SAND2024-14539C

Sandia National Laboratories

Exceptional service in the national interest

FEEDBACK-BASED CALIBRATION FOR TUNING AND DRIFT CONTROL OF A TRAPPED-ION QUANTUM PROCESSOR

Nathan Eli Miller[1,2*], Alicia Magann[1], Robin Blume-Kohout[1], Kevin Young[1]

[1]*Sandia National Laboratories*

[2]*Georgia Institute of Technology*

**nemill@sandia.gov / nathan.miller@gatech.edu*

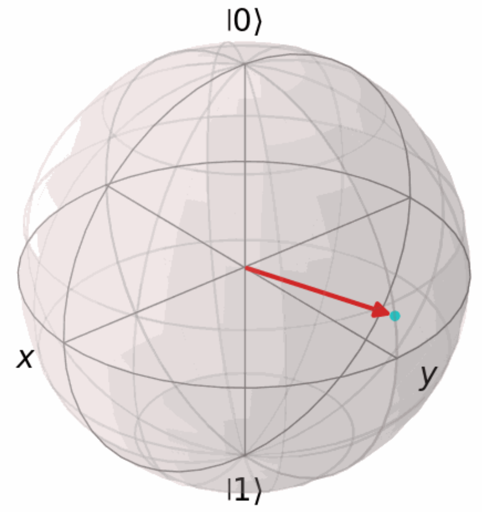
APS March Meeting 2024, B18.00009

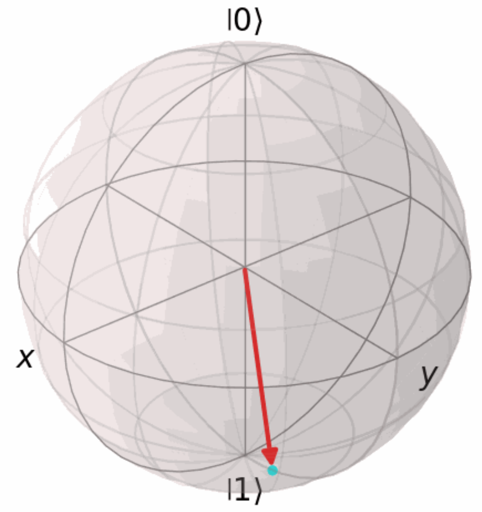
U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and 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.

FORMULATING THE PROBLEM

- The accuracy of quantum gates depends on many parameters, and we want to tune them shot-by-shot to rapidly calibrate for random variation and drift.
- We look at two classes of circuits with some over or under rotation angle δ caused by some control parameter η which is out of tune:
  - Indefinite outcome circuits with linear noise response (i.e. a $\pi/2$ rotation gate)
  - Definite outcome circuits with quadratic noise response (i.e. a π rotation gate)
- This work demonstrates a rapid, online method for tuning and drift control which is able to respond to drift and SPAM and is implementable in any quantum processor. We will also demonstrate control hardware considerations and progress towards calibration of Sandia's trapped ion processors.

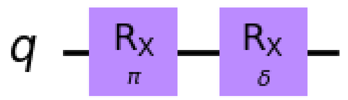




SENSITIVITY TUNING VIA COHERENT NOISE AMPLIFICATION

- We can coherently amplify the noise in a circuit by repeating the gates, effectively increasing sensitivity to changes in η
  - Calibrating a $\mathcal{G}_x\left(\frac{\pi}{2}\right)$ gate, we can repeat by $r = 4n + 1$ with n an integer, $s \propto r$
  - Calibrating a $\mathcal{G}_x(\pi)$ gate, we can repeat by $r = 2n + 1$ with n an integer, $s \propto r$
- Example: $\mathcal{G}_x(\pi + \delta)$

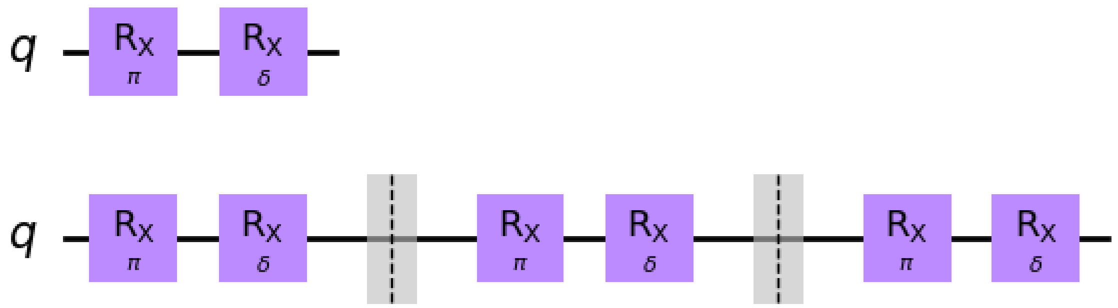
(a) A single noisy $\mathcal{G}_x(\pi)$ gate

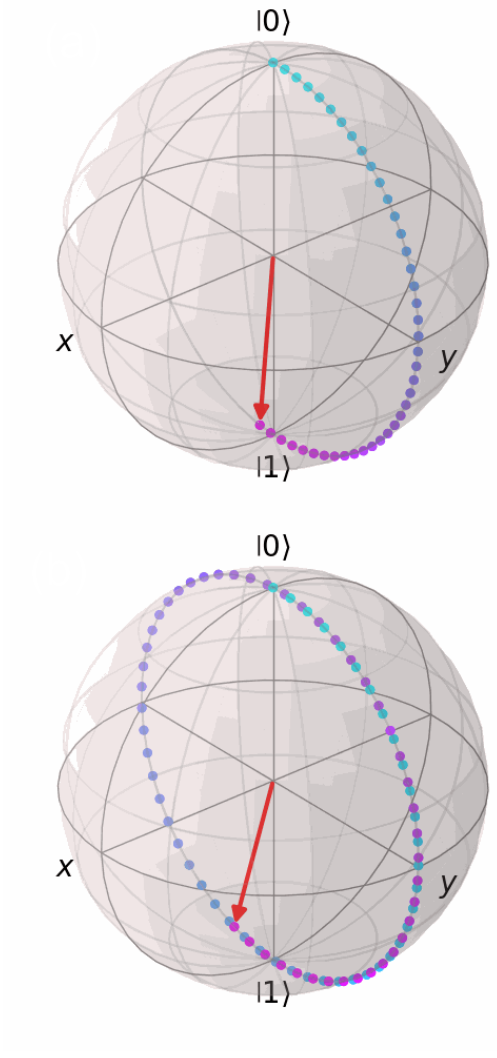


SENSITIVITY TUNING VIA COHERENT NOISE AMPLIFICATION (CONT.)

