PROGRESS ON A MINIATURE LASER-COOLED CESIUM FOUNTAIN FREQUENCY STANDARD[1]

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Abstract - **The Time and Frequency Division of the National Institute of Standards and Technology (NIST) is developing a miniature laser-cooled Cs-fountain frequency standard. We anticipate that this device will be useful as a transportable reference for comparison of frequency standards at other laboratories. Additionally, it could be useful for measuring the gravitational clock shift at various locations to study models of the geoid. We discuss the objectives of this device, the features of the physics package and preliminary results.**

I. INTRODUCTION

The miniaturization of a Cs-fountain frequency standard is appealing for several reasons. A transportable device similar in concept to the PHARAO (Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite) clock [1] allows for the comparison of standards and calibrations at other laboratories and remote sites. Also, such a device could be used to measure the gravitational clock shift at various locations. The gravitational clock shift is a dominant correction applied to primary frequency standards and relies on several different models of the geoid [2]. The ability to study the models by directly measuring the gravitational shift at various locations is appealing. We have also found our miniature fountain to be useful in the development of new hardware, software, and interrogation schemes for possible implementation into NIST-F1, and future fountain primary standards under development at NIST.

While a small fountain cannot achieve sub-hertz linewidths and the geometry does not conveniently lend itself to the formal evaluations needed to achieve the ultimate accuracy of a primary standard such as NIST-F1[3], the compact geometry is useful in achieving high stability. Since the Ramsey time is proportional to the square root of the toss height, we can expect good performance from a relatively small physics package. If the systematic error due to distributed cavity phase shift is ignored and large apertures (~1.5 cm diameter) are placed into the microwave cavities, the resulting increase in atom flux through the clock implies excellent potential stability. Assuming that $\approx 10^8$ Cs atoms are collected in 300 ms ($\approx 10^7$ after state selection) with a temperature of 2 μK and a 0.3 s Ramsey time, we expect all the state-selected atoms to return to the detection region. This implies an attainable stability of $\sigma_y(\tau) \approx 2 \times 10^{-14} \tau^{-1/2}$, provided there is a suitable local oscillator to support it.

II. PHYSICS PACKAGE

The physics package for the miniature fountain has been described in detail elsewhere [4], and is shown without the C-field and magnetic shields in Fig. 1. It consists of a cold Cs-source region (Magneto-Optical Trap (MOT) and optical molasses), state-selection cavity, detection region, and Ramsey microwave cavity. The apparatus fits into a ~30 cm × 30 cm × 1 m package suitable for transportation. Presently, the laser system is on a separate optical table and light is delivered via optical fibers to the physics package.

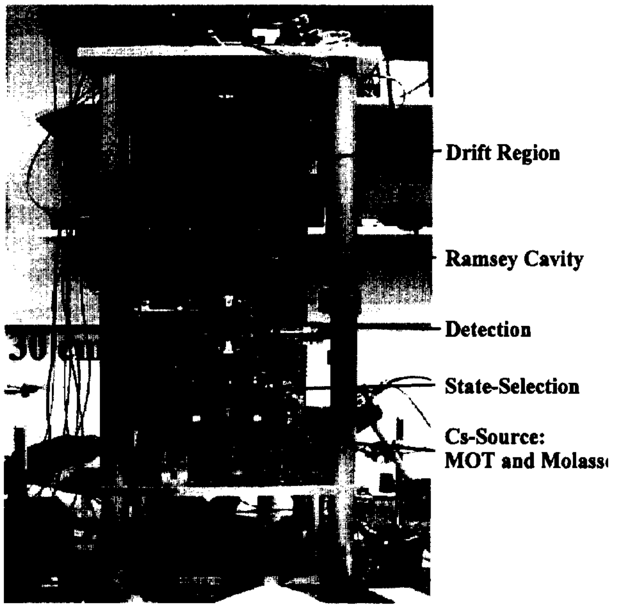

Fig. 1. The miniature fountain physics package with the magnetic shields removed.

