Q-CTRL Challenge Summary

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I. EXPERIMENTAL CHARACTERIZATION OF THE CLOUD QUBIT

Rabi rate calibration. In the notebook `Calibration.ipynb` we perform the calibration of the pulses for the *qubit-in-the-cloud*, based on the respective tutorial.

We first apply a constant pulse with a fixed real amplitude and varying duration, which allows us to retrieve the Rabi frequency, as shown in Figure 1.

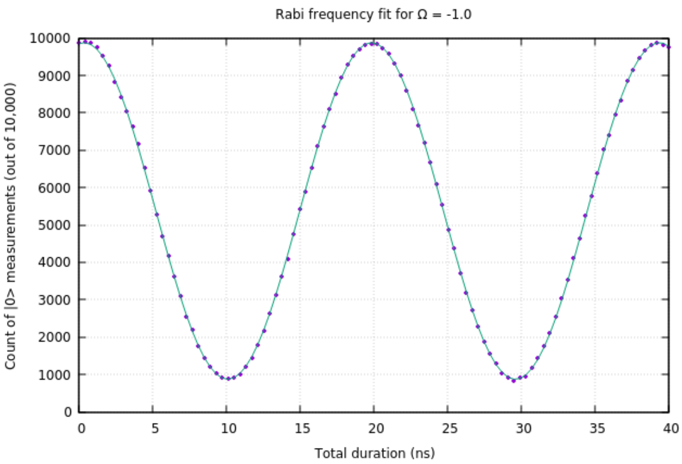

FIG. 1: Rabi oscillation fit

We then repeat the process for different pulse amplitudes, obtaining $f(\Omega)/\mathrm{GHz} = 0.0524(9)\Omega + 0.000(6)$, which can be seen in Figure 2. We found out that the maximum Rabi frequency is ~ 50 MHz.

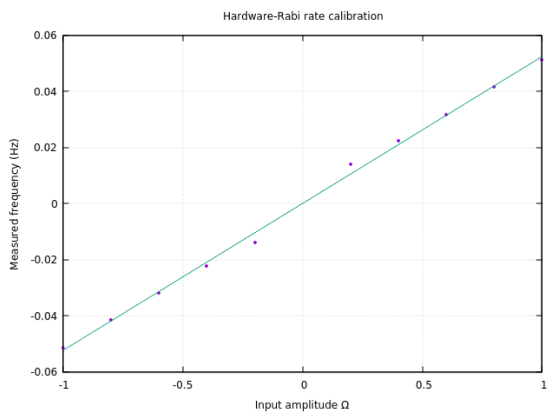

FIG. 2: Linear calibration of the correspondence between input and output pulse amplitudes.

SPAM Errors and Confusion Matrix. We expect the initial state of the quantum computer to be $|0\rangle$. To estimate the preparation error for this state, we consider some idle time and measure the state, estimating the SPAM error rate as the relative number of times that $|1\rangle$ was measured, rather than $|0\rangle$.

In fig. 3, the rate of $|1\rangle$ measurement is presented, as a function of the idle time, which spanned from 1×10^{-5} to 0.5 ns. Due to the low statistics, the median of the obtained result was used as the operational value for the $|0\rangle\langle 1|$ entry in the confusion matrix: the estimated value was of 0.8%. Because estimating the $|1\rangle\langle 0|$ entry with the same technique would require ideal preparation of a $|1\rangle$ state (i.e. ideal realisation of a `NOT` gate), we simply considered that the two entries match. This resulted in our estimated confusion matrix:

$$C = \begin{pmatrix} 0.993 & 0.007 & 0. \\ 0.007 & 0.993 & 0. \\ 0. & 0. & 1. \end{pmatrix} \tag{1}$$

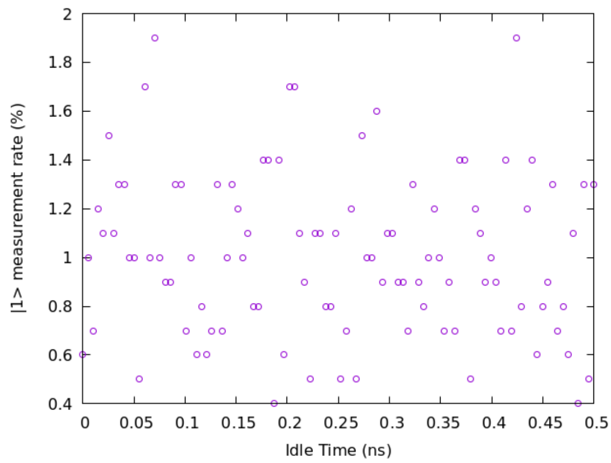

FIG. 3: Rate of measurement of $|1\rangle$ as a function of idling time (in ns).

