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Development of a Miniature Laser-Cooled Cs Fountain Frequency Standard at NIST

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Abstract

We are developing a small laser-cooled Cs fountain at NIST with the goal of achieving exceptional short-term stability of $\sigma_y(\tau) \approx 2\times10^{-14}\tau^{-1/2}$ with a long-term stability of $\approx 10^{-15}$. Although this device is not designed to achieve the accuracy of the NIST primary frequency standard NIST-F1, this small, portable system will prove valuable as a local oscillator with intermediate accuracy. Here we discuss the performance goals of this frequency standard, the design philosophy, the existing physics package, and future directions.

Introduction

The NIST-F1 primary frequency standard presently exhibits a stability of $\sigma_y(\tau) \approx 7\times10^{-13}\tau^{-1/2}$ and an ultimate uncertainty of $\sim 1\times10^{-15}$ [1]. This device was designed with the goal of achieving high accuracy through an elaborate evaluation process. However, it is often desirable to have a frequency standard, that possesses higher stability with less concern for ultimate accuracy, for example for use as a local oscillator. With this goal in mind, we are developing a "miniature" fountain frequency standard.

The stability of an atomic fountain can be written as

$$\sigma_y(\tau) = \frac{\delta\nu}{\pi\nu_o}\sqrt{\frac{1}{2N_{detected}}}\sqrt{\frac{T_{cycle}}{\tau}},$$

where $\delta\nu$ is the Ramsey linewidth, ν_o is the transition frequency, $N_{detected}$ is the total number of atoms contributing to the clock signal, and T_{cycle} is the time for a complete measurement cycle [2]. NIST-F1 has a toss tube of length ~ 1 m which allows for interaction times of ~ 1 s. The resulting linewidth of the central Ramsey fringe is ~½ Hz. Such a narrow fringe aids in the evaluation of systematic frequency biases for the standard. However, for such long interaction times, the number of atoms returning to the detection region is reduced, especially since the apertures in the microwave cavities in NIST-F1 are kept small to minimize the systematic shift due to distributed cavity phase shifts. Considering the t^2 dependence on toss height, a relatively small fountain with a toss height of ≈ 15 cm still produces a relatively long Ramsey time of ≈ 0.4 s. This, in conjunction with our reduced accuracy goal, allows us to enlarge apertures thus increasing the flux of detected atoms.

Assuming that the miniature fountain uses a standard optical-molasses Cs source with ~ 10^8 atoms collected in 300 ms with a temperature of 2 μK, and assuming a 0.3 s Ramsey time, the atomic stability is $\sigma_y(\tau) \sim 2\times10^{-14}\tau^{-1/2}$. Of course, the fountain requires a local oscillator with equivalent stability.

Physics Package

A diagram of the components of our miniature fountain is shown in Fig.1, and a photograph is shown in Fig. 2.

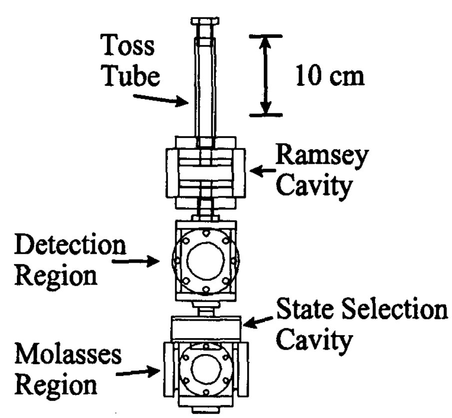

Figure 1. A drawing of the miniature fountain vacuum enclosure. The C-field and magnetic shield package have been omitted for clarity

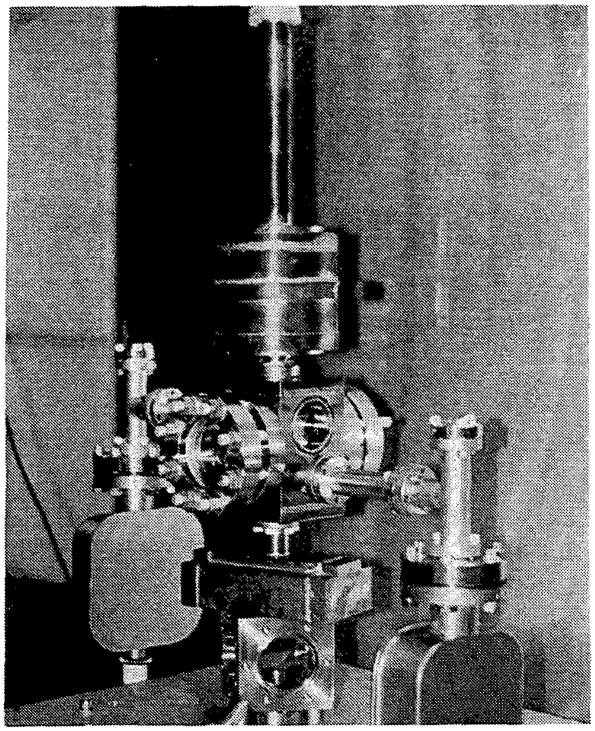

Figure 2. A Photograph of the miniature Cs fountain under development at NIST. The C-field assemblies and magnetic shields are not shown.

