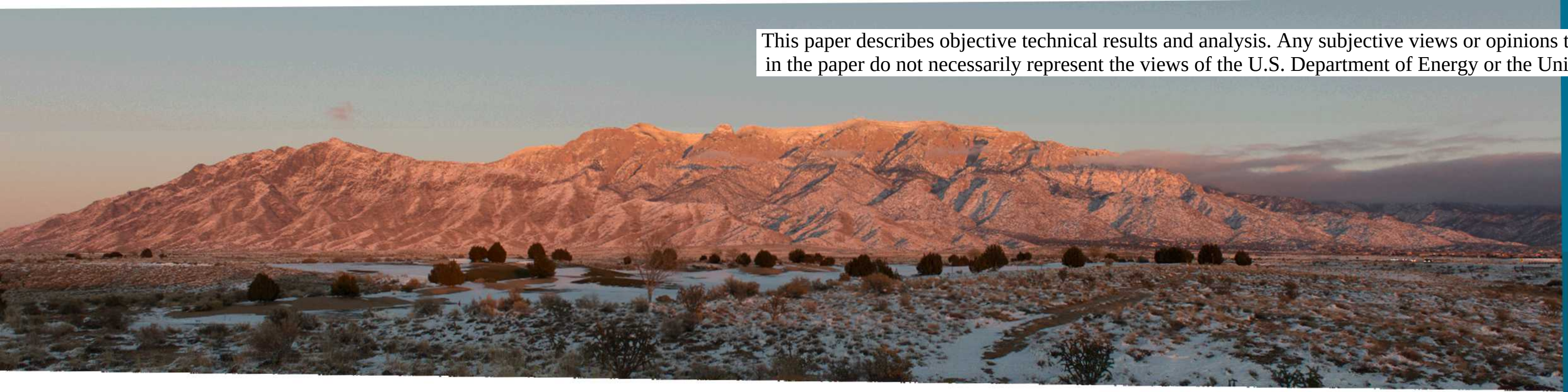
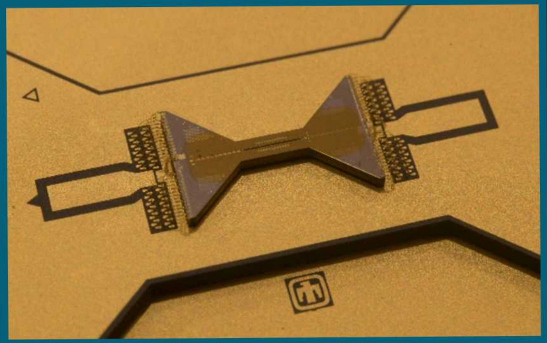
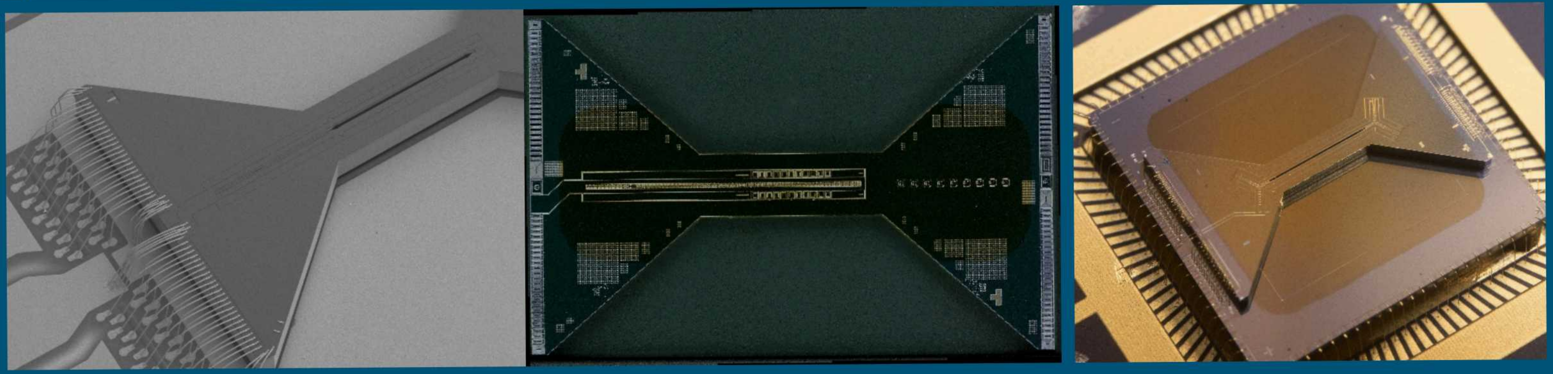
SAND2020-10849C



Classical and Quantum Control of a Trapped Ion Quantum Computing Testbed System

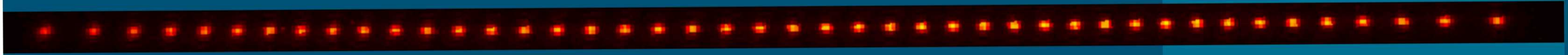




PRESENTED BY

Daniel Lobser

Sandia National Laboratories



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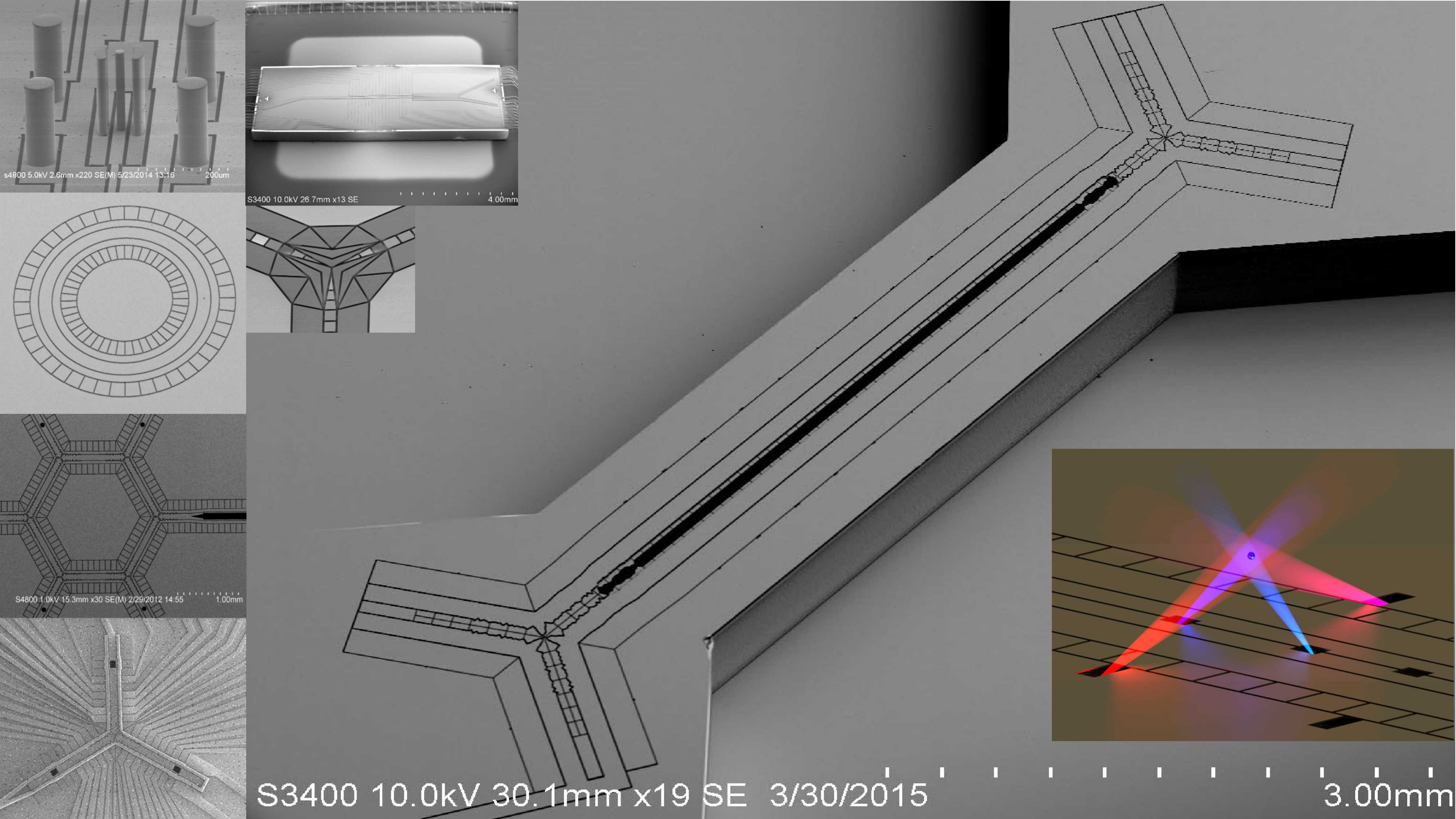
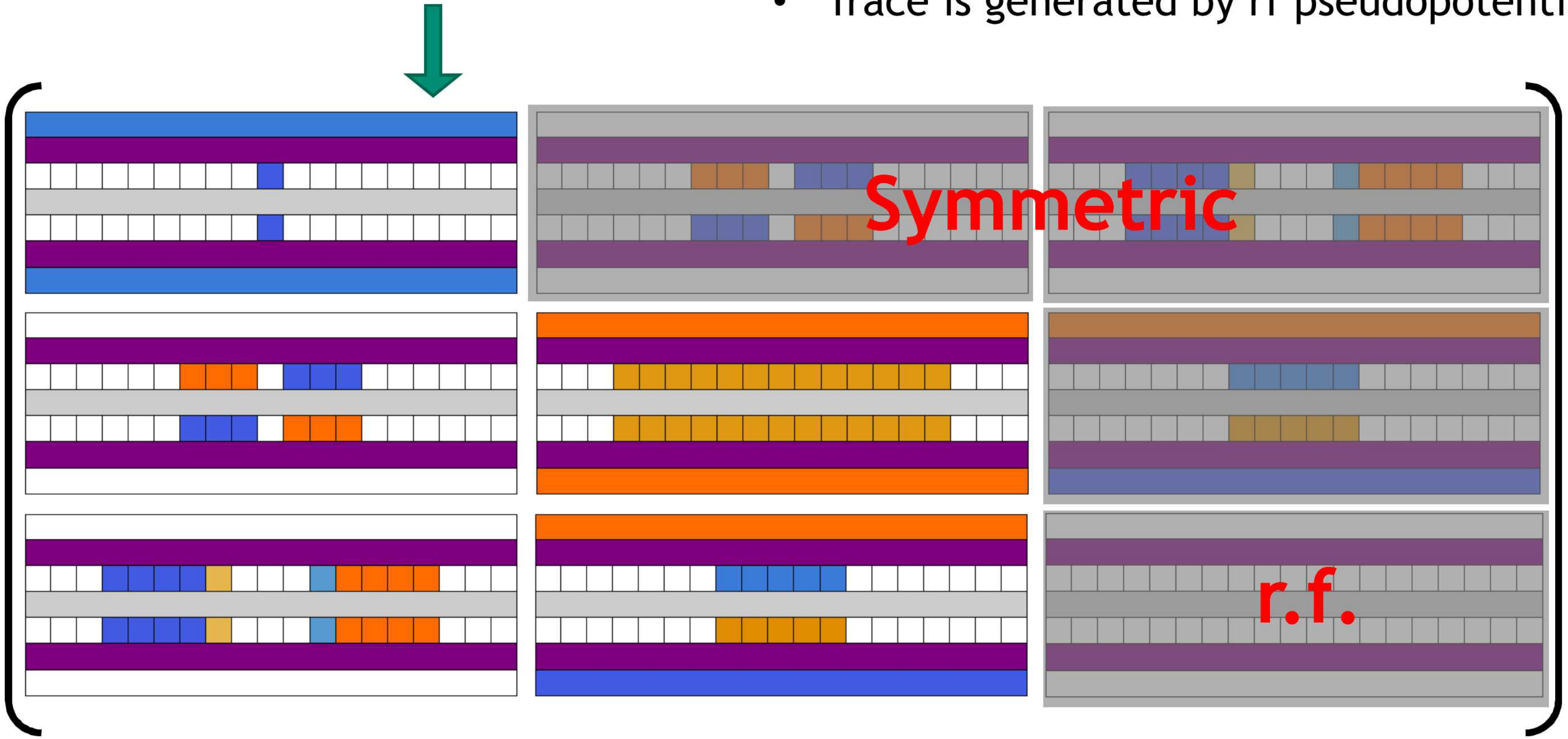

s4800 5.0kV 2.6mm x220 SE(M) 5/23/2014 13:16
200um
S3400 10.0kV 26.7mm x13 SE
4.00mm
S4800 1.0kV 15.3mm x30 SE(M) 2/29/2012 14:55
1.00mm
S3400 10.0kV 30.1mm x19 SE 3/30/2015
3.00mm

