

## NIST CESIUM FOUNTAIN FREQUENCY STANDARD: PRELIMINARY RESULTS

*S.R. Jefferts, D.M. Meekhof, L.W. Hollberg, D. Lee, R.E. Drullinger, F.L. Walls, C. Nelson, F. Levi\*,  
T.E. Parker*

Time and Frequency Division  
National Institute of Standards and Technology  
325 Broadway  
Boulder, CO 80303

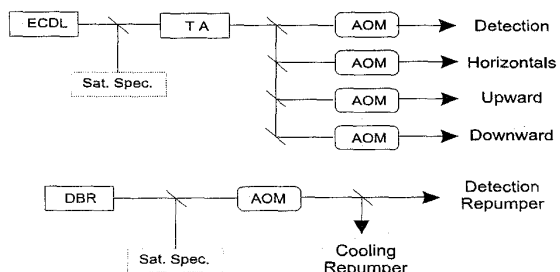
### Introduction

The Time and Frequency Division of the National Institute of Standards and Technology (NIST) has recently begun operation of a laser-cooled cesium atomic fountain for evaluation as a possible primary frequency standard. This device is conceptually similar to the Zacharias cesium fountain and is similar in layout to the BNM-LPTF (Observatoire de Paris) cesium fountain, which currently has the smallest stated uncertainty of any of the world's primary frequency standards[1][2]. This paper will give a brief description of the NIST Time and Frequency Division's cesium fountain and present some preliminary data.

### Physics Package Description

#### Laser System

The laser system for the cesium fountain is shown schematically in Fig. 1. Two laser light sources are used. The extended cavity diode laser (ECDL) is tuned and locked about 160 MHz red of the  $F=4 \rightarrow F'=5$  transition. This light is then amplified approximately 20 dB by the tapered amplifier (TA) giving about 300 mW of 852 nm light at the output of the amplifier. The light is then split and frequency shifted by the 80 MHz double-pass acousto-optic modulators



**Figure 1 - Schematic diagram of the laser sources and frequency offset generation.**

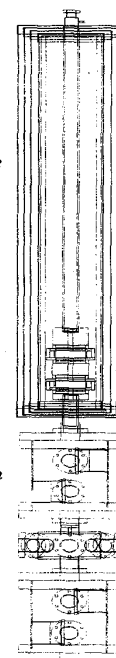
(AOM's) which brings the light back to near resonance. The six molasses and magneto-optic-trap (MOT) beams are generated as a horizontal beam which is split into two pieces both of which are retro-reflected to generate the required four horizontal beams and as separate up and down laser beams. The frequency of the up, down and horizontal beams are set by their respective AOM's which are driven by separate r.f. synthesizers locked to a common reference. The light output from the tapered amplifier is also used in the detection process described later in this paper.

#### Magnetic Shield Package

#### Microwave Cavities

#### Detection Region

#### Mot/Molasses Region



**Figure 2 - The NIST Time and Frequency cesium fountain. Schematic diagram of the physics package**

A second laser (distributed Bragg reflector)(DBR) tuned to the  $F=3 \rightarrow F'=4$  transition re-pumps atoms lost on the  $F=4 \rightarrow F'=5$  cycling transition. This laser is used in the MOT/molasses region as well as the detection region.

### Atom Trapping, Cooling and Tossing

The atoms are gathered from a cesium oven located in the region labeled MOT/molasses in Fig. 2. The cesium atoms are either trapped in a MOT located at the intersection of the six beams followed by an optical molasses step, or they are gathered as molasses with no initial MOT step. The cold atoms are then accelerated upward by detuning the downward laser beam to the red and the upward laser beam to the blue with the constraint that  $v_{up} + v_{down} = 2v_{horizontal}$ . The height of the toss is set by the magnitude of the detuning.

The initial vertical velocity is approximately 0.852 m/(s MHz) of detuning. After the atoms have been accelerated in the vertical direction the six beam molasses is detuned to the red of the transition by about  $16 \Gamma$  (optical line widths) while the amplitude of the beams is simultaneously decreased. This post-cooling step reduces the transverse atom temperature in the launched atom sample. After the launch the laser beams are blocked by mechanical shutters to avoid any light shift of the hyperfine transition frequency. After the atoms are launched and post-cooled they traverse the detection region shown in Fig. 2, and then enter the magnetically shielded region.

