Calibration of transmon qubits

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Outline

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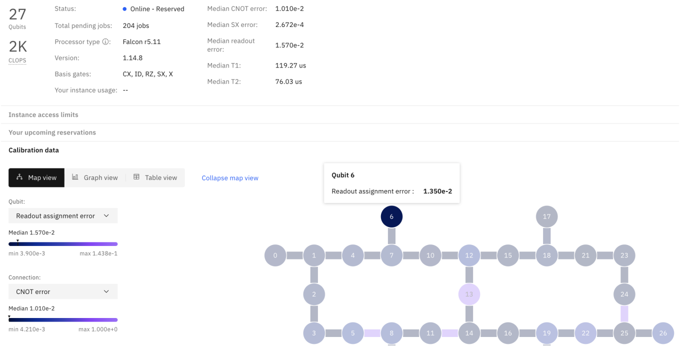
I. Scope of this presentation

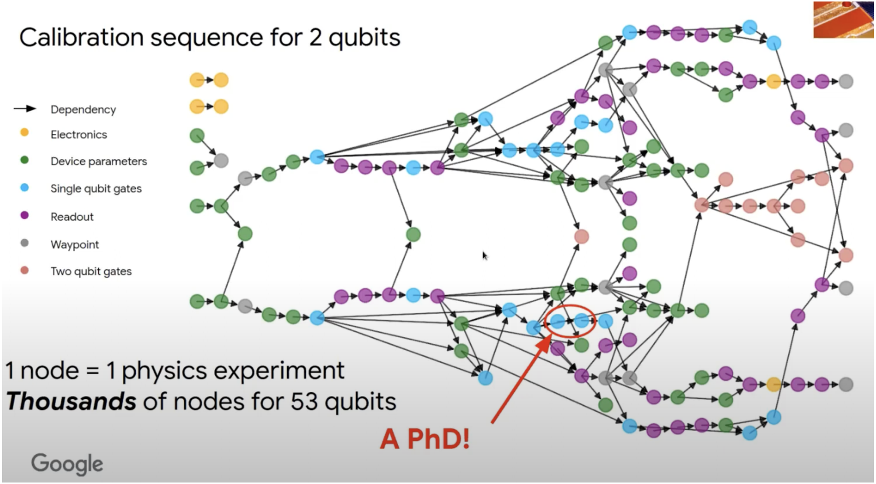


Calibration objective: Do quantum gates and read the results with accuracy:

- Qubit initial **Characterization**
- Weekly/daily **1Q Gates** calibration (*scope of the presentation)
- Weekly/daily **Readout** calibration
- Weekly/daily **2Q Gates** calibration
- Gates and Readout **Fidelities** computations
- **Coherence times** computations

II. How do we calibrate

We run an experiment for each parameter needed to control or read the qubit [1]:



III. Result of a calibration

The parameters drift away with time, each calibration finds the new optimal ones:

```diff
    Drag(4):
    - bus: drive_q4_bus
      pulse:
-       amplitude: 0.2468154279848783
        phase: 0
        duration: 40
        shape:
          name: drag
          num_sigmas: 4
-         drag_coefficient: -0.5065083452587257
      wait_time: 0
    M(4):
    - bus: readout_bus
      pulse:
-       amplitude: 0.115
        phase: 0
        duration: 1700
        shape:
          name: rectangular
      wait_time: 0
    CZ(2,4):
    - bus: flux_q4_bus
      pulse:
-       amplitude: 0.2542601211649558
        phase: 0
        duration: 37
        shape:
          name: rectangular
        options:
-         q2_phase_correction: -0.07398424745595358
-         q4_phase_correction: -1.7941789720751586
      wait_time: 0
```

```diff
    Drag(4):
    - bus: drive_q4_bus
      pulse:
+       amplitude: 0.2482782555554046
        phase: 0
        duration: 40
        shape:
          name: drag
          num_sigmas: 4
+         drag_coefficient: -0.4833691857031339
      wait_time: 0
    M(4):
    - bus: readout_bus
      pulse:
+       amplitude: 0.1284958495849585
        phase: 0
        duration: 1700
        shape:
          name: rectangular
      wait_time: 0
    CZ(2,4):
    - bus: flux_q4_bus
      pulse:
+       amplitude: 0.2583519020408991
        phase: 0
        duration: 37
        shape:
          name: rectangular
        options:
+         q2_phase_correction: 0.09944025716166253
+         q4_phase_correction: 5.059160743111809
      wait_time: 0
```

