

UC Riverside

UC Riverside Electronic Theses and Dissertations

Title

Trapping Electrons in a Monolithic PCB Paul Trap

Permalink

<https://escholarship.org/uc/item/0t07d99r>

ISBN

9798173720023

Author

Luo, Zijue

Publication Date

2026-08-25

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
RIVERSIDE

Trapping Electrons in a Monolithic PCB Paul Trap

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

Zijue Luo

September 2026

Dissertation Committee:

Dr. Boerge Hemmerling, Chairperson

Dr. Igor Barsukov

Dr. Shan-Wen Tsai

The Dissertation of Zijue Luo is approved:

Committee Chairperson

University of California, Riverside

ACKNOWLEDGMENTS

I would like to express my gratitude to my advisor, Professor Boerge Hemmerling, for his guidance, encouragement, and mentorship throughout my doctoral research. I am really grateful for the opportunity and trust he provided to me. I would also like to thank the members of my dissertation committee, Professor Igor Barsukov and Professor Shan-Wen Tsai, for reviewing this dissertation, their insightful discussions, and their constructive feedback. I am deeply grateful to our collaborators at the University of California, Berkeley, especially Professor Hartmut Häffner and his research group, for their generous support, fruitful discussions, and valuable insights into electron trapping and experiment design. I also extend my sincere appreciation to all members of the Hemmerling Laboratory throughout these years, including Li-Ren Liu, Miguel Aigurre, Tianyi Wang, Madhav Dhital, Noorulhoda Kazemi, Fan Lu, Chen Wang, Jae Eu, and Shirish Pathick, for their assistance in the laboratory. This work was supported in part by the Air Force Office of Scientific Research (AFOSR) under grant FA9550-24-1-0337. Portions of the text and figures presented in Chapters 2, 3, and 4 of this dissertation are based on or adapted from material published or prepared for publication with the collaborators mentioned above. The co-authors listed in these publications directed, supervised, or contributed to the research that forms the basis of this dissertation.

To my beloved parents and family,
for their unconditional love, patience, and endless support.

ABSTRACT OF THE DISSERTATION

Trapping Electrons in a Monolithic PCB Paul Trap

by

Zijue Luo

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, September 2026
Dr. Boerge Hemmerling, Chairperson

Ion traps are one of the most mature physical platforms for quantum information processing. The mainstream two-qubit gate of trapped ion qubits depends on the secular motional frequency, which is the main bottleneck for the speed of trapped ion qubits. This inspired the idea to trap electrons, particles with a much smaller mass than ions, to improve the speed of gates. Electrons also have other advantages such as a natural two-level system and laser-free detection and manipulation, but they also face challenges in high RF frequencies and new schemes for cooling and detection. In this dissertation, I designed and realized a monolithic PCB linear Paul trap with a half-wave resonator with a resonance frequency of ~ 1.7 GHz, and 20 DC electrodes with tracks of equal length for multipole control, which eliminates the need of mechanical assembly and would be beneficial to cryogenic experiments. The design is validated by ANSYS HFSS simulation for the resonator and Maxwell simulation for the electrode control. Using this monolithic PCB trap design, we successfully trapped electrons, characterized the dependence of trapping signals on experimental parameters, and investigated the stray field and trapping thresholds. We also conducted

thorough measurements of the electrons' motional frequencies and lifetimes. We found axial motional frequencies of the electrons up to $2\pi \times 55$ MHz and radial motional frequencies up to $2\pi \times 90$ MHz, as well as a lifetime of 2.13 ms. In addition, I introduced ideas to improve the trap design and presented an outlook for cryogenic trapping and non-destructive spin readout of trapped electrons.

CONTENTS

List of Figures	x
List of Tables	xvi
1 Introduction	1
1.1 Ion Traps	2
1.1.1 Paul Traps	3
1.1.2 Linear Paul Traps	8
1.1.3 Trapped-Ion Quantum Information Processing	17
1.2 Electron Traps	26
1.2.1 Why Electrons?	26
1.2.2 Current Status of Trapped Electrons	30
2 Single-PCB Electron Trap	32
2.1 Trap Design	32
2.2 Trap Simulation	38
2.2.1 RF Simulation	38
2.2.2 DC Simulation	42
2.2.3 Electron Trajectory Simulation	45
2.3 Trap Electrical Characterization	48
3 Room-Temperature Setup	54
3.1 Electron Source and Vacuum System	54
3.1.1 Electron Source	54
3.1.2 Vacuum Chamber	58
3.2 Laser System	60
3.3 Timing Sequence	63
3.4 Electronic System	65
3.4.1 RF Electrode Drive	66
3.4.2 DC Electrode Drive	67
3.4.3 Detection System	70

4	Room-Temperature Experiments	73
4.1	Commissioning and Initial Optimization	73
4.1.1	Stray Field Compensation	78
4.1.2	Trapping Thresholds	81
4.2	Motional Frequencies	82
4.3	Lifetimes	90
5	Conclusion	93
5.1	Summary	93
5.2	Improvement on the Single-PCB Trap	96
6	Outlook	100
6.1	Cryogenic Setup	100
6.2	Roadmap towards Non-Destructive Spin Readout of Trapped Electrons . .	104
	Bibliography	108

LIST OF FIGURES

1.1	Geometry of the classical design of Paul trap. (a) 3D view of the trap electrodes. (b) 2D Cross-section in the r - z plane.	3
1.2	Stability diagram of the Mathieu equation. (a) Stability chart of a single Mathieu equation in the (q, a) plane; shaded bands are stable. (b) Lowest stability region of the three-dimensional Paul trap in the (q_z, a_z) plane. A particle is trapped only in the overlap of the axial band (solid boundaries) and the radial band (dashed boundaries). For $a_z = 0$ the trapping region extends to $q_z \approx 0.908$	6
1.3	Geometry of a linear Paul trap. Four parallel rod electrodes are placed symmetrically around the trap axis at a distance r_0 and form two opposing pairs. One pair carries the RF drive and is continuous along the axis, so the radial confinement is uniform over the trapping region. The other pair is segmented into DC electrodes; biasing the outer segments relative to the center segment creates the potential well along the axis. The RF null is a line along the axis, which allows a string of ions to be trapped.	9
1.4	Linear Paul trap variants	10
1.5	Lowest stability region of the linear Paul trap in the (q, a) plane. Because $(a_y, q_y) = (-a_x, -q_x)$, the y stability band (dashed boundaries) is the mirror image of the x band (solid boundaries) about $a = 0$, and the trapping region formed by their overlap is symmetric about the q axis. On the $a = 0$ line the trapping region extends to $q \approx 0.908$	12

1.6	Energy levels of $^{40}\text{Ca}^+$ and the transitions used for trapping, cooling, and qubit operations. Doppler cooling and fluorescence detection use the 397 nm $S_{1/2} \rightarrow P_{1/2}$ transition with the 866 nm repumper; the optical qubit and sideband cooling use the narrow 729 nm $S_{1/2} \rightarrow D_{5/2}$ transition; the 854 nm laser resets the $D_{5/2}$ state. The inset shows the two-photon photoionization of neutral calcium (423 nm + a second photon at or below the 390 nm threshold).	19
2.1	(a) 3D model of the printed circuit board electron trap. The RF signal for the Paul trap is delivered to the board by an SMA-connected feedline (left side of the board), which is capacitively coupled to an on-board RF resonator. Electrons are trapped near the end of the resonator, at the center of the elongated plated slit. The DC signals are delivered by a D-sub connector (right side of board). (b) Zoomed view of the slit. The numbers 01 to 10 denote the DC electrodes on the top layer; a set of identical electrodes, 11 to 20, is located on the bottom layer. The slit is surrounded by a plated sidewall and a metal annular ring. (c) Schematics of the top (red) and bottom (blue) layers of the board. The RF signal is delivered by a coplanar RF resonator capacitively coupled in parallel to a feedline on the bottom half of the board. The DC signal traces are routed such that all have an equal length. Each DC trace has an added capacitor that acts as a low-pass filter.	33
2.2	Photo of the trap slit under an optical microscope. A discontinuity in the trace width is visible at the boundary between the slit section and the rest of the resonator.	36
2.3	Ansys HFSS model used for the RF simulation. The trap board is sandwiched between two copper shielding plates. Both the feedline and the resonator in the RF part are modeled in detail, including the via shielding. The SMA connectors are replaced by two simple wave ports. The slit region is also modeled according to the actual structure, including the DC electrodes and traces. DC traces far away from the center slit are neglected.	38
2.4	Simulated S parameters of the single PCB trap. (a) Magnitude and phase of the transmission S_{21} . (b) Magnitude and phase of the reflection S_{11} . (c) Absorption $A = 1 - S_{11} ^2 - S_{21} ^2$. Two resonances are predicted, at 1.753 GHz and 1.854 GHz.	39
2.5	Pseudopotential near the trap center, calculated for an RF input power of 4 W at the input SMA connector. Pseudopotential and its anharmonicity along (a) the x axis and (b) the y axis. (c) Pseudopotential in the x - y plane.	40
2.6	DC control matrix for the PCB trap. Each column represents the control voltages required to generate a unit of a multipole.	44

2.7	Electron trajectory simulation. Case 1 is the normal case for the electron trapping experiment. Case 2 is an extreme case with electrons dispersed over a larger volume with higher initial velocities. (a) Electron trajectories of 500 electrons in the two cases. (b) Total flight time of the electrons from the trapping region to the MCP. (c) Spatial distribution of the electron arrival positions on the MCP. The sample size for (b) and (c) is 10000. The simulation is performed in the presence of the extraction pulse (-20 V on electrodes 03 and 08).	47
2.8	Thermal camera images taken over 5 minutes. In the upper row, the trap is driven 400 MHz away from the resonance frequency. In the lower row, it is driven on resonance.	49
2.9	Measured S parameters of the single PCB trap. (a) Magnitude and phase of the transmission S_{21} . (b) Magnitude and phase of the reflection S_{11} . (c) Absorption $A = 1 - S_{11} ^2 - S_{21} ^2$. Only one resonance, at 1.752 GHz, is observed.	50
2.10	Comparison of the (a) simulated and (b) experimentally measured reflection, transmission, and absorption coefficients of the trap. The transmission (reflection) power coefficients $t = S_{21} ^2$ ($r = S_{11} ^2$) are extracted from the S parameters measured between the two SMA connectors (shown in Fig. 2.1). The absorption coefficient is calculated using the conservation of energy $1 - S_{11} ^2 - S_{21} ^2$.	51
3.1	Overview of our experiment system. The system hardware can be roughly divided into three parts: the vacuum chamber, the laser system, and the electronic control, each with its own power supplies. These systems need to work together synchronously and run experiments planned in batches, which is realized by the software system.	55
3.2	Electron generation scheme for our experiment. Field-induced ionization of a calcium atom via a Rydberg state. Two photons, at 390 nm and 422 nm, are used to excite the calcium atom.	56
3.3	Layout of our vacuum chamber. Four pairs of windows define four directions of the vacuum chamber, separated by 45° and taken by the trap board, the laser beams, the Ca atomic beam, and the electron flight trajectory for detection, respectively.	57

3.4	Fluorescence of the calcium atoms on the 422 nm transition. An excited calcium atom emits one 422 nm photon each time it relaxes to the ground state. The fluorescence only happens where the calcium atomic beam and the laser beam overlap. It spreads over a long distance across the vacuum system, which means the calcium atomic beam spreads over a large range even though we have limited it by an iris attached to the oven.	58
3.5	Laser system of our experiment. Solid lines represent laser beams, dashed lines represent communication between software systems, and dotted lines represent electrical signals. The system is physically separated into two sections. The source section contains the lasers and their control system, and the delivery section contains the components that merge the beams and finally deliver them to the trap center. The two sections are connected by single-mode fibers. Some functional parts such as beam expanders and mode-matching components are not shown in this flowchart.	61
3.6	Time sequence of the electron trapping experiment. The experiment can be divided into three phases: loading, waiting, and extraction.	64
3.7	Schematic diagram of the experiment. The oven provides a thermal beam of calcium atoms, which are photoionized to produce trappable electrons. The Paul trap is driven at 1.732 GHz. Further details are explained in the main text.	65
3.8	The RF drive system of the experiment. The signal is first generated by a signal generator controlled by the experiment control system, and then goes through two amplifier stages and is sent into the trap, and then monitored by a spectrum analyzer communicating with the experiment control system.	66
3.9	The signal processor for our DC electrodes. (a) Non-inverting DC amplifier on every DC channel, with a gain of 4.3. (b) Power stabilizer for the board. (c) 3D preview of the board.	68
3.10	The MCP signal processing and detection chain. A high-pass filter first removes the high voltage (~ 2600 V) on the anode to extract the signal. The signal is then amplified to be able to trigger the envelope threshold detector (ETDC), and goes through a low-pass filter to remove the noise induced by the RF drive. The ETDC and an arbitrary waveform generator (AWG) next turn the signal into a clean pulse, which can be stably read out by the ARTIQ Sinara device and finally recorded as an event timestamp.	70
3.11	An example of the MCP signal. The signal has a main pulse that lasts around 80 ns, followed by several periods of ringing over the next ~ 500 ns. The amplitude of the main pulse is around 5 mV.	71

4.1	Sample data of an electron trapping experiment and its alignment with the time sequence. The loading time and waiting time are both 200 μs , followed by a 900 ns extraction pulse. The data is accumulated over 400000 experiments taken with a tickling signal on resonance with the electron motion. The main histogram is calculated from the timestamp set with a bin width of 0.2 μs , and the zoomed histogram for the extraction is calculated with a bin width of 2.1 ns.	74
4.2	Electron signals versus experiment parameters. The survival signal and the loading signal, normalized by the number of repeats, are shown versus (a) the extraction pulse amplitude: the signal saturates when larger than 10 V; (b) the extraction pulse length: insensitive; (c) the frequency of the RF drive: resonances at 1.700, 1.732, and 1.747 GHz; (d) the frequency of the 422 nm laser: a resonance at 709.07659 THz measured by our wavelength meter; (e) the threshold voltage of the envelope threshold detector, which requires at least 32 mV to work; (f) the voltage on the MCP front: the higher the MCP voltage, the higher the detection efficiency.	76
4.3	Dependency of the electron signals on the E field. The maximum number of electrons is not reached when zero E field is applied at the trap center, but at some nonzero field. This suggests the existence of a stray field in our trap system.	78
4.4	Dependence of the optimal compensation field on different experiment parameters. Compensation electric field versus (a) mesh voltage; (b) multipole U_2 ; (c) RF amplitude.	80
4.5	Trapping thresholds of the single PCB trap, with the compensation field fixed and re-optimized. The trapping range gets significantly larger if we re-optimize the compensation field. (a) Electron signals versus the RF power, measured at $U_2 = -0.15 \text{ V/mm}^2$. (b) Electron signals versus U_2 , measured at an RF power of 3.47 W.	81
4.6	Example tickling spectra and resonance extraction. Normalized lost signal (lost signal / loading signal, panels b, d) and normalized trapped signal (surviving signal / loading signal, panels c, e) versus the tickle frequency. The data used here are already processed with baseline correction (asymmetric least squares, AsLS). (a) The comparison between the raw signal and the AsLS-corrected signal. (b, c) For a DC scan point at $U_2 = -0.22 \text{ V/mm}^2$ (RF input power 3 W), and (d, e) for an RF scan point at $P_{\text{rf}} = 3.29 \text{ W}$ ($U_2 = -0.35 \text{ V/mm}^2$). The result shows that the dips of the trapped signal appear at the same frequencies as the peaks of the lost signal.	83

4.7	Motional frequencies of the trapped electrons. (a) shows the motional frequency of the trapped electrons in the axial direction as a function of $ U_2 $. (b) and (c) show the motional frequencies in the radial direction as a function of the RF input power. Dashed lines are fits to the data of Eq. (4.1) and Eq. (4.2). The error bars of the data represent the average linewidth of the measured resonance peaks.	85
4.8	Dependence of the two radial branches on $ U_2 $. The points and error bars are the resonance frequency data and their linewidths. The dashed lines are the $U_1 = 0$ prediction of Eq. (1.13), whose slope $-\alpha_{\text{ax}}^2/2$ is fixed by the axial fit of Eq. (4.1). The solid lines are the prediction of the parasitic- U_1 model, which assumes $U_1 = \kappa U_2$	88
4.9	Trapped electron lifetime measurement. The data is fitted with an exponential decay, which yields a lifetime of 2.13 ms.	91
5.1	Examples of multi-layer stackups that integrate the shielding plates on board. (a) Buried grounded coplanar waveguide design, which keeps the current type of transmission line but integrates the shielding plates onto the trap board directly. (b) Stripline design, which changes the type of transmission line used in the design.	97
5.2	Backdrilling to remove the shielding effect on the DC field from the RF electrode. The layer stackup is based on the buried GCPW. (a) An ordinary through hole is manufactured first. Under this configuration, the DC line of sight is blocked by the RF electrode. (b) The backdrilling process then removes material only above Layer 2 and below Layer 3, with a drill width matching or slightly larger than the slot width plus the annular ring of the RF electrode. The DC line of sight is no longer blocked.	98
6.1	Cryogenic vacuum chamber of our lab. (a) Photo of the cryogenic chamber, the blue box is the exterior of the chamber, with optical setup and signal feedthroughs attached to it. (b) Structure of the cryogenic chamber. The chamber is a three-layer design, and the designed temperature for each layer from outside to inside is 300 K, 40 K, and 4 K. The inner layer is cooled by a pulsed-tube cryogenic refrigerator, and the outer layer is insulated from the 40 K layer by a superinsulation film.	101
6.2	Optical design of the cryogenic chamber. The thermal calcium atomic beam is replaced by laser ablation of a calcium target with a YAG laser (blue). The excitation lasers are duplexed from the same source section as the room-temperature setup, but not merged anymore. Instead, the two laser beams now intersect at the trap center, which makes sure electrons are only generated at this position.	103

LIST OF TABLES

2.1	Predicted parameters based on the simulated pseudopotential at $P_{\text{in}} = 4 \text{ W}$	42
2.2	Maximum voltages required to generate each multipole	43
2.3	Fitted resonator parameters	52
3.1	Layer stackup of the DC signal processor board	69

Chapter 1

Introduction

Quantum information processing is a promising technique with the potential to provide advantages in applications such as computation [1,2], simulation [3,4], and communication [5,6]. To realize these advantages, a physical platform that can reliably maintain, control, and measure the quantum state is required [7]. Trapped ions are one of the most well-established physical platforms in the field [8], providing extraordinarily long coherence times [9], high-fidelity control [10], and well-developed techniques for cooling [11], manufacturing [12], and readout [13].

The success of trapped ions naturally motivates the question of whether this framework of charged-particle quantum computing developed for ions can be extended to electrons. Electrons have several properties that are advantageous for quantum computing: a much smaller mass that supports faster operations [14–16], a simple two-level structure that fundamentally prevents state leakage to a third state [17–20], and a laser-free protocol for cooling, state control, and readout [14,15,17,21,22].

Despite these advantages, trapped-electron quantum computing faces its own challenges. The lighter mass of electrons requires a higher-frequency RF drive for stable confinement [23], and the Doppler cooling developed for trapped ions is not applicable to electrons [21, 23]. These constraints call for an alternative roadmap to trapped-electron quantum computing.

In this dissertation, I first establish the theoretical foundation for trapped ions and trapped electrons in Chapter 1. I then introduce our roadmap to trapped-electron quantum computing in Chapter ??, and discuss our trap design in Chapter 2 and the experimental system for trapping in Chapter 3. After that, I present the results of the trapping experiment in Chapter 4. Finally, I outline our future plans in Chapter 5.

1.1 Ion Traps

The Earnshaw theorem forbids trapping of charged particles by purely static electric fields [24]. To overcome this obstacle, two approaches have been developed: the Paul trap, which confines particles with time-varying electric fields [25], and the Penning trap, which confines them with a combination of static electric and magnetic fields [26]. Of these, the Paul trap is the most prevalent geometry used in quantum information processing. It is also the foundational technology we use for electron trapping.

In this section, we first discuss the three-dimensional trap, the canonical design of the Paul trap, in Sec. 1.1.1. We then extend the analysis to linear traps, the most practical design for the QCCD architecture, in Sec. 1.1.2. Finally, we summarize the foundations of trapped-ion quantum information processing in Sec. 1.1.3.

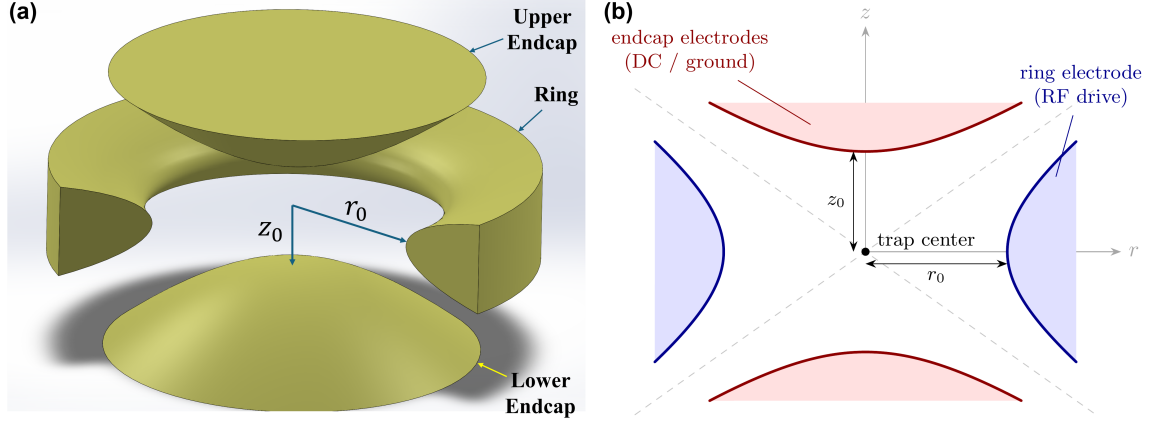


Figure 1.1: Geometry of the classical design of Paul trap. (a) 3D view of the trap electrodes. (b) 2D Cross-section in the r - z plane.

1.1.1 Paul Traps

The Paul trap was invented by Wolfgang Paul in the 1950s, initially designed as a quadrupole mass filter and later as a three-dimensional trap [27]. This invention earned Paul a share of the Nobel Prize in Physics in 1989 [25]. The limitation mentioned above is that a static electric field in free space can never produce a local minimum of the potential energy. The Paul trap addresses it by using oscillating electric fields. In this design, the trap geometry never generates a local minimum. Instead, it generates a saddle point of the potential energy and drives it faster than the particle can escape. As a result, when averaged over the drive period, the particle experiences a net restoring force towards the saddle point, as if the point were a potential minimum.

The classical design of the Paul trap is shown in Fig. 1.1. It consists of three electrodes whose surfaces are hyperboloids: a ring electrode of inner radius r_0 , and two endcap electrodes separated by $2z_0$ along the axis of rotation. The dimensions are designed to satisfy $r_0^2 = 2z_0^2$ to match the equipotential surfaces of an ideal quadrupole field [28]. A

voltage $U + V \cos(\Omega t)$, an RF drive with a DC bias, is applied between the ring electrode and the two endcaps. For atomic ions, the RF amplitude V is typically tens to hundreds of volts and the drive frequency $\Omega/2\pi$ is typically 10–100 MHz [8]. At these frequencies, the free-space wavelength is several meters, far larger than the trap dimensions, which means the field is quasi-static with respect to Maxwell’s equations and can be obtained from electrostatics at each instant. The applied voltage thus produces the potential

$$\Phi(x, y, z, t) = (U + V \cos(\Omega t)) \frac{x^2 + y^2 - 2z^2}{2r_0^2}, \quad (1.1)$$

which satisfies Laplace’s equation $\nabla^2 \Phi = 0$ at every instant [29]. The solution (1.1) makes the physical picture clear. At any instant, the potential is a saddle, confining the particle in the radial plane while expelling it axially, or vice versa. The RF drive exchanges these two roles at frequency Ω . The DC voltage U acts as a static bias to this effect, and the direction in which it strengthens or weakens the confinement depends on its sign.

The motion of a particle with mass m and charge e in this potential obeys Newton’s second law $m\ddot{u} = -e \partial \Phi / \partial u$ in each direction $u \in \{x, y, z\}$. Substituting the potential of Eq. (1.1), the three equations of motion decouple from each other, and each takes the form of the Mathieu equation

$$\frac{d^2 u}{dt^2} + \frac{\Omega^2}{4} [a_u - 2q_u \cos(\Omega t)] u = 0, \quad (1.2)$$

with the dimensionless parameters

$$a_x = a_y = -\frac{a_z}{2} = -\frac{4eU}{m\Omega^2 r_0^2}, \quad q_x = q_y = -\frac{q_z}{2} = \frac{2eV}{m\Omega^2 r_0^2}. \quad (1.3)$$

These two numbers fully determine the motion of the trapped particles. The physical parameters of the particle and the trap (m, e, U, V, Ω, r_0) affect the motion only through

their influence on a_u and q_u . This makes these two parameters the key quantities in trap design. In most experiments, particles are trapped in the regime of $|a_u|, q_u^2 \ll 1$, where the lowest-order solution of the equation is

$$u(t) \approx u_0 \cos(\omega_u t + \varphi_u) \left[1 + \frac{q_u}{2} \cos(\Omega t) \right], \quad \omega_u = \frac{\Omega}{2} \sqrt{a_u + \frac{q_u^2}{2}} \ll \Omega. \quad (1.4)$$

From this solution we can see that the motion divides into two components: a slow harmonic oscillation at frequency ω_u , called the secular motion, and a fast oscillation at the drive frequency Ω on top of the secular motion, with an amplitude $q_u/2 \ll 1$ times the instantaneous displacement of the secular motion, called the micromotion [29, 30].

The micromotion predicted by the solution above is unavoidable, because it originates from the RF field, the source of the confinement itself. It is usually small since its amplitude is proportional to the secular displacement, and a trapped particle stays mostly near the trap center, where the RF field is minimal. However, in practice, a second contribution called excess micromotion arises when stray static fields displace the equilibrium position of the particle away from the trap center, or when the RF phases on the electrodes are inconsistent. This excess micromotion does not scale with the secular motion, and therefore does not vanish near the trap center like its intrinsic counterpart.

This distinction matters because micromotion modulates the particle velocity at Ω . This causes first- and second-order Doppler shifts that broaden and shift spectroscopic lines, limits the efficiency of laser cooling, and degrades the fidelity of quantum gate operations [30–32]. For the intrinsic micromotion, these effects diminish as the particle is cooled toward the trap center. The excess part instead persists, and it eventually dominates the residual motion and limits the cooling itself. Excess micromotion must therefore be minimized, which

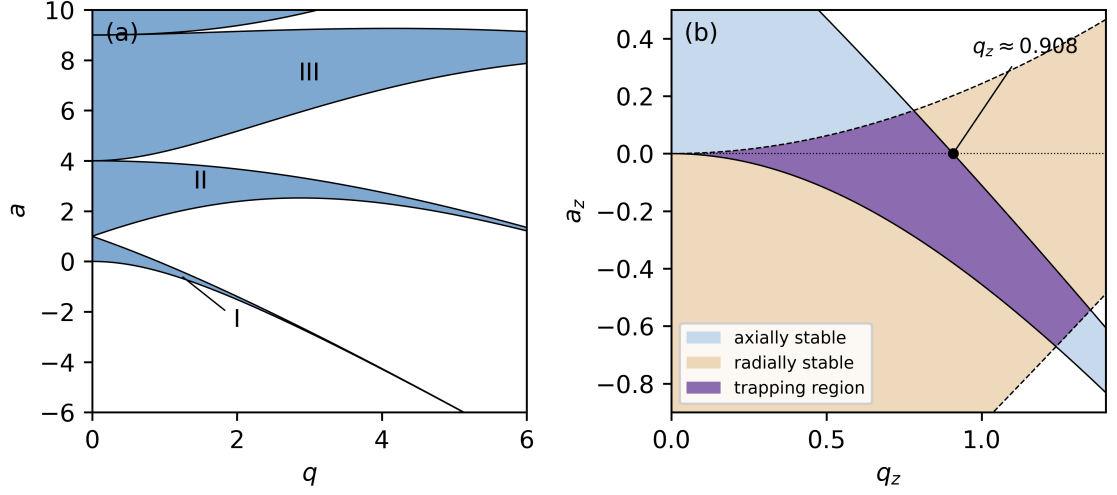


Figure 1.2: Stability diagram of the Mathieu equation. (a) Stability chart of a single Mathieu equation in the (q, a) plane; shaded bands are stable. (b) Lowest stability region of the three-dimensional Paul trap in the (q_z, a_z) plane. A particle is trapped only in the overlap of the axial band (solid boundaries) and the radial band (dashed boundaries). For $a_z = 0$ the trapping region extends to $q_z \approx 0.908$.

can be done by applying compensation voltages to the electrodes [30]. Such micromotion compensation is a standard preparatory step in any high-fidelity trapped-ion experiment.

However, the oscillatory solution of Eq. (1.4) does not exist for arbitrary (a_u, q_u) . In general, solutions of the Mathieu equation can be either stable or unstable. In unstable solutions, the distance of the particle from the trap center grows exponentially until the particle is lost. The boundaries between the two classes of solutions split the (a, q) plane into stability regions and instability regions, known as the Mathieu stability diagram, shown in Fig. 1.2(a). In practice, experiments operate almost exclusively in the lowest stability region, labeled I in Fig. 1.2(a). For $a = 0$, this stability region extends to $q \lesssim 0.908$ [29]. Moreover, a particle is trapped only if the parameters of all three axes lie simultaneously within a stable region. With the factor-of-two relations of Eq. (1.3), the overlap of the axial

and radial stability bands forms the trapping region shown in Fig. 1.2(b). In experimental terms, moving along the q axis corresponds to changing the RF amplitude V , and moving along the a axis corresponds to scanning the DC bias U on top of the RF signal.

While the Mathieu formalism above gives the full dynamics, most of the analysis involved in real experiments does not require such detailed information. For this reason, researchers simplified the mechanism into a classical model of an engineered potential minimum, known as the pseudopotential approximation. This approximation holds because in most quantum information experiments, particles are deep inside the lowest stability region, $q_u \lesssim 0.4$, where the secular motion is far slower than the drive ($\omega_u \ll \Omega$). In this regime, if we average the motion over one period of the drive to eliminate micromotion, then the remaining secular motion will evolve as if in an effective static potential, called the pseudopotential (or ponderomotive potential) [33]:

$$\Psi(x, y, z) = \frac{e^2 V^2}{4m\Omega^2 r_0^4} (x^2 + y^2) + \frac{eU}{2r_0^2} (2z^2 - x^2 - y^2). \quad (1.5)$$

This is a harmonic well whose oscillation frequencies reproduce the secular frequencies of Eq. (1.4),

$$\omega_r^2 = \frac{e^2 V^2}{2m^2 \Omega^2 r_0^4} - \frac{eU}{mr_0^2}, \quad \omega_z^2 = \frac{2eU}{mr_0^2}. \quad (1.6)$$

Equation (1.6) exposes a design trade-off of the three-dimensional Paul trap. A positive U provides axial confinement but radial anticonfinement, so a larger RF amplitude V is required to restore the radial confinement. The resulting harmonic confinement makes a trapped ion an exceptionally clean realization of the quantum harmonic oscillator, and the pseudopotential is therefore the standard working model for quantum information experiments [31].

However, as we mentioned above, the pseudopotential approximation averages the motion over a drive period. This makes the model incapable of capturing the micromotion of the ions and its consequences. Whenever the investigation targets the micromotion and its impact, the analysis must return to the full dynamics of Eq. (1.2).

1.1.2 Linear Paul Traps

While the three-dimensional Paul trap contains all the essential physics of RF confinement, it is inconvenient for quantum information experiments in two ways. First, its RF field vanishes at a single point, so at most one ion can be held free of intrinsic micromotion. When several ions are loaded, their mutual Coulomb repulsion pushes them away from the null point, and every ion picks up micromotion. Second, the electrodes enclose the trapping region almost completely, which leaves little room for laser access. The linear Paul trap removes both problems. Its RF null is not a point but a line along the trap axis, so a whole string of ions can sit on the null [34], and its open geometry lets laser beams reach the ions both along the axis and from the side. For these reasons, the linear trap has become the standard choice in quantum information experiments [29].

