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Characterizing mid-circuit measurements with a new form of gate set tomography. Part II: Experiment

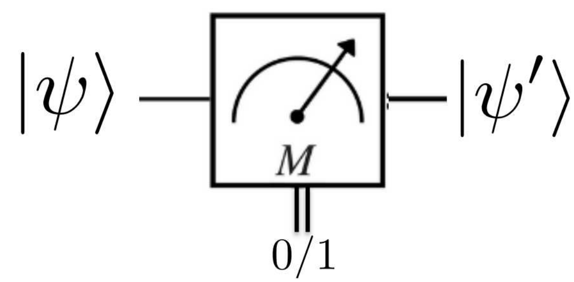
Guilhem Ribeill[1], Matthew Ware[1], Luke Govia[1], Kenneth Rudinger[2], Timothy Proctor[2], Erik Nielsen[2], Thomas Ohki[1], Kevin Young[2], Robin Blume-Kohout[2]

[1] Quantum Engineering and Computing, Raytheon BBN
[2] Quantum Performance Laboratory, Sandia National Laboratories

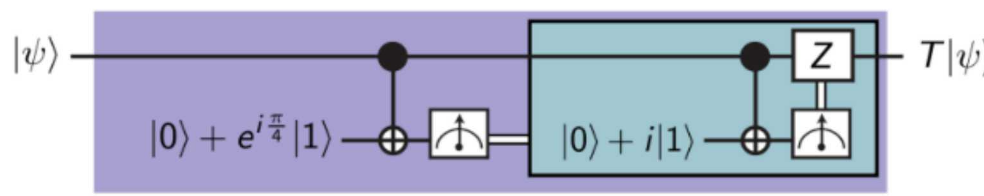
APS March Meeting 2020 – guilhem.ribeill@raytheon.com

Characterizing Intermediate Measurements

- Quantum error correction will require intermediate measurements while running circuits.
- We cannot assume that these are the same operations as the terminating measurements we use in QCVV protocols.

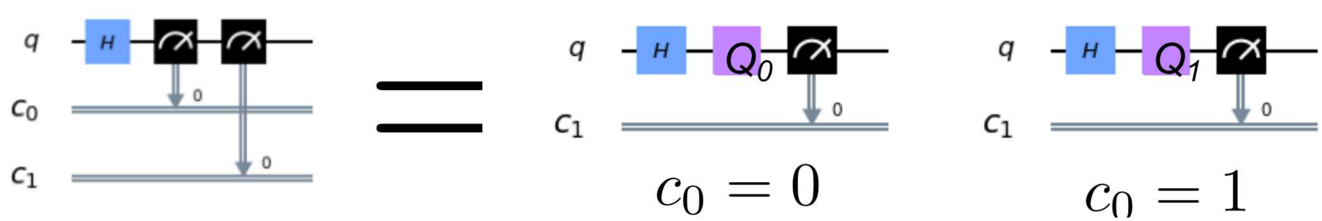


- Intermediate measurement errors can corrupt the quantum state or the classical state; want formalism to model all the possible error channels

