Characterizing Qubit Frequency, Relaxation Times, Dephasing Times, and Anharmonicity in Qubits

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1) Introduction:

The essay provides an exploration of various measurements and concepts related to quantum systems, specifically focusing on qubit frequency, relaxation times (T1 time), dephasing time (T2 time), and anharmonicity. The background section introduces these concepts and explains their significance in quantum computing. The implementation section describes the code used for measuring these parameters, highlighting the specific techniques employed for each measurement. The results section presents the obtained results and compares them to the calibration values. Finally, the discussion section analyses the discrepancies observed and proposes potential sources of error.

2) Background:

2.1) Qubit Frequency:

Understanding qubit frequency is fundamental to understanding how quantum computer's function. Qubit frequency in its most basic form refers to the difference in energies between two states, in this case the states |0> and |1>. The qubit frequency generally falls between 4-10GHz and differs from system to system. The qubit frequency is checked by way of sending pulses of various frequencies that excite the qubit hoping to make it transition to a different energy level. This pulse can be in many forms but typically is a microwave signal. The frequency of the pulse at which the qubit gains enough energy to transition between energy levels is the frequency of that qubit [1].

2.2) Relaxation Times:

Relaxation time essentially quantifies the time in which a qubit loses coherence and transitions from a superposition state and collapses into a ground state. Coherence is a very important concept as it dictates how long a qubit can retain information, as coherence is a measure of how long a qubit can maintain superposition. Decoherence refers to the time it takes for a qubit to lose its coherence and become entangled with the surrounding environment, leading to a collapse to ground states and annihilation of superposition [2]. T1 Relaxation Time describes the time it takes a qubit to lose superposition and collapse into ground states because of it losing energy over time due its interactions with electrical components and surrounding environment [3].

2.3) Dephasing Times:

Dephasing Times and Relaxation times follows similar concepts but measure slightly different times. Dephasing Times refers to the take it takes for decoherence to set in for a qubit. Essentially the time it takes for a qubit to lose its relative phase due to decaying energy and end up in different relative phase to what it was before. This time is denoted as T2 Dephasing time [4].

2.4) Anharmonicity of qubits:

Anharmonicity is the deviation from ideal harmonic behaviour in quantum systems. Harmonic energy-level structures refer to well-spaced, equidistant, and with a constant energy difference energy-levels. Anharmonic energy-levels are the opposite of this, as they have varying spacing and energy-level differences. This leads to non-linear energy-level structures. This may arise due to a multitude of reasons, the aforementioned quantum coupling and entanglement with various electrical elements, ambient noise and due to the anharmonicity that already exists at higher energy levels.

However as bad as it sounds, anharmonicity is actually desired in a quantum system. Anharmonicity provides distinct, well-spaced (although random) energy-levels, traits that are essential for precise and reliable qubit operations. Therefore, the higher the anharmonicity of the system the faster various operations are performed and the lower the chances of unintended energy transitions which give rise errors in the system [5].

3) Implementation:

The code was taken from the QISKIT website that posted a tutorial with code on how to measure various values of any quantum system [6]. The code was taken verbatim with minor changes made. These changes included changing the parameters for fitting functions and adding a short print of the final values describing the system. When looking at the code the values for each measurement were generated in different ways, below a short discussion on the basic theory behind each measurement will be shown:

3.1) Qubit Frequency:

To measure the frequency of the qubit, pulses of various frequencies in the range close to the calibrated value were pulsed through the qubit. When the qubit transitioned from one energy state to another, the measurement was taken, and that measurement related directly to the frequency of the qubit. As various frequency waves were pulsed through, the responses were plotted, and a line of best fit was drawn, and the frequency extracted.

3.2) T1 Relaxation Time:

To measure the T1 Relaxation Time, $\pi/2$ pulses in the Rabi experiment were used. The Rabi experiment sends π pulses through a qubit causing phase shifts and essentially exciting the qubit. The measurement begins as the qubit is excited and ends when the qubit collapses into its ground states. The time it takes for the qubit to collapse after the first measurement is the T1 relaxation time. These times are varied, and their results are plotted, a line of best fit is drawn and the time, T1, is extracted.

3.3) T2 Dephasing Time:

The method for measuring the dephasing time follows a similar manner to that of the measurement of the T1 time. The Rabi experiment is conducted, and the system is allowed to evolve for a certain period of time. Soon a π pulse is sent through and immediately a measurement is taken. By sending a π pulse through the qubit any phase shifts are essentially reversed, and the system should show no phase shifting. However, as evolution times are varied decoherence starts setting in. Therefore, the measurement is repeated for varying levels of evolution times and those times are plotted, a line of best fit is drawing and the time, T2, is extracted.

3.4) Anharmonicity:

The Ramsey experiment makes use of $\pi/2$ pulses to excite qubits and cause phase shifts in them. It sends two pulses to a qubit to excite it, and cause to go into a superposition state. Between pulses the qubit is allowed to evolve at varying times. Measurements are taken after the second pulse and that state of the qubit is analysed for interference patterns. The frequency of these oscillatory interference patterns relates directly to the anharmonic frequency of the qubit, which is the frequency deviation from harmonic states. Drawing lines of best fit allows extraction of the anharmonicity of the system.

4) Results:

The code was run on the *Ibmq_lima* server at 00:20 on the 26th of May 2023. The results and

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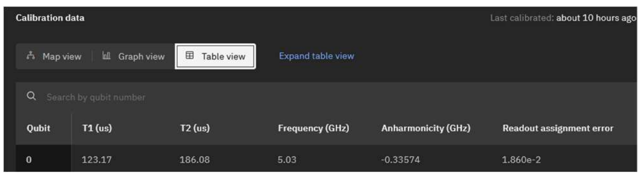
calibration values can be seen in Table 1 and Figure 1.

Table 1: Results from code.

Qubit	T1(μs)	T2(μs)	Frequency (GHz)	Anharmonicity (MHz)
qo	114.45	131.32	5.02975-5.02963	-0.11496



Calibration data Last calibrated: about 10 hours ago

Map view | Graph view | Table view | Expand table view

Search by qubit number

Qubit	T1 (us)	T2 (us)	Frequency (GHz)	Anharmonicity (GHz)	Readout assignment error
0	123.17	186.08	5.03	-0.33574	1.860e-2

Figure 1: Calibration values from IBM website for the system used.

5) Discussion:

As can be seen from the results the measured values are fairly close to the calibration values with certain discrepancies. The first major discrepancy exists between the anharmonicity values, the difference between the two values is quite significant. This could be due to the fact that calibration had occurred a significant period of time ago and hence the energy levels managed to come closer together decreasing the deviation from harmonic energy-levels. A secondary potential source of error could be due to parasitic coupling and noise that have altered the energy-levels.

The discrepancies between the other values which are quite minute compared to the anharmonicity is simply down to the calibration having been done so long ago. T1 and T2 correspond to their estimated behaviours in that as time goes on and noise and parasitic coupling effects increase, these times decrease.

6) Conclusion:

In conclusion, the essay highlights the importance of understanding and measuring key parameters in quantum systems. By accurately determining the qubit frequency, relaxation times, dephasing time, and anharmonicity, researchers can gain insights into the behaviour and performance of quantum systems. The implemented measurements and obtained results provide valuable information for assessing the stability and reliability of the quantum system under study. The observed discrepancies between the measured values and calibration values suggest the need for periodic recalibration to account for environmental factors and changes over time. Overall, these measurements and analyses contribute to advancing our understanding of quantum systems and optimizing their operation in quantum computing applications.

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