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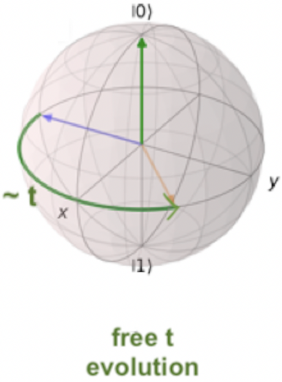
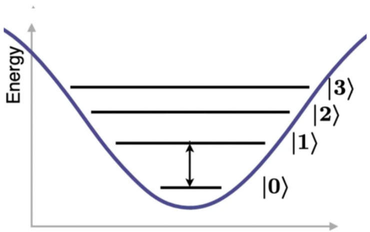
I. Bloch sphere, rotation reference frame

The difference in energy/frequency of states $|0\rangle$ and $|1\rangle$, intuitively describe the natural rotation frequency of the Bloch sphere of our qubit:

$$|0\rangle + |1\rangle \;\rightarrow\; |0\rangle + e^{i(E_1 - E_0)t/\hbar}|1\rangle = |0\rangle + e^{i\omega_{01}t}|1\rangle$$





II. Physical implementation of RX and RY

Physically, RX and RY gates are generated by a modulation drive of the form [2]:

$$\Omega(t)\cos(\omega_D t - \gamma) \;\sim\; Q(t)\cos(\omega_D t) + I(t)\sin(\omega_D t)$$

the rotation angle of the gates is set by the duration and the drive strength $\Omega(t)$.

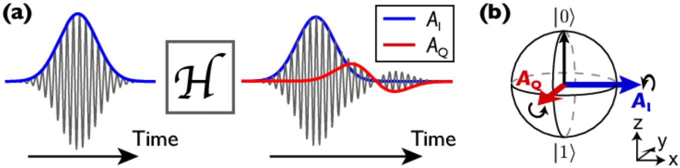
On-resonance ($\omega_D = \omega_{01}$):

- when $\gamma = 0$, the qubit state rotates around the X axis.
- when $\gamma = \pi/2$ the rotation is around the Y axis.

We can think, that since the Bloch sphere rotates on its own, the geometric X and Y axes in the Bloch sphere correspond to a $\pi/2$ phase difference in the drive fields.

III. Drag correction, Gaussian time distortion

But since the system is constantly evolving in time, a Gaussian pulse, would end up not really being a Gaussian when applied, producing leakage [3]:



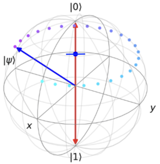
where we see that the $Q(t)$ components would generate $I(t)$ components and vice-versa. So we can try to correct this beforehand, changing the modulation to:

$$\varepsilon(t) = \Omega_{Gauss}(t)\cos(\omega_D t - \gamma) - \alpha\dot{\Omega}_{Gauss}(t)\sin(\omega_D t - \gamma)$$

IV. Native gates and Virtual Z

We can do **all 1Qubit gates with a drive pulse ($Drag$)**:

- Since we always measure the Z-axis, we can delete any RZ at the end.



- You can commute any RZ, adding more offsets to the drive modulations, Xs and Ys, that passes, until it reaches the end, where it's discarded:

$$D_{\alpha,\beta} Z_\gamma = (Z_\beta X_\alpha Z_{-\beta}) Z_\gamma = Z_\beta X_\alpha Z_{-\beta+\gamma} = Z_\gamma (Z_{\beta-\gamma} X_\alpha Z_{-(\beta-\gamma)}) = Z_\gamma D_{\alpha,\beta-\gamma}$$

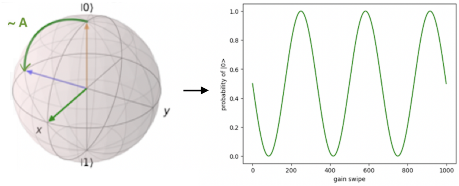
  so, no drive pulse needs to be sent, and that's why we call it Virtual-Z.