- We can coherently amplify the noise in a circuit by repeating the gates, effectively increasing sensitivity to changes in η
  - Calibrating a $\mathcal{G}_x\left(\frac{\pi}{2}\right)$ gate, we can repeat by $r = 4n + 1$ with n an integer, $s \propto r$
  - Calibrating a $\mathcal{G}_x(\pi)$ gate, we can repeat by $r = 2n + 1$ with n an integer, $s \propto r$
- Example: $\mathcal{G}_x(\pi + \delta)$

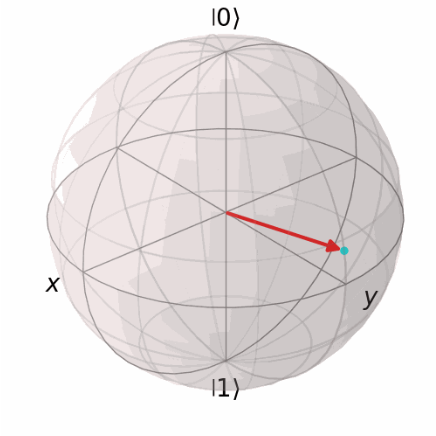
(a) A single noisy $\mathcal{G}_x(\pi)$ gate

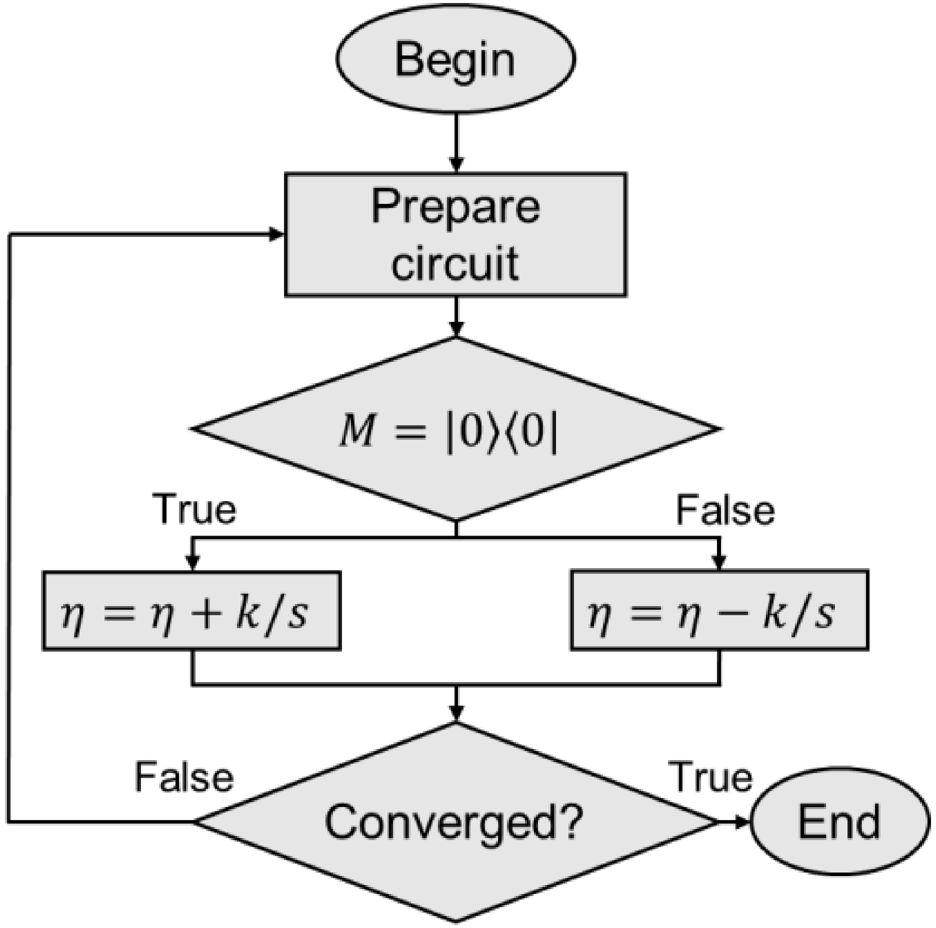




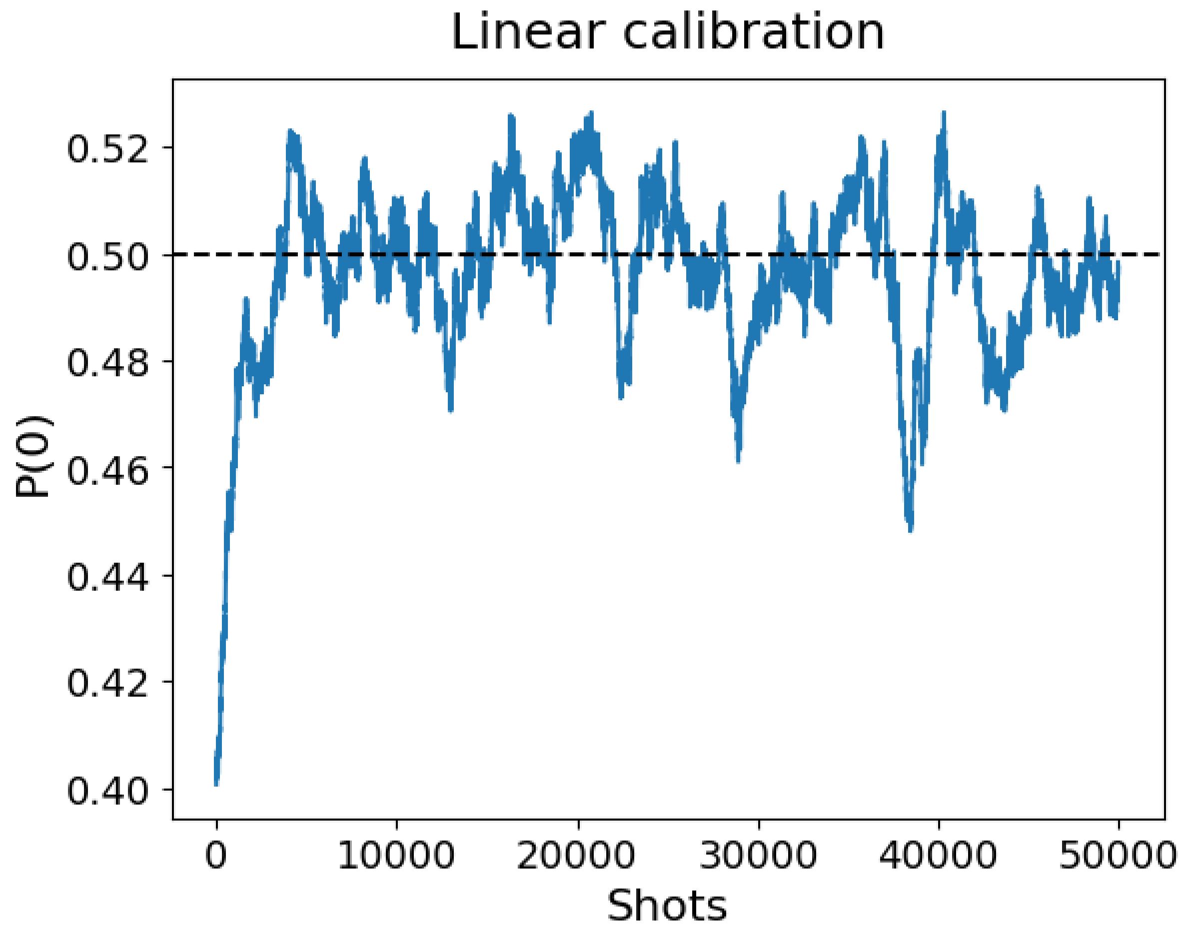
METHODS: INDEFINITE CIRCUITS (LINEAR CALIBRATION)