Fig. 1.3 shows a common realization of the linear Paul trap. Four parallel electrodes are placed symmetrically around the trap axis at a distance r_0 , forming two opposing pairs. One pair carries the RF drive and is continuous along the axis, so it provides the same radial confinement over the whole trapping region. The other pair is held at static voltages and is cut into segments, so that each segment can be biased individually. These voltages build the potential well along the axis. The linear design thus splits the task of trapping into two nearly independent parts: the RF field confines the particle in the radial

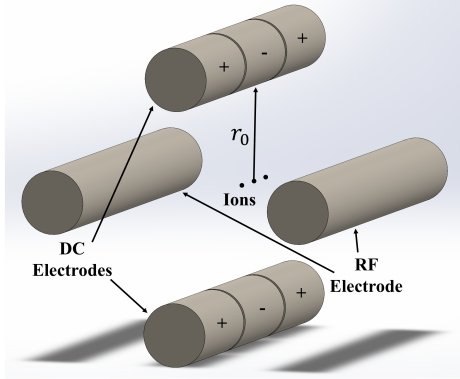


Figure 1.3: Geometry of a linear Paul trap. Four parallel rod electrodes are placed symmetrically around the trap axis at a distance r_0 and form two opposing pairs. One pair carries the RF drive and is continuous along the axis, so the radial confinement is uniform over the trapping region. The other pair is segmented into DC electrodes; biasing the outer segments relative to the center segment creates the potential well along the axis. The RF null is a line along the axis, which allows a string of ions to be trapped.

$(x-y)$ plane, and the DC electrodes confine it along z . This is in contrast to the 3D trap, where the axial confinement came from a DC bias on the same electrodes that carry the RF drive.

Historically, this linear geometry is even older than the 3D trap. Paul's original device was the linear quadrupole mass filter, in which ions travel along the axis while the RF field confines them radially. Since the Mathieu parameters scale inversely with the mass, scanning U and V along the operating line $a/q = 2U/V$ admits ions through the filter one mass at a time [25]. This is the core principle of the quadrupole mass spectrometer, and this geometry later developed into the most prevalent design in charged-particle trapping.

Theoretically, a set of perfect electrode surfaces should be hyperbolic cylinders that follow the equipotential surfaces of a two-dimensional quadrupole field. However, in practice, cylindrical rods, machined blades, or flat metal strips are more common because

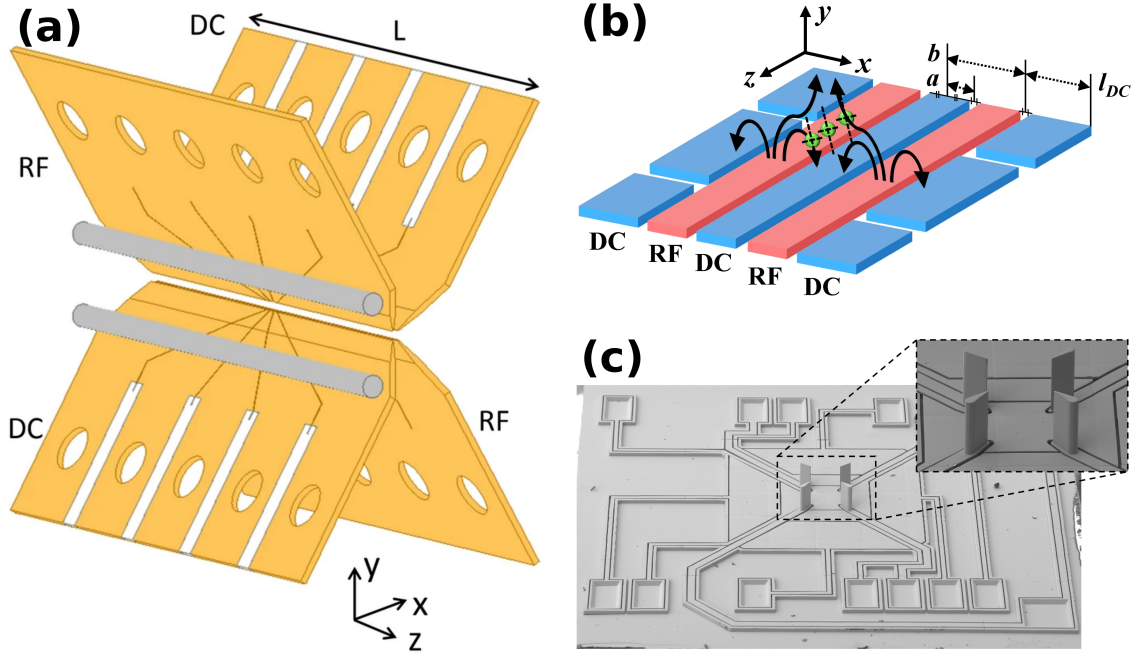


Figure 1.4: Common linear Paul trap geometries. (a) A segmented-blade trap. (b) A microfabricated surface-electrode trap. (c) An additively manufactured (3D-printed) trap. Panel (a) reproduced with permission from Springer Nature: J. Hong, M. Kim, H. Lee, and M. Lee, “Numerical investigation of a segmented-blade ion trap with biasing rods,” *Appl. Phys. B* **129**, 16 (2022) [36], under licence 6290451316215. Panel (b) reproduced from S. Hong, M. Lee, H. Cheon, T. Kim, and D.-i. Cho, “Guidelines for designing surface ion traps using the boundary element method,” *Sensors* **16**, 616 (2016) [37], licensed under CC BY 4.0.

they are much easier to manufacture. Near the trap axis, they still produce a field that is approximately quadrupolar. The price is that the field deviates from the ideal quadrupole field away from the axis, which appears as anharmonic terms in the trapping potential [35].

Most modern ion trap designs keep the logic of the linear Paul trap: an RF structure for radial confinement plus segmented DC electrodes for axial control. They differ mainly in how the electrodes are made and arranged. Fig. 1.4 shows three common examples. Blade traps replace the rods with machined blades whose sharp edges face the

trap axis, which opens a wider solid angle for laser access and imaging [36,38]. Surface traps place all electrodes in a single plane and hold the ions above the chip. The planar layout allows fabrication by lithography, which supports small feature sizes and large numbers of electrodes. This makes surface traps a leading candidate for scalability [12,39,40]. Printed circuit board (PCB) traps, on the other hand, pattern the electrodes as copper traces on one or several circuit boards, so the trap can be produced by standard commercial PCB manufacturing technology [23,41]. This is the approach taken in this dissertation. Finally, 3D-printed traps build the electrodes by additive manufacturing, which allows microscopic three-dimensional geometries that planar fabrication cannot reach [42].

We now return to the four-rod trap of Fig. 1.3 and put it on the same footing as Sec. 1.1.1. The RF pair is driven with a voltage $U + V \cos(\Omega t)$, where the DC bias U is kept here for generality. Near the axis, the resulting potential is

$$\Phi_{\text{rf}}(x, y, t) = (U + V \cos(\Omega t)) \frac{x^2 - y^2}{2\rho_0^2}, \quad (1.7)$$

where ρ_0 is the effective field radius, a length fixed by the electrode geometry. For ideal hyperbolic electrodes, it equals the electrode-to-axis distance r_0 . Compared with the quadrupole potential of the 3D trap, this field has no z dependence at all, which means it exerts no axial force, and thus its null is the whole line $x = y = 0$ instead of a single point.

Inserting Eq. (1.7) into Newton's second law gives a Mathieu equation for each RF controlled direction,

$$\frac{d^2 u}{dt^2} + \frac{\Omega^2}{4} [a_u - 2q_u \cos(\Omega t)] u = 0, \quad u \in \{x, y\}, \quad (1.8)$$

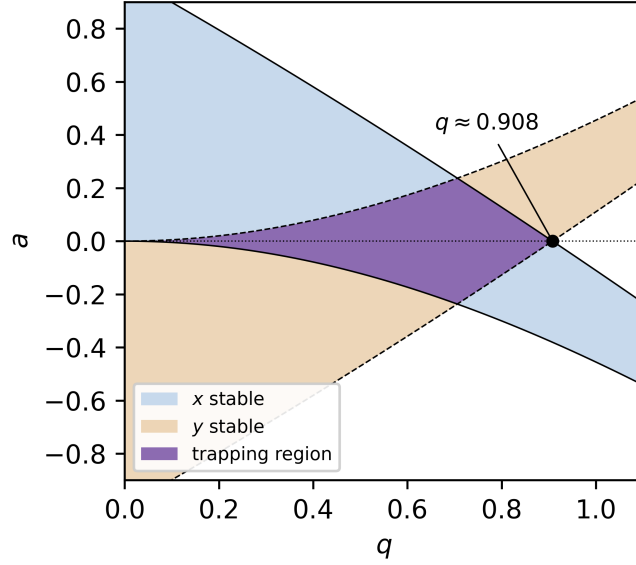


Figure 1.5: Lowest stability region of the linear Paul trap in the (q, a) plane. Because $(a_y, q_y) = (-a_x, -q_x)$, the y stability band (dashed boundaries) is the mirror image of the x band (solid boundaries) about $a = 0$, and the trapping region formed by their overlap is symmetric about the q axis. On the $a = 0$ line the trapping region extends to $q \approx 0.908$.

with the parameters

$$a_x = -a_y = \frac{4eU}{m\Omega^2\rho_0^2}, \quad q_x = -q_y = \frac{2eV}{m\Omega^2\rho_0^2}. \quad (1.9)$$

The two directions obey the same equation with opposite signs, $(a_y, q_y) = (-a_x, -q_x)$. Therefore, in the stability diagram, the y band is the mirror image of the x band about the line $a = 0$, which makes the trapping region, the overlap of the two bands, symmetric about the q axis in this layout, as shown in Fig. 1.5. In quantum information experiments, the RF electrodes usually carry no DC bias, so $a = 0$. The operating point then lies on the q axis, where the trapping region extends to $q \lesssim 0.908$, the same limit as in the 3D trap [29].

Deep inside the stability region ($q \lesssim 0.4$), we can again average the motion over one period of the drive, as in Sec. 1.1.1. The RF field then reduces to the pseudopotential

$$\Psi_{\text{rf}}(x, y) = \frac{e^2 V^2}{4m\Omega^2 \rho_0^4} (x^2 + y^2), \quad (1.10)$$

which is a two-dimensional harmonic well with the secular frequency

$$\omega_{r0} = \frac{q\Omega}{2\sqrt{2}} = \frac{eV}{\sqrt{2}m\Omega\rho_0^2} \quad (a = 0). \quad (1.11)$$

The RF field alone confines the two radial directions equally. We write ω_{r0} with a subscript zero because the DC field will shift the actual radial frequencies away from this value.

Axial confinement is provided by the DC electrodes. Since the trapping region contains no charge, the DC potential obeys Laplace's equation. A powerful tool to describe such a field is a spherical multipole expansion about the trap center [43]. Keeping multipoles up to the second order, we have

$$\begin{aligned} \Phi_{\text{dc}}(x, y, z) = & C + E_x \frac{x}{r_0} + E_y \frac{y}{r_0} + E_z \frac{z}{r_0} \\ & + U_1 \frac{x^2 - y^2}{r_0^2} + U_2 \frac{2z^2 - x^2 - y^2}{r_0^2} + U_3 \frac{xy}{r_0^2} + U_4 \frac{xz}{r_0^2} + U_5 \frac{yz}{r_0^2}, \end{aligned} \quad (1.12)$$

where r_0 is the length scale of the multipole expansion, a fixed length determined by the trap geometry.

Coefficients in the expansion have different physical meanings. The constant C is an offset on the potential and has no effect on the motion. The three dipole terms E_x , E_y , E_z describe a uniform electric field at the trap center along the three directions. They shift the equilibrium position of the particle without changing the shape of the well, and could increase excess micromotion if the equilibrium position is pushed off the RF null. A stray field from patch potentials or nearby dielectrics [44, 45] enters the expansion in exactly the

same way, so applying dipole terms of the opposite sign pushes the particle back onto the RF null line [46]. The five quadrupole terms U_1 to U_5 set the curvatures of the potential. Among them, U_2 is the term used for axial confinement since it has a curvature along the z direction. However, this term also has an inverse curvature in the other two directions. U_1 curves the two radial directions with opposite signs, and the cross terms U_3 , U_4 , U_5 rotate the principal axes of the well away from x , y , z .

Adding the DC curvatures to the RF pseudopotential of Eq. (1.10) gives the final secular frequencies of the linear trap,

$$\omega_z^2 = \frac{4eU_2}{mr_0^2}, \quad \omega_{x,y}^2 = \omega_{r0}^2 - \frac{1}{2}\omega_z^2 \pm \frac{2eU_1}{mr_0^2}. \quad (1.13)$$

Two points are worth noting here. First, the radial frequencies are not set by the RF field alone. The U_2 term, which confines the particle axially, anticonfines it radially and lowers both radial frequencies. This is forced by Laplace's equation, which requires the three curvatures of Φ_{dc} to sum to zero. Second, the U_1 term can be used to control the splitting between the two radial frequencies, and the splitting is theoretically zero when no U_1 field is applied.

The expansion of Eq. (1.12) stops at the second order, which is enough to place the well and set its frequencies. It also tells us that 8 DC electrodes are required for full control of the trapping position and strength. The constant C is left out of the count because it has no effect on the motion and does not need to be controlled. When finer control of the well shape is needed, the expansion is simply carried to higher order. The third- and fourth-order coefficients describe the anharmonicity of the potential, and including them in the control scheme lets the voltages be chosen to null the anharmonicity over the region

the particle explores. However, controlling higher-order multipoles would require more DC electrodes as well.

The multipole expansion can also be developed into a method to control the DC field with the electrode voltages directly. Since the electrostatics is linear, the potential of N electrodes held at voltages V_k is

$$\Phi_{\text{dc}}(\vec{r}) = \sum_{k=1}^N V_k \phi_k(\vec{r}), \quad (1.14)$$

where ϕ_k is the *basis potential* of electrode k , which means the potential produced when electrode k is held at 1 V and all other electrodes are grounded at 0 V. The basis potentials are fixed by the electrode geometry alone, so they can be computed once for a given trap design with a numerical field solver in advance. A widely used solver in the trapped-ion community is a Python-wrapped package based on the boundary-element method (BEM), developed by the National Institute of Standards and Technology (NIST) [47]. The BEM approach is well suited to the open geometries of ion traps and supports a large number of DC electrodes [48]. However, in this work, where only a single trap-center spot is controlled, we use the more classic finite-element solvers of Ansys [49, 50].

Each basis potential ϕ_k from the solver is then expanded with the basis functions of Eq. (1.12) in a small region around the trap center. The expansion reduces the simulated function ϕ_k to a handful of numbers, namely the multipole coefficients that electrode k produces per volt. These numbers can be organized into a compact form. We first collect the coefficients of all electrodes into a matrix M , called the multipole matrix, whose entry M_{nk} is the coefficient of multipole n produced by electrode k at 1 V. We then denote the

voltages applied to the N electrodes as a vector $\vec{V} = (V_1, \dots, V_N)^T$. Multiplying the two gives the multipoles of the total potential,

$$\vec{c} = M\vec{V}, \quad (1.15)$$

where $\vec{c} = (E_x, E_y, E_z, U_1, \dots, U_5)^T$ is the multipole vector, in which the constant C is dropped since it does not need to be controlled. The multipole matrix therefore has the size $8 \times N$.

However, in the experiment, we need the map in the opposite direction: pick the multipoles and ask for the voltages. A linear trap usually has more electrodes than multipoles ($N > 8$). This means the multipole matrix M is not a square matrix and thus not invertible. Nevertheless, solutions for the voltages still exist, but they are not unique. The standard solution for this situation is the Moore–Penrose pseudoinverse M^+ [51]. This matrix is computed once from the simulated M and can be used to calculate the control voltages $\vec{V}$ from the target multipole vector $\vec{c}_t$:

$$\vec{V} = M^+ \vec{c}_t. \quad (1.16)$$

We call M^+ the control matrix of the trap. The pseudoinverse resolves the ambiguity in a convenient way. Among all voltage sets that realize the target exactly, it returns the one with the smallest voltages. If the target cannot be reached exactly, it returns the closest one in the least-squares sense. In both cases, this default behavior is exactly what one wants from a control matrix. For this reason, this approach is selected as the DC control method for this dissertation.

The multipole language also brings in one operation we have not met yet: shuttling, which moves the particle along the trap axis. In practice, the voltage sets that place the well

at a series of closely spaced positions along the path are solved in advance, and interpolating between them in time produces a smooth waveform that carries the well, and the particle with it, to the target position [52]. Shuttling is what enables the segmented, multi-zone traps of the QCCD architecture, in which ions are shuttled between separate regions for storage, interaction, and readout [40, 53].

In short, the linear Paul trap separates the two jobs of confinement: an RF field holds a string of ions radially, and a set of segmented DC electrodes shapes the potential along the axis. The trap developed in this dissertation is built on this design, and both its RF drive and its DC control follow the schemes described in this subsection. The concrete implementation of the multipole control method in our trap, including the simulated basis potentials and the hardware that generates the voltages, is described later in this dissertation. The quantum information operations built on top of these tools are the subject of Sec. 1.1.3.

1.1.3 Trapped-Ion Quantum Information Processing

We now have all the tools to hold a string of ions. A linear Paul trap confines them on its RF null line, and the control matrix shapes the DC potential around them. Holding the ions, however, is only the starting point of quantum information processing. To serve as a quantum processor, a physical system must further provide a well-defined two-level system as the qubit, together with the means to initialize it, read it out, and apply a universal set of gates [7]. Trapped ions meet the first requirement with their internal electronic states, and the choice of the pair of states as qubit states determines what type of qubit it is. Optical qubits encode information in a ground state and a metastable excited

state of the ion, separated by an optical frequency of hundreds of THz. The classic example is the $S_{1/2}$ and $D_{5/2}$ states of $^{40}\text{Ca}^+$ [54]. The transition between them is dipole-forbidden, so the upper state decays only after 1.17 s on average [55]. Compared with the microsecond time scale of gate operations, this lifetime is not a practical limit for the circuit depths of today’s experiments. However, it does set an upper limit on the qubit’s memory time, which the other qubit types below do not have. The transition is driven directly by a laser. Since the qubit coherence can never outlive the coherence of the laser that drives it, the laser must be stabilized to an extremely narrow linewidth, for example below 20 Hz in a representative $^{40}\text{Ca}^+$ system [56]. Hyperfine qubits use two hyperfine ground states of an ion with nuclear spin, such as $^{171}\text{Yb}^+$, $^{43}\text{Ca}^+$, or $^9\text{Be}^+$ [57–60]. Their GHz splitting is driven by microwaves or by two-photon Raman transitions, and in magnetic-field-insensitive clock states the coherence time can exceed one hour [9]. Zeeman qubits, on the other hand, use two Zeeman sublevels of the ground state, with a splitting, usually at the MHz scale, introduced by an externally applied magnetic field [61, 62]. They have the simplest level structure among ion qubits, while being sensitive to the strength of the external magnetic field. In all three cases the qubit is carried by internal states of a single ion, and the rest of this subsection follows one ion species through a complete experiment to make the requirements concrete.

We choose $^{40}\text{Ca}^+$ as the example. Its level structure and the relevant transitions are shown in Fig. 1.6. A thermal beam of neutral calcium atoms is excited by a 423 nm laser and then ionized by another laser at or below 390 nm. The ion is then captured by the trap, while the freed electron simply escapes. This approach is isotope-selective if the

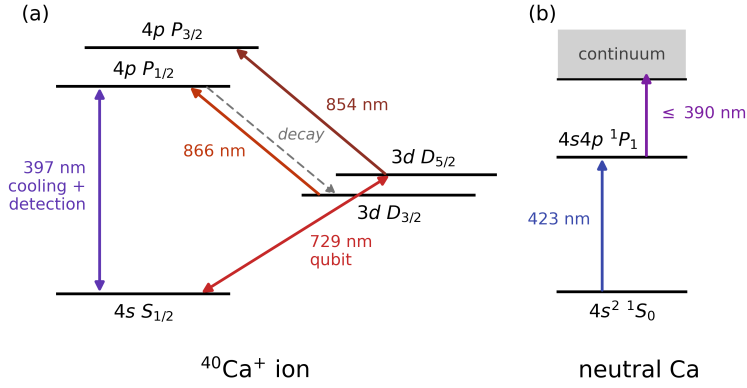


Figure 1.6: Energy levels of $^{40}\text{Ca}^+$ and the transitions used for trapping, cooling, and qubit operations. Doppler cooling and fluorescence detection use the 397 nm $S_{1/2} \rightarrow P_{1/2}$ transition with the 866 nm repumper; the optical qubit and sideband cooling use the narrow 729 nm $S_{1/2} \rightarrow D_{5/2}$ transition; the 854 nm laser resets the $D_{5/2}$ state. The inset shows the two-photon photoionization of neutral calcium (423 nm + a second photon at or below the 390 nm threshold).

laser linewidth is below 400 MHz, because the resonance frequency of the neutral atom's $^1S_0 \rightarrow ^1P_1$ transition shifts with the isotope [63].

The freshly loaded, hot ion is then Doppler cooled on the strong $S_{1/2} \rightarrow P_{1/2}$ transition at 397 nm. During the cooling process, the $P_{1/2}$ state occasionally decays to the metastable $D_{3/2}$ state, so an 866 nm laser is applied to repump these ions back to the cooling cycle. However, Doppler cooling alone cannot cool the ion to its motional ground state, because its final temperature is bounded from below by the Doppler limit, which is set by the natural linewidth of the cooling transition [64]. The motional mode relevant to quantum-gate operations is therefore further cooled close to its ground state using resolved-sideband cooling, a technique first demonstrated with trapped Hg^+ ions [11]. For $^{40}\text{Ca}^+$ [54], a narrow-linewidth 729 nm laser is tuned to the red motional sideband of the $S_{1/2} \rightarrow D_{5/2}$ transition, driving $|S_{1/2}, n\rangle \rightarrow |D_{5/2}, n-1\rangle$. This transition removes one

motional quantum from the selected mode. Because the $D_{5/2}$ state is metastable and does not decay sufficiently rapidly for efficient cooling, an 854 nm quench laser transfers the population to the short-lived $P_{3/2}$ state ($|D_{5/2}, n-1\rangle \rightarrow |P_{3/2}, n-1\rangle$). Spontaneous decay from the $P_{3/2}$ state returns the ion to the $S_{1/2}$ state while approximately preserving the reduced motional quantum number. Repetition of this cooling cycle removes one motional quantum per cycle and reduces the mean phonon occupation to $\bar{n} \ll 1$, corresponding to a high probability of occupying the motional ground state. After sideband cooling, coherent qubit rotations are driven on the carrier of the same 729 nm transition $|S_{1/2}, n\rangle \leftrightarrow |D_{5/2}, n\rangle$, which changes the internal qubit state without changing the motional quantum number. The red-sideband and carrier frequencies are typically addressed using the same stabilized 729 nm laser, with the required frequency shifts selected by an acousto-optic modulator. The qubit readout process is nondestructive and unusually intuitive, as the method directly visualizes the ion's qubit state as a bright or dark spot in a fluorescence image. During readout, the ion is illuminated at 397 nm. The ion repeatedly scatters photons if it is in the $S_{1/2}$ state, which makes it bright. When the ion is in $D_{5/2}$, the excitation does not happen and the ion stays dark. During this process, the 866 nm repumper is also applied, since the scattering cycle driven by the 397 nm laser passes through the $P_{1/2}$ state and can leak into $D_{3/2}$. This protocol is now very mature and has reached fidelities of over 99.99% [13, 65]. In addition, the 854 nm laser used in the sideband cooling cycle is also used for resetting the $D_{5/2}$ state after the operations on this ion are done.

With initialization and readout in place, single-qubit gates are easy to realize. They are resonant Rabi oscillations driven at 729 nm. Single-qubit gates are the most reliable operation of the platform [66–68]. The hard part is the two-qubit gate. The Coulomb interaction between two ions is strong, but it does not depend on their internal states, so by itself it produces no conditional dynamics. The solution is to route the interaction through the motion. The ions in a string share collective secular modes, and a state-dependent optical force can excite a shared mode conditioned on the qubit states. The shared mode therefore works as a quantum bus, and the bus connects any pair of ions in the same string regardless of their positions. This is what provides the all-to-all connectivity within an ion string. Two-qubit gates over this bus have been realized with $^{40}\text{Ca}^+$ ions [69].

The first protocol to run a gate over this bus was proposed by Cirac and Zoller in 1995 [70]. When two ions are confined in the same trap, their Coulomb interaction gives rise to collective two-ion motional modes, such as a center-of-mass (COM) mode and a stretch mode. One of these modes can be selected as a temporary quantum bus between the ions. The gate proceeds in three conceptual steps. First, a sideband pulse on ion 1 excites the selected two-ion mode conditionally on the state of ion 1. For example, with the mode initially in $|n = 0\rangle$, the pulse leaves $|S\rangle_1|0\rangle$ unchanged but maps $|D\rangle_1|0\rangle$ to $|S\rangle_1|1\rangle$. The state of ion 1 is therefore temporarily encoded in whether the shared mode contains zero or one motional quantum. Second, a pulse is applied to ion 2 whose action depends jointly on the state of ion 2 and on whether the motional excitation is present. The selected joint state undergoes a complete excitation cycle and returns to its initial population with a phase factor of -1 , while the other joint states remain unchanged. Finally, the first mapping is

reversed, restoring the qubit state of ion 1 and returning the motional mode to $|n = 0\rangle$. The motion is therefore used only as a temporary mediator and is disentangled from the ions at the end of the sequence, while the conditional phase acquired by one two-qubit basis state remains. This produces a controlled-phase gate with a conditional phase of π . Controlled-phase gates form a more general family, in which the conditional phase can take any value. The π case realized here is exactly the controlled- Z gate, up to single-qubit rotations. The protocol requires ground-state preparation of the selected motional mode and individual addressing of the two ions. It was realized experimentally with $^{40}\text{Ca}^+$ in 2003 [71].

The ground-state-cooling and individual-addressing requirements of the Cirac–Zoller protocol motivated the Mølmer–Sørensen (MS) gate, which uses the same collective motional bus in a different and less demanding way [72–74]. Rather than encoding one qubit temporarily in the collective motional states, the MS gate applies a bichromatic field to both ions. The field contains two coherent frequency components placed near the red and blue sidebands of a selected collective motional mode but with a small detuning δ from the exact sideband. Acting through the two sidebands at once, the light exerts a state-dependent dipole force whose sign is set by the ions’ internal states. Because the two components beat at the detuning δ , this force oscillates in time and drives the chosen motional mode around a closed loop in phase space rather than simply heating it. The frequencies, amplitudes, phases, and duration of the light are carefully designed such that, at the end of the pulse, the motional trajectory closes and the mode returns to its initial state with no residual spin–motion entanglement. Meanwhile, the area enclosed by the loop imprints a geometric phase that depends on the joint state of the two qubits. One

difference from the Cirac–Zoller case deserves attention. The force does not distinguish the qubit states $|S\rangle$ and $|D\rangle$ themselves but their superpositions, so the conditional phase is acquired in a rotated spin basis. In the computational basis the MS gate is therefore not a controlled-phase gate. Its native action coherently flips the two qubits together, for example driving $|SS\rangle$ and $|DD\rangle$ into a superposition of each other, which entangles the ions directly. With the loop area chosen appropriately, a single pulse turns a computational basis state into a maximally entangled state. The resulting operation is equivalent to the controlled- Z gate up to single-qubit rotations. Two-qubit gate fidelities have reached 99.9% with this approach [10, 75].

Unlike the Cirac–Zoller protocol, the MS gate does not require the selected mode to begin exactly in $|n = 0\rangle$, because the accumulated phase is geometric and depends only on the enclosed area. This significantly relaxes the cooling requirement of the Cirac–Zoller protocol, making the MS gate easier to implement and more robust. It has become the most common two-qubit gate in experiments today.

Both the Cirac–Zoller and the MS gate rely on spectrally resolved coupling to a selected collective motional sideband, and this reliance introduces a characteristic speed limit. A control pulse of duration T has a frequency bandwidth of order $1/T$, so shortening the pulse broadens its spectrum. If the pulse becomes too short, it can no longer distinguish the target motional sideband from the carrier transition or from the sidebands of other collective modes. Such a pulse drives unwanted transitions and leaves residual spin–motion coupling behind. The achievable gate speed is therefore constrained by the motional frequencies and by the frequency separations between nearby normal modes [31]. In practice,

with secular frequencies of a few MHz, high-fidelity gates typically take tens to hundreds of microseconds. Higher motional frequencies provide larger spectral separations and permit shorter sideband-selective operations. The secular frequency thus sets the operation speed of the processor. By the results of Sec. 1.1.2, it scales as $\sqrt{e/m}$ at fixed trap geometry and voltage, so the charge-to-mass ratio of the particle sets this speed.

This means the secular frequency acts as a speed limit for the platform. Approaches that work around this limit do exist. The fast-kick gate proposed by García-Ripoll abandons the sideband-selective drive altogether and entangles the ions with a train of short, strong state-dependent momentum kicks, which steers the motion around a closed loop without resolving any sideband [76]. Nonadiabatic shaped-drive gates keep the spin-dependent force of the MS gate but allow multiple motional modes to participate [77]. Rydberg-interaction gates step outside the motional bus entirely and entangle the ions through the strong dipolar interaction between trapped Rydberg ions [78]. While these solutions exist, each of them still faces its own challenges. The fast-kick gate remains experimentally demanding because it requires precise control of many ultrafast pulses and specialized laser hardware, and it comes with a trade-off on gate fidelities [79, 80]. The trade-off on gate fidelities also applies to the other two approaches [77, 78]. None of these approaches has widely displaced the MS gate so far, and most experiments today still run the MS gate or its variants. The secular frequency therefore remains a very important speed limit in practice.

The same motional spectrum that limits the speed of sideband-resolved gates also limits how far a single ion string can be scaled. As more ions are added, the number of collective modes increases and their frequencies become more closely spaced, making it

harder to address one mode without disturbing the others [8, 31]. The smaller ion spacing also makes individual optical addressing more susceptible to crosstalk [81, 82]. Moreover, as the ion chain gets longer, it becomes structurally unstable and undergoes a linear-to-zigzag transition, placing a practical limit on the size of a single linear crystal [83–85]. The trapped-ion community addresses this problem with the quantum charge-coupled device (QCCD) architecture [40, 53]. Instead of extending one ion string indefinitely, a QCCD processor divides the system into many short strings and shuttles selected ions between trapping zones. In this way, interactions can still be performed with the relatively simple mode spectrum and low error rates of a small ion crystal.

QCCD addresses the scaling limitations of a single ion string, and commercial quantum computers have been demonstrated based on it [86, 87]. However, it does not remove the trapped-ion platform’s reliance on multiple laser wavelengths and optical control channels, whose delivery across a large processor remains a major engineering challenge [88, 89]. Some approaches replace laser-driven coherent control with microwave or radio-frequency fields, including MAGIC and oscillating near-field-gradient schemes [90–92]. These methods are applicable to microwave-accessible Zeeman and hyperfine qubits and remove the need for optical gate beams, but laser light is still required for loading, cooling, state preparation, and fluorescence readout [89]. Integrated photonics instead retains the optical operations and routes the required wavelengths to the ions through on-chip waveguides, making it applicable to all qubit encodings and experimental stages that require light [93, 94]. This approach does not eliminate the optical scaling problem entirely, as

low-loss multi-wavelength delivery, independent control of many optical channels, optical crosstalk, and charging of exposed dielectric structures remain important challenges [95–97].

The optical control of trapped ions relies on their rich atomic level structure, such as cycling transitions and metastable levels. The same structure introduces costs as well. The spontaneous decay involved in readout and cooling creates the need for additional repumping lasers, and every level beyond the two qubit states is a possible destination for population that leaks out of the computation.

1.2 Electron Traps

Electrons, the main topic of this dissertation, are a newly emerging physical platform for quantum information processing, with the potential to be fast and reliable. Electrons in Paul traps have the potential to preserve most of the advantages of ions, such as long storage and coherence times, high-fidelity operations, and the QCCD architecture, while being faster and quantum mechanically more stable, with laser-free addressing. In this section, I provide an introduction to electron trapping and quantum information processing in Sec. 1.2.1, and an overview of the field of trapped-electron quantum information processing in Sec. 1.2.2.

