Superconducting Qubits Lab Report

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Introduction

My Lab partners were Leila Hudson and Nataliia Khotiaintseva, so expect same data with similar analysis between our reports. Moreover, I have ran these experiments across multiple of the IBM computers, so while I will report all required details in regard to one computer. All of the experiments and analysis was done using the IBM Brisbane computer. Lastly, the experiments below were modeled after information found in `https://github.com/Qiskit/textbook/blob/main/notebooks/quantum-hardware-pulses/calibrating-qubits-pulse.ipynb`

1 Transition frequency between $|0\rangle$ and $|1\rangle$

1.1 Experimental Design

To acquire a baseline frequency of the qubit, we accessed the backend data of qubit 0 (out of 127) in the IBM Brisbane computer. This frequency was $\approx 4.72186 GHz$. To find the transition frequency, we apply a frequency sweep by driving a pulse over a range of frequencies. Our sweep is restricted to a range of $40 Hz$, applying a new frequency in steps of $1 Hz$, meaning we plot 40 points on our resulting curve. Each pulse in the sweep has a width of $0.015 \mu s$ and occurs for $0.12 \mu s$. After driving this frequency pulse, we drive a measurment pulse. With these parameters defined, our experiment looks like

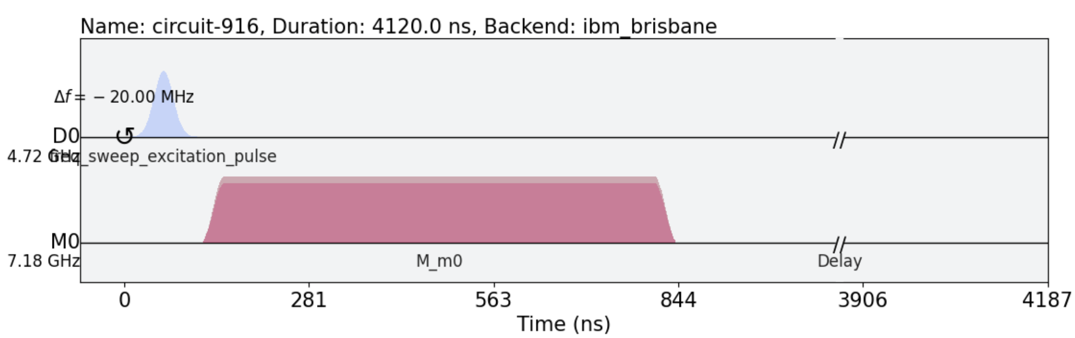

Figure 1: Pulse Schedule for Transition Frequency Experiment

where we repeat this process for 1024 shots per frequency pulse. The approximate transition frequency should occur at the peak measured signal as this indicates that we were able to drive the qubit off resonance. As a result, we expect the transition frequency to not be far off of the baseline frequency. With our data, we fit it to a resonance response curve, which has the general equation $\frac{A}{\pi}\left(\frac{B}{(x-\nu)^2+B^2}\right)+C$ for parameters A, B, C and ν the qubit frequency. Afterwards, we update our frequency estimate to the optimal value found by the fit function.

1.2 Data and Analysis

Using the above experimental design, we acquire the following data and fitted curve.