Control of Confining Potential

$$\mathcal{H} = \begin{pmatrix} \frac{\partial\phi}{\partial x\partial x} & \frac{\partial\phi}{\partial x\partial y} & \frac{\partial\phi}{\partial x\partial z} \\ \frac{\partial\phi}{\partial y\partial x} & \frac{\partial\phi}{\partial y\partial y} & \frac{\partial\phi}{\partial y\partial z} \\ \frac{\partial\phi}{\partial z\partial x} & \frac{\partial\phi}{\partial z\partial y} & \frac{\partial\phi}{\partial z\partial z} \end{pmatrix}$$

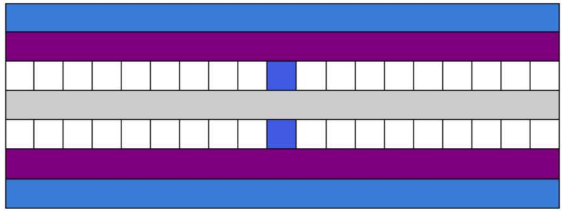
- Symmetric curvature tensor
- 6 degrees of freedom
- Determines trap frequencies and principal axes rotations
- Traceless for static fields
- Trace is generated by rf pseudopotential



Parametric Rotation Amplitudes

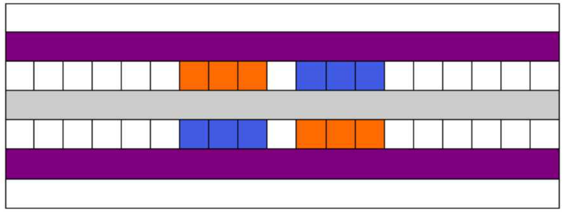
e_x, e_y, e_z: Eigenvalues

$\partial_{xx}\phi$



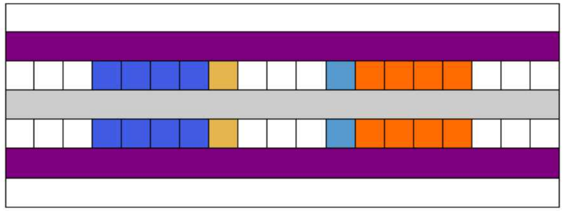
$$e_y \sin^2(\alpha) + e_x \cos^2(\alpha)$$

$\partial_{xy}\phi$



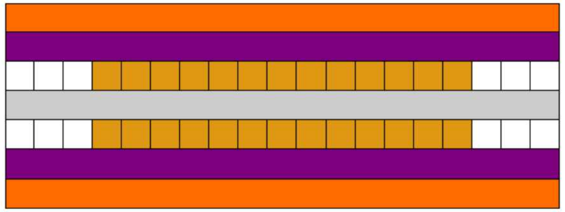
$$(e_y - e_x) \sin(\alpha) \cos(\alpha) \cos(\beta)$$

$\partial_{xz}\phi$



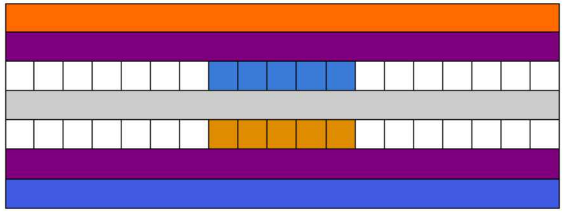
$$(e_x - e_y) \sin(\alpha) \cos(\alpha) \sin(\beta)$$

$\partial_{yy}\phi$



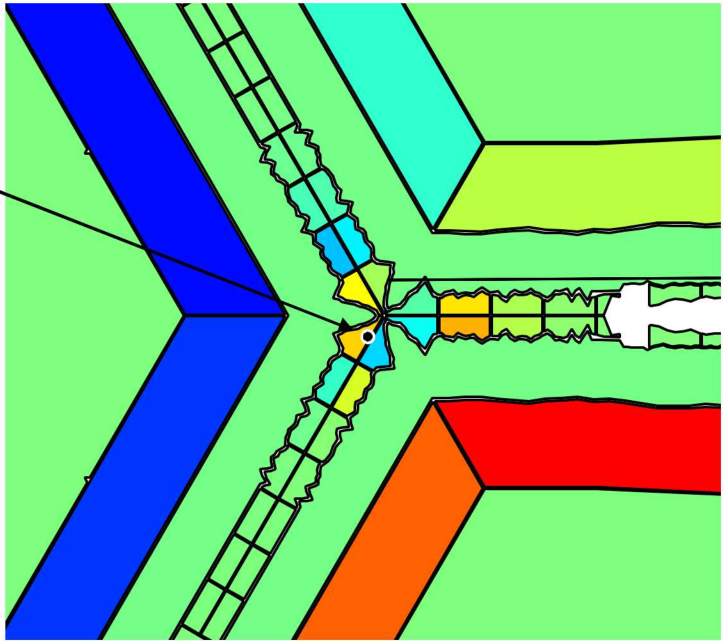
$$\left(\cos^2(\beta) - \sin^2(\beta)\right) \left(e_x \sin^2(\alpha) + e_y \cos^2(\alpha)\right) + e_z \sin^2(\beta) - e_z \cos^2(\beta)$$

$\partial_{yz}\phi$

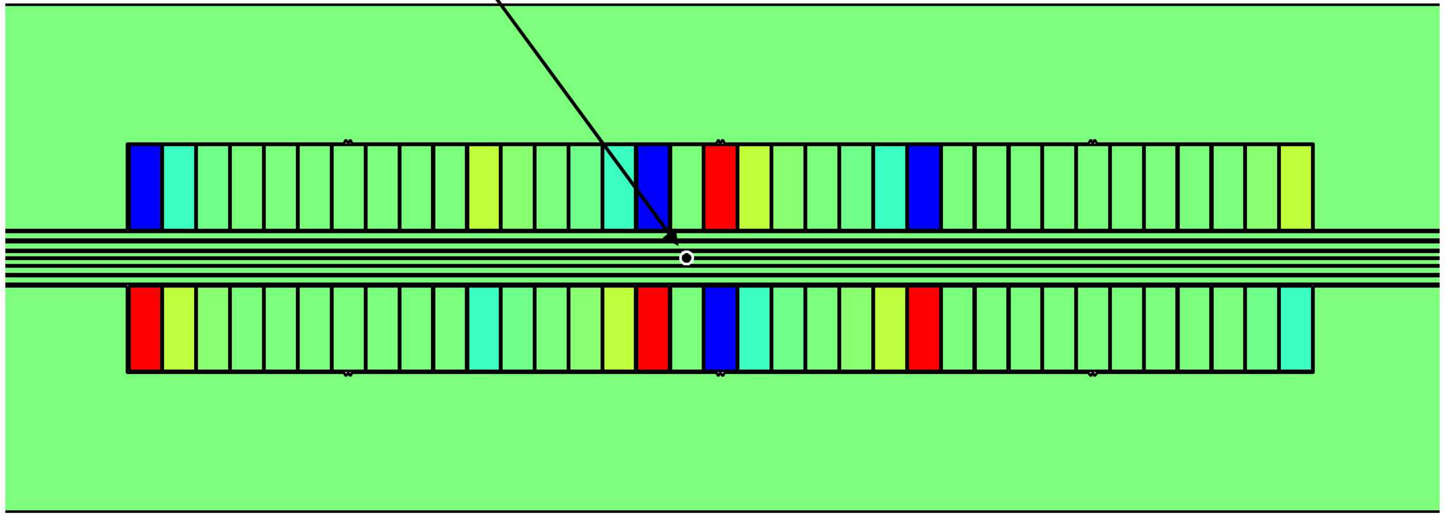


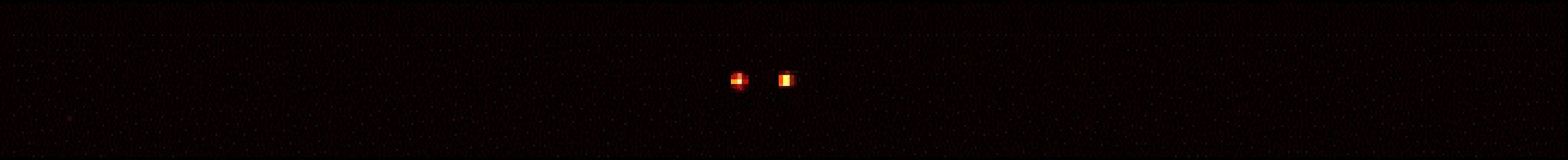
$$\sin(\beta) \cos(\beta) \left(-e_x \sin^2(\alpha) - e_y \cos^2(\alpha) + e_z\right)$$

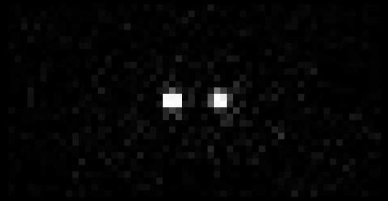
Application To Complicated Electrode Geometries

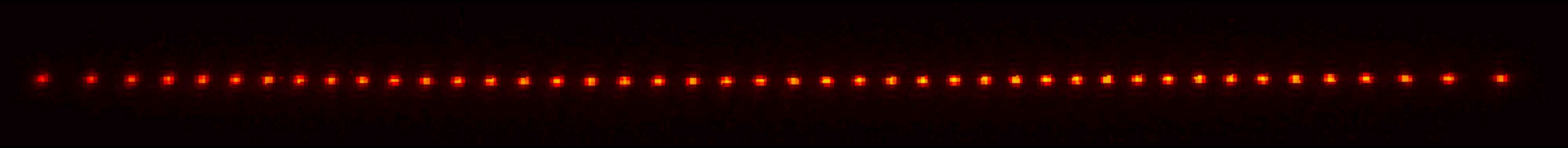


- YZ basis (rotation of the radial axes) near the junction on the HOA 2.1
- XY basis (rotation in the plane of the trap) on the microwave trap with tied electrodes









