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ATOMIC FOUNTAIN DEVELOPMENT AT U.S.N.O

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Introduction

Atomic fountain clocks are showing great promise as primary frequency standards (1). In light of this, we have started a program to develop atomic fountain clocks at the U. S. Naval Observatory. The mission of the observatory, however, dictates different design goals than that of a standards institution. In this paper we will discuss the goals of our atomic fountain project, a scheme for reducing the overall temperature sensitivity of the fountain, and the status of our efforts to launch atoms from a four beam optical lattice.

Design Goals

We have undertaken a research program to produce atomic fountain clocks to support the timekeeping mission of the U. S. Naval Observatory. The observatory maintains an ensemble of atomic clocks that consists of approximately 50 commercial cesium beam standards and 12 hydrogen masers. These standards are used to compute and produce several time scales, most importantly UTC(USNO).

The most important feature of a fountain clock for the observatory is that it have excellent long term frequency stability. Also important is a short term frequency stability that will allow realization of the long term stability floor in a short (approximately one week) time scale.

Of only minor importance is the frequency accuracy of the standard. The output timescale UTC(USNO) is steered to UTC, which will define the long term frequency. The fact that we do not require frequency accuracy makes it possible to consider atoms other than cesium for our fountain.

It is our hope to realize a fountain that has short term stability of 10^{-13} at one second and a systematic reproducibility of less than 2×10^{-16}. Initially, we will operate by reporting frequency offsets relative to a hydrogen maser that is part of our local clock ensemble.

Atomic Species

Recent results (2,3) have demonstrated that ultra-cold collisions between different spin states are suppressed in rubidium 87 as compared to other alkalis. This makes rubidium (^{87}Rb unless otherwise noted) a potentially attractive candidate for a stable frequency standard since the collisional frequency shifts will be greatly reduced.

We have made simple simulations of the collisional shift realized in a fountain with both rubidium and cesium at different launch temperatures. In these simulations, we assumed that the collisional shift at a given atomic density was a factor of 15 smaller for rubidium than in cesium (3,4).

We will now describe the simulation parameters and assumptions where the values will be quoted for the cesium atom simulations, with the rubidium atom value given in parenthesis if different. The initial spatial distribution of the atom cloud was assumed to be a three dimensional Gaussian with an initial RMS size given by σ=0.5 (0.68) cm. The initial temperature distribution is assumed to be isotropic. The atoms are allowed to expand for 0.15 seconds and are then aparatured in two dimensions by a hole with a diameter of 1 (1.35) cm, which reflects the hole in the microwave cavity. The aparatured distribution is then allowed to expand for 0.5 seconds, during which time the average of the density-weighted density averaged over the vertical extent of the cloud is computed for each transverse position. The atoms are then aparatured again by a hole with a diameter of 1 (1.35) cm and allowed to expand an additional 0.15 seconds, where they are "observed" by a detector that has a diameter of 1 (1.35) cm. The number of atoms detected and the average density-weighted density are computed per peak initial density in the cloud. These results are used to calculate the initial density of atoms that need to be launched to produce a shot noise limited short term performance of 10^{-13} at one second with a one second cycle time. The collisional shift of the fountain follows from this initial density.

The results of these simulations are summarized in Table 1. These data suggest that it should be possible to reduce the collisional shift by a factor of more than 30 if the rubidium fountain can be operated with the same launch

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temperature as the cesium fountain, as done by Gibble and co-workers (5).

Table 1: Frequency shift from cold atom collisions in a fountain as a function of launch temperature. The number of returning atoms is fixed to give a short term fractional frequency instability of 10^{-13} at one second.

Launch Temp. [μK]	Cs collision shift [x10^{-16}]	Rb collision shift [x10^{-16}]
1	2.3	0.060
1.5	2.6	0.067
2	2.8	0.073
3	3.2	0.083
4	3.5	0.090
6	4.0	0.10
8	4.5	0.11
10	5.4	0.12

Since we are primarily interested in stability of our fountain clock as opposed to accuracy, we will consider both rubidium and cesium atoms in this paper. It is clear that we will pursue the design and possibly the construction of rubidium fountains, but our initial apparatus uses cesium.

