Lasers for Hyperfine State Detection and Cooling of Ytterbium Ions

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29 August 2014

Abstract

The purpose of this REU project was to implement a system of lasers making it possible to cool trapped ytterbium ions. The cooling cycle accessed by these lasers could also be used to read out the hyperfine state of the ion— a process which could be an important operation in quantum information processing. In this paper, the theory behind using trapped ytterbium ions as ”qubits” for quantum computing is discussed, as are some methods to approach this goal, and a description of how one of the cooling lasers was set up, locked, and stabilized. Some improvements to attain a greater degree of laser frequency stability are also discussed.

1 Introduction

Researchers interested in creating a practical means of quantum information processing have been exploring suitable systems to store qubits. There are several requirements which must be fullfilled by potential systems— it must have two levels which can act as qubit states ($|0\rangle$ and $|1\rangle$, for instance), each qubit carrier must be individually addressable, it must be possible to entangle neighboring qubit states, the states must have long coherence times (relative to the timescale of information processes), and the system must remain decoupled from the environment. Researchers in various groups are investigating many possible systems including photons, superconducting Josephson junctions, quantum dots, and trapped atoms and ions.

Trapped ions are thought to present a promising solution to the problem of building a quantum computer. They can fullfill the aforementioned criteria for a qubit system, and offer several advantages. Ions in a trap are well-isolated from the environment so as to reduce unwanted couplings. This paper treats the case of ions trapped in a linear RF-Paul trap. This type of trap uses a combination of DC voltages and an oscillating rf voltage to trap ions in an almost harmonic 3D potential well [1]. Another advantage of trapped ions is that their internal electronic levels can be used as the qubit states, and entanglement can be generated using their motional levels. Entangled states of the ions can have long coherence times [2]. There are however several problems with trapped ions as a potential quantum computing platform. Firstly, it is difficult to scale up the system and to maintain coherence between larger numbers of entangled states. Additionally, performing operations on trapped ions can cause them to heat up and move. This causes decoherence, as motional levels of the ion are used for entanglement and information transfer between the ions. The next section will propose methods to prevent decoherence due to heating.

2 Technical Background

2.1 Laser Cooling

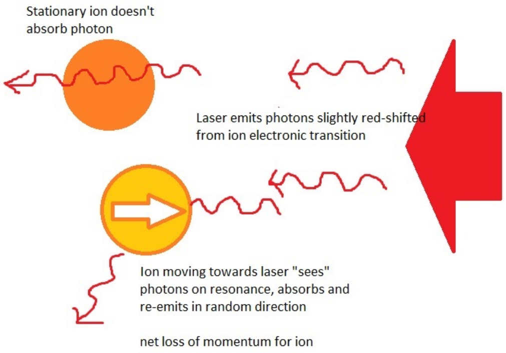

Fig. 1 Diagram of laser cooling.

Heating of the motional levels can be prevented by laser cooling. This method involves a laser slightly red-shifted from an internal electronic transition of the ion. An ion that os stationary or moving away from the light source will be unaffected, while an ion moving towards the laser will see the photons Doppler-shifted onto resonance and absorb them (**Fig. 1**). The ion will then re-emit the photons in a random direction. The ion's net change of momentum due to the emitted photons is zero—they all cancel out. All absorbed photons carry momentum opposing the ion's direction of motion. This causes the ion to slow down.

Laser cooling is a very effective method to cool ions, but introduces a new set of problems. The laser used for cooling excites an internal energy transition of the ion. The internal levels are also used for qubit processes, meaning that cooling and information processing cannot take place simultaneously. It is also very difficult to cool a single ion in a trap without exciting transitions in its neighbors.

2.2 Sympathetic Cooling

Sympathetic cooling could potentially offer a way to cool ions continuously, even while their qubit states are being accessed for information processes. This method requires two different species of ion whose internal transition energies do not overlap (**Fig. 2**). In this case, the laser used for cooling will excite transitions only in one ion species. The other can be used for qubit processes. Arrangng the ions in a configuration such as alternating species would also prevent the laser from exciting transitions in the neighbor of the ion it was meant to address.