II. ATTEMPTING OPTIMAL CONTROL

A. Attempting to Estimate Leakage

Our first approach was to attempt to perform optimal control on the system. For this, we needed to build an accurate model of the effective Hamiltonian acting on the qubit, when a given drive pulse was supplied. We had verified that there was significant leakage, so that this effect should be accounted for. On the other hand, the population at $|2\rangle$ was approximately a constant fraction (1.35%) of the population at $|1\rangle$ at any time, when observing the evolution of the system under the experimental `NOT` gate (fig. 4). This was further supported by the observation of quick decay from $|2\rangle$ to $|1\rangle$ under no drive (fig. 5) (such that it is reasonable to assume that the population of $|2\rangle$ very closely follows the dynamics of the population of $|1\rangle$).

Considering a term in the Hamiltonian of $H_{\mathrm{LEAK}} = \gamma(|1\rangle\langle 2| + |2\rangle\langle 1|$ to account for this leakage, we analytically calculated (with the aid of Mathematica) the oscillations of the population of $|1\rangle$ and $|2\rangle$ as a function of γ, under a drive of $H = H_{\mathtt{NOT}} + H_{\mathrm{LEAK}}$. This allowed us to obtain $\gamma = 0.116$ as a value that resulted in the population of $|2\rangle$ being 1.35% of the population of $|1\rangle$ when the latter was maximal.

However, this value was not ultimately used, as the Hamiltonian used considered a different form (cf. section II B).

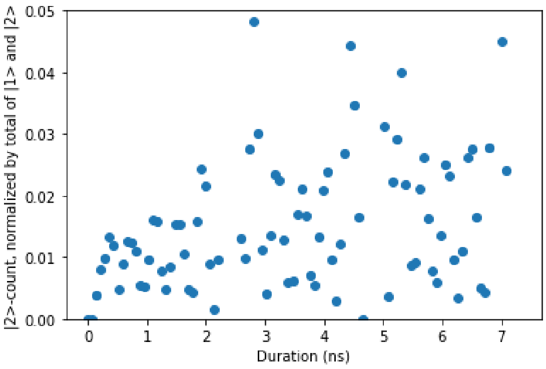

FIG. 4: Population of $|2\rangle$ as a fraction of the population in $|1\rangle$ under the action of a `NOT` gate. Although noisy, the value can be reasonably approximated by the median value, 1.35%. The transient mode into a steady state can also be observed when $t \approx 0$. Outliers for when the population at $|1\rangle$ was very close or equal to 0 have been removed.

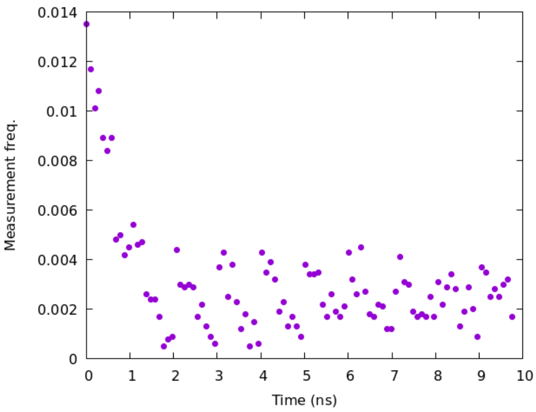

FIG. 5: Quick decay of the population leaked to $|2\rangle$; at $t = 0$, the population has been significantly ($> 80\%$) excited to the $|1\rangle$ state. After one nanosecond, the population of $|2\rangle$ has decayed significantly to a basal level.

