Characterizing a parabolic mirror for experiments with trapped ions

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Trapped ions are being investigated as a potential qubit candidate due to numerous factors that make them more easily prepared and measured. The dynamics of qubits are important to understand in order to take measurements of systems. One phenomenon affecting these dynamics is quantum jumps, which are seemingly random and cause decoherence. We aim to improve measurements of quantum jumps by increasing the collection of photons scattered by a trapped ^{138}Ba ion using a deep parabolic mirror of about 90 percent reflectivity. To have a better idea of how efficient the mirror is, we took measurements of its reflectivity and parabolicity. Understanding the evolution of the quantum state of a qubit is crucial in the development of qubits to be scaled up into quantum computers.

I. INTRODUCTION

Efforts to study viable qubit candidates have been underway since Richard Feynman's 1982 proposal of using quantum systems in simulations, as well as efforts to understand the factors affecting the dynamics of such quantum systems. Quantum jumps are one of these factors. Studies of quantum jumps have been limited by the photon detection efficiency, which affects the time resolution of measurements. To improve photon detection efficiency, we plan an experiment that traps a single ^{138}Ba ion in the focus of a deep, high numerical aperture parabolic mirror to catch a larger percentage of the light scattered by the ion. We conduct tests on both the reflectivity and the parabolicity of the mirror in order to accurately determine how efficiently our experiment will detect light.

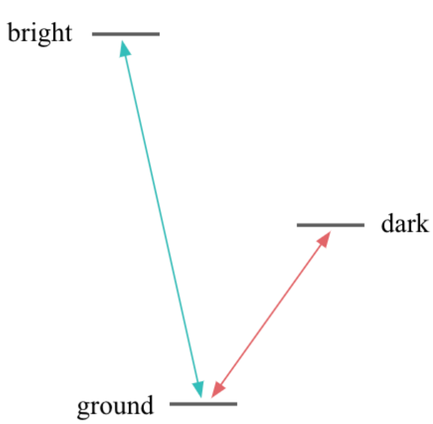

FIG. 1. Simplified energy level diagram for the electron shelving scheme used to observe quantum jumps.

II. BACKGROUND: QUBITS AND QUANTUM COMPUTING

Quantum computing is advantageous as qubits are capable of storing exponentially larger amounts of information than bits used in regular computing, as the information is encoded in a superposition of two states instead of simply $|0\rangle$ and $|1\rangle$, meaning a computer with n qubits can store 2^n units of information. The logistics of creating, studying, and implementing qubits have proven difficult as their fast decoherence times make their behavior unreliable and unpredictable. This impedes the processes of preparing the qubit and obtaining the information encoded in it. Trapped ions, and Ba-138 ions in particular, are viable qubit candidates due to their long coherence times and high fidelity qubit state initialization, manipulation, and detection, which makes them easier to prepare and observe in the desired state and behave more reliably. These factors also improve prospects for scaling up from a qubit to a computer. We use ^{138}Ba ions due to the slow decoherence time of the $5d_{5/2}$ dark state (32 seconds). Barium is also more feasible to use in experiments as the relevant transition frequencies are in the visible light spectrum, making the laser alignment easier.

Quantum jumps affect the dynamics of the quantum system, providing an incentive to study them and the process by which they occur. First theorized in 1913 by Niels Bohr as a spontaneous absorption or emission of light, quantum jumps were not experimentally observed until 1986 by the Dehmelt group, whose observations seemed to confirm Bohr's characterization of their evolution as stochastic and discontinuous. Quantum jumps occur between "bright" and "dark" states; the system is strongly coupled to the transition between the ground and bright state and oscillates between the two states, causing fluorescence. It is also very weakly coupled to a third dark state, which it can transition to in a quantum jump (Figure 1). An atom in a dark state does not scatter any photons; therefore, in order to detect a jump to a dark state, the transition from the ground state to the bright state is used in what is called an electron shelving scheme. When in the bright state, a ^{138}Ba ion scatters photons to the order of 10^7, so a jump can be detected when there are no photons scattered. This measurement technique addresses the issue of observations of quantum states inherently changing their properties.