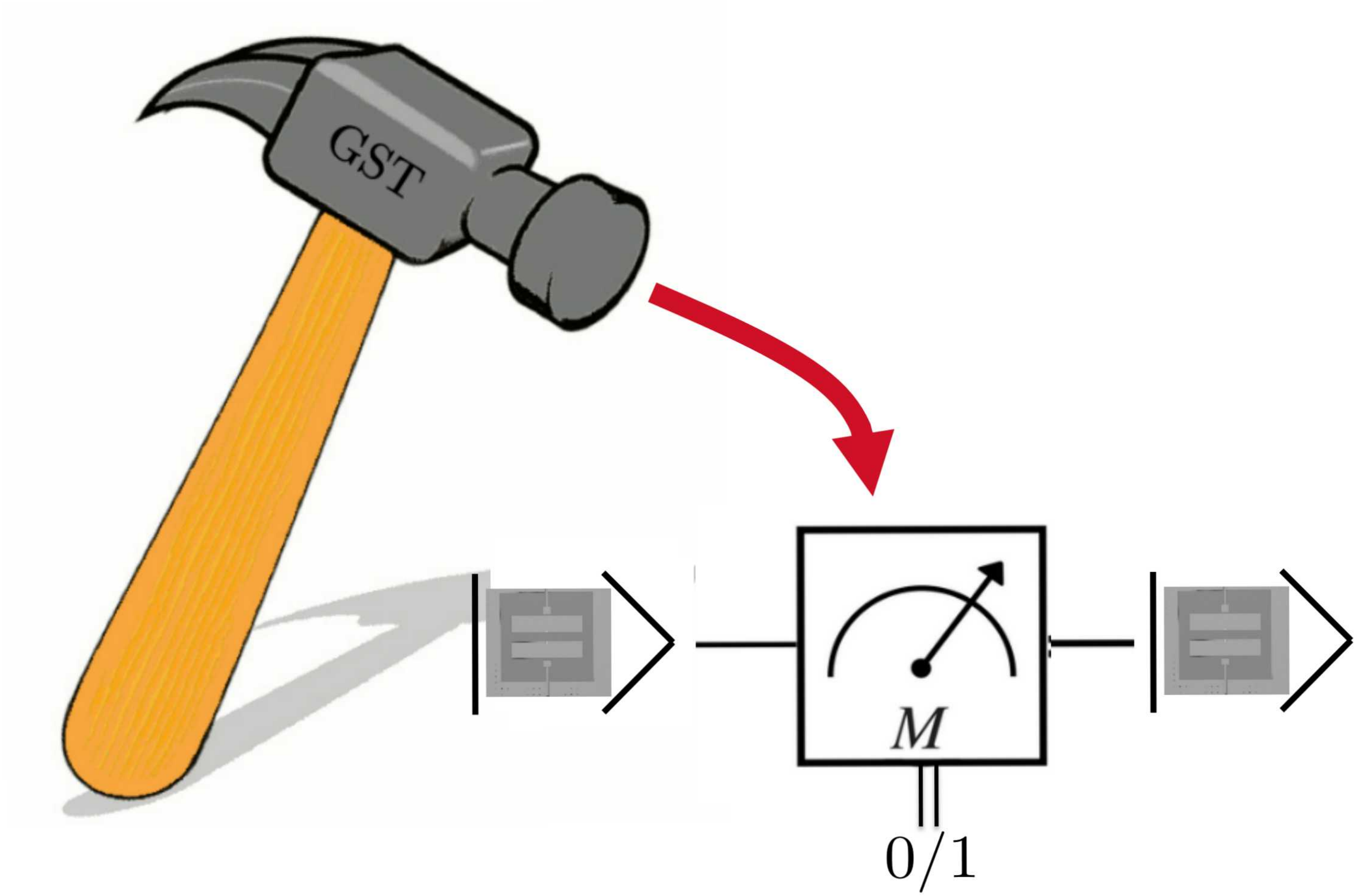


Ex: measurement-based T-gate

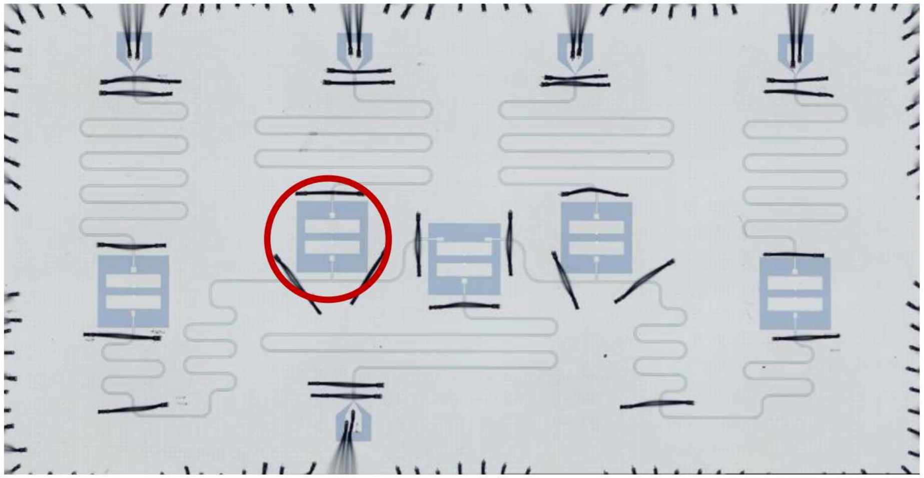
Extend the formalism of process matrices to *Quantum Instruments*

