Optimization of Trapped Ion Imaging System

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Quantum computing can be demonstrated by trapping ions and observing the changes in state after undergoing linear transformations. These changes in state can be measured using an objective microscope; ions in one state emit light while ions in another state are "dark". The purpose of this REU project was to simulate and implement an objective microscope that will capture a clear image of trapped ions. A clear image improves the accuracy of measuring the ion's state, thus making future quantum computing simulations faster and more precise.

I. INTRODUCTION

Classical computers have allowed us to perform large-scale calculations and simulate increasingly complex systems over the past few decades. Despite the capabilities of classical computers today, physical limitations keep classical computers from solving more intricate problems efficiently, such as how to model quantum systems - a system of atoms and their interactions with the environment for example - and how to factorize large prime numbers. [1] The ability to perform the necessary calculations to solve those problems are of immense value to scientific fields from condensed matter physics to spintronics to data encryption. The potential for innovations in those areas are among the primary motivations for the development of a scalable quantum computer. [2]

Quantum computers exploit principles of quantum mechanics in processing information. This information is stored in quantum bits, or qubits. Unlike classical bits, which can only exist in a 0 or 1 state, qubits can exist in a state of superposition, meaning that they can be in a 0, 1, or both states at the same time. Whereas classical computers use a "brute-force" method of iterating over each data point in an entire set, a quantum computer can perform calculations in parallel, effectively bypassing steps that a classical computer requires. As a result, quantum computers can perform calculations in seconds that classical computers need years to perform. [1] [3]

One of the leading methods of physically realizing quantum computers is trapped-ion quantum computing (TIQC). In this method, the trapped ion simulates a qubit, and is trapped inside a vacuum chamber. This secure isolation is advantageous because it minimizes the ions interaction with its environment, allowing precise manipulation of its state and long coherence times. Another advantage is that the operation times performed on these ions is in the order of microseconds, leading to faster computation times. Lastly, the basic requirements to model quantum computers have already been demonstrated [4] and are already implemented in our laboratory. [5]

This paper explores some of the techniques involved in simulating quantum computation through trapping ions. The next section provides an overview of the ion-trapping apparatus. Further improvements to the experimental apparatus are later discussed, particularly in the objective microscope system used to capture images of the trapped ions. These images indicate the measured state of the ion after it has undergone quantum gate transformations, which in our setup is done through lasers shining on the ion to drive energy transitions. Ions emitting light correspond to being in the 0 state, while ions appearing dark in the image correspond to being in the 1 state. The images of the trapped ions produced by our original setup were blurry, causing a source of ambiguity in the measured states of the ions. Improvements of the images can be measured qualitatively through comparing image qualities and quantitatively by measuring the images point-spread function and ensquared energy.

II. EXPERIMENTAL SETUP

A. Energy Transitions

One of the ions we trap is Ba+ 138. An advantage to using Barium is that its energy transitions are in the visible light spectra, therefore making manipulation of its transitions easier. [4] [6] Barium starts off in the ground state. A 791 nm laser is then shined on it, driving a transition to the ion ground state. A 450 nm laser is also shined, supplying enough energy that causes an electron to fly off, transitioning it to the ion ground state. A 493 nm laser is then shined on the ion, transitioning it to the 6 S to the 6 P state in an effect called Doppler Cooling. This phenomenon occurs when an atom absorbs a blue-shifted photon and is subsequently slowed down. The photon causes the atom to transition to an excited state. The atom re-emits the photon and changes direction in order to conserve momentum. [5]

One issue with Barium is that once its in the 6 P state, it makes an unwanted transition to the 5 D 3/2 state at a probability of one third. To work around this, we use a technique called shelving; 650 nm and 614 nm lasers are shined on the ions to pump it back to the 6 P state.

FIG. 1. The energy transitions of Ba+ 138 starting from its neutral ground state. The atom is driven to the 6P state by the 791 nm laser, then ionized by the 450 nm laser. A 493 nm laser drives the ion to the 6P state. The ion sometimes transitions to the 5D states, so 614 nm and 650 nm are shined to transition the ion back to the 6P state.