1.2.1 Why Electrons?

The electron was among the first charged particles to be stored with electromagnetic fields. In 1936, F.M. Penning added an axial magnetic field to a low-pressure discharge

tube, so that the electrons inside travel along much longer paths before they reach an electrode [98]. Inspired by Penning’s discharge geometry, Dehmelt later combined it with a static quadrupole potential which confines the electrons’ motion along the axial direction, and developed it into a precision instrument that stored electrons for spectroscopy in the 1960s [33, 99]. Later in 1973, a single electron was isolated and stored in a device following the same principle, and was observed continuously through the image current induced on the electrodes by its axial motion [100]. This device was later widely called the Penning trap, and the trapped particle became known as geonium. In 1977, the motional frequency and spin state of the single electron were measured nondestructively with high precision [101]. The nondestructive approach for electron spin readout is later known as the continuous Stern–Gerlach effect [102, 103].

Over the following decades, the single particle trapped in a Penning trap grew into one of the most precisely examined objects in physics. The geonium experiments compared the g factors of the electron and the positron [104], and later generations of the experiment resolved the quantum structure of the cyclotron motion itself, observing quantum jumps between the lowest cyclotron Fock states with quantum nondemolition measurements [105]. The same degree of control produced the modern values of the electron magnetic moment, with relative uncertainties of 0.28 parts per trillion in 2008 [106] and 0.13 parts per trillion in 2023 [107], and the agreement of these values with quantum electrodynamics stands among the most stringent tests of any physical theory. For this dissertation, the message of these experiments is a different one. A single electron can be stored for months and controlled at the level of single quanta [99]. However, these experiments were never aimed at quantum

information processing. Each of them operates one electron in one precision trap deep inside a multi-tesla solenoid, optimized for spectroscopy rather than for computation.

The success of electron trapping with the Penning trap naturally raises the question of whether trapped electrons can be used as qubits. Throughout the history of quantum information science, multiple proposals have been made. Around 2000, Mancini, Martins, and Tombesi proposed quantum logic with a single trapped electron, encoding qubits in its spin and in its motional states [108, 109]. However, in traditional single-particle Penning traps, each electron is stored in a large apparatus, which is a barrier to scaling up to many qubits. Several proposals have been made to address this issue. Ciaramicoli, Marzoli, and Tombesi proposed a scalable architecture based on a linear array of individually addressable Penning microtraps, with one electron confined at each site [16]. In addition, a planar Penning trap, with all electrodes fabricated on one chip surface, was designed as the unit cell of such arrays [110, 111]. However, single-electron detection in such planar traps has never been demonstrated, due to challenges stemming from the anharmonicity of the planar trap potential [112, 113]. Another route to electron qubits is to use electrons in solid-state materials. Spin qubits in semiconductor quantum dots were proposed in 1998 [18] and demonstrated down to the single-atom level in silicon [19]. In addition, other techniques such as electrons floating above the surface of liquid helium, held there by their image attraction, were proposed as qubits as well [114, 115]. The Paul trap route, however, is relatively new. Its proposals also use the electron spin as the qubit encoding, and couple the electron's image currents to superconducting electronics for cooling and detection [22]. Spin

readout and addressing are realized by applying oscillating magnetic fields or magnetic field gradients [116]. We will discuss the details of the Paul trap route roadmap in Chapter ??.

The appeal behind all of these proposals rests on the three characteristics of electrons. First, electrons keep the established strengths of trapped charged particles. They are strictly identical particles held in ultra-high vacuum, with potential trapping lifetimes over a second, and their spin is expected to support long coherence times [17]. In addition, the electron mass is about $1/(7.3 \times 10^4)$ times that of a $^{40}\text{Ca}^+$ ion. According to Eq. (1.11) and Eq. (1.9), under the same stability parameter q , the secular frequency scales as $\sqrt{e/m}$, so the electron's motional frequencies are expected to be 270 times higher than those of a $^{40}\text{Ca}^+$ ion, enabling much faster quantum gates. Second, the electron's spin-1/2 is a perfect two-level system, and all electrons are intrinsically identical. This means we do not need to worry about leakage to a third state or about manufacturing variations between qubits. In addition, the electron spin qubit can be controlled by only electronic signals such as microwaves, which removes the complexity of the laser system, a major source of challenges in trapped-ion experiments.

However, these advantages come with technical challenges that need to be overcome. The simple two-level structure of the electron also means that the traditional Doppler cooling and sideband cooling are not applicable. The electron also has no cycling transition for fluorescence readout of the quantum state. This means we need to develop new methods for cooling and readout, which will be discussed in Chapter 6.

1.2.2 Current Status of Trapped Electrons

In the last two decades, electron qubits have moved from proposals to experimental research along several different routes. These experiments can be roughly divided into three different kinds: surface confinement, Penning traps, and Paul traps. Surface confinement has two major directions, using liquid helium and solid neon respectively. In the direction of liquid helium, an electron is attracted by the image charge it induces under the surface of the liquid, and therefore floats at a height of a few nanometers above the liquid helium surface. In this setup, electrons have successfully been coupled to a superconducting resonator, which enables manipulation and detection of the electron with electronics [117]. The solid neon direction, on the other hand, uses the same principle of image charge attraction but replaces the liquid helium with a solid neon film. In this direction, electrons have successfully been engineered into qubits [118, 119]. Both of these techniques use the motional states of the trapped electrons to encode the qubit states. Another major direction towards trapped-electron quantum computing is the Penning trap, the oldest approach used to trap electrons. In this direction, single electrons have successfully been trapped recently [120]. The third approach, the Paul trap, which is the main topic of this dissertation, is relatively new but advancing steadily. In 2021, the UC Berkeley group trapped electrons at room temperature using a linear trap assembled from three PCBs [23], and in 2025, the University of Tokyo group realized non-destructive detection of the existence of a trapped electron in a 3D trap [121]. However, when pushing the experiment towards trapping at cryogenic temperatures, they encountered issues of thermal contraction because mechanical assembly

is involved in their designs. This raises the idea of developing a monolithic PCB trap that is free of mechanical assembly, which is the topic of this dissertation.

Chapter 2

Single-PCB Electron Trap

In order to realize the monolithic PCB electron trap, the board must deliver all the fields required for trapping: a radio-frequency (RF) drive at gigahertz frequency that generates the radial pseudopotential, and a set of direct-current (DC) voltages that provides axial confinement and stray-field compensation. In addition, the board must allow free-space access for the electrons to be created and trapped, as well as a clear path to extract them for detection. The basic idea of the monolithic trap design is therefore to arrange the trapping slit and the RF and DC electrodes in a compact area on a single PCB. In this chapter, we discuss the details of this PCB design in Sec. 2.1, present the simulation of the trap in Sec. 2.2, and present the experimental characterization of the trap in Sec. 2.3.

2.1 Trap Design

Our electron trap is made of a single printed circuit board (PCB) with two conductive layers, as shown in Fig. 2.1. The PCB is fabricated out of a 30 mil thick

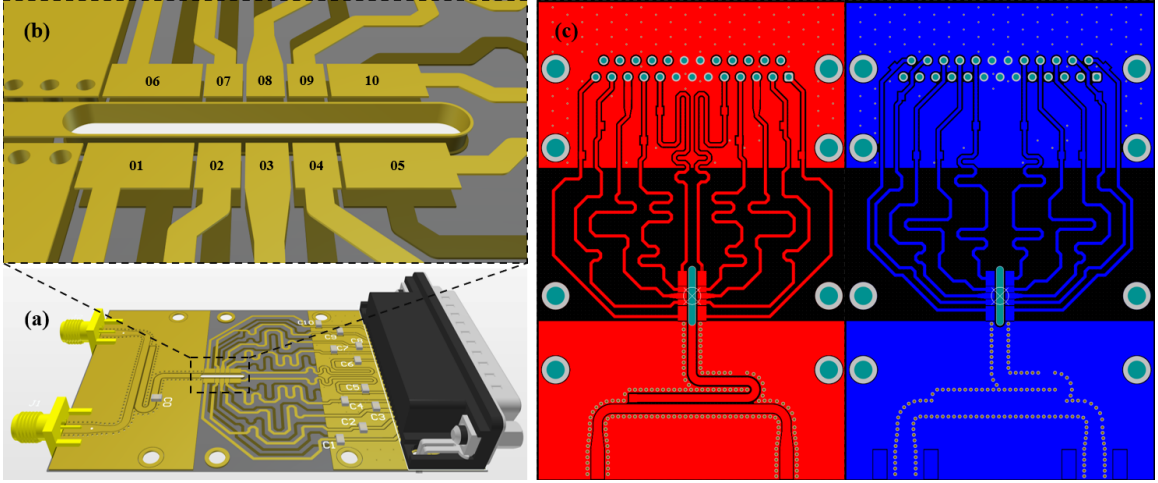


Figure 2.1: (a) 3D model of the printed circuit board electron trap. The RF signal for the Paul trap is delivered to the board by an SMA-connected feedline (left side of the board), which is capacitively coupled to an on-board RF resonator. Electrons are trapped near the end of the resonator, at the center of the elongated plated slit. The DC signals are delivered by a D-sub connector (right side of board). (b) Zoomed view of the slit. The numbers 01 to 10 denote the DC electrodes on the top layer; a set of identical electrodes, 11 to 20, is located on the bottom layer. The slit is surrounded by a plated sidewall and a metal annular ring. (c) Schematics of the top (red) and bottom (blue) layers of the board. The RF signal is delivered by a coplanar RF resonator capacitively coupled in parallel to a feedline on the bottom half of the board. The DC signal traces are routed such that all have an equal length. Each DC trace has an added capacitor that acts as a low-pass filter.

Rogers RO4350B substrate (1 mil = $25.4 \mu\text{m}$) with two $35 \mu\text{m}$ thick copper layers and finished with electroless nickel immersion gold (ENIG) plating. Six mounting holes are placed on the board to mount it inside the vacuum chamber, with the spacing between them chosen to be integer multiples of 0.5 inch, which is compatible with the mounting hole spacing of the vacuum chamber platform. In the final assembly, the board is sandwiched between two copper shielding plates that enclose the trap region. The RF simulations in Sec. 2.2.1 include these plates.

The board consists of two parts: a half-wave RF resonator on the left half, and 20 DC electrodes on the right half arranged around the trapping slit, ten on each copper layer

(Fig. 2.1(b)). Electrons are confined at the center of this elongated, side-plated slit cut into one end of the RF resonator, so both the RF and DC signals are routed to the slit. The signals enter the board through SMA connectors and a D-sub connector. The insulating cores of the SMA connectors are made of PTFE, which has the highest outgassing rate among the materials inside our vacuum chamber. Its outgassing is one of the factors that limit the base pressure of about 10^{-8} Torr. If lower pressure is needed in the future, materials with lower outgassing rates, such as PEEK or ceramic, would be required. The ground planes of the RF part and the DC part of the board are separate, and as a result the region near the slit is not covered by a ground plane. This design was originally intended to avoid mixing the RF and DC grounds. However, in later experiments, we found that it exposes bare dielectric surfaces on the trap that can hold charges and cause stray fields [44, 45]. A future revision should therefore use a single unified ground plane instead.

To eliminate any ambiguity in directions in the following discussion, we define a right-handed coordinate system centered on the trap, with $\hat{x}$ normal to the board surface and pointing towards the top layer, $\hat{y}$ in the board plane along the width of the slit pointing from electrode 03 to electrode 08, and $\hat{z}$ along the slit pointing from electrode 05 to electrode 01 (see Fig. 2.1(b) for the electrode numbering). The RF pseudopotential thus confines the electrons radially in the $\hat{x}$ - $\hat{y}$ plane, while the combined DC fields provide axial confinement along $\hat{z}$.

The RF subsystem consists of a half-wave coplanar resonator which is capacitively coupled in parallel to a feedline, both of which are designed as grounded coplanar waveguides (GCPW) with via fencing [122]. The resonator has a total length of 5.0 cm, which

corresponds to a designed resonance frequency of 1.87 GHz for both ends open. Here we use the design dielectric constant $\epsilon_r = 3.66$ of the RO4350B substrate [123]. The corresponding effective dielectric constant is $\epsilon_{\text{eff}} = 2.57$, and the impedance of the resonator is $Z_0 = 46.9 \, \Omega$. The widths of the RF resonator and the feedline are 54 mil and 60 mil, respectively, and their gaps to the ground plane are 10 mil and 5 mil, respectively. In addition, a soldering pad is placed at the midpoint of the resonator and is currently connected to the ground plane with a 10 pF capacitor, as suggested by colleagues at UC Berkeley. For the half-wave mode with both ends open, the midpoint of the resonator is a voltage node, so a connection to ground at this point does not disturb the trapping mode. The purpose of this connection is to fix the electric potential of the resonator, which is also the RF electrode of the trap, and to suppress spurious modes that have a voltage antinode at the center. The capacitor, however, provides a ground connection only at RF, while the DC potential of the resonator remains floating. In principle, it would therefore be better to replace the capacitor with a direct short to ground, which also pins the DC potential of the RF electrode. The trap of the UC Berkeley group is grounded in this way through a tap at the center of its resonator [23].

The feedline has an impedance of $39.7 \, \Omega$ and terminates in two SMA connectors soldered onto the trap board. Tapers are applied to smooth the impedance transition along the feedline and minimize reflection. The RF drive enters from one of the SMA connectors, and part of its power is coupled to the resonator. The residual power is transmitted and leaves the trap from the other SMA connector. This output is monitored by a spectrum analyzer (discussed in Chapter 3). The quality factor of the resonator is characterized in Sec. 2.3. This design couples the RF power from the feedline to the resonator and creates a

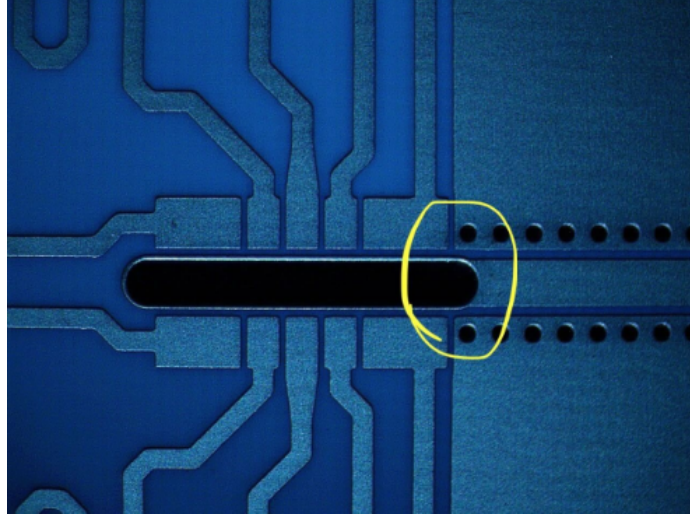


Figure 2.2: Photo of the trap slit under an optical microscope. A discontinuity in the trace width is visible at the boundary between the slit section and the rest of the resonator.

standing wave whose maximum voltage is located at the ends of the resonator, and therefore delivers the maximum RF voltage to the trap center at the designed resonance frequency.

As shown in Fig. 2.1(b), the slit that is cut into the resonator is a slotted pad with a drill width of 48 mil bounded by an annular ring of 3 mil. The resulting outer width of the slit section is $48 + 2 \times 3 = 54$ mil, which matches the width of the waveguide for a continuous transition to the trap region. The slit sidewalls are plated, so the RF electrode wraps around the trap center on all sides and provides confinement in the two directions transverse to the slit. A continuous ground plane on the back of the board (Fig. 2.1(c)) serves as the reference for the GCPW resonator and the feedline. This ground plane breaks the symmetry between the two sides of the board along $\hat{x}$. This asymmetry is reflected in the simulated radial pseudopotential (Sec. 2.2.1) and in the top- and bottom-layer entries of the DC control matrix.

The DC subsystem consists of 20 electrodes arranged in four rows, each containing five electrodes. These electrodes are arranged symmetrically along the slit in both the top and bottom layers of the board, with one row on each side of the slit on each layer, as shown in Fig. 2.1(b). The ten electrodes lying on the top layer are labeled 01 to 10 and the ten on the bottom layer are labeled 11 to 20. The clearance between the DC electrodes is 4 mil, and the clearance between DC traces and the ground plane is 8 mil. The DC electrodes are routed to a 25-pin D-sub breakout connector, and each trace has a 10 nF ceramic capacitor to filter high-frequency electrical noise. In addition to delivering static voltages for axial confinement and stray-field compensation, these electrodes are also used to deliver an extraction pulse for electron detection and a radio-frequency tickling signal for probing the secular motion of the electrons. These signals are added to the DC voltages with bias tees. All DC traces therefore have the same length, so that the propagation delays of all channels are equal. The routing of the traces, on the other hand, is not symmetric. We minimize the directly facing area between the traces to reduce the crosstalk between the channels.

In the manufacturing process, PCB manufacturers usually have a minimum annular ring requirement to ensure the quality of the plating. Our design requires an annular ring of only 3 mil, which is smaller than the guaranteed capability of several manufacturers. We ended up using *Sierra Assembly*, who confirmed that they could fabricate this annular ring. However, there are still some imperfections in the slit, as shown in Fig. 2.2. The slit section came out slightly wider than the rest of the resonator, which could affect the RF

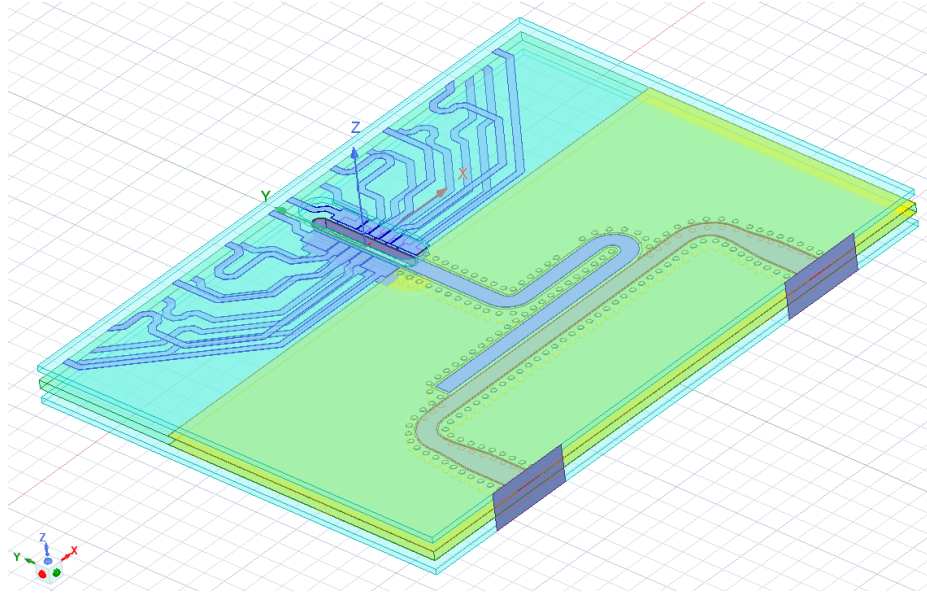


Figure 2.3: Ansys HFSS model used for the RF simulation. The trap board is sandwiched between two copper shielding plates. Both the feedline and the resonator in the RF part are modeled in detail, including the via shielding. The SMA connectors are replaced by two simple wave ports. The slit region is also modeled according to the actual structure, including the DC electrodes and traces. DC traces far away from the center slit are neglected.

performance. We have not investigated this in detail because the trap performs well, and we leave possible investigation and improvements to future work.

2.2 Trap Simulation

2.2.1 RF Simulation

The RF resonator is the crucial part of the trap, since it delivers the RF pseudopotential required for electron trapping. In order to predict and optimize its performance, we perform electromagnetic simulations with Ansys HFSS [49], which solves the full-wave Maxwell's equations. The model used in HFSS is shown in Fig. 2.3. The RF feedline, the resonator, and the structure near the trap center are modeled carefully to resemble the

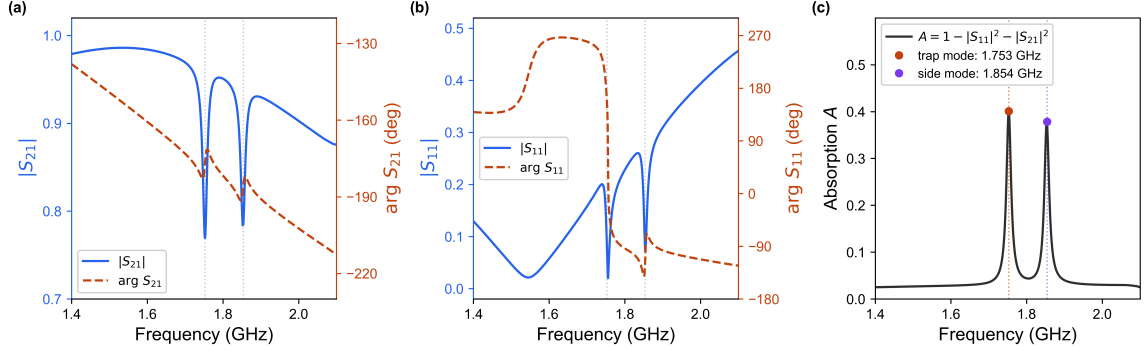


Figure 2.4: Simulated S parameters of the single PCB trap. (a) Magnitude and phase of the transmission S_{21} . (b) Magnitude and phase of the reflection S_{11} . (c) Absorption $A = 1 - |S_{11}|^2 - |S_{21}|^2$. Two resonances are predicted, at 1.753 GHz and 1.854 GHz.

actual design, including DC traces and via shielding. Mounting holes, the SMA connectors, and other structures far from the trap center are simplified or omitted.

In the design optimization phase, we need to simulate and verify multiple designs and find optimal parameters. Therefore, the dimensions of the 3D model are fully parameterized and can be scanned automatically. The difficulty I encountered during the design validation and parameter optimization is the computation cost: each simulation typically takes 20 minutes to 2 hours, which makes a grid search over all parameters unrealistic. For this reason, I only performed single-parameter scans or combined grid scans over 2 or 3 parameters in the optimization stage. This means the design is not globally optimal, and the interaction effects among parameters remain unexplored. To investigate these interactions and achieve a better design, more efficient approaches such as Design of Experiments (DoE) or optimization algorithms could be employed in the simulation, integrated in a PyAnsys script.

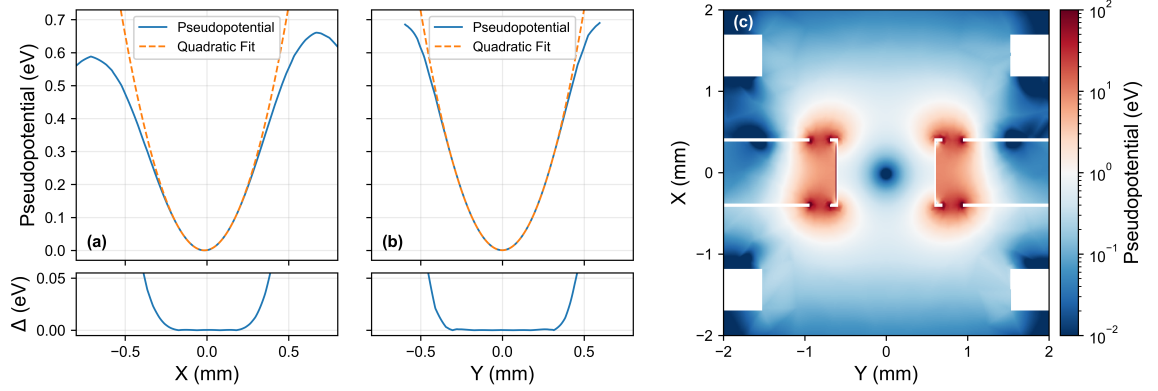


Figure 2.5: Pseudopotential near the trap center, calculated for an RF input power of 4 W at the input SMA connector. Pseudopotential and its anharmonicity along (a) the x axis and (b) the y axis. (c) Pseudopotential in the x - y plane.

The S parameters of the final design of the trap are shown in Fig. 2.4. Two resonances are predicted, at 1.753 GHz and 1.854 GHz. The absorption coefficient is calculated from the conservation of energy $E_{\text{in}} = E_{\text{ref}} + E_{\text{trans}} + E_{\text{abs}}$, where E_{in} represents the input RF energy, and $E_{\text{ref}} = |S_{11}|^2 E_{\text{in}}$, $E_{\text{trans}} = |S_{21}|^2 E_{\text{in}}$, and $E_{\text{abs}} = AE_{\text{in}}$ are the reflected, transmitted, and absorbed energy, respectively. Both predicted resonances are close to the design value of 1.87 GHz calculated from the length of the resonator, and the resonance at 1.854 GHz lies closest to it. The double resonance behavior could be due to the plated slit built for the trap center, which effectively creates two resonators, one whose length includes the slit and one whose length does not. However, this is only a hypothesis and has not been verified.

The S parameters provide the resonance frequency and the Q factor of the resonator, which are crucial performance metrics for our trap. The ultimate purpose of the design, however, is to deliver the pseudopotential required to trap the electron. According to Eq. (1.10), the main target we need to optimize is the magnitude of the RF electric field

near the trap center. Therefore, I exported the magnitude of the electric field near the trap center from HFSS, computed for an RF drive amplitude of 1 V. Since the field scales linearly with the drive amplitude, I scale the exported field to the amplitude $\sqrt{2PZ_0} = 20$ V, which corresponds to an input power of $P = 4$ W (36 dBm) into the $Z_0 = 50 \Omega$ feed. The pseudopotential is then calculated from the scaled field. Fig. 2.5 shows the resulting pseudopotential, and Table 2.1 shows the parameters calculated based on it. The trap depth is 588 meV along $\hat{x}$, set by escape through the saddle point normal to the board, and 684 meV along $\hat{y}$, set by hitting the plated slit sidewalls. The depth is evaluated separately for the two escape directions of each axis, and the smaller of the two is quoted here. These depths are large compared with both the room-temperature thermal energy $k_B T \approx 25$ meV and the typical initial kinetic energy of the photoionized electrons of about 10 meV (Sec. 2.2.3). The secular frequencies are obtained from a quadratic fit to the pseudopotential within ± 0.2 mm of the trap center. They correspond to a stability parameter of $q = 2\sqrt{2}\omega_r/\Omega \approx 0.25$, where Ω is the RF drive frequency. This is well below the stability boundary of $q \approx 0.908$. We quantify the anharmonicity as the deviation of the simulated pseudopotential U_{ps} from the fitted harmonic potential. The 5% anharmonicity distance listed in the table is the distance from the trap center beyond which this deviation exceeds 5% of the harmonic term. From the results in the table, we can see that the pseudopotential is relatively symmetric along the y axis but has a significant asymmetry along the x axis. This is expected from the top-bottom asymmetry introduced by the back-side ground plane (Sec. 2.1).

Table 2.1: Predicted parameters based on the simulated pseudopotential at $P_{\text{in}} = 4 \text{ W}$

Parameter	Unit	Value
Trap depth $+x$	meV	661
Trap depth $-x$	meV	588
Trap depth $+y$	meV	689
Trap depth $-y$	meV	685
Secular frequency $\omega_x/2\pi$	MHz	157.6
Secular frequency $\omega_y/2\pi$	MHz	161.2
5% anharmonicity distance $+x$	mm	0.319
5% anharmonicity distance $-x$	mm	0.264
5% anharmonicity distance $+y$	mm	0.414
5% anharmonicity distance $-y$	mm	0.416

2.2.2 DC Simulation

We have designed the DC electrodes near the trap slit to deliver the electrostatic potential that confines the electron along the $\hat{z}$ axis. The voltages applied to the electrodes are determined with the multipole control method introduced in Sec. 1.1.2. The multipole matrix M of Eq. (1.15) maps the 20 electrode voltages of our trap to the 8 controlled multipoles $\vec{c} = (E_x, E_y, E_z, U_1, \dots, U_5)^T$, and the control matrix M^+ of Eq. (1.16) maps a target multipole vector back to the electrode voltages.

Following this scheme, the goal of the DC simulation is to compute the multipole matrix M of our trap. To this end, we apply 1 V to one electrode at a time while keeping the other 19 electrodes grounded, export the electrostatic potential near the trap center, and expand it in multipoles about the trap center. The electrode geometry near the trap center is mirror-symmetric with respect to the $\hat{x}$ – $\hat{z}$ plane, and the asymmetric routing of the DC traces is far enough from the trap center to be neglected. We therefore obtain the potentials of electrodes 06–10 and 16–20 by mirroring those of electrodes 01–05 and 11–15, so 10 high-precision simulations are needed in total to construct M . I used Ansys Maxwell [50] for

the electrostatic simulation and automated it with PyAnsys. I then exported the potentials from Maxwell and performed the multipole expansion with the PaulTrapAnalysis package developed by the Häffner group at UC Berkeley [124].

Table 2.2 shows the maximum voltage $V_{\max}$ required among the 20 electrodes to generate one unit of each multipole, and the maximum multipole $C_{\max}$ we can apply to the trap center within the ± 10 V output range of the control DAC. The maximum $|U_2|$ we can reach is 0.407 V/mm². This is below the magnitude of the operating value $U_2 = -0.60$ V/mm² used in our earlier electron-trapping tests with the three-layer trap of the UC Berkeley group [23], and extra headroom on top of that is needed for stray-field compensation. For this reason, we developed a DC amplifier circuit with a gain of 4.3, which increases the maximum output voltage from ± 10 V to ± 43 V. Some channels are limited to ± 30 V by the voltage ratings of their components. The amplified range increases the reachable $|U_2|$ to about 1.75 V/mm². We will discuss the details of this amplifier box in Sec. 3.4.2.

Table 2.2: Maximum voltages required to generate each multipole

Multipole	Unit	$V_{\max}$ (V)	$C_{\max}$ (± 10 V output)
E_x	V/mm	8.55	1.169
E_y	V/mm	32.3	0.309
E_z	V/mm	23.4	0.427
U_1	V/mm ²	5.92	1.688
U_2	V/mm ²	24.6	0.407
U_3	V/mm ²	6.90	1.449
U_4	V/mm ²	32.3	0.309
U_5	V/mm ²	9.45	1.058

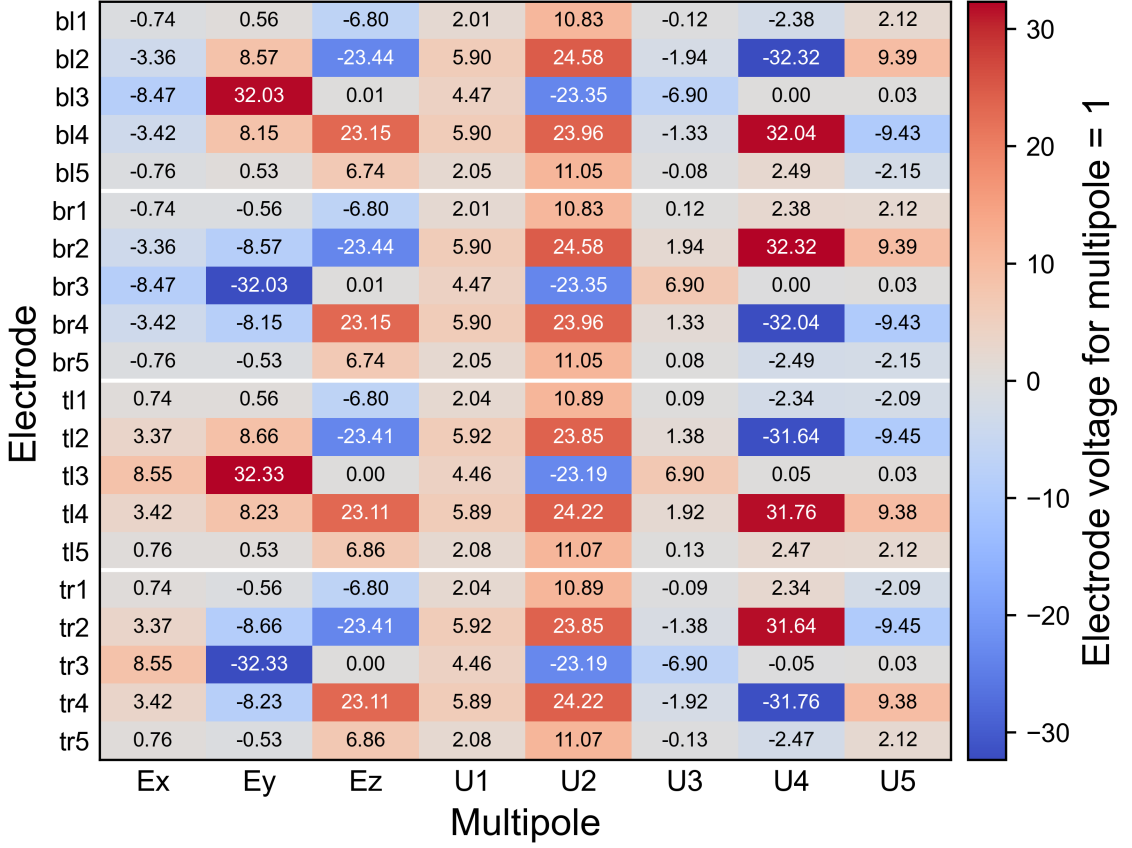


Figure 2.6: DC control matrix for the PCB trap. Each column represents the control voltages required to generate a unit of a multipole.

