Optimization of Chip Calibration on the QubiC Framework

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NEED for CALIBRATION

- **Ensures Precision Control of Qubits:** Calibrates control signals to qubits' frequencies.
- **Minimizes Computational Errors:** Adjusts for chip imperfections and external disturbances.
- **Maintains Entanglement and Coherence:** Fine-tunes interactions for qubit entanglement and prolongs coherence.
- **Boosts Algorithmic Efficiency:** Guarantees exact timing and synchronization of qubit operations.
- **Facilitates Scalability and Reproducibility:** Allows quantum algorithms to be consistently successful across various processors and configurations.

SUPERCONDUCTING TRANSMON CHIP

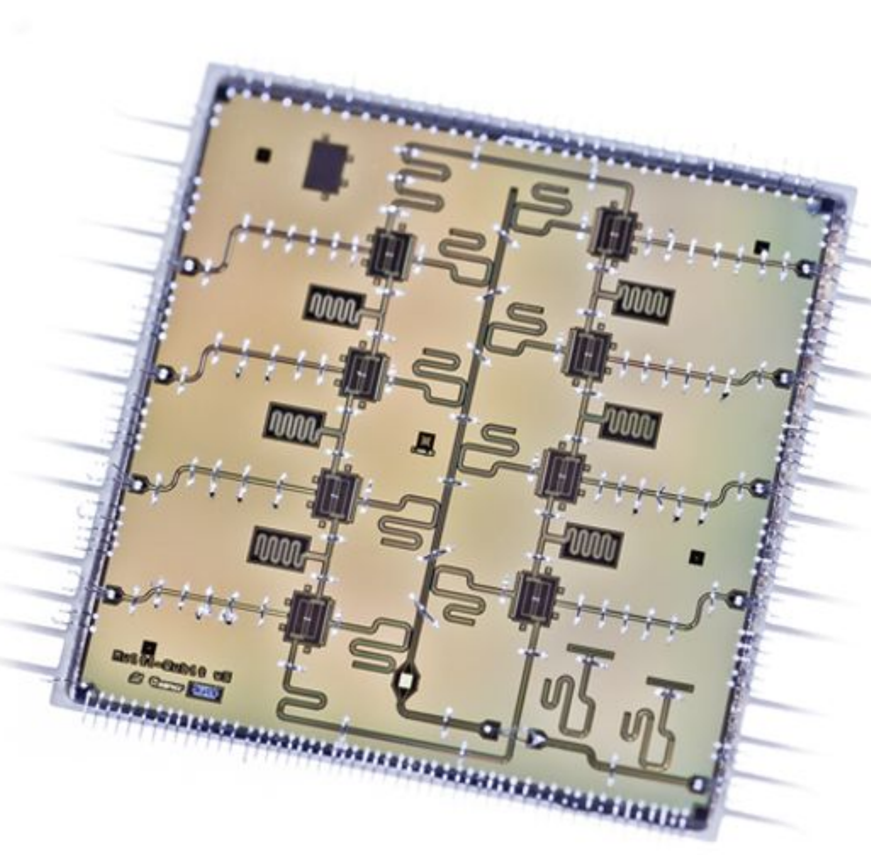


FIG. 1. 8-qubit superconducting Al-cored transmon chip (AQT)

Baseline AQT QPUs:

The current QPU available to users is the 8-qubit ring design chip. The specifications and typical parameters for this QPU are:

- Eight transmon qubits in ring, with nearest neighbor connectivity
- Resonance frequency range: 5.2-5.8 GHz
- Typical anharmonicity: 250 MHz
- Multiplexed readout with traveling-wave parametric amplification (TWPA)
- Three-state readout fidelities: >95%
- Coherence times: T1 ~ 100 μs, T2 Echo ~ 100 μs (with fluctuations)

Source: J M Kreikebaum et al 2020 Supercond. Sci. Technol. 33 06LT02

HARDWARE CONTROL

Zurich Instruments Devices

HDAWG (High Definition Arbitrary Wave Generator)
- Used for qubit control.
- Operating speed: 2.4 GSPS
- Bandwidth: 750 MHz.