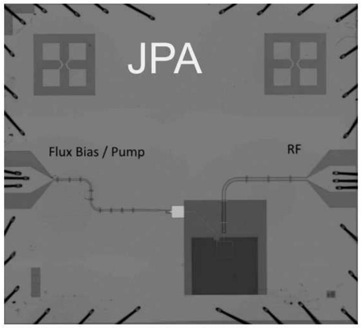


This talk



The system





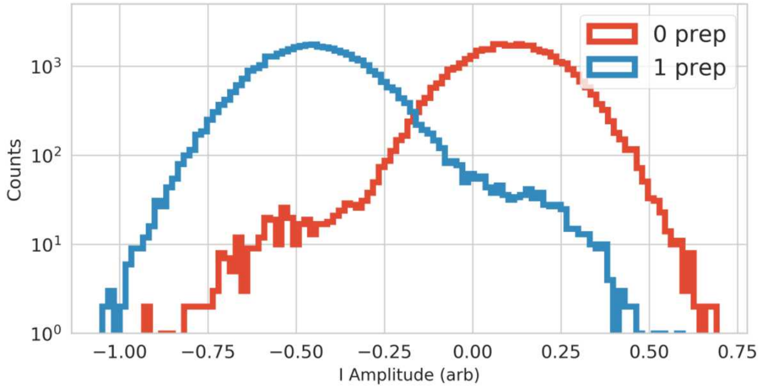
(typical, 24-hr average)

Device parameters	
T_1 (μs)	90
T_2^* (μs)	40
T_2^{echo} (μs)	105
F_{gate} (1Q, RB)	99.97 %
F_{gate} (2Q, RB)	95.6 %
$F_{readout}$	96 %

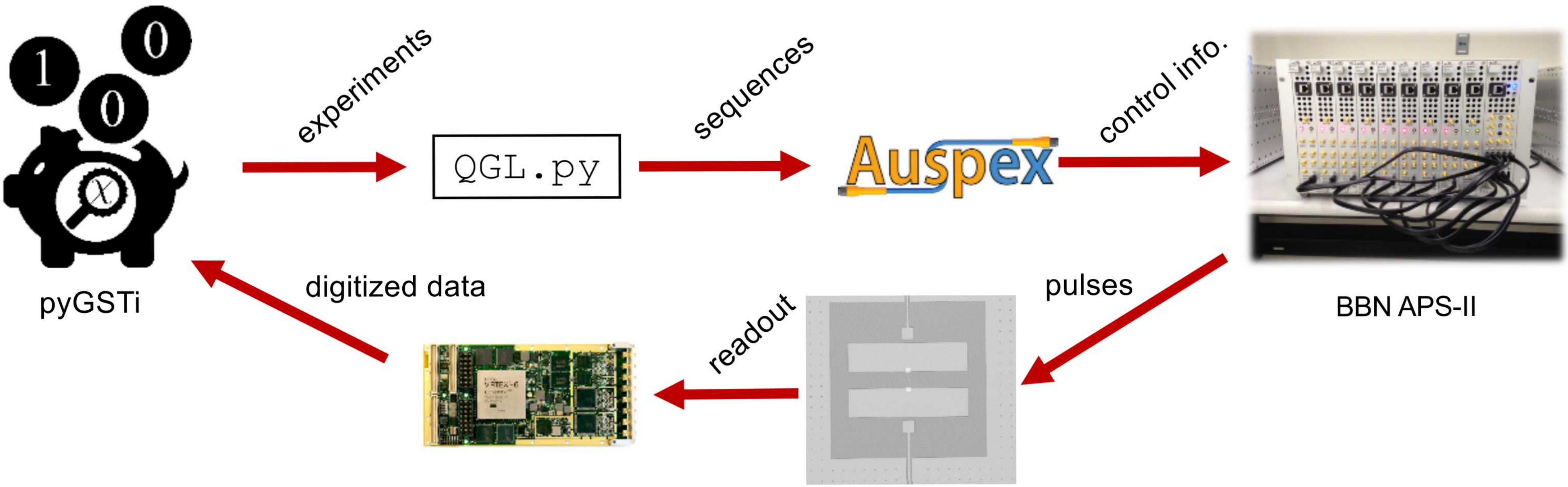
One qubit of BBN 5-qubit (fixed freq. transmon) device.

Standard cQED readout with BBN JPA
(18 dB gain, 300 MHz BW, Tn = 290 mK) for high fidelity in dispersive regime.

t_{meas} = 1 μs
t_{gate} = 60 ns



The software and hardware



Open-source control stack:

https://github.com/pyGSTio/pyGSTi
https://github.com/BBN-Q/QGL
https://github.com/BBN-Q/Auspex
https://github.com/BBN-Q/libaps2
https://github.com/BBN-Q/BBN-QDSP-X6