- Any longitudinal rotation gate is just a $Drag$ with extra RZ's, or what's the same, after commuting them, with extra phase offsets in the modulation drive!

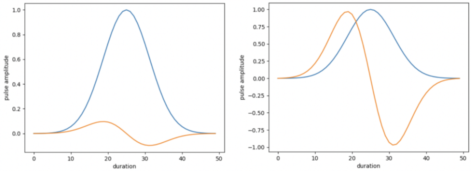
We can think of it, as changing the rotational reference frame of the Bloch sphere.

V. Parameters to calibrate for 1Qubit gates

- Frequency difference between state $|0\rangle$ and $|1\rangle$, for the **drive frequency**: $\omega_\mathbf{D}$
- **Amplitude of the single qubit** unique rotation: $\Omega(t) \sim \mathbf{A}\ e^{-0.5(t-\mu)^2/\sigma^2}$



- **The DRAG coefficient** α, for the leakage to higher excited levels [4] [5]:



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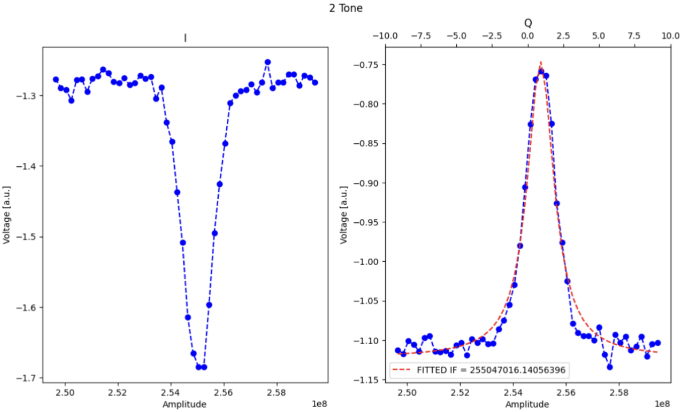
I. Qubit spectroscopy / Two-tone experiment

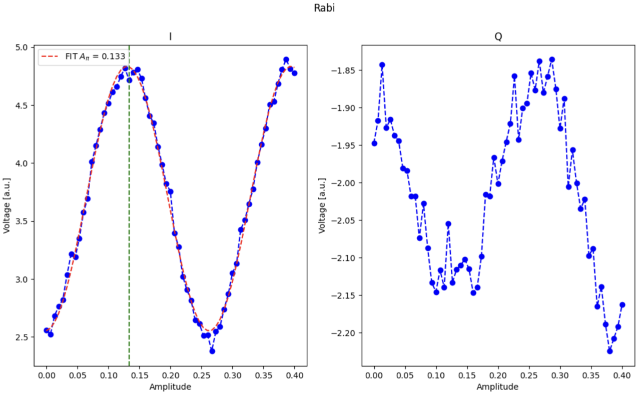
Drive frequency sweep, until we find resonance, $q: -RX_{\pi/2}(\omega_D) - M-$



where we fit a Lorentzian, and keep its maximum as optimal value.

II. Rabi experiment

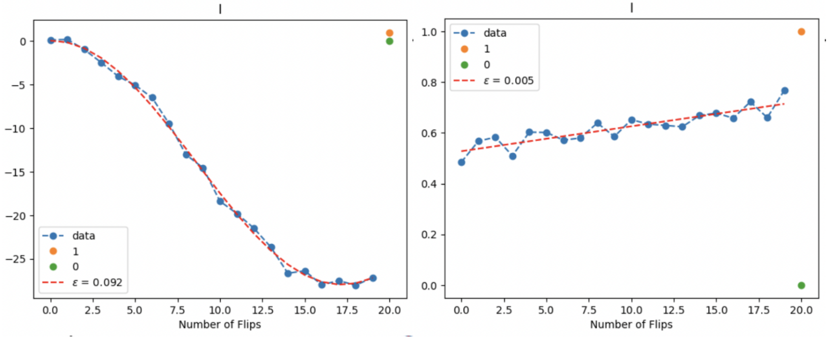
A Rabi allows us to find the amplitude from a wide range, $q : -RX_{\pi/2}(A) - M-$:



where we fit a sinus, and keep the first, non-immediate, stationary point.