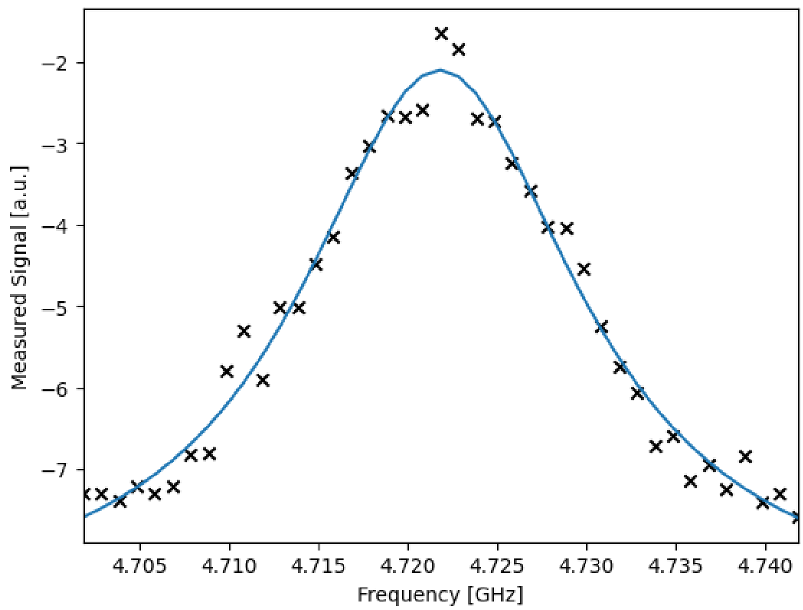

Figure 2: Measured signal of IBM Brisbane qubit 0 after drive pulses

where we have found $\nu = 4.72183 \pm 0.000146$ GH, so we've updated our qubit frequency estimate from 4.72186 GHz to 4.72183 GHz with uncertainty 0.000146 GHz, so we move forward to the next experiment updating our qubit frequency with this value.

2 Drive Strength to Realize a π pulse

2.1 Experimental Design

From section 1, we know the frequency required to apply a π pulse, as a π pulse is equivalent to applying a NOT gate to our qubit. We now seek to find the amplitude of this pulse so that we can fully realize a π pulse. We perform a similar sweeping experimental design as experiment 1, instead varying the drive amplitude of our pulses instead of the drive frequency. Like before, after applying a pulse with each drive amplitude, we measure the qubit. Note that the particular frequency of each pulse is the frequency found in Section 1 (4.72183 GHz). Moreover, we define the drive amplitude as a parameter ranging from 0 to 0.75, increasing the amplitude in steps of 0.015. This yields 50 data points on our Rabi Oscillation Curve, so that we will have rotated around the Bloch Sphere around twice. The above design correlates to the following schedule:

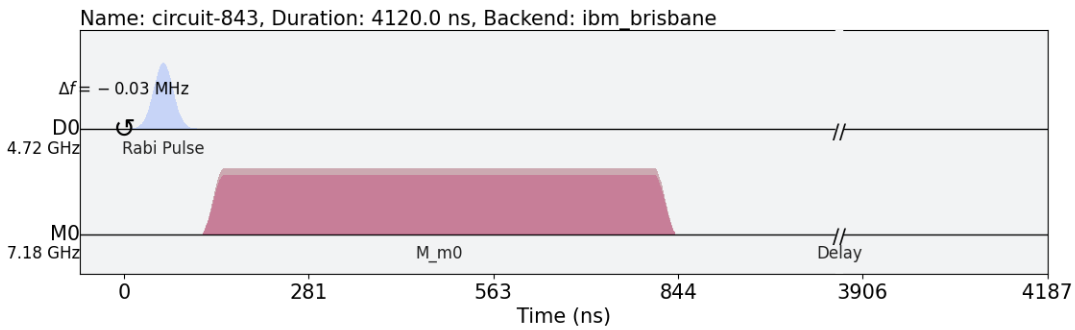

Figure 3: Pulse Schedule for π Amplitude Experiment

where we once again run each experiment 1024 times for a fixed drive amplitude and average over the results. After this, we graph our 50 data points, which will yield a sinusoidal graph due to the oscillatory nature between states. We fit this data to the following equation $A\cos(\frac{2\pi x}{T} - \phi) + B$ where A, B, ϕ are arbitrary parameters and T is the period of the graph. Since T represents the drive strength necessary to do a 360° rotation around the Bloch Sphere, we take the optimal T and save the desired $\pi-$pulse amplitude as $T/2$, since this is the drive amplitude required to move our qubit from state $|0\rangle$ to $|1\rangle$

2.2 Data and Analysis

The above experiment yielded the following data:

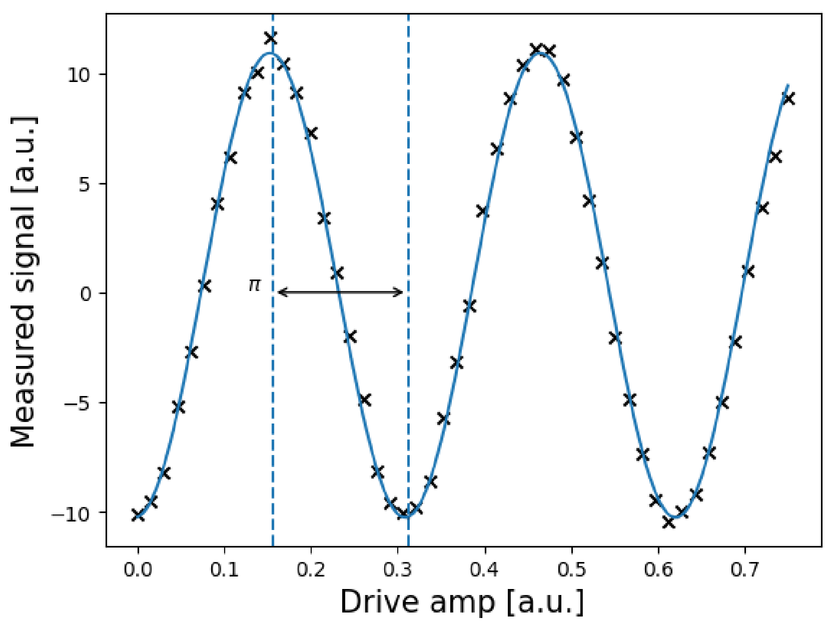

Figure 4: Results of the Rabi Experiment to determine π-pulse amplitude

We notice that the fitted curve starts at the $|0\rangle$ state, as indicated by the extremely negative measured signal. Then as the drive amplitude increases, the qubit rotates around the Bloch Sphere, transitioning completely to the $|1\rangle$ state when the drive amplitude is approximately 0.1559 ± 0.0003. We save this amplitude and create a π-pulse function for use in later experiments. Moreover, to better plot the points for future experiments, we utilize this $\pi-$ pulse to make a classifier to discriminate between the $|0\rangle$ and $|1\rangle$ states when measuring in experiments.

3 $T1$

3.1 Experimental Design

This experiment is also similar to previous experiments, where we drive a pulse through the qubit and then measure the qubit. As we want to measure the time it takes for the qubit to revert back to the $|0\rangle$ state from $|1\rangle$, we incorporate a delay parameter, which we vary through shots of the experiment and plot this against the measured signal. In particular, starting from our ground state qubit of $|0\rangle$, we drive a π pulse through the qubit using the information from Section 2. Then we wait for a varied delay τ so that the qubit can relax and apply a measurement pulse to see whether the qubit is in the ground or excited state. τ ranges from $1\mu s$ to $450\mu s$ and our step size is $6.5\mu s$. For each fixed value τ we average the results over 256 shots. The above procedure corresponds to the following schedule:

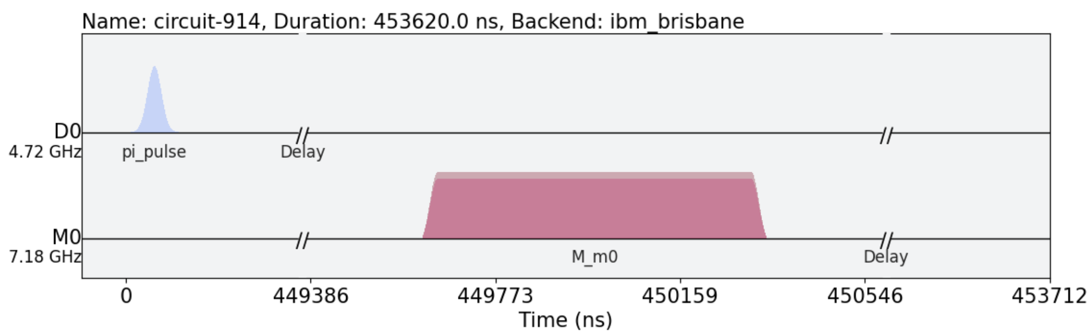

Figure 5: Experiment Schedule to determine the $T1$ of qubit 0

After running the experiment, we then plot the results to expecting to observe an exponential relationship between the measured state and delay time.we fit the data to the function $Ae^{-\frac{\tau}{T1}} + C$ where A, C are arbitrary parameters, τ is the delay as defined before, and $T1$ is the longitudinal relaxation time we desire to measure.