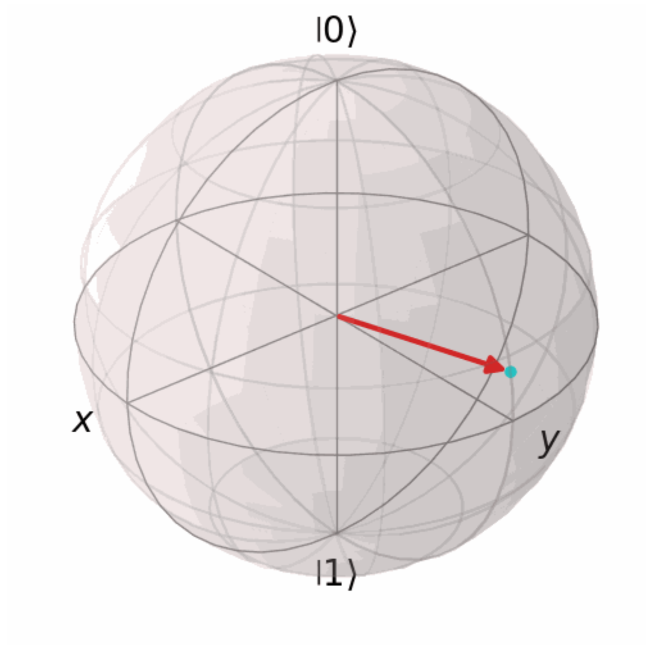
- Circuits with an unbiased, indefinite outcome (i.e. a π/2 gate) have an approximately linear response in their output to a noise parameter $\delta = s(\eta - \eta_{opt})$, $s \propto 4n + 1$
- Shot-by-shot:
  - If we measure $|0\rangle$, rotate towards $|1\rangle$ by $\eta \mathrel{+}= k/s$
  - If we measure $|1\rangle$, rotate towards $|0\rangle$ by $\eta \mathrel{-}= k/s$
- Goal: $\eta \to \eta_{opt}$ s.t. $P(z = \pm 1|\delta) \approx \frac{1}{2}(1 + z\delta) \to \frac{1}{2}$





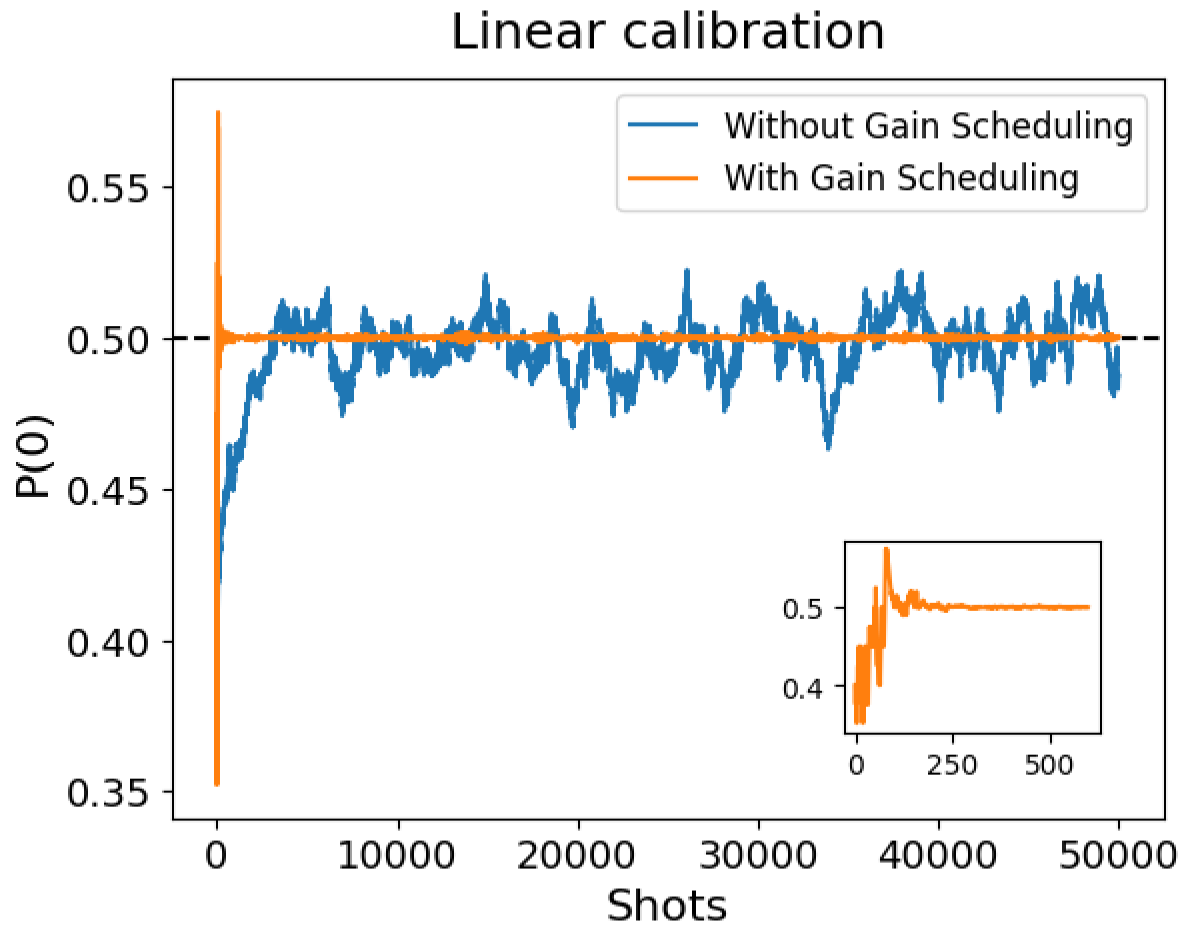
LINEAR CALIBRATION – BASELINE





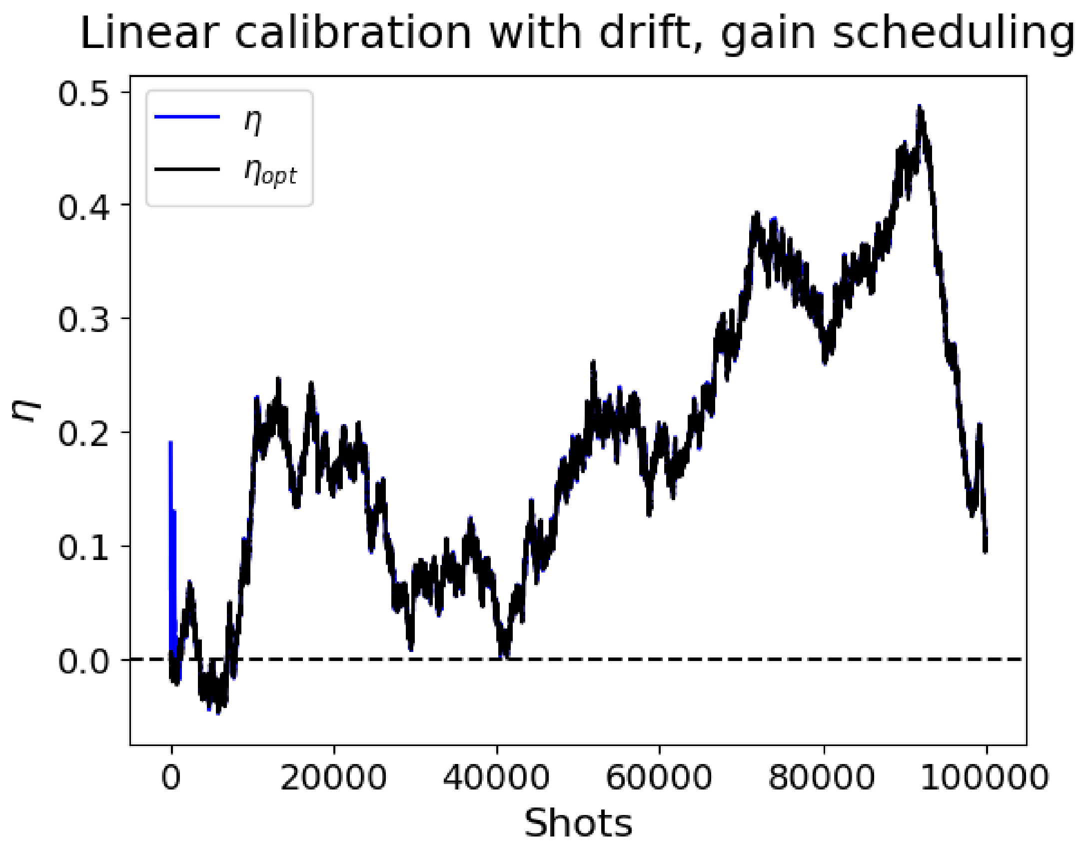
Results simulated in PyGSTi,
Erik Nielsen *et al* 2020 *Quantum Sci. Technol.* **5** 044002

