Quantum computing with cold neutral atoms and laser analysis with Pasqal

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Abstract

Pasqal is a quantum computing company that developes quantum processor units (QPU) based in ^{87}Rb cold neutral atoms. It consists of an array of optical traps where the atoms are trapped. Then, they are manipulated with laser sources (**Rydberg lasers**) to manipulate their quantum state. The System Performance Team's primary objective is to ensure the optimal functioning of the quantum system, essential for the accurate manipulation of cold neutral atoms.

I present here 3 different analysis and their respective results.

a) Oscillation frequencies of the atoms in the traps: Pasqal uses a laser protocol to characterize this feature. I developed a **model** and a **simulation** that could explain the behaviour of the experimental data.

b) Red Pulse Detuning Scan: There is a Double-Pass AOM to detune the 1013 nm pulse to characterize QPU's features. We recorded the power of the 1013 nm Rydberg laser in function of time for different detuning values in order to check possible **anomalies** in the square pulses. We observed **variations in the power** and **oscillations at the plateau** of the square pulse.

c) Pulse Amplitude Scan: We scanned laser pulses for different input Rabi frequencies, which directly depends on the laser power. The input is processed by the device *Quantum Machine (QM),* previously calibrated, to send a laser pulse with the correct power that creates a Rabi oscillation with the required frequency. After the assembly, we **calibrate** again the setup to know the **dependance of the input with the output power**.

Introduction

➢ The physical mechanism that Pasqal uses to control the quantum states of the atoms is a **two-photon transition**. The atom goes from the ground state to the excited state using two lasers with different frequencies. These address two transitions: first to an intermediate state (blue laser – 420 nm) and later to the excited state (red laser – 1013 nm).

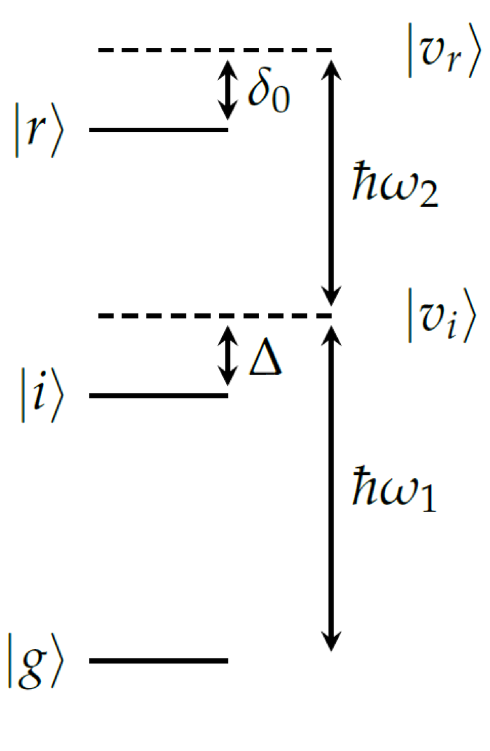

Fig. 1. Level diagram of the qubits in Pasqal's QPUs.

➢ The protocol to characterize the atom oscillation in a trap consists of turning on and off the dipole traps as shown in the image (protocol at left and experimental data at right).

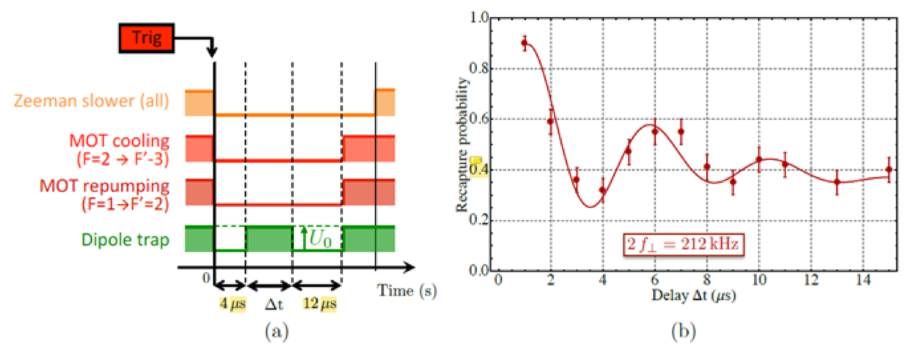

Fig. 2. Protocol and data to characterize the oscillation frequency of the atoms in an optical trap. From "Lucas Beguin. Measurement of the van der Waals interaction between two Rydberg atoms."

