Laser-Cooled ^{87}Rb Clock

Chad Fertig and Kurt Gibble

***Abstract*—We demonstrate a prototype of a laser-cooled ^{87}Rb fountain clock. We report a preliminary measurement of the frequency shift due to cold collisions and find the shift to be at least a factor of ten less than that in a laser-cooled Cs clock. We also demonstrate the use of the ac Zeeman shift to measure the response of a microwave cavity. Finally, we have demonstrated a juggling atomic fountain and discuss the application of this technique to fountain and microgravity atomic clocks.**

***Index Terms*—Atomic clock, microwave resonators, microwave spectroscopy, rubidium materials/devices.**

I. Introduction

THE most serious systematic error in laser-cooled clocks is the frequency shift due to cold collisions. Tiesenga *et al.* first calculated this shift [1] and Gibble and Chu [2] measured the shift for laser-cooled cesium (Cs) clocks to be $\delta\nu/\nu = -1.7 \times 10^{-12}$ at a density of 10^9 cm^{-3}. Due to Cs_2 molecular bound states near zero energy, the frequency shift cross section has nearly the maximal value of $\lambda_{\rm dB}^2/2\pi$, where $\lambda_{\rm dB}$ is the de Broglie wavelength. This large cross section led us to examine clocks based on other atoms, for which the cold collision shift might be smaller [3], [4].

In this paper, we describe the first operation of a rubidium (^{87}Rb) fountain frequency standard. We report the first indications of a small cold-collision frequency-shift for ^{87}Rb and demonstrate a novel technique to measure cavity mistunings. We also discuss our recent demonstration of a juggling atomic fountain. Juggling fountain clocks can achieve higher stability without requiring large improvements in the local oscillator. In this first juggling experiment, we studied the effects of collisions between two balls of Cs atoms.

II. Laser-Cooled ^{87}Rb Clock

A schematic of our laser-cooled Rb fountain clock prototype is shown in Fig. 1. The all-solid-state laser system consists of a frequency-stabilized external-cavity grating diode laser that injects six slave lasers, one for each trapping beam. We collect as many as 5×10^{10} ^{87}Rb atoms in the vapor cell MOT [5], [6] and then launch the atoms by cooling them to a temperature of 1.85 μK in a frame moving upward at (3–4) m/s.

We prepare nearly 50% of the atoms in the $|F=1, m=0\rangle$ clock state using the two TE_{102} selection cavities (Fig. 1). After launching, we first optically pump the atoms into the $F=1$ state using light tuned to the $5S_{\frac{1}{2}}$ $F=2 \rightarrow 5P_{3/2}$ $F'=1'$ transition. The lower selection cavity transfers the atoms from the $|F=1, m=0\rangle$ state to the $|2,0\rangle$ state. A laser tuned to the $5S_{\frac{1}{2}}$ $F=1 \rightarrow 5P_{3/2}$ $F'=2'$ transition optically pumps the atoms remaining in $F=1$ to $F=2$, thereby increasing the population in the $|2,0\rangle$ state. The upper selection cavity then transfers the population in the $|2,0\rangle$ state to the $|1,0\rangle$ state. We then clear away the atoms in the $|F=2, m\neq0\rangle$ states by scattering several thousand photons from a laser beam tuned to the $5S_{\frac{1}{2}}$ $F=2 \rightarrow 5P_{3/2}$ $F'=3'$ cycling transition.

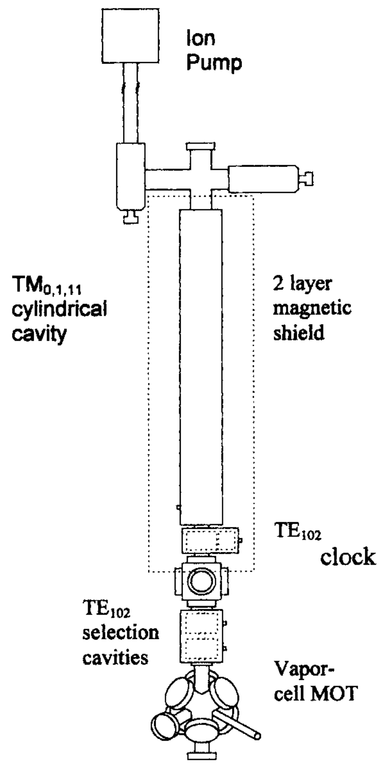

Fig. 1. Schematic of the ^{87}Rb fountain clock.