Gate Implementation at the Pulse Level

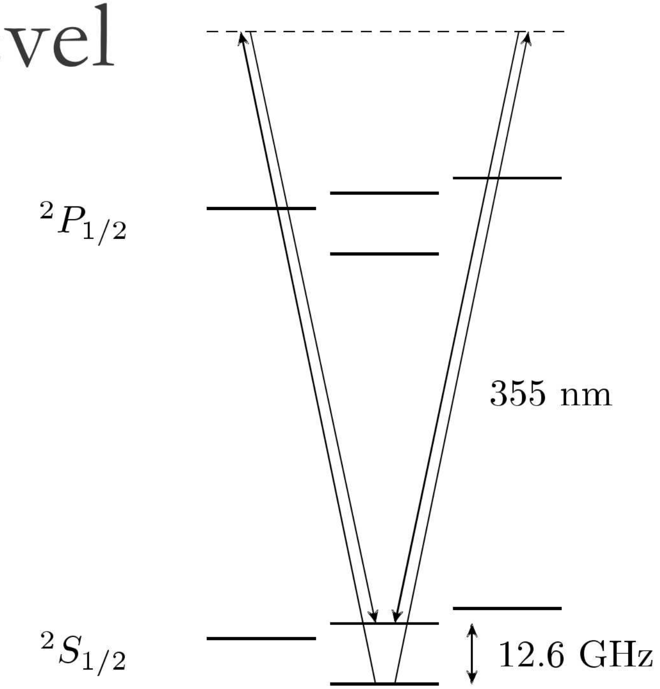
^{171}Yb^{+} qubit, clock state 12.6 GHz

Individual addressing requires lasers

Optical frequency comb to bridges 12.6 GHz via Raman transitions

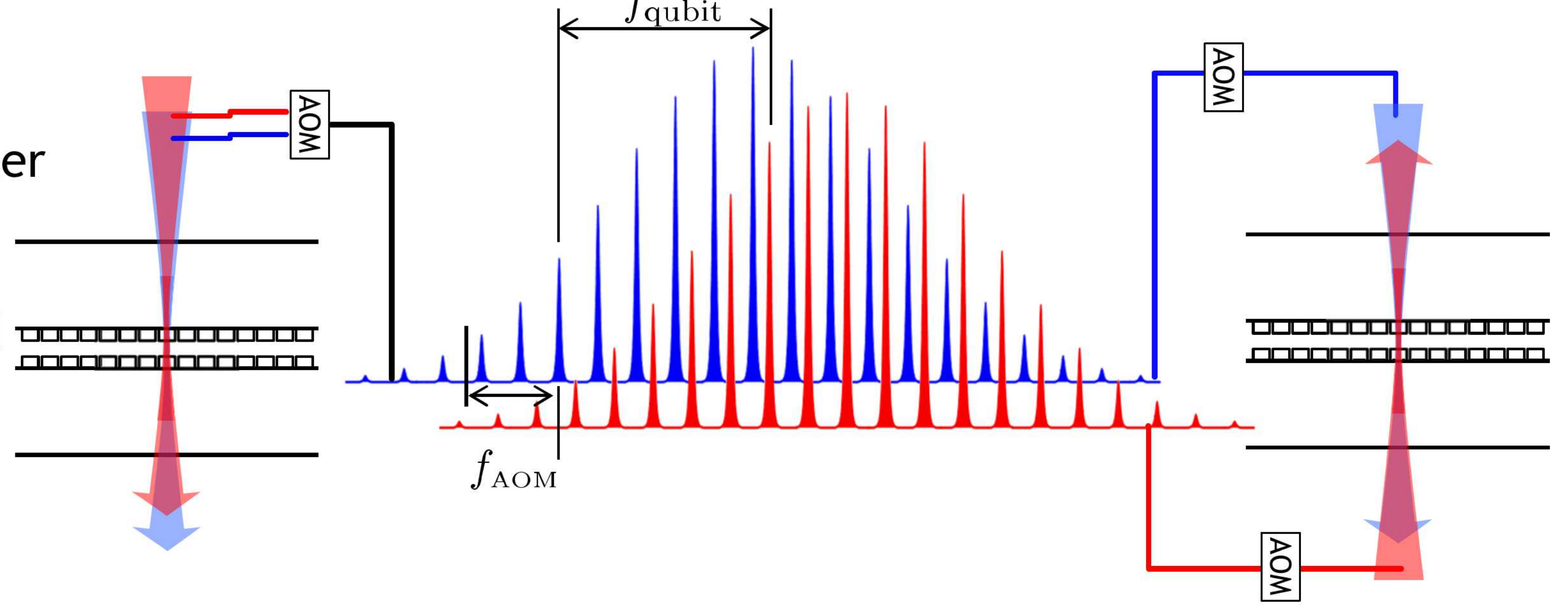
Frequency, phase, and amplitude control using RF signals applied to acousto-optic modulators (AOMs)

Two configurations: Co- and Counter-propagating



Co-propagating

- Immune to Doppler shifts
- Not affected by timing errors and pulse overlap



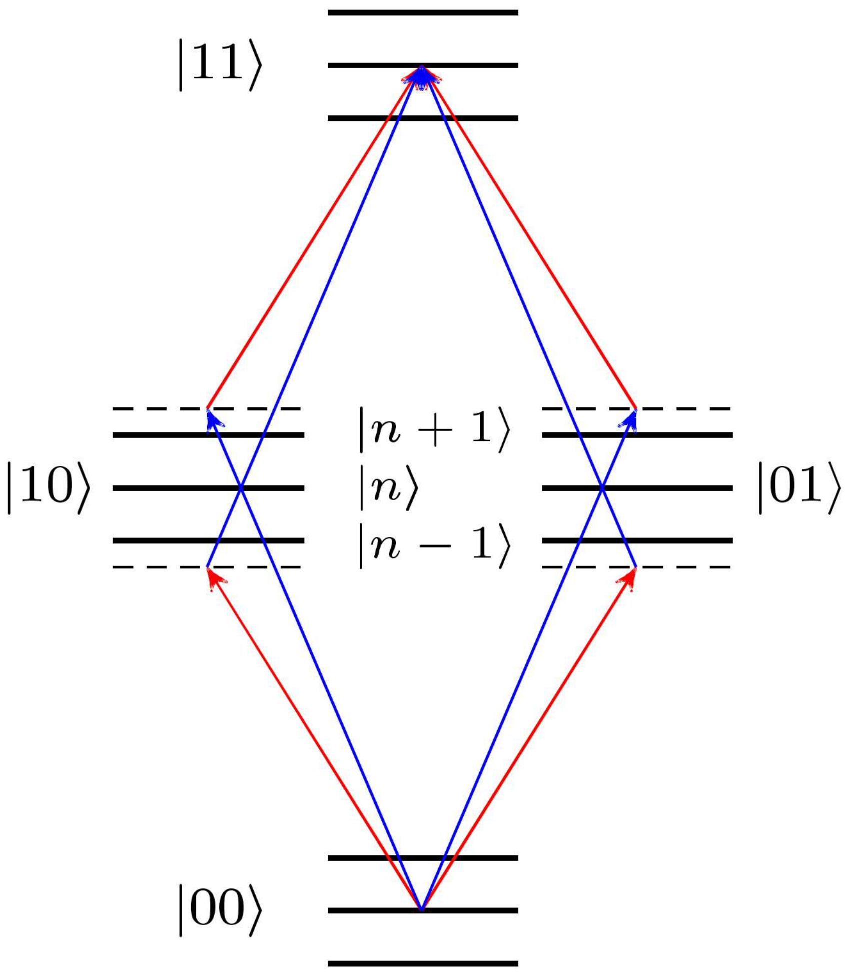
Counter-propagating

- Supports motional-state addressing and ground state cooling
- Affected by Doppler shifts
- Necessary for two-qubit gates

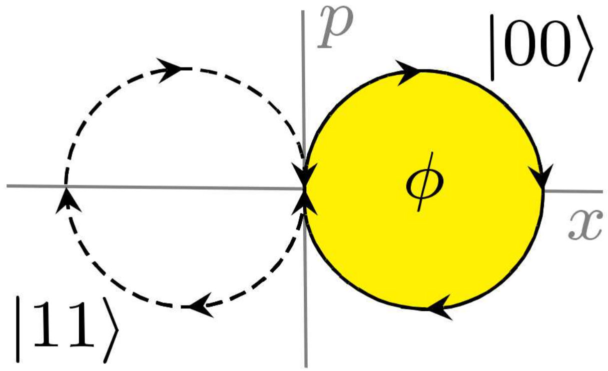
Two-Qubit Gate

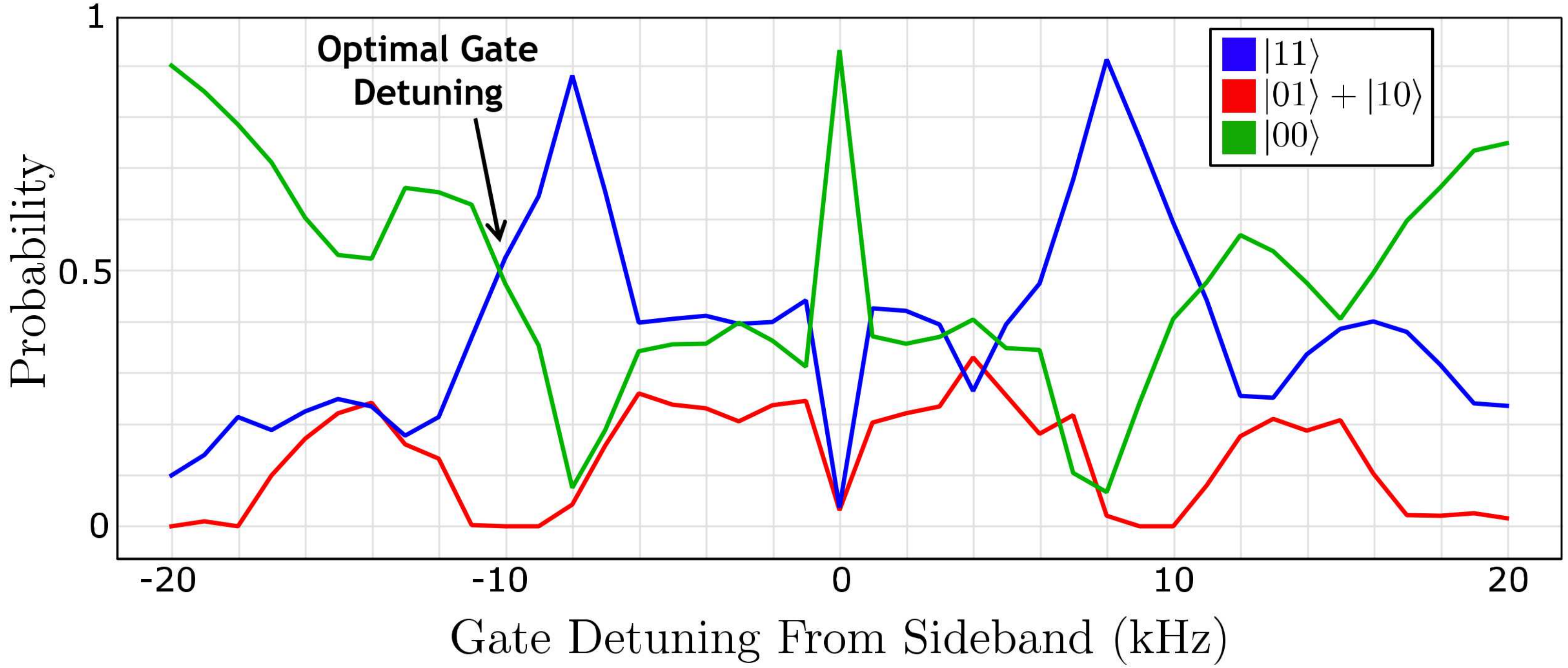
- Mølmer-Sørensen phonon-mediated bichromatic entangling gate

$$|00\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|00\rangle + e^{i\phi}|11\rangle\right)$$



- Residual motion → infidelity
- Must close loops in phase space

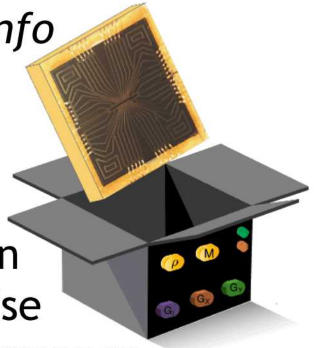




Gate Characterization

Gate Set Tomography (GST)

Check out the python GST package at pygsti.info



- Developed at Sandia
- No calibration required
- Detailed debug information
- Detects non-Markovian noise
- Efficiently measures performance characterizing fault-tolerance (diamond norm)
- Uses structured sequences to amplify all possible errors

Microwave Gates

- Process infidelity ≈ diamond norm -> no systematics!