UHFQA (Ultra High Frequency Quantum Analyzer)
- Used for qubit readout.
- Operating speed: 1.8 GSPS.
- Bandwidth: 600 MHz.

PQSC (Programmable Quantum System Controller)
- Orchestrates triggering and synchronicity among multiple devices.

Capabilities:
- Allows for fast, on-the-fly, detection, plus reset and fast feedback (less than a μs point-to-point).

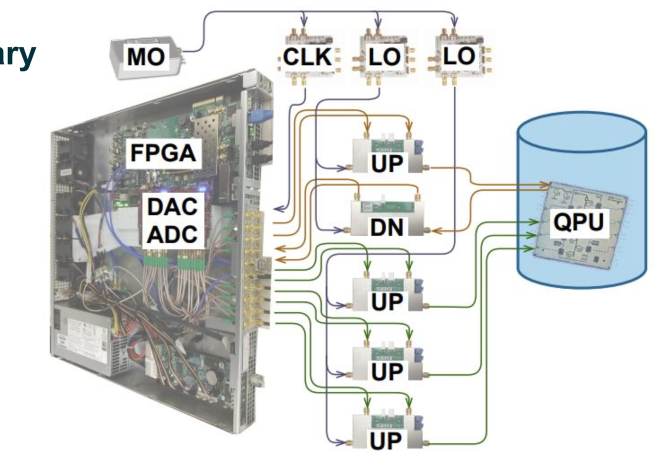


FIG. 2.

QubiC prototype hardware. MO: master oscillator, CLK: clock, LO: local oscillator, FPGA: field-programmable gate array, DAC: digital-to-analog converter, ADC: analog-to-digital converter, UP: up converter, DN: down converter, QPU: quantum processor unit. The yellow line indicates the measurement path, while the green line defines the qubit control path.

Source: Xu, et al, arXiv:2101.00071v3 [quant-ph] 2021

"Punch-Out"

- Formally known as one-tone or single-tone spectroscopy, "punch-out" is one of the first steps in qubit characterization/calibration and is used to determine whether a qubit is "alive" - functional and present.
- This process involves exciting a cavity/qubit system using high/low energy pulses and comparing cavity transmissions to determine the status of the qubit.
- Single-tone spectroscopy may also reveal information regarding the strength of coupling between the cavity and qubit and the qubit frequency relative to the cavity frequency.

