1999 Joint Meeting EFTF - IEEE IFCS

LASER-COOLED MICROGRAVITY CLOCKS

Chad Fertig,[1] Kurt Gibble,[1]
Bill Klipstein,[2] James Kohel,[2] Lute Maleki,[2] David Seidel,[2] and Rob Thompson[2]
Yale University, New Haven, CT 06511[1]
Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109[2]

ABSTRACT

Designs for planned space clock missions are described. The cold collision shift and multiple launching (juggling) have important implications for the design and the resulting clock accuracy and stability. In a recent fountain experiment, we have demonstrated some of the trapping and cooling techniques for our design of a microgravity 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 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 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.

2. GLACE

We currently have 2 projects scheduled for flight. The first is GLACE (Glovebox Laser-cooled Atomic Clock Experiment), a clock demonstration experiment for the ISS Glovebox with an emphasis on low-cost and short time-to-launch. The "clock" will essentially be a space-qualified Cs MOT with a state selection cavity and commercial Cs beam tube "bolted on" as shown in Fig. 1.

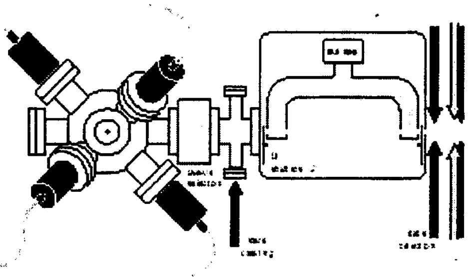

Fig. 1. Schematic for the Microgravity Glovebox Cs clock, GLACE. Laser beams for trapping, clearing after microwave state selection, and optical detection are shown.

3. COLD-COLLISION FREQUENCY-SHIFT IN MICROGRAVITY

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 10^5 s demands high S/N, and therefore the collision shift is problematic.

Specifically, with $\Delta\nu = 50$ mHz, a short-term stability of $\sigma_y(\tau) = 1\times10^{-15}\,\tau^{-1/2}$ requires $S/N = 1700\,\tau^{-1/2}$, which is not technically challenging. This implies that 3×10^6 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 $n = 0.6\times10^6$ cm^{-3} producing a cold collision shift of -1×10^{-15}. This can be extrapolated to an accuracy of $\pm1\times10^{-16}$. Of course the density when the atoms enter the interrogation region must be 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}.

Without Raman velocity selection, the shift for Cs is of order 10^{-14} to achieve $10^{-15}\,\tau^{-1/2}$ stability. For an ^{87}Rb microgravity clock, with a cold collision shift more than 100 times smaller, it may be possible to have these high stabilities and avoid Raman velocity selection.

0-7803-5400-1/99/ $ 10.00 © 1999 IEEE

4. 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 needs to be considered. In microgravity, a T=10 s interrogation time implies a very high Q of 1.4×10^{11}. On earth, increasing the Q becomes very 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.

5. 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 $\Delta\nu$ 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 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.

6. DESIGN OF JUGGLING CLOCKS

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. 2, 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 (Rb Atomic Clock Experiment).

The double-MOT[5,6] design 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 left-most vapor cell trap in Fig. 2 essentially continuously traps atoms and then launches them at 5-10 m/s to the UHV trap. 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 feature 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 shutter separating the UHV trap and interrogation region only has to close for 5 ms for each launch and therefore is always open. This allows the 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 (high juggling rates).

One also has to worry about the effect of the trapping light on the previously launched ball of atoms

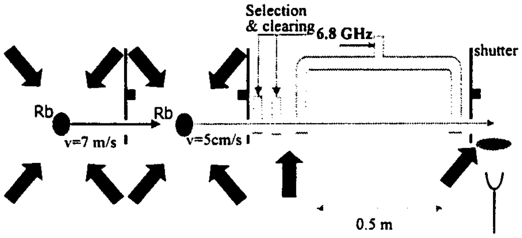

Fig. 2. Schematic for juggling microgravity Rb clock. The double MOT launches atoms at high speed from one trap to the other so that the first shutter can be nearly always closed while the 2nd is nearly always open except during the ≈5ms that the light for the 2nd trap is turned on.

from the 2nd 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 2nd trap, we can capture and launch balls of atoms essentially on top of one another.[5]

To achieve a high short-term stability, the diameter of each ball will be on the order of d = 1 cm. Therefore, a launch rate of $R = 5\ s^{-1}$ implies a launch velocity of $v \approx R \times d = 5$ cm/s since ball must leave the repumping beam of the UHV MOT before the next ball can be captured.

Having determined the launch velocity, an interrogation time of T= 10 s then dictates a length of the interrogation region of $L = R \times d \times T = 0.5$ 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 $R \leq L/(d\ T)$.

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 $R \leq gT/2d$. In the juggling work presented earlier,[5] 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 $E_{coll} = m\ g^2 / 4\ R^2$. 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.

7. 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 $\sigma_y(\tau) = 1\times10^{-15}\,\tau^{-1/2}$. At this stability, the largest error in a Cs microgravity clock is the cold collision frequency shift. To manage the cold collision shift, Raman velocity selection will be required to achieve stabilities below $1\times10^{-14}\,\tau^{-1/2}$. For ^{87}Rb, the cold collision shift appears small enough that Raman velocity selection might be avoidable. Finally, we propose a design using a double-MOT which simplifies the trapping and shutter design while maintaining a high throughput of cold atoms.

8. ACKNOWLEDGEMENTS

Financial support from NASA is acknowledged.

9. REFERENCES

1. K. Gibble and S. Chu, Phys. Rev. Lett. **70**, 1771 (1993).
2. S. J. J. M. F. Kokkelmans, B. J. Verhaar, K. Gibble, and D. J. Heinzen, Phys. Rev. A. **56**, 4389 (1997).
3. C. Fertig, R. Legere, W. Süptitz, and K. Gibble, "Laser-Cooled Rb clocks" in these proceedings (1998).
4. M. Kasevich, D. S. Weiss, E. Riis, K. Moler, S. Kasapi, and S. Chu, Phys. Rev. Lett. **66**, 2297 (1991).
5. R. Legere and K. Gibble, Phys. Rev. Lett. 81, 5780 (1998).
6. K. Gibble, S. Chang, and R. Legere, Phys. Rev. Lett **75**, 2666 (1995).