3.2 Data and Analysis

The above design yielded the following data and fitted curve:

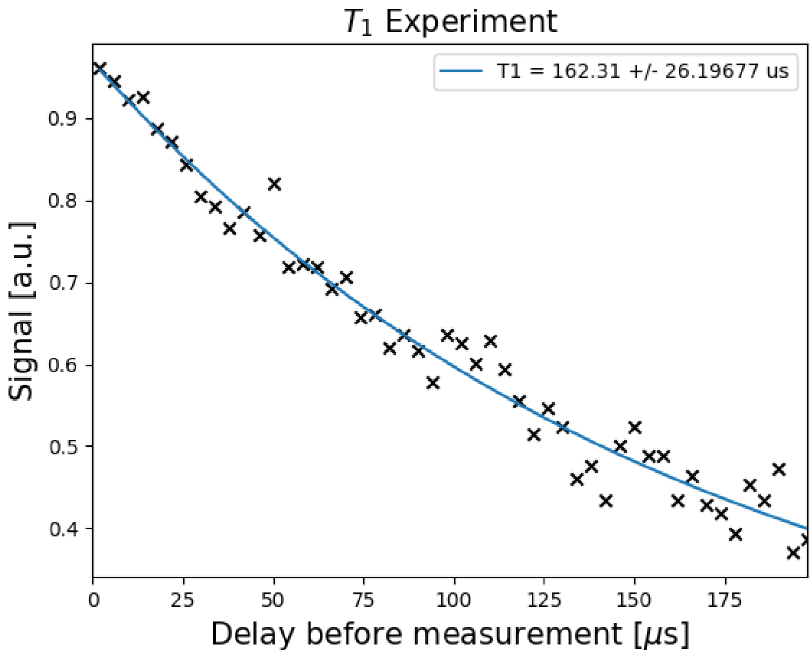

Figure 6: Results of Experiment 3 to determine the $T1$ of qubit 0 in IBM Brisbane

As one notices in Figure 6, we found the $T1$ to be approximately $162.31\mu s$ with an approximate uncertainty of $26.1968\mu s$. This result is particularly interesting since in IBM Brisbane's internal settings, the $T1$ of qubit 0 is registered as $125.03\mu s$, which is not present within the uncertainty scope of this experiment.

4 $T2^*$

4.1 Experimental Design

Just like the previous section, we incorporate delay in this experiment, but this time it is between two $\frac{\pi}{2}-$pulses. Moreover, our delay $\tau \in [0.1\mu s, 1.8\mu s]$ in steps of $0.025\mu s$. To find the $T2*$, we conduct a Ramsey pulse sequence on the quantum computer. This consists of driving a $\pi/2$ pulse, waiting for τ delay time, applying another $\pi/2$ pulse, and finally, measuring. We configure a $\pi/2$ pulse by driving a pulse with half the amplitude of a π pulse. We call this $x90$ since a $\pi/2$ pulse is just rotation around the X axis by $90°$. This produces the following schedule.

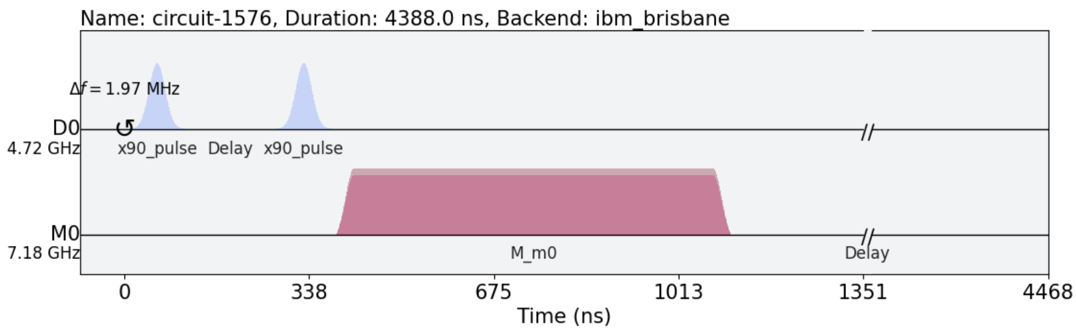

Figure 7: Experiment Schedule 4 to determine the $T2^*$ of qubit 0 in IBM Brisbane