Fig. 2.6 shows the final control matrix M^+ . This matrix is stored in a text file called the C-file (control file) and is referenced during experiments to set the electrode voltages.

The multipole expansion also provides a route to control the anharmonicity of the axial potential. If the expansion is carried beyond the second order, the higher-order coefficients describe the anharmonic terms of the potential, and the same control scheme can be used to set these coefficients to zero while generating the desired U_2 . This control comes at a cost. Exact control of all multipoles up to a given order requires at least as many

electrodes as controlled coefficients: 3 for the first order, 8 up to the second order, and 15 up to the third order. Controlling higher orders therefore requires more DC electrodes, and the voltages required to reach the same U_2 also increase. If, on the other hand, the number of electrodes is smaller than the number of controlled coefficients, the pseudoinverse realizes the target only in the least-squares sense, and extending the control to higher orders brings limited benefit. With its 20 electrodes, our trap can in principle control all multipoles up to the third order.

2.2.3 Electron Trajectory Simulation

The RF and DC simulations verify the pseudopotential and the control scheme of the electrodes, which ensures that we can trap electrons with our trap design. In the real experiment, however, we need to accelerate the electrons towards a detector in order to verify that we have actually trapped them. Therefore, an electron trajectory simulation is performed here for two purposes. First, it verifies that electrons trapped near the trap center can be guided towards the microchannel plate (MCP) detector [125] and generate a signal. Second, it determines their flight time, which sets the time scale of the detection sequence.

The detection geometry consists of three main components: the trap board that confines the electrons, an MCP detector, and a copper mesh between the trap board and the MCP. The mesh and the MCP are located 10 mm and 20 mm away from the trap center, respectively. During the experiment, voltages of around 130 V and 400 V are applied to the mesh and the front plate of the MCP, respectively. The extraction works by applying a negative voltage pulse to DC electrodes on the side of the board facing away from the MCP,

which kicks the electrons out of the trap and accelerates them towards the MCP. The mesh in between acts as an intermediate acceleration stage that improves the detection efficiency. The simulation must therefore include three sources of electric field: the pseudopotential generated by the RF trap drive, the electrostatic potential generated by the DC voltages applied to the 20 electrodes, and the guiding potential generated by the mesh and MCP front voltages. One complication is the limited region of validity of these field data. The pseudopotential and the DC trapping potential are high-precision data localized near the trap center, and they are not available far from the trap center. More importantly, the pseudopotential approximation only holds where the motion of the electron separates into a secular motion plus a micromotion, which is the case only near the trap center. To deal with this issue, I separated the three sources of field and computed the trapping potential only in a cubic box with an edge length of 0.6 mm centered at the trap center. This approach is reasonable since the trapping fields decrease rapidly with distance from the trap center. The electric field exported from Ansys is only available on a grid of points, so I applied cubic interpolation to enable the evaluation of the electric field at arbitrary positions. The simulation is performed with $U_2 = -0.5$ V/mm², $V_{\text{mesh}} = 250$ V, $V_{\text{MCP}} = 300$ V, an RF input power of 4 W, and an extraction pulse of -20 V acting on DC electrodes 03 and 08. The mesh and the MCP are modeled as solid equipotential rectangles of 5×5 mm² and 10×10 mm², respectively, so the geometric transmission of the mesh is not modeled. Electrons that leave the $16 \times 16 \times 22$ mm³ simulation volume are counted as lost. The extraction pulse is treated as an extra static voltage acting on the two electrodes because its length of 900 ns is much longer than the typical flight time of the electrons.

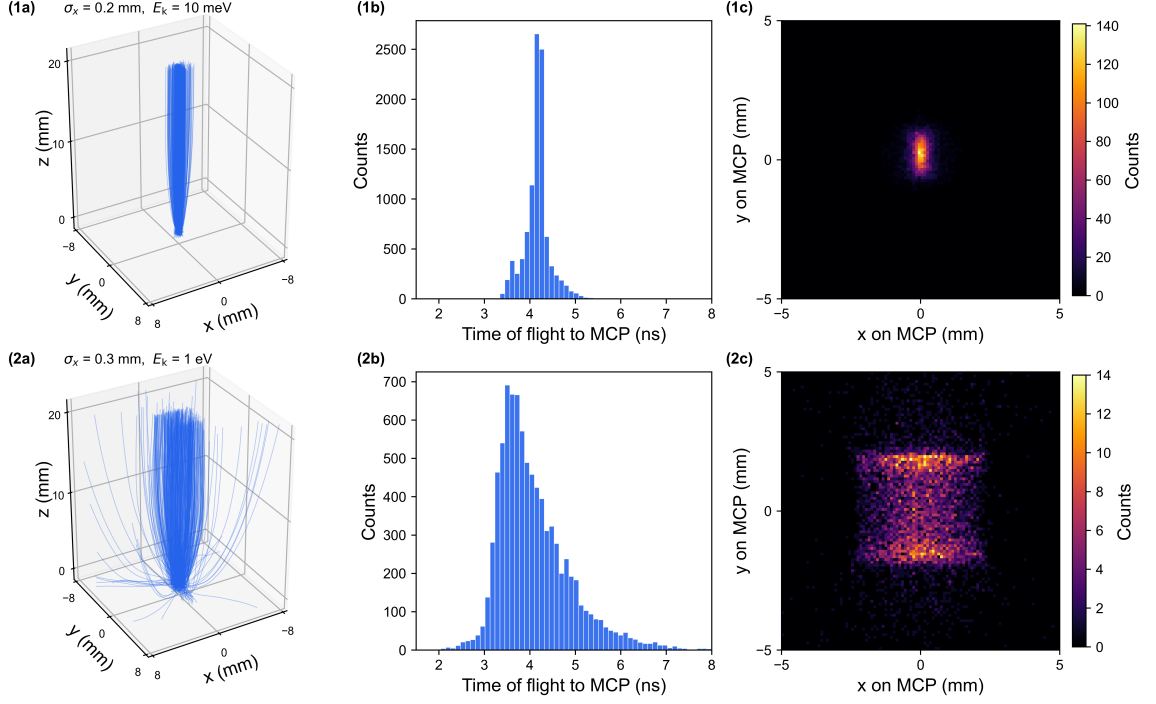


Figure 2.7: Electron trajectory simulation. Case 1 is the normal case for the electron trapping experiment. Case 2 is an extreme case with electrons dispersed over a larger volume with higher initial velocities. (a) Electron trajectories of 500 electrons in the two cases. (b) Total flight time of the electrons from the trapping region to the MCP. (c) Spatial distribution of the electron arrival positions on the MCP. The sample size for (b) and (c) is 10000. The simulation is performed in the presence of the extraction pulse (-20 V on electrodes 03 and 08).

Fig. 2.7 shows the results of these simulations for two cases of initial electron distributions. In both cases, the initial velocities and positions of the electrons follow normal distributions. Case 1 uses $\sigma_x = 0.2$ mm and $E_k = \frac{1}{2}m_e v_{\text{rms}}^2 = 10$ meV, where v_{rms} is the root-mean-square velocity. These values correspond to the expected initial cloud size and kinetic energy of the electrons created by photoionization (Sec. 3.1.1). Case 2 uses $\sigma_x = 0.3$ mm and $E_k = 1000$ meV as an extreme case. From the results, we know that in the normal case, 9992 out of 10000 electrons reach the MCP, with an average flight time of 4.17 ns, mostly hitting the center of the MCP. Even in the high-energy case, 8637 out

of 10000 electrons reach the MCP, with an average flight time of 4.09 ns but with more scattered arrival positions. As a consistency check, an electron starting at rest at the trap center and accelerated only by the simulated mesh and MCP voltages would reach the MCP in about 3 ns. The slightly longer simulated flight time reflects the additional time needed to leave the trap region. This result tells us that the detection system properly guides the trapped electrons towards the detector, and that the electrons arrive at the detector within a flight time that is negligible compared with the 900 ns extraction pulse in the experiment sequence (Sec. 3.3).

2.3 Trap Electrical Characterization

Simulation only provides us with predictions of the trap performance, and does not account for many complex or unpredictable factors, such as model simplifications and manufacturing errors. For this reason, we need to measure the electrical properties of the trap to see if the trap behaves as the simulation predicts, and to correct for any deviation.

The DC part of the trap only requires reliable connectivity, which is easy to validate. Therefore, the main part of the electrical validation falls on the RF resonator. The first step is to verify that the resonance exists.

Fig. 2.8 shows the temperature distribution across the trap board when the board is driven on resonance and 400 MHz off resonance, with images taken every minute for 5 minutes. It is clear that when the trap is driven on resonance, the temperature near the resonator is significantly higher than in the other parts of the trap. Off resonance, the temperatures of the feedline section and the resonator section are similar. This means

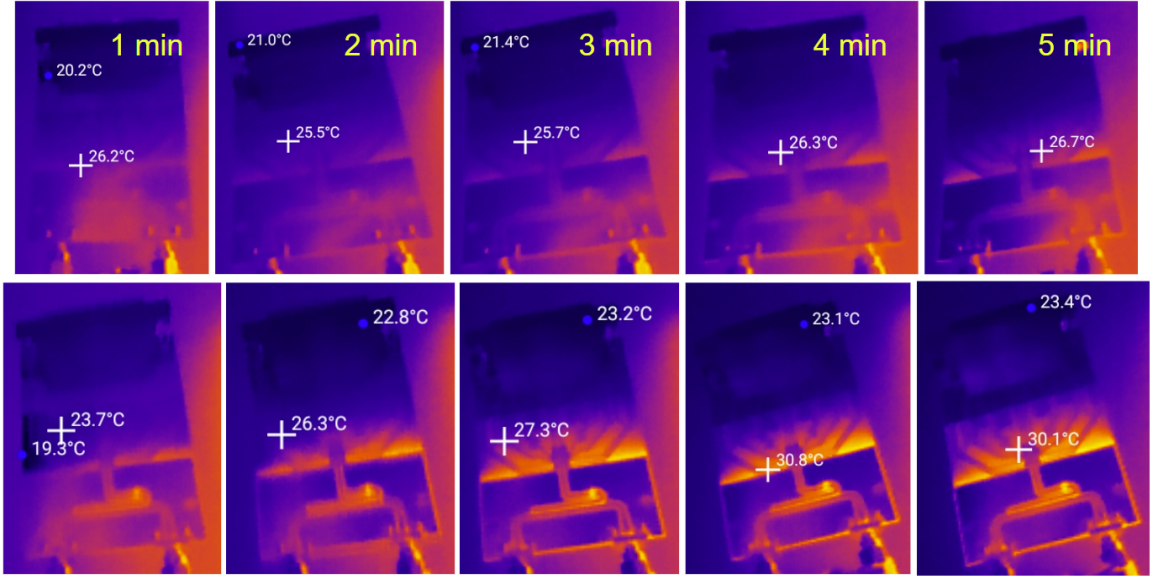


Figure 2.8: Thermal camera images taken over 5 minutes. In the upper row, the trap is driven 400 MHz away from the resonance frequency. In the lower row, it is driven on resonance.

that when on resonance, the RF power is coupled into the resonator and dissipated there, making the resonator the major heat source, while when off resonance, the power is not coupled into the resonator, so most of the power is simply transmitted through the trap board, and the dissipation on the trap occurs mainly on the feedline. This confirms that the fabricated board has the designed RF resonance.

After validating the existence of the resonance, we next perform a thorough measurement of it for a quantitative analysis of the trap and a comparison with the simulation. The device used for the measurement is a NanoVNA-F V3 vector network analyzer. Fig. 2.9 shows the result of the measurement. The resonance is observed at 1.752 GHz in this absorption spectrum, which matches the predicted frequency of 1.753 GHz from the simulation almost perfectly. The side mode at 1.854 GHz does not appear in the measurement. We

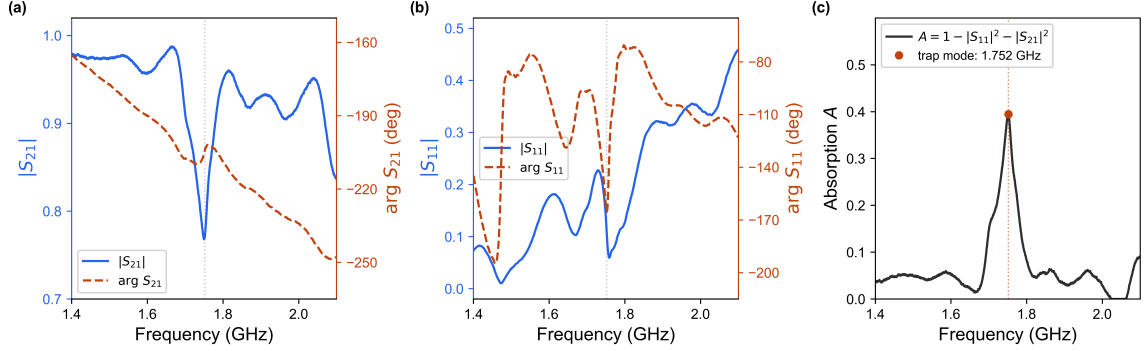


Figure 2.9: Measured S parameters of the single PCB trap. (a) Magnitude and phase of the transmission S_{21} . (b) Magnitude and phase of the reflection S_{11} . (c) Absorption $A = 1 - |S_{11}|^2 - |S_{21}|^2$. Only one resonance, at 1.752 GHz, is observed.

have not investigated the reason, because this mode does not affect our experiment, which operates on the 1.75 GHz resonance.

For a quantitative comparison between the measurement and the simulation, we model the resonator as a hanger resonator coupled to a feedline [126]. In this model, the forward transmission coefficient S_{21} of the RF transmission is described by

$$S_{21}(\omega) = g(\omega) \cdot e^{i(\alpha - \omega\tau)} \left(1 - \frac{Q_L e^{i\varphi}/Q_c}{1 + 2iQ_L(\omega/\omega_0 - 1)} \right), \quad (2.1)$$

where Q_c , Q_i , and Q_L are the coupling, internal, and loaded quality factors of the resonator, following $1/Q_L = 1/Q_i + 1/Q_c$, ω_0 is the resonance frequency, τ is the transmission line delay coefficient, α is the initial phase, and φ is the asymmetry parameter. To account for the frequency-dependent transmission-line loss, we introduce a linear magnitude correction $g(\omega) = a - b\omega/2\pi$ to the model. By fitting Eq. (2.1) to the complex-valued simulated and measured S_{21} (shown as power coefficients in Fig. 2.10), we extract the resonance frequency ω_0 , the quality factors Q_L , Q_c , and Q_i , and the asymmetry parameter φ , listed in Table 2.3. Note that the frequency quoted above, 1.752 GHz, is the position of the

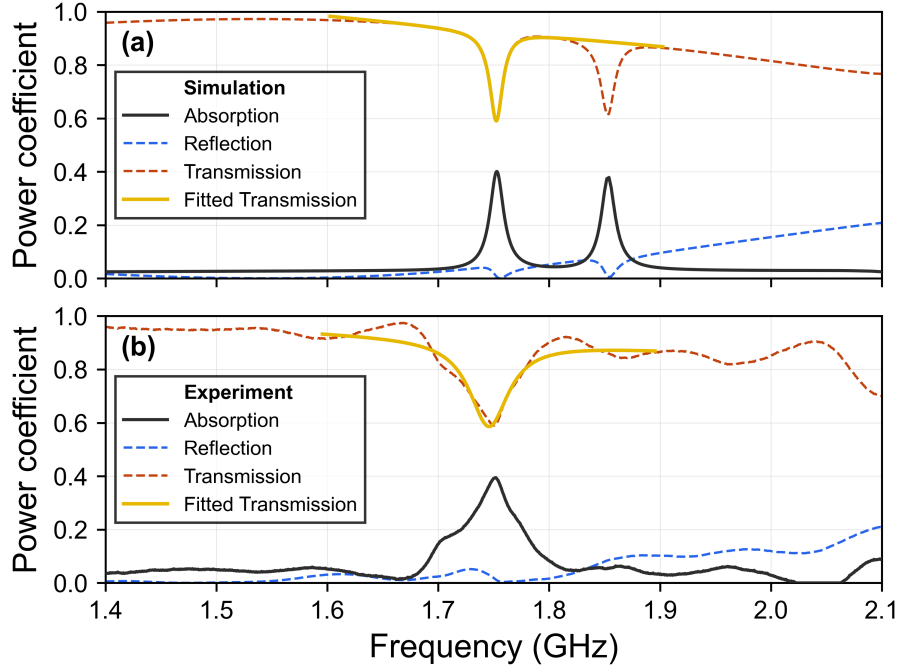


Figure 2.10: Comparison of the (a) simulated and (b) experimentally measured reflection, transmission, and absorption coefficients of the trap. The transmission (reflection) power coefficients $t = |S_{21}|^2$ ($r = |S_{11}|^2$) are extracted from the S parameters measured between the two SMA connectors (shown in Fig. 2.1). The absorption coefficient is calculated using the conservation of energy $1 - |S_{11}|^2 - |S_{21}|^2$.

absorption maximum, while the fitted resonance frequency is $\omega_0/2\pi = 1.746$ GHz. The fitted quality factors of the fabricated trap deviate significantly from the simulation. The loaded quality factor is $Q_L = 40.7$, compared with the simulated value of 124. Since the RF voltage delivered to the trap center depends on the quality factors, we use the fitted values to correct the secular-frequency prediction of Sec. 2.2.1.

Table 2.3: Fitted resonator parameters

Parameter	Simulation	Experiment
$\omega_0/2\pi$ (GHz)	1.753	1.746
Q_L	124 ± 1	40.7 ± 0.9
Q_c	618 ± 2	207 ± 4
Q_i	156 ± 1	51 ± 2
a	1.31 ± 0.01	1.14 ± 0.01
b (GHz $^{-1}$)	0.020 ± 0.003	0.109 ± 0.004
α (deg)	16.1 ± 0.4	4.8 ± 0.4
τ (ns)	0.307 ± 0.001	0.336 ± 0.001
φ (deg)	-2.4 ± 0.2	1.0 ± 1.0

To relate the fitted Q factors to the secular frequency, we note that for an on-resonance hanger resonator, the stored energy as a function of the input power P_{rf} and the resonance frequency ω_0 is given by [126, 127]

$$E_{\text{res}} = 2Q_L^2 \frac{P_{\text{rf}}}{\omega_0 Q_c}. \quad (2.2)$$

Under the pseudopotential approximation, the trapping motional frequency is proportional to the RF voltage amplitude at the resonator, $\omega_r \propto U_{\text{rf}} \propto \sqrt{E_{\text{res}}}$. Combining this with Eq. (2.2) yields $\omega_r \propto Q_L/\sqrt{Q_c}$. Therefore, the corrected prediction $\tilde{\omega}_r$ follows from the simulated value $\omega_{r,\text{sim}}$ as

$$\frac{\tilde{\omega}_r}{\omega_{r,\text{sim}}} = \frac{Q_{L,\text{exp}}}{Q_{L,\text{sim}}} \sqrt{\frac{Q_{c,\text{sim}}}{Q_{c,\text{exp}}}} = 0.565, \quad (2.3)$$

where the subscripts exp and sim denote the values fitted from the measured and simulated S_{21} , respectively. Applying this correction to the simulated values, we predict the corrected radial frequencies $\tilde{\omega}_x \approx 2\pi \times 89.0$ MHz and $\tilde{\omega}_y \approx 2\pi \times 91.1$ MHz at an input power of 4 W.

In addition, we can apply a similar correction to the trap depth using the fitted quality factors. The corrected trap depth follows from

$$\frac{\tilde{D}}{D_{\text{sim}}} = \frac{\tilde{E}_{\text{res}}}{E_{\text{res},\text{sim}}} = \left(\frac{Q_{L,\text{exp}}}{Q_{L,\text{sim}}} \right)^2 \frac{Q_{c,\text{sim}}}{Q_{c,\text{exp}}} = 0.319. \quad (2.4)$$

Therefore, the corrected trap depth $\tilde{D}$ is 211 meV along the $+\hat{x}$ direction, 188 meV along $-\hat{x}$, 220 meV along $+\hat{y}$, and 219 meV along $-\hat{y}$ at an input power of 4 W at the input SMA connector of the trap.

In summary, the fabricated trap board shows the designed RF resonance, and its measured S parameters allow us to correct the simulated secular frequencies for the lower quality factor of the fabricated resonator. Together with the DC control matrix and the trajectory simulation, this completes the electrical verification of the single-PCB trap. Trapping electrons with this board requires a vacuum system, an electron source, and the drive and detection electronics. These are the subject of Chapter 3.

Chapter 3

Room-Temperature Setup

After introducing the trap board I designed, I now present the experiment system built to support the electron trapping experiment. In the electron trapping stage, our experiment is carried out in a room-temperature ultra-high vacuum (UHV) environment with multiple subsystems, including the electron source and laser system, the trap drive, hardware control and synchronization, and electron detection, as shown in Fig. 3.1. All of these subsystems must work together to make electron trapping happen. In this chapter, I introduce the details of these subsystems.

3.1 Electron Source and Vacuum System

3.1.1 Electron Source

To trap electrons, we first need to generate them. There are multiple ways to generate electrons, such as simply heating a filament [128]. However, electrons generated

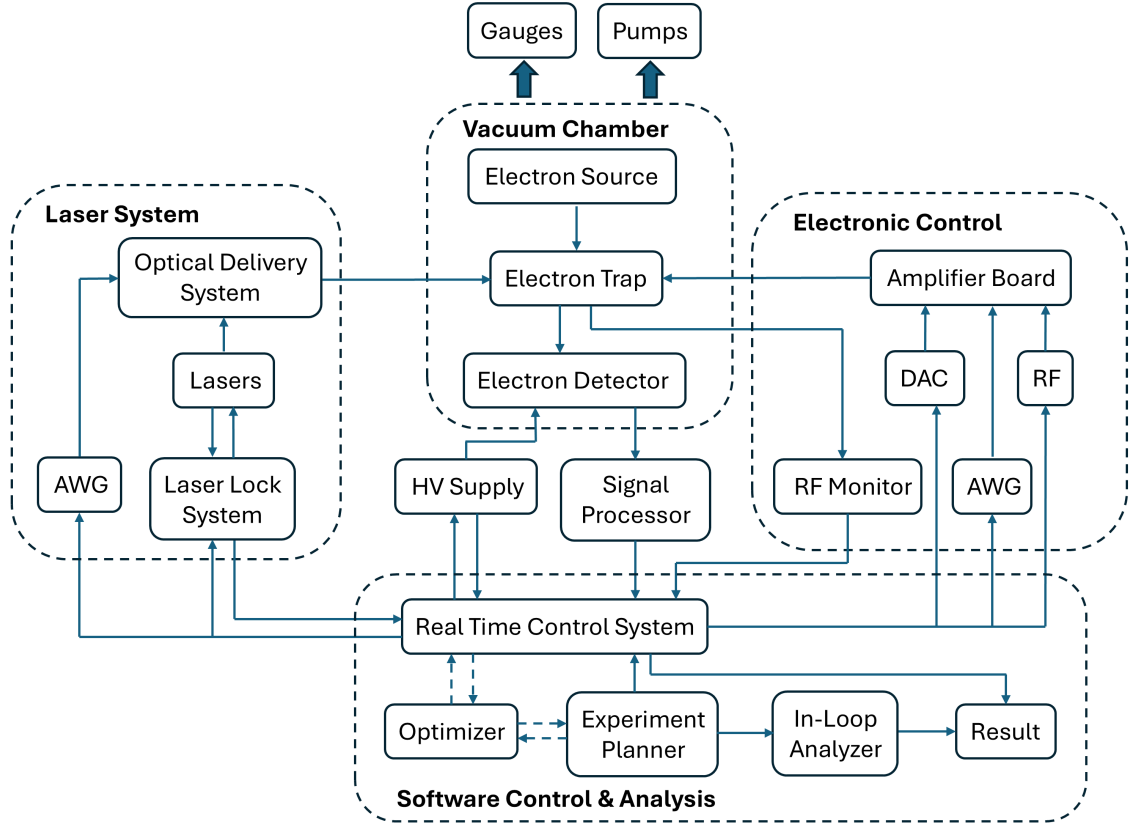


Figure 3.1: Overview of our experiment system. The system hardware can be roughly divided into three parts: the vacuum chamber, the laser system, and the electronic control, each with its own power supplies. These systems need to work together synchronously and run experiments planned in batches, which is realized by the software system.

by these traditional approaches usually have too much kinetic energy. More importantly, these electrons are generated outside the trapping potential, which means they inherently have a potential energy higher than the trap depth. To handle these problems, we need either to cool the free electrons after their generation, or to generate low-energy electrons right at the trap center. Fortunately, there is a well-established approach that satisfies the second requirement [23].

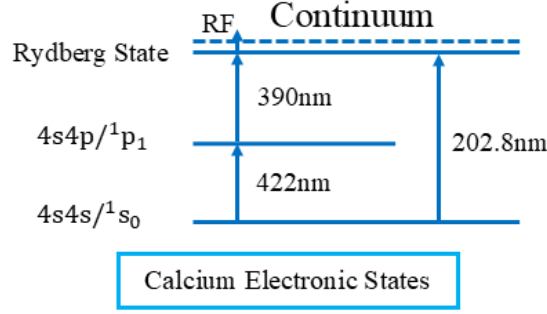


Figure 3.2: Electron generation scheme for our experiment. Field-induced ionization of a calcium atom via a Rydberg state. Two photons, at 390 nm and 422 nm, are used to excite the calcium atom.

The idea is to use the same approach that the ion trapping community widely uses to generate calcium ions, but to keep the ionized electrons instead. As shown in Fig. 3.2, the calcium atom is first excited to its first excited state by a 422 nm laser. Then, instead of directly photoionizing the electron to the continuum with a 375 nm laser, we use a 390 nm laser to further excite the atom to a Rydberg state. The electron in the Rydberg state is only loosely bound and is easily ionized by our RF drive field (the main resonance at ~ 1.75 GHz) used for electron trapping. This route provides us with electrons that carry almost no excess energy from the laser beams. The velocity of the free electrons generated by this approach is expected to be similar to the velocity of the calcium atomic beam. Therefore, the ratio of their kinetic energies is approximately the ratio of their masses, $E_{k,e} = (m_e/m_{Ca})E_{k,Ca}$. For example, if the temperature of the calcium oven is 750 K [63, 129], the energy of the electron would be $1.33 \mu\text{eV}$. For comparison, an RF photon at around 1.75 GHz carries an energy of $7.24 \mu\text{eV}$. This means the electrons generated by this approach have energies on the μeV scale, far below the trap depth of 188 meV calculated in Sec. 2.3.

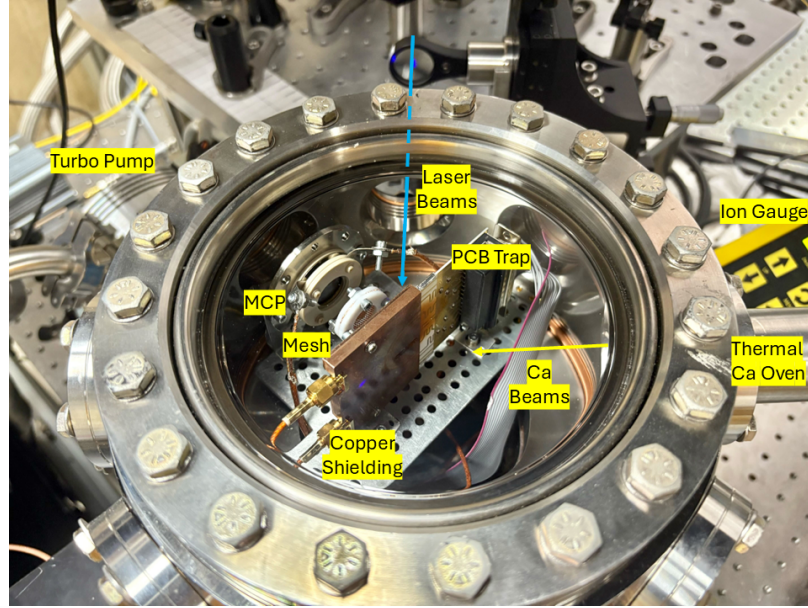


Figure 3.3: Layout of our vacuum chamber. Four pairs of windows define four directions of the vacuum chamber, separated by 45° and taken by the trap board, the laser beams, the Ca atomic beam, and the electron flight trajectory for detection, respectively.

Experimentally, this approach is realized by using two laser beams to excite a calcium atomic beam. To be specific, a resistive thermal oven filled with calcium granules is used to generate the calcium atomic beam [130], whose direction is controlled by an aluminum iris. Two laser beams are overlapped and delivered perpendicular to the atomic beam to minimize the Doppler shift. The two beams cross at the center of the trap slit, which is exactly our trap center. Therefore, the calcium atoms fly to the trap center, are excited to the Rydberg state, and are then stripped of one electron by the RF trap drive. We need to turn on the oven, both lasers, and the RF drive simultaneously to generate the electrons.

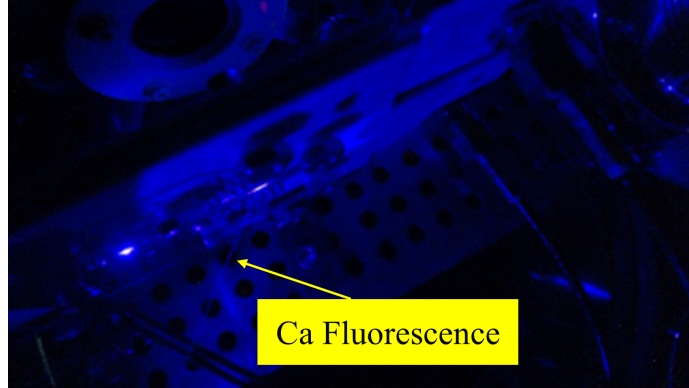


Figure 3.4: Fluorescence of the calcium atoms on the 422 nm transition. An excited calcium atom emits one 422 nm photon each time it relaxes to the ground state. The fluorescence only happens where the calcium atomic beam and the laser beam overlap. It spreads over a long distance across the vacuum system, which means the calcium atomic beam spreads over a large range even though we have limited it by an iris attached to the oven.

3.1.2 Vacuum Chamber

As shown in Fig. 3.3, our electron trapping experiment is carried out in a UHV chamber pumped down to approximately 10^{-8} Torr. This UHV chamber is maintained by a two-stage pumping system. A foreline is first pumped to a pressure of around 10^{-3} Torr by an Agilent IDP-7 scroll pump, and the vacuum chamber, connected after the foreline, is further pumped to 10^{-8} Torr by an Agilent TwisTorr 305 FS turbo pump. The foreline level is separated from atmospheric pressure by KF flanges and monitored by an MKS 275 mini-convectron gauge, and the UHV chamber is isolated by copper gaskets and monitored by a HORNET IGM401YED ion gauge.

The main components of the UHV chamber are purchased from Kimball Physics and Kurt & Lesker, together with a few customized components. The chamber has four

directions defined by its four pairs of windows, with a 45° angle between neighboring directions. Taking the trap board as the reference and counterclockwise in the top-down view as the positive direction, the laser beams and the Ca atomic beam for electron production (introduced in Sec. 3.1.1) fall on $\pm 45^\circ$, respectively, perpendicular to each other. The mesh and the MCP, on the other hand, are placed on the line of $+90^\circ$ for electron detection. To be specific, the trapped electrons are ejected from the trap by an extraction pulse applied to the trap DC electrodes, accelerated towards a mesh at high voltage, and then further accelerated towards the MCP detector. All four directions intersect at the central axis of the vacuum chamber, where our trap center lies, accessed through the plated slit. The chamber is designed to have four safe high voltage (SHV) feedthroughs for the high-voltage supplies of the mesh and the MCP, two SMA connectors for the RF drive of the trap, and one 25-pin D-sub feedthrough for the DC electrodes of the trap. The trap board, the mesh, and the MCP are held on an aluminum platform with a mounting-hole array at 1/4 inch spacing. The thermal calcium oven is attached to one of the chamber's window ports with a spring whose direction can be controlled by three adjustable screws. With these screws, we can adjust the orientation of the calcium atomic beam to optimize its alignment for the best electron creation. The oven has two metallic pin feedthroughs outside the vacuum chamber, which enable us to feed current into the oven inside the vacuum. The current is driven by a BK Precision 1745A linear power supply, optionally with an extra BK Precision 1672 in parallel if a current larger than 10 A is required. Fig. 3.4 is a fluorescence photo taken for the $^1P_1$ to $^1S_0$ transition, which only happens when atoms are excited by the 422 nm laser.