QILGST

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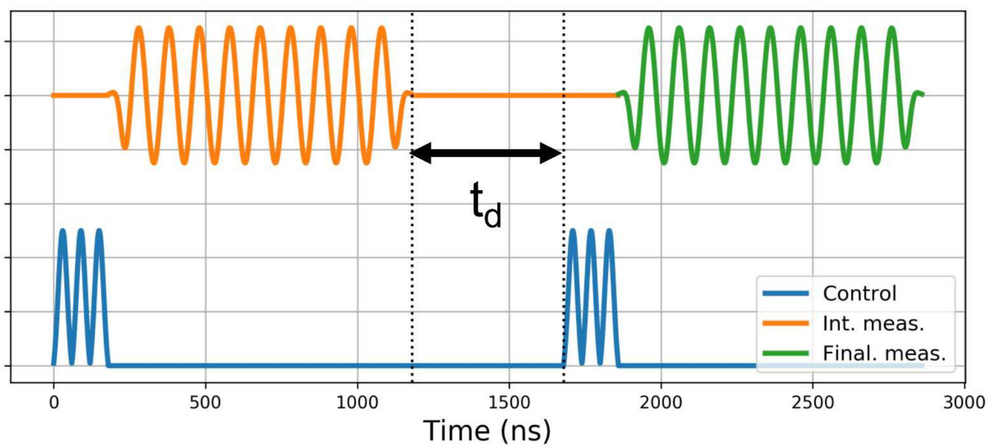
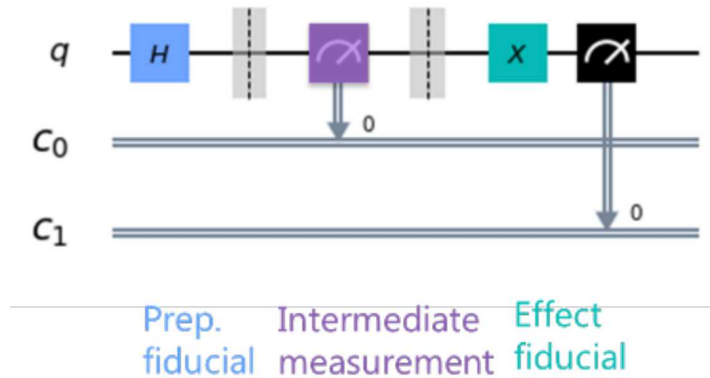
GST experiments with an intermediate measurement ("Iz") in the gate set.

L=1 GST: 128 circuits, of which 58 have an Iz

Example: $Y_{\frac{\pi}{2}} Y_{\frac{\pi}{2}} Y_{\frac{\pi}{2}} I_z X_{\frac{\pi}{2}} X_{\frac{\pi}{2}} X_{\frac{\pi}{2}}$



t_d : 500 ns minimum delay between Iz and next measurement to prevent measurements that are "too close". Annoying but fixable electronics limitation.



Collect 4096 shots per circuit in rastered fashion to minimize effect of drift.

Record joint probabilities of both measurements.

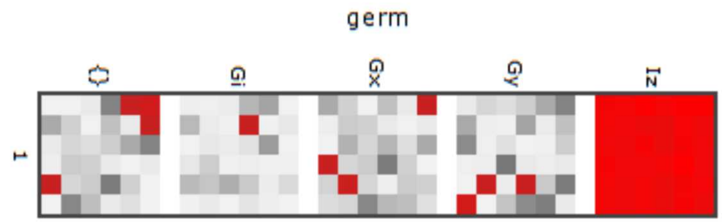
About 10 minutes per experiment.

What do we see?

First, look at “model violation”: how well does our model of a single gateset describe the data?

Not well at all: Nσ = 400

Gates also look bad?



QILGST goodness of fit

What do we see?

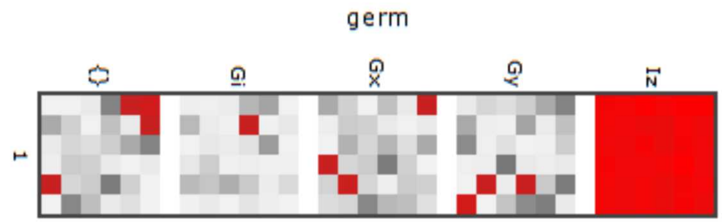
First, look at “model violation”: how well does our model of a single gateset describe the data?

Not well at all: Nσ = 400

Gates also look bad? No!

Gates are not non-Markovian. **Nσ = 2**

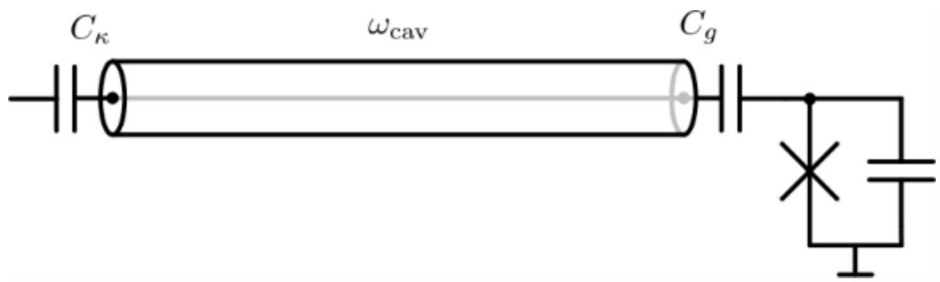
Something is different between gates before and after the Iz…