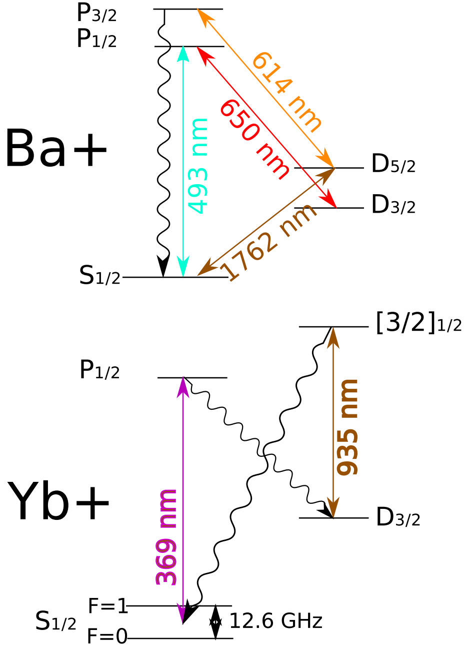

Fig. 2 Ba^+ and Yb^+: Ion species with no overlapping energy transitions.

Although only one type of ion is directly laser cooled, strong interactions between the ions of both species cause the qubit ions to be cooled as well. This paper proposes the use of Ba^+ ions to be laser cooled, and Yb^+ ions as the candidate for qubit storage.

2.3 State Detection in Ytterbium Ions

Yb^+ is an attractive option for information processing because of the hyperfine structure of its ground state. The $S_{1/2}$ state has two hyperfine levels (F=0 and F=1) split by 12.6 GHz [3]. Lasers can be tuned so as to include only one of these levels in a cooling cycle (**Fig. 3**). In this case when the laser impinges on the ion, the initial hyperfine state can be read out— if the ion fluoresces, it started out in the state contained within the cooling cycle. If no fluorescence is observed, it can be known that the ion was initially in the other state— the "dark state" excluded from the cooling cycle.

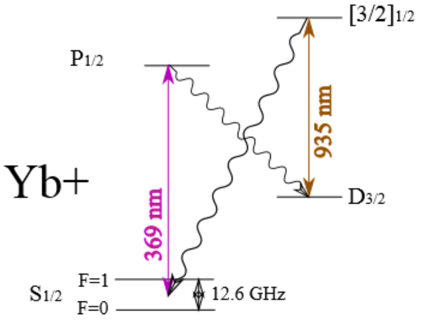

Fig. 3 Cooling cycle for Yb^+. If the ion is initially in the F=1 hyperfine state, the 369 nm laser will excite an electronic transition to the $P_{1/2}$ level. As the ion returns to its ground state, it will emit a photon. Detection of this photon would indicate that the initial state was F=1. If the ion started in the F=0 state, it would remain "dark" and emit no photons.

In Yb^+, the principle transition is the $S_{1/2} \rightarrow P_{1/2}$. A 369 nm laser is used to excite this transition. However, the $P_{1/2}$ level sometimes decays to a low-lying $D_{3/2}$ state. For this reason an additional laser at 935 nm is needed to pump the ion out of that state and allow it to decay back to ground.

3 Methods

The ionization and cooling (or state detection) of ytterbium requires the use of three lasers: the 369 nm and 935 nm to excite cooling cycle transitions, and another at 399 nm used only for ionization. Ytterbium is ionized by a two-photon process, wherein the 399 nm laser excites the neutral atom, and a second laser completes the ionization (the 369 nm light can be used for this process as well).

The REU project carried out this summer was to set up, lock, and test the stability of the 935 nm laser. To ensure frequency stability, a portion of the 935 nm beam was picked off and sent through a reference cavity into a photodiode detector. The detector output could be viewed on a scope (**Fig. 4**). The peaks in voltage visible on the output correspond to resonant modes of the cavity. Without a locking mechanism, the laser will often mode-hop— rapidy switching between frequency modes of the cavity. Temperature controllers were also used for the reference cavity and for the laser.