Therefore, it represents the intersection between the calcium atomic beam and the laser beam, and it shows that the calcium atomic beam is still spread out even after the iris.

3.2 Laser System

The laser system is crucial for electron generation because it excites the calcium atoms to the Rydberg state. Our laser system is shown in Fig. 3.5. The system needs to deliver frequency-stabilized laser beams precisely to the trap center, with the ability to switch the electron creation process on and off. Therefore, a Toptica DL Pro and a MOGLABS LDL, both external cavity diode lasers (ECDLs), are used to generate the 422 nm and 390 nm laser beams required to excite the calcium atoms to the Rydberg state. The laser power at the ECDL output is 10 mW for the 422 nm laser and 4 mW for the 390 nm laser. A pair of cylindrical lenses is placed after the 390 nm light source to correct the elliptical output mode of the 390 nm laser. Each beam then goes through a pickup that sends $\sim 1\%$ of its power to a Bristol Instruments 871 wavelength meter for frequency locking. The main power of the 390 nm beam then goes through a Brimrose TEF-85-20-390 acousto-optic modulator (AOM), while the 422 nm beam travels directly. Both beams are later coupled into single-mode fibers that send the light to the delivery section. To be specific, the fibers are 12-inch-long Thorlabs SM300 for the 390 nm beam and SM400 for the 422 nm beam, with FC/APC connectors. The fiber only accepts light that is carefully aligned to it. Therefore, by coupling the first diffraction order of the 390 nm laser into the fiber and applying amplitude modulation to the AOM's RF drive with a pulse signal, the first order of the diffracted light can be turned on and off, which switches the 390 nm laser

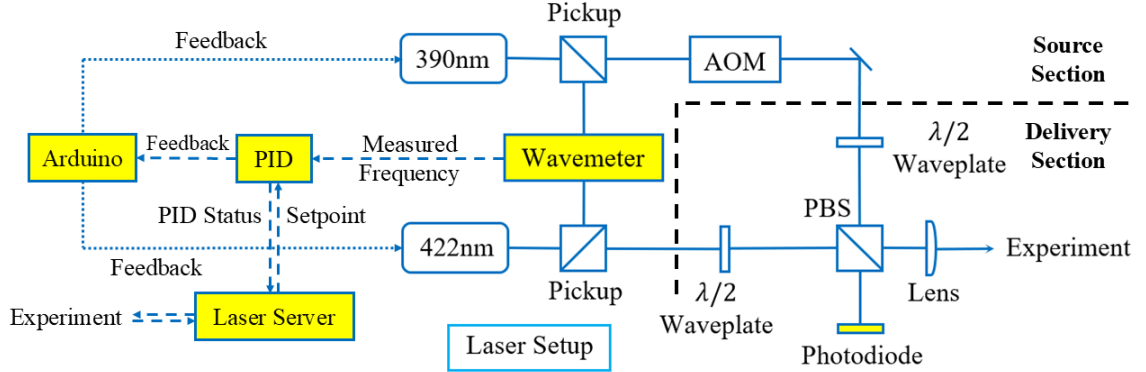


Figure 3.5: Laser system of our experiment. Solid lines represent laser beams, dashed lines represent communication between software systems, and dotted lines represent electrical signals. The system is physically separated into two sections. The source section contains the lasers and their control system, and the delivery section contains the components that merge the beams and finally deliver them to the trap center. The two sections are connected by single-mode fibers. Some functional parts such as beam expanders and mode-matching components are not shown in this flowchart.

on and off on the experiment side. The fiber coupling is the main source of the beams' power loss and requires careful optimization. If the fiber coupling is carefully optimized, we can reach a maximum output power of 2 mW for the 422 nm beam and 700 μ W for the 390 nm beam at the fibers' output.

In the delivery section, the main goal is to merge the beams and deliver as much laser power as possible precisely to the trap center. For this reason, we selected a polarizing beam splitter (PBS) with half-wave plates to merge the laser beams. The PBS is a specialized beam splitter with a coating that has high reflectivity for one polarization and low reflectivity for the other. Therefore, if the two beams enter the PBS from two different directions, with one beam mostly reflected and the other mostly transmitted, they are merged into the same direction. The key to this procedure is to control the polarization of the beams, which is realized by the half-wave plates. The residual power from the merging

is sent to a photodiode for power monitoring. After merging the laser beams, we need to focus them onto the trap center. The focusing of a Gaussian beam by a convex lens follows the formula

$$w_0 = \frac{\lambda f}{\pi w_1}, \quad (3.1)$$

where w_0 is the beam waist after focusing, w_1 is the beam radius at the convex lens, λ is the wavelength of the beam, and f is the focal length of the lens [131]. This means that for the same beam and lens, the thicker the beam at incidence, the smaller the beam waist at the focus. With the 250 mm focal length convex lens we have and an incident diameter of 1.2 mm, the beam diameter at the focal point would be $103 \mu\text{m}$ for the 390 nm laser and $112 \mu\text{m}$ for the 422 nm laser, which is below the 5% anharmonicity distance calculated in Sec. 2.2.1. However, in reality, there are imperfections in the beam mode as well as misalignment of the position along the beam's propagation direction, which make the actual beam waist at the trap center larger than this theoretical value. A smaller beam diameter means the electrons are created closer to the trap center and therefore have lower kinetic energy, so we want to focus the laser beams as tightly as possible. For this reason, I introduced a Galilean beam expander that expands the beam diameter by a factor of 2, and measured the beam diameter at different distances with a Thorlabs BC207VIS beam profiler. The final beam diameter achieved is $\sim 80 \mu\text{m}$ for both the 390 nm and 422 nm lasers. To be able to adjust the focal point of the laser beams, we use a 3D stage to hold the final focusing lens.

Even though we have successfully delivered the laser beams to the trap center with the control needed, the laser is a sensitive system that is easily affected by small

temperature fluctuations, current noise, or minor mechanical instabilities. This makes the output frequency of the ECDL drift constantly with time. This is the reason why we pick up a fraction of the laser power for the wavemeter frequency measurement. We have a feedback control system with a software proportional, integral, and derivative (PID) core, which collects the frequency setpoint from the experiment control system and the measured frequency from the wavemeter to calculate the feedback signal. This signal is then sent to an Arduino DAC that generates the feedback voltage for the lasers. Therefore, we can keep the laser frequency fixed at our setpoint and keep the atom excitation constantly active. In practice, we observed that the electron creation process is sensitive to the frequency of the 422 nm laser at 709.07824 THz, which matches the measured energy levels of the calcium atom [132], but insensitive to the frequency of the 390 nm laser. For this reason, we usually lock the frequency of the 422 nm laser only, but our system has the ability to lock both lasers simultaneously. The phenomenon that the electron creation is not sensitive to the frequency of the 390 nm laser could be due to the high density of Rydberg states, together with the AC Stark effect that further splits each of them into tens of levels spread across the spectrum.

3.3 Timing Sequence

To verify electron trapping and perform experiments on top of it, we need an experiment sequence that is capable of both. We followed the experiment sequence developed by our colleagues at UC Berkeley [23]. Fig. 3.6 shows the timing sequence of our experiment. The experiment is divided into three phases: loading, waiting, and extraction. In

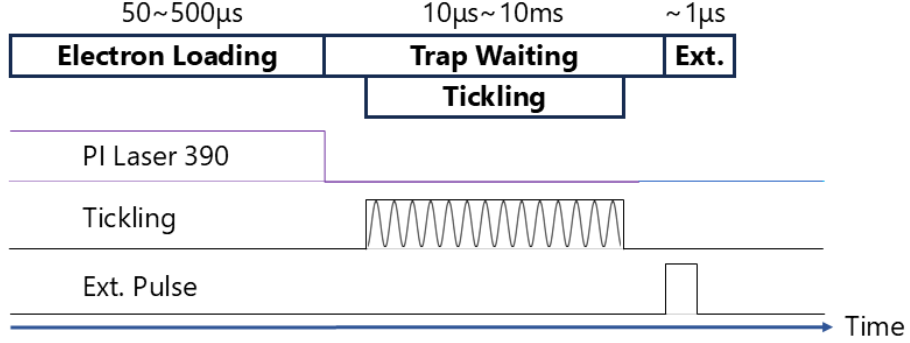


Figure 3.6: Time sequence of the electron trapping experiment. The experiment can be divided into three phases: loading, waiting, and extraction.

the loading phase, the 390 nm laser is turned on to generate electrons near the trap center. Some electrons created in this phase are loaded into the trapping potential, and the others that are not captured fly away, with some guided towards the MCP and detected. We expect a moderate number of electrons to be detected during this phase. In the waiting phase, the 390 nm laser is switched off and the electrons are held inside the trapping potential. This is the key verification of electron trapping, showing whether the electrons are kept by our trap. This is also the key phase for carrying out experiments. For example, we can modify the duration of this phase to check how long we can store the electrons, and we can also apply an RF excitation (tickling) to the trapped electrons to investigate their motional frequencies. The trapped electrons can leak naturally or be excited by the applied RF excitation and leave the trap in this phase, which leads to electrons being detected during it. The extraction phase lies after the waiting phase. After holding the electrons for a period of time, we apply a pulse to our DC electrodes to kick the electrons out of the trap towards the MCP. If electrons are stored inside our trap, we should immediately see a spike in the electron signal, according to the simulation results in Sec. 2.2.3. With this

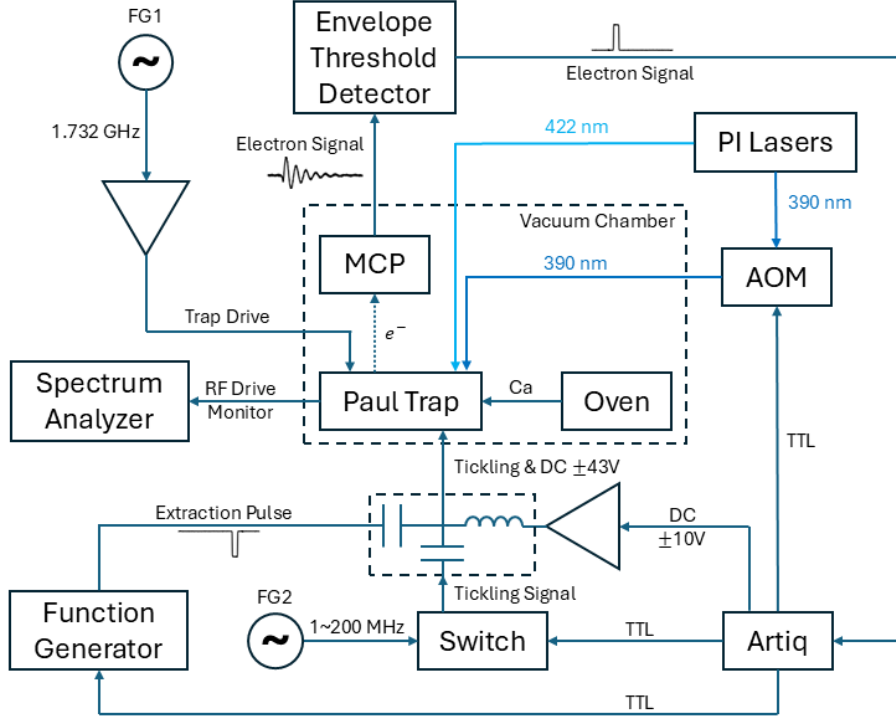


Figure 3.7: Schematic diagram of the experiment. The oven provides a thermal beam of calcium atoms, which are photoionized to produce trappable electrons. The Paul trap is driven at 1.732 GHz. Further details are explained in the main text.

experiment sequence, we can verify the trapping of electrons and perform measurements of their properties. The sequence also makes the control requirements of our system clear. We need precise timing control of the 390 nm laser, the tickling RF signal, and the extraction pulse.

3.4 Electronic System

The electronic system is responsible for delivering the signals required to load, trap, and detect electrons to the trap board, for processing the signal generated by the detection, and for the power supply and synchronization of all of these components. Fig. 3.7 shows the

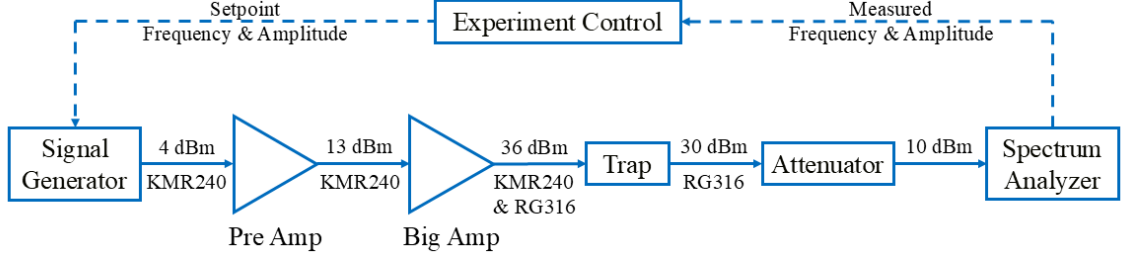


Figure 3.8: The RF drive system of the experiment. The signal is first generated by a signal generator controlled by the experiment control system, and then goes through two amplifier stages and is sent into the trap, and then monitored by a spectrum analyzer communicating with the experiment control system.

structure of this system. In this section, we first introduce the delivery of the RF and DC signals in Sec. 3.4.1 and Sec. 3.4.2, including the amplifier and bias-tee board mentioned in Sec. 2.2.2, and then the signal processing chain in Sec. 3.4.3.

3.4.1 RF Electrode Drive

The role of the RF electrode drive is to deliver RF power into the resonator on the trap and generate the pseudopotential for electron trapping. The RF signal is also important for the field-induced ionization process in electron generation. The system should be able to deliver at least the 4 W (36 dBm) of power used in Sec. 2.2.1, with the ability to monitor the power and frequency.

Fig. 3.8 shows the structure of our RF delivery system. The signal is first generated by a Rohde & Schwarz SMB 100A signal generator, which is capable of generating frequencies from 100 kHz to 31.8 GHz at up to 11 dBm. The signal is then amplified by two cascaded amplifiers: a Mini-Circuits ZJL-5G+ as a preamplifier and a Mini-Circuits ZHL-5W-422+ as a high-power amplifier. The amplifiers work near the saturation region,

so the cable loss before the signal enters the vacuum chamber is important. We chose KMR-240 low-loss RF cables for the transmission before the vacuum chamber to minimize the power loss before reaching the trap board. However, this cable cannot be used inside the vacuum chamber due to its coating material, which leaves us with a segment of RG316 cable inside the vacuum chamber that accounts for a power loss of ~ 1.5 dB. After reaching the trap board, some of the power is coupled into the trap resonator, but a notable portion is transmitted and exits the vacuum chamber. We send this part of the power to a -20 dB attenuator array and then to a Keysight N9000B spectrum analyzer.

3.4.2 DC Electrode Drive

The DC electrodes are responsible for three different purposes: carrying the voltages required for confining the electrons in the $\hat{z}$ direction, delivering the extraction pulse that kicks the trapped electrons out of the trap, and delivering the tickling RF signal that excites the electrons' motion. This means the DC electrodes need to carry both RF and DC signals generated from different sources, which can be realized by using bias-tees. The extraction pulse we apply has an amplitude of -20 V, a length of 900 ns, and rising and falling edges of 16.8 ns, with a repetition period of several hundred microseconds. The frequency of the tickling signal follows the motional frequencies of the electrons, which lie in the range of 10 to 200 MHz. In addition, the DAC we use is an ARTIQ Zotino with an output range of ± 10 V. According to the simulation results in Sec. 2.2.2, we need an amplifier module to extend the output range of our DAC. This also means we need a bias-tee with a high DC voltage rating.

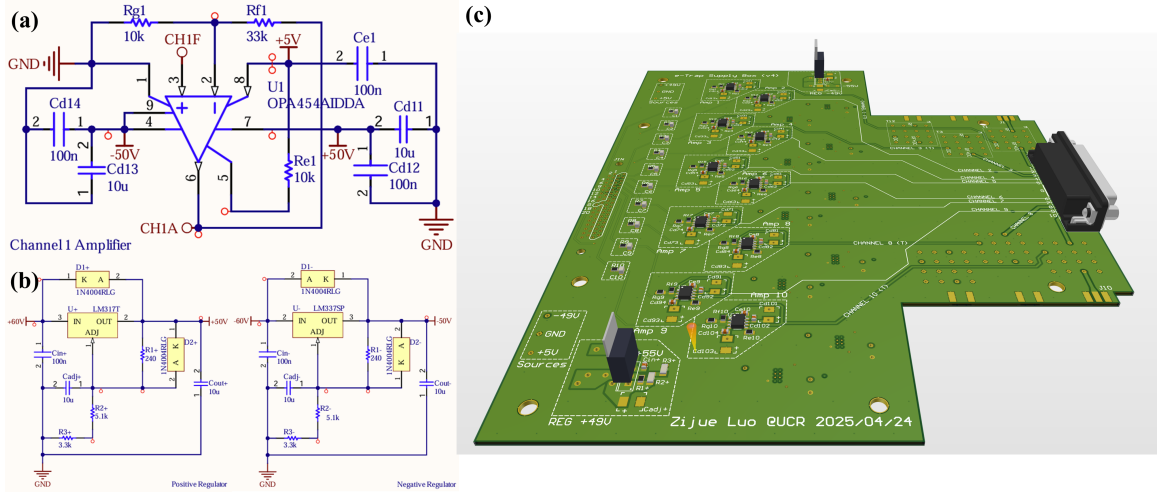


Figure 3.9: The signal processor for our DC electrodes. (a) Non-inverting DC amplifier on every DC channel, with a gain of 4.3. (b) Power stabilizer for the board. (c) 3D preview of the board.

For this reason, I introduced a customized PCB DC signal processor to satisfy all these needs in our DC delivery. The DC voltages are fed into the board by a 68-pin SCSI connector, which is compatible with the ARTIQ Zotino DAC output. On each channel, the signal first goes through an RC filter with a cutoff frequency of 338.6 Hz, and then through a non-inverting amplifier with a gain of 4.3 driven by a Texas Instruments OPA454 operational amplifier. On part of the channels, the signal additionally goes through a bias-tee for superimposing RF signals on top of the DC voltages. The final processed signal then leaves the board and enters the vacuum chamber through a 25-pin D-sub feedthrough. The operational amplifier requires a pair of power supplies at ± 50 V, which is provided by a pair of BK Precision 1623A linear power supplies at around ± 55 V and stabilized to ± 49 V through regulator circuits with an LM317T and an LM337SP. The circuit board has six layers, and the details of the layers are listed in Table 3.1. The bias-tee I chose for the board is a Mini-Circuits PBTC-1GW+, which has a frequency range of 0.1 MHz

to 1000 MHz and a voltage rating of 30 V DC. The bias-tees are integrated on electrodes 01, 03, 08, 10, 12, and 19. Among them, electrodes 03 and 08 are for electron extraction, and electrodes 01, 10, 12, and 19 represent four different positions under the symmetry of the trap. I only chose non-center electrodes because the tickling drive should induce a field that is not symmetric in all three directions, to make sure it can excite all of the motional modes.

Table 3.1: Layer stackup of the DC signal processor board

Layer	Purpose	Material	Thickness (mm)
Top Layer	Components & Signal	Copper	0.035
Prepreg	Dielectric	3313*1	0.0994
Inner Layer L2	Power +50 V	Copper	0.0152
Core	Dielectric	FR-4	0.55
Inner Layer L3	Power +5 V & Signal	Copper	0.0152
Prepreg	Dielectric	2116*1	0.1088
Inner Layer L4	Ground & Signal	Copper	0.0152
Core	Dielectric	FR-4	0.55
Inner Layer L5	Power -50 V	Copper	0.0152
Prepreg	Dielectric	3313*1	0.0994
Bottom Layer	Components & Signal	Copper	0.035

The performance of this PCB signal processor satisfies our needs well. All of the 20 channels have almost perfect linearity in the whole designed output range of ± 43 V. On channels with bias-tees, we limit the output voltage to ± 30 V through software. With this system, we can enter the target DC multipole we want to deliver to the trap center. The software calculates the voltages required for it and handles the safety of the components. The ARTIQ Zotino DAC then generates the voltages, which are amplified by the processor box. Finally, the required RF signals are added on top of the correct electrodes through the bias-tees and delivered to the trap board.

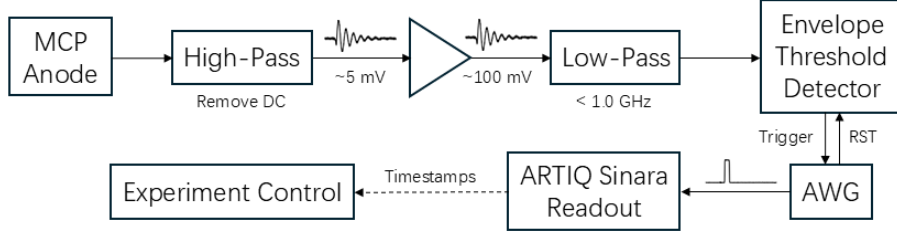


Figure 3.10: The MCP signal processing and detection chain. A high-pass filter first removes the high voltage (~ 2600 V) on the anode to extract the signal. The signal is then amplified to be able to trigger the envelope threshold detector (ETDC), and goes through a low-pass filter to remove the noise induced by the RF drive. The ETDC and an arbitrary waveform generator (AWG) next turn the signal into a clean pulse, which can be stably read out by the ARTIQ Sinara device and finally recorded as an event timestamp.

3.4.3 Detection System

The main job of the detection system is to receive electrons from our trapping device and record them correctly. The system we use can be broken down into two parts: one part guides the electrons towards the MCP and creates a signal, and the other part processes this signal and finally turns it into a timestamp recorded in our experiment control system. The part guiding the electrons towards the MCP, as we discussed in Sec. 2.2.3 and Sec. 3.1.2, consists of the trap board, the mesh, and the MCP. The MCP is powered by three SRS PS350 high voltage power supplies, and the mesh is powered by a BERTAN Series 230. The MCP power supplies are switching power supplies that have switching noise at a frequency of around 16 kHz, so we added low-pass filters with cutoff frequencies below 1 Hz on each of the high-voltage power lines. Due to its multi-channel design, the MCP has the ability to resolve the spatial distribution of the electrons with a phosphor screen. However, our MCP is equipped with an anode, so an electron only creates a signal on the final output voltage. This means we only extract the arrival time of the electrons.

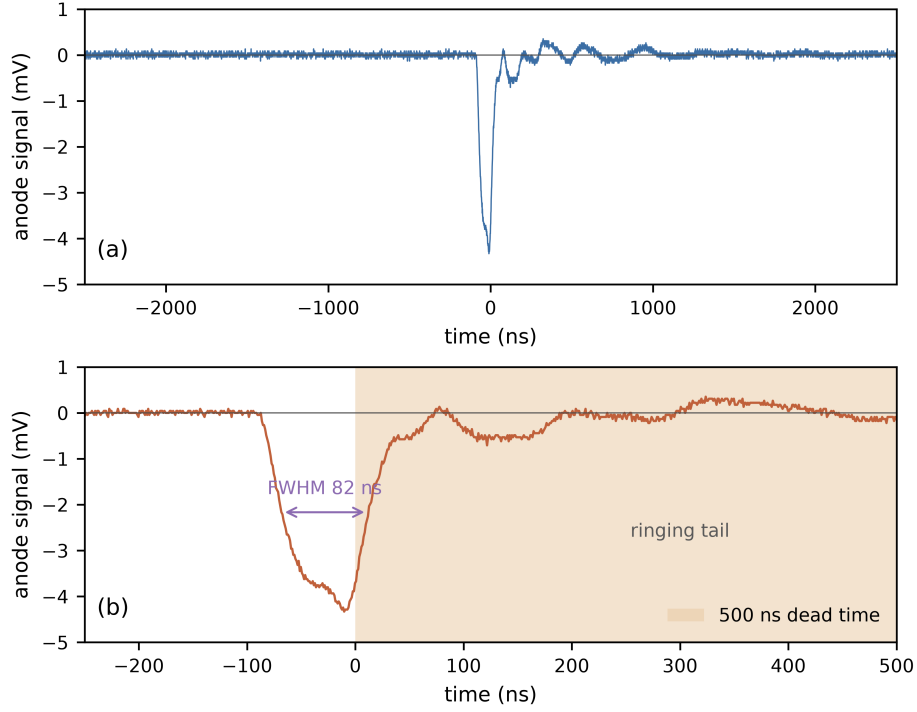


Figure 3.11: An example of the MCP signal. The signal has a main pulse that lasts around 80 ns, followed by several periods of ringing over the next ~ 500 ns. The amplitude of the main pulse is around 5 mV.

A typical signal created by the MCP usually consists of a sharp initial negative deflection with an amplitude of around 5 mV, followed by a series of successively smaller alternating deflections that settle back to the baseline within ~ 500 ns, as shown in Fig. 3.11. The amplitude and duration vary for different signal events. This signal is too weak for our ARTIQ Sinara detector to detect, and it could trigger multiple events due to its ringing. For this reason, we need a signal processing chain that turns this signal into identical and clean pulses that can be reliably read out. Fig. 3.10 shows the signal processing chain we use for this purpose. The signal is extracted at the capacitor side of a high-pass filter and then amplified by a Mini-Circuits ZFL-500LN+ amplifier, which increases its amplitude to ~ 80 mV. This amplified signal then goes through a Mini-Circuits BLP-1200+ low-pass

filter because the RF drive induces high amplitude noise on the MCP's raw output. This low-pass filter has a sharp cutoff frequency at 1000 MHz, which ensures that any noise induced by the RF drive signal is eliminated. I verified that this filter does not distort the MCP signal by analyzing the spectrum of the raw MCP signal with the spectrum analyzer, and I found that most frequency components of the MCP signal lie in the range of DC to 500 MHz. The filtered signal is then sent to an Analog Devices ADL5904 EVALZ envelope threshold detector (ETDC), whose threshold voltage input is controlled by a potentiometer and usually set at 60 mV. The output of the ETDC flips from LOW to HIGH when the envelope of the signal input exceeds the threshold input, which turns our electron signal into a rising edge with a fixed amplitude and speed. A RIGOL DG4162 arbitrary waveform generator (AWG) is then triggered by the rising edge from the ETDC, which further turns the rising edge into a standardized pulse defined by the output setting of the AWG. The output signal from the AWG is then sent to the ARTIQ Sinara for timestamp readout, and the SYNC output from the AWG is sent back to the ETDC as a reset signal that enables detection of the next event. The frequency of the AWG is set to 700 kHz, which is much higher than the average rate at which we receive events, while its period is longer than the duration of a full signal trace to prevent triggering multiple events for a single signal.

Chapter 4

Room-Temperature Experiments

With the electron trap board and the experiment setup in place, we next perform the electron trapping experiment. In this chapter, we provide the experimental results of electron trapping with our trap. Sec. 4.1 shows the initial trapping of electrons and the dependence of electron trapping on different experiment settings. Sec. 4.2 presents the measurement and analysis of the secular frequencies of the electron motion, and Sec. 4.3 presents the measurement and optimization of the trapping lifetime of our trapped electrons.

4.1 Commissioning and Initial Optimization

We successfully trapped electrons with our experiment system. Fig. 4.1 shows typical data of our electron trapping experiment and its alignment with the experiment sequence. During the loading phase, we have a uniform and moderate level of electron detection, because, as we mentioned in Sec. 3.1.2, the region where the electrons are generated is quite spread out due to the atomic beam. This means we detect many electrons

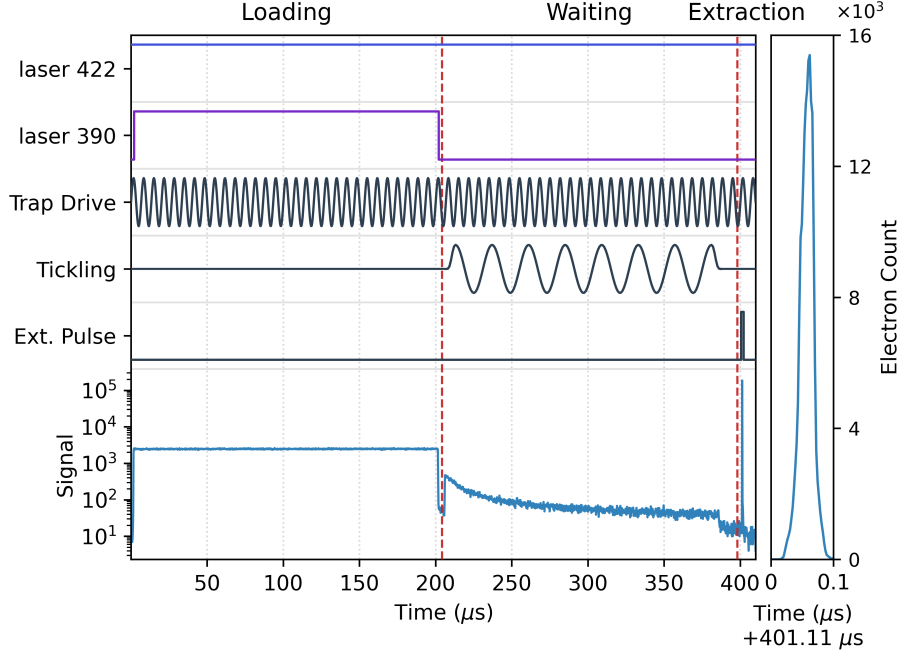


Figure 4.1: Sample data of an electron trapping experiment and its alignment with the time sequence. The loading time and waiting time are both $200\ \mu\text{s}$, followed by a $900\ \text{ns}$ extraction pulse. The data is accumulated over 400000 experiments taken with a tickling signal on resonance with the electron motion. The main histogram is calculated from the timestamp set with a bin width of $0.2\ \mu\text{s}$, and the zoomed histogram for the extraction is calculated with a bin width of $2.1\ \text{ns}$.

generated outside the trap that are guided towards our MCP detector. We call the number of electrons detected during this phase the *loading signal*. In the waiting phase, we have a low level of electron detection as a background. However, while the tickling signal is driving the electrons out of the trap, we see a significantly higher number of electrons, and this number decreases over time. This is because the electrons are not being generated in this phase, so the tickling signal only increases the loss rate of the trapped electrons. Once an electron is lost from the trap, there is a chance that it will be detected, and fewer electrons remain inside the trap to be driven out. This results in a declining pattern that is higher than the background. Since the electrons detected in this phase are mostly electrons lost

from the trap, we call the number of electrons detected during this phase the *lost signal*. In the extraction phase, a sharp and significantly higher spike is observed immediately when the extraction pulse is sent. This spike is zoomed in on the right side of the figure. Almost all electrons arrive at the detector within 100 ns after the extraction pulse is sent. These electrons survived the whole waiting period, so we call the number of electrons detected during this phase the *survival signal*. We also frequently use the ratios of the survival signal and the lost signal to the loading signal to overcome the long-term drift of the electron trapping signals.

The initial investigation of the dependence of our signals on the experiment parameters is done together with the initial optimization of the signal intensity. During all of these experiments, no tickling signals are applied to any DC electrodes on the trap. Fig. 4.2 shows the dependence of the experiment signals on the amplitude and duration of the extraction pulse, the frequency of the trap's RF drive, the frequency of the 422 nm laser, the threshold voltage of the envelope threshold detector, and the MCP front voltage.