Results

a) Model explaining the data behaviour for a protocol that determines its oscillation frequency:

1. Oscillation with a determined energy during a time t0 due to the presence of a potential well.
2. Free space propagation until t1.
3. Oscillation with a determined (different) energy until t2 due to the presence of a potential well.
4. Free space propagation until t3.

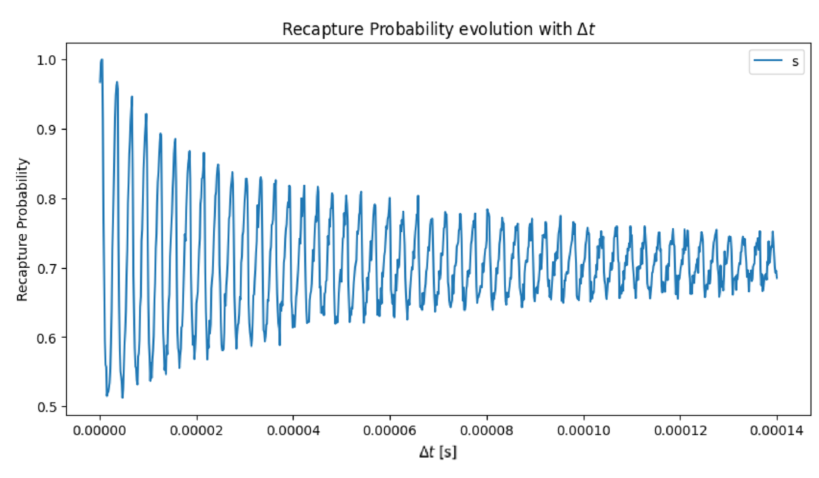

Fig. 3 Monte-Carlo simulation of the recapture probability for obtaining the atom oscillation frequency using a dipole potential.

b) Red Pulse Detuning Scan:

The laser pulse is prepared with 0 detuning and power around 100 mW with a Fabry-Perot Cavity and an Single- Pass AOM and it is assumed to work correctly. Then, the laser goes through the setup presented in the figure (4). It is detuned with a Double-Pass AOM (DP AOM), an ALS amplifier maintains the power constant and the Single-Pass AOM (SP AOM) modulates the pulse power.

The laser analysis shows a **decrease of the power** and **increase of the oscillation frequency** of the signal **with detuning**. Both present a **quadratic behaviour**, what suggests a correlation between these phenomena. See figures (5), (6).

Explanation: In absence of the ALS, the **DP AOM changes the pulse power** as a side effect of the physical mechanism with a dependance given by the equation (1), being ΔF the detuning. For small detuning values this behaves approximately quadratic as we see. The **oscillations must be caused by a slow amplification of the ALS.** It amplifies the pulse power performing damped oscillations that tend to the desired power value. It is suggested that the oscillation frequency is higher when the pulse power is more deviated due to the mechanism how the ALS works. However, we must analyse longer pulses to be sure.

$$\frac{I_1}{I_0} = \eta\,\mathrm{sinc}^2\left(\sqrt{\eta + \frac{\Delta\phi^2}{4}}\right);\quad \Delta\phi = \frac{\pi\lambda}{v}\frac{\Delta F}{2}\frac{L}{\Lambda_0};\quad \frac{I_1}{I_0} = a_0 + a_2\Delta F^2 + \mathcal{O}(\Delta F^4) \qquad (1)$$

c) Pulse Amplitude Scan:

We will assume a simplistic model of a photon transition of an atom in which the intensity of light is constant in space. When a sinusoidal coherent source of light is applied to the atom, with a detuning Δ and electric field intensity E_0, the probability of finding the atom in the ground state changes as a sinus with time with a frequency called *Rabi frequency (RF):* $\Omega = \frac{E_0 d^{\varepsilon}_{01}}{\hbar}$ where $d^{\varepsilon}_{01} = \vec{\varepsilon}\langle 0|\vec{\hat{d}}|1\rangle$ is the a matrix element of the dipole operator.