Ramsey fringes with a width of 0.82 Hz for a 46 cm high fountain are shown in Fig. 2. Using a shorter fountain with a 1 Hz linewidth, we obtain an SNR of 120:1 for each launch (limited by the local oscillator) yielding a short-term stability of $\sigma_y(\tau) = 4\times10^{-13}\tau^{-\frac{1}{2}}$. The center frequency in Fig. 2 is at 6 834 682 610.9 Hz and the accuracy of this is limited by the accuracy of a GPS-slaved reference oscillator. The magnetic bias field is 710 μG throughout the cavity and flight region, which we probe by exciting a $\Delta m = 1$ (sigma) transition in the cylindrical $TM_{0,1,11}$ cavity. This bias field produces a quadratic Zeeman shift of $\delta\nu/\nu = 4 \times 10^{-14}$.

We have performed a preliminary measurement of the cold collision shift for ^{87}Rb. To measure the shift, we vary the

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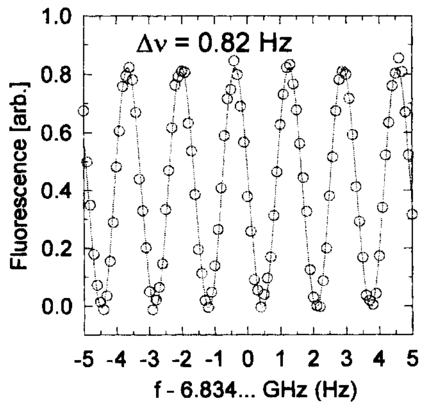

Fig. 2. The ^{87}Rb Ramsey fringes. The circles are the data and the line is a fit to the data. The linewidth is 0.82 Hz.

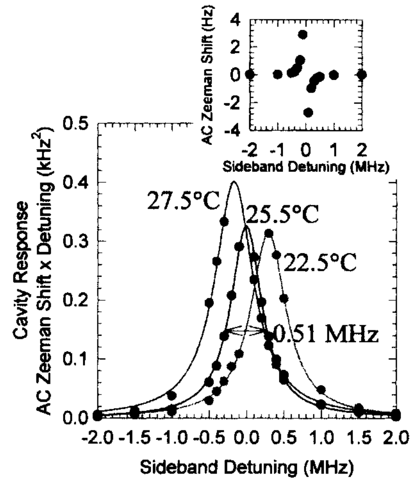

Fig. 3. Cavity response versus microwave frequency for three temperatures. The cavity response is measured using the ac Zeeman shift of the clock transition due to a microwave sideband. The small inset shows the ac Zeeman shift for various sideband detunings.

atomic density by varying the strength of the microwave field in the upper selection cavity. The measured shift is $+0.25(17)$ mHz for a density of 10^9 cm^{-3}, which does not agree with the predicted shift of -0.8 mHz [4]. We are currently looking for potential systematic errors in the measurement. However, our preliminary search for systematic errors indicates no errors near the size of the cold collision shift for Cs so that it is already clear the collision shift for ^{87}Rb is at least a factor of ten smaller than that for Cs.

III. Laser-Cooled Clocks Based on Other Atoms

We have also considered building clocks, especially in microgravity, based on ^{85}Rb. For ^{85}Rb, the calculated cold collision shifts are more interesting. We predict [3] that the frequency shift produced by the population in the $|F = 3, m = 0\rangle$ state is $+45$ mHz at $n = 10^9$ cm^{-3} and, for the $|F = 2, m = 0\rangle$, -5 mHz. By adjusting the strength of the first microwave pulse in the clock cavity, one can vary the population ratio of the two clock states in the fountain to cancel the cold collision shift [3]. Using this method, the extrapolation of the shift to zero density doesn't rely on accurate measurements of density ratios and may potentially allow much higher clock stability and accuracy.

