Automation and Control of a Superconducting Quantum Processor

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Presentation Overview

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    - Measurement
    - Benchmarking
    - DRAG Modulation
2. Building Blocks
    - ALLXY Calibration
    - Improvement with DRAG
    - ORBIT Tune-up
3. Bringing Everything Together
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    - Pulse Calibration
    - Benchmarking
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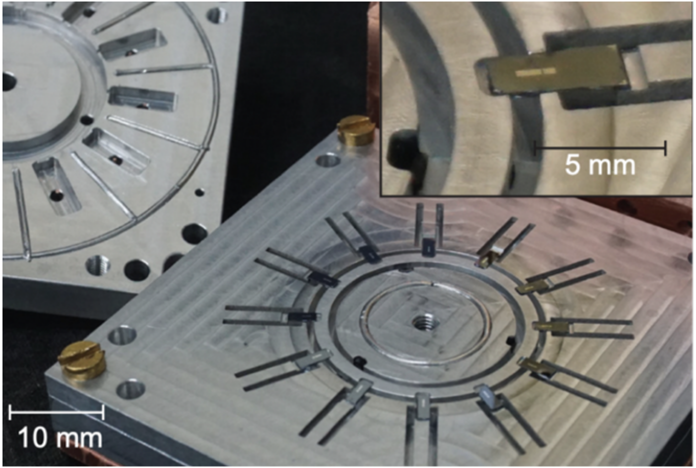
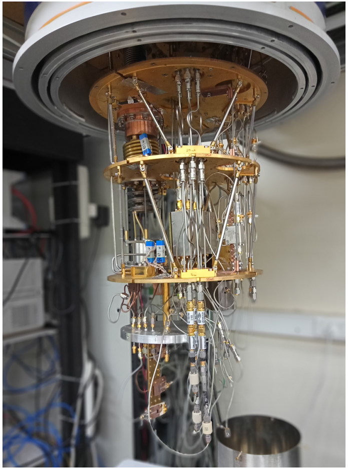
Superconducting QPU