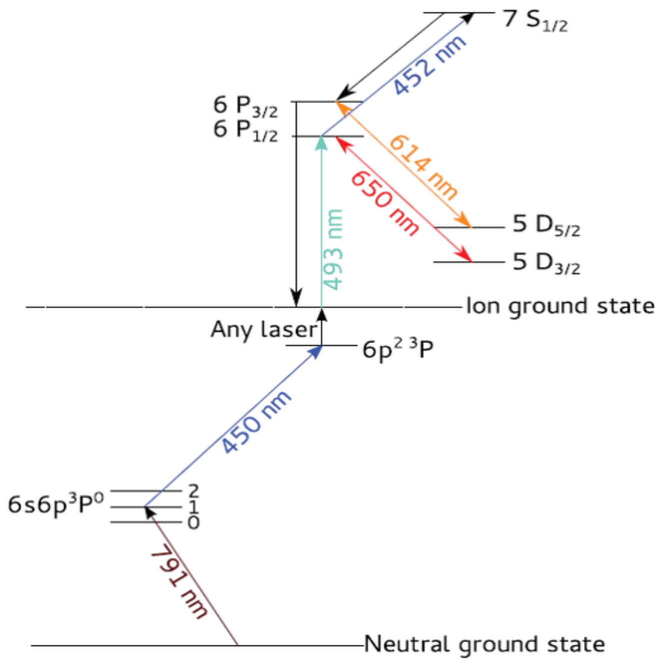
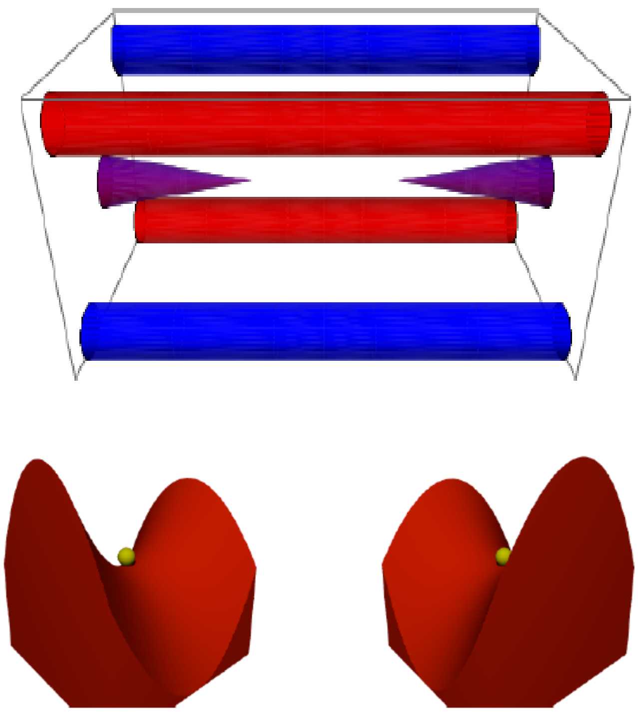


FIG. 2. TOP: A schematic drawing of the Linear Paul RF Trap. The cylinders are the rods where the potentials are applied. BOTTOM: A visualization of how the oscillating potentials trap the ion.



B. Ion Trapping

To visualize how ion-trapping works, imagine a ball resting on a saddle. Eventually, the ball will roll down the saddle and onto the ground. Then, imagine the saddles orientation suddenly change, keeping the ball from rolling to the ground; what was a valley before is now a hill. Ion-trapping works under similar principles. Ions are confined inside a vacuum chamber and are surrounded by four poles which have potentials oscillating at radio frequency, shown in Figure 2. A voltage is applied to two poles diagonal to each other, while the other two are grounded, forming a saddlepoint of potentials. The potentials of these poles are quickly reversed, hence limiting the ions range of movement, trapping it at that point in space. [4] [6]

C. Objective Imaging System

Once trapped, the ion is imaged using our objective microscope. The first stage begins with the trapped ion, which in optical terms is referred to as our object in this stage. Photons that are emitted from the ions energy transitions propagate as light waves and first hit the vacuum viewport, where aberration occurs. The light rays then exit to an air surface and hit the flat surface of the aspherical lens. The aspherical lens collimates the light

