ENHANCING ION-LOADING EFFICIENCY THROUGH ABLATION-BASED METHODS AND BARIUM COMPOUND ANALYSIS

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Ion traps are crucial tools in physics and chemistry that use electric fields to confine charged particles. Trapping ions makes possible long measurement times and exquisite levels of single particle control, which have applications in quantum computing, high-precision spectroscopy, and fundamental physics research. However, a key step in the operation of an ion trap is creating the charged particle and then loading it into the trap. The goal of this research project is to develop a new ablation-based ion-loading source for our lab's ion trap. Ablation is the process of removing a minuscule amount of material from a target using a high-energy laser pulse. This laser focuses a large amount of energy onto a tiny point on the target, creating a microscopic explosion and vaporizing a small amount of the material into a cloud of neutral and ionized atoms. We will present our designs for a target holder as well as plans to bring the pulse laser beam into the experiment vacuum chamber.

ACKNOWLEDGMENTS

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I. INTRODUCTION

The technological capability to experimentally study, truly individual particles did not arise until the 1950's when Wolfgang Paul designed and demonstrated his invention of the quadrupole mass filter. The quadrupole mass filter was able to effectively use electric fields to confine a charged particle while getting around Earnshaw's Theorem, which states that electrostatic forces alone are insufficient to maintain charged particles in a stable and stationary equilibrium configuration, via oscillating the electric fields. In the quadrupole configuration, if two opposite poles starts with a positive voltage and then oscillate to a negative voltage, while the opposite pair simultaneously oscillates in the opposite direction, individual charged particles can be confined. By then adjusting the parameters of the device such as the quadrupole dimensions, voltage peaks, and the frequency of oscillation, an ion of a specific mass can be trapped. [1] The quadrupole mass filter design later became known as the Paul trap.

Once a particle is trapped, ion traps not only confine the particle but also allow for precise control and manipulation of the particle, while effectively isolate it from any outside environmental noise. This level of precision and stability makes ion traps a crucial tool in a variety of applications, including high-precision spectroscopy, the development of optical atomic clocks, and quantum computing.

In our case, we will be using a slightly modified version of the traditional Paul trap, known as a linear Paul trap, as illustrated in Figure 1. Unlike the original version, the linear Paul trap consists of six electrodes: four long rods arranged in a quadrupole configuration and two shorter electrodes at the ends, known as end-caps. The four long electrodes generate the oscillating electric field that confines charged particles in the radial x–y plane while the two end-cap electrodes produce a static electric field that provides confinement along the z axis direction.

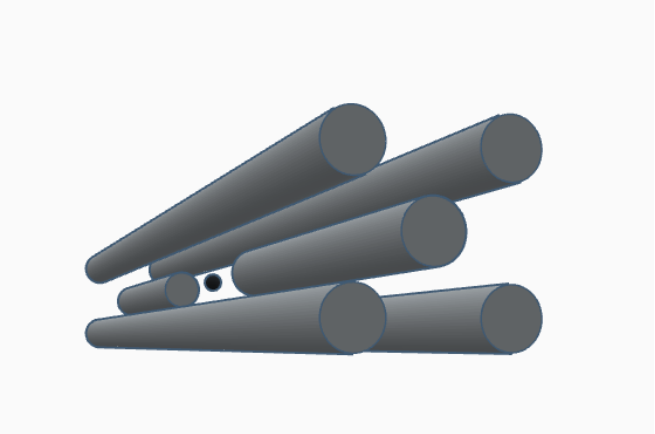


FIG. 1: 3D model of a linear Paul trap

Another key difference between the two trap designs is that while the original Paul trap is better suited for trapping individual particles, the linear Paul trap is capable of trapping long chains of ions, making it much more favorable for applications in quantum computing. On top of the standard high level of isolation and control of ions in a Paul trap, the linear Paul traps ability to trap chains of ions enables the ability to have each ion function as an individual qubit. We plan to continue development of our current ion trapping system with the goal of not just being able to study trapped particles for new physics, but also eventually develop our own quantum computing platform.

Currently, we intend to use barium ions as our qubit of choice, as they exhibit properties that make them a highly promising candidate for serving as a high-fidelity qubit. [2] However, regardless of the application, we will

first need to be able to effectively and reliably load the ion trap with charged particles.

