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RACE: LASER-COOLED RB MICROGRAVITY CLOCK

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Abstract

RACE is a high performance Rb clock slated to fly on the International Space Station. RACE aims to realize high accuracy and short-term stability. The cold collision shift and multiple launching (juggling) have important implications for the design and the resulting clock accuracy and stability. We present and discuss the double clock design for RACE. This design reduces the noise contributions of the local oscillator and simplifies and enhances an accuracy evaluation of the clock.

1. Introduction

The principal advantage of microgravity for atomic clocks is interrogation times longer than 1 s. With a 10 s interrogation time, a clock has a 50 mHz linewidth suggesting that accuracies may approach 10^{-17}. However, to achieve greater accuracy within the same averaging time, greater stability is needed.

RACE, the Rubidium Atomic Clock Experiment, is based on Rb to circumvent the large cold collision shift of Cs. This may allow simultaneously high short-term stability and accuracy. For RACE, we have 3 primary goals:

1) Demonstrate new clock techniques for laser-cooled atoms to enable frequency comparisons with accuracies of 1 part in 10^{17}.
2) Significantly improve the classic clock tests of general relativity.
3) Distribute accurate time and frequency from the ISS.

In this paper, we review the design constraints and discuss the double clock design for RACE.

2. Cold-Collision Frequency-Shift in Microgravity

As in fountains, the frequency shift due to cold collisions[1] plays an important role in the design of a microgravity clock. For RACE, we have chosen Rb because the cold collision shift is 30 times smaller than that for Cs.[2-4] One might naively expect that the cold collision shift is much less in microgravity since the interrogation time is so long and therefore the atoms spread out and have a much lower density. However, the requirement that the stability be high enough so that the accuracy is achieved in 1 day of averaging (10^5 s) demands high S/N, and therefore the collision shift is non-negligible.

It is interesting to examine the scaling of the cold collision shift with the interrogation time T with a fixed physical size of the clock and also demanding the same short-term stability. The fractional stability for 1 s of averaging is $\frac{\delta\upsilon}{\upsilon}=\sigma(\tau=1s)=\frac{\Delta\upsilon}{\pi\upsilon S/N}$ where S/N is the signal to noise, ν is the transition frequency, and $\Delta\nu$ is the transition linewidth. If the S/N is limited by shot-noise, then $S/N=\sqrt{N}=\sqrt{n_f A\frac{L}{T}(1s)}$ where N is the number of detected atoms, n_f is the final atomic density, A is the area of the cavity aperture, and L is the length of the interrogation region. Given the equation for the instability at 1 s, we then get $n_f=\frac{1}{\left[2\pi\upsilon\sigma(1s)\right]^2 ALT(1s)}$. Assuming that the source is 20 cm from the cavity and the cavity is 50 cm long, this geometry implies that the average density is 7.8 times the final (for interogation times of 3-100s). Therefore, the collision shift, for a fixed length and short-term stability, scales as 1/T so that the long interrogation times in microgravity helps to decrease the frequency error due to cold collisions.

Specifically, with T=10s, a short-term stability of $\sigma_y(\tau) = 3\times10^{-15}\tau^{-1/2}$ requires S/N = $600\,\tau^{-1/2}$, which is not technically challenging. This implies that 0.4×10^6 Cs atoms/s are detected and, with a 1.1 cm microwave cavity aperture and a 5 cm/s launch velocity, the *final* density is $n_f = 7\times10^4$ cm^{-3}, and the average density n = 6×10^5 cm^{-3} producing a cold collision shift of -1.4×10^{-15}. This can be extrapolated to an accuracy of about $\pm1\times10^{-16}$. Using the same length, interrogation time, and short-term stability for ^{87}Rb, we get a collision shift of -3×10^{-17} collision which can be cancelled by spin exchange tuning with a likely uncertainty less than 10^{-17}.[3]

3. Comparison of Microgravity Rb and Cs Clocks

Given that the collision shift is much smaller for ^{87}Rb than for Cs, it is interesting to compare the potential performance of Rb and Cs clocks in microgravity. One of the important differences is the smaller hyperfine transition frequency of ^{87}Rb. For terrestrial fountains the linewidth is essentially fixed at 1 Hz and a 30% lower line Q for ^{87}Rb has some impact on the clock's performance. In microgravity, a T=10 s interrogation time implies a very high Q of 1.4×10^{11}. On earth, increasing the Q is difficult as the fountain height increases as T^2 whereas in microgravity, the length of the clock only increases linearly (or not at all if the launch velocity is reduced).