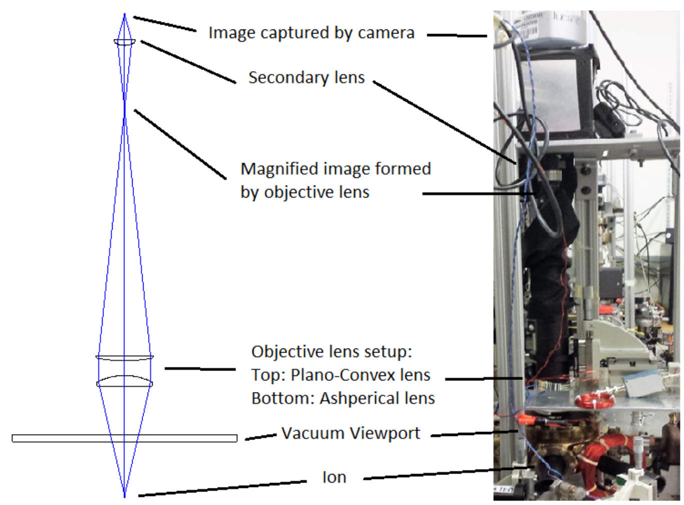
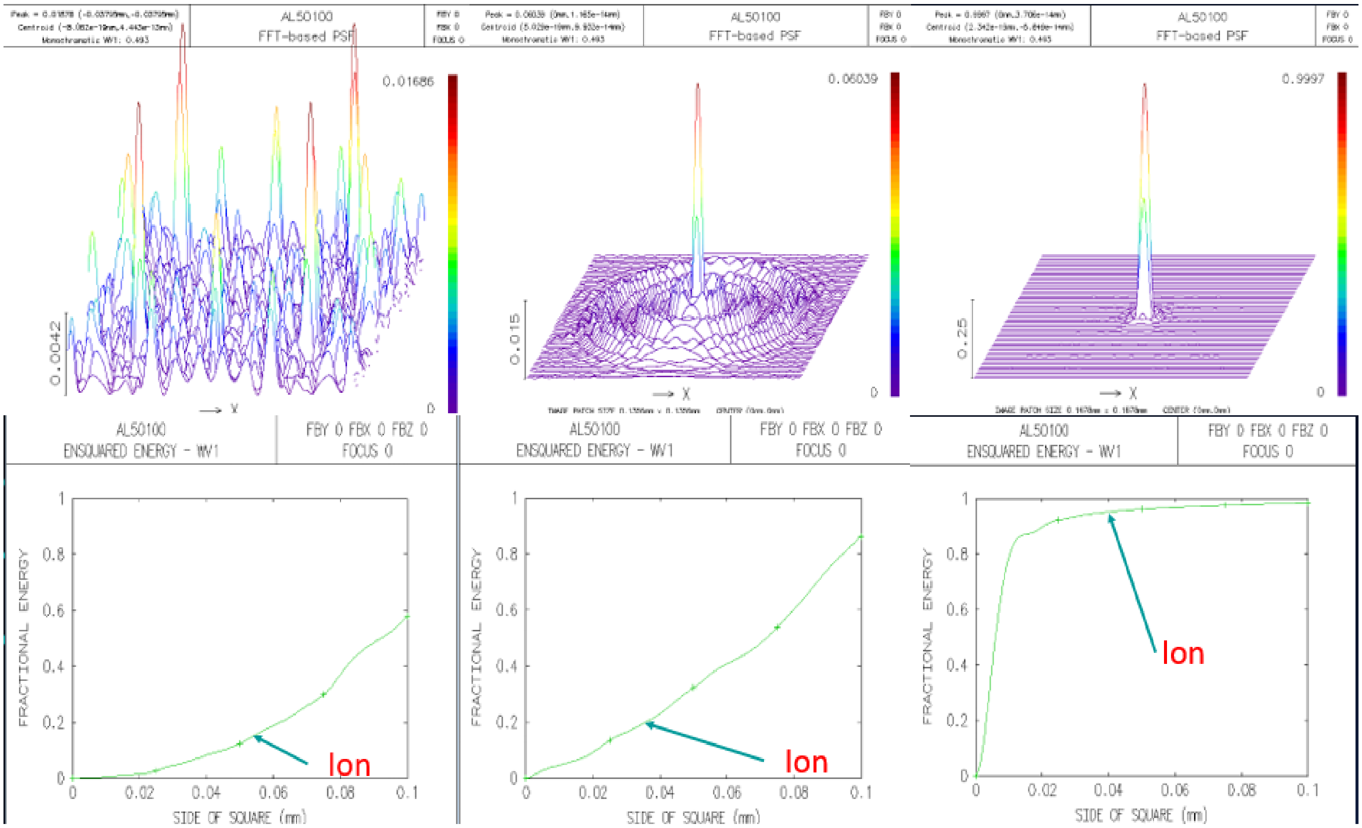