II. BACKGROUND AND MOTIVATION

When loading an ion trap with charged particles, there are a number of tried and tested methods that have been proven effective solutions. However, our interest in trapping barium presents a unique set of challenges due to its chemical properties. As an alkaline earth metal, barium is highly reactive and readily oxidizes upon contact with the atmosphere, forming a shell of barium oxide that renders the remaining metallic sample ineffective for most ion-loading techniques. [1–3] Due to this reactivity pure metallic barium is not a naturally forming mineral and will have to be carefully synthesized, refined, and either stored in vacuum or suspended in a non-reactive substance such as oil. Because of this, developing an ion loading system for barium can be extremely difficult and expensive. Furthermore, working with this material even has some safety concerns as powdered barium will react violently with the air.

The two most common methods used to load barium ions into a trap are atomic beam ovens and laser ablation, the latter being the focus of this paper. Currently, our lab utilizes an atomic oven as our primary loading system. This device is capable of producing a stream of neutral atoms directed towards the trap by taking advantage of the property of thermal evaporation. The oven consists of a small metal cell containing a coil or sample of Barium that is kept in vacuum. By running an electric current through the metal cell, we are able to resistively heat the barium to nearly $600K$, initiating thermal evaporation and evaporating the surface layers of barium. The resulting vapor then exits the cell and travels towards the trap, where the neutral atoms that intersect with the center of the trap are then photoionized and subsequently trapped. Figure 2 shows a photo we captured of fluorescing barium ions produced via this method.

While the atomic oven is an effective and reliable source of neutral atoms, it does present several drawbacks. Firstly, the oven introduces a significant thermal load to the system. Because the oven is directly connected to our temperature controlled vacuum chamber, there is a great deal of heat constantly being added to the system that our cryogenic system will have to work to remove. [3] This issue can be especially an issue with miniaturized or portable trap designs, such as those intended for space based applications. Additionally, the excess heat can limit the performance of any trap designed to operate in a cryogenic vacuum chamber, as is the case for main state of the art traps used in quantum computing experiments.

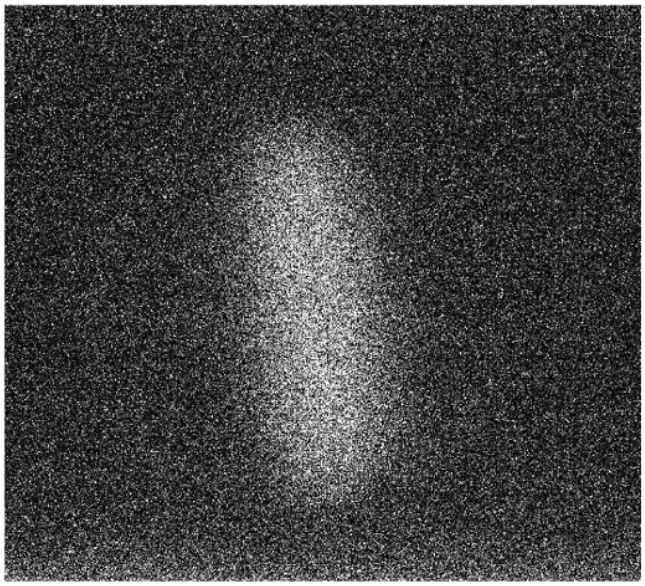


FIG. 2: This is an image we took of fluorescing barium atoms that have been emitted from our atomic oven. The barium atoms emit fluorescence photons after passing through a 413nm laser beam which brings it to an excited state. They then decay, emitting the fluorescent photon that we observe here.

Secondly, although the large flux of barium atoms generated by the oven is generally ideal for loading an ion trap, a majority of the emitted atoms are never ionized and instead end up coating the equipment and walls of the vacuum chamber. Compounded with the oven's generally long warm up and cool down times, which further lead to more unwanted material deposition, the excess material coating can lead to surface charging effects which negatively impact trap performance and capabilities. [3]

Finally, while the atomic oven is capable of reaching temperatures to induce thermal evaporation in a large number of materials such as Barium, other materials of interest, such as Lutetium (which we plan to investigate in future experiments) require much higher temperatures to induce thermal evaporation and are far beyond the capabilities of conventional atomic ovens. For materials such as these, alternative loading methods such as laser ablation become necessary.