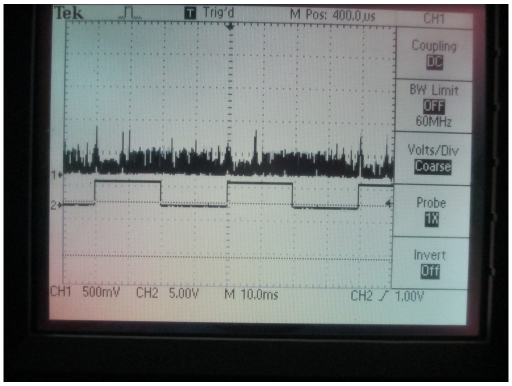

Fig. 4 (Poorly resolved) voltage peaks at frequencies corresponding to modes of the cavity.

A lockbox was constructed and installed in the setup to prevent the laser from mode-hopping. The circuitboard for the lock was printed using ultraviolet lithography and the circuit was assembled. The output of the photodiode detector was connected to the input of the lock, and the output of the lock fed back onto the piezo driver. When tuned correctly, the lockbox should be able to lock the frequency of the laser to a single peak (of those shown in Fig. 4), theoretically ensuring a very high degree of stability. Another portion of the laser beam was picked off and sent to the wavemeter— this allowed for the frequency to be easily monitored.

4 Results

The laser was locked, and its frequency was monitored using the wavemeter for approximately five hours (5:38:32 PM to 10:28:55 PM). **Fig. 5** shows the output over the whole time. As is evident in the figure, the frequency loses all stability around 7:57 PM. After that, the lock is unable to find any peaks to lock to, and the laser jumps rapidly between frequencies.

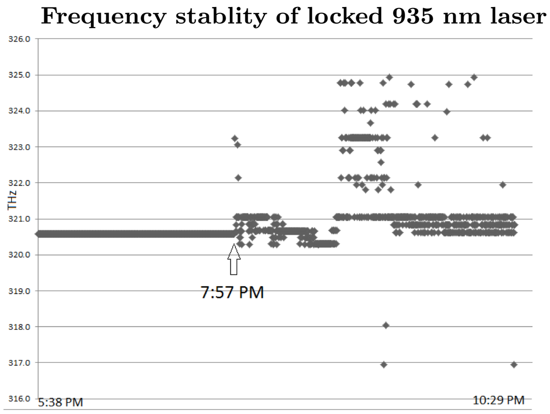

Fig. 5 Frequency of the laser over the approximately 5 hour test period. After 7:57 PM, the laser jumps, and the lockbox is unable to lock the frequency.

Due to the scale of the y-axis in Fig. 5, it is difficult to judge the degree of frequency stability before 7:57 PM. **Fig. 6** shows a clearer picture of the laser's behavior during that time. The laser is initially locked to its starting frequency (in this test, around 320.58000 THz). At around 7:05 PM, the lock loses its peak, and the laser jumps to a new frequency (around 320.57930 THz)— corresponding to a different mode of the cavity. It is able to lock once again, and remains there for another quarter of an hour.

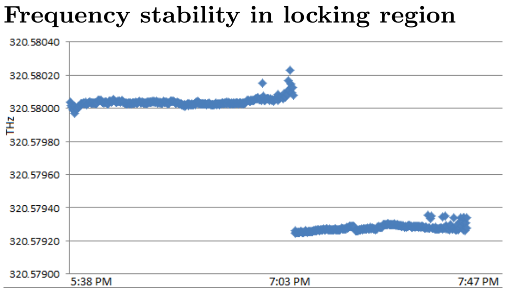

Fig. 6 A better view of the frequency stability of the early region of Figure 5. The laser is initially locked, then jumps, but manages to lock to another peak.