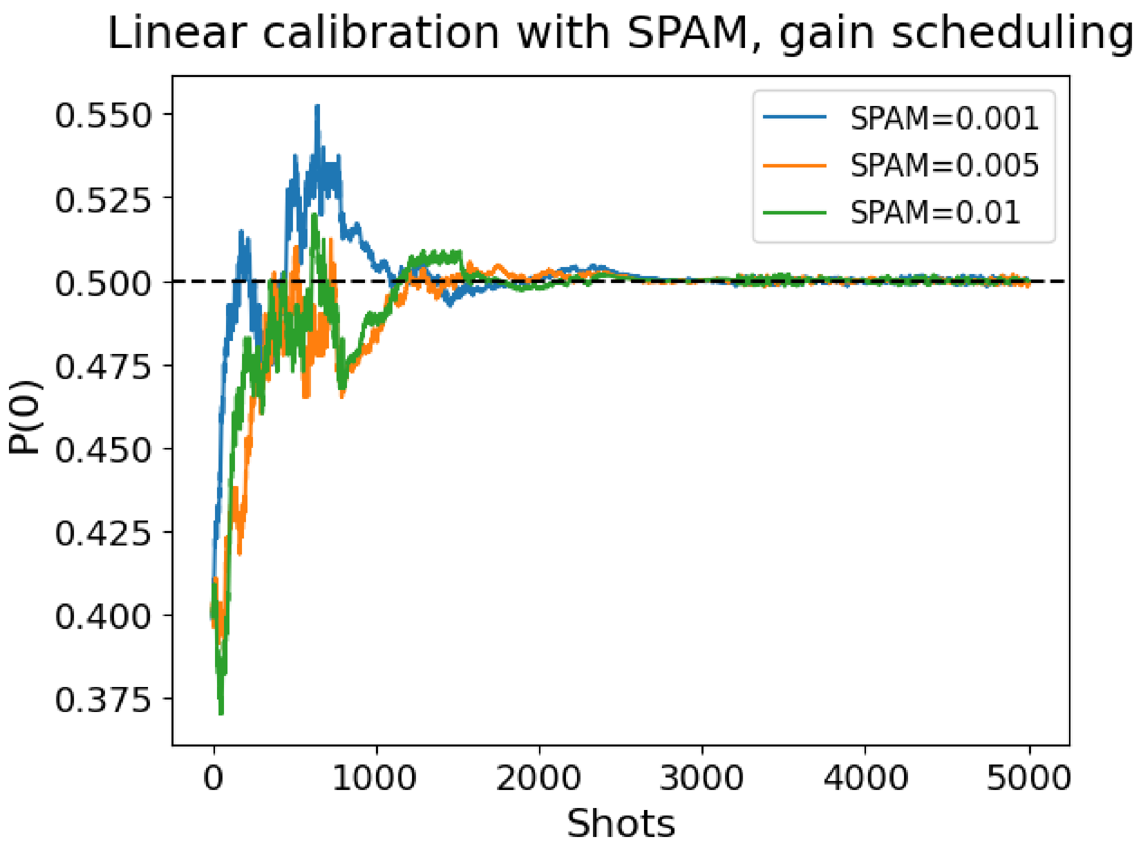
LINEAR CALIBRATION – GAIN AND SENSITIVITY SCHEDULING



1. Start with a high gain and a single gate ($s = 1$), increase s and reduce k as $k = 1/s$ every $4/k$ shots
2. Beyond a sensitivity cap, set $k = ls$ (here $l = 0.001$, cap s at 250)
3. Tweak l based on measurement history
   a) If measurements are uncorrelated, reduce k to reduce stationary variance
   b) If measurements are correlated, increase k to correct for errors quicker