The survival signal increases with the amplitude of the extraction pulse when the amplitude is smaller than 10 V, and saturates after that. The loading signal, on the other hand, does not change with the extraction pulse amplitude, which makes sense because the extraction pulse is only applied in the extraction phase for kicking out the surviving electrons. Experimentally, we noticed that the extraction pulse induces noise on the MCP signal at its rising and falling edges, whose intensity is proportional to the pulse amplitude. This requires us to use a higher threshold voltage, which filters out more real electron signals. Therefore, based on this experiment, I use an extraction pulse amplitude of 16 V

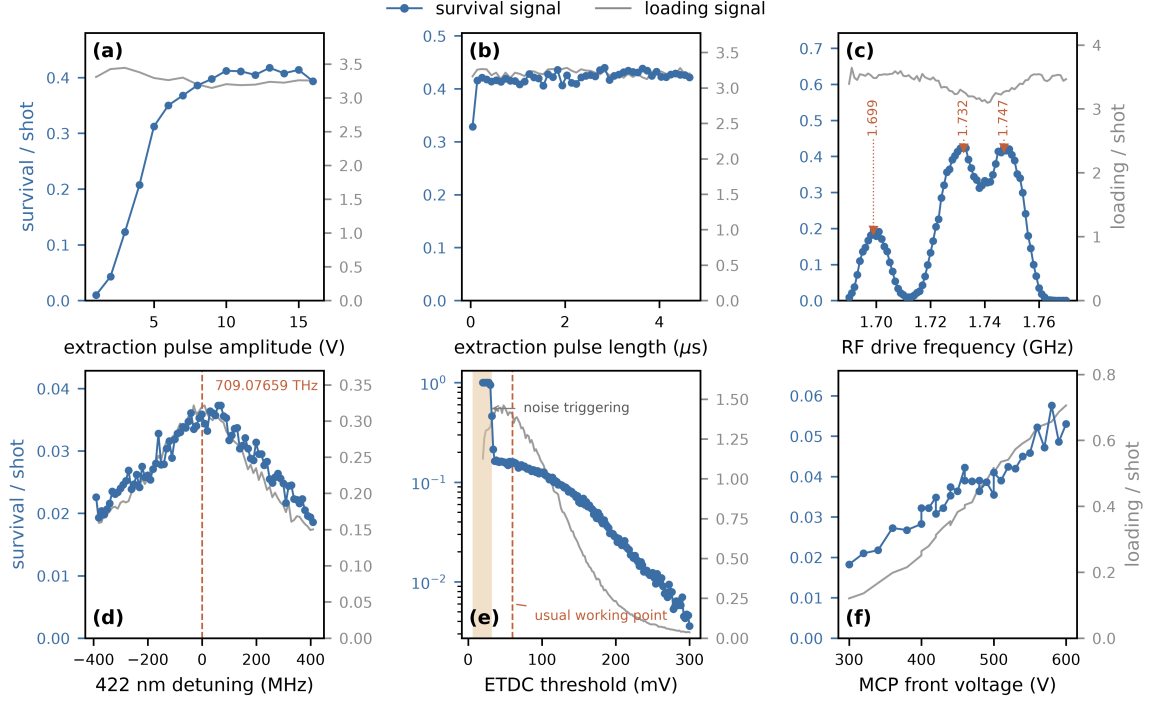


Figure 4.2: Electron signals versus experiment parameters. The survival signal and the loading signal, normalized by the number of repeats, are shown versus (a) the extraction pulse amplitude: the signal saturates when larger than 10 V; (b) the extraction pulse length: insensitive; (c) the frequency of the RF drive: resonances at 1.700, 1.732, and 1.747 GHz; (d) the frequency of the 422 nm laser: a resonance at 709.07659 THz measured by our wavelength meter; (e) the threshold voltage of the envelope threshold detector, which requires at least 32 mV to work; (f) the voltage on the MCP front: the higher the MCP voltage, the higher the detection efficiency.

instead of 20 V in the other measurements. Unlike the extraction pulse amplitude, both the survival signal and the loading signal are insensitive to the length of the extraction pulse. This aligns with the result we observed in the sample signal (Fig. 4.1), where the electrons extracted by the pulse all arrive at the MCP within 100 ns.

The dependence on the RF drive frequency, measured from the electron trapping signal, shows three resonances at 1.700, 1.732, and 1.747 GHz, which are close to our simulation result. We do not know why the resonance is split into three in the electron

trapping measurement, but based on this measurement, we chose 1.732 GHz as the RF drive frequency for the experiments.

The 422 nm laser frequency, on the other hand, shows a clean single peak at 709.07659 THz. This result is about 1.7 GHz off from the precisely measured frequency for this transition, which is at 709.07824 THz [132]. This is because our wavelength meter is not aligned to an absolute frequency reference. This offset is acceptable, because we only need to stabilize the laser frequency to maintain the transition, instead of measuring the transition frequency.

The threshold voltage dependence shows the distribution of the signal amplitudes of the electron events, as well as the noise level of the raw MCP signal. The noise acting on the raw MCP signal mainly comes from the rising and falling edges of the extraction pulse, since the other noise sources, such as the high-voltage power supplies and the RF drive, are eliminated by the filters mentioned in Sec. 3.4.3. The scan shows that the amplitude of the noise induced by the extraction pulse is around 32 mV. In addition to the extraction pulse noise, the tickling signal also causes noise on the MCP signal, which can become the dominant noise when the tickling amplitude is higher than 0 dBm. Therefore, we finally picked 60 mV as the usual threshold for most of our experiments.

The MCP front voltage has a relatively straightforward influence on the electron signals. The larger the MCP front voltage, the higher the electron signals. This is because a higher MCP front voltage means a higher detection efficiency. However, part of this field reaches the trap center and impacts our trap performance, so we do not want the MCP front

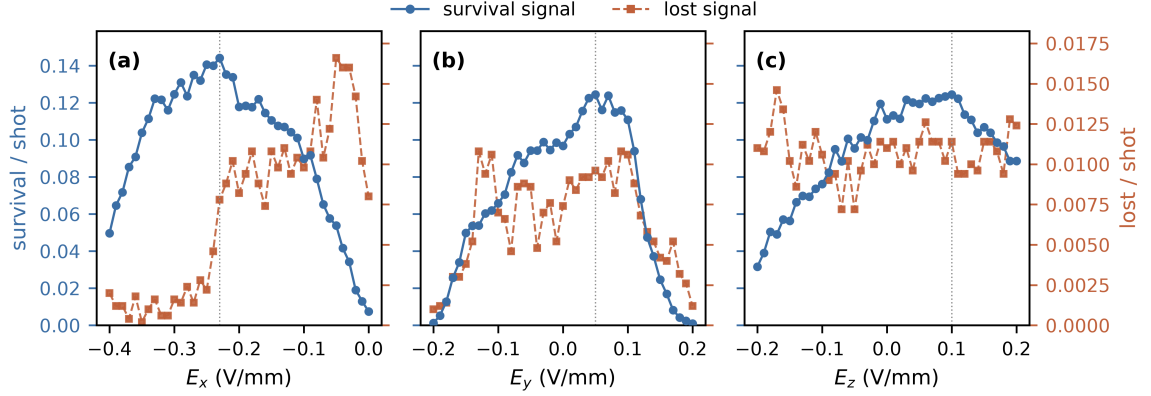


Figure 4.3: Dependency of the electron signals on the E field. The maximum number of electrons is not reached when zero E field is applied at the trap center, but at some nonzero field. This suggests the existence of a stray field in our trap system.

voltage to be as high as possible even though it increases the signal. The most commonly used MCP front voltage in our experiment is 400 V.

Other parameters, such as the oven current, the oven alignment, and the laser alignment and overlap, have a significant effect on the trapped electron signal as well. All three electron signals increase exponentially as we increase the oven current. However, a larger oven current also causes the calcium filling to be consumed quickly. When running at a current of 13 A, the oven empties within 30 minutes. Therefore, in our experiment, we set the oven current to 7.5 A, with a 1.6 V voltage, corresponding to a 12 W oven power. The alignments of the oven and the lasers are optimized by tuning them to the maximum of the electron survival signal. The laser overlap is also optimized using our beam profiler.

4.1.1 Stray Field Compensation

The stray field is an important topic in Paul traps. It is caused by charging of the dielectrics and voltage fluctuations across the conductors in the system [30,44,45]. The most

common way to tackle the stray field is to apply an external field to compensate it, which corresponds to the E_x , E_y , E_z multipole components in Eq. (1.12). As shown in Fig. 4.3, both the survival signal and the lost signal are affected by the E field components. The survival signal has optima on all three components at a nonzero point at $(-0.23, 0.05, 0.10)$, which suggests the existence of a stray field in our system. The lost signal, on the other hand, is mainly affected by E_x , which points perpendicular to the trap board away from the MCP. When $E_x > -0.23$, the same threshold as the maximum of the survival signal, we detect significantly more lost electrons. This means the source of the stray field along E_x is mainly the mesh. The critical point $E_x = -0.23$ compensates the field exerted by the mesh at the trap center, and therefore determines the direction in which the lost electrons fly. In the E_y direction, the direction of the width of the slit, the survival signal and the lost signal show similar behavior. This is because in this direction, the shape of the potential well distorts and becomes no longer able to confine the electrons, resulting in a drop of both the survival signal and the lost signal. The E_z direction is along the slit, so the lost signal is not affected.

After confirming the existence of the stray field in the experiment system, the next natural question is whether we can simply use a constant compensation field in different experiments. To answer this question, I measured the optimal E field under different mesh voltages, axial confinement U_2 , and radial confinement RF amplitude. Fig. 4.4 shows the result of this investigation. Since the availability of data for the three experiments is different, I used different approaches to extract the compensation field data. Fig. 4.4(a) is generated by a 3D Gaussian fitting from a measurement of 200 points in the (E_x, E_y, E_z)

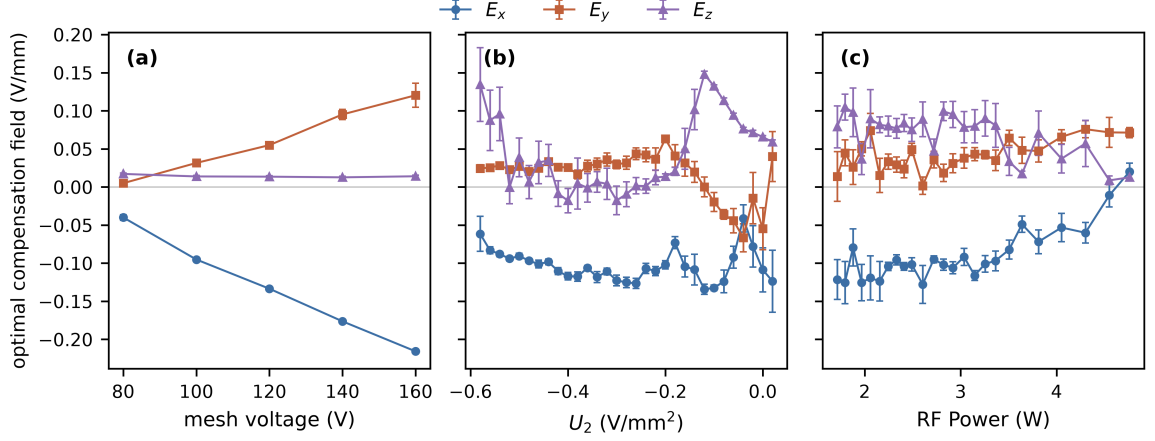


Figure 4.4: Dependence of the optimal compensation field on different experiment parameters. Compensation electric field versus (a) mesh voltage; (b) multipole U_2 ; (c) RF amplitude.

space for each mesh voltage value, while Fig. 4.4(b) and (c) are measured directly by a built-in Bayesian optimizer in our experiment system. When increasing the mesh voltage, we require more E field in the $+\hat{y}$ and $-\hat{x}$ directions, while the E_z compensation remains unchanged. For the axial confinement U_2 , we have a range where the compensation is relatively stable, which is $-0.40 \leq U_2 \leq -0.20$ V/mm². Beyond this range, the compensation field changes significantly as U_2 changes. In our motional frequency experiment, which is introduced in Sec. 4.2, we keep U_2 inside this stable range. In this way, we can simply use the same compensation field for all motional frequency measurements without running any optimizer in the loop, which would raise the concern that the variables are not controlled in the experiment.

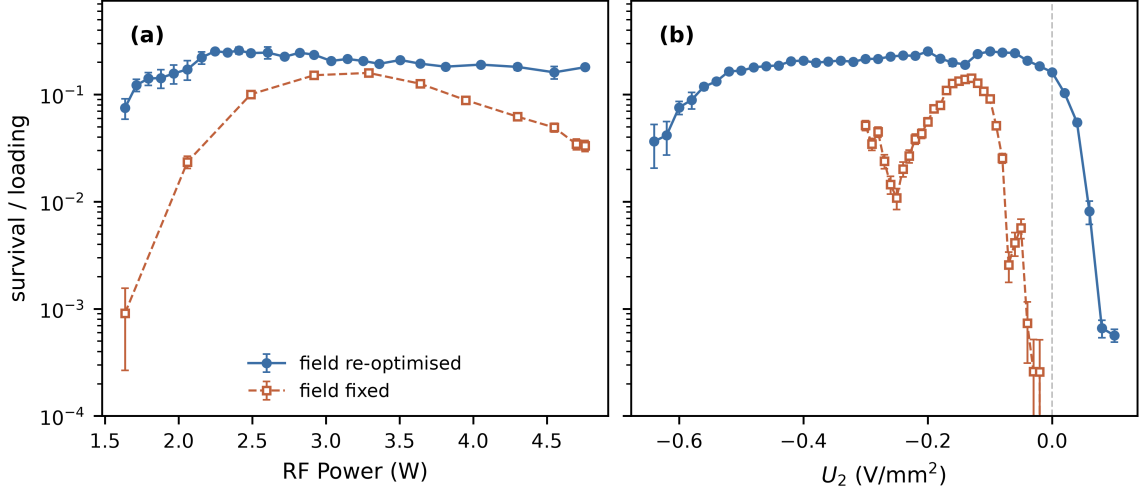


Figure 4.5: Trapping thresholds of the single PCB trap, with the compensation field fixed and re-optimized. The trapping range gets significantly larger if we re-optimize the compensation field. (a) Electron signals versus the RF power, measured at $U_2 = -0.15$ V/mm². (b) Electron signals versus U_2 , measured at an RF power of 3.47 W.

4.1.2 Trapping Thresholds

One of the important characterizations is to find the range of trapping parameters in which we can trap the electrons. Fig. 4.5 shows the results of the measurement performed in two different ways: holding the compensation field (E_x, E_y, E_z) fixed while scanning the RF power (radial confinement) and U_2 (axial confinement), and running the compensation field optimizer for each value of the RF power and U_2 . The results show significantly wider trapping regions when we re-optimize the E field for each trapping parameter, showing the impact of the stray field introduced in Sec. 4.1.1. The electron trapping starts to work when the RF power is greater than 1.5 W, and the signal increases with the RF power and saturates when it reaches 2.3 W. The axial confinement, on the other hand, starts to work when U_2 is smaller than +0.05 V/mm², and the signal quickly reaches its maximum and holds at a stable high level, which could be due to some RF confinement in the axial

direction. However, when U_2 becomes too negative, specifically when $U_2 < -0.50$ V/mm², the electron signal drops again. This is because the U_2 field has an anticonfinement effect on the radial directions, as we discussed in Sec. 1.1.2.

4.2 Motional Frequencies

The motional frequency is one of the major targets we need to measure for this project. As we mentioned in Chapter 1, the motional frequency sets the speed of MS-based gates, and the major advantage of trapped electrons is faster operations on quantum states. The approach we use to measure the motional frequency of the electrons is to apply an RF signal in the waiting phase called tickling, as discussed in Sec. 2.1. For this measurement, we use a loading time of 200 μ s and a waiting time of 140 μ s. The tickle pulse is applied to electrode 12 for a duration of 130 μ s, activated 5 μ s after the start of the waiting phase. If the frequency of the tickling signal matches the motional frequency of the electron, the electron's motional amplitude is driven larger and larger until the electron finally leaves the trap, resulting in a drop of the survival signal and a rise of the lost signal. Therefore, if we scan the frequency of the tickling signal, ranging from 20 to 140 MHz in steps of 0.5 MHz, we can get the motional spectrum of the electron. Two examples of the tickling spectrum are shown in Fig. 4.6. For each trapping parameter, we repeated the experiment multiple times to detect time drift of the experiment system and improve the quality of the data. The experimental cycle is repeated 20000 times for each frequency point to build up statistics. Measuring a single spectrum takes around 1 hour, which means the whole experiment takes several days and thus may be subject to long-term environmental drift.

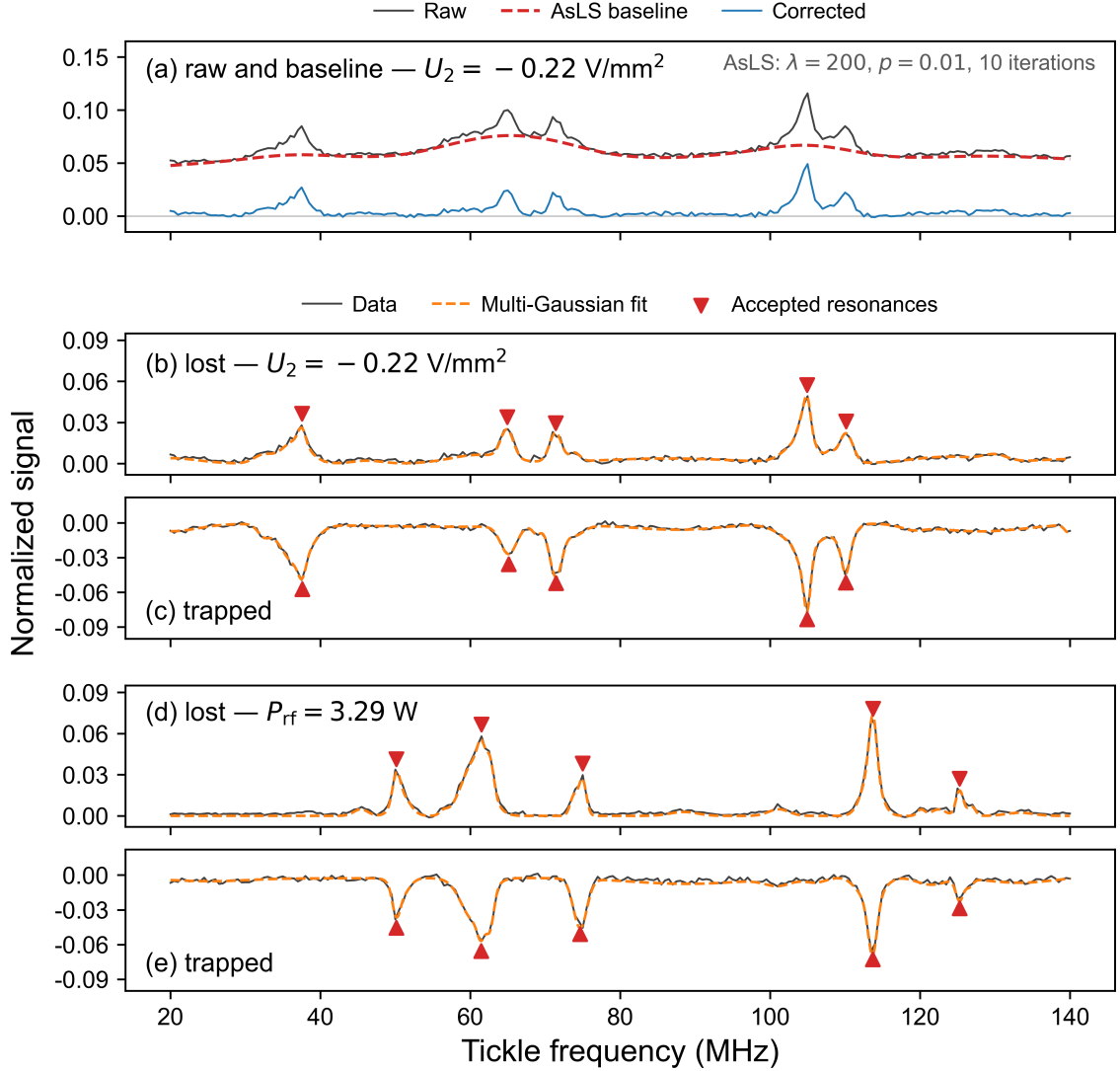


Figure 4.6: Example tickling spectra and resonance extraction. Normalized lost signal (lost signal / loading signal, panels b, d) and normalized trapped signal (surviving signal / loading signal, panels c, e) versus the tickle frequency. The data used here are already processed with baseline correction (asymmetric least squares, AsLS). (a) The comparison between the raw signal and the AsLS-corrected signal. (b, c) For a DC scan point at $U_2 = -0.22 \text{ V/mm}^2$ (RF input power 3 W), and (d, e) for an RF scan point at $P_{\text{rf}} = 3.29 \text{ W}$ ($U_2 = -0.35 \text{ V/mm}^2$). The result shows that the dips of the trapped signal appear at the same frequencies as the peaks of the lost signal.

To deal with this, we repeated the measurement of each trapping parameter 3 to 6 times in a random sequence.

The raw tickling spectrum is the dark grey trace in Fig. 4.6(a), from which we can already see the resonance frequencies we would like to extract. However, the raw data contains imperfect peaks and a broad elevation near the resonance, which complicates the peak fitting and filtering process. Therefore, I applied the asymmetric least squares (AsLS) method [133] with $\lambda = 200$, $p = 0.01$ for the lost signal and $p = 0.99$ for the survival signal, with 10 iterations, to remove the baseline of the signal, shown as the blue trace in Fig. 4.6. After removing the baseline from the data, we averaged the data from repeated shots in which no long-term frequency drift happened, creating an averaged spectrum for each trapping parameter. Then we need to extract the resonance frequency from the averaged spectrum through Gaussian fitting. I built an adaptive multi-peak Gaussian fitter that maximizes the robustness of the fitting. In each pass, it adds one peak to the model by selecting the model with the highest coefficient of determination (R^2) among 120 candidates fitted with different initial μ , and repeats this procedure until the corrected Akaike information criterion (AICc) [134, 135] starts to increase or R^2 reaches 0.995. This procedure can become too time-consuming because the time complexity scales as $O(N^3)$ as the number of Gaussian peaks N increases. Therefore, I introduced an adaptive spectrum splitting that splits the spectrum at a point near its center that is not on a peak. Most of the peaks on the spectrum are finally fitted by 2 to 3 Gaussian peaks, which means we need to select the main peak from the fitter's output. I applied the following procedure to pick the main peak. First, I selected the peaks that satisfy the following requirement: the relative amplitude is

greater than 0.10, where the normalization is such that the minimum of the spectrum is 0 and the maximum of the spectrum is 1.0. The remaining peaks are then grouped by their overlap using the criterion of $|\mu_1 - \mu_2| \leq 3\sqrt{\sigma_1^2 + \sigma_2^2}$, where μ_i and σ_i are the center position and width of the i -th peak. To identify the dominant resonance peaks within each group, we sum all Gaussians to form a composite curve and locate its local maxima. A peak is accepted if its prominence is greater than 0.06 and its amplitude-to-width ratio is greater than 0.06. Because the peak at the group's global maximum naturally represents a genuine spectral feature, it is exempted from the prominence requirement, but it must still have an amplitude-to-width ratio greater than 0.06. This selection procedure is applied independently to each averaged spectrum. The resulting accepted resonance peaks are marked in Fig. 4.6(b)–(e) as downward triangles for the lost spectra and upward triangles for the trapped spectra.

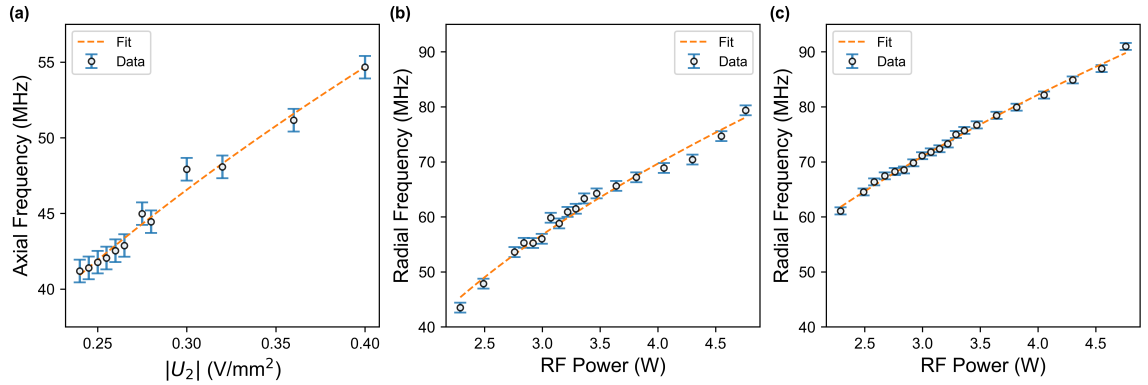


Figure 4.7: Motional frequencies of the trapped electrons. (a) shows the motional frequency of the trapped electrons in the axial direction as a function of $|U_2|$. (b) and (c) show the motional frequencies in the radial direction as a function of the RF input power. Dashed lines are fits to the data of Eq. (4.1) and Eq. (4.2). The error bars of the data represent the average linewidth of the measured resonance peaks.

After identifying the main peaks on the spectrum, we next need to identify the axial resonance and the radial resonance and fit them with physical models. To achieve this, we track the resonance peaks across different parameter settings (U_2 or RF power) into continuous branches called “families”. Each family is initialized by seeding from its maximum end (largest $|U_2|$ and highest RF power), and the tracking then propagates across successive parameter steps through a mutual nearest-neighbor assignment. For each family, we linearly extrapolate its existing points to predict the resonance frequency μ in the next parameter step and assign the nearest peak within a 5 MHz tolerance. To avoid misassignment, if two candidate peaks within the same parameter step are separated by less than 2 MHz, both peaks are discarded. Using this algorithm, I identified the families that represent the axial and radial motional frequencies, shown in Fig. 4.7. Part (a) shows the axial motional frequency as a function of U_2 for a fixed RF input power of 3 W. We observe axial frequencies from $2\pi \times 40$ to $2\pi \times 55$ MHz as $|U_2|$ increases from 0.25 to 0.4 V/mm². Following [31], we fit the result to

$$\omega_{\text{axial}}/2\pi = \alpha_{\text{ax}} \cdot \sqrt{|U_2| - o_{\text{ax}}} \quad (4.1)$$

and find $\alpha_{\text{ax}} = 90.68 \text{ MHz}/(\sqrt{\text{V}}/\text{mm})$ and $o_{\text{ax}} = 0.04 \text{ V}/\text{mm}^2$.

Parts (b) and (c) show two different branches of the first order radial motional resonances. These measurements were taken at a fixed U_2 of $-0.35 \text{ V}/\text{mm}^2$. Here we observe frequencies ranging from $2\pi \times 44$ to $2\pi \times 78$ MHz and $2\pi \times 60$ to $2\pi \times 90$ MHz, respectively. At $\omega_{\text{radial}} = 2\pi \times 90$ MHz, the corresponding stability parameter of the electron trap is $q = 2\sqrt{2}\omega_{\text{radial}}/\Omega_{\text{rf}} = 0.147$. We fit the radial frequency data to

$$\omega_{\text{radial}}/2\pi = \alpha_{\text{ra}} \cdot \sqrt{P_{\text{rf}} - o_{\text{ra}}} \quad (4.2)$$

which yields $\alpha_{\text{ra}} = 40.43 \text{ MHz}/\sqrt{\text{W}}$, $o_{\text{ra}} = 1.03 \text{ W}$ for plot (b), and $\alpha_{\text{ra}} = 41.44 \text{ MHz}/\sqrt{\text{W}}$, $o_{\text{ra}} = 0.07 \text{ W}$ for plot (c).

In Sec. 2.3, we simulated the corresponding motional frequencies of the RF pseudopotential to be $\tilde{\omega}_x \approx 2\pi \times 89.0 \text{ MHz}$ and $\tilde{\omega}_y \approx 2\pi \times 91.1 \text{ MHz}$ at an input power of 4 W, without considering the effect of DC fields. In addition, in Sec. 1.1.2, we derived the full form of the motional frequency predictions in Eq. (1.13):

$$\omega_z^2 = \frac{4eU_2}{mr_0^2}, \quad \omega_{x,y}^2 = \omega_{r0}^2 - \frac{1}{2}\omega_z^2 \pm \frac{2eU_1}{mr_0^2}.$$

Assuming $U_1 = 0$ and substituting Eq. (1.11), we can write the theoretical model as

$$\frac{\omega_{\text{axial}}}{2\pi} = \alpha_{\text{ax}}\sqrt{|U_2|}, \quad \frac{\omega_{\text{radial}}}{2\pi} = \alpha_{\text{ra}}\sqrt{P_{\text{rf}} - \frac{\alpha_{\text{ax}}^2}{2\alpha_{\text{ra}}^2}|U_2|}, \quad (4.3)$$

which means we have a prediction that

$$o_{\text{ax}} = 0, \quad o_{\text{ra}} = \alpha_{\text{ax}}^2|U_2|/2\alpha_{\text{ra}}^2.$$

The fitted offset $o_{\text{ax}} = 0.04 \text{ V/mm}^2 \approx 0$. Thus, we find reasonable agreement with the theoretical expectation of a square-root scaling with a negligible offset for the axial resonance. For the radial resonance, we first check the overall scale set by the RF field, which enters the prediction of o_{ra} as an input. The fitted slopes α_{ra} (40.43 and 41.44 MHz/ $\sqrt{\text{W}}$) match the Q -factor-corrected predictions from the RF simulation in Sec. 2.3 ($\tilde{\omega}_x/2\pi\sqrt{4\text{W}} = 44.50 \text{ MHz}/\sqrt{\text{W}}$ and $\tilde{\omega}_y/2\pi\sqrt{4\text{W}} = 45.55 \text{ MHz}/\sqrt{\text{W}}$) to within 9%. Both branches fall below the simulation by the same amount, which could be caused by a deviation in the RF power delivery.

We can now test the prediction for o_{ra} , which is the part of the model that links the radial fit to the axial one. If we use the fitted slope $\alpha_{\text{ra}} = 40.43 \text{ MHz}/\sqrt{\text{W}}$ from plot

(b), the predicted power offset is $o_{\text{ra}} = (90.68)^2 \times 0.35 / (2 \times 40.43^2) \approx 0.88$ W, which is close to the fitted value of 1.03 W. If we use plot (c) with $\alpha_{\text{ra}} = 41.44$ MHz/ $\sqrt{\text{W}}$, the predicted offset is $o_{\text{ra}} \approx 0.84$ W, which does not agree with the fitted value of 0.07 W. This means that for the RF power dependence, the $U_1 = 0$ model fits the axial mode and the lower radial mode well, but it does not fit the upper radial mode.

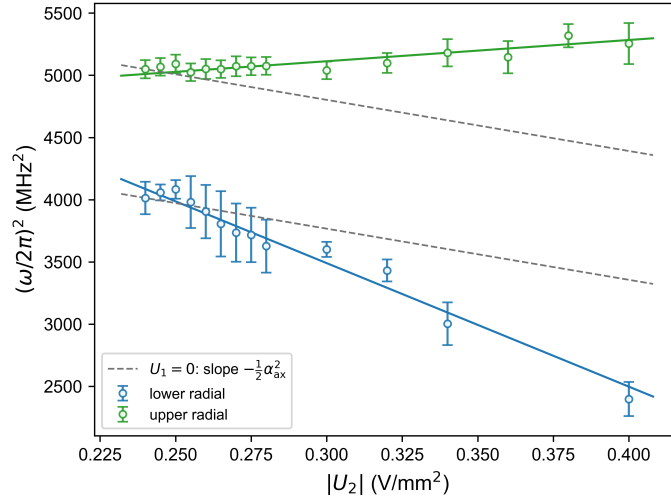


Figure 4.8: Dependence of the two radial branches on $|U_2|$. The points and error bars are the resonance frequency data and their linewidths. The dashed lines are the $U_1 = 0$ prediction of Eq. (1.13), whose slope $-\alpha_{\text{ax}}^2/2$ is fixed by the axial fit of Eq. (4.1). The solid lines are the prediction of the parasitic- U_1 model, which assumes $U_1 = \kappa U_2$.