Below the threshold for fault-tolerant error correction!
See P. Aliferis and A. W. Cross, Phys. Rev. Lett. 98, 220502 (2007)

Gate	Process Infidelity	1/2 ◊-Norm
G_I	$6.9(6) \times 10^{-5}$	$7.9(7) \times 10^{-5}$
G_X	$6.1(7) \times 10^{-5}$	$7.0(15) \times 10^{-5}$
G_Y	$7.2(7) \times 10^{-5}$	$8.1(15) \times 10^{-5}$

Raman Gates

co-propagating

Gate	Process Infidelity	1/2 ◊-Norm
G_I	$1.17(7) \times 10^{-4}$	$5.3(2) \times 10^{-4}$
G_X	$5.0(7) \times 10^{-5}$	$3(6) \times 10^{-4}$
G_Y	$6.9(6) \times 10^{-5}$	$4(9) \times 10^{-4}$

counter-propagating

Gate	Process Infidelity	1/2 ◊-Norm
G_I	$11.1(6) \times 10^{-4}$	$22.8(1) \times 10^{-4}$
G_X	$4.0(4) \times 10^{-4}$	$13.2(6) \times 10^{-4}$
G_Y	$4.1(4) \times 10^{-4}$	$8.4(8) \times 10^{-4}$

Two-Qubit GST

limited to the symmetric subspace

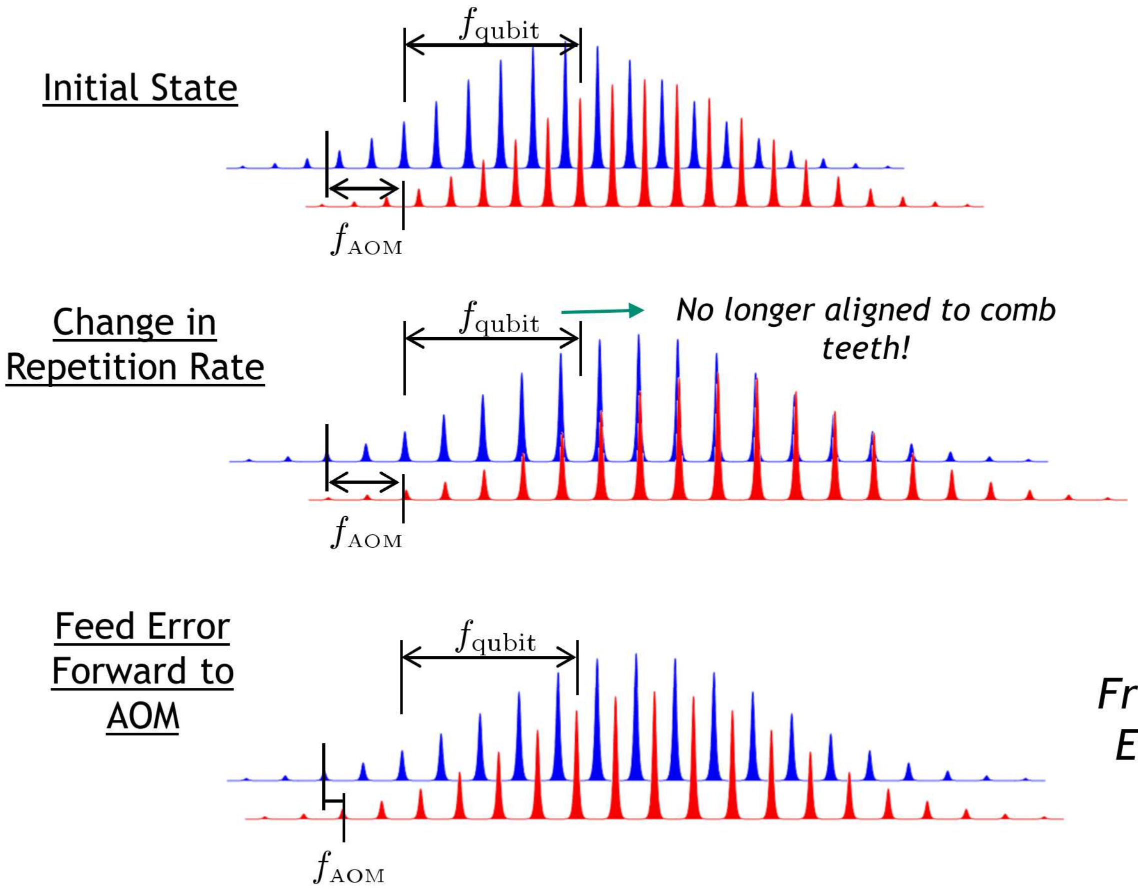
Gate	Process infidelity	$\frac{1}{2}$ Diamond norm
G_I	$1.6 \times 10^{-3} \pm 1.6 \times 10^{-3}$	$28 \times 10^{-3} \pm 7 \times 10^{-3}$
G_{XX}	$0.4 \times 10^{-3} \pm 1.0 \times 10^{-3}$	$27 \times 10^{-3} \pm 5 \times 10^{-3}$
G_{YY}	$0.1 \times 10^{-3} \pm 0.9 \times 10^{-3}$	$26 \times 10^{-3} \pm 4 \times 10^{-3}$
G_{MS}	$4.2 \times 10^{-3} \pm 0.6 \times 10^{-3}$	$38 \times 10^{-3} \pm 5 \times 10^{-3}$

95% confidence intervals

Challenges: Shimming Out Errors

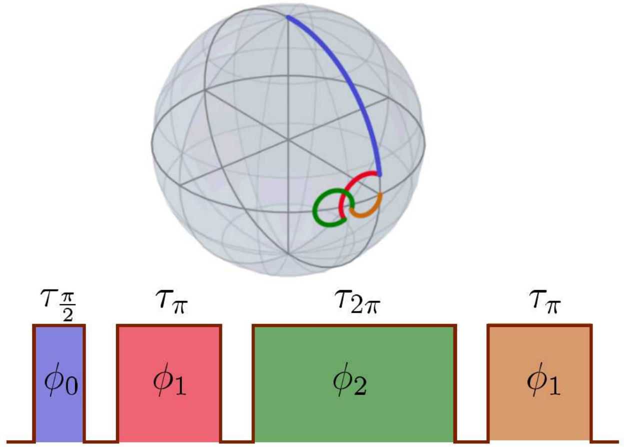
Comb Instability → Beat Note Lock

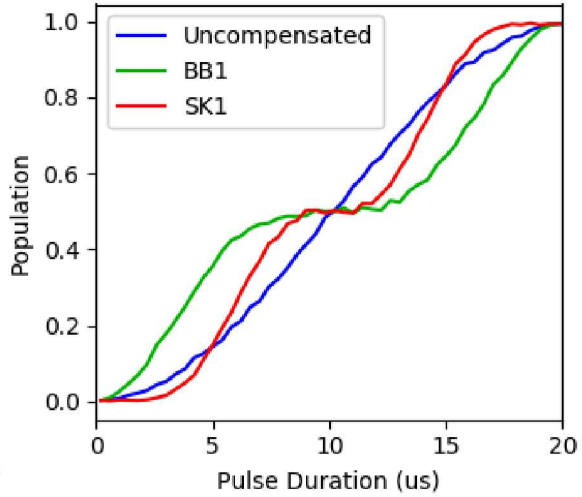
- Industrial pulsed laser, low price for high power
- Cavity-length drifts cause the frequency comb to "breathe"
- Track repetition rate and feed error signal forward to AOM



Fast Drift → Compensated Pulses

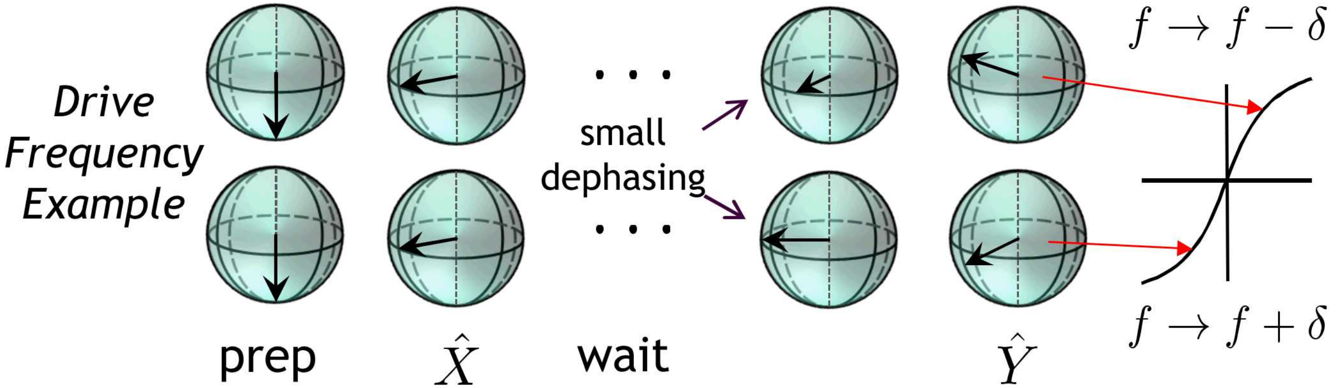
- BB1-type dynamical-decoupling pulses used
- Corrects pulse-length errors