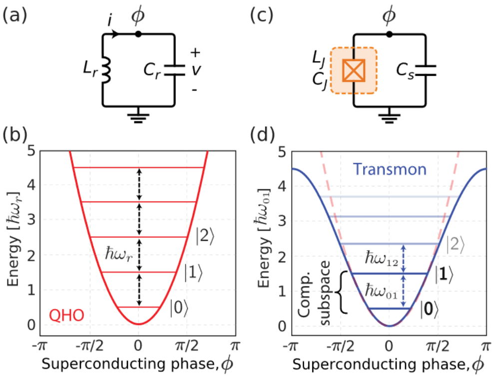


(a) Ring resonator with qubits

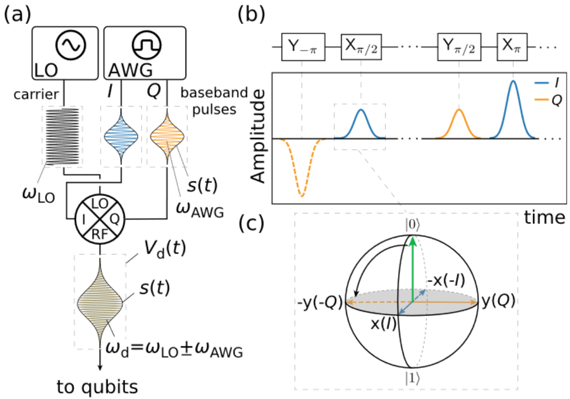


(b) Dilution fridge

The Transmon Qubit



(a) Transmon vs QHO

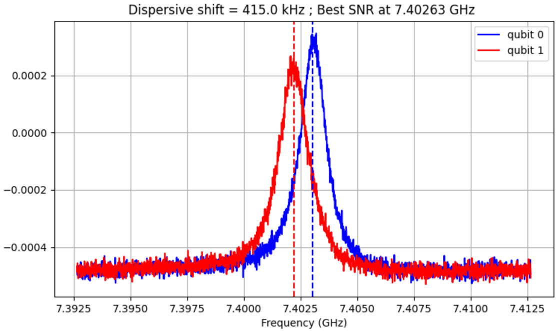


(b) Driving a qubit

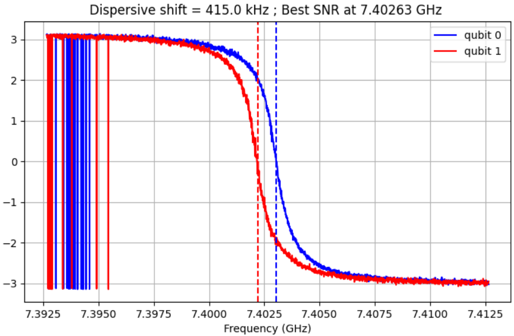
Figure: Taken from Krantz et al., 2019

Dispersive Readout

Dispersive readout maps the quantum degree of freedom of the qubit onto the classical response of the linear resonator. The qubit state induces a phase shift in the readout resonator response.



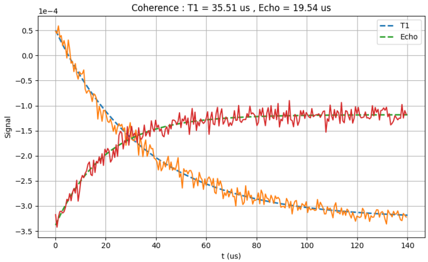
(a) Real response



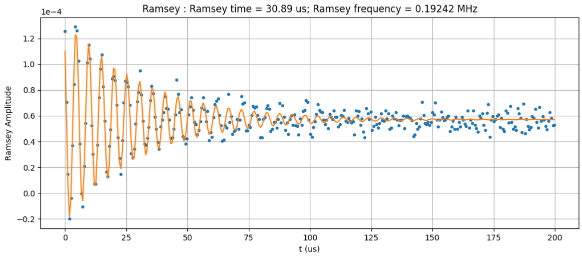
(b) Phase response

Qubit Coherence

The T1, Ramsey and Echo experiments characterize qubit decoherence due to longitudinal relaxation, pure dephasing and transverse relaxation.



(a) T1 and Echo time

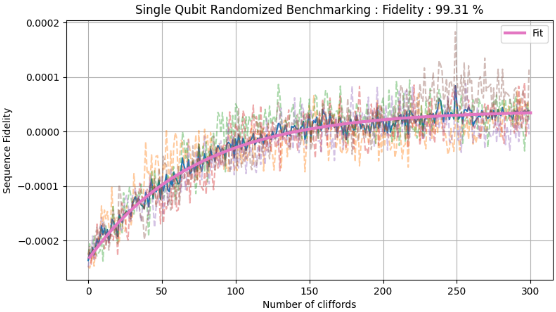


(b) Ramsey time

- T_1 measures longitudinal (energy) relaxation.
- T_2^* (Ramsey) and T_{2E} (Echo) measure transverse relaxation (decoherence).

Clifford-based Randomized Benchmarking

- The Clifford group consists of π and $\pi/2$ pulses along X and Y as well as the identity operation.
- In RB, random sequences of Clifford operations of varying lengths are run on the qubit and ensemble-averaged.
- Each sequence is suffixed with an inverse gate $\Rightarrow$ deviation from identity operation is infidelity.



Derivative Removal by Adiabatic Gate (DRAG)

If the spectral content of our drive overlaps with $1 \rightarrow 2$ transition, we see:

1. **Leakage errors:** Qubit is taken out of computational subspace.
2. **Dephasing errors:** Drive creates a repulsion between $|1\rangle$ and $|2\rangle$ levels.

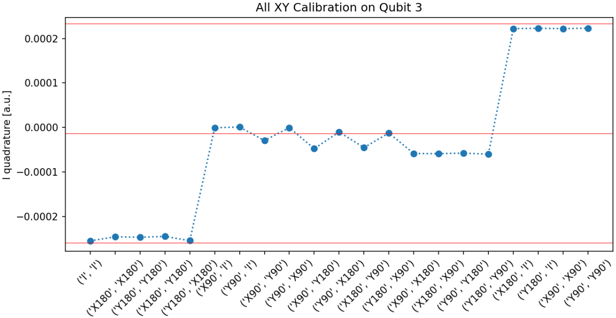
DRAG (Motzoi et al., 2009) corrects this by applying an extra signal in the out-of-phase component.

$$s(t) \rightarrow s'(t) = \begin{cases} s(t) & \text{on} \quad I \\ \lambda \frac{\dot{s}(t)}{\alpha} & \text{on} \quad Q \end{cases}$$

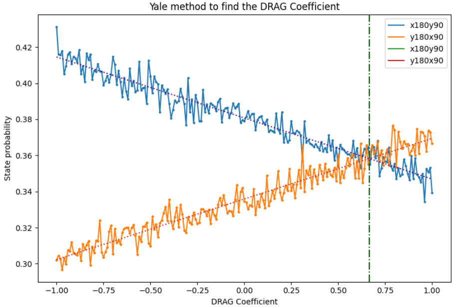
The theoretically optimal choice for reducing dephasing error is $\lambda = 0.5$ and for reducing leakage error is $\lambda = 1$.

