Trapped-Ion Quantum Computing: An Experimental Overview

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^{40}Calcium Scheme

After ^{40}Ca atoms are evaporated by current from the oven, 423 nm light and light with wavelength less than 390 nm are used to ionize the neutral ^{40}Ca. 397 nm lasers are used for the main cooling transition and state detection via fluorescence. For some $^{40}Ca^+$ ions that decay to the $3d^2\ D_{3/2}$ state, an 866 nm laser is used to repump them to the $4p^2P_{1/2}$ state in order to maintain the cooling cycle. The 866 nm (and 854 nm) lasers and the 397 nm laser are both passing through the endcap. Additionally, 729 nm lasers are used for the qubit transition in quantum information processing with trapped $^{40}Ca^+$ ions.

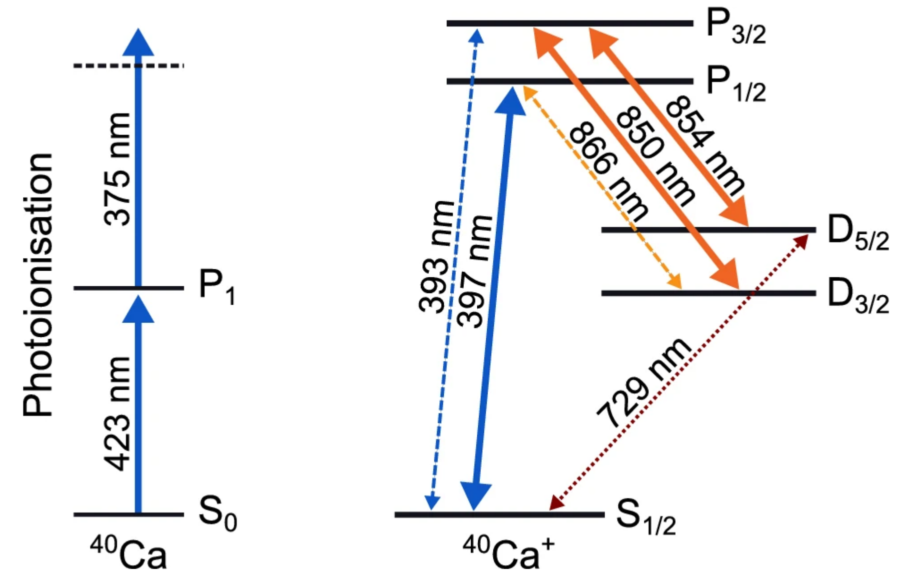

Figure 1. Relevant energy levels for the ionisation of ^{40}Ca and operation of a $^{40}Ca^+$ atomic clock.

Experimental Setup and Trapped Ion

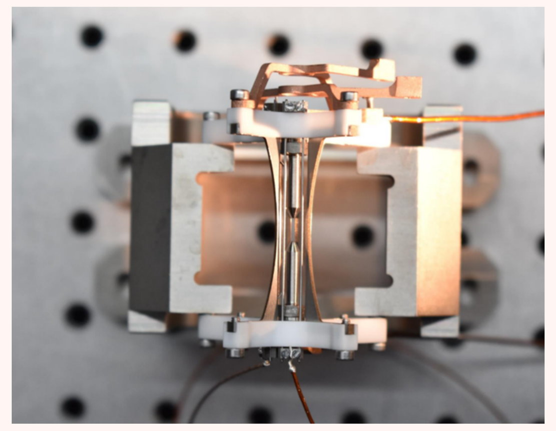

Figure 2. Experimental setup inside the chamber: DC endcaps, RF electrodes, and compensation rods.

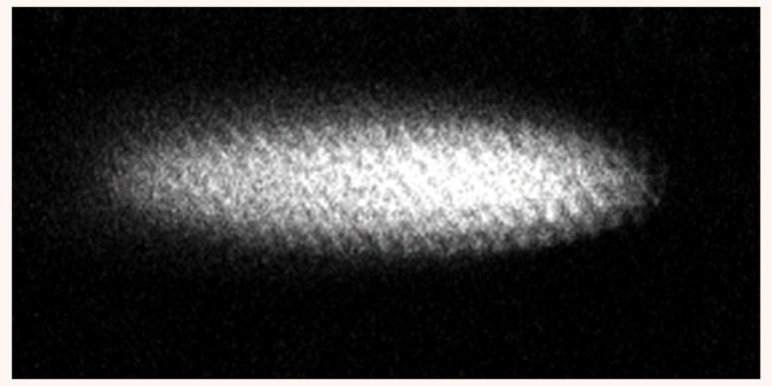

Figure 3. Observed ion Coulomb crystals in the ion trap system.