QILGST goodness of fit

LGST goodness of fit (same data)

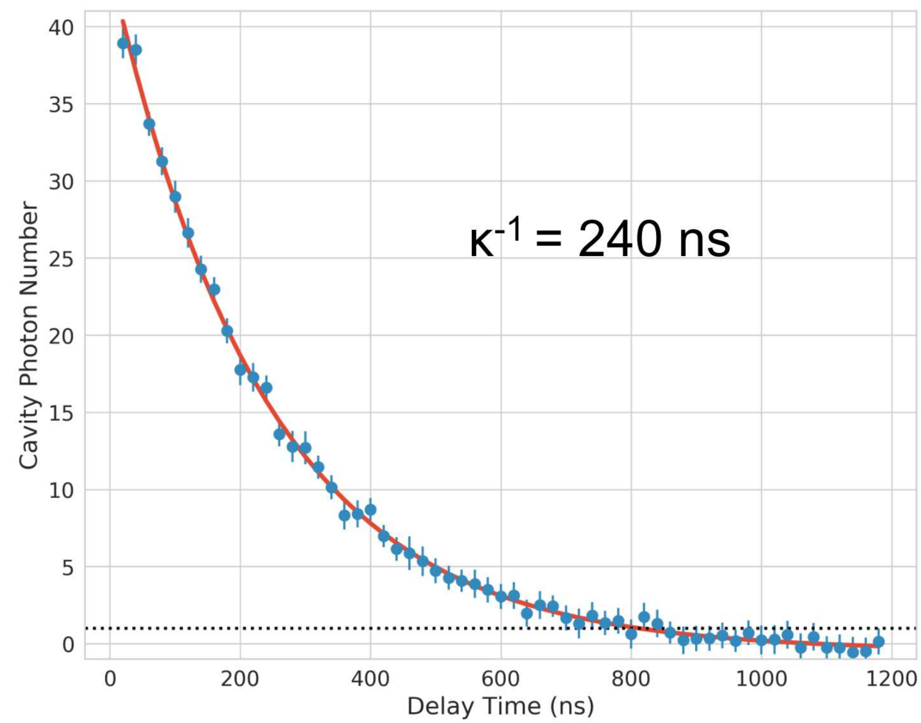
What's going on in the cavity, anyways?



Circuit QED readout is not so simple… qubit is addressed through high Q cavity. And we are measuring dressed states of the system anyways!

Measure photon population in cavity:
    38 photons in steady state (dispersive)

But! Cavity decays over significant amount of time compared to gates.