The initial locking phase lasts for approximately 90 minutes, which would be a sufficiently long time for experiments on cooling or hyperfine state detection to be performed. Once again, the scale of Fig 6 is not able to convey a sense of the stability of the locked laser. **Fig. 7** displays the results during the time that the laser remains locked to its initial frequency. In this region the frequency oscillates over a range of about 80 MHz.

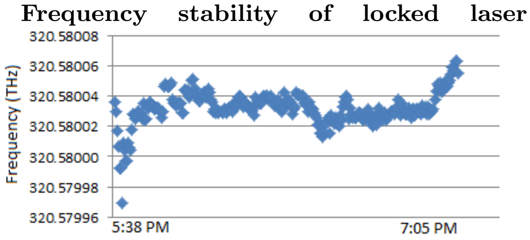

Fig. 7 When locked to its initial frequency, the laser displays oscillations within 80 MHz due to temperature.

Some variation is expected in the locked frequency due to changes in temperature. The reference cavity is very sensitive to small temperature changes. The cavity is connected to a temperature-controller, but in order to reach a better stability— ideally around 10 MHz— stricter temperature regulation would be necessary.

5 Summary

Trapped ions are thought to be a good platform for a quantum information processing system. They are well-isolated in a trap, and their internal electronic levels could be used for qubit storage. Motional levels can be used to generate entanglement, and entangled states can remain coherent on relatively long time scales. In particular, trapped Yb^+ ions sympathetically cooled with Ba^+ ions could provide a means to begin realizing such a system. Yb^+ ions have several advantages. Firstly, the hyperfine splitting of the ground state provides a convenient way to read out the ion state, which could be utilized for quantum logic operations. Secondly, due to the spin 1/2 nucleus of $^{171}Yb^+$, the hyperfine levels of the ion's ground state are first-order magnetic field-insensitive [4].

The hyperfine state of the ion can be read out by means of a cooling cycle, which makes use of several lasers. This paper discusses the setup and locking of the 935 nm laser, which pumps the ion out of a low-lying $D_{3/2}$ state back to ground by way of the $[3/2]_{1/2}$ state. The experiment described in the Results section found that with the lock, the laser is stable to about 80 MHz for approximately 90 minutes. The variation during this time is expected due to changes in temperature of the cavity, which is very sensitive. Additional temperature regulation for the cavity will be necessary to reduce the oscillation of the locked frequency, ideally to within about 10 MHz. It should also be mentioned that although 90 minutes is a sufficiently long time to perform experiments using the locked laser, the lock time could also likely be extended. The peaks shown in Fig 4 are poorly resolved above the noise and could almost certainly be improved simply by a more thorough alignment of the laser setup. With better-resolved voltage peaks, the lock would be less likely to lose its hold and cause the frequency to jump, as it did in Fig 6 at 7:05 PM.

6 Acknowledgements

I would like to thank Boris Blinov for welcoming me into his lab, as well as John Wright, Tomasz Sakrejda, and the rest of the group for helping me with my project. I am very grateful to Subhadeep Gupta, Alejandro Garcia, Shih-Chieh Hsu, as well as Linda Vilett and Janine Nemerever for organizing this REU program, and Ron Musgrave for teaching the machine shop class. Thank you to the NSF for funding.

References

[1] Wineland, Monroe, Itano, Leibfried, King, Meekhof. Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions. *Journal of Research of the NIST. Vol. 103 Number 3.* May-June 1998.

[2] Blatt, Wineland. Entangled states of trapped atomic ions. *Nature Vol. 453.* 19 June 2008.

[3] Hayes. 2012. *Remote and Local Entanglement of Ions using Photons and Phonons.* (Doctoral dissertation).

[4] S. Olmschenk, K. C. Younge, D.L. Moehring, D. Matsukevich, P. Maunz, C. Monroe. Manipulation and Detection of a Trapped Yb^+ Ion Hyperfine Qubit. *Phys. Rev. A* ***76**, 052314.* 19 November 2007.