### State Selection and Ramsey Interrogation

A ball of cold cesium atoms enters the magnetically shielded region on the way to the first of two microwave cavities. These  $TE_{011}$  cavities, described in a paper elsewhere in these proceedings [3], are tuned to be resonant at 9.192 GHz. The first microwave cavity is intended for state selection. In this first cavity the microwave power is set such that the  $|F=4, m=0\rangle$  state undergoes a  $\pi$  transition in this cavity. Light resonant with  $F=4 \rightarrow F'=5$  is then applied to the atom ball removing atoms still in the  $F=4$  state. The atom sample, now  $|F=3, m=0\rangle$  next encounters the upper microwave cavity where the Ramsey interrogation begins. This technique has not yet been verified experimentally.

The magnetically shielded region is surrounded by four layers of molybdenum-Permalloy cylindrical shields. Directly inside the innermost shield is an end corrected solenoid which provides the quantization field for the Ramsey interrogation (the C-field) region. The data presented here were gathered with a C-field strength of about  $10^{-6}$  T. We have not yet measured the uniformity of the C-field as installed on the fountain.

### Atom Detection and Normalization

An atom sample falling out of the Ramsey region must next be interrogated to measure the populations in the

$F=4$  and  $F=3$  hyperfine levels. At present we detect the populations in a scheme similar to that used in the LPTF fountain. Atoms falling from the Ramsey zone encounter four distinct laser fields. First is a standing wave with  $\sigma^+$  polarization tuned on the  $F=4 \rightarrow F'=5$  transition. Atoms in  $F=4$  scatter approximately  $10^4$  photons of which 20% are detected. The atoms next encounter a traveling wave tuned as above; this laser removes  $F=4$  atoms from the sample. As the atoms continue to fall they next encounter a laser beam tuned from  $F=3 \rightarrow F'=4$  which pumps  $F=3$  atoms to the  $F=4$  level. Finally the atoms which were in  $F=3$  (now in  $F=4$ ) encounter a standing wave which is similar to the first standing wave (the polarizations of the two standing waves may or may not be the same) described above. The clock signal is then the number of detected photons from either the first or second standing wave region divided by the sum of the signals from the two standing wave detection regions. This normalization suppresses the effects of noise in the atom number as well as slow laser noise on the final signal. The detection system is shown schematically in Fig. 3.

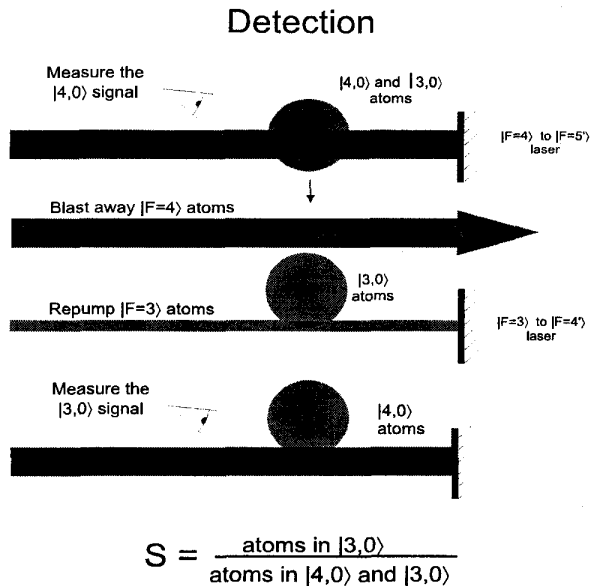


Figure 3 - The sequence of detection for atoms in  $|F=4\rangle$  and  $|F=3\rangle$  levels.

### Magnetic Field Mapping

We have installed a system for mapping the magnetic field in the drift region; it should allow relatively simple mapping of the C field. Briefly the two sets of coils generate a magnetic field normal to the C-field direction and by sequencing the current in these coils a rotating magnetic field can be imposed on the atoms in the drift tube. This polarized low frequency ( $\nu \approx 350$  Hz with a  $10^{-7}$  Tesla C-field) magnetic field causes  $\Delta m=1$  transitions when the

frequency and field strength are properly adjusted. The transition frequency is a linear function of the C-field strength at the position of the atom when it is excited by this rotating field and serves as a measure of the local magnetic field. This technique allows one to induce either  $\Delta m = +1$  or  $\Delta m = -1$  transitions unambiguously. In fact interesting superposition states can also be generated with the simultaneous application of  $\Delta m = +(or-)1$  and  $\Delta F = +(or-) 1$  radiation. The Millman effect can be completely suppressed by applying the low frequency pulse symmetrically about apogee. We have not yet verified the operation of this system and will report on its efficiency at a later date.

