LASER-COOLED MICROGRAVITY CLOCKS

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Introduction

The principle 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 potentially exceed 10^{-16}. However, to achieve greater accuracy within the same averaging time, greater stability is needed. Achieving greater stability in a microgravity clock constrains the design differently than for earth based fountains.

In this paper, we will discuss the design considerations for laser-cooled microgravity clocks highlighting the considerations that differ from those for earth-based fountains. As in earth-based fountains, the frequency shift due to cold collisions[1] plays an important role in the design of the clock. Given our predictions[2] (and measurements[3]) for the shift in laser-cooled Rb clocks, we currently anticipate building a high performance Rb clock and will discuss the relative merits of Rb and Cs microgravity clocks. Finally, we will present our tentative designs for 2 microgravity clocks that are scheduled to fly in the coming years.

Microgravity Clock Configurations

The three basic types of laser-cooled microgravity clocks are shown in Fig. 1. In the *in situ* clock, it is difficult to get the trapping beams, the detection laser beam, and the scattered fluorescence in and out of the cavity. The design also leads to trade-offs in the design of the microwave cavity. More importantly, this simple design precludes achieving high stability by juggling atoms as discussed below.

The preferred configuration for a laser-cooled space clock is a traditionally "Ramsey" beam tube. This design allows juggling and therefore high stability. The one drawback is an end-to-end cavity phase. This is not so serious given the 50 mHz transition linewidth and the ease with which the interrogation time can be changed in a laser-cooled clock to evaluate the end-to-end cavity phase shift.

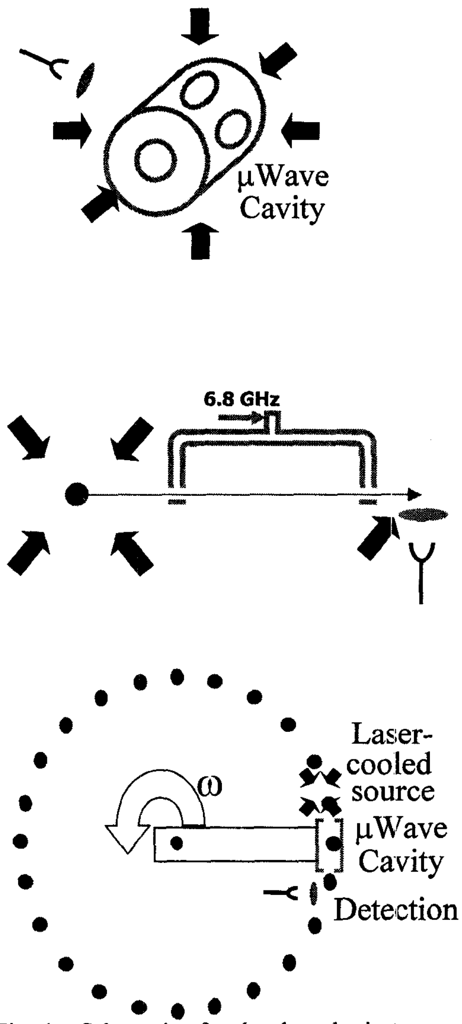

Fig. 1. Schematics for the three basic types of laser-cooled microgravity clocks: (a) *in situ* interrogation (b) traditional Ramsey beam clock (c) space fountain.

It is possible to construct a fountain in space as in Fig. 1. Here, since there's "no" gravity to return the atoms through the cavity, the laser-cooled source, cavity, and detection optics must rotate twice through each sample of trapped atoms. This is clearly more cumbersome and complex than the traditional cavity. It doesn't seem that the extra expense and weight is justified to eliminate the small end-to-end shift. It is interesting to note that a spin rate of a few rpm, used for free flying satellites, gives 5-10 mHz linewidths so that this may not be such a whimsical design for these.

Stability of Microgravity Clocks

If we launch a single ball of ^{87}Rb atoms through the beam clock in 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.

$$\frac{\delta \upsilon}{\upsilon} = \frac{\Delta \upsilon}{\pi \upsilon \mathrm{S/N}} = 2.3\times 10^{-15}$$

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

$$\sigma_y(\tau) = \frac{\Delta \upsilon}{\pi \upsilon \mathrm{S/N}}\sqrt{\frac{T}{\tau}} = 7.3\times 10^{-15} \Big/ \sqrt{\tau}.$$

Since $\Delta\nu$ and S/N both scale as 1/T, the Allan variance is proportional to $T^{½}$. This seemingly presents a serious problem if we require higher stability to achieve the high accuracy potential of microgravity clocks.

Juggling allows one to reclaim the high stability potential of a microgravity clock. By launching atoms at a rate R = 5 s^{-1}, the stability is

$$\sigma_y(\tau) = \frac{\Delta \upsilon}{\pi \upsilon \mathrm{S/N}\sqrt{R\tau}} = 1\times 10^{-15} \Big/ \sqrt{\tau}$$

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.