Temperature Compensation

To realize a stable frequency standard, we must minimize systematic frequency shifts that are driven by external parameters. One such shift is the temperature sensitivity of the atomic fountain "physics package". It appears that we should be able to reduce the overall temperature sensitivity of the fountain by balancing two temperature dependent effects.

An additional motivation on our part is the operational simplicity that a reduced temperature coefficient could allow. A low enough temperature coefficient would allow the physics package to be housed in one of our large environmental chambers without any additional temperature stabilization.

The first temperature dependent frequency shift that we will consider is the Black Body shift. This shift is due to the AC Stark and Zeeman shifts of the atomic clock transition in the presence of Black body radiation characterized by a temperature T. The size of the Black Body shift is given by

$$\Delta y_{BB} = -A\left(\frac{T}{300}\right)^4 \qquad A_{Cs} = 1.69x10^{-14} \qquad A_{Rb} = 1.25x10^{-14} \tag{1}$$

where the temperature is in Kelvin. The Black Body shift has been measured in a cesium beam standard (6) and is being measured in a cesium fountain standard (7). The DC polarizability of cesium, which is a key parameter in calculating this shift has also been measured with a cesium fountain (8).

The second temperature dependent shift is cavity line pulling, with its temperature dependence coming from the temperature tuning of the microwave cavity. If we assume that the microwave cavity is tuned so that the TE_{011} mode is resonant with a clock transition at a frequency f_0 the shift of the cavity frequency is given by

$$\frac{d}{dT} f_{cavity} = -1.62x10^{-5} f_0 \quad Hz/^0C. \tag{2}$$

This temperature tuning of the cavity creates a temperature dependent line pulling. The line pulling of the clock is (9)

$$\Delta y_{linepulling} = \frac{f_0 - f_{cavity}}{f_0}\left(\frac{Q_{cavity}}{Q_{atoms}}\right)^2. \tag{3}$$

If the atoms spend a time τ above the microwave cavity the Q of the atomic transition is given by

$$Q_{atoms} = \frac{f_0 \tau}{2}. \tag{4}$$

Using this expression for the atomic line Q and assuming that the cavity is tuned onto the atomic resonance at a temperature T_0, the line pulling reduces to

$$\Delta y_{linepulling} = 1.62x10^{-5}\left(\frac{2Q_{cavity}}{f_0 \tau}\right)^2 (T - T_0). \tag{5}$$

Since the Black body and line pulling shifts have different temperature dependencies and signs, they can be made to cancel at a temperature given by

$$T = 300\left[\frac{Q_{cavity}^2 4.86x10^{-3}}{A f_0{}^2 \tau^2}\right]^{1/3}. \tag{6}$$

In practice, the temperature at which these effects cancel would be chosen to be T_0.

It remains to be seen if these temperatures allow practical construction of a device. If the temperature calculated above is too high, one can load the cavity to reduce the Q and have a comfortable operating temperature. However, this will result in a higher distributed cavity phase shift (10). If, however, the Q is lowered by increasing the radius of the cavity while keeping the radius of the hole for the atoms constant, there should be no adverse effect on the distributed cavity phase shift. This is due to the fact that the distributed cavity phase shift scales like

$$\Delta\varphi_{dist} \propto \frac{1}{Q}\left(\frac{r}{R}\right)^{N} \tag{7}$$

where r is the radius of the hole in the cavity end, R is the cavity radius, and N is the number of symmetrically spaced microwave feeds (two in our current design). In our case, the reduction in cavity Q is offset by the fraction of the mode that the atoms sample.

The compensation temperature can also be raised by decreasing the time that the atoms spend above the microwave cavity, but this has the undesirable effect of degrading the short term stability of the fountain.

In order to calculate the compensation point, we need to calculate the Q of the microwave cavity. The theoretical maximum Q of an evacuated TE_{011} cavity is given by

$$Q = \frac{D}{\delta}\frac{1+\left(\frac{x'_{01}}{\pi}\right)^{2}\left(\frac{D}{R}\right)^{2}}{1+\left[\frac{\left(x'_{01}\right)^{4}J_{0}^{2}\left(x'_{01}\right)}{4\pi^{2}*1.191}\right]\left(\frac{D}{R}\right)^{3}} \tag{8}$$

where D is the height and R is the radius of the cavity, x'_{01} is the first root of the derivative of the zeroth Bessel function, and δ is the skin depth of the cavity material. The Q for copper cavities resonant with both the cesium and rubidium clock frequencies are plotted in Figure 1 as a function of R. We have left the following calculations of cavity Q and compensation temperature expressed as a function of cavity radius to allow alteration of the designed cavity geometry to change cavity Q and the density of nearby cavity modes.