Resonator Power Scan

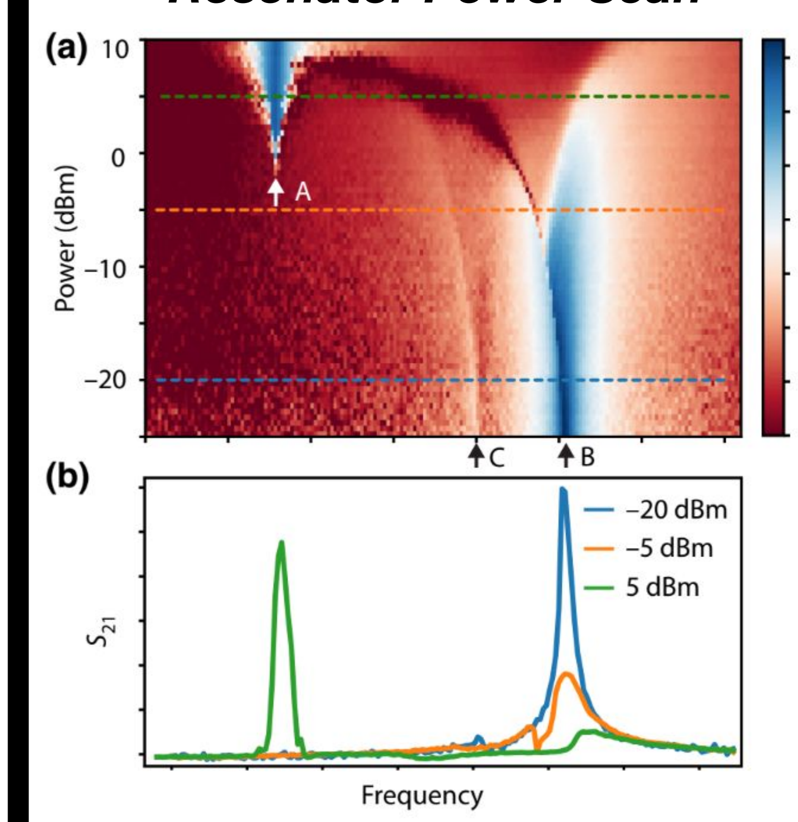


FIG. 3. (a) Cavity resonance (S_{21} color scale: blue=high, red=low) for varying power levels. **(b)** Differences in cavity transmission frequencies for transitions between critical high/low power regimes.

- **Frequency Shifts:** A change in the frequency of the cavity transmission resonance when probed with high/low power indicates the qubit is present and coupled with the cavity.
- **Nonlinear v. Linear Behavior:** When the system is probed with low power, the qubit is assumed to be in its ground state; the resulting cavity resonance is considered "dressed" - impacted by the nonlinear behavior of the qubit. When probed with high power, the qubit is "washed out" i.e. its impact on the cavity resonance is negligible - "bare".
- **"Punch-Out":** Shift in the frequency of cavity resonance for high/low probe signals - the presence of a qubit! The cavity is said to have "punched-out" when a shift is observed.

Source: Yvonne Y. Gao et al Practical Guide for Building Superconducting Quantum Devices

Q2 "Punch-Out"

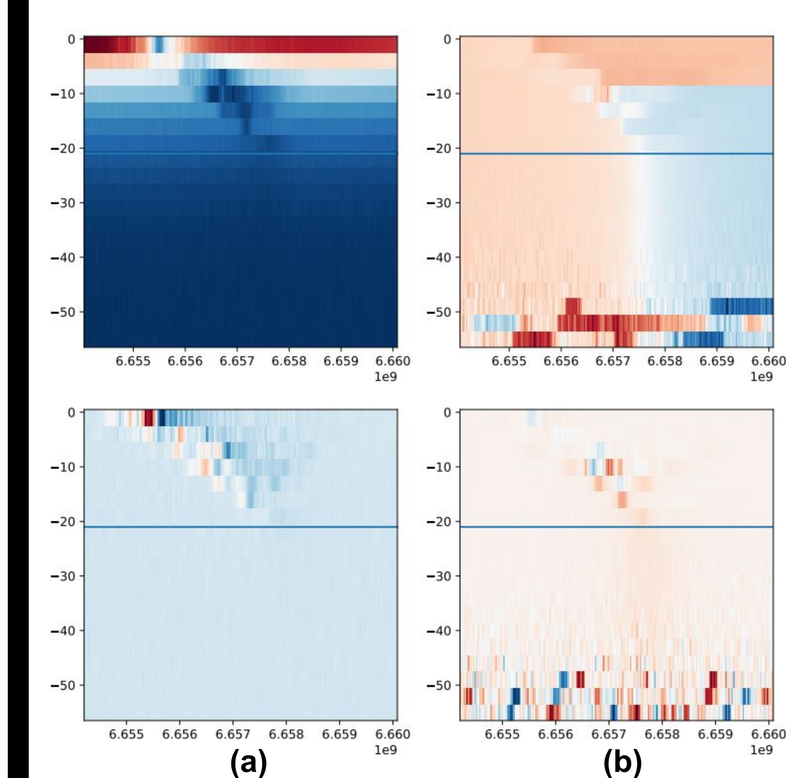


FIG. 4. (a) Amplitude of readout from cavity after probing with low power and amp difference. **(b)** Angle of readout and difference from baseline. Bottom left plot highlights frequency shift for low power drive - qubit detected!