Design of Juggling Clocks

Juggling, or multiple launching, in a microgravity clock imposes several constraints on the design. First, shutters are needed to block the light scattered from trapping, state preparation, and detection from the interrogation region. A pair of shutters is shown in Fig. 2 surrounding the Ramsey cavity. Since we need many atoms for

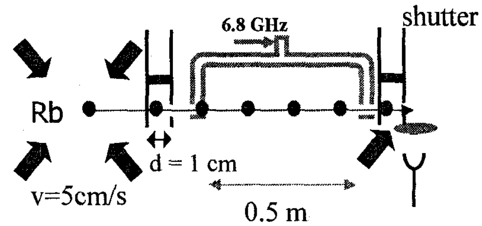

Fig. 2. Schematic for a juggling clock. Rotary shutters block scattered light from the atoms flying through the interrogation region.

high stability, the size of each ball will be on the order of d = 1 cm. Therefore, a launch rate of R = 5 s^{-1} and a distance between shutters of 1 cm implies a launch velocity of v = R×d = 5 cm/s.

Having determined the launch velocity, an interrogation time of T= 10 s then dictates a length of the interrogation region of L = R×d×T = 0.5 m. Since there are always size and weight restrictions for a microgravity clock, another view is that for a given interrogation time T and cavity length L, there is a maximum launch rate R ≤ L/dT. In addition, as will be discussed below, making L > R×d×T reduces the cold collision shift.

The maximum launch rate and its impact on the collision shift are quite different than in earth-based fountains. For fountains, as T increases higher launch rates are easier because the launch velocity is proportional to T so that atoms leave the launching region more quickly giving a constraint R ≤ gT/2d. In the juggling work presented earlier,[3] we demonstrated juggling launches with delays as short as 7 ms corresponding to R = 140 s^{-1}. In fact, a launch rate more than 30 to 50 s^{-1} will probably be too fast as the cold collision shift increases for low collision energies $E_{coll} = mg^2/4R^2$. This is not a limitation in microgravity clocks as the juggled balls do not have to pass through one another. However, the juggling does increase the density of atoms in the clock as described below.

In Table 1, we summarize the performance for three illustrative designs. The essential points are: 1) The short-term instability is independent of T & L (for long T) and is proportional to $R^{-½}$ so that high launch rates are advantageous; 2) For T>10 s, shot-noise limited detection is achievable so that stability doesn't improve but accuracy should; 3)

Table 1. Stability and linewidth for various clock design parameters.

T = 10 s	R = 5 s^{-1}	L = 0.5 m	$\sigma_y(1s)=1\times10^{-15}$	$\Delta\nu$ = 50 mHz
T = 10 s	R = 1 s^{-1}	L = 0.1 m	$\sigma_y(1s)=2\times10^{-15}$	$\Delta\nu$ = 50 mHz
T = 50 s	R = 1 s^{-1}	L = 0.5 m	$\sigma_y(1s)=2\times10^{-15}$	$\Delta\nu$= 2 mHz

A high launch rate R lessens the demands on the flywheel oscillator; 4) The length of the clock is $L > R \times d \times T$ so that there is an obvious trade-off of size and cost versus performance. Finally, we note that some systematic errors, such as the quadratic Zeeman shift, are in principle proportional to R although, for ranges considered here, these are unimportant.

Cold Collision Frequency Shift in Microgravity

Intuitively, one might 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 10^4 to 10^5 s, demands high S/N and therefore the collision shift is problematic.

Specifically, for a launch rate of $R = 5\ s^{-1}$ and with S/N = 1700, the short-term stability is $\sigma_y(\tau) = 1\times10^{-15}\,\tau^{-1/2}$. This implies that 3×10^6 atoms/s are detected and, with a 1.1 cm microwave cavity aperture, the *final* density is $n = 0.6\times10^6\ cm^{-3}$ producing a cold collision shift of -1×10^{-15} which can be extrapolated to an accuracy of $\pm1\times10^{-16}$. Of course the density when the atoms enter the interrogation region must be substantially higher. If Raman velocity selection is used to narrow the transverse velocity distribution,[1,4] the average density will be about 4 times higher leading to an inaccuracy of 4×10^{-16}.

In this analysis, we've assumed that the length of the interrogation region is $L = R \times d \times T$. For $L > R \times d \times T$ ($v > R \times d$), the average density scales as 1/L since the atoms will be spread over a larger distance. Essentially, this is just compromising the stability for accuracy since a higher R could be used with a longer L. Since the same results could be achieved using a lower density per ball and a higher R, this strategy is probably preferred.

Without Raman velocity selection, the shift must be greater than 10^{-13} to achieve $10^{-15}\,\tau^{-1/2}$ stability for a launch temperature of 1 μK. Even for Rb clocks with small cold collision shifts, it is clear Raman velocity selection is needed to achieve high stability and accuracy.