Trapping Frequency Acquisition

Trapping Frequency Acquisition refers to methods used to determine the oscillation frequencies of ions in a trap. It is measured by detecting resonance with the RF frequency of compensation rods. If the count of photons in the Region of Interest (ROI) decreases sharply, it indicates that the frequencies at which ions oscillate are similar to the AC frequencies of the compensation rods. These frequencies are primarily determined by the trap's electric field configuration. This measurement is crucial for implementing precise quantum gates.

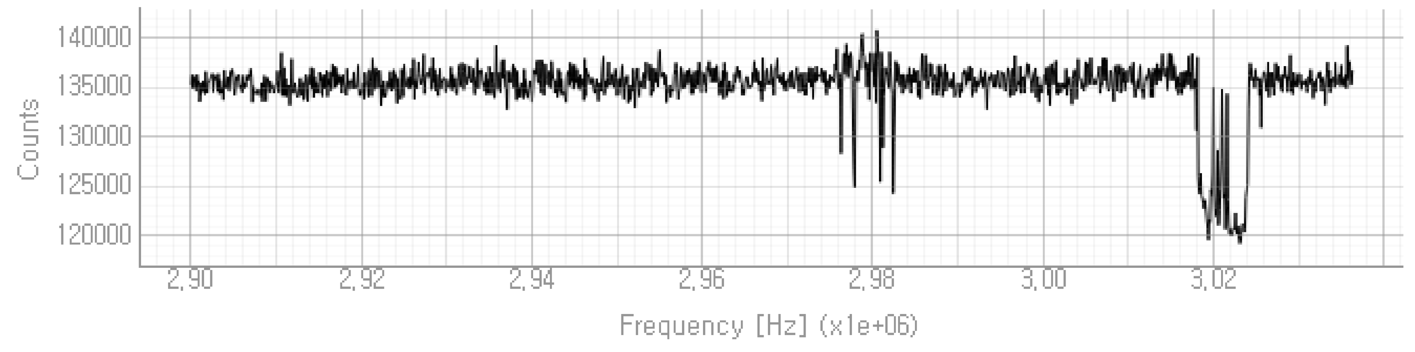

Figure 4. Trapping frequency acquisition results using AC signals from compensation rods.

397 nm Spectroscopy

397 nm spectroscopy is implemented using laser excitation of the $S_{1/2}$ to $P_{1/2}$ transition in Ca^+ ions. The frequency of the detuned 397 nm laser, which is applied to both the radial and axial axes, is scanned around the transition using an acousto-optic modulator. Fluorescence photons emitted by the ion as it decays back to the ground state are detected during Doppler cooling. The spectral profile of the 397 nm transition provides information about the ion's temperature. Ions at low temperatures have lower average velocities and a smaller range of Doppler shifts, resulting in a narrower spectral line with the peak near resonance. Additionally, 397 nm spectroscopy is crucial for optimizing Doppler cooling by detecting the maximum photon emission count. We implemented several actions to improve the shape of the graph, which indicates the ion's coldness. These actions include:

1. DC endcap voltage scan with combinations maintaining a constant average voltage (300V) between DC1 and DC2.
2. DC endcap voltage scan with combinations maintaining the same geometric configuration within a specific Region of Interest (ROI).
3. RF power modification; however, this increased the radial trapping frequency to 3.8 MHz, exceeding the suitable value of 3.0 MHz.
4. Impedance matching of the helical resonator between the RF electrodes' impedance and the trap impedance by detecting the reflected signal.
5. Class A Grounding; When we used the existing distribution board for grounding, which was shared by other devices, we observed noise that could affect the trapped-ion quantum computing (QC) system. To address this issue, we implemented Class A grounding for the optical table and the chamber. This modification eliminated the previous noise and resulted in a more stable system.