Laser ablation is the process of using a high-energy, pulsed laser to blast away a minuscule amount of matter from a target. The laser focuses its energy onto a tiny point on the target creating a microscopic explosion that vaporizes a small amount of the material into a plume of neutral and ionized atoms, as illustrated in Figure 3. [4]

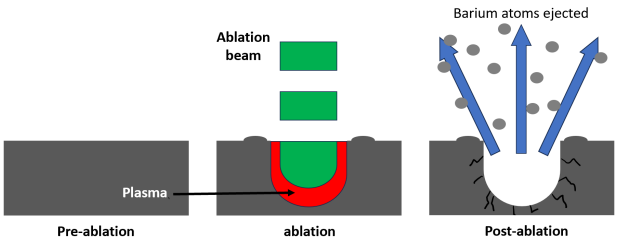


FIG. 3: Graphical illustration of laser ablation

There are several reasons why switching from the atomic beam oven to an ablation-based based loading source would be beneficial. First, ablation introduces significantly less thermal load and contaminant buildup to the system when compared to the oven.[3] Although the point of ablation on the target can reach temperatures several magnitudes higher than the oven, the heating is localized to a small point and occurs over a very short timescale. The laser we will be using is a nanosecond-pulse laser, meaning it will emit its high-intensity pulse and vaporize a small portion of the target material all within the span of nanoseconds. This results in a negligible thermal load on the system, especially in comparison to the atomic oven which must maintain its elevated temperatures continuously during operation as well as when cooling down, producing sustained thermal stress. Additionally, the plum of debris created from the ablation only lasts for tens of nanoseconds, resulting in a much smaller quantity of emitted particles compared to the constant atomic beam created by the oven.

Another advantage of ablation is the flexibility it offers in terms of usable target materials. Barium, as we discussed earlier, is highly reactive and readily oxidized upon contact with the atmosphere making it challenging to work with. However, the high energy of the ablation pulse allows us to ablate through the oxidized layer that would normally render the sample useless as a loading material and access the pure metallic barium beneath. Furthermore, the ablation beam is even capable of breaking apart many chemical compounds, enabling the use of more stable barium-containing materials such as $BaCl_2$, BaO, and $BaTiO_3$. [2–4]

III. METHODOLOGY

For this project, several important factors must be considered during the planning and design process. First, we will be designing a mount that fits within a small, hard to access space located inside a cryogenically cooled vacuum chamber. This factor alone is heavily restricting as everything introduced into the vacuum system must be thoroughly cleaned and vacuum compatible, which significantly narrows our choice of materials and designs. In addition, some of the existing equipment will need to be modified to ensure compatibility with our setup. Outside of the vacuum chamber, we must also configure and precisely align the ablation laser to strike the target through a view port on the vacuum chamber.

A. Ablation Laser

For our ablation laser, we will be using an Amplitude Minilite II 532nm Q-switched Nd:YAG nanosecond pulse laser, as seen in Figure 4. This laser emits a beam with a 3mm diameter with an energy of 25 mJ per pulse. Because of the high intensity of this laser, we will need to use specialized 532 nm coated mirrors optimized for maximum reflectivity at this wavelength, along with anti-reflection (AR) coated lenses to minimize energy loss and prevent damage to the optics. These optical coatings are critical for high energy beams such as our ablation laser as without them, the laser can degrade and even burn components leaving them unusable. Extra caution is needed when working with our vacuum chamber, as some of the side facing view ports are not AR coated, and replacing these lenses is both expensive and a multi-day project.