Comparison of Microgravity Rb and Cs Clocks

Given that the collision shift is small for at least one of the Rb isotopes, 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 the Rb isotopes, especially ^{85}Rb where $\nu = 3035$ MHz. While this is a serious limitation for terrestrial fountains where the linewidth is essentially fixed at ≈ 1 Hz, for a T=10 s interrogation time, the line Q is still nearly 10^{11} and can easily be higher.

We've already noted that the short-term stability is independent of the interrogation time and here we show it's also independent of the hyperfine frequency ν. For a higher ν, the size of the hole in the cavity must be smaller so that the area decreases 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 offer an advantage of a factor of about 2 in stability over Rb. However, for both cases, one can easily achieve enough phase space density to reach a short-term stability of $\sigma_y(\tau) = 1\times10^{-15}\,\tau^{-1/2}$ so that the significant limitation to the stability of a Cs clock is that the density must be lowered to manage the cold collision shift

Space Clock Designs

We currently have 2 projects scheduled for flight. The first is a technology demonstration experiment with an emphasis on low-cost and short time-to-launch. The flyable laser system is being developed in collaboration with Lute Maleki's group at JPL. The "clock" will essentially be a space-qualified Cs MOT with a commercial Cs beam tube "bolted on" as shown in Fig. 3.[5] For simplicity, there will be no shutters for multiple launching but we would like to implement a detection shutter for faster data accumulation. State preparation will be done with a microwave selection and a clearing laser beam.

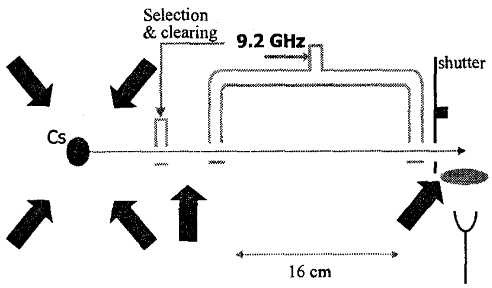

Fig. 3. Schematic for the Microgravity Glovebox Cs clock. Laser beams for trapping, clearing after microwave state selection, and optical detection are shown.

One of the problems with the design of Fig. 2 is that the first set of shutters must be very close to the trap. If they're not, they block about half of the atoms since the atomic clouds spread by more than a ball diameter before the ball reaches the shutter for small (v = 5 cm/s) launch velocities. Of course, placing the shutters close to the trapping beams presents other difficulties.

In Fig. 4, we show our concept for the high performance laser-cooled Rb microgravity clock. Here, we circumvent the shutter problem by using a double-MOT[6] trapping system. Atoms are launched at high speed from the first MOT. With a launch rate of $R = 5\ s^{-1}$, successive balls of atoms are well separated. The first shutter opens only for a short time to let the ball of atoms through and when it opens, the trapping light is turned off. The 2nd trap then catches the ball of cold atoms. The essential point here is that the light for the 2^{nd} trap only has to be turned on for ≈5 ms to launch the ball at 5 cm/s through the clock. For our juggling Cs experiment,[3] this step was crucial to be able to study collisions at low energies (high juggling rates). In this way, the 2^{nd} shutter only has to close for 5 ms while the light for the 2^{nd} trap is turned on and it can therefore be placed relatively far from the 2^{nd} trap.

One also has to worry about the effect of the trapping light on the previously launched ball of atoms from the 2^{nd} trap. Again, this was a crucial step in the 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 2^{nd} trap, we can capture and launch balls of atoms essentially on top of one another.[3] In Fig. 4, the state selection is shown schematically as a series of 2 microwave cavities. In fact, if we measure that the cold collision shifts for the Rb isotopes are not smaller than what we calculate,[3] these will be

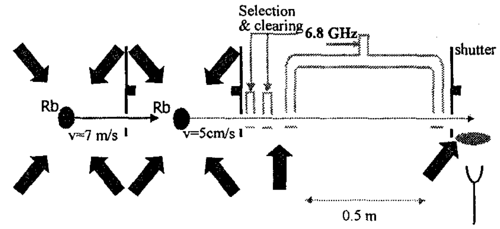

Fig. 4. Schematic for juggling microgravity Rb clock. The double MOT launches atoms at high speed from one trap to the other so that the first shutter can be nearly always closed while the 2^{nd} is nearly always open except during the ≈5ms that the light for the 2^{nd} trap is turned on.

replaced with state and velocity selection using 2 additional lasers.

Conclusion

To achieve the potential accuracy of laser-cooled microgravity clocks with reasonable integration times, atoms must be multiplied launched (juggled). The short-term stability is proportional to the launch rate and this in turn implies that high accuracy and stability require long interrogation regions. To manage the cold collision shift, Raman velocity selection will be required in order to achieve stabilities approaching $\sigma_y(\tau) = 1\times10^{-15}\ \tau^{-1/2}$. Since the cold collision shift is likely to be the largest error, we expect Rb clocks will offer better stability and accuracy. The design of our high performance Rb clock is based on a double-MOT. This configuration simplifies the trapping and shutter design while maintaining a high throughput of the cold atoms.

Acknowledgements

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