FIG. 3. The objective imaging system

rays and transmits them to a 50 cm focal length plano-convex lens. An image is then formed roughly 48 cm away from the flat surface of the plano-convex lens, acting as the object for the secondary lens. Rays continue to propagate and hit the secondary lens, a 2 cm focal length plano-convex, then forms an image approximately 20 cm away that is captured by a camera.

FIG. 4. TOP: The PSF's of each setup. BOTTOM: The EE of each setup. From left to right: The original setup with a plano-convex lens as the objective lens, the asphere-plano-convex lens as the objective lens before optimizing the viewport-objective distance, and the theoretical PSF of the setup with the asphere-plano-convex lens as the objective lens with the optimal viewport-objective distance.



III. IMAGING SIMULATIONS

A. Point-Spread Function

The point-spread function (PSF) is a diffraction pattern of light as well as a measure for measuring the resolution performance of an imaging system. Light from the object is collected by the objective, then the light waves converge and interfere at the focal point, forming a pattern of concentric rings. The amount of light captured can be measured as an intensity distribution. The ideal PSF would have one sharp central peak with significantly smaller peaks surrounding it, indicating that the image is focused at the center and not blurry [7].

Figure 4 shows the results of the PSF simulations. The original setup performed poorly when simulated. The objective only captured 1.7% of the light and a central peak was not even present. The switch to the aspherical setup improved the amount of light captured to 6% and created a more prominent central peak. By moving the objective lens so that its distance to the ion is much closer to the lens working distance, the point spread function can be dramatically improved; the amount of light captured can theoretically be very close to 100%.

B. Ensquared Energy

Using the point-spread function, the fraction of total energy collected as a function of how big the central spot is can be measured. This is called the ensquared energy. Steep sloped ensquared energy graphs are desired as they imply that most of the energy captured in a small area. A high magnification image system is also desirable as this would form an image with a large area, thus being able to collect a larger fraction of the energy [8].

Figure 4 on the bottom shows the ensquared energies of the different setups. The original setup had a higher magnification and thus a larger area to capture energy. Despite this, it was able to measure less than 20% of light. The aspherical setup pre-optimization does not perform much better on top of suffering from a smaller magnification. At the optimal viewport-objective distance, about 95% of the light was captured. This comes with a smaller first stage magnification at 5x compared to the previous magnification of 6x, but still presents a significant upgrade nonetheless.

C. Experimental Error

The delicacy of the working distance of aspherical lenses lends itself to large swings in error with small changes in distances. As shown in figure 5, there is only a 1 mm range in viewport-objective lens distance in which the PSF is at 90% or higher. Deviating further by another 1 mm in either direction yields a PSF of less than 30%. The ensquared energy is more flexible, maintaining 90% at a 2 mm range, but falls off when the viewport-objective distance deviates by more than 2 mm from the optimal distance.

Another crucial source of error is the tilted angle of the stages of the lens. The preceding simulations assumed that our objective lens and ion are perfectly aligned along the same axis, which is not the case. Even a slight misalignment causes noticeable comatic aberration. According to Figure 6, in order to maintain a PSF of greater than 90%, the angle of the secondary lens with respect to the z-axis of the objective lens must not exceed .06 degrees. This corresponds to less than 0.1 mm deviation between the centers of the objective lens and the secondary lens. The ensquared energy on the other hand does not display significant deviation as a function of field angle.