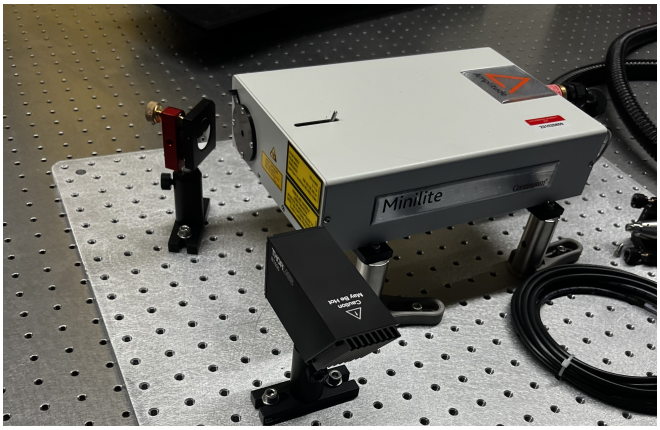


FIG. 4: Amplitude Minilite II 532nm Q-switched Nd:YAG nanosecond pulse laser

B. Ion Shield

The ejected debris from ablation consists of both a cloud of ionized and neutral atoms. Our goal for this section is to create an 'ion shield' to stop any of the ions produced from the ablation plume from reaching the trap. This may sound a bit counterintuitive as our goal is to catch ions in our trap, not block them. If our goal was to simply capture any particular ion, this shield would not be necessary. However, by implementing it, we can selectively determine which type of particle gets ionized and confined to the trap.

To build this ion shield, we will need to create a physical metal barrier that will capture the majority of the excess material from the ablation plume, as shown in

Figure 5. This metal shield will have a small hole in the center of it to allow any neutral atom with the correct trajectory to pass through and enter the center of the trap. To ensure that only neutral atoms are able to make it through this opening, we will place an electric charge on the shield to either attract or repel the ions created in the blast while leaving the neutral atoms that we want unaffected.

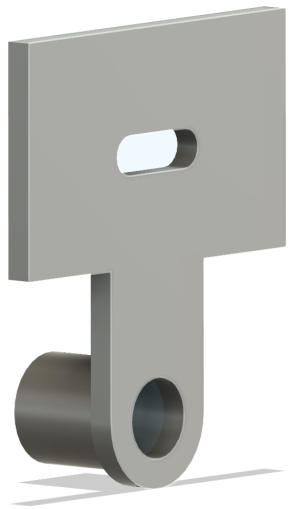


FIG. 5: 3D model of base ion-shield design.

One necessary step required with creating this shield is to ensure that it is electrically isolated from the rest of the vacuum chamber. If the ion shield's charge were to spread to the rest of the system, it would compromise the traps ability to trap ions effectively and potentially even damage other equipment. Because of this we will have to use a vacuum rated insulator such as ceramic washers.

C. Photoionization

The next step of our loading process is the photoionization of the neutral barium atoms that pass directly though the center of the trap. We can accomplish this goal with the use of a 413nm laser, which will travel directly through the center of the trap and perpendicular to the inflow of barium. To ionize neutral barium, an atom has to absorb two 413nm photons. The first photon will excite an outer electron from the 6s2 $1S_0$ ground state to the excited 5d6p $3D_1$ 5d6p 3D1 state. Directly after, the second photon will provide the same electron with additional energy, enabling it to be ejected from the atom, thereby ionizing the atom. In the case of selecting a specific isotope to ionize, we can minutely adjust our lasers frequency to a specific isotope. As represented in Figure 6, each of the barium isotope's absorptions lines are approximately 100Mhz apart, allowing us to chose a specific isotope to photoionize. However, if an atom does not receive the second 413nm photon, the excited electron will revert to its original ground state and fluoresce, releasing a photon, as seen in back in Figure 2. These two properties are extremely useful; the first ionizes the neutral atom, allowing it to be captured by the trap, while the second results in the barium atoms releasing their own photons, which we can use to visually detect and confirm the presence of a flux of neutral barium ions traveling through the trap. Therefore, as the neutral barium atoms begin their journey through the center of the trap, we can visually observe and record them with a specialized camera, as they interact with the 413nm laser and therefore ionize the atoms while inside the trap.