For a two-photon transition, the *effective Rabi frequency is* $\Omega_{eff} = \frac{\Omega_1\Omega_2}{2\Delta}$. Then, given an input ERF, the QM translates it into two laser pulses whose power is proportional to the voltage signal of the photodiodes. Moreover, given the voltajes, we will obtain an experimental RF:

$$(V_{meas,0}, V_{meas,1}) = f(\Omega_{input});\quad \Omega_{meas} = g(V_{meas,0}, V_{meas,1});\quad \Omega_{meas} = h(\Omega_{input}) \qquad (2)$$

In this article we only obtain the first calibration.

The figures (7), (8) show a quadratic behaviour of the plateau voltage with the input amplitude. The input value is actually the RF that we want to apply. Using the previous definitions:

$$V = \frac{1}{2}\frac{\varepsilon_0 c\hbar^2}{d^2_{jk}}\frac{1}{\alpha}\cdot\Omega^2 \qquad \alpha = \frac{k}{A} \qquad (3)$$

with *k* the voltage-power proportionality constant and *A* the beam area. We conclude that the plot has an appropriate quadratic behaviour.

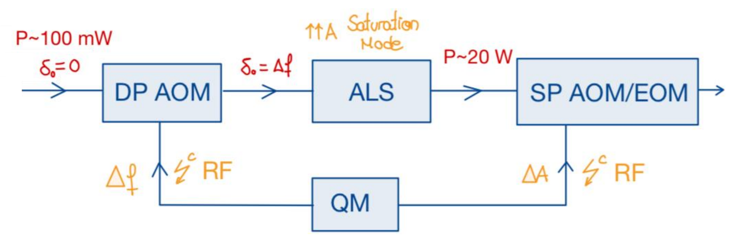

Fig. 4. Laser setup scheme.

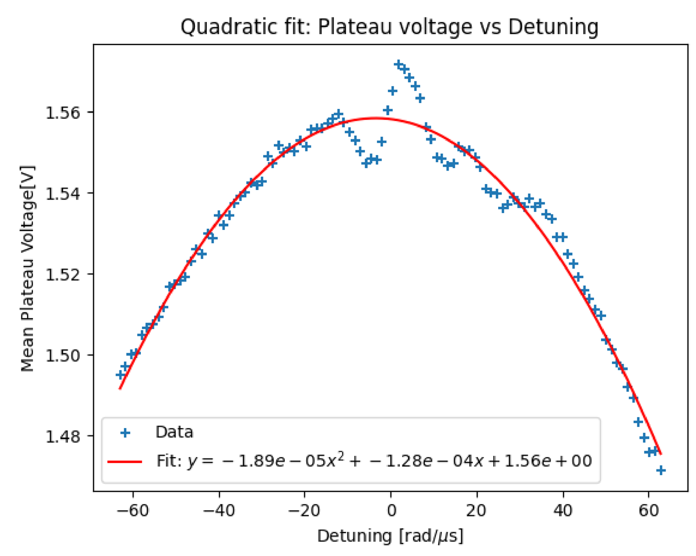

Fig. 5. Mean plateau voltage values for each detuning value δ.

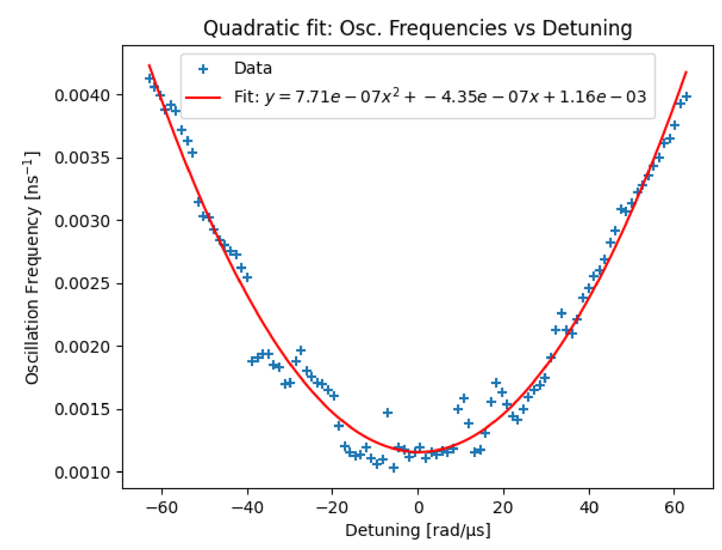

Fig. 6. Oscillation frequency and detuning.