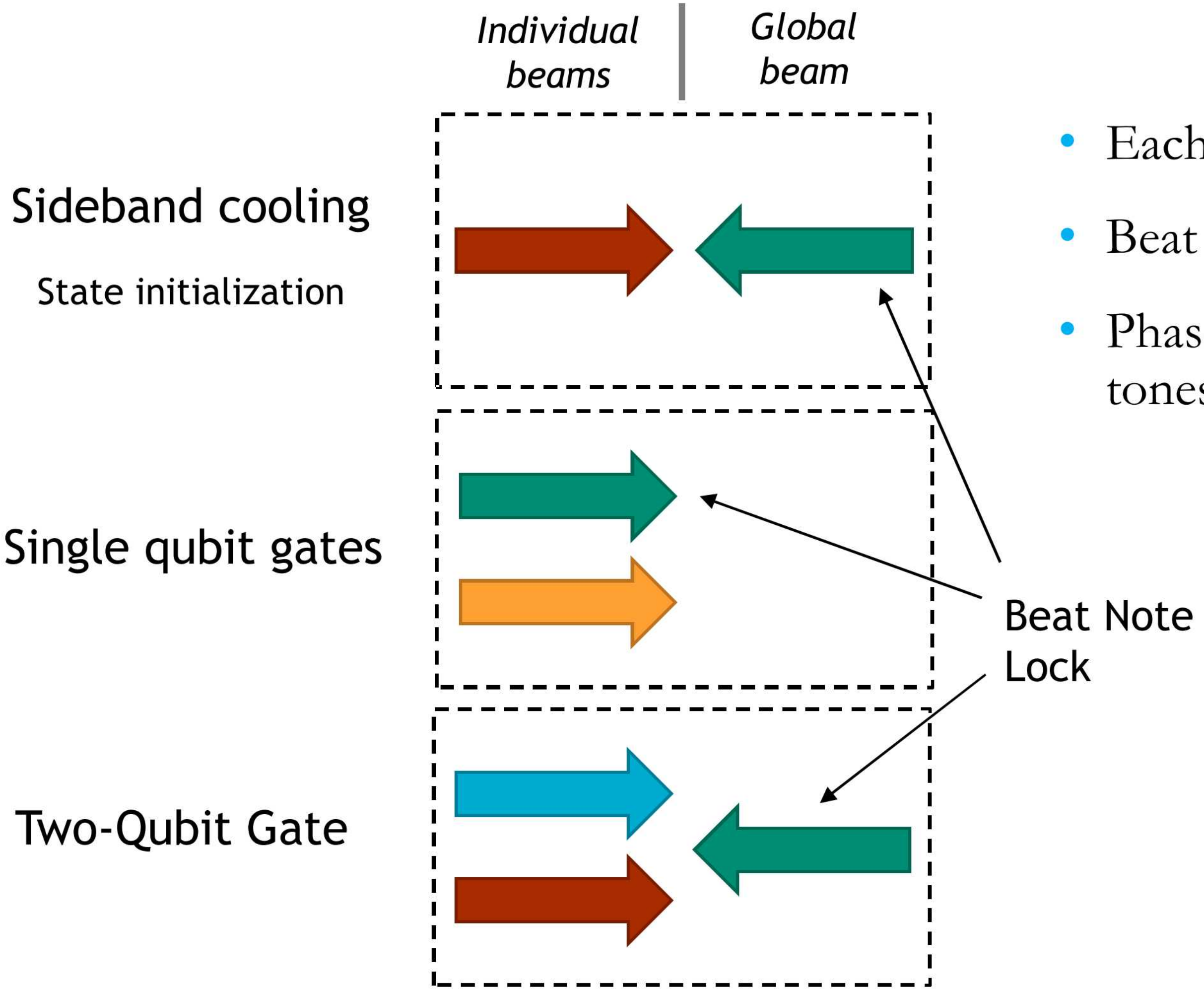
Slow Drift → "Drift Control"

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



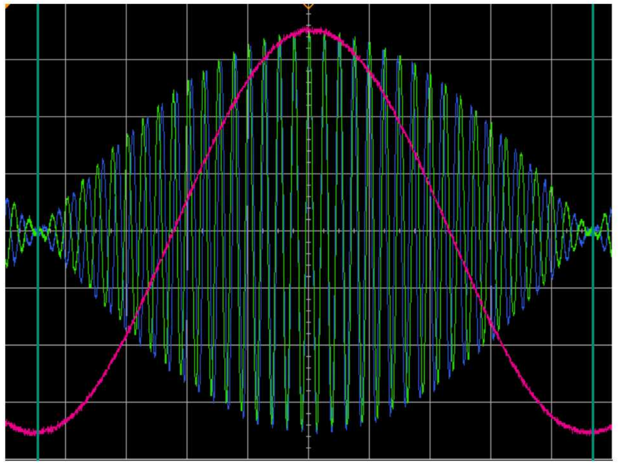
Challenges: RF Reproducibility and Agility

Three basic configurations



Absolute phase control is imperative!

- Each configuration requires different frequencies
- Beat note lock needs to be applied to different tones
- Phase of beat note produced by red and blue sideband tones determines global phase of Mølmer-Sørensen gate

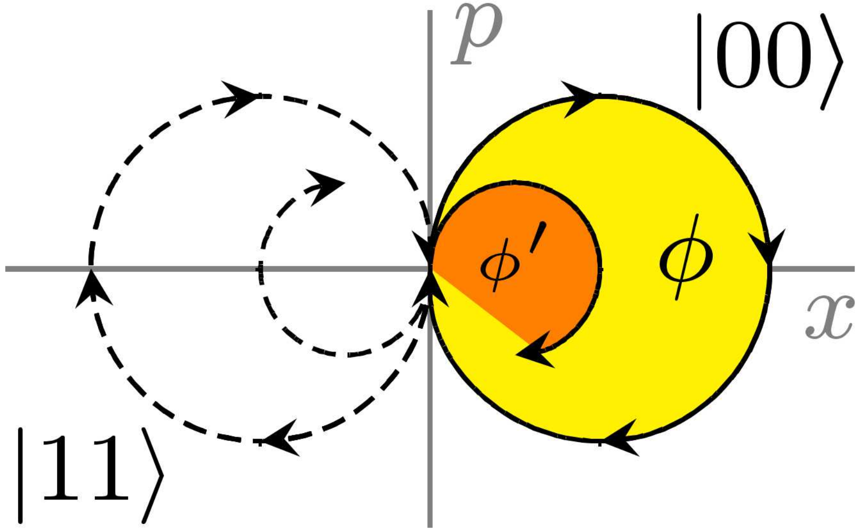


Requirements: 2 Tones per channel, Fast beat note lock reconfigurability, Absolute phase control

Challenges: RF Reproducibility and Agility

Two-qubit Gates

- Residual population in motional states leads to infidelity
- Small off resonant coupling from other modes factor in



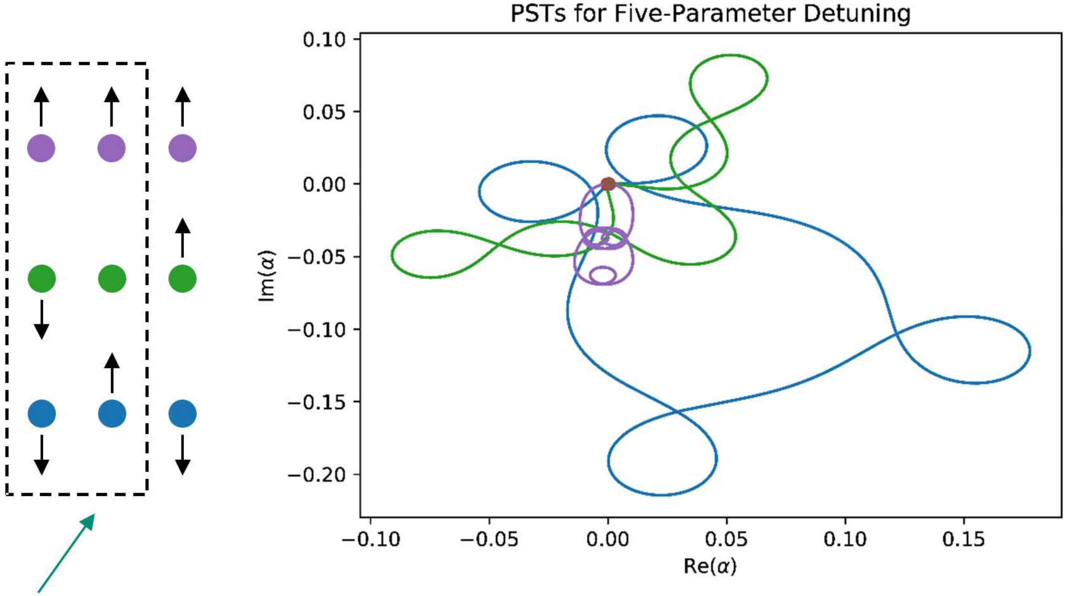
$$\# \text{ of modes} \propto \# \text{ of ions}$$

- Must close *all* loops in phase space!

Compensated Two-Qubit Gates

- Requires modulation of control parameters (frequency, phase, or amplitude)

Closing loops with frequency modulation for 3 qubits



- Parameters might change depending on which ions are being addressed, due to differences in Lamb-Dicke parameters

Requirements: Fast & continuous parameter modulation, Synchronous control across channels

Hardware Implementation

General Requirements

- 2 tones per channel
  - Up to 350 MHz
- Absolute phase control
  - Re-synchronize phases without bookkeeping
- Fast & continuous parameter modulation
  - Spline modulation on all parameters simultaneously
- Synchronous control across channels
  - Full parallelism
- Long sequences of gates
- Scalable