The compensation temperature for the maximum possible Q is shown in Figure 2, where the time above the cavity is assumed to be 1/2 second. The Q used in these calculations is higher than will be realized in an actual cavity due to construction imperfections, the holes in the endcaps to allow access by the atoms, and loading from the coupling to the cavity.

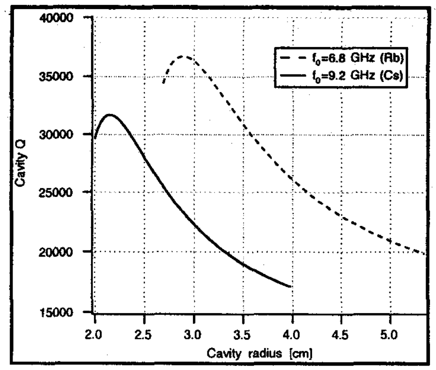

Figure 1: Maximum cavity Q for the TE_{011} mode of a copper cavity. The cavity aspect ratio is fixed for each value of the cavity radius to keep the mode resonant with either the cesium or rubidium clock frequency.

If we restrict ourselves to operation of the fountain at or above 30 °C, there is only a small range of cavity radii that can work for cesium. A wider range of cavity geometries will work for rubidium.

A key assumption in this analysis has been that the temperature of the cavity and the drift region are the same. In addition, it has been assumed that the AC Stark and Zeeman shifts from Black Body radiation can be characterized by this single temperature.

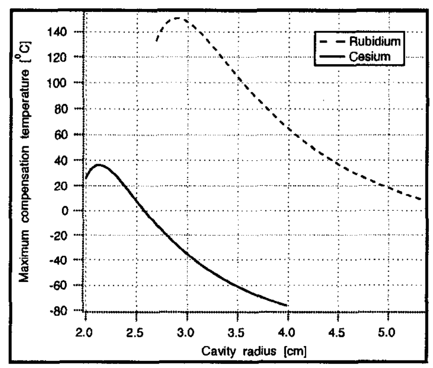

Figure 2: Upper bound on the temperature at which a fountain cancels the temperature coefficients of cavity line pulling and black body shift. The atoms are assumed to spend 1/2 second above the microwave cavity. The compensation temperature can be lowered by loading down the Q of the cavity from the value in Figure 1.

In summary, we have found a range of construction parameters that allow the cancellation of the temperature coefficients of the Black Body shift and the cavity line pulling in an atomic fountain. While the compensation is possible with both cesium and rubidium fountains, the sets of parameters that provide the cancellation appear more useful with a rubidium fountain.

While this technique will not be useful in high line Q laser cooled space clocks (11), this general idea may find useful application in other clock designs that need to operate in environments without well stabilized temperatures.

Launching Atoms from a 4-Beam Optical Lattice

One common way of launching atoms in a fountain uses two (usually vertical) laser beams with different frequencies that are directed towards each other. Atoms in this optical field will laser cool into a moving frame where the two (Doppler shifted) laser frequencies appear to be the same to the moving atoms. This type of launching requires additional transverse cooling for use in a fountain.

We have been pursuing a slightly different technique for launching our atomic sample. We are hoping to use a launching scheme built from a 4 beam optical lattice (12). The geometry of the laser beams used in the launch is shown in Figure 3. In this arrangement, there are two beams going downward with the same angle (45 degrees) from vertical and two beams going upward with the same angle from vertical. Each of the laser beams is linearly polarized. This arrangement of beams produces a three dimensional lattice of optical potential wells with either right or left circular polarization of the resulting optical field at the potential minima. The lattice potentials will translate when the phase of any of the laser beams changes, but the spatial potential and polarization structure of the lattice is unchanged.