ALLXY Pulse Calibration

All combinations of one or two single-qubit rotations from the Clifford group are performed on a qubit. Each pulse combination is sensitive to various errors to varying degrees. Each error carries a distinctive signature deviation from the ideal response $\Rightarrow$ simultaneous diagnosis of multiple linearly independent errors (Reed, 2013).



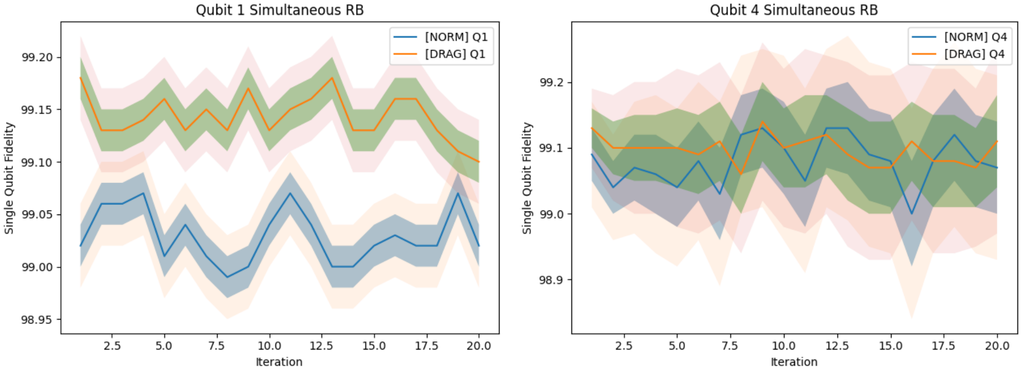
(a) ALLXY Error Syndrome



(b) DRAG parameter calibration

Improvement with DRAG Pulses

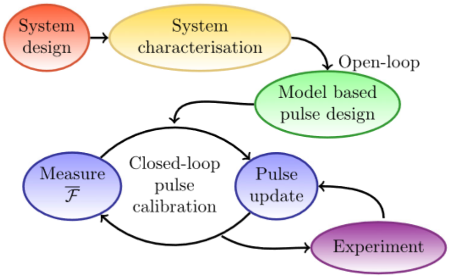
A pair of qubits were *simultaneously* operated with and without DRAG modulation to observe the improved robustness to leakage. RB variation of 1σ and 2σ is shaded.



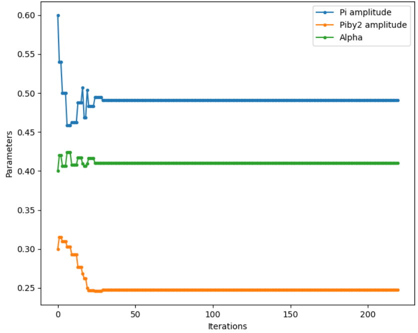
(a) Qubit 1 (High SNR) (b) Qubit 4 (Low SNR)

Ad-HOC and ORBIT Tune-Up

The adaptation by hybrid optimal control (Ad-HOC, Egger and Wilhelm, 2014) protocol and optimized randomized benchmarking for immediate tune-up (ORBIT, Kelly et al., 2014) cost function can be used for closed-loop pulse calibration.