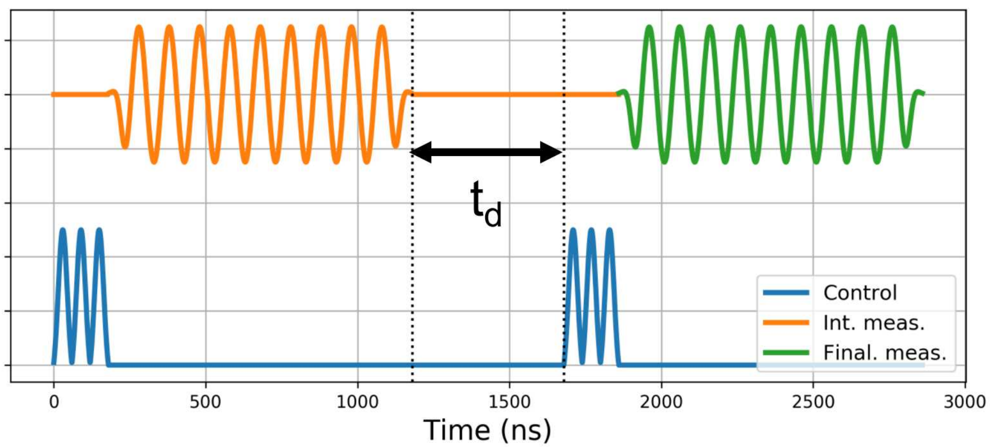


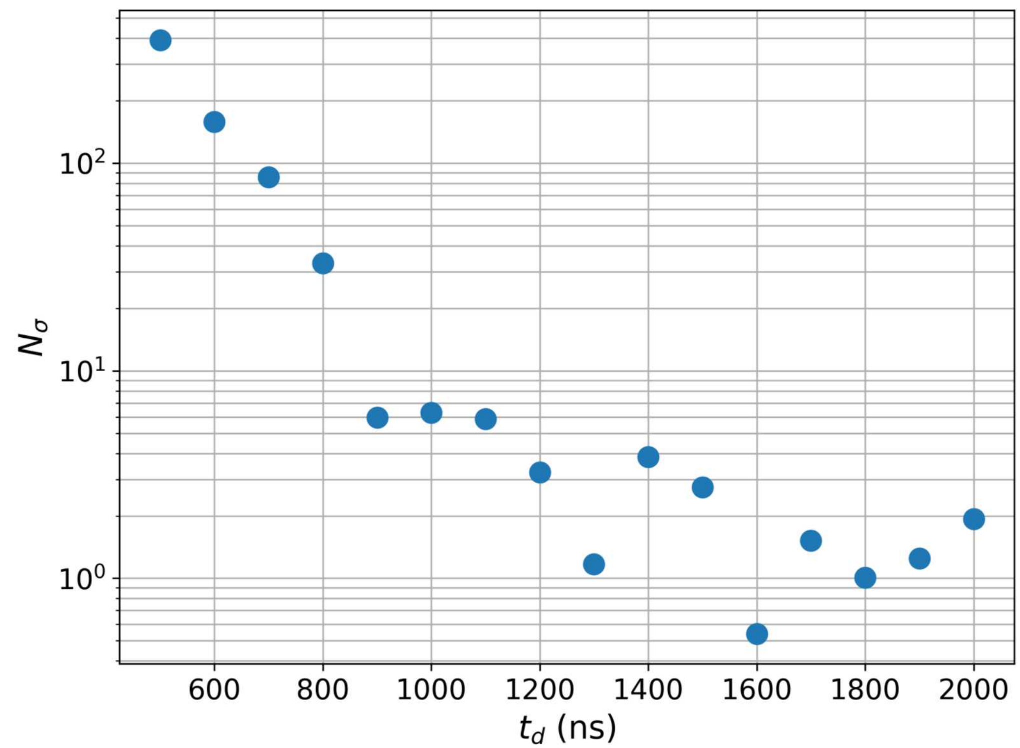
Investigate further…

Sweep time delay to see how waiting after Iz affects the GST reconstruction.

Recover good fit to model as expected.

QILGST needs to consider context-dependence of gates: work in progress!





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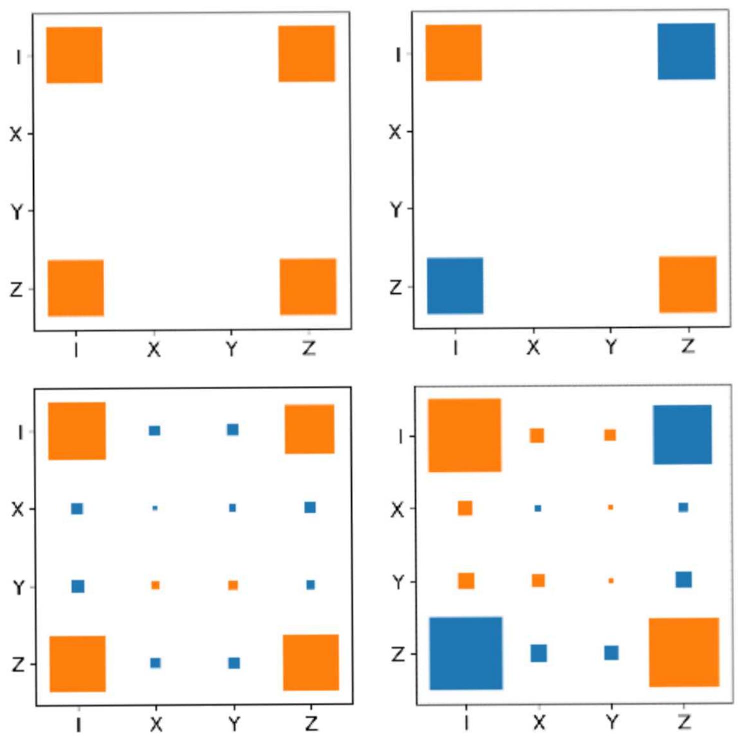
More details

