PROGRESS TOWARD THE DEVELOPMENT OF A YTTERBIUM ION STANDARD*

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Abstract

A ytterbium ion standard is currently under development at JPL for both ground and space applications. We have chosen the ytterbium ion for its large hyperfine splitting of 12.6 GHz, and accessibility of its first excited electronic energy levels with light from frequency-doubled semiconductor and solid state lasers. Performing microwave-optical double resonance spectroscopy we have achieved 25 mHz Ramsey fringes with a signal-to noise ratio better than 350:1 in the shot noise limit, which corresponds to an inferred stability on the order of 1.8 x $10^{-14}/\sqrt{\tau}$.

Introduction

A ytterbium ion standard has been under development at JPL, for ground and space applications. The trapped mercury ion standard has achieved fractional frequency stability of 7 x $10^{-14}/\sqrt{\tau}$ for $20s < \tau < 10,000s$ and has made possible stabilities of 7 x 10^{-16} at 100,000 seconds of averaging time, a performance unsurpassed by any other frequency standard [1,2]. However ytterbium is also an attractive ion for frequency standards applications since preparation and observation of its clock transition at 12.5 GHz may be made utilizing compact semiconductor or solid state laser systems [3,4]. This feature enables designs methodologies that reduce the size and the mass of the standard without necessarily compromising its performance. It also allows laser cooling [5-8] of the ions to improve stability performance of the standard. Thus a small ion standard based on ytterbium could be ideal for spacecraft applications.

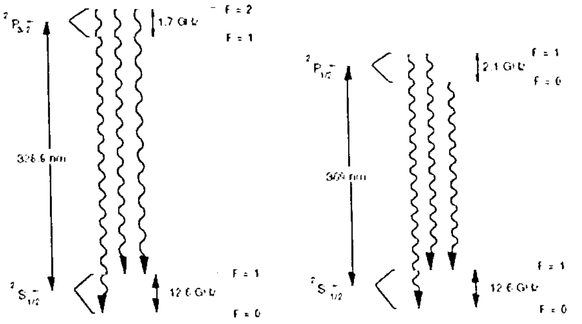

Figure 1: Hyperfine structure of the ground and first excited states in $^{171}Yb^+$

In a previous paper [9] we had described results on the laser spectroscopy of ytterbium ions trapped in a linear rf/dc hybrid trap. In the present work we report on observation of Ramsey fringes obtained by excitation of the clock transition. Here again a laser was used to prepare and interrogate the ions. The resulting signal and the observed line Q of the ions allow us to infer stability of a standard based on this scheme. Since the 12.5 GHz ground state hyperfine transition of ytterbium is about four times more susceptible to magnetic field perturbations than the corresponding transition in the mercury ion, we also have performed an extensive study to characterize the magnetic sensitivity of ytterbium in our particular trap configuration. Despite its apparent advantages, ytterbium has difficulties with population trapping which effectively removes the ion from the cycling process [9-14]. We have also studied this problem and determined a means for effectively reducing population trapping influences. Finally, we will describe future plans to perform actual stability