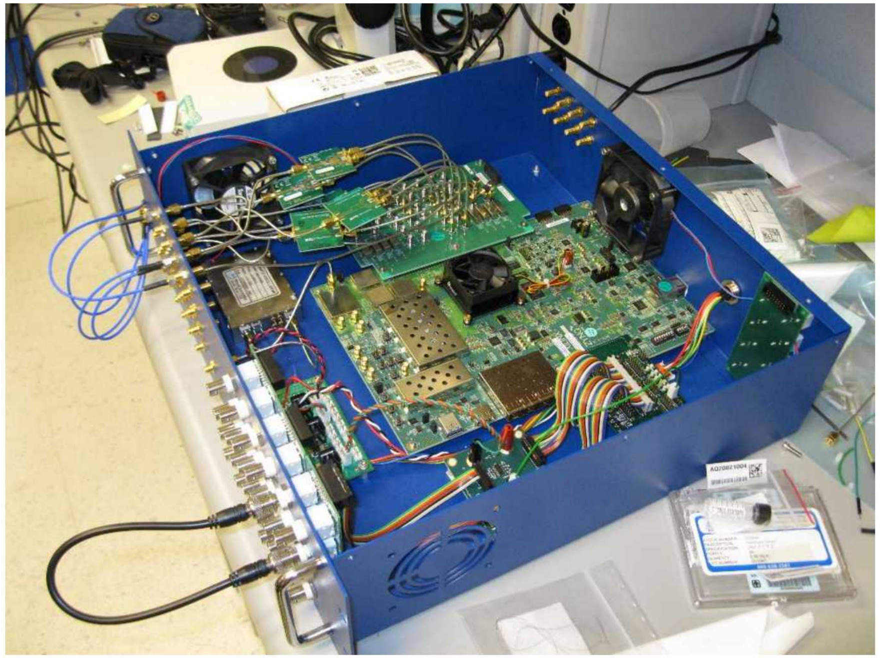
Error Handling Requirements

- Fast repetition rate lock reconfigurability
- Cross talk cancellation

Solution

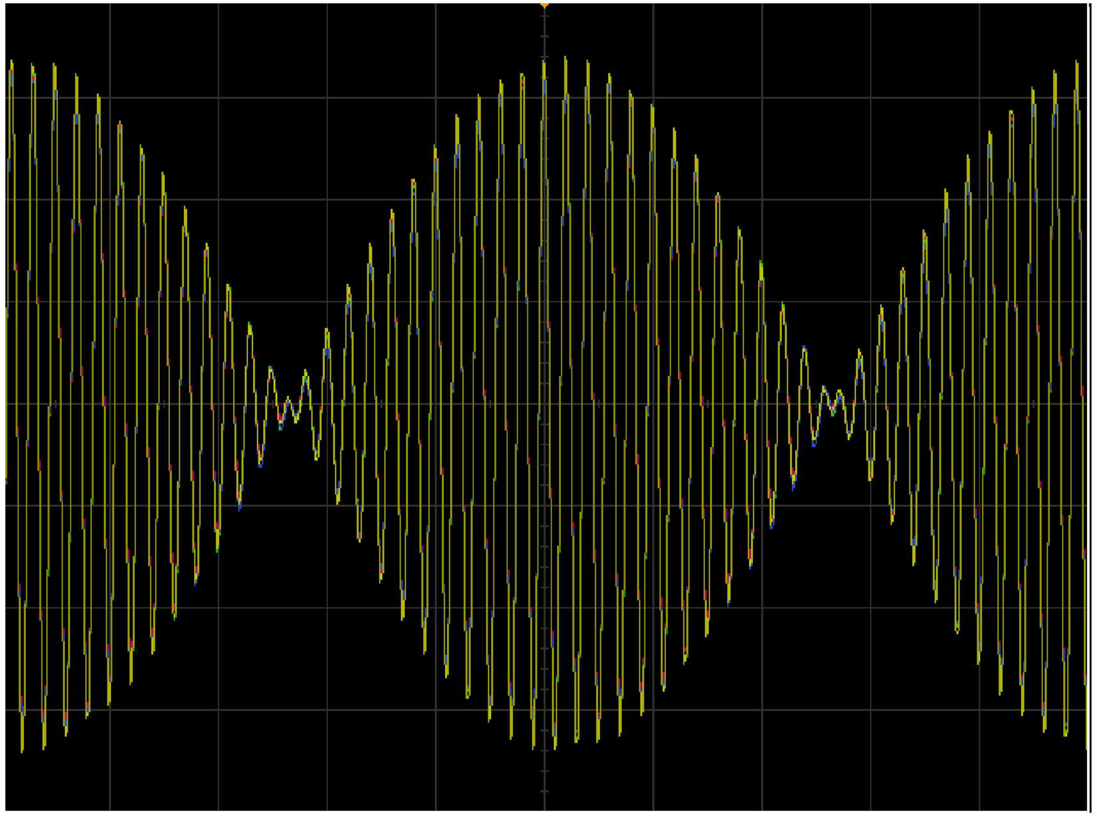
- Custom firmware design using a Xilinx RFSoC
- Currently using ZCU111 evaluation boards
- 8 DACs per board, 6.5 GSPS

A Packaged "Octet"