FIG. 5. Top to bottom: The PSF and Ensquared Energy of the aspherical objective lens setup as a function of the distance between the viewport and the flat surface of the objective lens

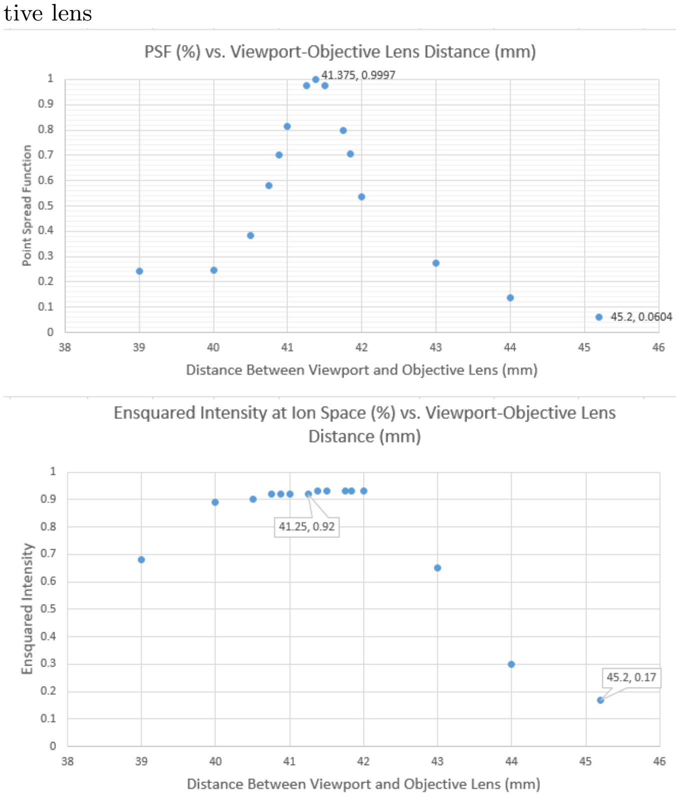
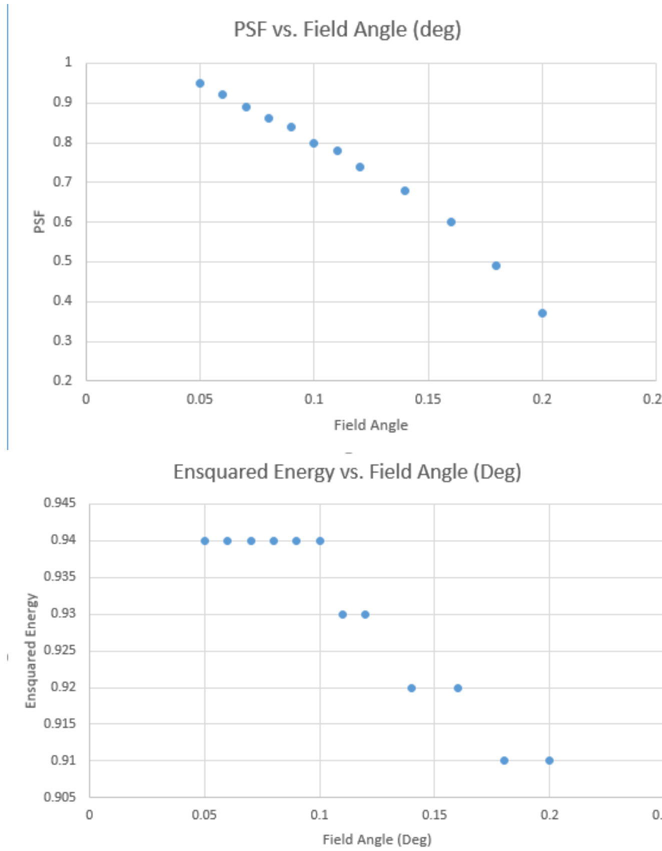