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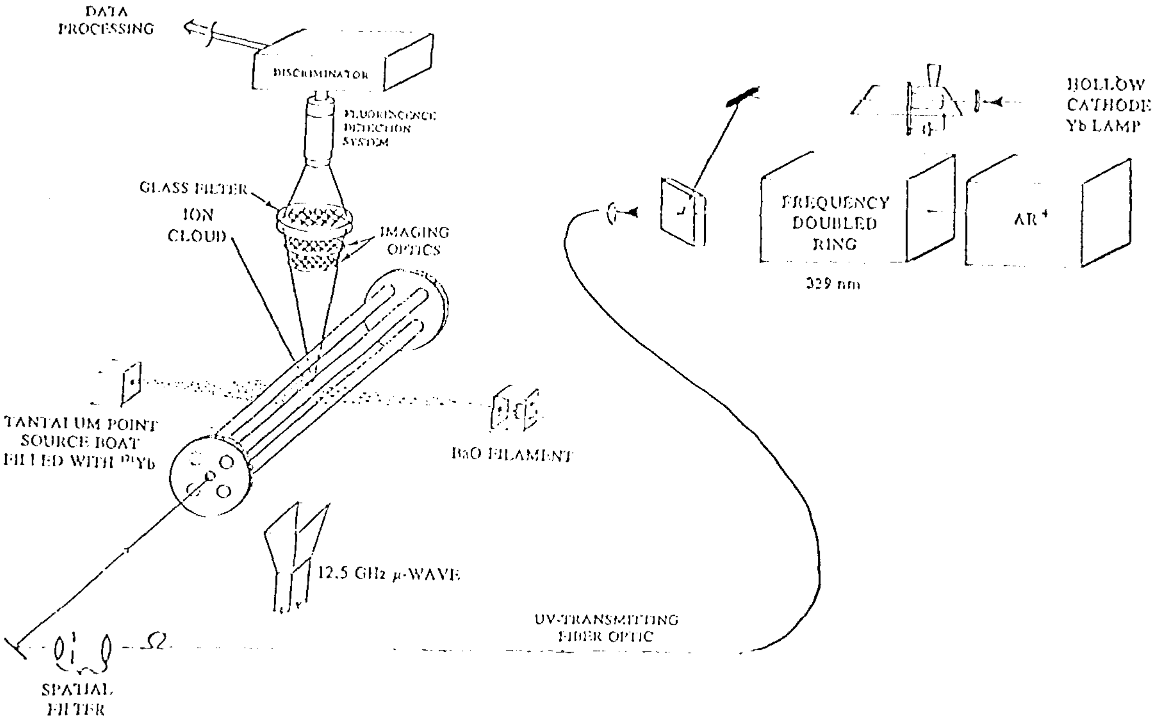

Figure 2: Simplified experimental setup used to carry out spectroscopy on trapped ^{171} Yb$^+$ ions.

measurements with the ytterbium ion standard.

Experimental setup

The ytterbium isotope 171 ion has a hyperfine structure similar to the mercury isotope 199 ion, with an energy splitting corresponding to 12.64 GHz, as compared to mercury's 40.5 GHz. Its $^2P_{1/2}$ or $^2P_{3/2}$ excited states can be reached from the ground state with 369nm or 329nm radiation respectively (see fig 1). The use of lasers for optical pumping ytterbium ions readily leads to a ten fold improvement in the signal-to-noise ratio (SNR) over mercury's lamp based system, while only giving up a factor of 40.5/12.6 in line Q for equivalent interrogation times. Since the short term stability is given by

$$\sigma(\tau) \propto \frac{1}{Q_l}\frac{1}{SNR}\sqrt{\frac{t_i}{\tau}} \tag{1}$$

(where Q_l is the line Q $= f/\delta f$, and t_i is the total cycle time from one measurement to the next) there is the potential for a two to three fold improvement in the short term stability. In our experiment we were able to cycle the ions, a process that scatters many optical photons for each microwave photon absorbed. This was accomplished through excitation of the ($^2S_{1/2}$,F= 1) <> ($^2P_{3/2}$,F= 2) transition while only pumping in the doppler wings of the ($^2S_{1/2}$,F= 1) <> ($^2P_{3/2}$,F= 1) clearing transition. The cycling of the ($^2S_{1/2}$,F= 1) <> ($^2P_{3/2}$,F= 2) transition is possible due to the narrow linewidth (~ 1 MHz) of the laser and large 1.7 GHz hyperfine splitting of the $^2P_{3/2}$ state.

Figure (2) shows the experimental setup used to study the clock transition in trapped ytterbium ions. The hybrid linear rf/dc trap, which is modeled after the one first used with mercury ions at JPL [15], is composed of four rf electrodes in the form of rods with dimensions of 3.18 mm in diameter and 88.9 mm long. The rods are configured equally spaced with their center on a 17.48 mm diameter circle. Hollow cylindrical dc endcaps with inner radii of 1.19 mm and outer radii of 3.18 mm are placed on the axis of the quadrupole trap. The endcaps protrude into the trap 15.24 mm from the end, leaving a total trap length of 58.42 mm from endcap to endcap. The effective trap length, or length of the ion cloud, in the trap depends on the dc voltage applied to the endcaps. For our experiment an rf drive amplitude of