However, a recent experiment using an artificial superconducting three-level atom showed that quantum jumps are continuous, as predicted in quantum trajectory theory. Their results also showed a latency period preceding quantum jumps, showing that a jump is about to occur and making quantum jumps predictable; this latency period consists of a decrease in the excitation of the bright state. It is therefore possible to anticipate a quantum jump and reverse it mid-flight by applying a control field. They conclude that their results can be reconciled with the Dehmelt experiment on the basis that their more advanced experimental setup was able to detect more photons, resulting in better time resolution with which to observe the dynamics of the system.

Using a trap in a parabolic mirror, we aim to obtain results with better time resolution by detecting more photons. Photon detection efficiency above 80% is necessary to anticipate and reverse the quantum jump as Minev describes. Understanding the time dynamics of quantum jumps is recognized as an important aspect of quantum feedback control as it allows for the detection and correction of errors caused by decoherence, as proven by the Minev group, and a better time resolution will provide a more complete view of these time dynamics.

III. PARABOLIC MIRROR DESIGN AND TRAP SETUP

The mirror has a numerical aperture covering 95% of the solid angle, with expected reflectivity of at or above 90%. Total photon detection efficiency using a high quantum efficiency photon detector is expected to be around 70%. The mirror is made of aluminum diamond turned, with a focal length of 2.7 mm, a height of 10 cm, and an aperture diameter of 6.5 cm. Expected photon detection efficiency is much higher than the mirror previously used, which had a solid angle coverage of 40% and photon detection efficiency of around 10%.

The ion will be trapped at the focus of the mirror using a stylus trap based on a design developed by NIST; the mirror has a 1 mm hole in the back behind its focal point to provide access to the stylus trap and apertures in the sides for electrode and laser access, which causes about a 1% loss of solid angle coverage. The laser paths are angled to minimize aperture size.

The stylus trap consists of a central ground electrode and concentric RF electrode, separated by an alumina insulator. This creates an RF pseudopotential null that traps the ion at a certain location. The stylus trap will be mounted on a micrometer so that its axial position can be directly controlled and moved so that the trapped ion is at the mirror's focus.

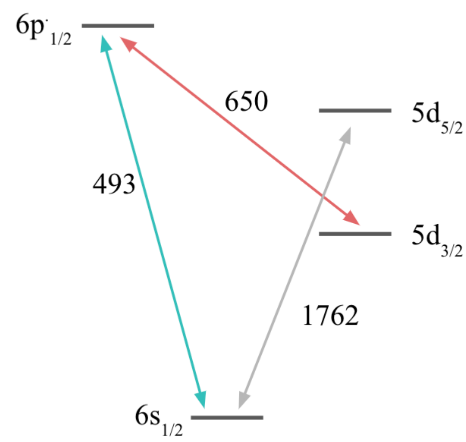

FIG. 2. Energy level diagram for electron shelving scheme using ^{138}Ba. The 493 nm laser strongly couples the ground and $6p_{1/2}$ bright state, while the 1762 nm laser drives the weak transition from the ground state to the metastable $5d_{5/2}$ dark state. The 650 nm laser drives the repump transition.

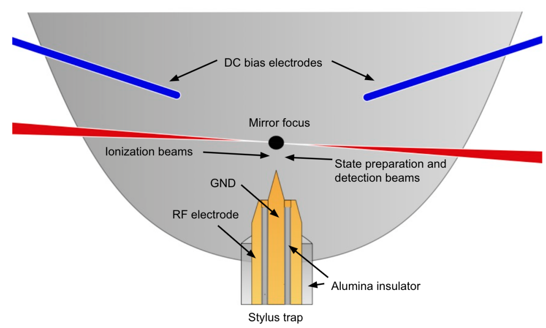

FIG. 3. The overall trap setup consists of a stylus trap that will position the trapped ^{138}Ba ion at the focus of the mirror. The mirror has a hole in the back for the stylus trap and holes in the sides for the electrodes and beams necessary to prepare, trap, and observe the ion.

The trap will be placed in a vacuum chamber. Neutral atoms will be sent into the aperture at the top of the mirror, and a single atom will be ionized and cooled by counterpropagating beams and trapped by the stylus. The ion's radial position will be controlled by two orthogonal DC electrodes on the same plane as the focus.