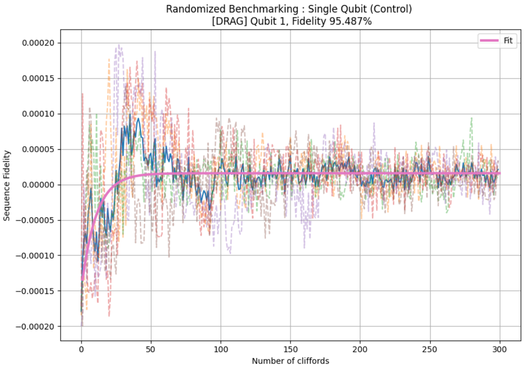
(a) The Ad-HOC protocol



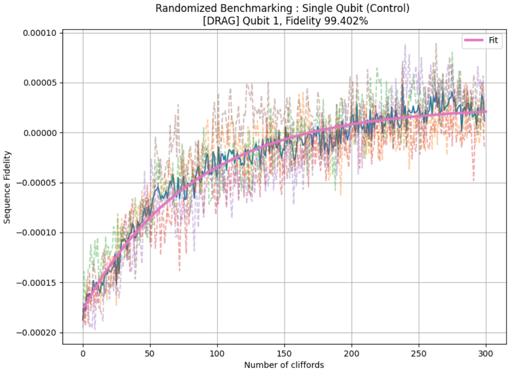
(b) ORBIT parameter convergence

Tune-up from poor initialization

ORBIT is able to tune up multi-parameter (π amp, $\pi/2$ amp, DRAG parameter) pulses even from very poorly initialized parameters to over 99% fidelity.

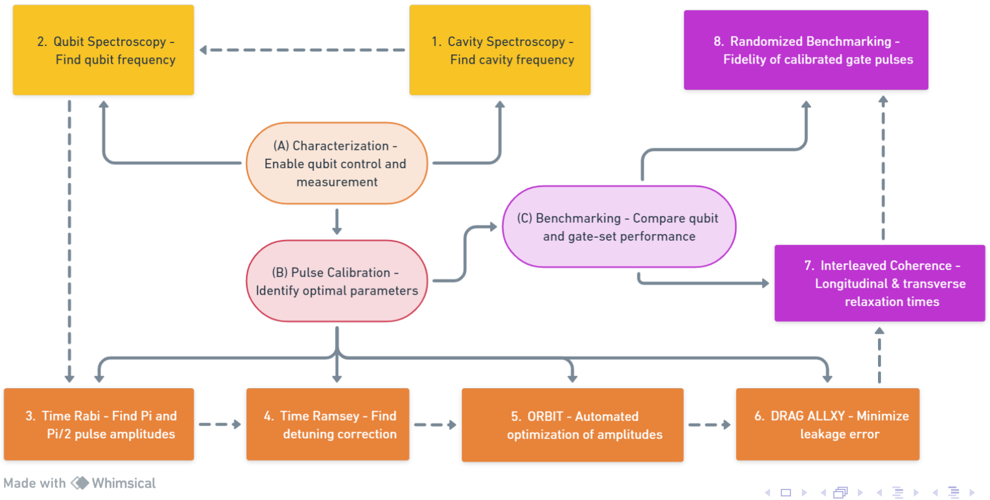


(a) Initial RB fidelity



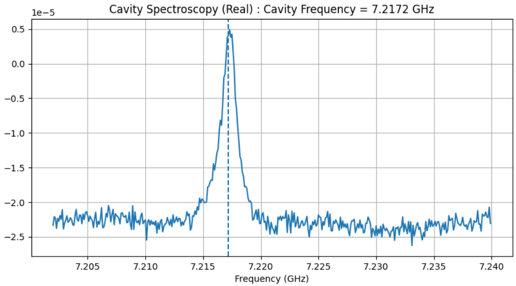
(b) Optimized RB fidelity

Integrated Tune-Up Protocol

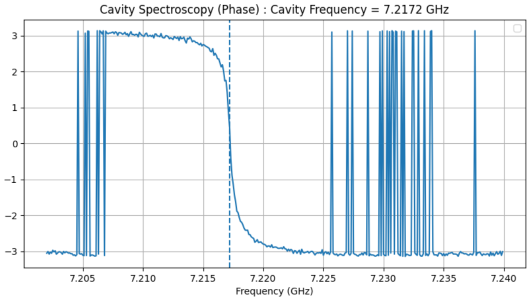


Cavity Spectroscopy

For ideal lossless cavities, all the reflected information will only be visible in the phase response. However, in practical cavities, one can use the peak in the real response to find the cavity resonance as well.