The cold Cs source is at the bottom of the device and is comprised of an off-the-shelf stainless steel cube with NW 35 CF flanges on each face. The six windows, assembled using the Kasevich technique[3], and allow for large (~3 cm) beams into the source. The Cs oven is located along one of the diagonal axes of the cube such that Cs is deposited into the center of the molasses region. This geometry is the standard (0,0,1) cooling/launch geometry used in NIST-F1.

Above the source is a state-selection cavity which is a rectangular microwave cavity operating in the TE_{104} mode. The apertures in the cavity have a relatively large diameter of 1.50 cm allowing for passage of large numbers of atoms. A cylindrical state selection cavity in use on NIST-F1 transfers ~98% of the $|F=4, m_F=0\rangle$ atoms to the $|F=3, m_F=0\rangle$ state, and we expect similar performance on the miniature fountain. The remaining $|F=4, m_F=0\rangle$ atoms are removed with $|F=4, m_F\rangle \rightarrow |F=5, m_F\rangle$ light as the sample travels up through the detection region.

The detection region, shown in Fig.3, is located above the state-selection cavity and has four windows. Two large windows allow the detection beams to enter the vacuum system, while the remaining two are re-entrant windows to allow efficient collection of photons. It is designed to permit for the detection of the number of atoms in both the $|F=4, m_F=0\rangle$ and $|F=3, m_F=0\rangle$ states. Atoms returning from microwave interrogation first encounter a standing wave of $|F=4, m_F\rangle \rightarrow |F=5, m_F\rangle$ light. The large windows allow for the detection of ~13 % of the scattered photons ($>10^3$ photons/atom). The atoms in $|F=4, m_F=0\rangle$ are then removed with a traveling wave of $|F=4, m_F\rangle \rightarrow |F=5, m_F\rangle$ light. The number of atoms in the $|F=3, m_F=0\rangle$ state are detected by first repumping the atoms into the $|F=4, m_F=0\rangle$ state and then detecting then using the same technique as above.

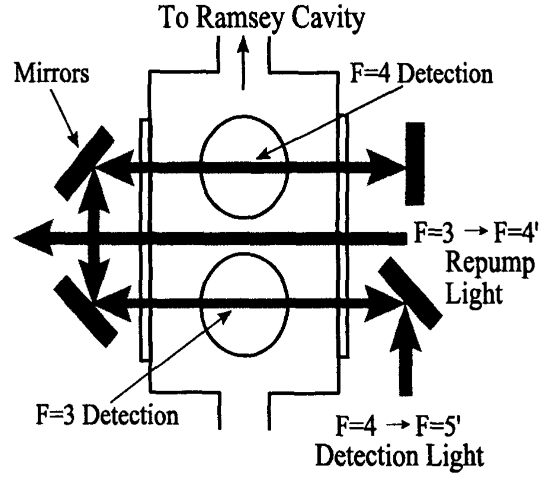

Figure 3. A schematic diagram of the detection region optics.

The Ramsey microwave cavity and toss tube are located above the detection region. The cavity is cylindrical and operates in the TE_{011} mode at 9.19263 GHz with an unloaded Q of ≈18,000. It is constructed from copper and has inner dimensions of r_{cavity} = 3.50 cm and h_{cavity} = 1.98 cm. The apertures in the cavity endcaps have a large diameter (1.4 cm) which, as with the state selection cavity, allows large numbers of atoms to reach the detection region. Microwave radiation is introduced into the cavity via two loop antennas (≈3 mm diameter) located opposite from each other in the midplane of the cavity.

The C-field and magnetic shields (not shown in Fig.2) consist of several layers. There is an inner C-field bobbin and one layer of shielding around the Ramsey cavity and toss tube, which provide a uniform field of 0.05 μT. A second C-field and shield system covers the detection region, state selection cavity and the atom source. This region will operate at ~0.5 μT, simplifying the state-selection process. A final outer shield will cover the entire physics package.

The optical system for the fountain is in a separate system and light is delivered to the physics package via optical fibers.

Conclusion

We are now completing the final assembly of the physics package. Because the miniature fountain is designed to couple to the laser system using optical fibers, we can use many of the same optical systems that are currently employed on the PARCS space clock project at NIST. Thus, we expect to be testing the miniature fountain in the next few months.

Acknowledgments

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References

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