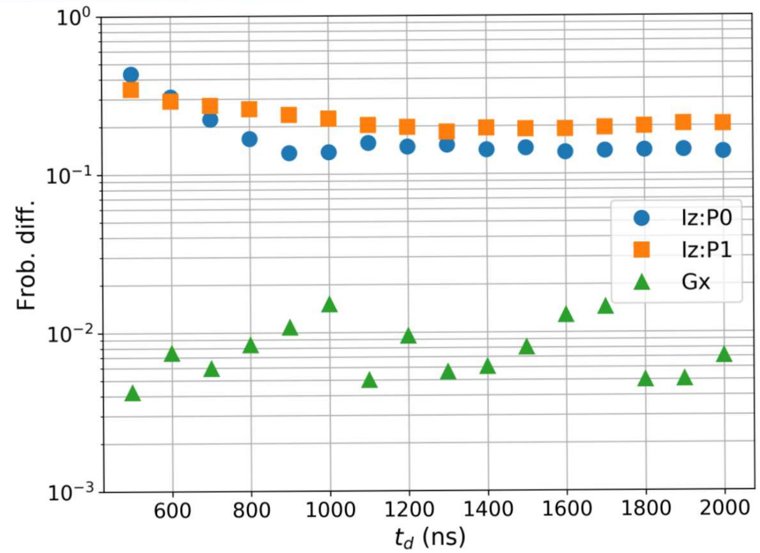
Iz:p0 Iz:p1

target

QILGST
1200ns



QILGST estimates of our quantum instrument

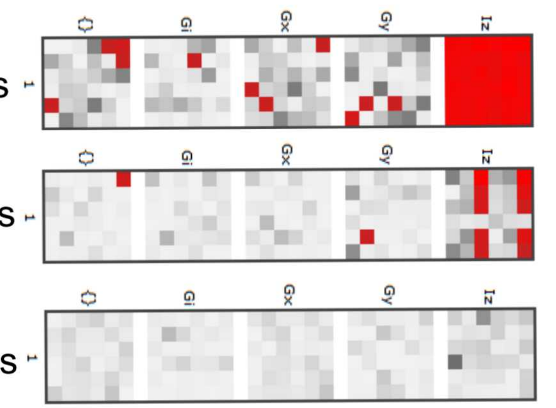


t_d

500ns

700ns

1200ns



Future directions and summary

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- Working on cavity reset protocols (CLEAR, etc…)
- Wildcard errors to better capture effect of intermediate measurements on subsequent gates.
- Thinking about "error rates" applicable to QEC protocols
- What does QILGST tell us about our device and our models?
- Extensions to more than one qubit, L > 1 GST

- **Intermediate measurements are a key ingredient in QEC protocols; we should assume they are a 'solved' problem!**

Questions? guilhem.ribeill@raytheon.com kmrudin@sandia.gov

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Raytheon BBN: Andrew Wagner, Brian Hassick, Diego Ristè, Graham Rowlands, Spencer Fallek
Raytheon IDS: Pam Saledas, Ram Chelakara

Backups

Dataset comparisons

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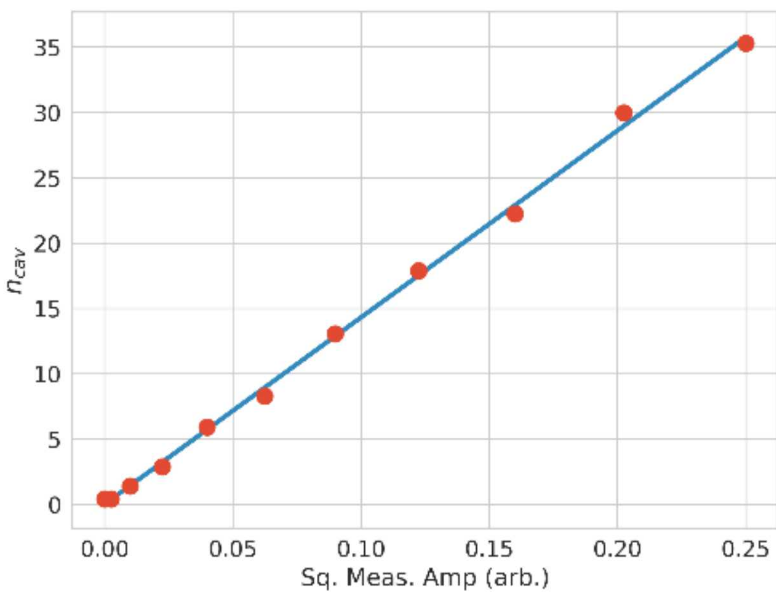
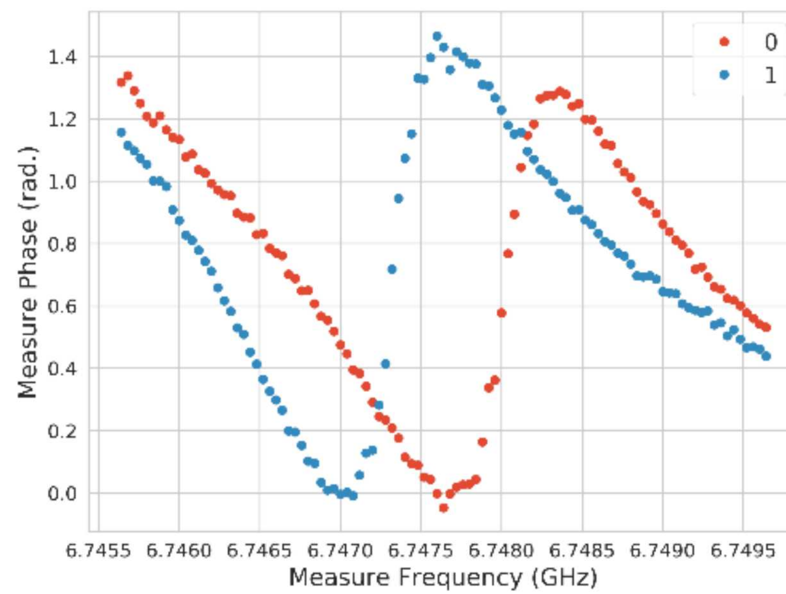
Dataset 1 (columns) vs. Dataset 2 (rows)