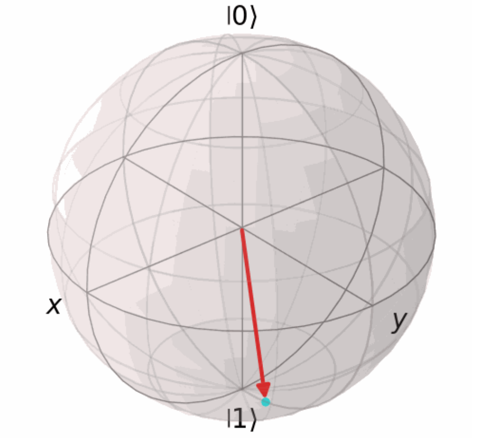
LINEAR CALIBRATION – DRIFT AND SPAM

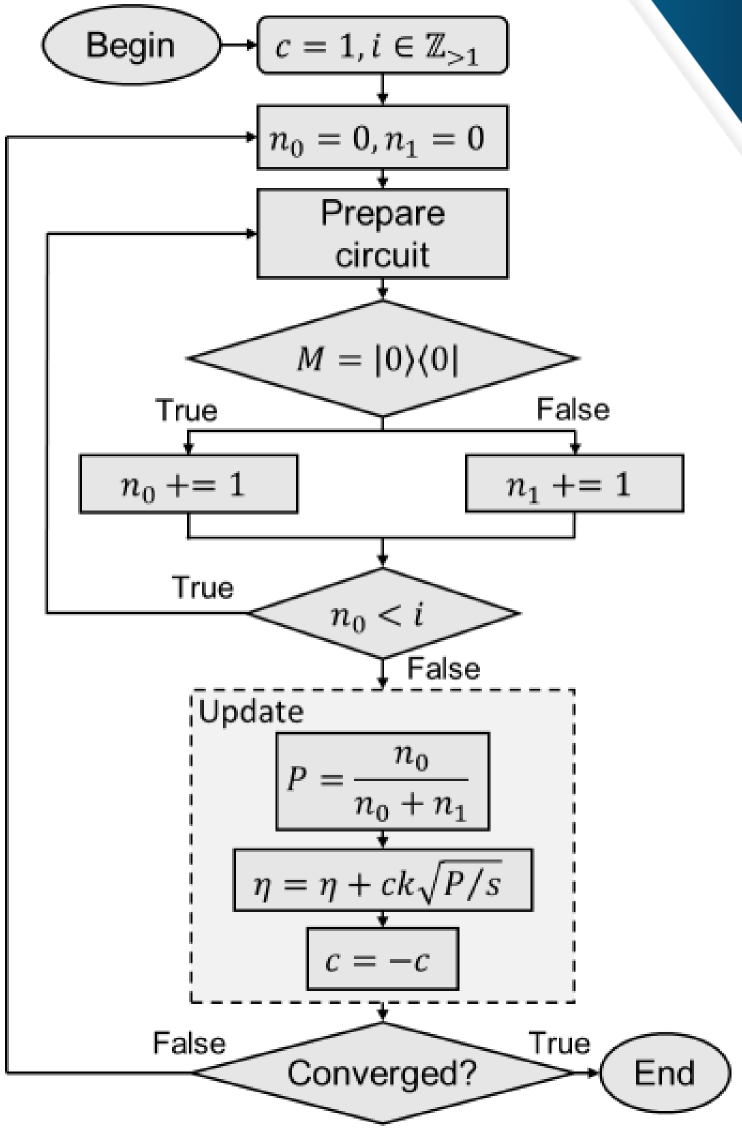




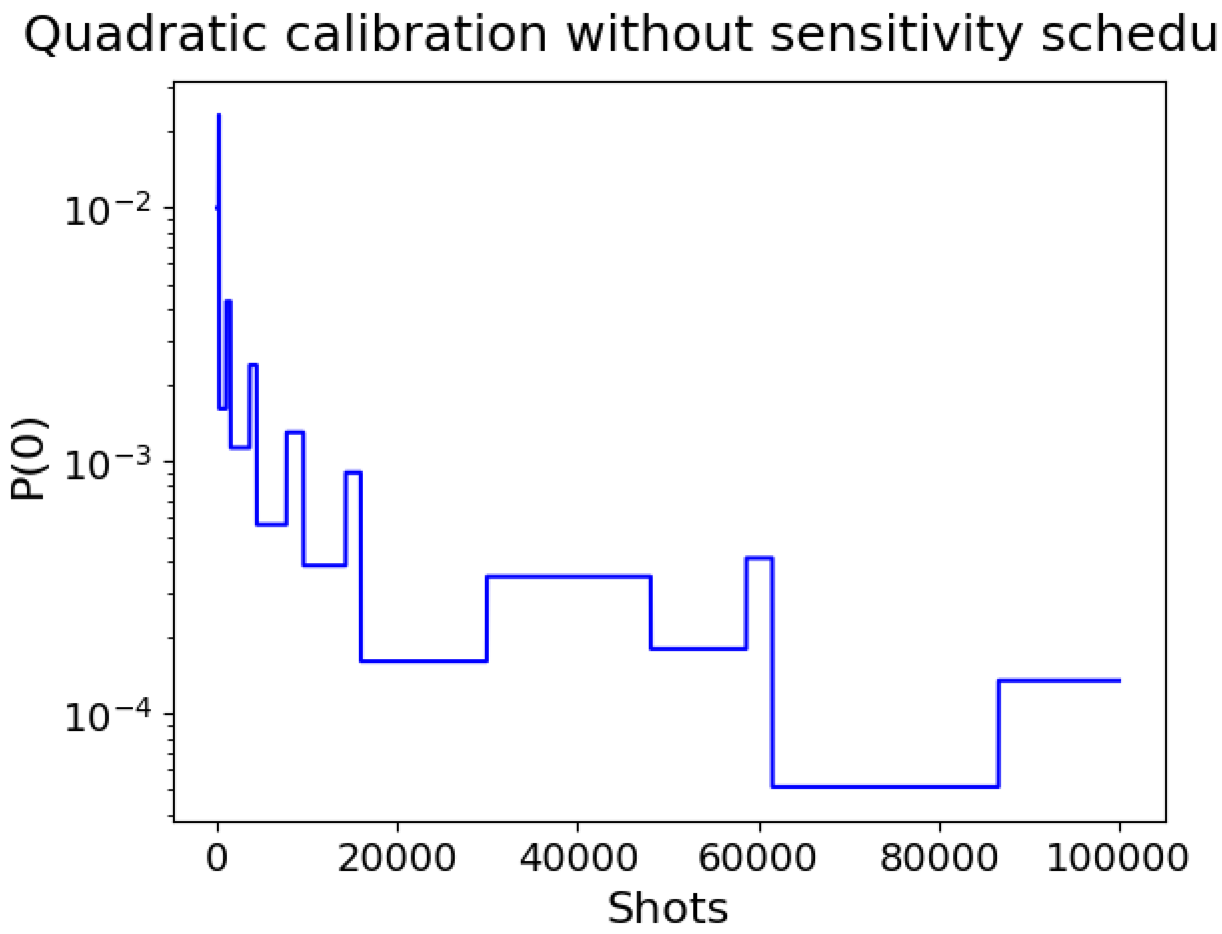
METHODS: DEFINITE CIRCUITS (QUADRATIC CALIBRATION)

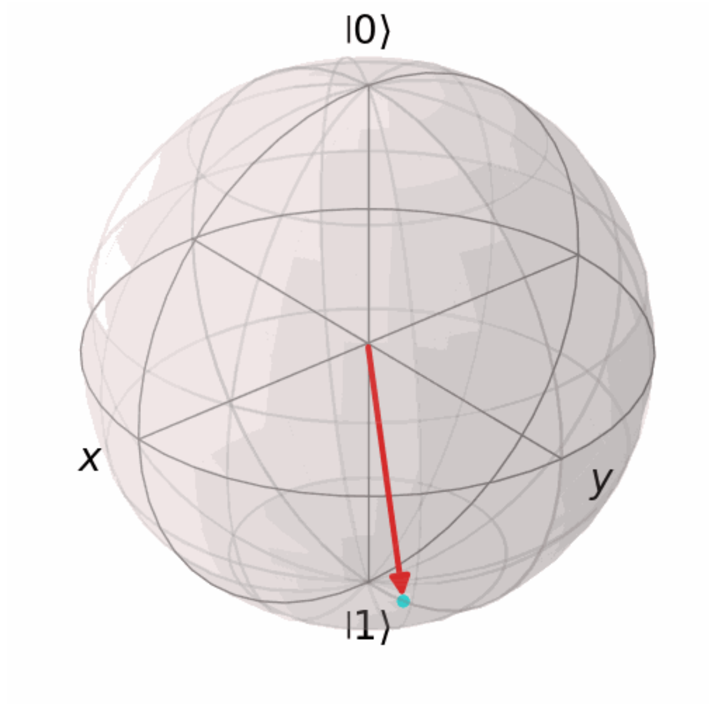
- Circuits with an ideally definite outcome (i.e. a π gate) have a probability of measuring an undesired result which is approximately quadratic with respect to the noise parameter $\delta = s(\eta - \eta_{opt})$, $s \propto 2n + 1$
- Measure until a certain number of errors are seen
  - The maximum likelihood estimator is $\hat{p} = \frac{n_0}{n_0 + n_1}$
  - Update η as $\eta \mathrel{+}= ck\sqrt{P/s}$
- Goal: $\eta \to \eta_{opt}$ s.t. $P(z = 1) \to 1$