The cold Cs-source uses the (0,0,1) beam geometry and operates first as a MOT and then is switched into an optical molasses. Approximately 10^8 atoms are launched upwards by detuning the two vertical beams. The state-selection cavity is a rectangular cavity operating in the TE_{104} mode. The apertures have a relatively large diameter of 1.50 cm, thus allowing for a large flux of atoms. Directly above the state-selection cavity is the detection region, which is designed to measure both F=4 and F=3 atom signals in order to generate a normalized transition-probability signal.

The Ramsey microwave cavity and toss-tube assembly is

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constructed from high-purity oxygen-free copper. The cavity is cylindrical, operates in the TE_{011} mode, and has an unloaded Q of approximately 18,000. As with the state-selection cavity, the apertures in the Ramsey cavity have a large diameter of 1.4 cm. In contrast, the microwave cavity apertures in NIST-F1 have a diameter of 1 cm to minimize the distributed cavity phase shift. Here in order to achieve high stability at some expense in accuracy, the apertures have been made larger. Since the atom flux through the cavity scales with the area of the apertures, a modest increase in the diameter of the apertures has a significant impact on the flux. Microwave radiation is introduced into the cavity with two loop antennas located opposite each other in the mid-plane of the cavity.

The C-field bobbin has a winding pitch that produces a field of 500 nT/mA. The magnetic shield package consists of two layers: one around the Ramsey cavity and toss tube, a second covering the first and extending down to shield the detection region. Figure 2 shows the physics package with the inner (not visible) and outer shields installed. For the preliminary results presented here, only the innermost shield was installed on the system.

The electronics and computer that control the miniature fountain fit easily into a standard laboratory rack enclosure. Additionally, we are in the process of designing a compact laser system that can be easily transported along with the physics package and control electronics.

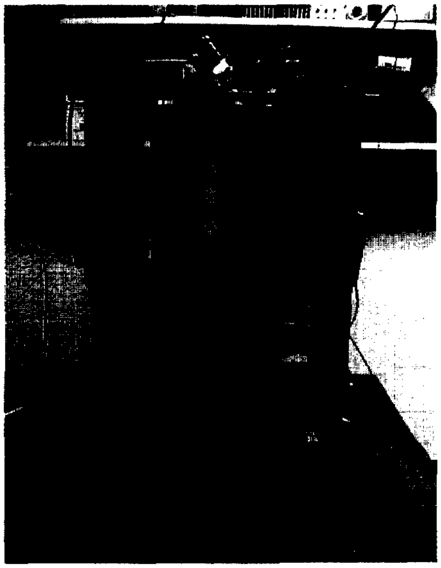

Fig. 2. The assembled miniature fountain physics package.

III. PRELIMINARY RESULTS

The measurements presented here were made using only one detection zone (the signal is a measure of the number of atoms in F=4). Therefore, the data are un-normalized and contain noise due to shot-to-shot variations in the atom number. Figure 3 is a scan of the detected number of atoms in F=4 versus the frequency of the microwave radiation in the Ramsey cavity, and shows Ramsey fringes and the underlying Rabi pedestal.

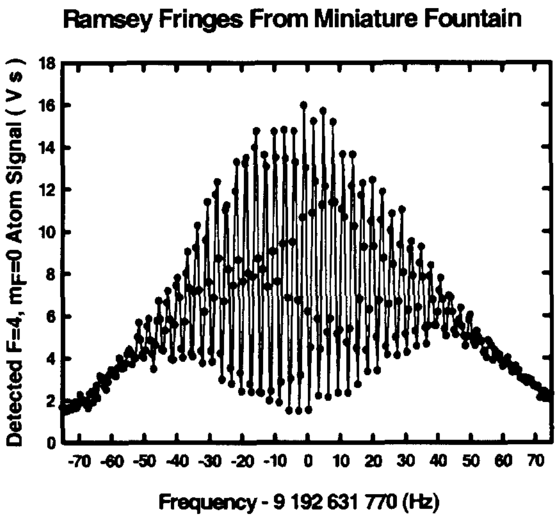

Fig. 3. Ramsey fringes obtained with the miniature fountain.