IV. Measuring the Response of a Cavity

A large detuning of a high-Q clock cavity can mimic, and even cancel, the cold collision frequency shift. Traditionally, the resonant frequency of the cavity is measured electrically, either in reflection, or preferably, in transmission. Recently, Drullinger *et al.* have used the offset of the $m = 0$ Rabi pedestal from the Ramsey resonance to ascertain the cavity mistuning [7]. Here we show that the ac Zeeman shift of the clock transition due to a RF spectral component can be used to map the response of the cavity.

To measure the cavity response, we introduce a strong RF single sideband into the feed to the clock cavity. In detail, for the sideband we use $+15$ dBm from a tunable microwave frequency synthesizer (HP 83 711B) and use a power combiner to combine it with the usual clock signal. The clock signal comes from a 6880 MHz dielectric resonator oscillator, phase-locked to a high-quality 5 MHz quartz oscillator, and mixed with 46 MHz from a low-frequency synthesizer. The clock signal is attenuated by 26 dB before the power combiner, and there is a 3 dB attenuator on the input to the clock cavity waveguide to reduce potential standing wave effects in the cavity feed.

In Fig. 3, we show the shift of the clock transition for various detunings of the RF sideband. For sideband detunings Δ much larger than the 50 Hz Rabi width, the ac Zeeman shift is $\Delta\nu = \Omega^2/\Delta$ where Ω is the sideband's Rabi frequency at resonance. In Fig. 3 we plot the frequency shift of the clock transition multiplied by Δ. This is then, effectively, just the cavity response—the intensity of the sideband in the cavity as a function of frequency. The Lorentzian fits to the data indicate the cavity is centered on the Rb transition at 25.5 °C and the cavity linewidth is 0.51 MHz yielding $Q = 13\,000$. Curves at higher and lower temperatures are also shown in Fig. 3. This technique seems to be widely applicable, as there are a number of different cavity designs that are difficult to probe electrically once the clock is assembled. Further, using the atoms as a probe ensures that the cavity is not adversely perturbed by the probe (as when probes are inserted into the cavity) and also that one detects any loading of the cavity by the atoms.

V. Juggling Clocks

High short-term stability is needed to achieve high accuracy within a particular averaging time. One can achieve significantly higher stabilities by *juggling* atoms in the fountain [8] as shown in Fig. 4. For example, a laser-cooled ball of atoms can be launched every 20 to 30 ms with an interrogation time of 0.5 s. In addition to higher stability, juggling also largely eliminates the dead time between cavity passages, thereby reducing the requirements for the local oscillator. If, on a single launch, one could achieve a $S/N = 5 \times 10^3$, the resulting frequency uncertainty is $\delta\nu/\nu = \Delta\nu/\pi\nu\ S/N = 1\times10^{-14}$. If the cycle time is 1 s, then $\sigma_y(\tau) = 1\times10^{-14}\tau^{-\frac{1}{2}}$. By launching atoms at a rate of 30 s^{-1}, a short-term stability

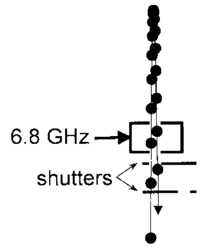

Fig. 4. Schematic for a juggling fountain clock. Balls of laser-cooled atoms are launched rapidly such that the delay between launches is much less than the interrogation time.

of $\sigma_y(\tau) = 2 \times 10^{-15}\tau^{-\frac{1}{2}}$ follows. This improvement is achieved without the technical difficulties of achieving higher S/N or using higher atomic densities, which results in a larger collisional shift.

Juggling introduces two important problems.

1) Shutters, as shown in Fig. 4, must be used to block the trapping and cooling light from the interrogation region of the clock.
2) Collisions between balls of atoms dictate that the launching rate be limited to about 50 to 30 s^{-1}.

For higher launch rates, the energy of collisions between atoms in successively launched balls decreases, so that the frequency shift cross section increases. These collisions may then limit the clock's accuracy and long-term stability.