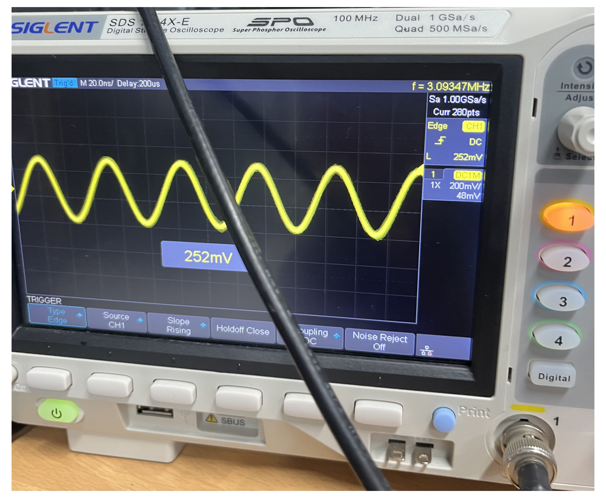

Figure 5. The oscilloscope result obtained using the existing distribution board for grounding.

Figure 6. The oscilloscope result after connecting the optical table and chamber to Class A grounding.

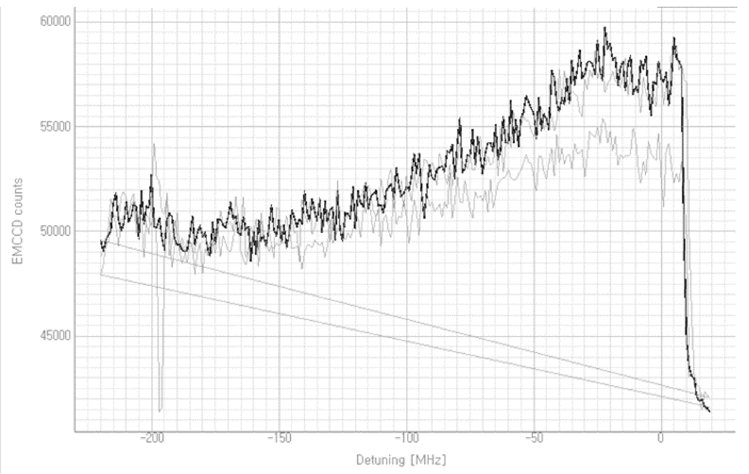

Figure 7. 397nm Spectroscopy results with DC1 endcap at 245V and DC2 endcap at 455V, without DC rods applied, before improvement.

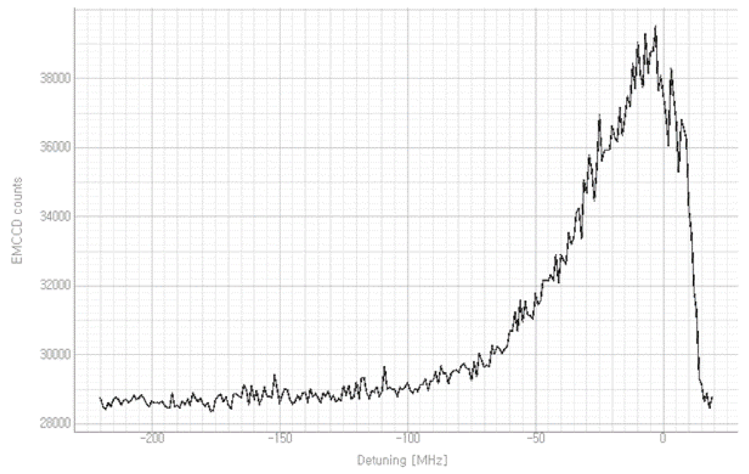

Figure 8. 397nm Spectroscopy results with DC1 endcap at 80V and DC2 endcap at 150V, without DC rods applied, after grounding improvement.

Micromotion Optimization via 2D Scanning with DC Compensation Rods

For cases where cooling the ion by modulating the endcap DC voltage is ineffective, applying DC voltage to compensation rods located vertically can slightly control the motion of the ions. Micromotion optimization in trapped ion systems refers to minimizing unwanted oscillatory motion of ions in a Paul trap by scanning the voltage of the rods to identify the cold conditions. A 60 MHz red-detuned 397 nm laser was used, where colder conditions result in fewer photon counts, emphasizing the contrast between cold and hot conditions. Optimal performance was observed when the DC1 rod was near 0 V and the DC2 rod was near -1175 V.