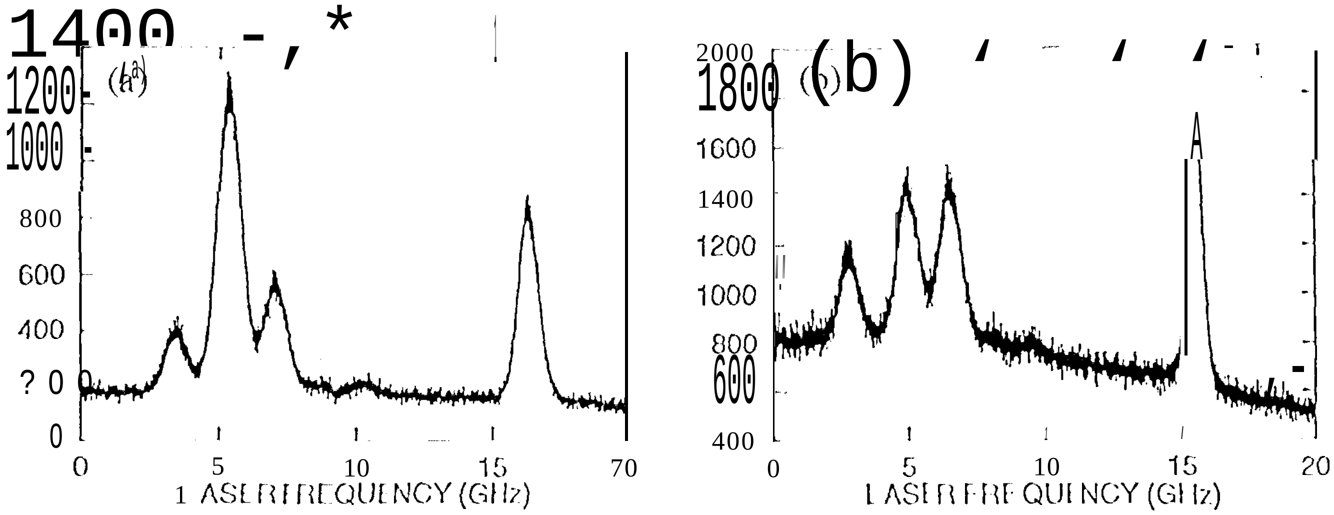

Figure 3: Resonance lineshape spectra vs. uv-laser power. (a) Laser power ~ 50 nW. (b) Laser power ~ 250 nW.

110 V_{rms} at 4S3 kHz was applied on the four rods, with +15 dc volts applied on the endcaps. To reduce the effect of rf heating on the ions a helium buffer gas was introduced through a quartz leak to collisionally cool the ions. In addition, nitrogen gas was introduced through a variable leak to collisionally quench the lower lying metastable states, which otherwise contain the ions in a "dark" state. The helium background in the trap was maintained at a nominal pressure of 1×10^{-5} torr while the nitrogen pressure was approximately 1×10^{-6} torr. We estimate that these parameters allow the trap to hold a 9111111 diameter cloud of 10^7 ions. The mixture of nitrogen and helium was quite effective in cooling the ion cloud and quenching the dark state.

The $4f^{14}({}^1s)6s\,{}^2S_{1/2} <> 4f^{14}({}^1S)6p\,{}^2P_{3/2}$ transition was excited using 328.9 nm radiation generated by a coherent 699-21 ring dye laser running with 1)CM special laser dye and an intracavity lithium iodate doubling crystal. Up to 2 milliwatts of uv power was generated in this manner, and a homemade hollow cathode lamp was used to maintain the laser was on resonance. In order to move the trap away from the large magnetic fields associated with the argon ion laser and stainless steel optical table the uv-radiation was then injected into a 10 meter length of fiber optic cable and introduced axially into the trap.

The magnetic field inhomogeneities associated with the argon ion laser and steel optical table, as well as the ambient earth's field, arc quit large, leaving a very poor environment for carrying out precision spectroscopy on the hyperfine structure of an atom. For this reason it was necessary to place the ion trap inside a three axis set of five focal diameter Helmholtz coils. With this set up we were able to cancel the ambient magnetic field in the room and set, up a magnetic field environment stable enough to allow greater than 20 second coherence times.

Optical Resonance Lineshapes

Resonance fluorescence lineshapes at two different laser powers are shown in figure 4. Lower optical power improves the signal to noise by reducing the background scattered light and improving the photon counting efficiency by ensuring the counting system is running below saturation). Axial temperature measurements are also improved by reducing the artificial narrowing of the the resonance line by rapid pumping of the ions into an alternate level while the laser is scanning through the transition.