- **Limitations:** Although single-tone spectroscopy provides a simple, easily reproducible procedure for detecting a qubit, to effectively calibrate and optimize a quantum system you need additional data the "punch-out" experiment cannot provide.
- **Two-Tone Spectroscopy:** Determine the qubit frequency by stimulating cavity with constant low power drive and sweep with an additional microwave signal until a shift in cavity transmission is detected. When excited with qubit frequency, the qubit will transition from ground state into an excited state and alter cavity transmission. This data is crucial for further system calibration.

"Chevron"

- A tool for visualizing and calibrating Rabi flopping (driving on resonance) between single or multi- qubit systems under controlled conditions.
- Useful for aligning the frequency and duration of the pulses to precisely control the quantum state transitions necessary for implementing gates.
- Used to fit a Gaussian Mixture Model (GMM) for state discrimination and to optimize the control parameters.

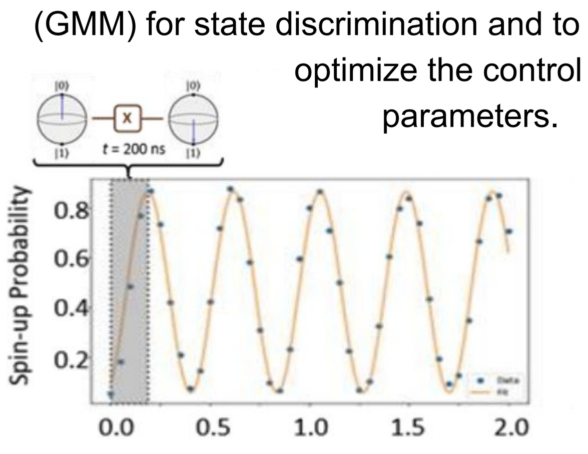


FIG. 5. Time-Rabi-based X-Gate definition

Source: Eendebak, et al. DOI: 10.1117/12.2551853 March 2020

INSIGHTS from the Plot of Frequency Response

- The clearest pattern usually at zero detuning signifies optimal resonance with the qubit frequency, confirming accurate calibration.
- The fringe spacing in the Chevron pattern indicates the Rabi frequency, which informs the timing and strength of pulses needed for quantum gates.
- The clarity of the Chevron pattern provides insights into the qubit's coherence properties; a well-defined pattern suggests good coherence, while a blurred pattern may indicate environmental noise issues.