The short-term stability is also not adversely affected by the lower hyperfine frequency ν. For a lower ν, the size of the hole in the cavity can be larger so that the area increases as ν^{-2}. Therefore the shot-noise-limited S/N scales as ν^{-1} so that the stability is independent of ν. One could argue that the lower transverse velocities achievable with Cs, as compared to Rb, allow 3 times as many atoms to be detected. However, for both cases, one can easily have enough phase space density to reach a short-term stability of $\sigma_y(\tau) = 1\times10^{-15}\,\tau^{-1/2}$ so that the important limitation to the stability of a Cs clock is that the density must be reduced to manage the cold collision shift.

4. Stability of Microgravity Clocks

If we launch a single ball of ^{87}Rb atoms through the microgravity clock (see Fig. 1), we can calculate the uncertainty in the frequency. Here, for an interrogation time T = 10 s, we detect 10^6 atoms so that the signal-to-noise S/N is 10^3.

$$\frac{\delta\upsilon}{\upsilon} = \frac{\Delta\upsilon}{\pi\upsilon \mathrm{S/N}} = 2.3\times10^{-15}$$

Launching a ball of atoms approximately every T = 10 s gives an Allan variance of

$$\sigma_y(\tau) = \frac{\Delta\upsilon}{\pi\upsilon \mathrm{S/N}}\sqrt{\frac{T}{\tau}} = 7.3\times10^{-15}\Big/\sqrt{\tau}.$$

Since Δν and S/N both scale as 1/T, the Allan variance is proportional to $T^{1/2}$. This seemingly presents a serious problem if we require higher stability to achieve the high potential accuracy of microgravity clocks.

Multiply launching balls of atoms, or juggling,[5] allows one to reclaim the high stability potential of a microgravity clock. By launching atoms at a rate $R = 5\ \mathrm{s}^{-1}$, the stability is

$$\sigma_y(\tau) = \frac{\Delta\upsilon}{\pi\upsilon \mathrm{S/N}\sqrt{R\tau}} = 1\times10^{-15}\Big/\sqrt{\tau}$$

which is independent of the interrogation time T. This clearly indicates the importance of juggling to achieve high stability and accuracy in laser-cooled microgravity clocks.

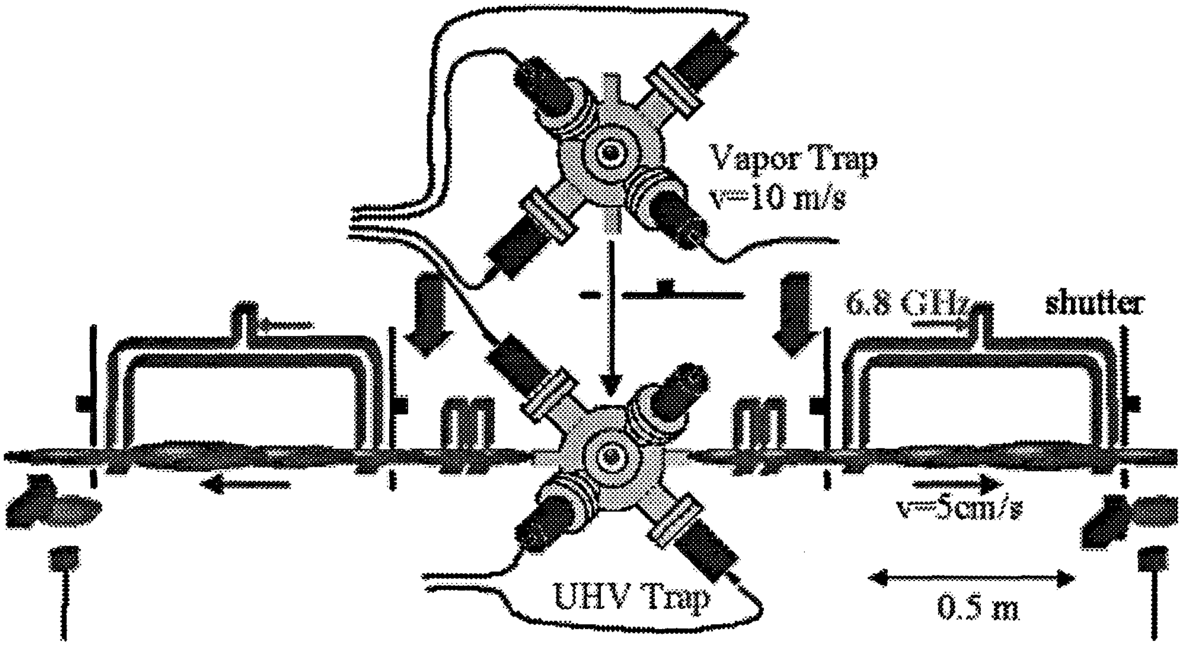

Figure 1. Schematic for juggling microgravity Rb clock RACE. The double MOT launches atoms at high speed from the (upper) vapor trap to the (lower) UHV trap so that the shutter between the traps can be nearly always closed. The shutters between the UHV trap and the cavities are nearly always open except during the ≈5ms that the light for the UHV trap is turned on. The atoms are alternately launched left or right to go through one clock cavity or the other.