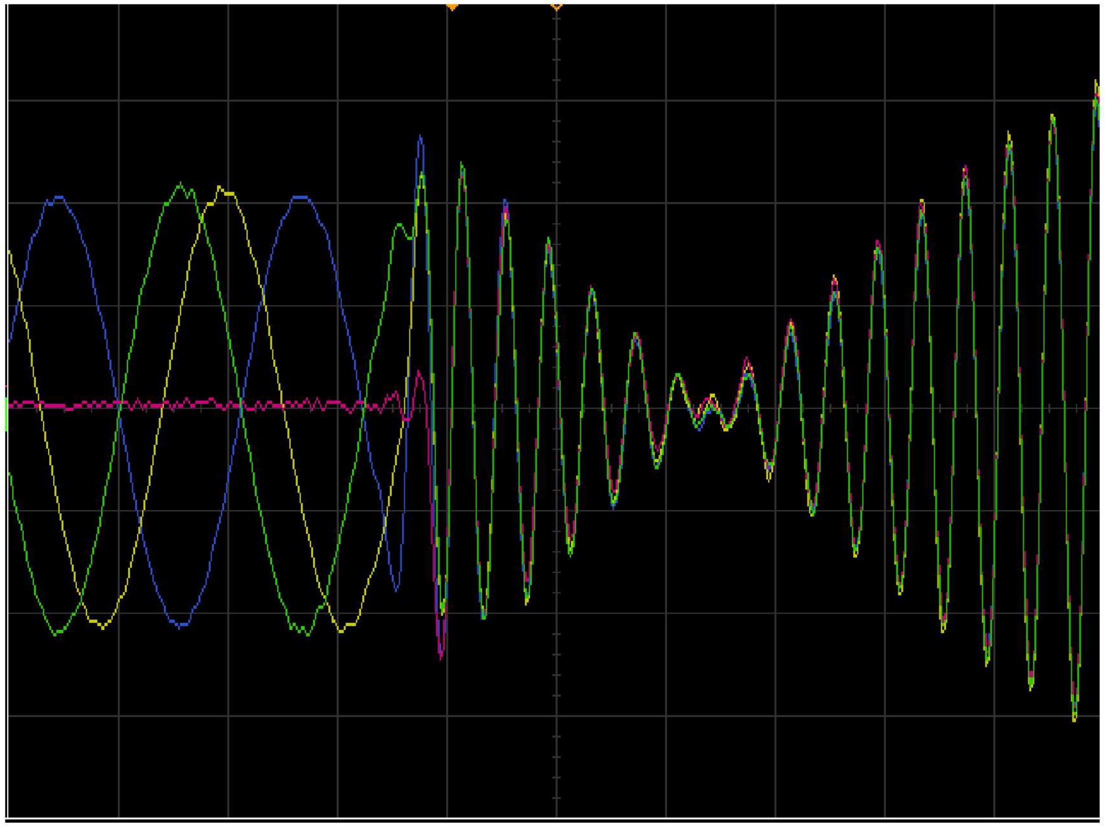


Global Phase Synchronization

Tones being manually synchronized to an earlier state

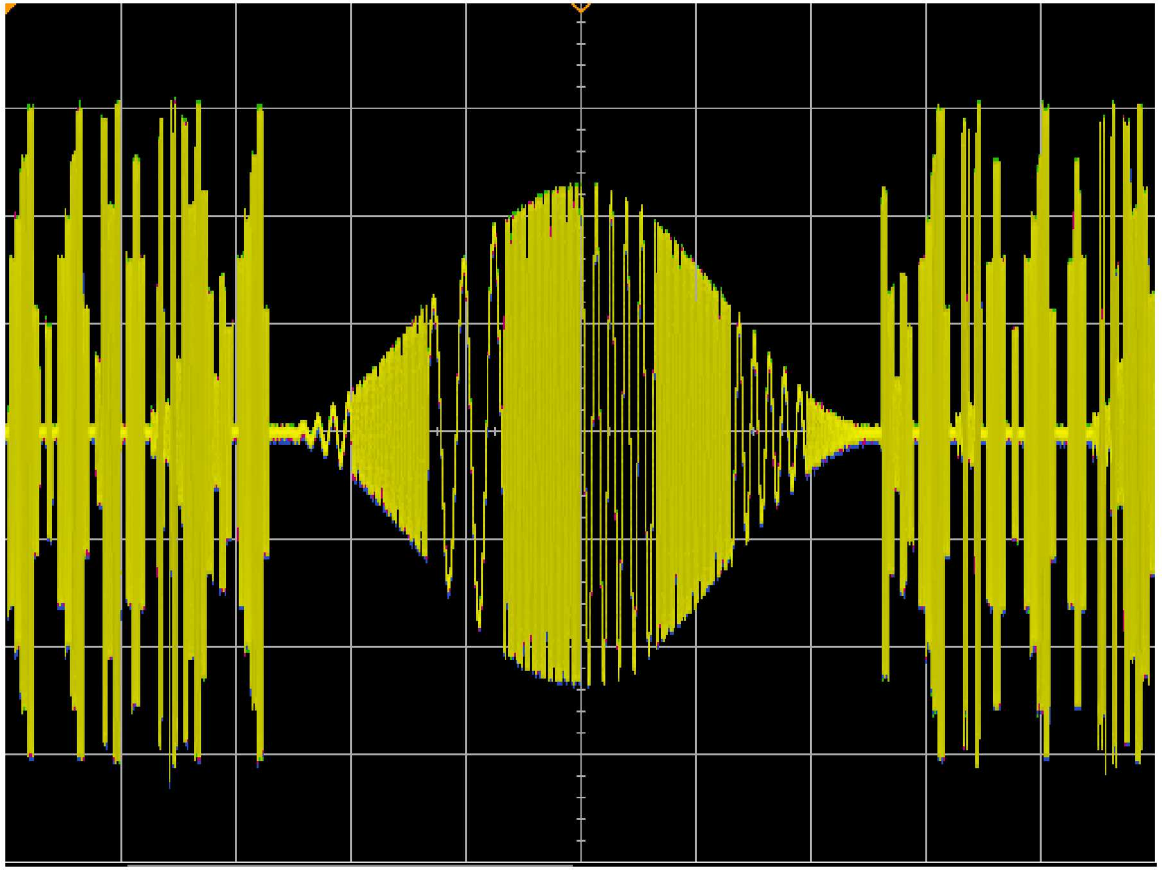


Changing parameters while applying synchronization

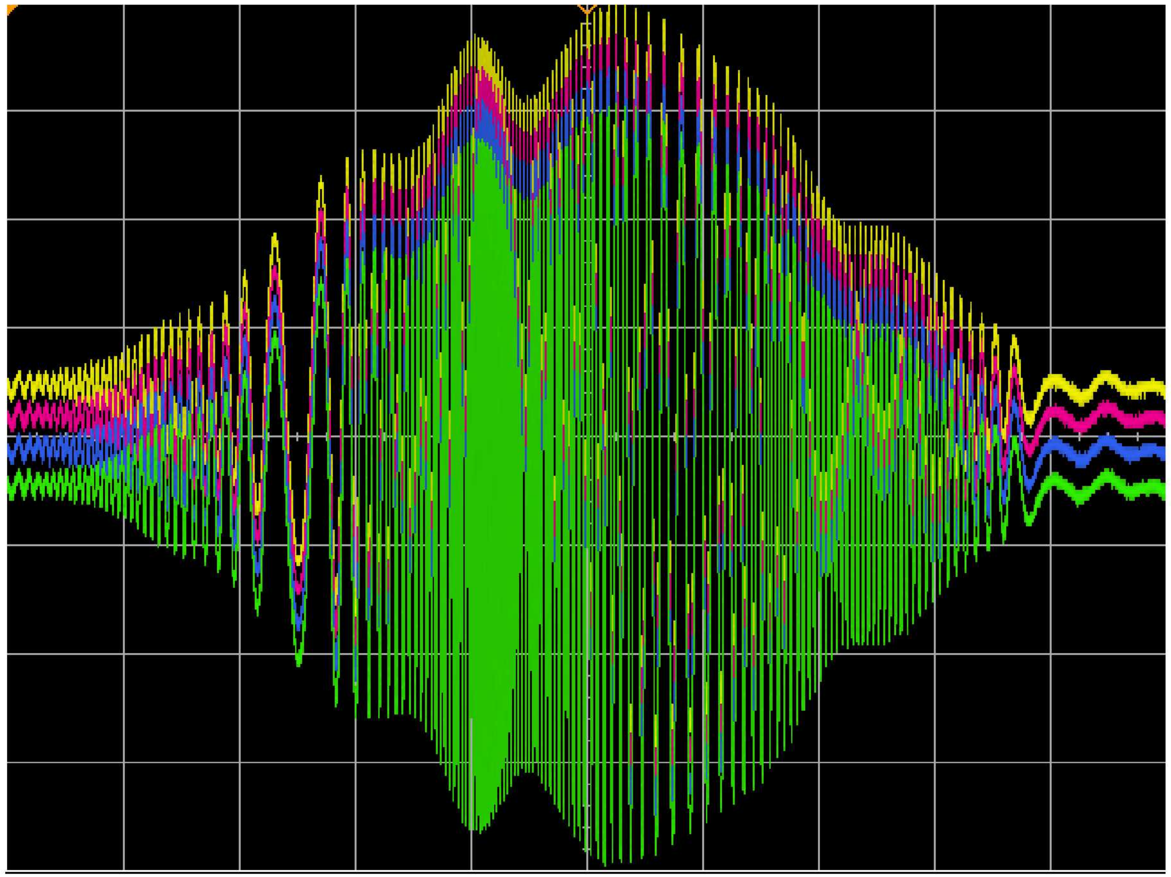


Parameter Modulation

Smooth and/or discrete updates to parameters



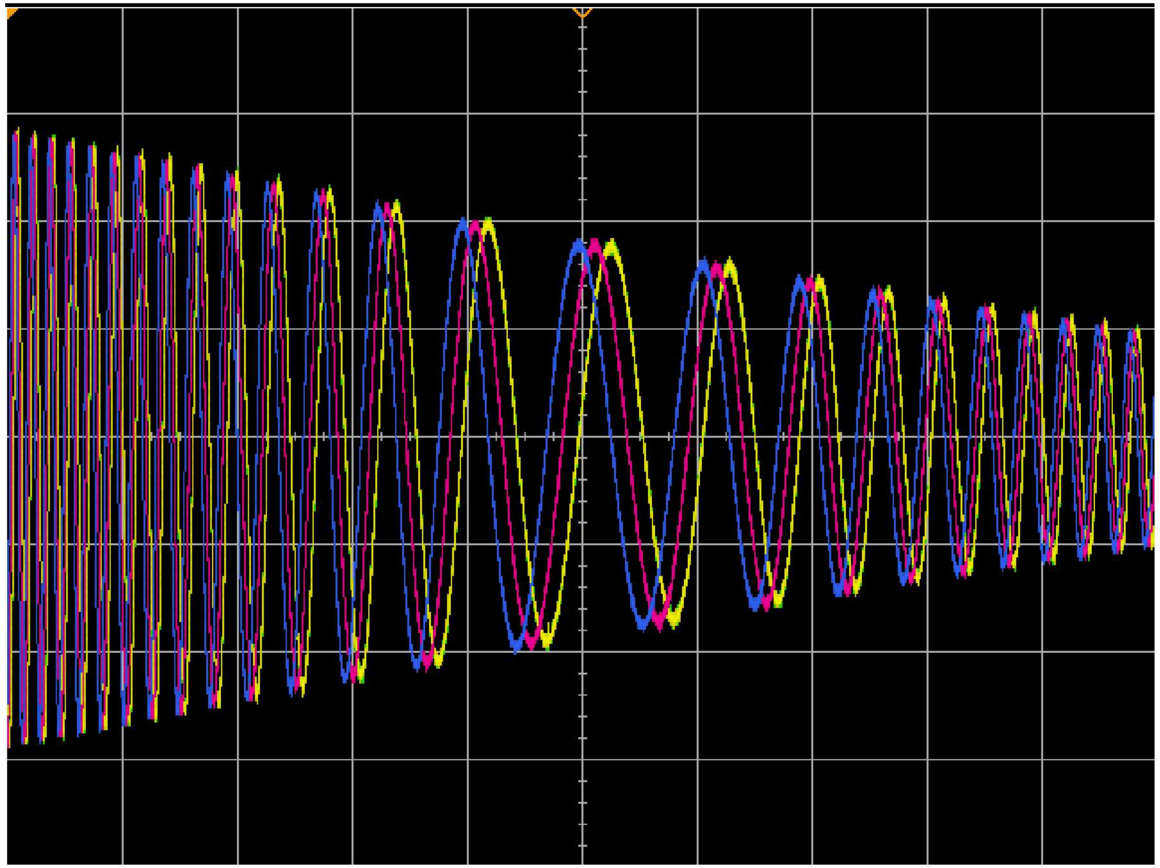
Simultaneous across all channels



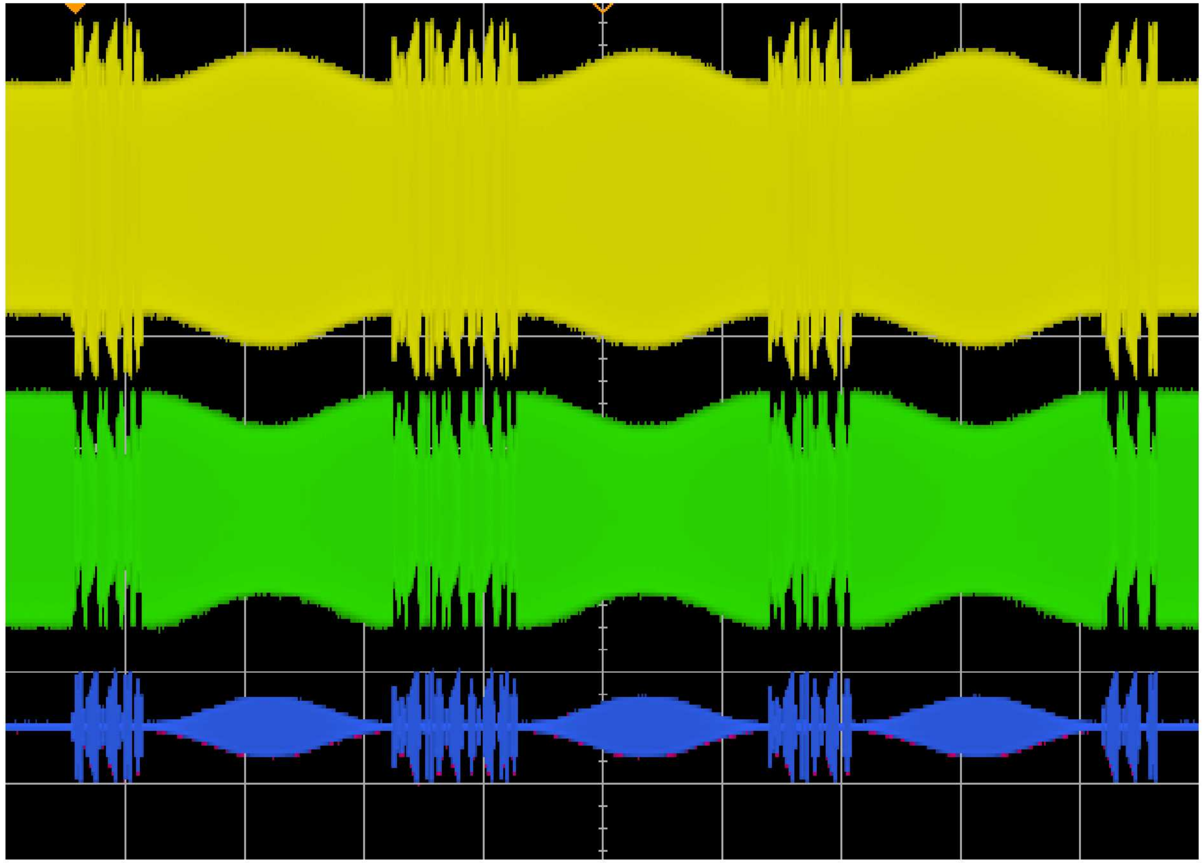
Implementation modeled after “pdq” spline interpolation: pdq.readthedocs.io

Cross Talk Compensation

Full Phase Tunability



Example of crosstalk correction applied to two static tones (opposite amplitude)

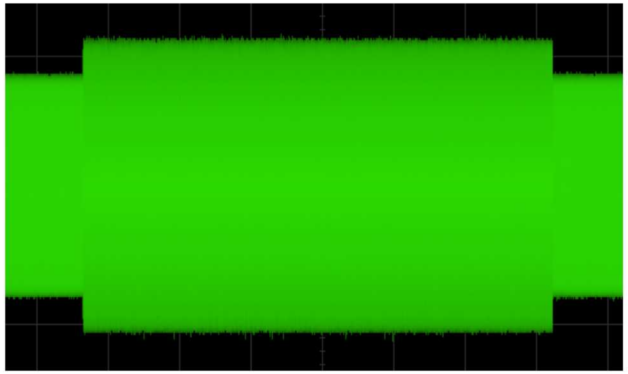


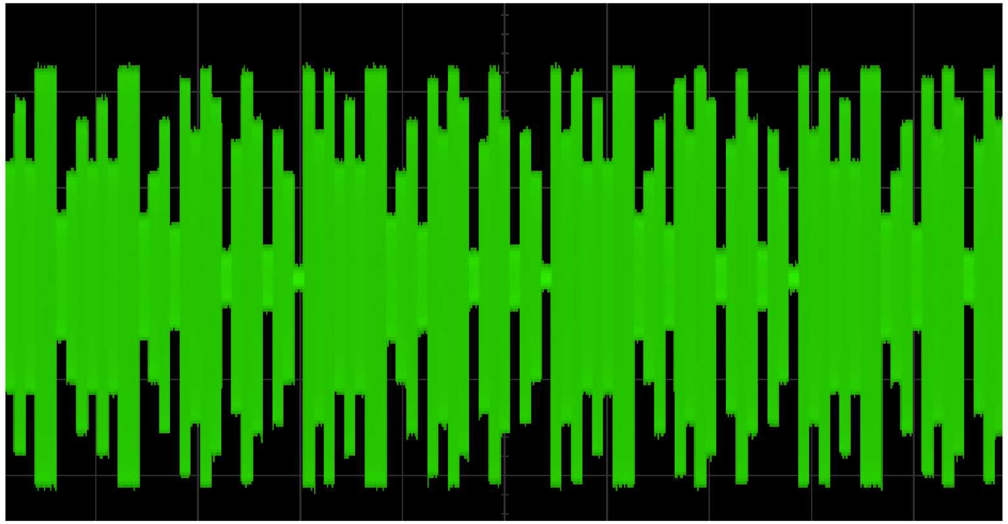
Gate Sequencer

Data can be compressed in fabric lookup tables (LUTs) for greater throughput.