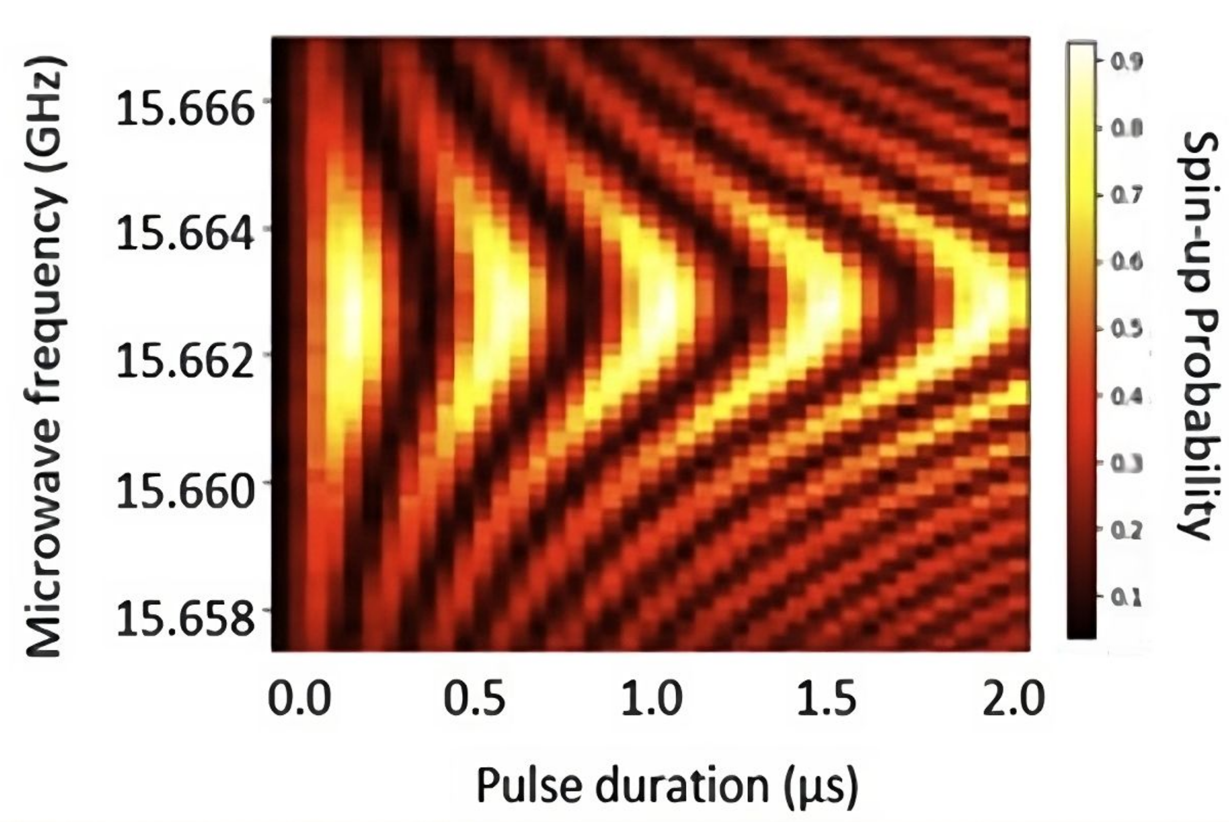


FIG. 6. Plot of frequency response on single qubit readout, showing how excited state probability changes with pulse duration and frequency detuning. The strongest oscillation contrast and slowest rate occur when the drive precisely matches the qubit transition frequency, ideally calibrated to 0 Hz detuning.

Source: Eendebak, et al. DOI: 10.1117/12.2551853 March 2020

VALUE

- **Calibration**: Identified resonance frequency to calibrate the microwave pulses for precise control over the qubit, i.e. set the pulse generator to this frequency for optimal qubit manipulation.
- **Quantum Gate Optimization**: Based on the Rabi frequency and the optimal pulse duration (from the vertical extent of the Chevron pattern), adjust the timing and strength of pulses used to implement quantum gates.
- **Error Correction and Mitigation**: If the Chevron plot indicates potential issues, such as decoherence or noise (suggested by a lack of clear pattern definition), implement error correction protocols or improve qubit isolation and environmental shielding.
- **Benchmarking and Testing**: Perform further tests and benchmarks, such as randomized benchmarking, to evaluate the performance of quantum gates and the overall quantum processor, validating Chevron information.