The relevant transitions in our experimental setup are shown in (Figure 2.). A 493 nm laser drives the cooling transition between the $6s_{1/2}$ ground state and the $6p_{1/2}$ bright state, and a 1762 nm laser drives the weakly coupled transition to the $5d_{5/2}$ dark state. Fluorescence from the $6p_{1/2}$ to $5d_{3/2}$ state is common, so we use a 650 nm laser for the repump transition.

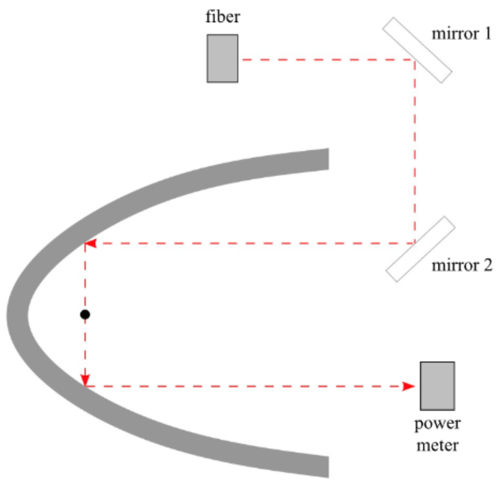

FIG. 4. Reflectivity test setup. The light from a fiber optic cable reflects off two flat mirrors into the parabolic mirror, then out into the power meter.

IV. TESTING REFLECTIVITY

The test for reflectivity was fairly straightforward, as we simply measured the power of the incident and reflected beams and found the ratio between reflected and incident light. We used 369 nm, 493 nm, and 650 nm light for these measurements, as these are the wavelengths that will be used in our experiments. Our setup is shown in Figure 4: the beam goes from a fiber optic cable and reflects off two mirrors into the parabolic mirror, where it reflects twice and enters the power meter. The fiber optic cable focuses and collimates the beam so that the light going into the power meter covers a smaller area for more precise measurements, and the two flat mirrors allow for easier adjustment of the position and angle at which the beam hits the parabolic mirror.

To account for possible aberrations in the surface, the mirror was mounted on a rotational apparatus and rotated 10 degrees between measurements. The measured values were then averaged. When calculating the overall reflectivity for each wavelength, we took into account the fact that the beam is twice reflected by the mirror using the equation $1 - 0.5 * (1 - r)$, with r being the averaged value of the ratio between reflected and incident light.

We first tested the reflectivity of a mirror that had been manufactured with a coating, which caused it to reflect more red light. We then tested an uncoated mirror, which gave more consistent reflectivities for the three wavelengths used and which will be used in the experiment instead of the coated mirror. The results are shown in I and II.

TABLE I. Reflectivity measurement results for uncoated mirror.

Wavelength (nm)	Average Percent Reflectivity	Standard Deviation
650	89.79	1.208
493	90.11	0.802
369	93.10	4.301

TABLE II. Reflectivity measurement results for coated mirror.

Wavelength (nm)	Average Percent Reflectivity	Standard Deviation
650	89.06	0.545
493	79.30	1.483
369	67.35	0.928

V. TESTING PARABOLICITY

Coming up with a test for parabolicity was complicated by the depth of our mirror, as most parabolicity tests are for testing mirrors used in telescopes, which are not deep. We considered interferometric tests using an optical wedge and a spherical null element (source), which would use interferometry to create an image of the parabolicity. In the case of the spherical null test, the image would be a contour map showing the aberration of the reflected light from a perfect sphere, as there would be no image if the mirror were perfectly parabolic. However, it was not feasible to obtain the materials needed for these tests given that we did not require a large amount of precision, so we decided to test parabolicity using a needle.

The needle test simulates a point source of light by positioning the tip of the needle at the focus of the mirror (Figure 5). The light then reflects off the mirror, and a 3 cm focal length spherical lens focuses the light into a CCD camera to create an image of the mirror's surface. Resulting images are showin in Figures 6,7,8,9, and 10, with the numbered axes showing pixel numbers.

