Assembling and Characterizing a 493*nm* Diode Laser

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Abstract

The objective of this project was to assemble a 493nm diode laser for use in trapped ion experiments. These include characterizing quantum jumps in Barium ions and quantum computing experiments. This 493nm laser is used in the Doppler cooling cycle for Barium ions, to stimulate the principle cooling transition. The laser structure is detailed and a description of the physical implementation is provided. The procedure employed to search for Barium ions in the parabolic mirror trap is described and CCD camera pictures of 2-Dimensional crystals that were achieved are presented.

I. Introduction

Quantum computing is a promising field of physics research which seeks to apply principles from quantum mechanics, notably superposition and entanglement, to greatly increase computing power. Quantum computers rely on the use of qubits, in analogy with the binary digit or bit which is the fundamental unit of computation of classical computers. As many two-level quantum systems can act as qubits, there are multiple candidates for qubits today, including Josephson junctions, quantum dots, and trapped ions. The latter offers a wide variety of candidate qubits, as different chemical species and isotopes of those species can be used. Furthermore, different transitions within the electronic structure can also be utilized as potential qubits and ions have been shown to have very long coherence time, i.e. they can store the information being processed for a long period of time (on the order of seconds or tens of seconds, whereas superconducting qubits currently display coherence times on the order of microseconds).

II. Production and Doppler Cooling of Barium Ions

To facilitate the implementation of quantum gates on Barium Ions, a Paul trap is employed and placed in an Ultra High Vacuum (UHV) chamber. Ideally, one would use a static electric field with a stable minimum to trap ions as they are electrically charged. However, because electric potentials must follow Laplace's equation we have [Dietrich, 2009]:

$$\nabla^2\phi = \nabla^2\left(\frac{\alpha x^2}{2} + \frac{\beta y^2}{2} + \frac{\gamma z^2}{2}\right) \tag{1}$$

$$\alpha + \beta + \gamma = 0 \tag{2}$$

Equation 1 implies that there cannot be a static electric field with a stable minimum, as at least one of the three left hand terms of Equation 2 must be negative. This would correspond to a saddle point. Paul traps employ an oscillating, radio-frequency (RF) field, which produces a stable minimum electric field, allowing the ions to be trapped. These oscillating fields quickly switch between two saddle points, in effect changing which of the three terms in Equation 2 is negative. This generates a pseudo-potential with a stable minimum, even though there is no static stable minimum. The ions are produced by ionizing a stream of neutral Barium atoms, provided by an oven which evaporates the atoms off a piece of Barium when a current is run through the oven. These atoms are then ionized by removing one of the valence electrons through a two step ionization process. First the electron is excited from the $1S_0$ state to an excited $3P_1$ state, the atom is the ionized by a pulsed UV laser [Lilieholm, 2019]. This ionization scheme is described in Figure 1. Once produced these

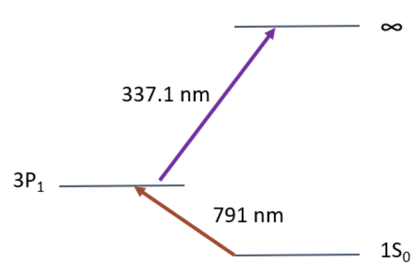

Figure 1: *Barium two step ionization scheme*

ions are traveling at a few hundred meters per second [Wright, 2015], and must be cooled to be successfully trapped. This is possible thanks to the cooling scheme described in Figure 2, in which the remaining valence electron is excited from the $6S_{1/2}$ to the $6P_{1/2}$ half orbital. This transition is around 607.42615 THz but will hereafter be referred to as the 493*nm* transition for conciseness. However, the 493*nm* laser is slightly red-detuned, meaning the frequency is slightly lowered, usually by around 100 MHz, so that the absorption only occurs when the light is Doppler shifted due to the ion's antiparallel motion with respect to the laser beam. As the 493*nm* photon emitted due to de-excitation is then emitted in random directions, there is a net decrease in the ion's momentum and consequently in its temperature. This process is called Doppler cooling. However, the 493*nm* laser is responsible for 80% of the cooling efficiency, as for a certain fraction of transitions (around 30% of the time), the ion decays to the $5D_{3/2}$ orbital which is a metastable state, meaning it is long lived (tens of seconds). As the 493*nm* transition is stimulated on the order of every nanosecond, the ions would quickly find themselves all trapped in the $5D_{3/2}$ state if only the 493*nm* laser was used. To solve this problem, a second cooling beam, also slightly red-detuned, at 650*nm* is used to return the ions to the $6P_{1/2}$ orbital anytime they find themselves in the $5D_{3/2}$ orbital. This laser accounts for the remaining cooling and can also be conveniently used to make the ions dark. Indeed, if this laser is turned off while the 493*nm* laser remains on, the ions will quickly find themselves in the $5D_{3/2}$ state, at which point fluorescence from the 493*nm* transition will cease. This can be used to check for the presence of ions, as the measured fluorescence will decrease when the 650*nm* is turned off if there are ions present and will again increase once it is turned back on. The use of both lasers allows the ions to be cooled to around 2mK [Wright, 2015].