Microwave-Optical Double Resonance Spectroscopy

Ramsey fringes were obtained by first preparing the ions in the $({}^2S_{1/2}, F=0)$ state through optical pumping by tuning the laser to overlap the $({}^2S_{1/2}, F=1) <> ({}^2P_{3/2}, F=1)$ transition. With the laser off the ions were irradiated with a pair of 400 ms $\pi/2$ microwave pulses separated by a time t_i. If the microwave frequency matched the energy splitting of the ground state hyperfine levels, the ions would be effectively transferred from the $({}^2S_{1/2}, F=0)$ back up to the (%,/2,1': 1) level. The laser which was tuned to overlap the $({}^2S_{1/2}, F=1)$ <:' $({}^2P_{3/2}, F=2)$ transition was then turned on and the ion fluorescence was

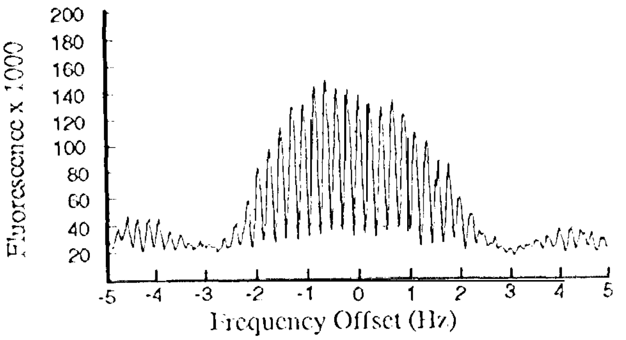

Figure 4: 100 mHz ramsey fringes corresponding to a 5 second separation between $\pi/2$ pulses.

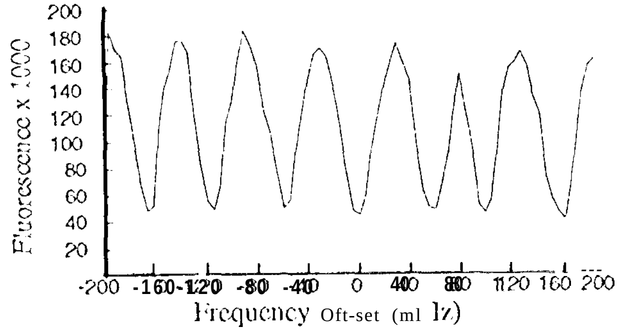

Figure 5: 25 mHz ramsey fringes corresponding to a 20 second separation between $\pi/2$ pulses.

monitored for two seconds, The level of fluorescence corresponds to the number of ions in the upper hyperfine state, which in turn depends on how close the microwave frequency matched the energy difference between the ground state hyperfine levels. Once the fluorescence was recorded the laser was then scanned over the $(^2S_{1/2}, F=1) \leftrightarrow (^2P_{3/2}, F=1)$ transition to ensure all the ions were back in the $(^2S_{1/2}, F=0)$ level and ready for the next pair of microwave pulses. Figures 4 and 5 show the effect of slowly stepping the microwave frequency after each pair of microwave pulses.

As shown in figure 5 we achieved 25 mHz Ramsey fringes with single shot photon counts of 130.000 above a 50,000 count background; this corresponds to a signal-to noise ratio exceeding 350:1 in the shot noise limit, and inferred stability of $\sigma_y(\tau) \sim 1.8 \times 10^{-14}/\sqrt{\tau}$. It is clear from figure 5 that we are not yet realizing the full 350:1 SNR, probably because of magnetic field fluctuations. At the 100 mgauss magnetic field that we set up to separate the $\Delta M_F = 0$ from the $\Delta M_F = \pm 1$ transitions the transition frequency sensitivity to magnetic fluctuations is $62\,mHz/mgauss$. The relatively high sensitivity of the 12.64 GHz resonance transition to magnetic fluctuations coupled with the lack of magnetic shields in our present experimental system prohibits actual measurements of long term stability.

Zeeman and Motional Sideband Spectroscopy

The frequency of the $(^2S_{1/2}, F=0, M_F=0) \leftrightarrow (^2S_{1/2}, F=1, M_F=0)$ transition in the presence of a magnetic field is given by

$$\nu = \nu_o + 311\,\mathrm{Hz}\left(\frac{B}{1\ \mathrm{gauss}}\right)^2 \tag{2}$$

Since we are interested in fractional frequency stability and this function has a quadratic nature it is desirable to work at values of applied magnetic field as low as possible since the sensitivity to magnetic fluctuations is given by

$$\left.\frac{\partial\nu}{\partial B}\right|_{B=B_o} = 622\left(\frac{B_o}{1\ \mathrm{gauss}}\right)\frac{\mathrm{Hz}}{\mathrm{gauss}}. \tag{3}$$

With this in mind we decided to investigate the Zeeman and motional sidebands at various orientations of the applied static magnetic field (C-field) with respect to the microwave polarization and trap axis orientation. Similar work was carried out by Enders et. al. on ytterbium ions confined in a hyperbolic trap [16].