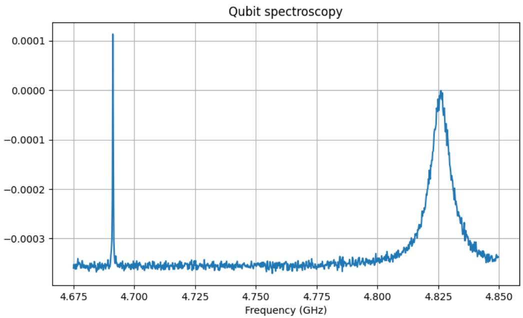
(a) Real response



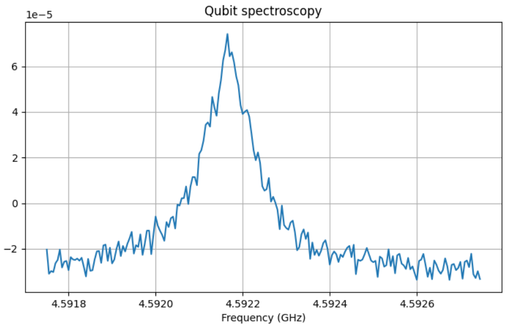
(b) Phase response

Qubit Spectroscopy

Qubit profiles are power sensitive and with sufficient intensity, the 2-photon $0 \to 2$ transition can be excited. This is a sharp narrow peak at half-anharmonicity detuning.



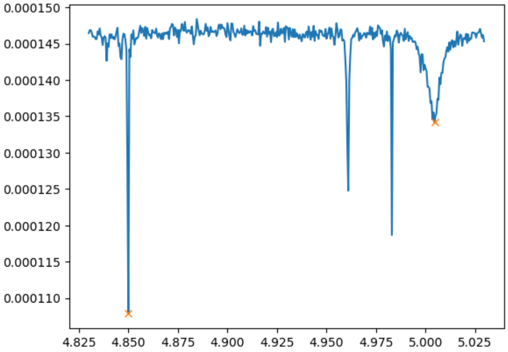
(a) Ideal spectroscopy scan



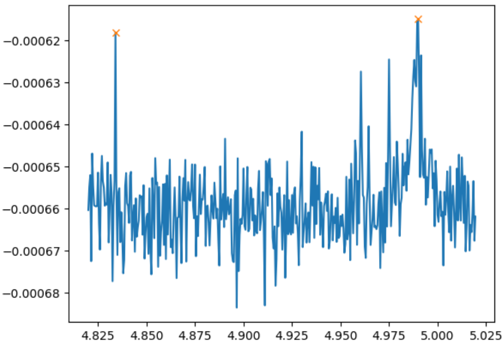
(b) Increased resolution at low power

Challenges in Spectroscopy

- At high powers, other transitions or spurious TLS may be excited.
- Low readout SNR requires noise robustness and longer averaging.



(a) Can have TLS or unknown transitions



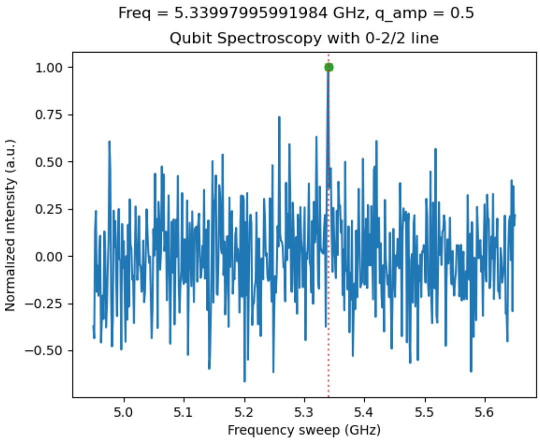
(b) Low readout fidelity and SNR data

AutoSpectroscopy

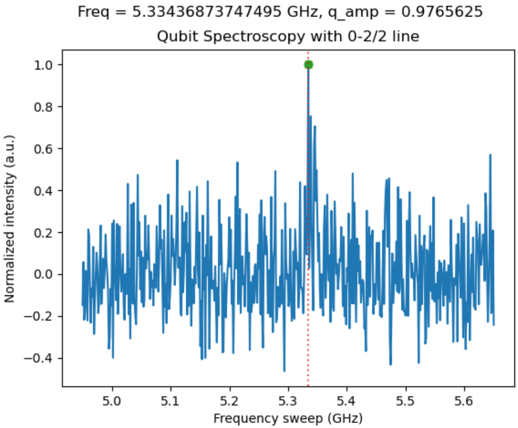
This protocol has characterized various qubit designs even with significantly noisy signals. It has 3 key functions:

1. **Signal-to-Noise Ratio (SNR):** Normalized signal is passed through a discrete, linear convolution filter with a window proportional to the sample population. SNR is the ratio of the power of the filtered signal and the rejected signal.
2. **Broad sweep:** A peak finding function discriminates the normalized signal on the basis of height and spacing between candidate peaks. The largest FWHM is likely to be the qubit. The sweep is repeated with a higher power if $(0-2)/2$ is not found, and the largest FWHM is tracked to confirm the qubit.
3. **Fine sweep:** The frequency span is narrowed and power reduced iteratively to sharpen the qubit peak and improve precision arbitrarily.

Broad Sweep



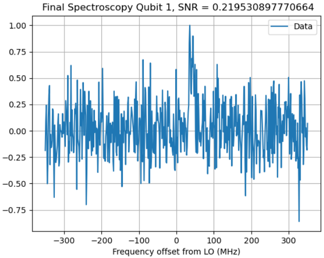
(a) $q_{amp} = 0.5$



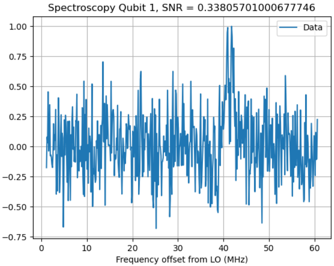
(b) $q_{amp} = 0.98$

Fine Sweep

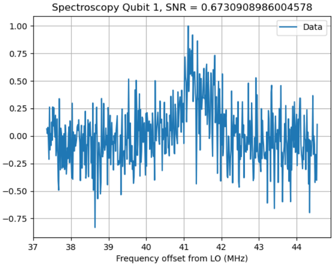
In very few iterations, one can gain precise spectroscopy analysis. As we fix on the qubit peak, the structure is easier to find and the SNR threshold reduces ensemble averaging time considerably.



(a) 700 MHz span

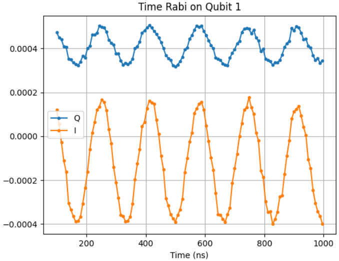


(b) 60 MHz span

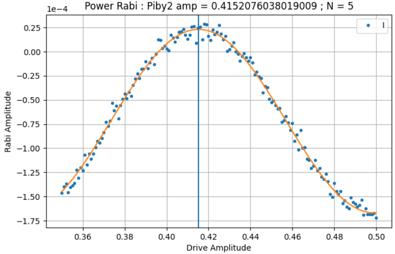


(c) 7 MHz span

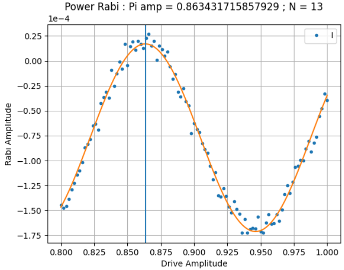
Rabi Oscillations



(a) Time Rabi experiment Oscillations in both I and Q if blobs overlap



(b) Power Rabi $\pi/2$ pulse low N $\Rightarrow$ broad peak, less precise

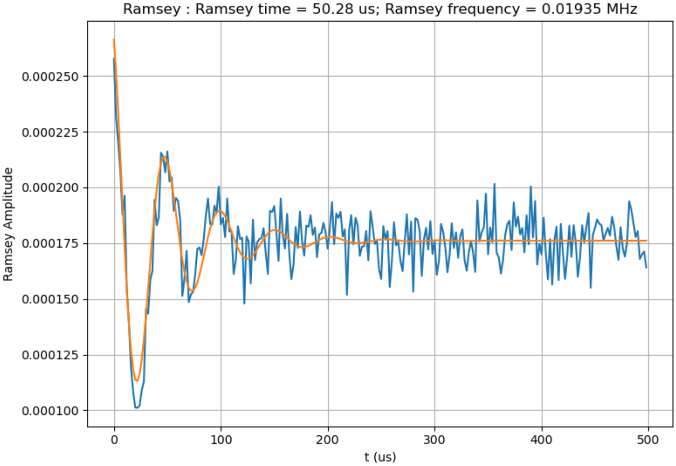


(c) Power Rabi π pulse high N $\Rightarrow$ narrow peak, more precise

Instead of the expensive Power Rabi amplitude calibration, we can take an initial guess based on the Rabi amplitude and frequency and scale appropriately for our desired pulse length to find the approximate pulse amplitude necessary for π pulse.