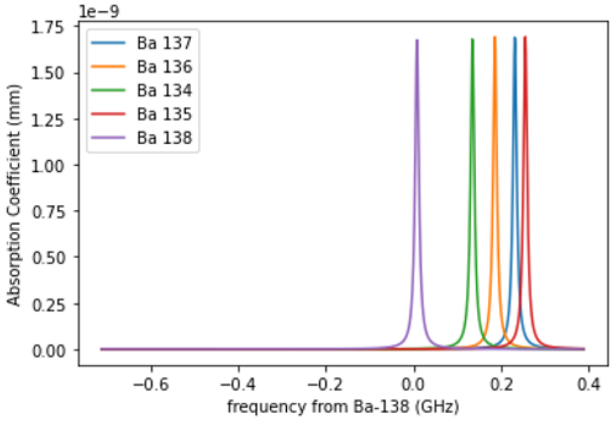


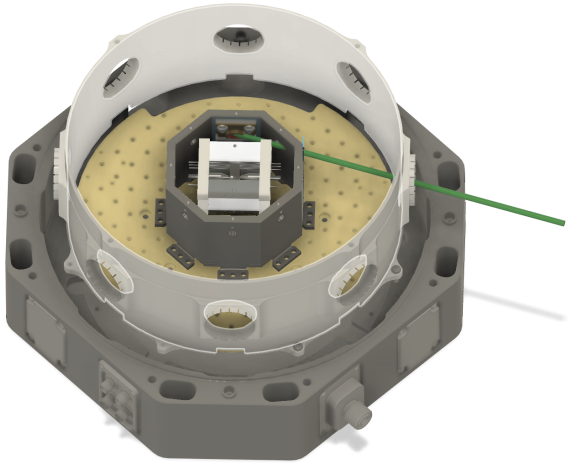
FIG. 6: Graphical illustration of the absorption coefficients plotted against frequency for various isotopes of barium. Each peak represents the different absorption line of the barium isotopes and how each isotope is slightly shifted apart from one another.

D. Vacuum Chamber

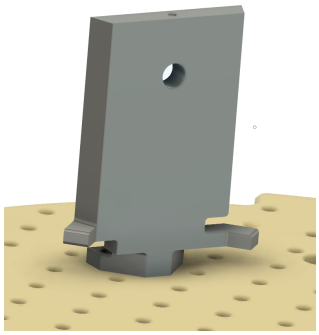
One of the most challenging aspects of this project was designing a suitable holder for our ablation target material that could function effectively within the cryogenic vacuum environment that our linear Paul trap resides in. When designing components for use in vacuum systems, a wide range of constraints must be addressed in each iteration of the design. One of the most significant challenges is avoiding potential causes of outgassing, or the steady leak of trapped gases and other substances from materials within a vacuum system. Materials such as Al_2O_3, the oxidized outer layer of Aluminum, are very porous and can act like a sponge for gases. Upon going under vacuum, this trapped gas will steadily begin to leak from the material, causing outgassing, which makes it difficult to maintain the desired vacuum levels.Threaded holes in vacuum systems require venting channels to prevent gases from becoming trapped, which can further also

contribute to outgassing.

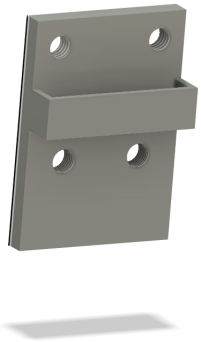
Standard hardware components, such as bolts and nuts often come coated in zinc, which evaporate in high vacuum conditions, contaminating the chamber. Polymers can freeze and become brittle, undergoing a glass transition at low temperatures. Ceramics, which are frequently used in vacuum systems, can sometimes be vulnerable to thermal shock during the vacuuming process, which weakens them. These factors have made the design of the ablation target holder particularly challenging, necessitating multiple complete redesigns. However, we now have a finalized design currently in development, as shown in Figure 7.



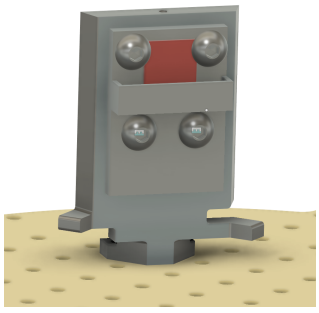
(a) 3 dimensions representation of the ion trap with its internal thermal shielding walls and path of ablation laser



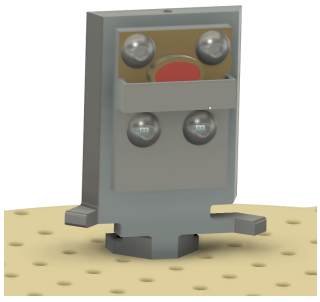
(b) Standard internal thermal shielding wall



(c) Base ablation target holder



(d) Ablation target for solid target material



(e) Ablation target for soluble target material

FIG. 7: This represents the current designs behind the future ablation target.