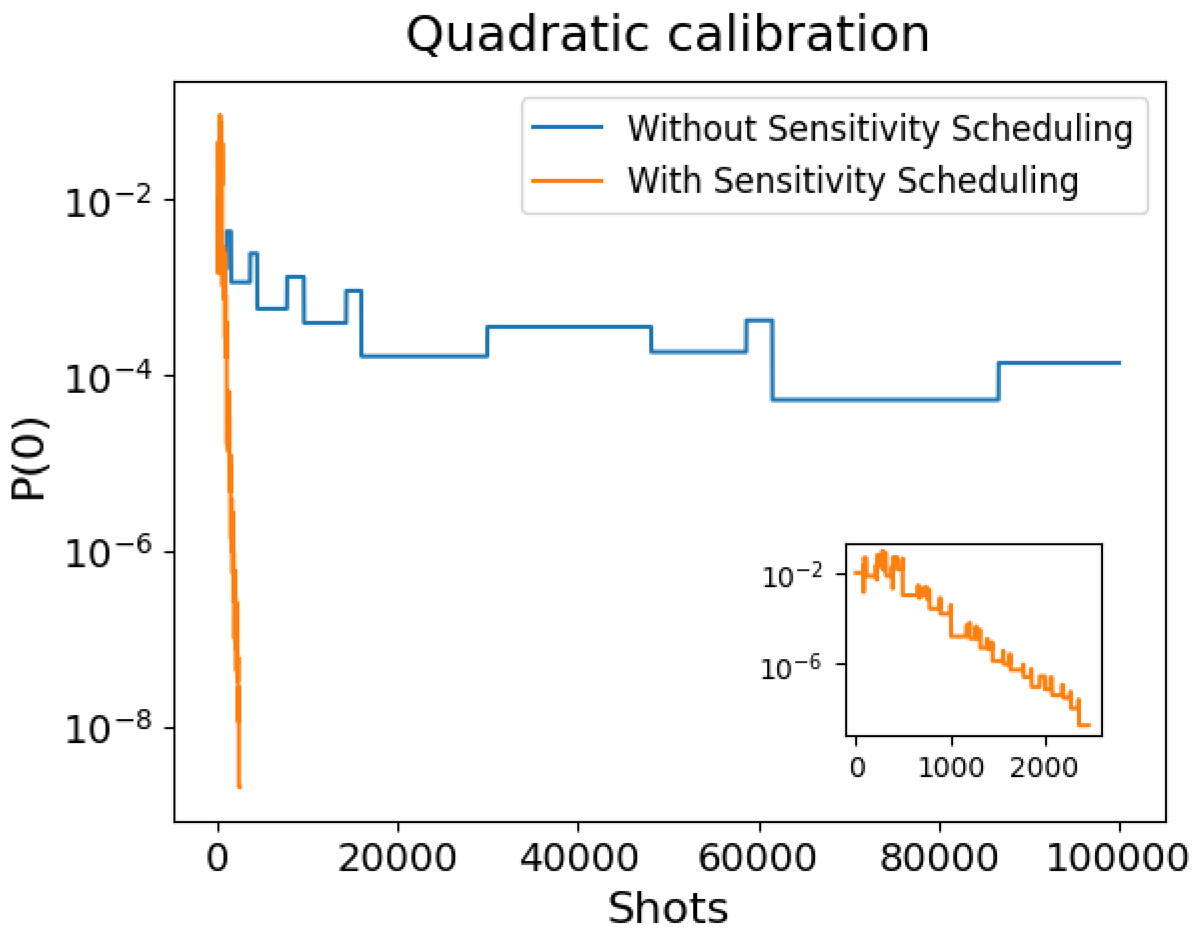


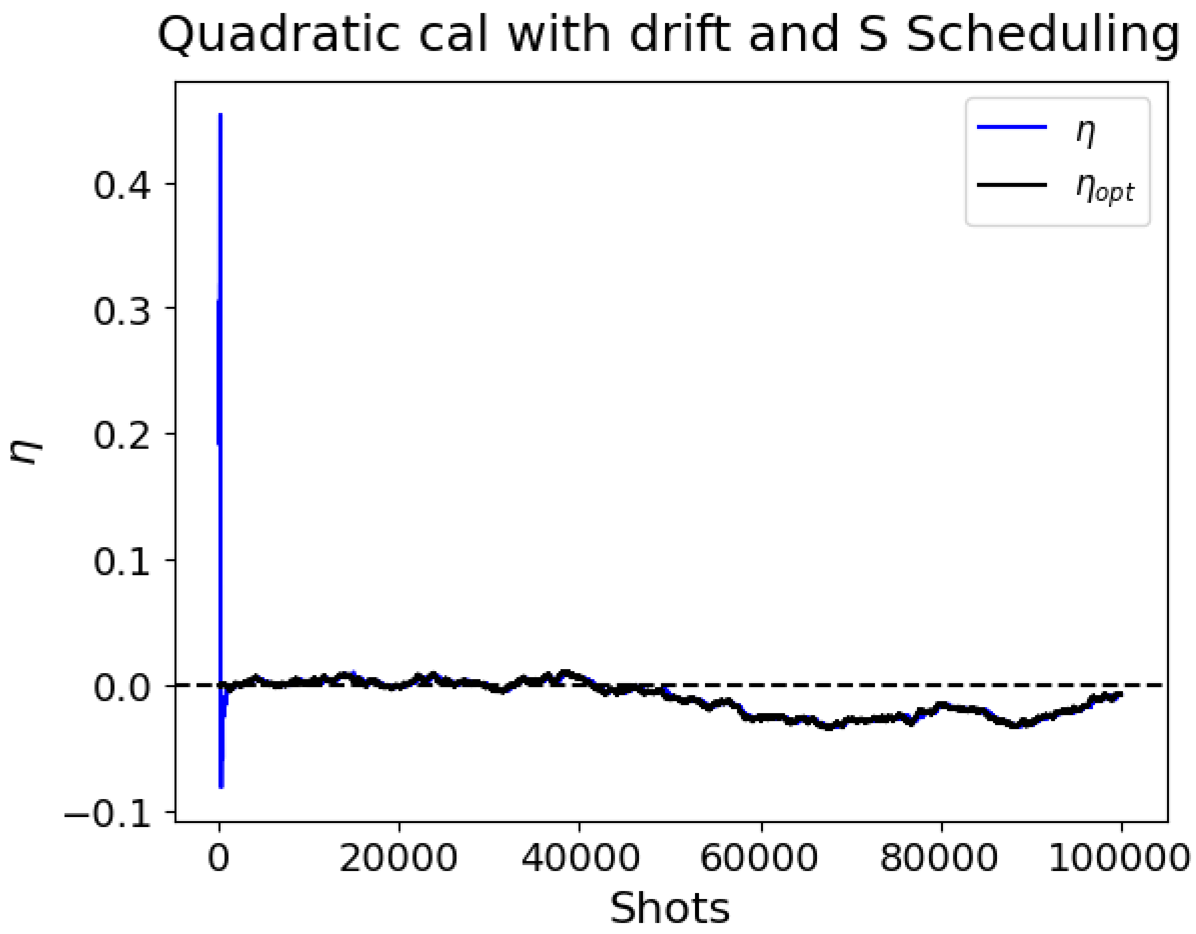
QUADRATIC CALIBRATION – BASELINE