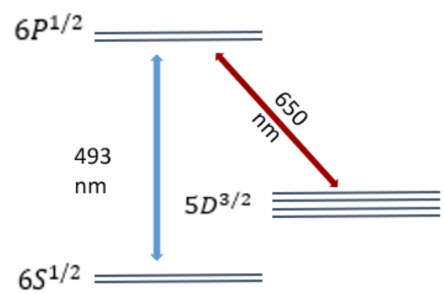

Figure 2: *Cooling cycle for Ba+, splitting of energy levels is due to the Zeeman effect*

III. Principle of operation of a diode laser

As a laser operates through the use of stimulated emission, a diode laser must involve feedback in a cavity in which a standing electromagnetic wave can be established. This can be achieved by using a diffraction grating mirror, in which the 0th order beam is used as the laser beam, and the 1st order diffracted is used for feedback (as its intensity is lesser than the 0th order). This setup is pictured in Figure 3. The two labeled screws are used to align the 0th order with the collimating lens, which allows the feedback to be set up. As the angle at which different wavelengths of light are diffracted is a function of the wavelength, the desired wavelength can be selected by slightly changing the angle between the collimating lens and the diffraction grating. A rough alignment can be achieved using the horizontal alignment screw and the piezo actuator, controlled by a piezo controller, is used to finely adjust the angle (with a 100V range corresponding to around a 0.2mm difference. This allows for fine control of the emitted wavelength and will serve in the future to lock the laser.

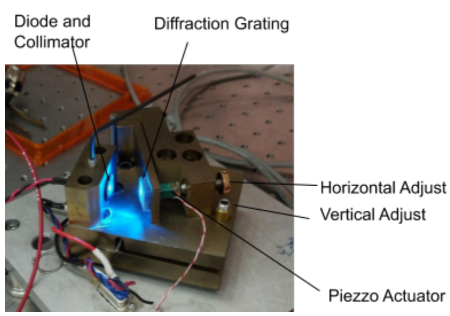

Figure 3: *Labeled picture of the diode laser*

IV. Diode Laser Structure and Assembly

Until recently, affordable laser diodes close to the necessary 493*nm* wavelength were not available to our lab. This beam was therefore produced by the use of a 986*nm* laser combined with a doubling crystal. The 986*nm* laser in the parabolic mirror trap experiment in our lab had gradually lost power due to aging and the use of the doubling crystal had always been an important source of loss of power (around 75% losses). This was thought to be a likely cause of difficulties trapping ions and a proposed solution was to construct a 493*nm* laser using a laser diode, as these would not require the use of a doubling crystal, greatly decreasing the losses. I tested five laser diodes by measuring their emission spectrum (which is very roughly Gaussian) and identified the diode whose central emission frequency was closest to the 493*nm* transition. Once the diode was installed and the cavity aligned, the emitted frequency remained around 0.8*nm* above the desired wavelength. As the frequency emitted by laser diodes is a function of temperature, this wavelength could be achieved by heating the diode. This was achieved by drilling a hole in the laser housing and by stabilizing the temperature through the use of a Thermoelectric Cooler (TEC), controlled by a Thorlabs temperature controller. The laser housing was then insulated in foam and by an outer layer of cardboard, as shown in Figures 4 and 5.

Figure 4: *Picture of the inner insulating foam*

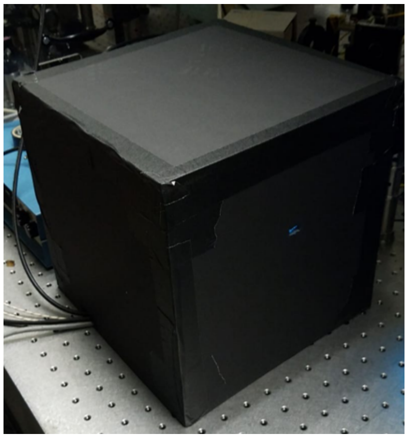

Figure 5: *Picture of the insulating outer cardboard box*

V. Ion Trapping

Once this laser was installed in the parabolic mirror trap experiment, I moved on to searching for ions in this experiment and later to search for ions in the 2D crystal experiment.