B. Optimal Control With Given Hamiltonian

Our approach to perform optimal control was to assume the qubit Hamiltonian

$$H(t) = \frac{\chi}{2}(a^\dagger)^2 a^2 + (1 + \beta(t))(\gamma(t)a + \text{h.c.}) + \frac{\alpha(t)}{2} a^\dagger a\,,$$

with $a = |0\rangle\langle 1| + \sqrt{2}\,|1\rangle\langle 2|$, and the confusion matrix, obtained experimentally, in Eq. 1.

Unfortunately, it was not possible to do an *a priori* estimate of the anharmonicity χ, shift $\alpha(t)$, and $\beta(t)$ terms, so these were approximated to be zero. The driving pulse $\gamma(t) = I(t) + iQ(t)$ was considered to only directly controllable parameter. Applying the `calculate_optimization` to find the $\gamma(t)$ that minimized the infidelity, for the NOT and Hadamard gates, led to the plots in Figs. 6 and 7, respectively.

Although both cases converged to an infidelity lower than 10^{-10} for the ideal case, once the scenario in the cloud was test, it was verified that the NOT case only obtained $|1\rangle$ 23% of the time, and, for the Hadamard case, $|1\rangle$ was only measured 4% of the time. In the NOT case, $|2\rangle$ was also measured $\sim 0.1\%$ of the time.

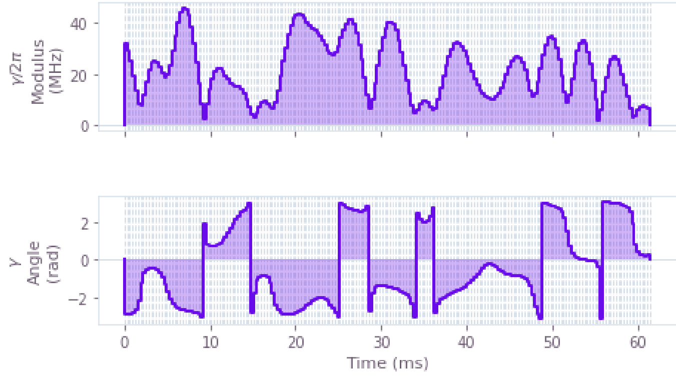

FIG. 6: Pulse obtained using optimal control, for the NOT gate.

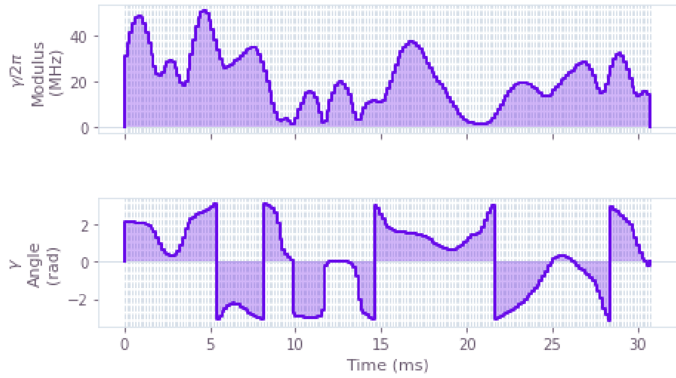

FIG. 7: Pulse obtained using optimal control, for the Hadamard gate.

III. ATTEMPTING LEARNING CONTROL

Finally we tried using learning control to generate a pulse to approximate the `NOT` and Hadamard gates. We based ourselves on the code in the user guide *Automate closed loop hardware optimization of quantum devices*, changing the `run_experiments` to take as input the parameter set and encode it in the control pulse dictionary that is then fed as input to the cloud qubit. Running the closed form optimization loop we were able to achieve the `NOT` gate with an infidelity of roughly 0.08.

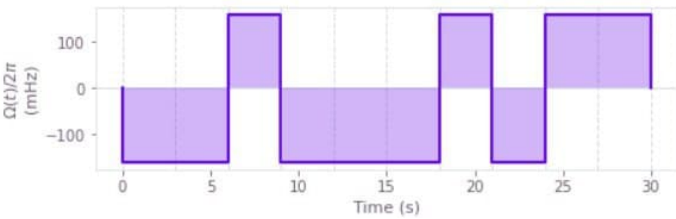

FIG. 8: The pulse for the `NOT` gate obtained with learning control.