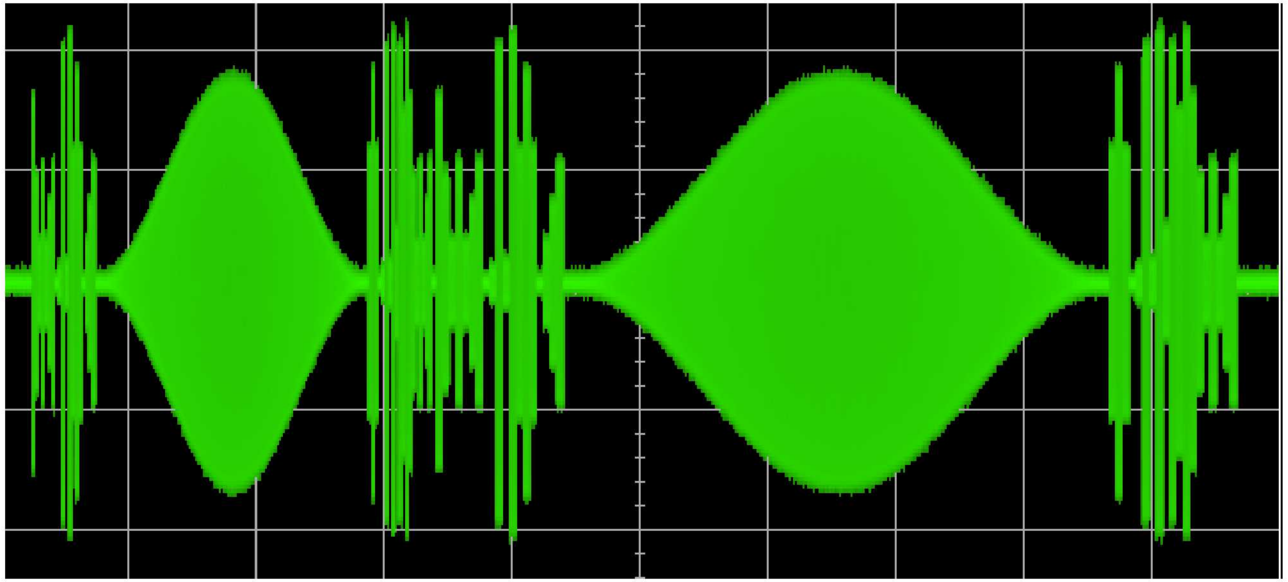
12,000,000

100 ns pulses

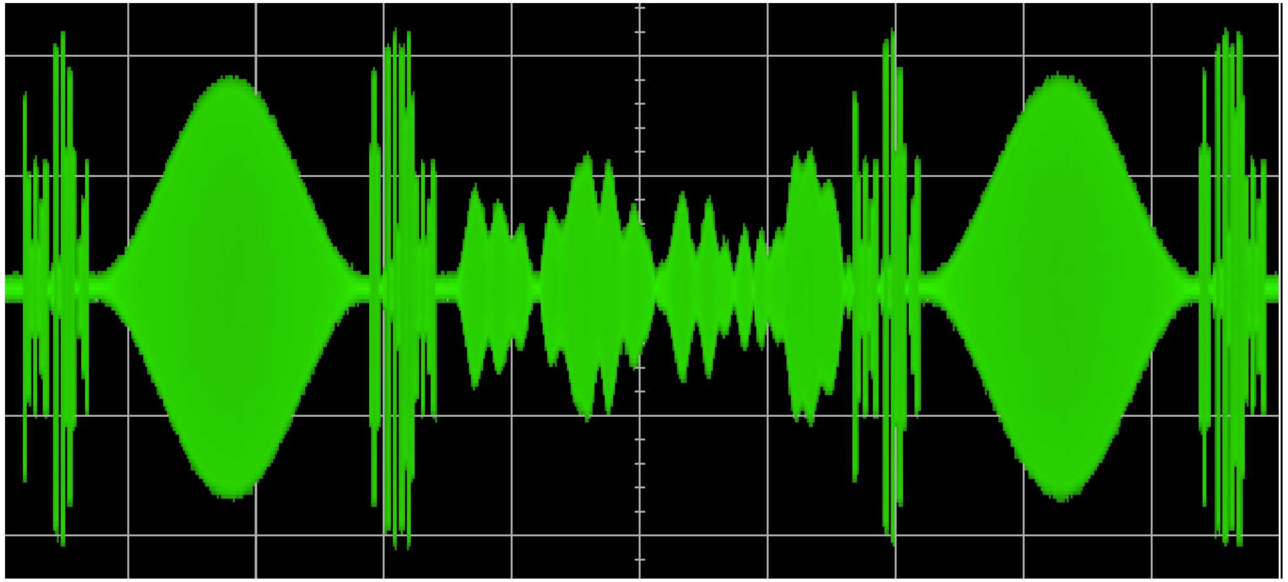




LUTs can be quickly reprogrammed



Sequenced and raw data can be interleaved



Jaqal: “Just another quantum assembly language”

Example Jaqal Code

```
from QSCOUT.std.v1 usepulses *

register q[8]

let pi4   0.78539816339
let mpi2 -1.57079632679

macro Hadamard target {
  Sy target
  Px target
}

macro CNOT control target {
  Sy control
  MS control target 0 pi4
  < Rx control mpi2 | Rx target mpi2 >
  Sy control
}

prepare_all
Hadamard q[1]
CNOT q[2] q[1]
measure_all
```

Features

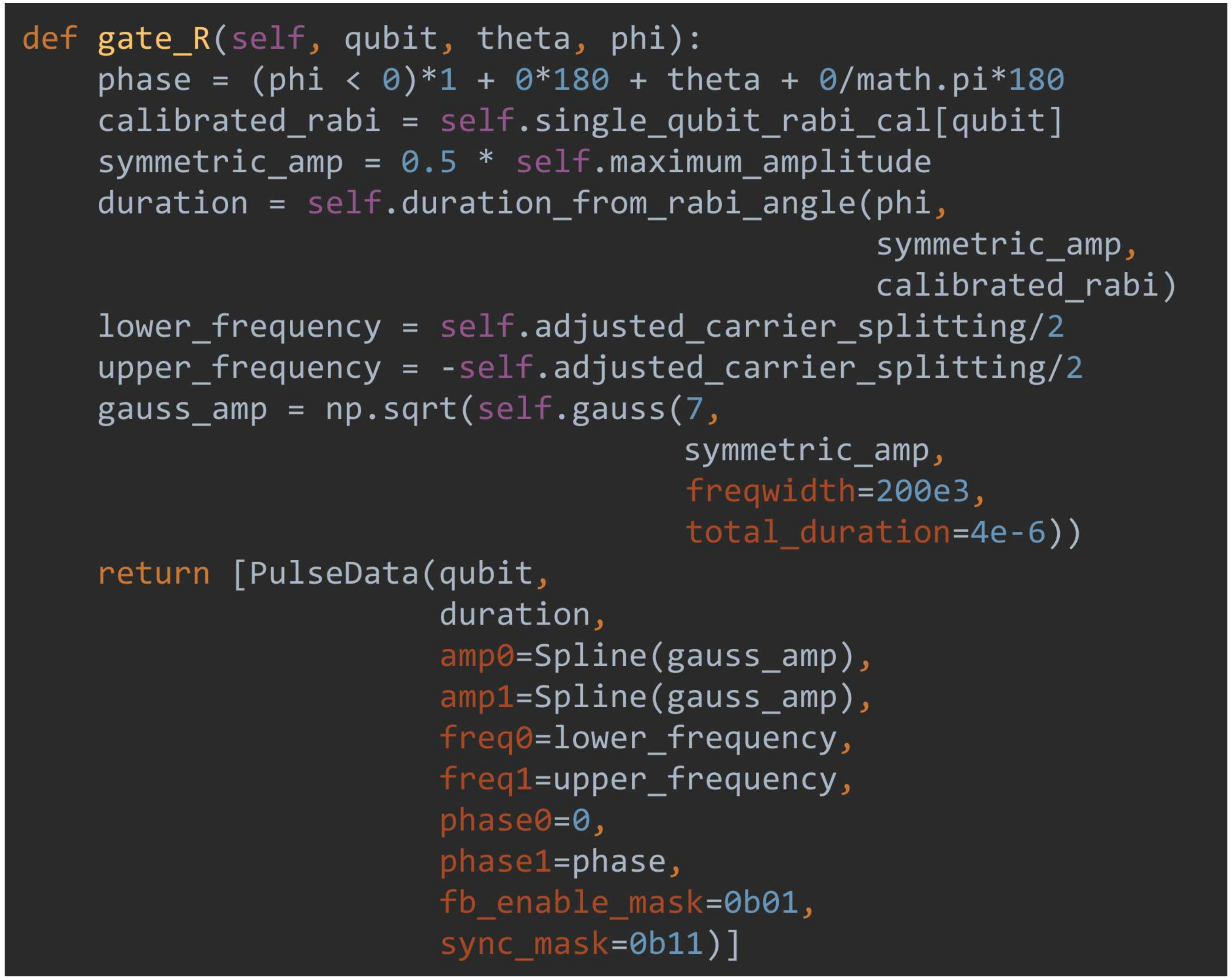
- Simple interface, easy to learn
- Provides a natural way to write gates that can be run in sequence or in parallel
- Basic elements such as parameter definitions, macros, loops, and qubit aliases to ease programming while maintaining readability and explicitness
- Quickly switch between low-level gate definitions
- Extensible via custom gate definitions

JaqalPaw: Jaqal “Pulses and waveforms”

Features

- Uses Python for flexibility
- Pulse representation is a simple data structure
- Modulation expressed as tuples of spline knots or lists of discrete values
- Splines can be specified for multiple parameters simultaneously an with different lengths

Example JaqalPaw Code



```
def gate_R(self, qubit, theta, phi):
    phase = (phi < 0)*1 + 0*180 + theta + 0/math.pi*180
    calibrated_rabi = self.single_qubit_rabi_cal[qubit]
    symmetric_amp = 0.5 * self.maximum_amplitude
    duration = self.duration_from_rabi_angle(phi,
                                             symmetric_amp,
                                             calibrated_rabi)
    lower_frequency = self.adjusted_carrier_splitting/2
    upper_frequency = -self.adjusted_carrier_splitting/2
    gauss_amp = np.sqrt(self.gauss(7,
                                   symmetric_amp,
                                   freqwidth=200e3,
                                   total_duration=4e-6))
    return [PulseData(qubit,
                      duration,
                      amp0=Spline(gauss_amp),
                      amp1=Spline(gauss_amp),
                      freq0=lower_frequency,
                      freq1=upper_frequency,
                      phase0=0,
                      phase1=phase,
                      fb_enable_mask=0b01,
                      sync_mask=0b11)]
```

QSCOUT Team and QIS Ion Trapping at Sandia

Trap design & experimentation

Susan Clark
Craig Hogle
Daniel Lobser
Peter Maunz
Melissa Revelle
Dan Stick
Josh Wilson
Christopher Yale

RF Engineering

Christopher Nordquist
Stefan Lepkowski

Software

Jay Van Der Wall

Trap design & fabrication

Matthew Blain
Jason Dominguez
Ed Heller
Becky Loviza
John Rembetski
Corrie Sadler

Mechanical & Optical Engineering

Jessica Pehr
David Bossert
Zachary Kreiner
William Sweatt

External Collaborators

Ken Brown (Duke)
Peter Love (Tufts)

Trap packaging

Ray Haltli
Andrew Hollowell
Tipp Jennings
Anathea Ortega

Theory

Andrew Landahl
Setso Metodi
Ben Morrison
Timothy Proctor
Kenny Rudinger
Antonio Russo
Brandon Ruzic
Kevin Young

Visit **qscout.sandia.gov** for more info
QSCOUT inquiries – email **qscout@sandia.gov**