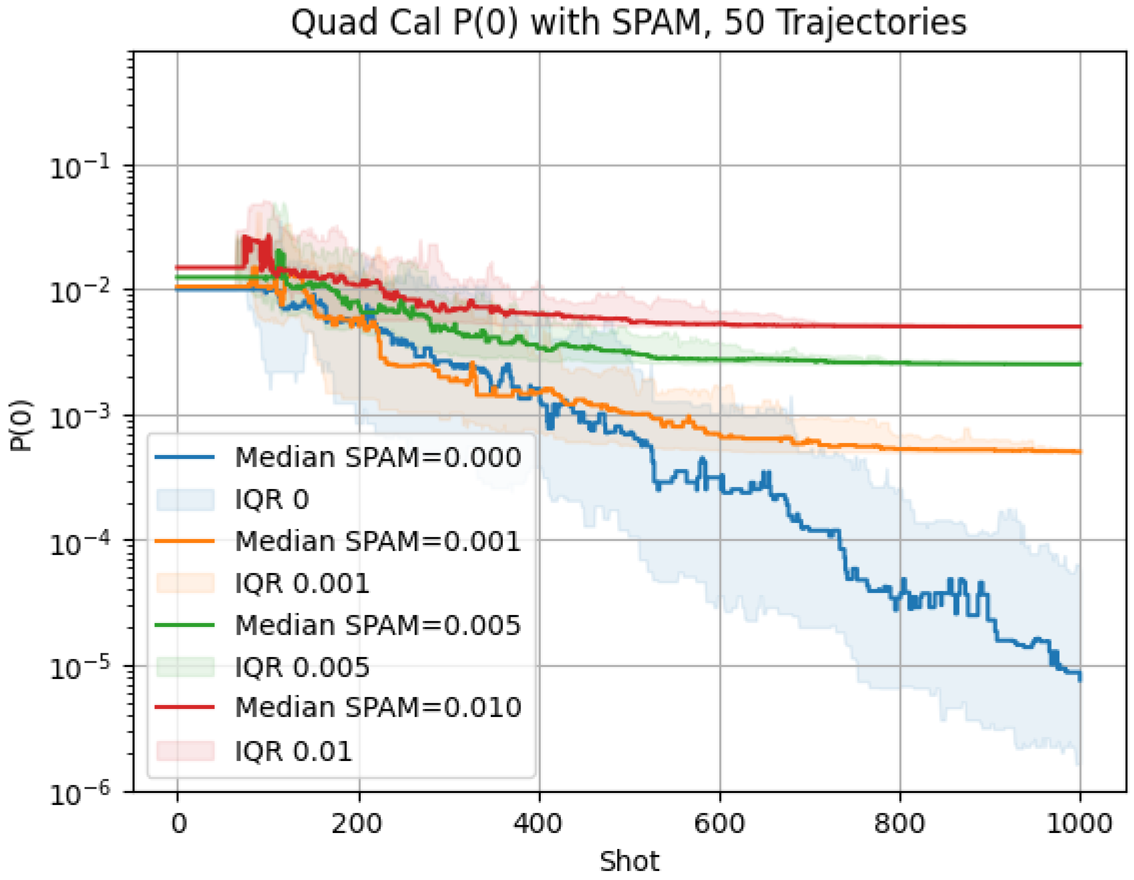


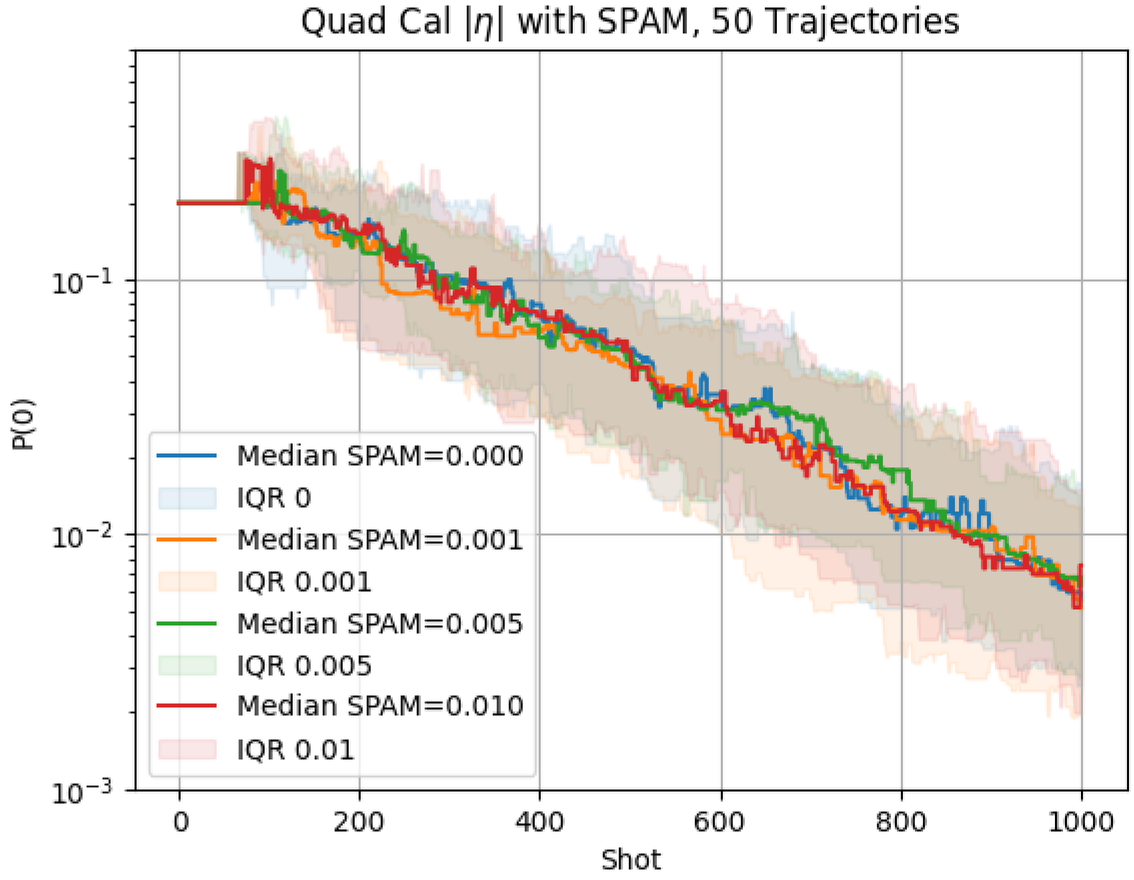
QUADRATIC CALIBRATION – SENSITIVITY SCHEDULING