5. Design of Juggling Clocks and RACE

Multiple launching imposes several constraints on the design of a microgravity clock. Shutters are needed to block the light scattered from trapping, state preparation, and detection from the interrogation region. In Fig. 1, we show a design for a juggling microgravity clock that has a pair of shutters surrounding the Ramsey cavity. This is a design for our Rb microgravity clock, RACE. First we discuss the laser trapping and cooling techniques and then the advantages of have 2 clock cavities.

The double-MOT[5,6] allows a high throughput of cold atoms and therefore a high short-term stability. The high throughput is possible as the double-MOT can rapidly capture many cold atoms and then efficiently launch them through the Ramsey cavity. The "upper" vapor cell trap in Fig. 1 essentially continually traps atoms and then launches them at 5-10 m/s to the UHV trap "below." Because of the high launch velocity from the vapor cell trap, the atoms pass quickly through the shutter separating the 2 traps. This implies that the shutter only needs to open for the short time the ball of atoms flies through and, only during that time, the lasers for the vapor-cell trap must be extinguished (so that no laser light enters the interrogation region).

The real advantage of the double-MOT design is that the UHV trap can capture and launch a ball of atoms in as little as 5 ms. This implies that the shutter separating the UHV trap and interrogation region only has to close for 5 ms for each launch and therefore is nearly always open. This allows a high throughput since, if the shutter is ~10 cm from the center of the UHV trap, the ball of atoms will have expanded considerably before reaching the shutter. For our juggling Cs experiment,[5] it was crucial to reduce the trapping and cooling time of the UHV trap be able to study collisions at low energies (juggling rates as high as 140 s^{-1}).

One also has to worry about the effect of the trapping light on the previously launched ball of atoms from the 2nd trap. Again, this was a crucial step in our Cs juggling experiment. By "hiding" the ball in the lower hyperfine state immediately after the launch, and by carefully controlling the low intensity repumping light to the 2nd trap, we can capture and launch balls of atoms essentially on top of one another.[5]

The RACE schematic in Fig. 1 shows 2 clock cavities. After atoms are collected in the lower laser trap, they are launched either through one cavity or the other. Having 2 cavities is important for a number of reasons which we discuss below. One advantage is that it greatly reduces the requirements for the local oscillator. Few oscillators can perform at the $\sigma_y(\tau) = 3\times10^{-15}\,\tau^{-1/2}$ level and there is significant work required to develop their flight worthiness. The essential problem with only a single cavity is that the microwave frequency fed to the cavity must be changed from one side of the transition to the other. During the switchover, all of the atoms must be cleared from the cavity and this means the oscillator is not tracked for about 10s when T = 10s. With 2 cavities, we can do the switchover for one cavity while still monitoring the oscillator with the other cavity and therefore the stability of the clock isn't compromised by the local oscillator's instability.

Vibrations on the ISS in the direction of the launch velocity with cause a noise in the interrogation time. With 2 cavities, the 2 detected signals will behave oppositely so that the effects of vibrations can be identified, correlated with an accelerometer, and removed.

One of the largest systematic errors is the AC Stark shift due to Blackbody radiation at 300K. A measurement of the red shift and time dilation with frequency inaccuracies of 10^{-17} demands absolute knowledge of the average temperature in the clock cavity at the 0.01K level. Having 2 cavities will allow a critical check on our accuracy evaluation.

In addition, having 2 cavities gives important redundancy. For example, if a shutter fails, we will still be able to achieve mission success goals (although require longer averaging times).

6. ConclusionS

To achieve the potential accuracy of laser-cooled microgravity clocks with reasonable integration times, atoms must be multiply launched (juggled). The short-term stability is proportional to the launch rate and this in turn implies that high accuracy and stability favor long interrogation regions. Laser-cooled microgravity clocks can achieve short-term stabilities approaching $\sigma_y(\tau) = 3\times10^{-15}\,\tau^{-1/2}$. At this stability, the largest error in a Cs microgravity clock is the cold collision frequency shift. By using ^{87}Rb, the collision shift is 30 times smaller allowing an accuracy of 10^{-17}. Finally, we propose a design using a double-MOT and 2 cavities which simplifies the trapping and shutter design while maintaining a high throughput of cold atoms, minimizes the local oscillator requirements, eliminates vibrations, and provides failure and accuracy redundancy.

7. Acknowledgements

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8. References

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