To investigate the origin of the splitting between the two radial branches, we analyzed their dependence on $|U_2|$. As shown in Fig. 4.8, we found that the lower radial branch weakens as $|U_2|$ increases, with a slope of -10360 MHz²/(V/mm²), while the upper branch remains almost unaffected, with a slope of 1425 MHz²/(V/mm²). The dashed lines represent the predicted model of the $|U_2|$ weakening of the radial confinement, in which both branches are predicted to have a slope of -4112 MHz²/(V/mm²). This means neither of the two branches agrees with the prediction. However, I noticed that the average of the

two slopes, $-4468 \text{ MHz}^2/(\text{V}/\text{mm}^2)$, is quite close to the model prediction. This suggests that the $|U_2|$ dependency of one of the radial modes is “transferred” from the upper branch to the lower branch, which also matches the fitting result that the upper branch has an almost zero offset in its RF power dependence. Therefore, one natural hypothesis is that a parasitic U_1 field is applied simultaneously when we apply U_2 . If we assume a parasitic $U_1 = \kappa U_2$, then the U_1 term in Eq. (1.13) becomes $\pm \frac{\kappa}{2} \omega_z^2$, and the two radial frequencies are

$$\left(\frac{\omega_{\pm}}{2\pi}\right)^2 = \alpha_{\text{ra}}^2 P_{\text{rf}} - \frac{1 \mp \kappa}{2} \alpha_{\text{ax}}^2 |U_2|. \quad (4.4)$$

The two branches now fall with different slopes $-\frac{1 \mp \kappa}{2} \alpha_{\text{ax}}^2$, with their sum remaining unchanged. We fit this model to the $|U_2|$ scan, allowing an additional static U_1 . The fit gives $\kappa = 1.42$ and a static U_1 of $-0.23 \text{ V}/\text{mm}^2$, and reproduces both branches to better than 0.7 MHz, shown as the solid lines in Fig. 4.8.

However, we have not found a physical origin of this parasitic field. At $|U_2| = 0.35 \text{ V}/\text{mm}^2$, the model would carry a parasitic $U_1 \approx 0.27 \text{ V}/\text{mm}^2$, which is comparable to the U_2 field itself. We first verified the C-file and the electrode connections, then measured the voltage on every DC electrode at the feedthrough and reconstructed the DC potential from these measured voltages. However, the calculation from these measurements suggests a parasitic ratio of only $U_1/U_2 = 0.004$. The simulated field of the U_2 multipole is symmetric as well, with curvatures $\partial_x^2 : \partial_y^2 : \partial_z^2 = -0.986 : -0.953 : +2.003 \text{ V}/\text{mm}^2$ per unit U_2 , so the designed geometry is not expected to produce a parasitic U_1 either. The remaining candidates, such as imperfections of the simulation model and manufacturing tolerances, are orders of magnitude too small to account for a U_1 that is comparable to U_2 itself. The

parasitic- U_1 model therefore describes the data well, but without any identified source. This means the splitting of the radial modes remains an open issue that requires further exploration.

4.3 Lifetimes

Another important parameter for electron trapping is the trapping lifetime, since storage is the prerequisite for performing any operation. During the waiting phase of the experiment, the trapped electrons have a chance to leave the trap at every moment, so the probability that the electron is still stored in the trap follows an exponential decay

$$p(t) = p_0 e^{-t/\tau}, \quad (4.5)$$

where p_0 is the probability that the electron is trapped at the end of the loading phase, and τ is the trapping lifetime. If the electrons are still kept in the trap after the waiting phase, they are kicked out of the trap by the extraction pulse towards the MCP. If we repeat the experiment N times with a waiting phase duration of T , we get a survival signal of $n_{\text{survival}} = N p_0 e^{-T/\tau}$. Thus, by scanning the wait time and fitting the survival signal with an exponential formula, we can extract the electron trapping lifetime τ .

In our experiment, the loading time is set to $200 \mu\text{s}$ and the waiting time is varied from 0 to 5 ms. For each point, 500 to 2500 averages are taken and each measurement is repeated 100 times to build up statistics. The reason for increasing the number of averages is to address the weak survival signal for longer waiting times. The measured survival signal normalized to the loading signal is shown in Fig. 4.9. We fit the data with the exponential

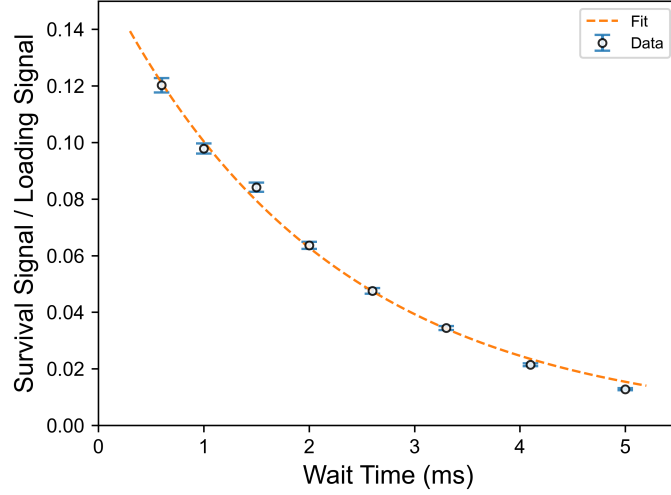


Figure 4.9: Trapped electron lifetime measurement. The data is fitted with an exponential decay, which yields a lifetime of 2.13 ms.

decay mentioned above, which yields $\tau = 2.13 \pm 0.27$ ms. This lifetime is short compared with typical trapped-ion lifetimes, which can be on the order of hours or even days. We attribute this limitation to several factors. Imperfections in the electric fields due to finite manufacturing tolerances can lead to anharmonicities of the trapping potential. Furthermore, with the given setup, it is very challenging to fully compensate excess micromotion in the trap since the usual compensation techniques used in ion traps [30] are not applicable. Here, we systematically scanned the compensation fields while maximizing the trapped electron signal. However, this approach does not necessarily minimize excess micromotion. Implementing more advanced techniques requires cooling and detection of the motion of electrons, for which a cryogenic system will be necessary [116]. Finally, we presume that the most likely reason for the short lifetime is that the trapped electrons are not actively cooled in our room-temperature setup. This stands in contrast to trapped ions, which are typically laser cooled to near the Doppler cooling limit. In our trap, the temperature of

the electrons depends on where in the trap they are loaded. High-temperature electrons describe large orbits and are more prone to exiting the trap when they get near the edge of the trapping potential.

Chapter 5

Conclusion

5.1 Summary

In this dissertation, I have designed and fabricated a monolithic PCB electron Paul trap using standard PCB manufacturing processes with RO4350B RF substrate. The PCB trap integrates a half-wave grounded coplanar waveguide (GCPW) resonator with via shielding, capacitively coupled to a GCPW feedline, and 20 DC electrodes fed by signal traces of equal length. The monolithic design eliminates the need for multi-part assembly. Before manufacturing, the trap design is validated by three different simulations: an HFSS simulation that validates the resonance frequency and the pseudopotential generated by the RF supply when on resonance, a Maxwell simulation and multipole expansion that build the control matrix for the DC electrodes, and a Python-based electron trajectory simulation that validates the electron detection system based on the extraction pulse, the mesh, and the MCP. The base of the experimental system is a room-temperature UHV chamber with a pressure of $\sim 1 \times 10^{-8}$ Torr. I also built an electron generation system using field-induced

ionization via Rydberg states so that we can create electrons that have minimal kinetic energy right at the trap center. On the detection side, the electron is extracted from the trap by a fast negative pulse on the DC electrodes, then guided to the MCP detector by a mesh, and finally processed by a signal processing chain that turns it into a timestamp signal. The timing design of the experiment follows the sequence developed by our collaborators at UC Berkeley. Using this system, I have successfully trapped electrons, optimized the trapping signals, characterized their motional frequencies, and measured their trapping lifetimes.

During this process, we have generated both simulated and measured results of our electron trap. The measured results include measurements at different levels, including electrical characterization and trapping experiments. The resonance frequency of the trap is consistent across these levels. In HFSS simulation, the resonance frequency is predicted to be 1.753 GHz, matching well with the measured resonance frequency of 1.752 GHz from electrical characterization and 1.732 and 1.747 GHz from electron trapping experiments. The measured loaded quality factor Q_L , on the other hand, is a main source of discrepancy between the simulation prediction and measurements, which is 40.7 from electrical characterization and 124 from HFSS simulation. Using these values, and the theoretical model of the hanger resonator, I made a prediction of the electrons' radial motional frequencies and trap depths based on the exported magnitude of electric field near the trap center generated by the HFSS simulation of the RF resonator of the trap. The predicted radial motional frequencies of the electrons are 157.6 MHz and 161.1 MHz based on the simulated Q_L of 124, and 89.0 MHz and 91.1 MHz based on the measured Q_L of 40.7. The prediction based on

the measured Q_L matches the measured radial motional frequencies from trapping experiments, ranging from 44 MHz to 78 MHz and from 60 MHz to 90 MHz, clearly better. The highest measured radial motional frequency corresponds to a stability parameter $q = 0.147$, which sits deep inside the stability region of the Mathieu equation. The lifetime of the trapped electrons is measured to be 2.13 ms. Through this work, I have demonstrated that a monolithic PCB trap can be used to trap electrons at room temperature, which shows that electrons can be trapped with a design that does not require multi-part assembly. The performance of our trap design is comparable to that of the three-layer trap design from UC Berkeley, which reports radial motional frequencies of the same order of magnitude [23]. The monolithic design would be a better candidate for trapping electrons in a cryogenic environment, because it is mechanically more stable under thermal contraction. However, there are several known limitations of the current system. The secular frequency measured in our design is lower than the values reported for the UC Berkeley three-layer trap, which means there is still much room to optimize our RF resonator. For example, we can apply multi-layer PCB techniques, which integrate more than two conductor layers within a monolithic PCB. This could enable us to choose a better geometry of RF transmission lines and coupling that would increase the quality factor of our resonator and thus increase the trapping pseudopotential that leads to higher secular frequencies. This approach also has the potential to improve the DC field delivery of our trap because the DC electrodes could have more direct access to the trap center without being shielded by the conductors of the RF resonator. This eliminates the need for an amplifier board and enables a wider range of DC confinement strength. The significant stray fields observed in our experiment also

suggest that the design of the trap that separates the RF and DC grounds and leaves the dielectric material exposed at the center of the trap is not ideal. All of this means we still have much room to improve our trap design.

In addition to the trap improvement, trapping electrons at room temperature is only the first validation towards the ultimate goal of trapped electron quantum computing. The trapped electron spin qubit works in a cryogenic environment and requires methods to cool the motional state of the electrons, to manipulate and detect the spin state of the electrons non-destructively, and to store, move, and combine the electrons in a reliable way. This means we still have much work to do in the future, and the next step is to trap electrons in a cryogenic environment, and then detect the electrons in a non-destructive way. Therefore, beyond this dissertation, we still need to push the project forward, as well as improve the trap design to achieve better performance. In the following part of this dissertation, I will discuss the outlook of the future development of this project, including the potential improvement of the trap design in Sec. 5.2 and the cryogenic setup we have already built in the lab in Sec. 6.1. I will also include some information about our future roadmap of this project in Sec. 6.2.

5.2 Improvement on the Single-PCB Trap

The goal of improving the trap design is to overcome three main weaknesses of our current trap design. First, I need to add shielding plates that enclose the RF part of the trap board to make the RF resonator work well, as I mentioned in Sec. 2.1. Next, the design that separates the RF and DC ground leaves the middle part of the board bare. This exposure of

dielectrics creates a pool for stray charges in the design, which would contribute to the issue of stray field we observed in Sec. 4.1.1. Besides, in the current design, the conductor of the RF electrode blocks the direct line of sight from the DC electrode to the trap center, which means the DC potential is partially shielded and the delivery efficiency of the electrostatic potential we need is weakened. This leads to the introduction of the amplifier module we have in Sec. 3.4.2.

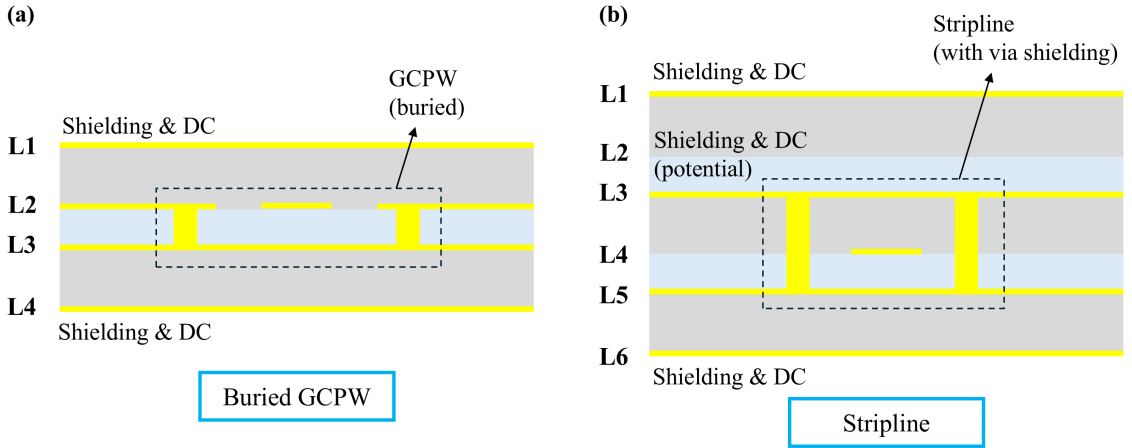


Figure 5.1: Examples of multi-layer stackups that integrate the shielding plates on board. (a) Buried grounded coplanar waveguide design, which keeps the current type of transmission line but integrates the shielding plates onto the trap board directly. (b) Stripline design, which changes the type of transmission line used in the design.

Among these three issues, the problem that the separated ground increases the stray field is relatively easy to solve. We only need to drop the design that separates the RF and DC ground and fill the whole layer with a continuous layer of copper. Then the stray charges that originally fall on the dielectric material would now land on copper and be guided away. For the shielding plate, one of the possible solutions is to integrate the shielding plate onto the trap board itself, which leads to the idea to use a multi-layer process

for our trap design. Fig. 5.1 shows two possible layer stackups we can use for the next trap. Both designs bury the RF resonator in an internal layer so the ground and DC signal lines on the top and bottom layer can serve as the shielding we added in our experiment. If we want to minimize the interference from the RF drive to the DC electrodes, we can also add more layers that enclose the RF components on internal layers completely with separate internal layers designated for shielding, and arrange DC signals outside of these layers.

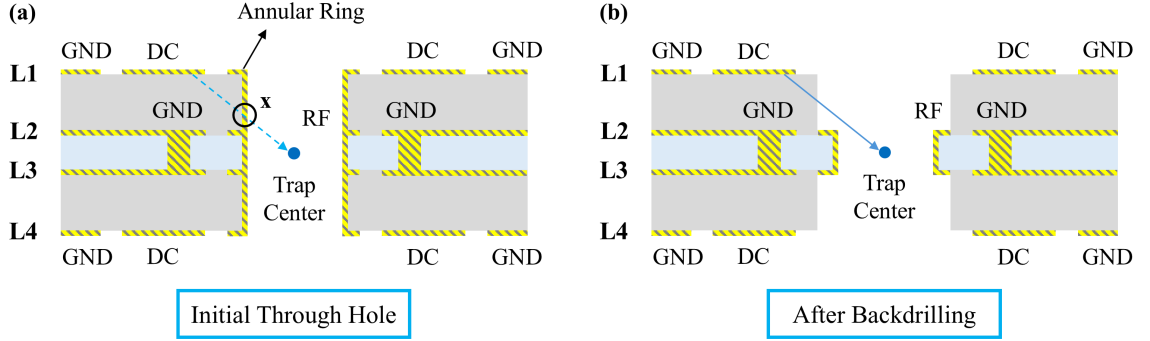


Figure 5.2: Backdrilling to remove the shielding effect on the DC field from the RF electrode. The layer stackup is based on the buried GCPW. (a) An ordinary through hole is manufactured first. Under this configuration, the DC line of sight is blocked by the RF electrode. (b) The backdrilling process then removes material only above Layer 2 and below Layer 3, with a drill width matching or slightly larger than the slot width plus the annular ring of the RF electrode. The DC line of sight is no longer blocked.

For the problem that the DC line of sight is shielded by the conductor of the RF electrode, a possible solution is to use backdrilling technology in the PCB manufacturing process. As shown in Fig. 5.2, we can first manufacture a board whose center slit is an ordinary slotted pad with a metalized annular ring, which is within the capability of the PCB process, and then use a technology called backdrilling, which enables mechanical drilling of controllable depth, to precisely remove the conductor and dielectric of the annular ring down to the internal layer for the RF electrode from both sides of the PCB. Through this

process, we can remove the part of the conductor that blocks the line of sight from the DC electrode to the trap center, and therefore solve the issue that the DC field delivery is shielded by the RF electrode.

On top of these three major directions of improvement, the design also has other aspects that can be improved. For example, according to Table 2.3, the coupling quality factor Q_c is significantly higher than the internal quality factor Q_i , which indicates that the coupling between the feedline and the resonator is too weak. This is also the reason why our resonance depth is only around 2 dB. If we can optimize the coupling strength between the feedline and the resonator, we can achieve a much deeper resonance depth and therefore a stronger pseudopotential.

Chapter 6

Outlook

Beyond the trap design and its improvement, we have a long-term goal of turning trapped electrons into a new platform for quantum computing. The roadmap towards this goal is described by our collaborators at UC Berkeley [\[17\]](#). The envisioned trapped electron quantum computer operates in a cryogenic environment, with resistive cooling of the electron, image current detection of the electron spin, and microwave manipulation of the electron spin. Therefore, two of the most important things for the next step of our project are to trap electrons at a cryogenic temperature, and to detect the trapped electrons in a non-destructive way. These will be covered by the two sections in this chapter.

6.1 Cryogenic Setup

To trap electrons in a cryogenic environment, we need to build a trapping system similar to the one we have at room temperature, including the electron source, the electron detection, and the trap that delivers the confinement potential to the electrons. We have

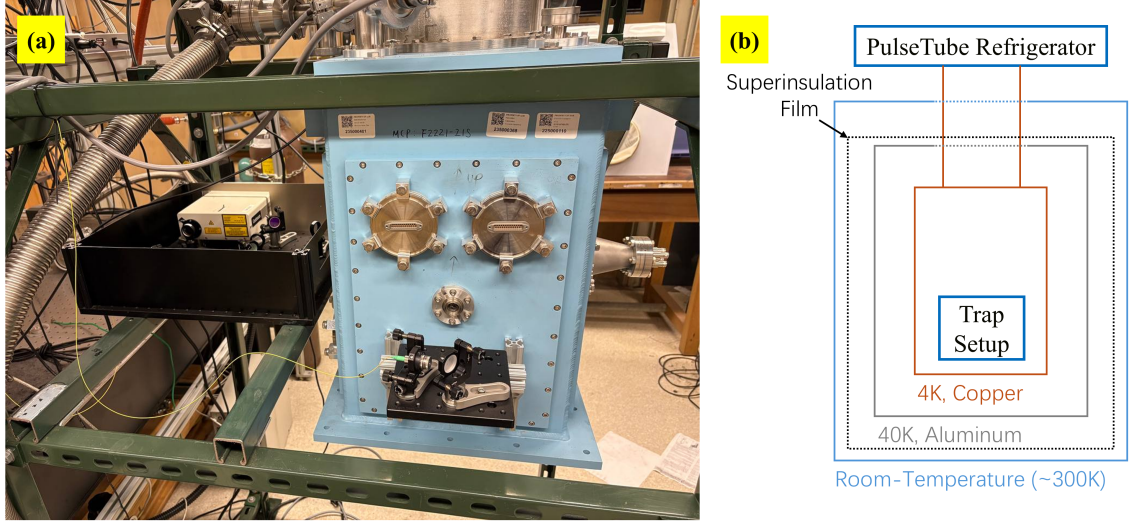


Figure 6.1: Cryogenic vacuum chamber of our lab. (a) Photo of the cryogenic chamber, the blue box is the exterior of the chamber, with optical setup and signal feedthroughs attached to it. (b) Structure of the cryogenic chamber. The chamber is a three-layer design, and the designed temperature for each layer from outside to inside is 300 K, 40 K, and 4 K. The inner layer is cooled by a pulsed-tube cryogenic refrigerator, and the outer layer is insulated from the 40 K layer by a superinsulation film.

built some of these systems in our lab already, including a cryogenic vacuum chamber and the detector we are going to use for the first trapping experiment. Fig. 6.1 shows the cryogenic vacuum chamber we have built in our lab. The chamber is a three-layer design. The outer layer is made of aluminum. It is the vacuum seal as well as the first thermal isolation stage of the chamber, separating the interior of the chamber from the room-temperature environment. The middle layer is also made of aluminum, with a designed temperature of 40 K. This layer is insulated from the outer layer by a superinsulation film. The inner layer is made of copper, with a designed temperature of 4 K. This is the layer that is directly cooled by our refrigerator, which is a CRYOMECH PT420-RM and CRYOMECH RM60420 pulsed-tube refrigerator backed by a CRYOMECH CPA1114 compressor and an Optitemp OTI-30WL water chiller. The inner layer is also the layer on which we will

install our trap and other components required for the experiment. Each of these layers is monitored by a temperature sensor connected to a Lakeshore Model 218 temperature monitor. Cryogenic tests show that the minimum temperature we can reach on the 4 K layer in the chamber is 3.4 K.

The chamber is also equipped with a vacuum system that can keep its pressure at 10^{-6} Torr at room temperature and 10^{-8} Torr under cryogenic conditions. The chamber is sealed by plates and tubes with KF flanges and pumped by an Agilent TwisTorr 74 FS turbo pump backed by an Agilent IDP-7 scroll pump. The chamber pressure is monitored by a HORNET IGM401YFD ion gauge, and its foreline pressure is monitored by an MKS 275 mini-convectron gauge. In addition, we have also developed the ability to perform leak checks of the chamber by equipping the chamber with an SRS RGA100 residual gas analyzer, which enables us to locate a leak by spraying helium gas on the exterior of the chamber and monitoring the helium signal in the RGA.

The chamber is also designed to have optical and electrical access to the interior of the chamber so that we can send all sorts of signals required in our experiment. For electrical feedthrough, the chamber has three 25-pin D-Sub, two SMA, and four SHV connectors. On the optical side, we designed three different optical directions, two of which are perpendicular to each other. This allows us to have the two excitation lasers involved in electron generation cross each other instead of merging in advance, which enables us to precisely define the location where we would like to generate electrons. All of these ports for electrical and optical access are replaceable.

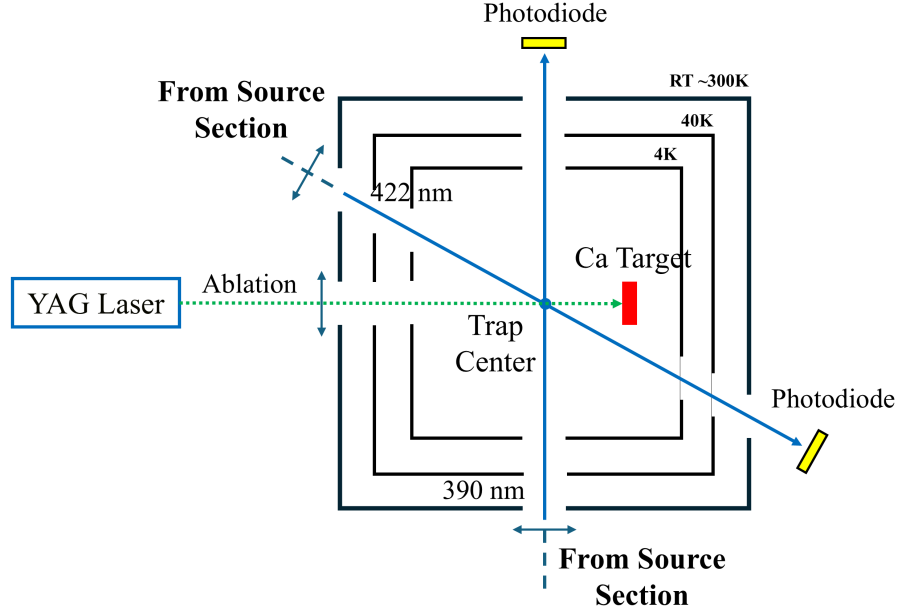


Figure 6.2: Optical design of the cryogenic chamber. The thermal calcium atomic beam is replaced by laser ablation of a calcium target with a YAG laser (blue). The excitation lasers are duplexed from the same source section as the room-temperature setup, but not merged anymore. Instead, the two laser beams now intersect at the trap center, which makes sure electrons are only generated at this position.

We are also going to adjust the electron generation scheme in the cryogenic setup.

In addition to the plan to cross the laser beams instead of merging them, we also plan to replace the thermal calcium atomic beam with the laser ablation of a calcium target, because this enables us to locally create only the small number of calcium atoms required for the experiment. A Continuum ML-II YAG laser is already deployed for this new calcium atom source, but the target and ablation process have not been tested. These changes also make the laser system for the cryogenic setup slightly different from the room-temperature setup. The spatial relation between the beams in this setup is shown in Fig. 6.2. The 390 nm and 422 nm laser beams are delivered from the same laser source section as the room-temperature setup through fibers duplexed by flip mirrors. In the phase of trapping

tests, we plan to keep the destructive measurement of electrons, but we are also going to replace the MCP detector we used in the room-temperature setup with a similar electron multiplier called a Channeltron. The Channeltron also has a front-back-anode structure, which means we do not need significant modifications to our power supply network for the cryogenic system.

With these setups prepared, we already have the basic prerequisites for cryogenic trapping. The next step is to test electron generation through laser ablation. To be specific, we would need to make a calcium target and design a suitable mount inside the chamber. In addition, we would need to be able to walk the ablation laser beam so that the laser can ablate calcium atoms from different parts of the target. Once the laser ablation is working, we could proceed to the next step to test trapping in the chamber, and then develop non-destructive readout of the electron spin.

6.2 Roadmap towards Non-Destructive Spin Readout of Trapped Electrons

After trapping electrons at a cryogenic temperature, we would proceed to the next step, which is to switch our current destructive approach of electron detection to a non-destructive approach that not only can verify the presence of the electron, but also read out the spin state of the electron. Such an approach has been proposed by our collaborators at UC Berkeley, and it is capable of both electron spin readout and cooling [17, 116].

When the electron is confined inside the trap, its secular motion is an oscillation near the trap center. This motion would induce an image current on a nearby electrode.

The magnitude of this image current is given by $I = ev/d_{\text{eff}}$ [26, 136], where v is the velocity of the electron, e is its charge, and d_{eff} is the effective distance from the electron to the electrode. We can utilize this image current for our electron detection. An electrode called the pickup electrode receives this current and couples it to a cryogenic high-impedance LC tank circuit. Then the image current would dissipate energy in the resistance of this circuit. Since this current is driven by the secular motion of the electron, the energy dissipated on the tank circuit also comes from the electron secular motion. Therefore, the electron motion is damped, which corresponds to motional cooling. The time constant of this damping is $\tau = m_e d_{\text{eff}}^2 / (e^2 \text{Re}(Z))$, where Z is the impedance of the tank circuit when on resonance [136]. This technique is called resistive cooling. It has long been used in electron trapping experiments in Penning traps [136]. Through this approach, we can cool the electron to the temperature of the tank circuit, which corresponds to the point where the image current is damped to a magnitude small enough that the Johnson noise becomes the dominant current in the circuit. Using $d_{\text{eff}} = 138 \mu\text{m}$ and $Z = 80 \text{ k}\Omega$ as an example, the time constant for the cooling is around $8 \mu\text{s}$. When cooled to 0.4 K , the electron has an average motional occupation of $\bar{n} = 4$ at a 2 GHz secular frequency [17].

The same signal and setup can not only cool the electron, but also detect the presence and spin of the electron. To detect the presence of the trapped electron, the tank circuit should be on resonance with the secular motion of the electron, and a low-noise amplifier is attached to the tank circuit to extract its signal. When no electron is trapped, the Johnson noise in the circuit would drive the tank circuit on resonance and therefore create a Lorentzian spectrum centered at the resonance frequency of the tank circuit. When

electrons are trapped inside the trap, the Johnson noise would drive the electron while at the same time the electron would be cooled by the resistance of the tank circuit, and this suppresses the Johnson noise level below its resonance peak level. On the spectrum, this is reflected as a dip at the electron's secular frequency. Since the resonance frequency of the tank circuit equals the secular frequency of the electron, the final signal would look like a Lorentzian peak with a sharp dip at its center. This technique does not require extracting the electron towards the MCP and is therefore non-destructive. This technique requires good harmonicity of the trapping potential because anharmonicity would make the secular frequency of the electron drift with its motional amplitude, and therefore broaden the dip. The dip would be undetectable if it is broadened too much. For spin readout, we would apply an oscillating magnetic field gradient whose frequency matches the axial motional frequency of the electron. This magnetic field gradient would then drive the electron with a force whose direction is opposite for the two spin states. The electron therefore undergoes a forced oscillation with a spin-dependent force, resulting in a motion whose phase encodes the information of the spin. Since the image current is induced by the motion of the electron, we would be able to detect the electron spin from the image current signal. This would require us to perform parametric amplification that amplifies the electron motion while keeping its phase, to make the image current signal detectable. The electron presence detection is possible without a cryogenic environment, but the spin readout would require one, since it requires that the phase signal of the electron motion is not lower than the random fluctuation of the motion. This would be tested in our experiment after we successfully trap electrons in the cryogenic chamber.

Beyond the non-destructive readout of the electron spin, there are several other things we can do to proceed towards trapped electron qubits or trap improvement. The single qubit gate of the trapped electron qubit would be performed through a microwave signal at around 100 MHz, and the Zeeman splitting between the spin states would be created artificially by an externally applied magnetic field [17]. We can also employ 3D printing technologies to manufacture our trap, which enables significantly lower anharmonicities by allowing complex 3D structures in the trap design [42]. At that time, we would be able to make trapped electrons into a complete physical platform for quantum information processing, and enable faster and more reliable quantum computing.

Bibliography

- [1] P.W. Shor. Algorithms for quantum computation: discrete logarithms and factoring. In *Proceedings 35th Annual Symposium on Foundations of Computer Science*, pages 124–134, 1994.
- [2] Lov K. Grover. A fast quantum mechanical algorithm for database search. In *Proceedings of the Twenty-Eighth Annual ACM Symposium on Theory of Computing*, STOC '96, page 212–219, New York, NY, USA, 1996. Association for Computing Machinery.
- [3] Richard P. Feynman. Simulating physics with computers. *International Journal of Theoretical Physics*, 21(6):467–488, 1982.
- [4] Seth Lloyd. Universal quantum simulators. *Science*, 273(5278):1073–1078, 1996.
- [5] Charles H. Bennett and Gilles Brassard. Quantum cryptography: Public key distribution and coin tossing. *Theoretical Computer Science*, 560:7–11, 2014. Theoretical Aspects of Quantum Cryptography – celebrating 30 years of BB84.
- [6] Nicolas Gisin, Grégoire Ribordy, Wolfgang Tittel, and Hugo Zbinden. Quantum cryptography. *Rev. Mod. Phys.*, 74:145–195, Mar 2002.
- [7] David P. DiVincenzo. The physical implementation of quantum computation. *Fortschritte der Physik*, 48(9-11):771–783, 9 2000.
- [8] Colin D. Bruzewicz, John Chiaverini, Robert McConnell, and Jeremy M. Sage. Trapped-ion quantum computing: Progress and challenges. *Applied Physics Reviews*, 6:021314, 2019.
- [9] Pengfei Wang, Chun-Yang Luan, Mu Qiao, Mark Um, Junhua Zhang, Ye Wang, Xiao Yuan, Mile Gu, Jingning Zhang, and Kihwan Kim. Single ion qubit with estimated coherence time exceeding one hour. *Nature Communications*, 12(1):233, Jan 2021.
- [10] C. J. Ballance, T. P. Harty, N. M. Linke, M. A. Sepiol, and D. M. Lucas. High-fidelity quantum logic gates using trapped-ion hyperfine qubits. *Physical Review Letters*, 117:060504, 2016.
- [11] F. Diedrich, J. C. Bergquist, Wayne M. Itano, and D. J. Wineland. Laser cooling to the zero-point energy of motion. *Phys. Rev. Lett.*, 62:403–406, Jan 1989.