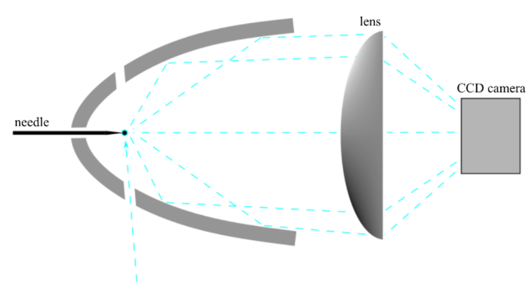

FIG. 5. Parabolicity test setup. The light enters through a hole in the side of the mirror, reflects off the tip of the needle, reflects off the mirror, and is focused through a lens into a CCD camera.

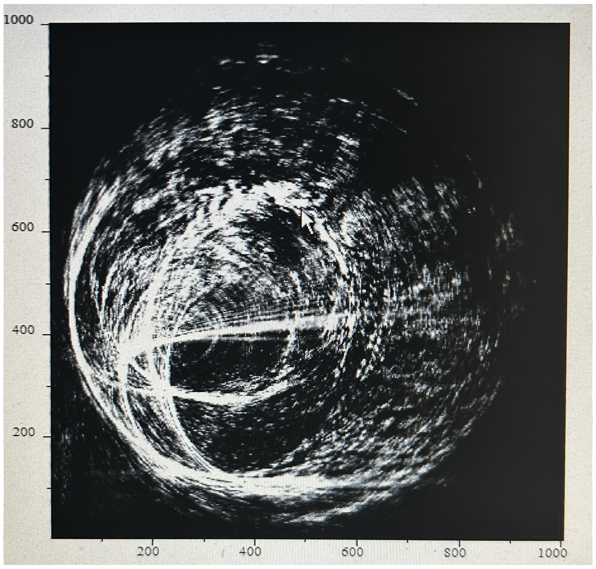

FIG. 6. Image of mirror's surface; the needle is off axis and positioned too far into the mirror so that the light reflects off of more of the needle than just the tip. (Note that the x- and y- axes correlate to pixel numbers.)

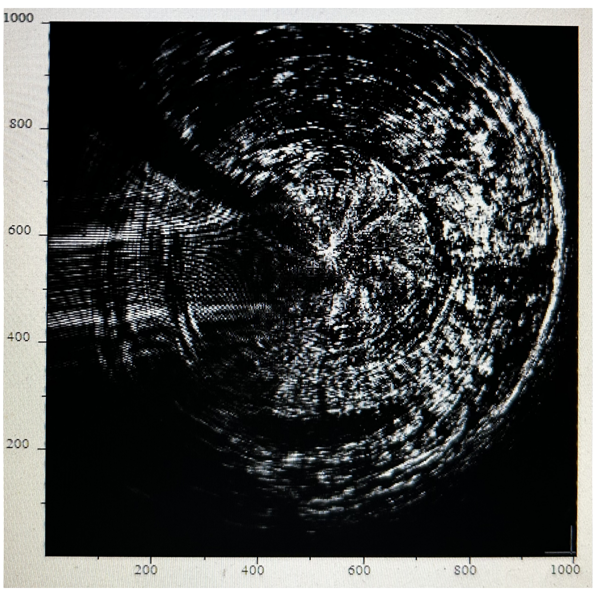

FIG. 7. For this image, the needle is better aligned, but it is still positioned too far into the mirror.

Because the needle tip is so small - on the order of 10 microns - the positioning of the needle requires a considerable amount of precision, which is what presents the most difficulty in this test. Initially, the needle was too far into the beam of light entering the mirror through the side, meaning the beam was reflecting off more of the needle than just the tip (Figures 6 and 7). The needle also has to be perfectly on-axis; an off-axis alignment results in a limaçon-shaped image, as in Figure 6.