Our design of a microgravity laser-cooled Rb clock in Fig. 5 is based on the juggling fountain we have recently demonstrated [8]. Here, we use a double-MOT [9] trapping system where the first is a vapor-cell MOT. If a single MOT was used, since the atoms will be launched with a small velocity through the clock cavity ($v \approx$5 cm/s), the shutter blocking light from the clock cavity would block a large fraction of the atoms if it is placed a reasonable distance from the trap. The double MOT circumvents the difficulty of placing a shutter very close to a trap. In the double MOT, the vapor cell MOT in Fig. 5 can be nearly always trapping atoms. It launches atoms at a high velocity, (5–10) m/s, into the second MOT in Fig. 5. In this way, the first shutter only needs to open for a short time. The second MOT then captures the atoms in $\approx$5 ms and launches them at $v = 5$ cm/s with a low temperature. Thus, for the double MOT system, the second shutter only needs to be closed for the 5 ms required to capture and launch the ball, and therefore, it can be comfortably far from the second MOT. This allows a large throughput of atoms while blocking all the laser light from the interrogation region.

We have recently demonstrated a juggling Cs fountain using the techniques needed for the microgravity Rb clock. In this first juggling experiment, we studied collisions between two balls of Cs atoms observing the s-wave energy dependence, the p-wave quantum scattering threshold, and the quantum interference between s and p-waves [8]. To observe low-energy collisions between the two balls, we launch atoms with delays as short as 7 ms, corresponding to launching rates as high as 140 s^{-1}. For such short delays, we found the second MOT laser beams could trap and efficiently launch the atoms in as little as 4 ms. An obstacle for short launch delays in the Cs fountain is that the two balls overlap when the second

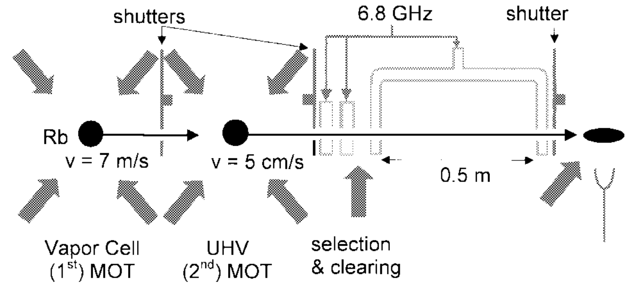

Fig. 5. Schematic for juggling microgravity Rb clock. The double MOT launches atoms at high speed from the vapor cell MOT to the UHV MOT so that the first shutter can be nearly always closed while the second one is nearly always open.

ball is launched. It is therefore essential to *hide* the atoms in the first ball in the $F = 3$ hyperfine state so that they don't absorb the light for the launch of the second ball. In addition to hiding with hyperfine pumping, we also minimize the intensity and carefully mask the trapping and repumping beams. Both of these techniques, capturing in a short time and hiding the ball after it is launched, are important for the microgravity Rb clock. If the launch rate is $R = 5$ s^{-1}, then pulsing the second MOT for only 5 ms implies a duty cycle of >95% open for the second shutter in Fig. 5. It is essential to hide the cold atoms already launched from the second MOT from future launches if the second shutter is comfortably far from the second MOT.

VI. Conclusion

We have demonstrated a prototype of an ^{87}Rb fountain clock. Using two state selection cavities, we prepare nearly half of the atoms in the $m = 0$ clock state and control the density of cold atoms. We observe a small shift of the clock frequency indicating that the collision shift for ^{87}Rb is at least a factor of ten smaller than the shift in a laser-cooled Cs clock. By introducing a strong microwave sideband, we have demonstrated a new technique to probe the detuning and Q of microwave cavities in atomic clocks. We have demonstrated a juggling Cs atomic fountain and some of the important techniques needed for future laser-cooled juggling fountain and microgravity atomic clocks.

Acknowledgment

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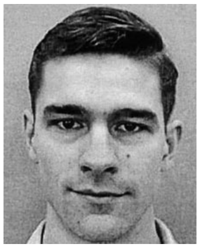

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