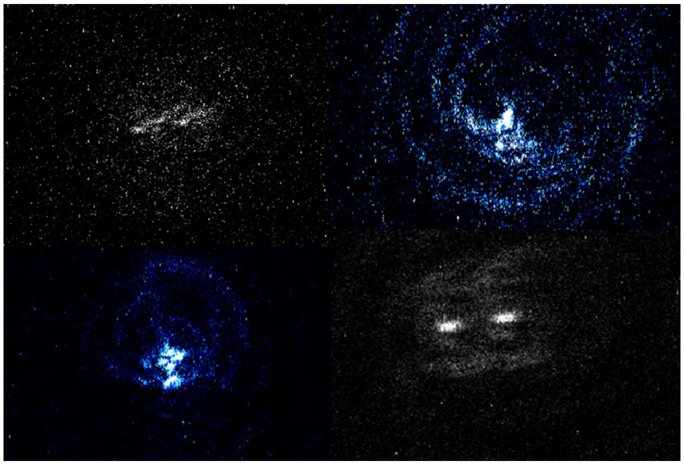
FIG. 6. Top to bottom: The PSF and Ensquared Energy of the aspherical objective lens setup as a function of the field angle



IV. RESULTS

Our initial attempts at imaging ions display mixed results as shown in Figure 7. Due to the delicate nature of the setup, multiple iterations are needed in order to adjust the viewport-ion distance at its optimal distance and capture the sharpest images. The top left is an image of two ions where the objective lens is not at the optimal distance. It is difficult to infer anything from that image, even the number of ions trapped. The top right is an image of two ions captured when the lens is not at the optimal alignment, but close to the optimal distance. The bottom left is an image of a single ion captured at our first attempt at adjusting to the optimal distance, but without adjusting for comatic aberration. The bottom right is an image of two ions at the optimal distance and a partial adjustment for comatic aberration. The image is significantly sharper than the other pictures, giving a clearer readout of the ions state.

FIG. 7. Top left: Objective lens at the wrong working distance Top right: Objective lens near the working distance, before adjusting for comatic aberration Bottom left: 1st adjustment attempt at adjusting to working distance Bottom right: Objective lens at the right working distance, partially adjusting for comatic aberration



V. FUTURE WORK

As demonstrated by the captured images, further optimization can still be done to create sharper images. Having sharper images should give more accurate readouts of the states of our ions. The inherently probabilistic nature of quantum computing requires that simulations be iterated numerous times, thus the readout of the ions states must be as accurate as possible.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

[1] Shor, Peter W. "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer." SIAM Rev. SIAM Review 41.2 (1999): 303-32. Web.

[2] "What Can We Do with a Quantum Computer?" Institute for Advanced Study. N.p., n.d. Web. 15 Aug. 2016

[3] Simon, D.r. "On the Power of Quantum Computation." Proceedings 35th Annual Symposium on Foundations of Computer Science (n.d.): n. pag. Web.

[4] Dietrich, Matthew R. Barium Ions for Quantum Computation. Thesis. University of Washington, 2009. N.p.: n.p., n.d. Arxiv. Web.

[5] Graham, R. D., S.-P. Chen, T. Sakrejda, J. Wright, Z. Zhou, and B. B. Blinov. "A System for Trapping Barium Ions in a Microfabricated Surface Trap."AIP Advances 4.5 (2014): 057124. Web.

[6] Wright, John Albert, Chen-Kuan Chou, and Carolyn Auchter. Mixed Species Ion Chains for Scalable Quantum Computation. Thesis. University of Washington, 2015. N.p.: n.p., n.d. Print.

[7] Rottenfusser, Rudi, Erin E. Wilson, and Michael W. Davidson. "Education in Microscopy and Digital Imaging." ZEISS Microscopy Online Campus. N.p., n.d. Web. 10 Aug. 2016.

[8] OPTICAL TEST EQUIPMENT: Ensquared and encircled energy testing attains 'automated' status. (n.d.). Retrieved August 13, 2016, from http://www.laserfocusworld.com/articles/print/volume-47/issue-9/features/optical-test-equipment-ensquared-and-encircled-energy-testing-attains-automated-status.html