Figures 6 and 7 each show 26 possible magnetic field orientations that almost completely map out all possible orientations. They were obtained by tuning the laser to overlap the $(^2S_{1/2}, F=1) \leftrightarrow (^2P_{3/2}, F=1)$ transition while scanning the microwaves 500 kHz in a phase continuous manner over a period of 10 seconds and summing together 50 scans. The total static magnetic field was kept constant at approximately 86 mgauss and the following static magnetic field orientations were setup, $B(x,y,z) = (0,0,\pm1); (0,\pm1,0); (\pm1,0,0); (0,\pm1,\pm1); (\pm1,0,\pm1); (\pm1,\pm1,0); (\pm1,\pm1,\pm1)$. The trap axis is oriented along the x direction. Figure 6 shows the 26 static magnetic field orientations when the microwave polarization was oriented perpendicular to the trap axis, and figure 7 shows the same 26 magnetic field orientations with the microwave polarization oriented parallel to the trap axis. In both cases the the

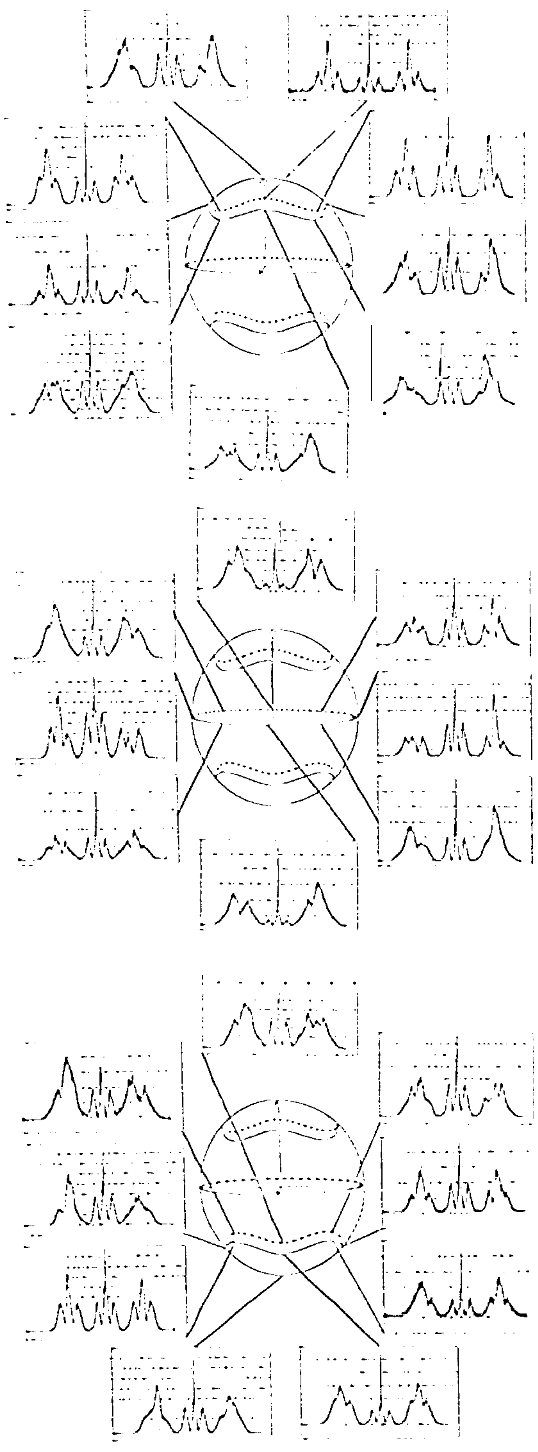

Figure G: Zeeman and motional sideband spectra at 86 mgauss total magnetic field and microwave polarization parallel to the trap axis. The positions indicated on the spheres correspond to the 26 static C-field orientations B(x,y,z) = (0,0,±1); (0,±1,0); (±1,0,0); (0,±1,±1); (±1,0,±1); (±1,±1,0); (±1,±1,±1).