Ramsey Interferometry

- Run Ramsey with 20 KHz detuning $\Rightarrow$ the qubit will precess about the Z axis $\Rightarrow$ we see a beating in the decay.
- Beating (Ramsey) frequency should be exactly 20 KHz; any difference is used to precisely correct the qubit IF.



ORBIT Amplitude Calibration

We replace manual Power Rabi calibration for pulse amplitudes with the automated ORBIT tune-up. Observe how X and Y pulse amplitudes converge to distinct values, particularly for $\pi/2$ pulses, indicating asymmetry in evolution dynamics.

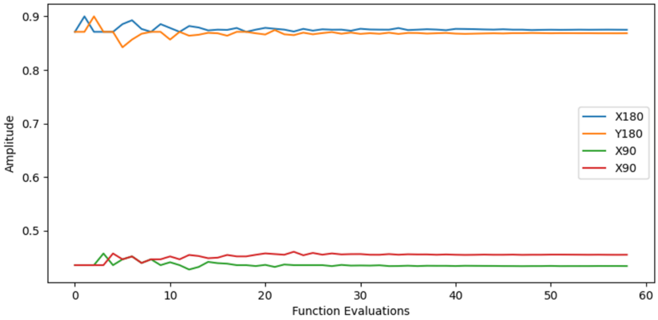
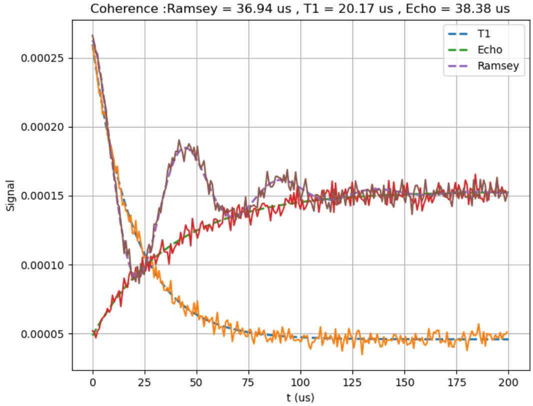
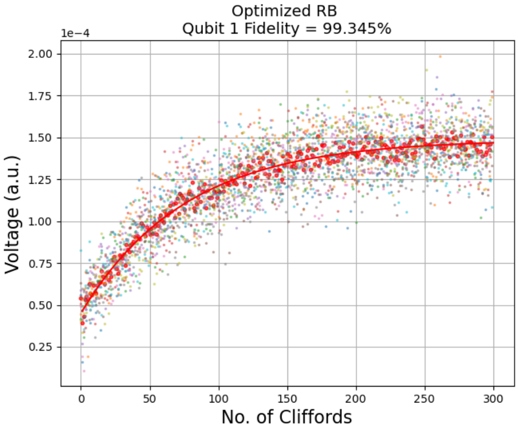


Figure: Parameter convergence for amplitudes of 4-tuple (X_π, Y_π, $X_{\pi/2}$, $Y_{\pi/2}$) pulses

Tuned-up Qubit



(a) Coherence at par with manual tune-up



(b) Randomized benchmarking fidelity over 99%

Conclusion

In this Bachelor's thesis, I have:

- Developed an integrated automated tune-up protocol for QPU operation.
- Demonstrated DRAG modulation, ALLXY benchmarking and ORBIT tune-up.
- Designed a custom AutoSpectroscopy tool robust to low SNR and spurious peaks.

Over the coming months, we plan to:

- Extend the automated tune-up protocol to the two-qubit Cross-Resonance gate.
- Benchmark QPU performance with simultaneous experiments.
- Incorporate robustness using a geometric error metric to address ZZ errors.

References

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- Motzoi, F. et al. (2009). "Simple Pulses for Elimination of Leakage in Weakly Nonlinear Qubits".
- Reed, Matthew (2013). Entanglement and Quantum Error Correction with Superconducting Qubits.
- Kelly, J. et al. (June 2014). "Optimal Quantum Control Using Randomized Benchmarking".
- Egger, D. J. and F. K. Wilhelm (June 2014). "Adaptive Hybrid Optimal Quantum Control for Imprecisely Characterized Systems".