i. Searching for Ions in the Parabolic Mirror Experiment

One of the difficulties in ion trapping, illustrated in Figure 6 stems from the necessity to precisely align the four laser beams used to ionize the atoms (791*nm*, UV) and cool the ions (493*nm*, 650*nm*) with the stream of neutral Barium emanating from the oven. All of the above must be aligned in a point close enough to the trap's RF-null, which is the area of the pseudo-potential at which the electric potential is null and where ions can be trapped. Furthermore, an imaging path composed of a magnifier and a beam splitter which sends light to a Photomultiplier Tube (PMT), which measures 493*nm* photon counts, and a Charged Coupled Device (CCD) camera which is used for visually imaging the ions must also be aligned with this RF-Null. If this imaging path is not aligned correctly, ions may be trapped without being observed. Incorrect detuning of the cooling lasers can also be a hindrance to trapping. Indeed, the optimal detuning of the 650*nm* and 493*nm* laser can be calculated but will not be confirmed until ions are successfully trapped. Another tunable parameter is the amplification of the RF signal sent to the trap to establish the pseudo-potential, and all of these are altered around their expected values during searching. Ions are searched for both by looking at the PMT counts and the image from the CCD camera. To check for presence of ions, the 650*nm* beam is switched off, which causes any ions present to become dark, resulting in a sharp decrease in PMT counts if they are present, and/or ions to disappear from the CCD image, although the PMT is more sensitive to smaller scintillation intensities. When the 650*nm* beam is turned back on and ions are present, the scintillation increases sharply again, and/or the ions re-appear on the CCD image. This is repeated multiple times to check that background fluctuations did not cause the observed changes.

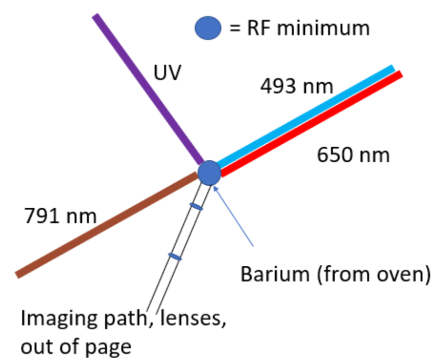

Figure 6: *Graphical (not to scale) Representation of Alignment Required for Trapping Ions*

ii. Successful 2-Dimensional Crystal Formation

I then assisted with another project which used a different modified Paul trap. One of the objectives of this project was to form and study 2-dimensional crystals of Barium Ions. As the repulsion from the Coulomb force between two ions is much greater than that between atoms, crystals of trapped ions form with much greater gaps between ions than gaps between atoms in atomic crystals. This makes these Barium crystals much more accessible for study and experimentation, and bias voltages can be applied to the trap to alter the crystal's shape. On my very last day at the UW physics REU, we were able to successfully trap crystals of ions after a two-week dead time. A picture of an 8 ion crystal is shown in Figure 7, note that although there are only 7 bright spots on the picture, the presence of a dark ion can be inferred by symmetry in the upper left corner. These dark ions are most often a different isotope than the most prevalent trapped isotope. In our case, Ba138 is most likely the prevalent isotope, and Ba137 the dark isotope. The dark species does not scintillate because the 493*nm* transition is slightly different from the other isotope due to nuclear effects. In Figure 8, a much larger crystal containing 20 to 24 ions can be seen.

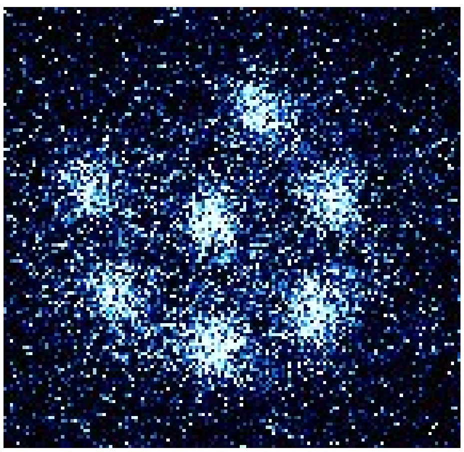

Figure 7: *CCD Camera Picture of an 8 Ion Crystal*

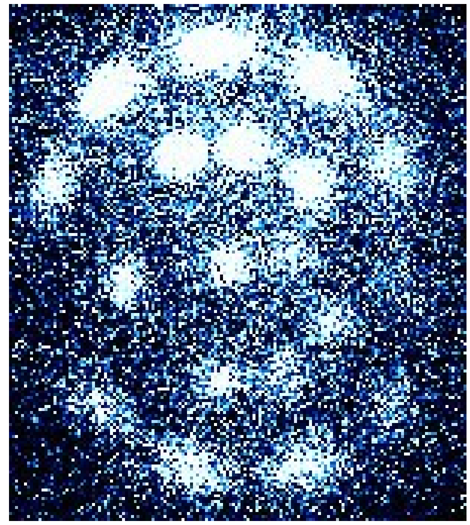

Figure 8: *Graphical (not to scale) Representation of Alignment Required for Trapping Ions*

References

[Dietrich, 2009] Dietrich, M. (2009). Barium Ions for Quantum Computation. PhD Dissertation, University of Washington Physics and Astronomy Department.

[Lilieholm, 2019] Lilieholm, J. (2019). Experiments with Trapped Ions: Entanglement, 2-d Ion Crystals and Quantum Jumps General Exam Presentation, University of Washington Physics and Astronomy Department.

[Wright, 2015] Wright, J. A. (2015). Mixed Species Ion Chains for Scalable Quantum Computation PhD Dissertation, University of Washington Physics and Astronomy Department.

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