In this figure we can see five different sub figures. Figure 7.a provides a bird's-eye view of the vacuum chamber, the two thermal walls, the linear Paul ion trap, and the ablation beam path. To build our ablation target holder, we will begin with one of the innermost thermal walls (shown in Figure 7.b) and drill two holes to connect it to our base ablation target holder (Figure 7.c). Given our intention to test multiple target materials, such as solid metallic barium or $BaCl_2$, a soluble crystalline substance, we can utilize a modular design that allows us to swap between different materials. For solid targets such as metallic barium, we will use the design seen in Figure 7.d. This design features a shelf-like protrusion with railings on either side, raised 2.5 mm to support the solid material and capture any fragments that may break off. The red cube at the center is used to represent the placement of the target material. However, because of the difficulties of barium's reactivity, getting precisely shaped and machined pieces of pure barium is exceptionally expensive and is much more practical to utilize unshaped shards or chunks. To secure a shard of unknown dimensions in place, we will anchor a wire to the surrounding screws seen in the figure, allowing us to accommodate future target materials that will vary in size and shape.

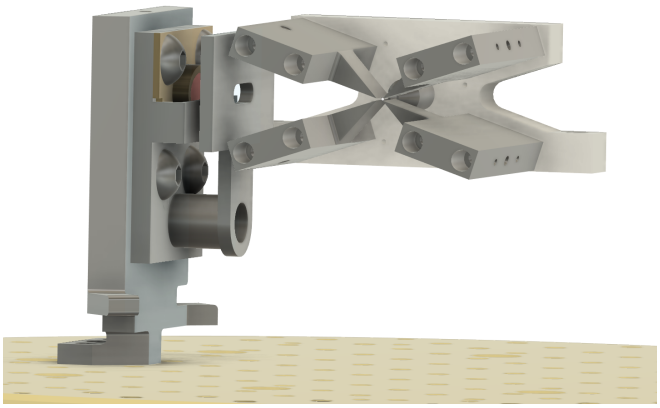


FIG. 8: Side view of the ablation target holder and linear Paul trap. For better imagery, the closest end-cap was removed to be able to see the center of the trap

For when our intended target is a soluble material such as $BaCl_2$, we designed a removable housing that can be

fastened to the base target holder. To load the system, we can dissolve the material in water to create a paste-like substance, which can then be applied to the interior surface of the cylindrical housing. Once vacuum is pulled in the system, the $BaCl_2$ paste will bake out the remaining water, leaving behind pure $BaCl_2$ crystals which will serve as our ablation target.

Finally, Figure 8 shows what the complete assembly of all ablation target holder components alongside our linear Paul trap looks like. This visualization highlights how each component fulfills its role in the project and emphasizes the necessity of seamless integration into the vacuum system to avoid potential interference or damage to the overall setup.

IV. NEXT STEPS

This project will continue into the Summer 2025 semester where we intend to have our ablation target holders will be finalized and machined. Once these parts are completed and in hand, we can begin work to integrate them into the vacuum system and test its effectiveness. To evaluate the efficiency of the various barium targets chosen, we will use two methods. The first method involves measuring the fluorescence of the neutral barium atoms, which occurs when the atom absorbs a single 413nm photon. This method will measure only the flux of barium as the 413nm absorption line is unique to barium. The second method consists of measuring the speed of the ion-loading rates entering the trap. While this method does not directly gauge the rate of photoionization, it provides one of the most direct measurements to calculate the efficiency of each ablation target. By utilizing these two methods, we can thoroughly evaluate various barium compounds and determine which one yields the highest quantity of barium atoms for the trap and achieves the fastest loading time

[1] N. Greenberg, *Trapping of Ba+ using an Autoionizing Resonance and Construction of an Academic Ba+ Testbed*, Ph.D. thesis, University of Waterloo (2024).

[2] B. M. White, P. J. Low, Y. de Sereville, M. L. Day, N. Greenberg, R. Rademacher, and C. Senko, Isotope-selective laser ablation ion-trap loading of $^{137}Ba^{+}$ using a $BaCl_2$ target, arXiv (2021), arXiv:2110.08456 [physics.atom-ph].

[3] B. Bramman, *Ablation loading and qudit measurements with barium ions*, Ph.D. thesis, University of Waterloo (2023).

[4] J. C. Miller and R. F. Haglund, Laser ablation and desorption (1998).