Dataset 2 \ Dataset 1	0500	0600	0700	0800	0900	1000	1100	1200	1299	1400	1500	1600	1699	1799	1900	2000
0500		35.1	99.7	141.8	171.8	190.2	182.7	194.6	185.0	188.1	181.4	190.3	192.7	188.9	187.0	187.2
0600	35.1		4.3	29.1	54.5	75.0	78.4	83.9	74.1	69.5	65.3	73.3	77.4	73.4	73.5	70.8
0700	99.7	4.3		-4.3	14.2	31.3	39.3	40.6	32.1	25.5	24.2	29.0	32.3	29.5	30.1	27.3
0800	141.8	29.1	-4.3		-7.1	4.5	12.1	14.1	9.8	4.5	4.1	4.9	8.3	4.8	7.2	4.6
0900	171.8	54.5	14.2	-7.1		-9.7	-4.8	-2.3	-3.6	-6.7	-6.1	-6.6	-6.3	-7.8	-6.6	-7.3
1000	190.2	75.0	31.3	4.5	-9.7		-10.8	-8.3	-7.8	-7.8	-7.7	-9.6	-9.9	-11.2	-10.3	-10.1
1100	182.7	78.4	39.3	12.1	-4.8	-10.8		-12.1	-10.3	-7.9	-8.4	-10.2	-11.1	-11.7	-10.8	-10.5
1200	194.6	83.9	40.6	14.1	-2.3	-8.3	-12.1		-10.8	-10.0	-8.4	-9.9	-11.8	-11.4	-10.9	-10.0
1299	185.0	74.1	32.1	9.8	-3.6	-7.8	-10.3	-10.8		-11.8	-11.9	-11.8	-12.2	-11.6	-11.0	-11.1
1400	188.1	69.5	25.5	4.5	-6.7	-7.8	-7.9	-10.0	-11.8		-12.7	-11.5	-11.4	-11.8	-11.6	-11.8
1500	181.4	65.3	24.2	4.1	-6.1	-7.7	-8.4	-8.4	-11.9	-12.7		-11.6	-11.3	-12.9	-11.5	-11.1
1600	190.3	73.3	29.0	4.9	-6.6	-9.6	-10.2	-9.9	-11.8	-11.5	-11.6		-13.2	-13.3	-12.2	-12.5
1699	192.7	77.4	32.3	8.3	-6.3	-9.9	-11.1	-11.8	-12.2	-11.4	-11.3	-13.2		-13.0	-12.2	-12.0
1799	188.9	73.4	29.5	4.8	-7.8	-11.2	-11.7	-11.4	-11.6	-11.8	-12.9	-13.3	-13.0		-13.3	-12.5
1900	187.0	73.5	30.1	7.2	-6.6	-10.3	-10.8	-10.9	-11.0	-11.6	-11.5	-12.2	-12.2	-13.3		-12.1
2000	187.2	70.8	27.3	4.6	-7.3	-10.1	-10.5	-10.0	-11.1	-11.8	-11.1	-12.5	-12.0	-12.5	-12.1	

Stark Shift



35
30
25
20
15
10
5
0
n_{cav}
0.00
0.05
0.10
0.15
0.20
0.25
Sq. Meas. Amp (arb.)



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Measure Phase (rad.)
6.7455
6.7460
6.7465
6.7470
6.7475
6.7480
6.7485
6.7490
6.7495
Measure Frequency (GHz)
0
1