A launch can be realized by having the upward going laser beams at a higher frequency than the downward going laser beams. This creates an optical lattice that is moving upwards with a velocity that is given by v_{launch}[meters/second] = 0.60 $\Delta\nu$ [MHz], where $\Delta\nu$ is the difference in the laser beam frequencies. The atoms are cooled in three dimensions into the upward moving reference frame.

There are several potential advantages to launching atoms from a 4-beam optical lattice. The first is that there is no vertical laser beam. This is an advantage because it makes the construction of the magnetically shielded free precession region of the fountain much simpler.

A second potential advantage is that it requires only two laser frequencies, simplifying the experimental realization. In addition, since the four beam optical lattice potentials and polarizations are stable under a phase disturbance of any laser beam, it should be easier to realize adiabatic cooling (12) in the moving frame as the last phase of the atomic launch.

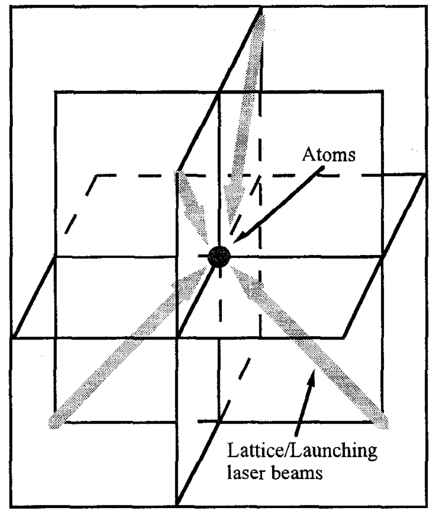

Figure 3: 4-beam optical lattice diagram. This geometry of laser beams forms an optical lattice. The atoms in the lattice can be launched as well as cooled by tuning the two upward going laser beams to a higher frequency than the downward going laser beams.

It should be noted that some of these advantages are also realized in a six beam launching scheme (5). The primary advantages of a 4-beam lattice launch should be in ease of realization and engineering.

We have set up a preliminary version of a launch from a four beam optical lattice. The atoms are collected in a magneto-optical trap. The magneto-optical trap is then turned off and the lattice beams are turned on with different frequencies for the upward and downward going beams.

Using this system, we have been able to accelerate the atoms from rest to launch velocities of up to 7.2 m/s in 1.5 milliseconds. This acceleration was achieved with the average frequency of the lattice beams 8 MHz to the red of the atomic resonance and with a peak intensity of 0.6 mW/cm^2 in each lattice beam. By having the upward going laser beams close to resonance (roughly one half to one linewidth), the initial imbalance in the scattering rate between upward and downward going beams, and therefore the initial vertical acceleration, is enhanced. It should be noted that after this initial, violent launch, the atoms are hot. The lattice laser beams will then need to have their detuning and intensity changed to further cool the atoms in the moving frame to be useful in a fountain.

For these tests, a light sheet was positioned a short distance above the launch location to monitor the initial launch conditions. We saw no change in the number of launched atoms for launch velocities from 2.4 meters/second to 7.2 meters/second. These initial velocities would correspond to launch heights of 0.29 to 2.6 meters.

We have also cooled the atoms to temperatures of less than 1.5 μK in an optical lattice with no launch. These temperatures should be achievable in the moving frame as well. With the optimization of the final adiabatic expansion phase (13) the temperature should be even further reduced.

In initial attempts to launch atoms with a second post-cooing phase in the moving frame, we have realized a launch with a 2 μK temperature and a 0.75 m/s launch velocity. Final fountain launch heights will have to wait for a reconstruction of our vacuum chamber.

In the near future, we plan on extending this four beam lattice launch in several ways. The first will be to optimize the separate initial launch and subsequent cooling parameters of the lattice in the moving frame. The last cooling in the lattice will be an adiabatic expansion of the lattice wells by ramping down the intensity of the laser beams. In addition, all of the beams will be optical fiber coupled directly to the vacuum chamber, improving the spatial quality of the lattice.

Conclusion

In conclusion we have outlined our goals for building an atomic fountain at the U. S. Naval Observatory with an emphasis on stability over accuracy. We have presented an idea for reducing the overall temperature dependence of the fountain by designing the apparatus so that the temperature dependencies of the black body shift and the cavity line pulling cancel. Finally, we described our work with a four-beam optical lattice including preliminary results for both cooling and launching.

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