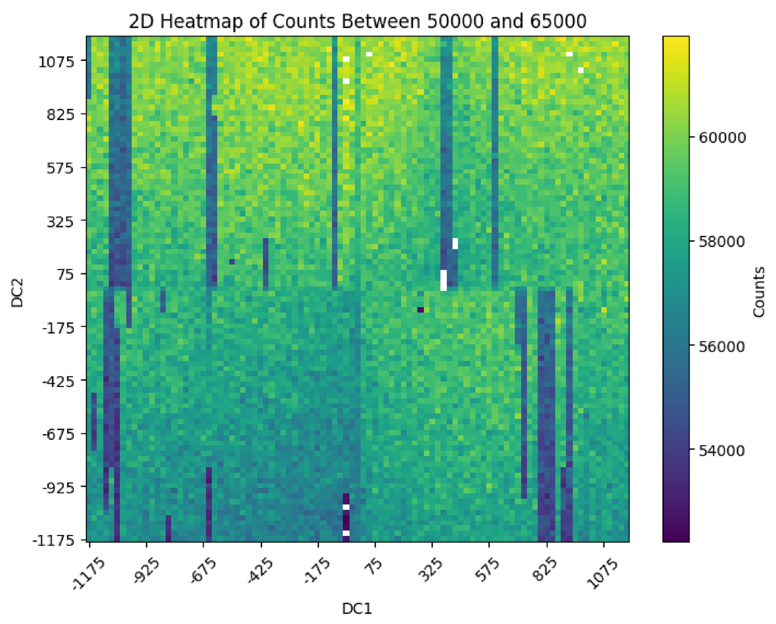

Figure 9. Visualization of 2D scanning with DC compensation rods for micromotion optimization, excluding outlier.

729 nm Spectroscopy

The 729 nm spectroscopy process consists of three steps: Doppler cooling (397 nm, 866 nm, 854 nm for 3 ms), state manipulation (729 nm for 3 ms), and state detection (397 nm, 866 nm for 22 ms). During state manipulation, the frequency of the 729 nm laser is scanned for 3 ms to change the state of the qubit. In the state detection step, using the 397 nm and 866 nm lasers, the state of the qubit is determined by observing photon counts. If the qubit is in the $D_{5/2}$ state ($|0\rangle$), it does not emit fluorescence during Doppler cooling and appears dark. However, if the qubit is in the $S_{1/2}$ state ($|1\rangle$), it emits fluorescence when illuminated by the 397 nm and 866 nm lasers, appearing bright. The higher the probability peak of the dark state in the results, the higher the fidelity of the state transition to $|0\rangle$. This process is crucial for determining which Zeeman sublevels to use as $|0\rangle$ and $|1\rangle$.

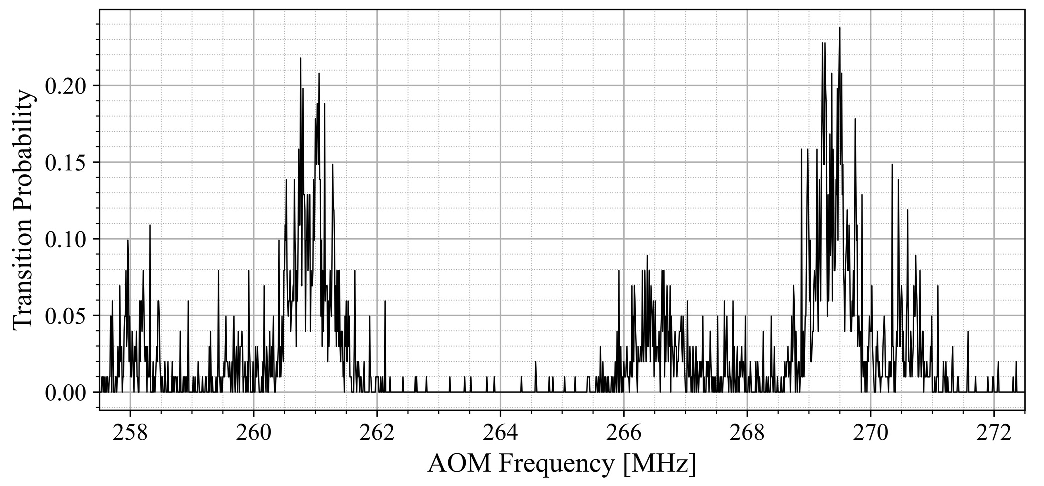

Figure 10. 729 nm spectroscopy results with 6 mW of 729 nm power, along the axial direction (endcap to endcap). The optimal transition occurs between $S_{1/2}, m_j = 1/2$ and $D_{5/2}, m_j = 1/2$.

References

[1] X. Fernandez-Gonzalvo and M. Keller, "A fully fiber-integrated ion trap for portable quantum technologies," *Scientific Reports*, vol. 13, no. 1, Jan. 2023, doi: `https://doi.org/10.1038/s41598-022-27193-9`.