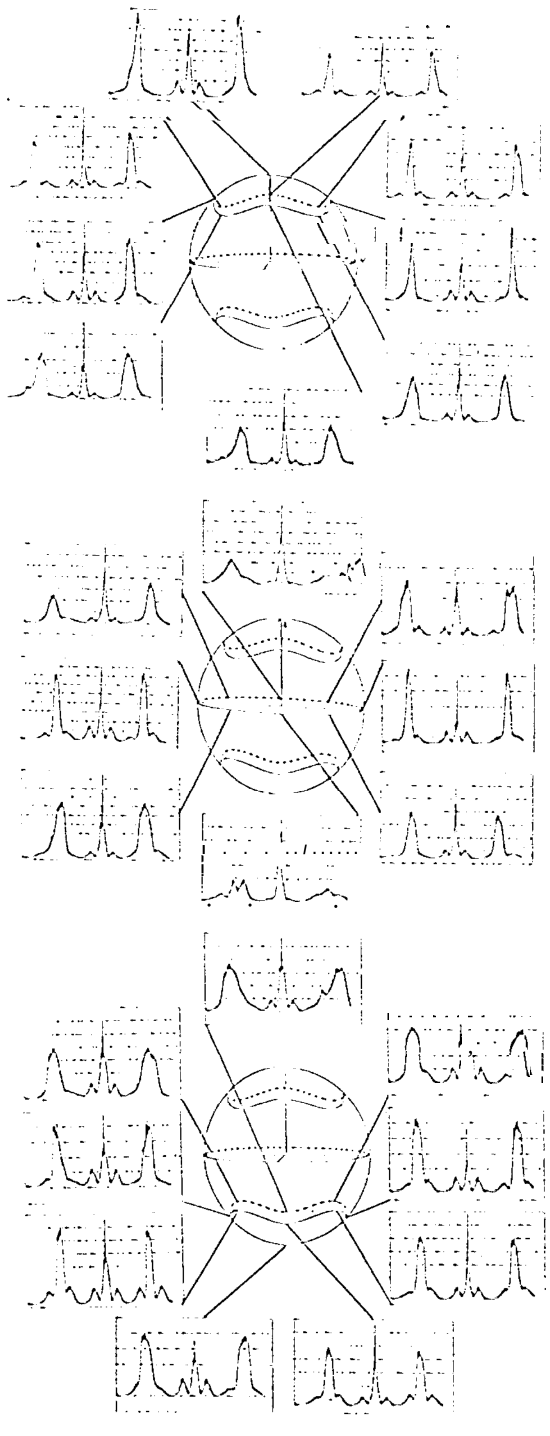

Figure 7: Zeeman and motional sideband spectra at 86 mgauss total magnetic field and microwave polarization perpendicular to the trap axis. The positions indicated on the spheres correspond to the 26 static C-field orientations [B(x,y,z) = (0,0,±1); (0,±1,0); (±1,0,0); (0,±1,±1); (±1,0,±1); (±1,±1,0); (±1,±1,±1)].

microwave propagation direction was perpendicular to the trap and oriented in the z-direction.

Conclusion

We have carried out extensive microwave-optical double resonance spectroscopy of trapped $^{171}Yb^{+}$ in order to determine the feasibility of ytterbium as the active atom in a trapped ion frequency standard. An inferred stability on the order of 1.8×10^{-14} has been obtained with 25 mHz Ramsey fringes. These results show great promise for ytterbium as a candidate ion in a frequency standard, we intend to perform actual stability measurements in the near future after the addition of magnetic shields, which are needed to reduce the effect of environmental magnetic fluctuations on the splitting of the 12.64 GHz microwave resonance transition.

A new ion trap and vacuum system is currently under design with emphasis on small size, ease of magnetic shielding, and high photon collection efficiency. The collection efficiency of the current system is only ~ 0.1% which can easily be improved ten to fifty fold. In addition, the current system is not suited for the addition of magnetic shields which are necessary to perform stability measurements.

While the design and fabrication of the next generation ytterbium system is taking place we will further study the influence of different buffer gases on the lifetime of ytterbium's meta-stable states. The construction of a stabilized compact .369 nm laser source will also be addressed so that ytterbium will be able to advance to a stand alone field frequency standard.

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