- [12] S. Seidelin, J. Chiaverini, R. Reichle, J. J. Bollinger, D. Leibfried, J. Britton, J. H. Wesenberg, R. B. Blakestad, R. J. Epstein, D. B. Hume, W. M. Itano, J. D. Jost, C. Langer, R. Ozeri, N. Shiga, and D. J. Wineland. Microfabricated surface-electrode ion trap for scalable quantum information processing. *Phys. Rev. Lett.*, 96:253003, Jun 2006.
- [13] A. H. Myerson, D. J. Szwer, S. C. Webster, D. T. C. Allcock, M. J. Curtis, G. Imreh, J. A. Sherman, D. N. Stacey, A. M. Steane, and D. M. Lucas. High-fidelity readout of trapped-ion qubits. *Phys. Rev. Lett.*, 100:200502, May 2008.
- [14] R. Tyler Sutherland, Qian Yu, Kristin M. Beck, and Hartmut Häffner. One- and two-qubit gate infidelities due to motional errors in trapped ions and electrons. *Physical Review A*, 105:022437, 2022.
- [15] Andris Huang, Edith Hausten, Qian Yu, Kento Taniguchi, Neha Yadav, Isabel Sacksteder, Atsushi Noguchi, Ralf Schneider, and Hartmut Häffner. Numerical investigations of electron dynamics in a linear paul trap. *ArXiv:2503.12379*, 2025.
- [16] G. Ciaramicoli, I. Marzoli, and P. Tombesi. Scalable quantum processor with trapped electrons. *Phys. Rev. Lett.*, 91:017901, 2003.
- [17] Qian Yu, Alberto M. Alonso, Jackie Caminiti, Kristin M. Beck, R. Tyler Sutherland, Dietrich Leibfried, Kayla J. Rodriguez, Madhav Dhital, Boerge Hemmerling, and Hartmut Häffner. Feasibility study of quantum computing using trapped electrons. *Phys. Rev. A*, 105:022420, Feb 2022.
- [18] Daniel Loss and David P. DiVincenzo. Quantum computation with quantum dots. *Phys. Rev. A*, 57:120–126, 1998.
- [19] Jarryd J. Pla, Kuan Y. Tan, Juan P. Dehollain, Wee H. Lim, John J. L. Morton, David N. Jamieson, Andrew S. Dzurak, and Andrea Morello. A single-atom electron spin qubit in silicon. *Nature*, 489:541–545, 2012.
- [20] Luka Trifunovic, Oliver Dial, Mircea Trif, James R. Wootton, Rediet Abebe, Amir Yacoby, and Daniel Loss. Long-distance spin-spin coupling via floating gates. *Phys. Rev. X*, 2:011006, 2012.
- [21] Shlomi Kotler, Raymond W. Simmonds, Dietrich Leibfried, and David J. Wineland. Hybrid quantum systems with trapped charged particles. *Physical Review A*, 95:022327, 2021.
- [22] Nikos Daniilidis, Dylan J Gorman, Lin Tian, Hartmut Häffner, and Häffner Hartmut. Quantum information processing with trapped electrons and superconducting electronics. *New J. Phys.*, 15:073017, 2021.
- [23] Clemens Matthiesen, Qian Yu, Jinen Guo, Alberto M. Alonso, and Hartmut Häffner. Trapping electrons in a room-temperature microwave paul trap. *Phys. Rev. X*, 11:011019, Jan 2021.

- [24] S. Earnshaw. On the nature of the molecular forces which regulate the constitution of the luminiferous ether. *Trans. Cambridge Philos. Soc.*, 7:97, 1842.
- [25] Wolfgang Paul. Electromagnetic traps for charged and neutral particles. *Reviews of Modern Physics*, 62:531–540, 1990.
- [26] Lowell S. Brown and Gerald Gabrielse. Geonium theory: Physics of a single electron or ion in a penning trap. *Reviews of Modern Physics*, 58:233–311, 1986.
- [27] Wolfgang Paul and Helmut Steinwedel. Notizen: Ein neues Massenspektrometer ohne Magnetfeld. *Zeitschrift Naturforschung Teil A*, 8(7):448–450, July 1953.
- [28] Pradip Ghosh. *Ion Traps*. Clarendon Press Publication, 2021.
- [29] D. Leibfried, R. Blatt, C. Monroe, and D. Wineland. Quantum dynamics of single trapped ions. *Reviews of Modern Physics*, 75:281–324, 2021.
- [30] D. J. Berkeland, J. D. Miller, J. C. Bergquist, W. M. Itano, and D. J. Wineland. Minimization of ion micromotion in a paul trap. *Journal of Applied Physics*, 83:5025–5033, 1998.
- [31] D. J. Wineland, C. Monroe, W. M. Itano, D. Leibfried, B. E. King, and D. M. Meekhof. Experimental issues in coherent quantum-state manipulation of trapped atomic ions. *Journal of Research of the National Institute of Standards and Technology*, 103:259–328, 1998.
- [32] J. I. Cirac, L. J. Garay, R. Blatt, A. S. Parkins, and P. Zoller. Laser cooling of trapped ions: The influence of micromotion. *Phys. Rev. A*, 49:421–432, Jan 1994.
- [33] H.G. Dehmelt. Radiofrequency spectroscopy of stored ions i: Storage. In D.R. Bates and Immanuel Estermann, editors, *Advances in Atomic and Molecular Physics*, volume 3, pages 53–72. Academic Press, 1968.
- [34] M. G. Raizen, J. M. Gilligan, J. C. Bergquist, W. M. Itano, and D. J. Wineland. Ionic crystals in a linear paul trap. *Phys. Rev. A*, 45:6493–6501, May 1992.
- [35] D. R. Denison. Operating parameters of a quadrupole in a grounded cylindrical housing. *Journal of Vacuum Science and Technology*, 8(1):266–269, 01 1971.
- [36] Jungsoo Hong, Myunghun Kim, Hyegoo Lee, and Moonjoo Lee. Numerical investigation of a segmented-blade ion trap with biasing rods. *Applied Physics B*, 129(1):16, 2022.
- [37] Seokjun Hong, Minjae Lee, Hongjin Cheon, Taehyun Kim, and Dong-il Cho. Guidelines for designing surface ion traps using the boundary element method. *Sensors*, 16(5):616, 2016.
- [38] K. G. Johnson, J. D. Wong-Campos, A. Restelli, K. A. Landsman, B. Neyenhuis, J. Mizrahi, and C. Monroe. Active stabilization of ion trap radiofrequency potentials. *Review of Scientific Instruments*, 87(5):053110, 05 2016.

- [39] J. Chiaverini, R. B. Blakestad, J. Britton, J. D. Jost, C. Langer, D. Leibfried, R. Ozeri, and D. J. Wineland. Surface-electrode architecture for ion-trap quantum information processing. *Quantum Information and Computation*, 5:419–439, 2021.
- [40] J. M. Pino, J. M. Dreiling, C. Figgatt, J. P. Gaebler, S. A. Moses, M. S. Allman, C. H. Baldwin, M. Foss-Feig, D. Hayes, K. Mayer, C. Ryan-Anderson, and B. Neyenhuis. Demonstration of the trapped-ion quantum ccd computer architecture. *Nature*, 592(7853):209–213, April 2021.
- [41] Kenneth R. Brown, Robert J. Clark, Jaroslaw Labaziewicz, Philip Richerme, David R. Leibbrandt, and Isaac L. Chuang. Loading and characterization of a printed-circuit-board atomic ion trap. *Phys. Rev. A*, 75:015401, Jan 2007.
- [42] Shuqi Xu, Xiaoxing Xia, Qian Yu, Abhinav Parakh, Sumanta Khan, Eli Megidish, Bingran You, Boerge Hemmerling, Andrew Jayich, Kristin Beck, Juergen Biener, and Hartmut Häffner. 3d-printed micro ion trap technology for quantum information applications. *Nature*, 645(8080):362–368, September 2025.
- [43] Martin W. van Mourik, Esteban A. Martinez, Lukas Gerster, Pavel Hrmo, Thomas Monz, Philipp Schindler, and Rainer Blatt. Coherent rotations of qubits within a surface ion-trap quantum computer. *Phys. Rev. A*, 102:022611, Aug 2020.
- [44] M Harlander, M Brownnutt, W Hänsel, and R Blatt. Trapped-ion probing of light-induced charging effects on dielectrics. *New Journal of Physics*, 12(9):093035, sep 2010.
- [45] Shannon X. Wang, Guang Hao Low, Nathan S. Lachenmyer, Yufei Ge, Peter F. Herskind, and Isaac L. Chuang. Laser-induced charging of microfabricated ion traps. *Journal of Applied Physics*, 110(10):104901, 11 2011.
- [46] S Charles Doret, Jason M Amini, Kenneth Wright, Curtis Volin, Tyler Killian, Arkadas Ozakin, Douglas Denison, Harley Hayden, C-S Pai, Richart E Slusher, and Alexa W Harter. Controlling trapping potentials and stray electric fields in a microfabricated ion trap through design and compensation. *New Journal of Physics*, 14(7):073012, jul 2012.
- [47] NIST Ion Storage Group. bem: Triangulation, boundary element method and fast multipole method code for Python. <https://github.com/nist-ionstorage/bem>. Accessed: 2026-07-13.
- [48] Kilian Singer, Ulrich Poschinger, Michael Murphy, Peter Ivanov, Frank Ziesel, Tommaso Calarco, and Ferdinand Schmidt-Kaler. Colloquium: Trapped ions as quantum bits: Essential numerical tools. *Rev. Mod. Phys.*, 82:2609–2632, Sep 2010.
- [49] Ansys, Inc. Ansys HFSS, 3D high-frequency electromagnetic simulation software. <https://www.ansys.com/products/electronics/ansys-hfss>. Canonsburg, PA. Accessed: 2026-07-13.

- [50] Ansys, Inc. Ansys Maxwell, electromechanical device analysis software. <https://www.ansys.com/products/electronics/ansys-maxwell>. Canonsburg, PA. Accessed: 2026-07-13.
- [51] R. Penrose. A generalized inverse for matrices. *Proceedings of the Cambridge Philosophical Society*, 51(3):406–413, 1955.
- [52] A. Conta, S. Bogino, F. Köhncke, F. Schmidt-Kaler, and U. G. Poschinger. Toolchain for shuttling trapped-ion qubits in segmented traps. *AVS Quantum Science*, 8(2):023801, 05 2026.
- [53] D. Kielpinski, C. Monroe, and D. J. Wineland. Architecture for a large-scale ion-trap quantum computer. *Nature* 2002 417:6890, 417:709–711, 2021.
- [54] Ch. Roos, Th. Zeiger, H. Rohde, H. C. Nägerl, J. Eschner, D. Leibfried, F. Schmidt-Kaler, and R. Blatt. Quantum state engineering on an optical transition and decoherence in a paul trap. *Phys. Rev. Lett.*, 83:4713–4716, Dec 1999.
- [55] P. A. Barton, C. J. S. Donald, D. M. Lucas, D. A. Stevens, A. M. Steane, and D. N. Stacey. Measurement of the lifetime of the $3d^2D_{5/2}$ state in $^{40}\text{Ca}^+$. *Phys. Rev. A*, 62:032503, Aug 2000.
- [56] Philipp Schindler, Daniel Nigg, Thomas Monz, Julio T Barreiro, Esteban Martinez, Shannon X Wang, Stephan Quint, Matthias F Brandl, Volckmar Nebendahl, Christian F Roos, Michael Chwalla, Markus Hennrich, and Rainer Blatt. A quantum information processor with trapped ions. *New Journal of Physics*, 15(12):123012, dec 2013.
- [57] S. Olmschenk, K. C. Younge, D. L. Moehring, D. N. Matsukevich, P. Maunz, and C. Monroe. Manipulation and detection of a trapped yb^+ hyperfine qubit. *Phys. Rev. A*, 76:052314, Nov 2007.
- [58] J. Benhelm, G. Kirchmair, C. F. Roos, and R. Blatt. Experimental quantum-information processing with $^{43}\text{Ca}^+$ ions. *Phys. Rev. A*, 77:062306, Jun 2008.
- [59] T. P. Harty, D. T.C. Allcock, C. J. Ballance, L. Guidoni, H. A. Janacek, N. M. Linke, D. N. Stacey, and D. M. Lucas. High-fidelity preparation, gates, memory, and readout of a trapped-ion quantum bit. *Physical Review Letters*, 113:220501, 2021.
- [60] C. Monroe, D. M. Meekhof, B. E. King, W. M. Itano, and D. J. Wineland. Demonstration of a fundamental quantum logic gate. *Phys. Rev. Lett.*, 75:4714–4717, Dec 1995.
- [61] A Keselman, Y Glickman, N Akerman, S Kotler, and R Ozeri. High-fidelity state detection and tomography of a single-ion zeeman qubit. *New Journal of Physics*, 13(7):073027, jul 2011.
- [62] T. Ruster, C. T. Schmiegelow, H. Kaufmann, C. Warschburger, F. Schmidt-Kaler, and U. G. Poschinger. A long-lived Zeeman trapped-ion qubit. *Applied Physics B*, 122(10):254, September 2016.

- [63] D. M. Lucas, A. Ramos, J. P. Home, M. J. McDonnell, S. Nakayama, J.-P. Stacey, S. C. Webster, D. N. Stacey, and A. M. Steane. Isotope-selective photoionization for calcium ion trapping. *Phys. Rev. A*, 69:012711, Jan 2004.
- [64] D. J. Wineland and Wayne M. Itano. Laser cooling of atoms. *Phys. Rev. A*, 20:1521–1540, Oct 1979.
- [65] A. H. Burrell, D. J. Szwer, S. C. Webster, and D. M. Lucas. Scalable simultaneous multiqubit readout with 99.99% single-shot fidelity. *Phys. Rev. A*, 81:040302(R), Apr 2010.
- [66] Craig R. Clark, Holly N. Tinkey, Brian C. Sawyer, Adam M. Meier, Karl A. Burkhardt, Christopher M. Seck, Christopher M. Shappert, Nicholas D. Guise, Curtis E. Volin, Spencer D. Fallek, Harley T. Hayden, Wade G. Rellergert, and Kenton R. Brown. High-fidelity bell-state preparation with $^{40}\text{Ca}^+$ optical qubits. *Phys. Rev. Lett.*, 127:130505, Sep 2021.
- [67] I. Pogorelov, T. Feldker, Ch. D. Marciniak, L. Postler, G. Jacob, O. Kriegelsteiner, V. Podlesnic, M. Meth, V. Negnevitsky, M. Stadler, B. Höfer, C. Wächter, K. Lakhmanskiy, R. Blatt, P. Schindler, and T. Monz. Compact ion-trap quantum computing demonstrator. *PRX Quantum*, 2:020343, Jun 2021.
- [68] M. C. Smith, A. D. Leu, K. Miyanishi, M. F. Gely, and D. M. Lucas. Single-qubit gates with errors at the 10^{-7} level. *Phys. Rev. Lett.*, 134:230601, Jun 2025.
- [69] Jan Benhelm, Gerhard Kirchmair, Christian F. Roos, and Rainer Blatt. Towards fault-tolerant quantum computing with trapped ions. *Nature Physics*, 4(6):463–466, June 2008.
- [70] J. I. Cirac and P. Zoller. Quantum computations with cold trapped ions. *Phys. Rev. Lett.*, 74:4091–4094, May 1995.
- [71] Ferdinand Schmidt-Kaler, Hartmut Haffner, Mark Riebe, Stephan Gulde, Gavin P. T. Lancaster, Thomas Deuschle, Christoph Becher, Christian F. Roos, Jürgen Eschner, and Rainer Blatt. Realization of the Cirac–Zoller controlled-NOT quantum gate. *Nature*, 422(6930):408–411, March 2003.
- [72] Klaus Mølmer and Anders S Sørensen. Multiparticle entanglement of hot trapped ions. *Phys. Rev. Lett.*, 82:1835, 2021.
- [73] Anders Sørensen and Klaus Mølmer. Quantum computation with ions in thermal motion. *Phys. Rev. Lett.*, 82:1971–1974, Mar 1999.
- [74] Anders Sørensen and Klaus Mølmer. Entanglement and quantum computation with ions in thermal motion. *Phys. Rev. A*, 62:022311, Jul 2000.
- [75] J. P. Gaebler, T. R. Tan, Y. Lin, Y. Wan, R. Bowler, A. C. Keith, S. Glancy, K. Coakley, E. Knill, D. Leibfried, and D. J. Wineland. High-fidelity universal gate set for be 9 + ion qubits. *Physical Review Letters*, 117:060505, 2021.

- [76] J. J. García-Ripoll, P. Zoller, and J. I. Cirac. Speed optimized two-qubit gates with laser coherent control techniques for ion trap quantum computing. *Phys. Rev. Lett.*, 91:157901, Oct 2003.
- [77] V. M. Schäfer, C. J. Ballance, K. Thirumalai, L. J. Stephenson, T. G. Ballance, A. M. Steane, and D. M. Lucas. Fast quantum logic gates with trapped-ion qubits. *Nature*, 555(7694):75–78, March 2018.
- [78] Chi Zhang, Fabian Pokorny, Weibin Li, Gerard Higgins, Andreas Pöschl, Igor Lesanovsky, and Markus Hennrich. Submicrosecond entangling gate between trapped ions via Rydberg interaction. *Nature*, 580(7803):345–349, April 2020.
- [79] J. D. Wong-Campos, S. A. Moses, K. G. Johnson, and C. Monroe. Demonstration of two-atom entanglement with ultrafast optical pulses. *Phys. Rev. Lett.*, 119:230501, Dec 2017.
- [80] M.I. Hussain, D. Heinrich, M. Guevara-Bertsch, E. Torrontegui, J.J. García-Ripoll, C.F. Roos, and R. Blatt. Ultraviolet laser pulses with multigigahertz repetition rate and multiwatt average power for fast trapped-ion entanglement operations. *Phys. Rev. Appl.*, 15:024054, Feb 2021.
- [81] D. F. V. James. Quantum dynamics of cold trapped ions with application to quantum computation. *Applied Physics B*, 66(2):181–190, February 1998.
- [82] Ana S. Sotirova, Bangshan Sun, Jamie D. Leppard, Andong Wang, Mohan Wang, Andres Vazquez-Brennan, David P. Nadlinger, Simon Moser, Alexander Jesacher, Chao He, Fabian Pokorny, Martin J. Booth, and Christopher J. Ballance. Low cross-talk optical addressing of trapped-ion qubits using a novel integrated photonic chip. *Light: Science & Applications*, 13(1):199, August 2024.
- [83] J. P. Schiffer. Phase transitions in anisotropically confined ionic crystals. *Phys. Rev. Lett.*, 70:818–821, Feb 1993.
- [84] Daniel H. E. Dubin. Theory of structural phase transitions in a trapped coulomb crystal. *Phys. Rev. Lett.*, 71:2753–2756, Oct 1993.
- [85] D. G. Enzer, M. M. Schauer, J. J. Gomez, M. S. Gulley, M. H. Holzscheiter, P. G. Kwiat, S. K. Lamoreaux, C. G. Peterson, V. D. Sandberg, D. Tupa, A. G. White, R. J. Hughes, and D. F. V. James. Observation of power-law scaling for phase transitions in linear trapped ion crystals. *Phys. Rev. Lett.*, 85:2466–2469, Sep 2000.
- [86] S. A. Moses, C. H. Baldwin, M. S. Allman, R. Ancona, L. Ascarrunz, C. Barnes, J. Bartolotta, B. Bjork, P. Blanchard, M. Bohn, J. G. Bohnet, N. C. Brown, N. Q. Burdick, W. C. Burton, S. L. Campbell, J. P. Campora, C. Carron, J. Chambers, J. W. Chan, Y. H. Chen, A. Chernoguzov, E. Chertkov, J. Colina, J. P. Curtis, R. Daniel, M. DeCross, D. Deen, C. Delaney, J. M. Dreiling, C. T. Ertsgaard, J. Esposito, B. Estey, M. Fabrikant, C. Figgatt, C. Foltz, M. Foss-Feig, D. Francois, J. P. Gaebler, T. M. Gatterman, C. N. Gilbreth, J. Giles, E. Glynn, A. Hall, A. M. Hankin,

- A. Hansen, D. Hayes, B. Higashi, I. M. Hoffman, B. Horning, J. J. Hout, R. Jacobs, J. Johansen, L. Jones, J. Karcz, T. Klein, P. Lauria, P. Lee, D. Liefer, S. T. Lu, D. Lucchetti, C. Lytle, A. Malm, M. Matheny, B. Mathewson, K. Mayer, D. B. Miller, M. Mills, B. Neyenhuis, L. Nugent, S. Olson, J. Parks, G. N. Price, Z. Price, M. Pugh, A. Ransford, A. P. Reed, C. Roman, M. Rowe, C. Ryan-Anderson, S. Sanders, J. Sedlacek, P. Shevchuk, P. Siegfried, T. Skripka, B. Spaun, R. T. Sprenkle, R. P. Stutz, M. Swallows, R. I. Tobey, A. Tran, T. Tran, E. Vogt, C. Volin, J. Walker, A. M. Zolot, and J. M. Pino. A race-track trapped-ion quantum processor. *Phys. Rev. X*, 13:041052, Dec 2023.
- [87] M. DeCross, R. Haghshenas, M. Liu, E. Rinaldi, J. Gray, Y. Alexeev, C. H. Baldwin, J. P. Bartolotta, M. Bohn, E. Chertkov, J. Cline, J. Colina, D. DelVento, J. M. Dreiling, C. Foltz, J. P. Gaebler, T. M. Gatterman, C. N. Gilbreth, J. Giles, D. Gresh, A. Hall, A. Hankin, A. Hansen, N. Hewitt, I. Hoffman, C. Holliman, R. B. Hutson, T. Jacobs, J. Johansen, P. J. Lee, E. Lehman, D. Lucchetti, D. Lykov, I. S. Madjarov, B. Mathewson, K. Mayer, M. Mills, P. Niroula, J. M. Pino, C. Roman, M. Schecter, P. E. Siegfried, B. G. Tiemann, C. Volin, J. Walker, R. Shaydulin, M. Pistoia, S. A. Moses, D. Hayes, B. Neyenhuis, R. P. Stutz, and M. Foss-Feig. Computational power of random quantum circuits in arbitrary geometries. *Phys. Rev. X*, 15:021052, May 2025.
- [88] C. Monroe and J. Kim. Scaling the ion trap quantum processor. *Science*, 339:1164–1169, 2021.
- [89] Bjoern Lekitsch, Sebastian Weidt, Austin G. Fowler, Klaus Mølmer, Simon J. Devitt, Christof Wunderlich, and Winfried K. Hensinger. Blueprint for a microwave trapped ion quantum computer. *Science Advances*, 3(2):e1601540, 2017.
- [90] Florian Mintert and Christof Wunderlich. Ion-trap quantum logic using long-wavelength radiation. *Physical Review Letters*, 87:257904, 2021.
- [91] C. Ospelkaus, U. Warring, Y. Colombe, K. R. Brown, J. M. Amini, D. Leibfried, and D. J. Wineland. Microwave quantum logic gates for trapped ions. *Nature*, 476:181–184, 2011.
- [92] R Srinivas, S C Burd, H M Knaack, R T Sutherland, A Kwiatkowski, S Glancy, E Knill, D J Wineland, D Leibfried, A C Wilson, D T C Allcock, and D H Slichter. High-fidelity laser-free universal control of two trapped ion qubits. *arXiv:2102.12533*, 2021.
- [93] R. J. Niffenegger, J. Stuart, C. Sorace-Agaskar, D. Kharas, S. Bramhavar, C. D. Bruzewicz, W. Loh, R. T. Maxson, R. McConnell, D. Reens, G. N. West, J. M. Sage, and J. Chiaverini. Integrated multi-wavelength control of an ion qubit. *Nature*, 586(7830):538–542, October 2020.

- [94] Carmelo Mordini, Alfredo Ricci Vasquez, Yuto Motohashi, Mose Müller, Maciej Malinowski, Chi Zhang, Karan K. Mehta, Daniel Kienzler, and Jonathan P. Home. Multizone trapped-ion qubit control in an integrated photonics qccd device. *Phys. Rev. X*, 15:011040, Feb 2025.
- [95] M. Ivory, W. J. Setzer, N. Karl, H. McGuinness, C. DeRose, M. Blain, D. Stick, M. Gehl, and L. P. Parazzoli. Integrated optical addressing of a trapped ytterbium ion. *Phys. Rev. X*, 11:041033, Nov 2021.
- [96] C. W. Hogle, D. Dominguez, M. Dong, A. Leenheer, H. J. McGuinness, B. P. Ruzic, M. Eichenfield, and D. Stick. High-fidelity trapped-ion qubit operations with scalable photonic modulators. *npj Quantum Information*, 9(1):74, July 2023.
- [97] Joonhyuk Kwon, William J. Setzer, Michael Gehl, Nicholas Karl, Jay Van Der Wall, Ryan Law, Matthew G. Blain, Daniel Stick, and Hayden J. McGuinness. Multi-site integrated optical addressing of trapped ions. *Nature Communications*, 15(1):3709, May 2024.
- [98] F.M. Penning. Die glimmentladung bei niedrigem druck zwischen koaxialen zylindern in einem axialen magnetfeld. *Physica*, 3(9):873–894, 1936.
- [99] Hans Dehmelt. Experiments with an isolated subatomic particle at rest. *Rev. Mod. Phys.*, 62:525–530, Jul 1990.
- [100] D. Wineland, P. Ekstrom, and H. Dehmelt. Monolectron oscillator. *Physical Review Letters*, 31:1279–1282, 1973.
- [101] R. S. Van Dyck, P. B. Schwinberg, and H. G. Dehmelt. Precise measurements of axial, magnetron, cyclotron, and spin-cyclotron-beat frequencies on an isolated 1-meV electron. *Physical Review Letters*, 38:310–314, 2021.
- [102] Hans Dehmelt. Continuous stern-gerlach effect: Principle and idealized apparatus. *Proceedings of the National Academy of Sciences*, 83(8):2291–2294, 1986.
- [103] H. Dehmelt. New continuous Stern–Gerlach effect and a hint of “the” elementary particle. *Zeitschrift für Physik D Atoms, Molecules and Clusters*, 10(2):127–134, June 1988.
- [104] Robert S. Van Dyck, Paul B. Schwinberg, and Hans G. Dehmelt. New high-precision comparison of electron and positron g factors. *Phys. Rev. Lett.*, 59:26–29, Jul 1987.
- [105] S. Peil and G. Gabrielse. Observing the quantum limit of an electron cyclotron: Qnd measurements of quantum jumps between fock states. *Phys. Rev. Lett.*, 83:1287–1290, Aug 1999.
- [106] D. Hanneke, S. Fogwell, and G. Gabrielse. New measurement of the electron magnetic moment and the fine structure constant. *Phys. Rev. Lett.*, 100:120801, Mar 2008.
- [107] X. Fan, T. G. Myers, B. A. D. Sukra, and G. Gabrielse. Measurement of the electron magnetic moment. *Phys. Rev. Lett.*, 130:071801, Feb 2023.

- [108] Stefano Mancini, Ana M. Martins, and Paolo Tombesi. Quantum logic with a single trapped electron. *Phys. Rev. A*, 61:012303, Dec 1999.
- [109] G. Ciaramicoli, I. Marzoli, and P. Tombesi. Realization of a quantum algorithm using a trapped electron. *Phys. Rev. A*, 63:052307, Apr 2001.
- [110] S. Stahl, F. Galve, J. Alonso, S. Djekic, W. Quint, T. Valenzuela, J. Verdú, M. Vogel, and G. Werth. A planar Penning trap. *The European Physical Journal D - Atomic, Molecular, Optical and Plasma Physics*, 32(1):139–146, January 2005.
- [111] P. Bushev, S. Stahl, R. Natali, G. Marx, E. Stachowska, G. Werth, M. Hellwig, and F. Schmidt-Kaler. Electrons in a cryogenic planar Penning trap and experimental challenges for quantum processing. *The European Physical Journal D*, 50(1):97–102, November 2008.
- [112] J. Goldman and G. Gabrielse. Optimized planar penning traps for quantum-information studies. *Physical Review A*, 81:052335, 2021.
- [113] P. Bushev, D. Bothner, J. Nagel, M. Kemmler, K. B. Konovalenko, A. Lörincz, K. Ilin, M. Siegel, D. Koelle, R. Kleiner, and F. Schmidt-Kaler. Trapped electron coupled to superconducting devices. *The European Physical Journal D*, 63:9–16, 2011.
- [114] P. M. Platzman and M. I. Dykman. Quantum computing with electrons floating on liquid helium. *Science*, 284:1967–1969, 2021.
- [115] S. A. Lyon. Spin-based quantum computing using electrons on liquid helium. *Physical Review A - Atomic, Molecular, and Optical Physics*, 74:052338, 2006.
- [116] Pai Peng, Clemens Matthiesen, and Hartmut Häffner. Spin readout of trapped electron qubits. *Physical Review A*, 95:012312, 2017.
- [117] Gerwin Koolstra, Ge Yang, and David I. Schuster. Coupling a single electron on superfluid helium to a superconducting resonator. *Nature Communications*, 10:1–7, 2021.
- [118] Xianjing Zhou, Gerwin Koolstra, Xufeng Zhang, Ge Yang, Xu Han, Brennan Dizdar, Xinhao Li, Ralu Divan, Wei Guo, Kater W. Murch, David I. Schuster, and Dafei Jin. Single electrons on solid neon as a solid-state qubit platform. *Nature* 2022, 605:46–50, 2022.
- [119] Xianjing Zhou, Xinhao Li, Qianfan Chen, Gerwin Koolstra, Ge Yang, Brennan Dizdar, Yizhong Huang, Christopher S. Wang, Xu Han, Xufeng Zhang, David I. Schuster, and Dafei Jin. Electron charge qubit with 0.1 millisecond coherence time. *Nature Physics*, 20:116–122, 2023.
- [120] Zirui Fang, Benedict A. D. Sukra, and Xing Fan. Single electrons in a dual-plane printed-circuit-board penning trap, 2026.
- [121] K. Taniguchi and A. Noguchi. Image current detection of electrons in a room-temperature paul trap. *Physical Review A*, 112:022420, 2025.

- [122] G.E. Ponchak, Donghoon Chun, Jong-Gwan Yook, and L.P.B. Katehi. The use of metal filled via holes for improving isolation in ltcc rf and wireless multichip packages. *IEEE Transactions on Advanced Packaging*, 23:88–99, 2000.
- [123] Rogers Corporation. RO4350B laminates data sheet, RO4000 series high frequency circuit materials. <https://www.rogerscorp.com/advanced-electronics-solutions/ro4000-series-laminates/ro4350b-laminates>. Accessed: 2026-08-21.
- [124] Häffner Group, UC Berkeley. PaulTrapAnalysis: a toolkit for developing and analyzing RF Paul traps. <https://github.com/HaeffnerLab/PaulTrapAnalysis>. Accessed: 2026-08-21.
- [125] Joseph Ladislav Wiza. Microchannel plate detectors. *Nuclear Instruments and Methods*, 162(1):587–601, 1979.
- [126] C. R. H. McRae, H. Wang, J. Gao, M. R. Vissers, T. Brecht, A. Dunsworth, D. P. Pappas, and J. Mutus. Materials loss measurements using superconducting microwave resonators. *Review of Scientific Instruments*, 91:091101, 2020.
- [127] M. S. Khalil, M. J. A. Stoutimore, F. C. Wellstood, and K. D. Osborn. An analysis method for asymmetric resonator transmission applied to superconducting devices. *Journal of Applied Physics*, 111:054510, 2012.
- [128] Kevin L. Jensen. *Introduction to the Physics of Electron Emission*. John Wiley & Sons, Chichester, 2017.
- [129] Anand Prakash, Akhil Ayyadevara, E. Krishnakumar, and S. A. Rangwala. Low divergence cold-wall oven for loading ion traps. *Review of Scientific Instruments*, 95(3):033202, 2024.
- [130] S. Gulde, D. Rotter, P. Barton, F. Schmidt-Kaler, R. Blatt, and W. Hogervorst. Simple and efficient photo-ionization loading of ions for precision ion-trapping experiments. *Applied Physics B*, 73:861–863, 2001.
- [131] H. Kogelnik and T. Li. Laser beams and resonators. *Applied Optics*, 5(10):1550–1567, 1966.
- [132] Jack Sugar and Charles Corliss. Atomic energy levels of the iron-period elements: Potassium through nickel. *Journal of Physical and Chemical Reference Data*, 14(Suppl. 2):1–664, 1985.
- [133] Sung-June Baek, Aaron Park, Young-Jin Ahn, and Jaebum Choo. Baseline correction using asymmetrically reweighted penalized least squares smoothing. *The Analyst*, 140:250–257, 2015.
- [134] CLIFFORD M. HURVICH and CHIH-LING TSAI. Regression and time series model selection in small samples. *Biometrika*, 76:297–307, 1989.
- [135] P. Stoica and Y. Selen. Model-order selection. *IEEE Signal Processing Magazine*, 21:36–47, 2004.

- [136] D. J. Wineland and H. G. Dehmelt. Principles of the stored ion calorimeter. *Journal of Applied Physics*, 46:919–930, 2021.