To obtain the most accurate image (Figure 8), we first

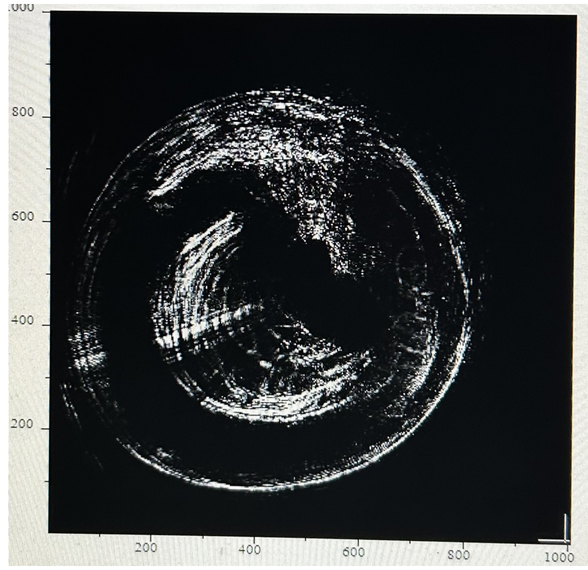

FIG. 8. The most accurate image obtained of the mirror's surface, which is not ideal.

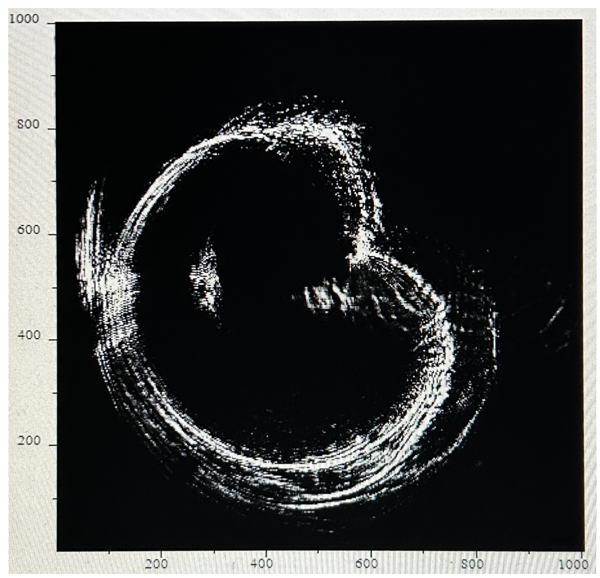

FIG. 9. Image obtained with the needle's tip at the focus of the mirror, as required, before further adjustments. The needle's tip can be seen to the right of the image.

positioned the needle so that the tip was at its focus, as the outline of the needle is visible in the image (Figure 9). We then made slight adjustments while observing the resulting image to have the needle positioned in such a way that it was both on axis and centered. However, the images obtained using this technique are still not ideal (Figures 8 and 10), so further testing is needed.

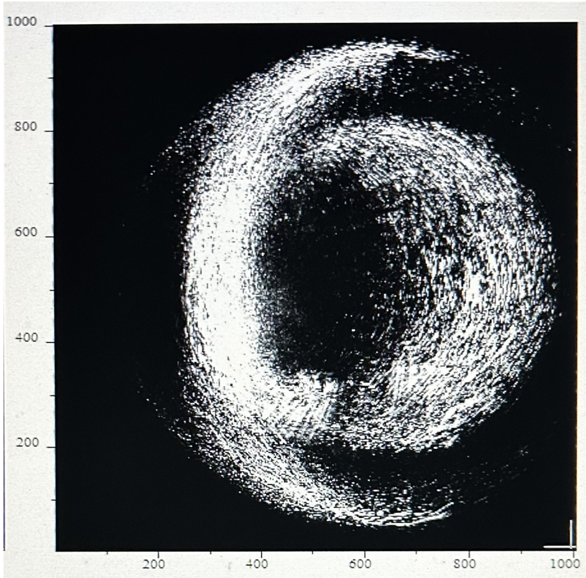

FIG. 10. Image obtained with the needle's tip at the focus of the mirror; the needle is off axis.

VI. CONCLUSION

Although further testing is needed to accurately determine the parabolicity of the mirror, we confirmed that the reflectivity is at 90%, which is required for the desired photon detection efficiency. We are therefore able to use this mirror in experiments related to quantum jumps. With the increased time resolution from the necessary photon detection efficiency, we will be able to better examine the dynamics of a quantum information system using a trapped ^{138}Ba ion.

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