Coherence Measurements

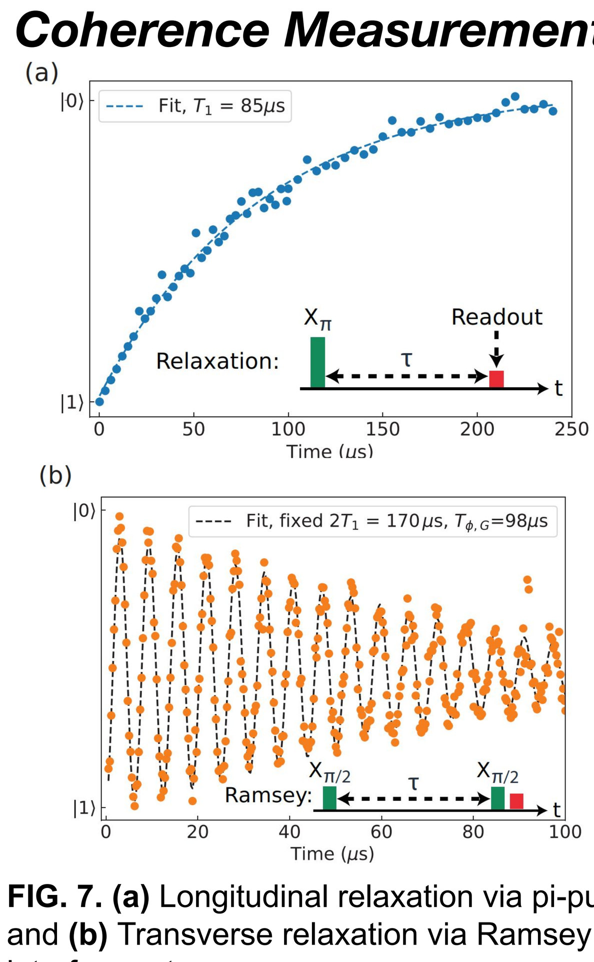
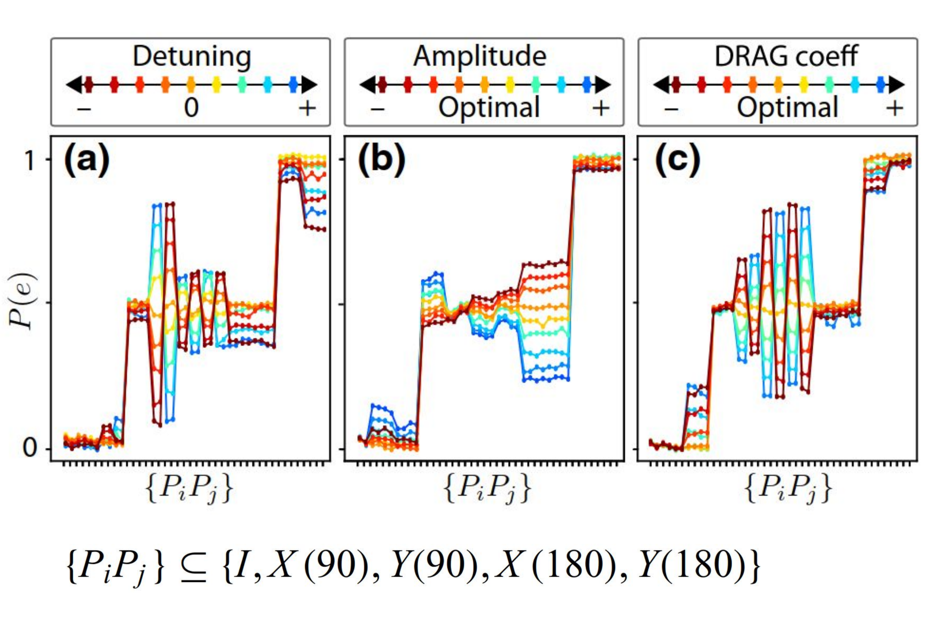


FIG. 7. (a) Longitudinal relaxation via pi-pulse and **(b)** Transverse relaxation via Ramsey interferometry

Source: Krantz, Philip, et al. "A quantum engineer's guide to superconducting qubits." Applied physics reviews 6.2 (2019).

ALLXY Experiment



$$\{P_iP_j\} \subseteq \{I, X(90), Y(90), X(180), Y(180)\}$$

FIG. 8. 21 combinations of 2 qubit gates with error syndromes **(a)** detuning from resonance, **(b)** variations in drive amplitudes, and **(c)** variations in the DRAG coefficient.