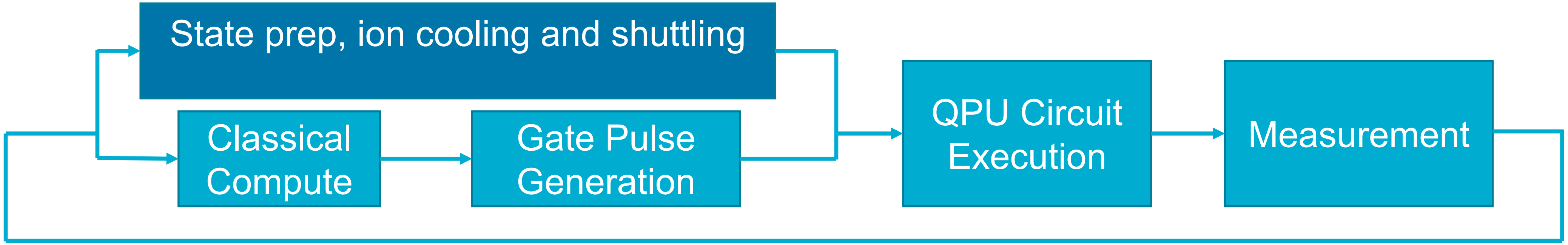


QUADRATIC CALIBRATION – SPAM





REAL TIME CALIBRATION OF TRAPPED ION PROCESSORS



- Sandia's Octet pulse compiler has multiple options for fast tuning of gate pulses
  - Continuously modulated spline generation using parameters input to a direct digital synthesis (DDS) module which requires less data than an AWG
  - Alternatively, more basic pulses can be generated from registered parameter values from a DMA engine in less time
- We can perform updates of gate pulses from measurement data in parallel with cooling and shuttling of ions in the trap, allowing for faster response to drift

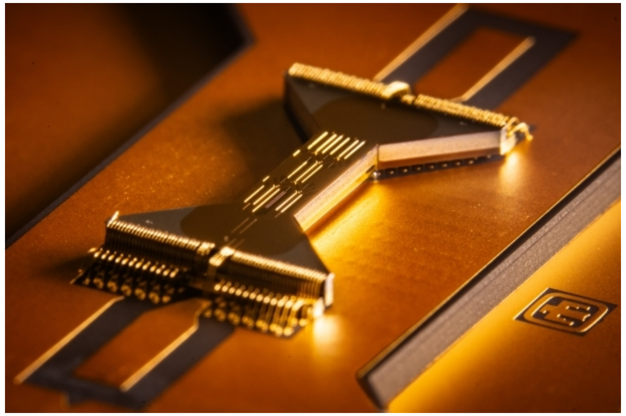


Photo: Craig Fritz, SNL

REAL TIME CALIBRATION OF A ROTATION GATE

- Using QSCOUT's API, we can control registered parameters of pulse sequences to implement calibration of a simple rotation gate.
  - In the rotation gate code below, we can modify the length of the gate pulse without full recompilation in order to perform rapid tuning.
  - Additional modifiable parameters include pulse amplitude, frequency and phase
- An initial implementation in the on-board real time processing unit (RPU) is in progress, with goals of implementing logic in the control system's FPGA fabric for lower latency.

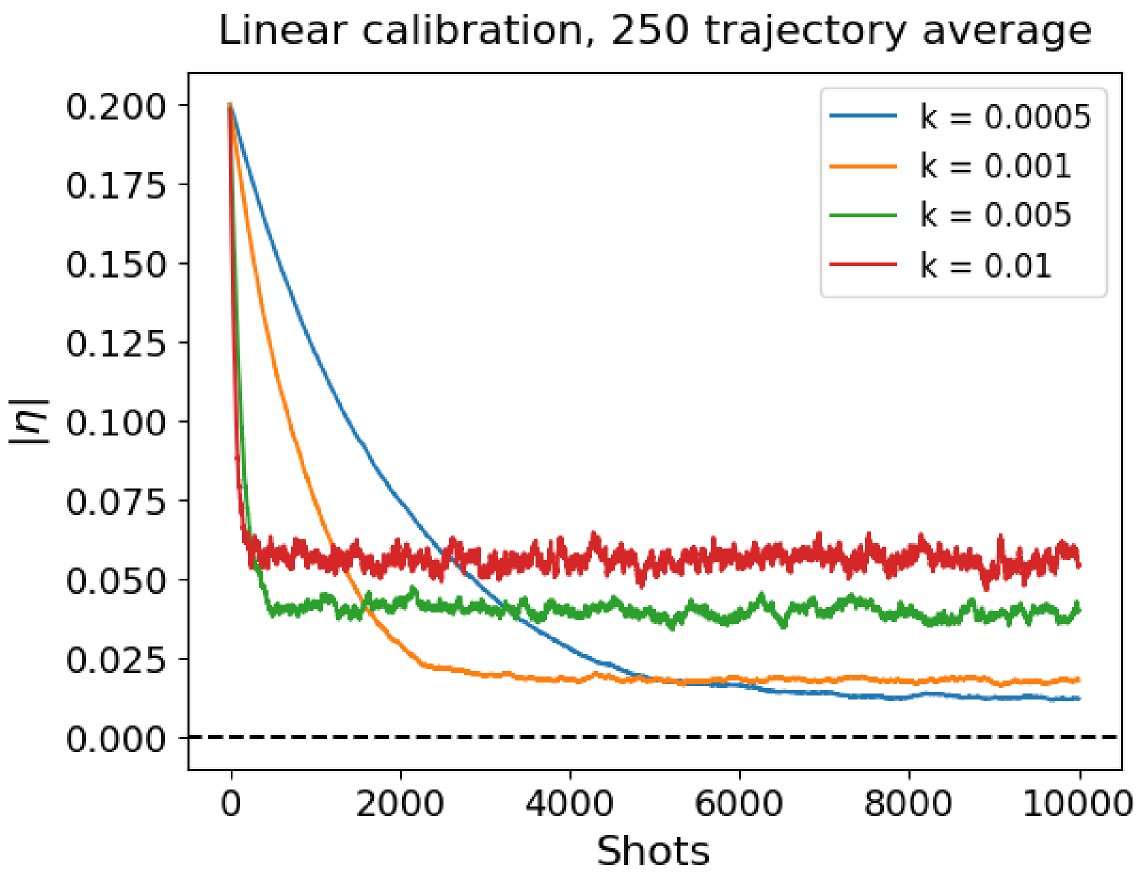
```
function gate_R_custompi(parameters::Dict{String,Any},qubit::Float64, theta::Float64, args3::Float64)
    calibrated_pi_time=get(parameters, "calibrated_pi_time", 20e-6)
    Gate(PulseData(remap_qubit(parameters, qubit), calibrated_pi_time*abs(theta)/pi;
                   amp0=Discrete([9.5]),
                   amp1=Discrete([98.5]),
                   freq0=Discrete([200e6]),
                   freq1=Discrete([230e6]),
                   phase0=Discrete([args3]),
                   framerot0=Discrete([10.0]),
                   ForwardFrame0Tone0=true,
                  ))
    # return
end
```

QUESTIONS?

EMAIL: NEMILL@SANDIA.GOV / NATHAN.MILLER@GATECH.EDU

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.

LINEAR CALIBRATION CONVERGENCE



Gain	Mean of $\|\eta\|$	σ^2 of $\|\eta\|$
0.0005	0.01259	2.575e-7
0.001	0.01794	3.550e-7
0.005	0.03975	4.274e-6
0.01	0.05608	7.268e-6

Large gains converge quickly but poorly. This motivates gain and sensitivity scheduling, for fast convergence and reduced mean and stationary variance of η.

MORE QUADRATIC SPAM EXPERIMENTS