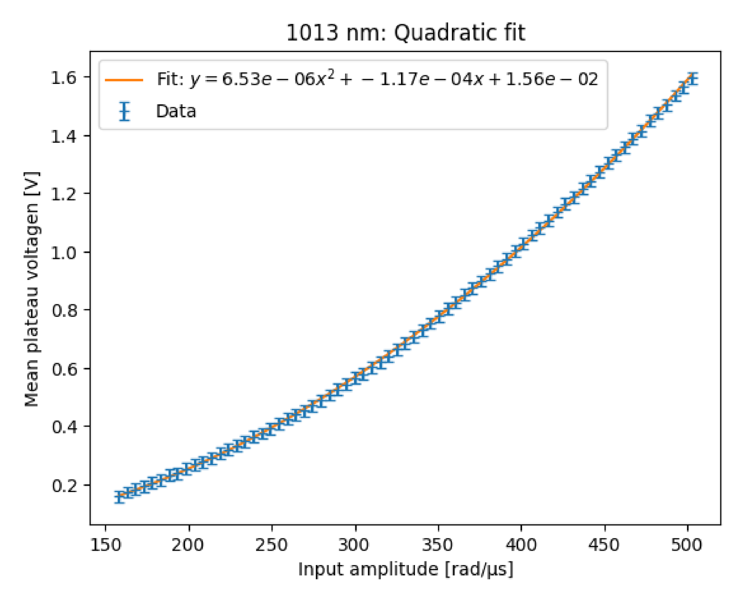

Fig. 7. Square laser pulse of 1013 nm created with the SP AOM. The optical power input is 431.75 rad/μs.

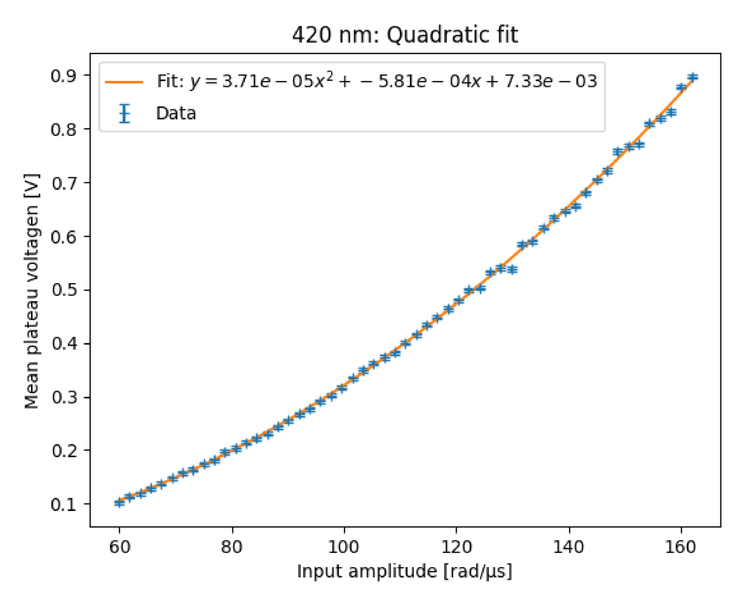

Fig. 8. Square laser pulse of 420 nm created with the EOM. The optical power input is 154.45 rad/μs.

Conclusions and Perspectives

➢ It was developed a theoretical model to explain the behaviour of an atom in an optical trap while a laser protocol that characterizes their oscillation frequency was performed. The experimental data behaviour matched the one of the simulated data so we consider it to be a successful model.

➢ We could explain the variation of the voltage and oscillation frequency of the square pulses with the detuning. However, we must analyse longer square pulses to determine whether the origin of the oscillations is as proposed.

➢ The relation of the pulse voltage with the input value behaves quadratically, as expected. The next step is to calibrate the voltages with the real RF to finally obtain the relation between the input and measured RF. This way, we will be able to create Rabi Oscillations with a desired RF without measuring it every time. To conclude, the fitting parameters can be used to set a relation between the proportionality factor *k* and the dipole matrix element for each laser.