Source: Gao, Yvonne Y., et al. "Practical guide for building superconducting quantum devices." PRX Quantum 2.4 (2021): 040202.

Drive Frequency

- Finetune using a repeated Ramsey experiment (FIG 7b).
- The frequency of the observed oscillations corresponds to the detuning between the drive frequency and qubit frequency.
- An intentional detuning is added to exaggerate any low frequency deviations.

Drive Amplitudes

- "Pulse-train" experiment - apply an initial X(90) pulse and a train of 2N repeated X(180) pulses.
- Excited state population should be independent of N, but deviations from the correct amplitude will be exaggerated by the sequence of pulses.

DRAG Coefficient

- DRAG (Derivative Reduction by Adiabatic Gate) pulses attempt to reduce phase errors due to the presence of higher transmon level.

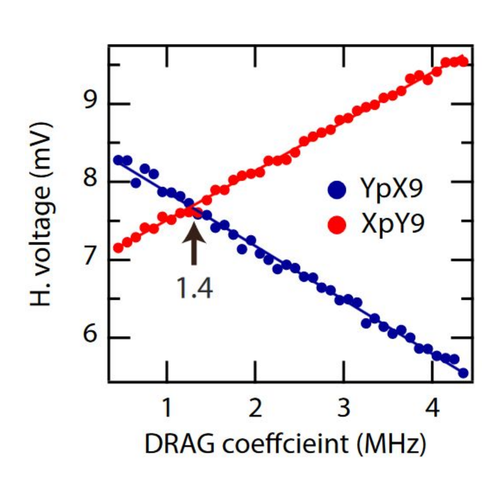


FIG. 9. 21 Two of the AllXY pulse sequences with opposite errors measured varying DRAG coefficient to find the optimal value

Source: M. Reed, Entanglement and quantum error correction with superconducting qubits. PhD Dissertation, Yale University, 2013

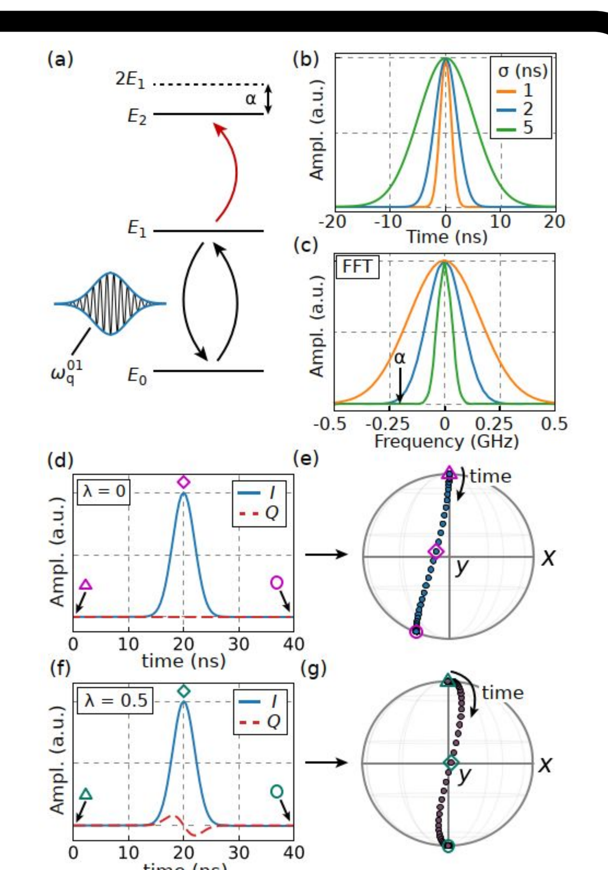


FIG. 10. The effect of DRAG modulating an X(90) on a weakly anharmonic transmon qubit (α = −200 MHz and ω_q = 4 GHz)

Source: Krantz, Philip, et al. "A quantum engineer's guide to superconducting qubits." Applied physics reviews 6.2 (2019).