We also utilize this Ramsey experiment to update our qubits frequency admist fluctuations present in the environment. In particular, we can use the measurements from this experiment to find the offset of the qubit frequency in its current environment. We accomplish this by manually offsetting the qubit slightly by 2 MHz to start the experiment. After running the experiment for 512 shots for each delay τ, we plot the results and fit them to a sinusoidal curve where we expect some damped oscillation shape. As a result, we fit the results to $Ae^{-\frac{x}{T2^*}}\cos(2\pi\Delta\nu x - C) + B$ where A, B, C are arbitrary parameters, x is the varied delay time variable, and $\Delta\nu$ is the difference between our offset qubit frequency and the actual qubit frequency.

4.2 Data and Analysis

The above procedure yielded the following data and fit: We found $\Delta\nu \approx 0.099$GHz, so we update our qubit's

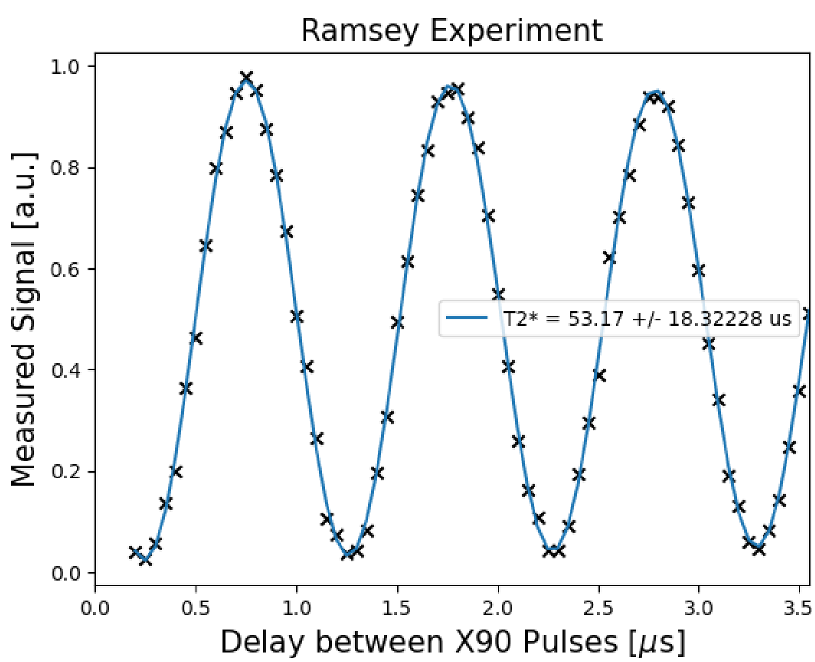

Figure 8: Results of Experiment 4 to determine the $T2^*$ of qubit 0 in IBM Brisbane

frequency from 4.721829GHz to 4.622843GHz. More importantly, we found our $T2^* = 53.17 \pm 18.32\mu s$

5 $T2$

5.1 Experimental Design

Much like the $T1$ and $T2^*$ experiments, we apply pulses with a delay. The schedule of a $T2$ Hahn Echo experiment, however, varies in some major ways from these prior experiments. For instance, we will apply a $\frac{\pi}{2}-$pulse, wait a varied delay τ, apply a $\pi-$pulse, wait τ time, apply a final $\frac{\pi}{2}-$pulse, and we finally apply a measurement pulse to the qubit. Our delay ranges from $\tau \in [2\mu s, 200\mu s]$ increasing in steps of $4\mu s$, but since we apply two delays, we will be plotting the total delay on the $x-$axis for our curve. This design yields the following schedule:

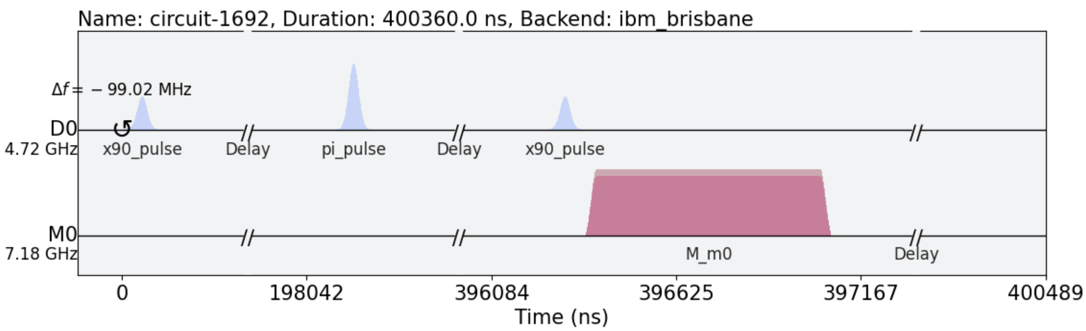

Figure 9: Experiment 5 Schedule to determine the $T2$ of qubit 0 in IBM Brisbane

We run the experiment for 512 shots per delay τ. We fit the data from this experiment to the equation $Ae^{-\frac{\tau}{T2}} + B$ where A, B are arbitrary parameters and $T2$ is the $T2$ time.

5.2 Data and Analysis

The above experiment design yielded the following data and fit: As seen in the graph, we found the T2 time

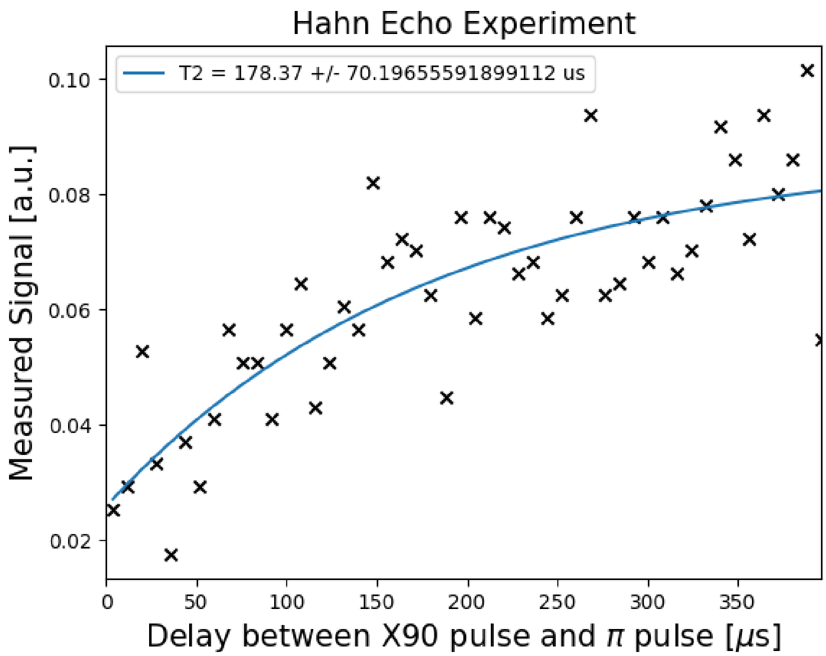

Figure 10: Experiment 5 Data to determine $T2$ of qubit 0 in IBM Brisbane

to be around $178.37 \pm 70.197\mu s$. The data is extremely variable for unknown reasons, resulting in a large error threshold. Perhaps with a better data (and thus a better fit), we will acquire a better time. IBM reports the $T2$ of this qubit 0 to be $71.29\mu s$, which is once again considerably different from the measured values.

6 Transition frequency between $|1\rangle$ and $|2\rangle$

6.1 Experimental Design

We take our qubit which is in the ground state $|0\rangle$ with its default system settings and first get it into the $|1\rangle$ state by applying an X gate, aka a $\pi-$pulse. This is essentially performing experiment 1 again. To get to the $|2\rangle$ state, we recall that there is anharmonicity between energy levels in superconducting qubits. For IBM Brisbane, this particular qubit has an anharmonicity of around -0.312GHz. We apply a frequency sweep and plot the results to find the transition frequency to get from $|1\rangle$ to $|2\rangle$. This sweep will have a range of 30MHz above and below the default qubit frequency + the default anharmonicity. This results in a sweep range of $\approx 4.41GHz \pm 30Hz$. We apply 75 pulses within this range. Each of these varies pulses will be applied over $160ns$ of width 40. This design yields the following experiment schedule:

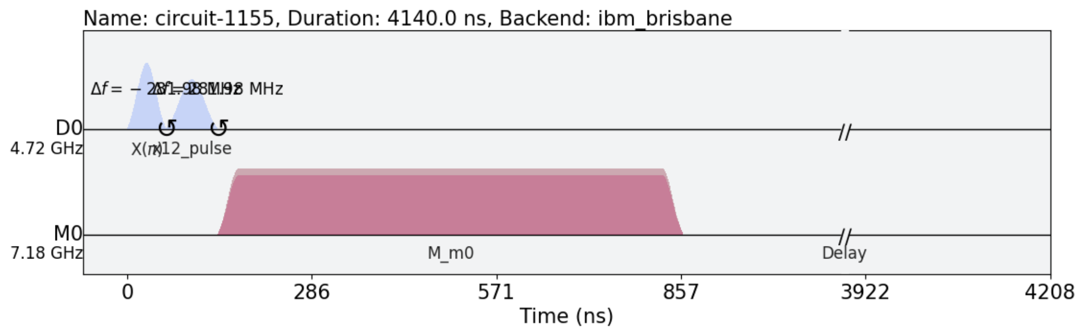

Figure 11: Experiment 6 Schedule to determine the Transition Frequency to get from $|1\rangle \rightarrow |2\rangle$ of qubit 0 in IBM Brisbane

We fit this to the equation we used in experiment 1. For reference, the equation is $\frac{A}{\pi}\left(\frac{B}{(x-\nu)^2+B^2}\right)+C$ for parameters A, B, C and ν the qubit frequency.

6.2 Data and Analysis

The above design yielded the following data and fit: We can see that the qubit is driven off resonance the

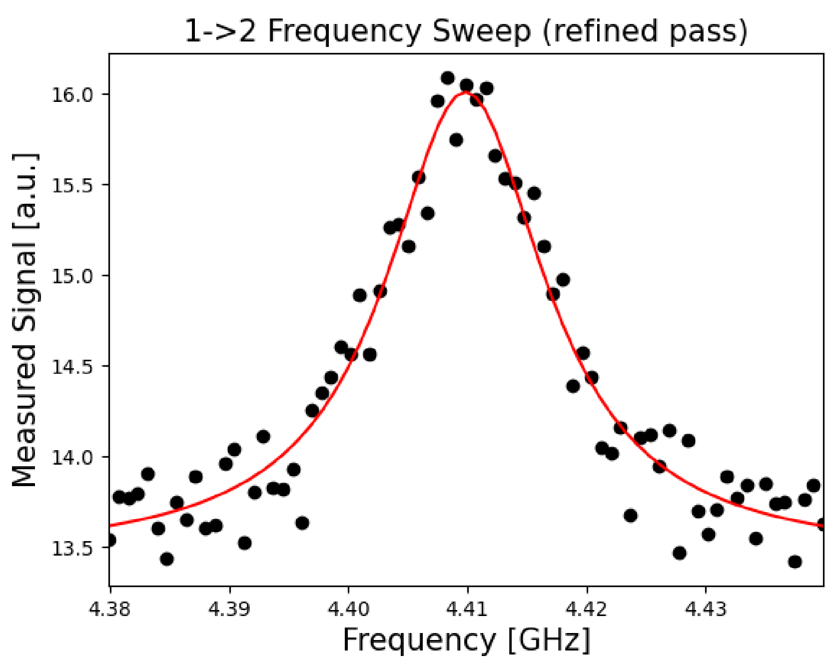

Figure 12: Experiment 6 Results to determine the Transition Frequency to get from $|1\rangle \rightarrow |2\rangle$ of qubit 0 in IBM Brisbane

most when we apply a $\approx 4.41 \pm (2.978 \times 10^{-7})$GHz frequency pulse into the qubit, so this is the transition frequency to drive this particular qubit from $|1\rangle \rightarrow |2\rangle$.