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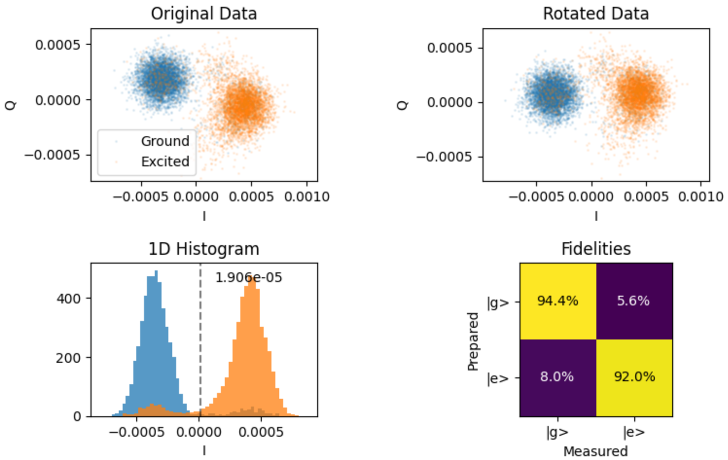
- I would also like to thank the larger QuMaC family, in particular Jay Deshmukh and Binoy Nambiar, for mentoring my journey so far.

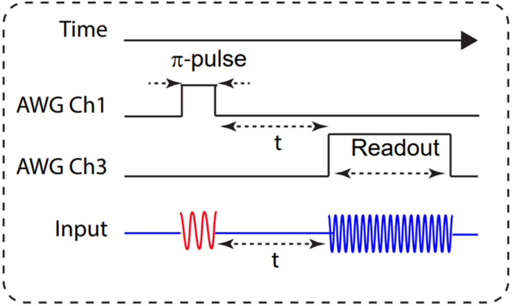
Single Shot Measurement

- If IQ blobs are well separated, single-shot measurement (and active reset) is possible.
- Rotate such that all information is along one axis (I or Q).
- If IQ blobs overlap, ensemble averaging is necessary.

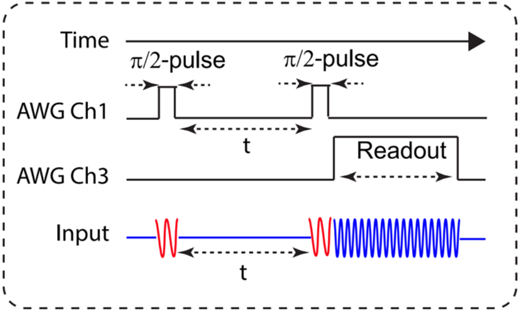


Coherence Measurement

The pulse protocols for the T_1 and Ramsey coherence experiments. Echo has a π pulse symmetrically between the Ramsey time delay to refocus dephasing errors.

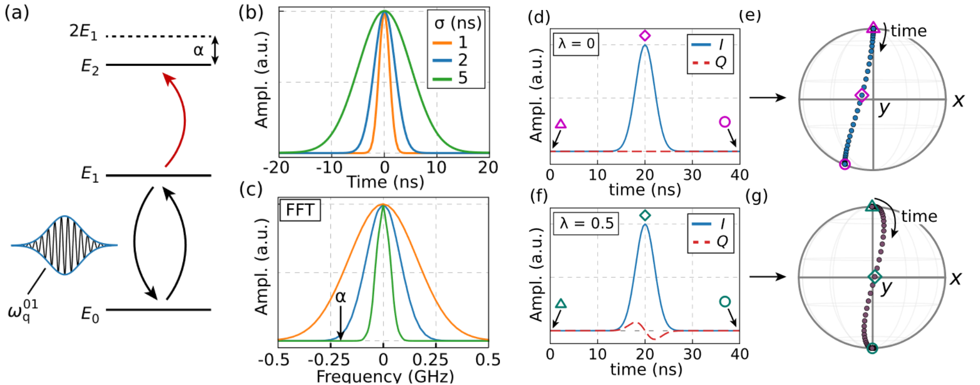


(a) T1 experiment



(b) Ramsey experiment

Leakage and Dephasing Correction



(a) Spectral overlap increases for short pulses (b) DRAG correction addresses dephasing

Figure: Taken from Krantz et al., 2019