III. Flipping Experiment

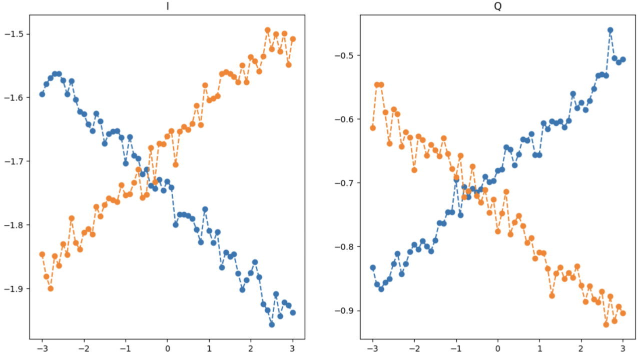
Then after having done a Rabi, we can improve it by doing lots of Rabis, to accumulate the error, $q : -RX_\pi - ... - RX_\pi - M-$ (two calibrations results):



where we fit a sinus, or for very small corrections a straight line ($e^x \approx 1 + x$), and divide the accumulated error, by the number of total complete rotations.

IV. Drag experiment

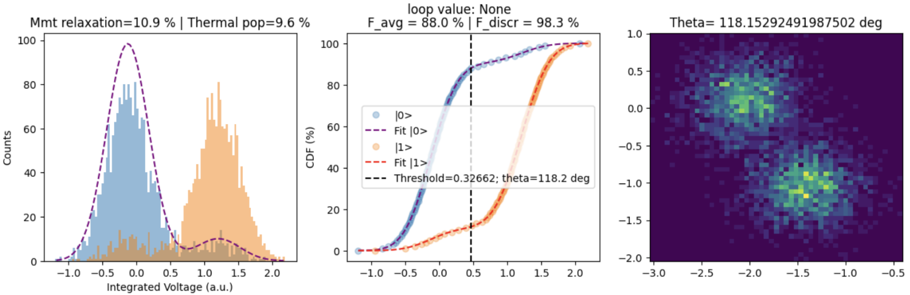
Then the Drag experiment is done sweeping the Drag coefficient with two circuits $q : -RX_{\pi/2}(drag) - RY_{\pi}(drag) - M-$ and $-RY_{\pi/2}(drag) - RX_{\pi}(drag) - M-$



where, the swept value in which these two different circuits coincide, is the optimal drag parameter.

V. SSRO, readout threshold (Extra)

The ssro, is where we send lots of $|0\rangle$ and $|1\rangle$ states, and see where they land:



to then in the phase space of these 2 quadratures $Q(t)$ and $I(t)$, find the line that better distinguishes the two gaussians.

Thank you for your time!

[1] Julian Kelly, Peter O'Malley, Matthew Neeley, Hartmut Neven, and John M. Martinis. Physical qubit calibration on a directed acyclic graph, 2018.

[2] David C. McKay, Christopher J. Wood, Sarah Sheldon, Jerry M. Chow, and Jay M. Gambetta. Efficient z gates for quantum computing. *Phys. Rev. A*, 96:022330, Aug 2017.

[3] Simon Gustavsson, Olger Zwier, Jonas Bylander, Fei Yan, Fumiki Yoshihara, Yasunobu Nakamura, Terry P. Orlando, and William D. Oliver. Improving quantum gate fidelities by using a qubit to measure microwave pulse distortions. *Phys. Rev. Lett.*, 110:040502, Jan 2013.

[4] F. Motzoi, J. M. Gambetta, P. Rebentrost, and F. K. Wilhelm. Simple pulses for elimination of leakage in weakly nonlinear qubits. *Phys. Rev. Lett.*, 103:110501, Sep 2009.

[5] J. M. Gambetta, F. Motzoi, S. T. Merkel, and F. K. Wilhelm. Analytic control methods for high-fidelity unitary operations in a weakly nonlinear oscillator. *Phys. Rev. A*, 83:012308, Jan 2011.