The atom toss height above the center of the Ramsey cavity was 13.2 cm (40 cm above the source), resulting in a Ramsey time of 0.33 s and a Rabi time of 1.2×10^{-2} s, which are in good agreement with the measured fringe data. Each point in the scan is the average of two individual measurements. Figure 4 is a scan of the central Ramsey fringes. Here each point is the average of 8 individual measurements and the solid line is a fit of the data to a sine wave. The central fringe is offset by $\approx$ 2 Hz due to the relatively large C-field ($\approx 7 \mu T$) applied during the measurements.

CONCLUSIONS

We expect to lock to the central Ramsey fringe in the near future and begin measurements of the short-term stability. To achieve long-term stability in the miniature fountain , systems will be implemented to control the largest systematic shifts: second-order Zeeman, blackbody, and spin exchange.

ACKNOWLEDGMENT

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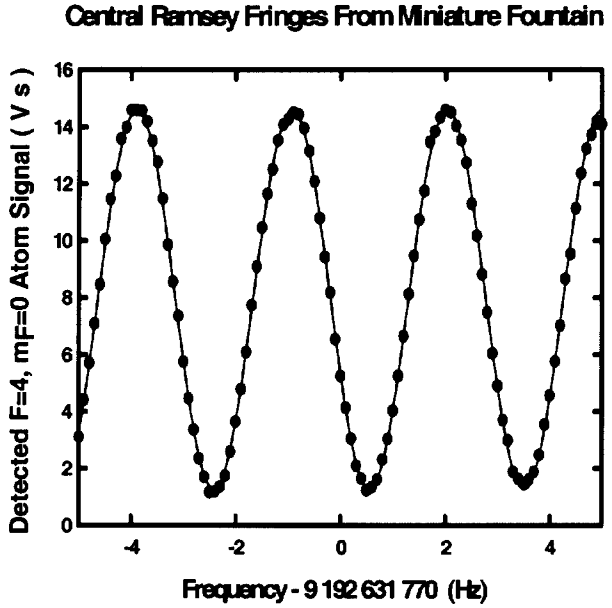

Fig. 4. A narrow scan of the central Ramsey fringes. The offset is due to the relatively large C-field. The solid line is a fit to a sine wave.

REFERENCES

[1] M. Abgrall, P. Lemonde, Ph. Laurent, G. Santerelli, P. Petit, A. Clairon, "The Transportable PHARAO Fountain Clock", *Proc. of the 14th European Frequency and Time Forum 2000,pg. 52,* Torino, Italy, March 14-16, 2000.

[2] N.K. Pavlis and M.A. Weiss, "Use of New Data to Determine the Relativistic Red Shift to 3x10^{-17} at NIST, Boulder" *15th European Freq. And Time Forum,* pp. 112-116, Neuchâtel, Switzerland, March 6-8, 2001.

[3] S.R. Jefferts, J. Shirley, T.E. Parker, T.P. Heavner, D.M. Meekhof, C. Nelson, F. Levi, G. Costanzo, A. DeMarchi, R. Drullinger, L. Hollberg, W.D. Lee, F.L. Walls, "Accuracy Evaluation of NIST-F1", to appear in *Metrologia,* 39(5), 2002.

[4] T. Heavner, D. Meekhof, D. Kujundzic, S. Jefferts, "Development of a Miniature Laser-Cooled Cs Fountain Frequency Standard at NIST", *2000 IEEE/EIA Int. Freq. Control Symp.,* pp. 711-713, Kansas City, MO, June 7-9, 2000.