## Experimental Results

### Atom Number

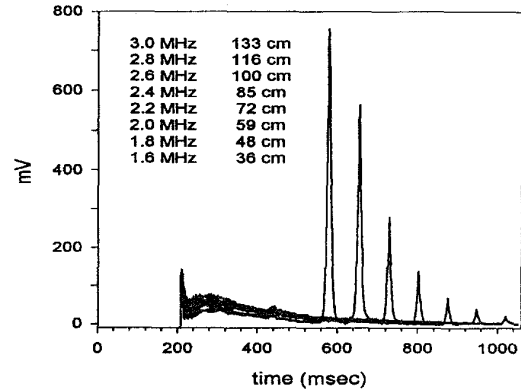
The stability of an atomic fountain can be written as

$$\sigma_y(\tau) = \frac{\delta\nu}{\pi\nu_0} \sqrt{\frac{1}{2N_{\text{detected}}}} \sqrt{\frac{T_{\text{cycle}}}{\tau}} \quad (1)$$

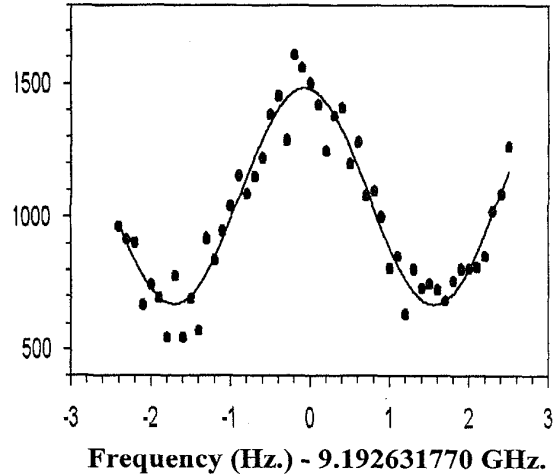
where  $\delta\nu$  is the Ramsey line width,  $\nu_0$  is the transition frequency,  $N_{\text{detected}}$  is the total number of atoms which contribute to the clock signal and  $T_{\text{cycle}}$  is the time for a complete measurement cycle [4]. Equation (1) assumes that both the microwave power and the modulation width have been optimized. Equation (1) can be rewritten in terms of the atom temperature and the size of the aperture in the microwave cavity as

$$\sigma_y(\tau) = \frac{1}{2\pi\nu_0} \frac{v_{\text{thermal}}}{r_{\text{aperture}}} \sqrt{\frac{1}{N_{\text{launched}}}} \sqrt{\frac{T_{\text{cycle}}}{\tau}}, \quad (2)$$

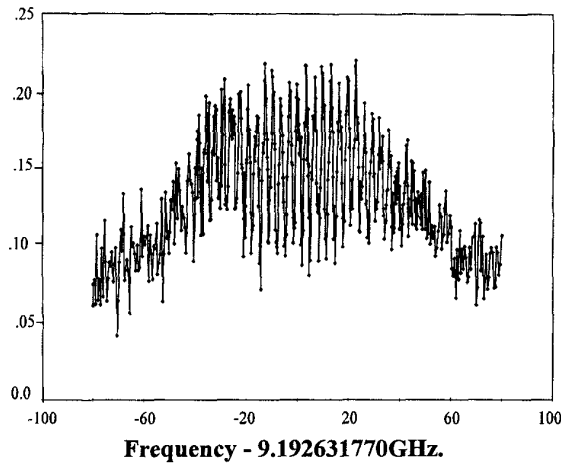
where  $v_{\text{thermal}}$  is the thermal velocity of the atoms and  $r_{\text{aperture}}$  is the radius of the aperture in the microwave cavity. Equation (2) is valid under the assumption that atoms start from a point source, the atom ball temperature is high enough that it expands to a size greater than the cavity aperture and the cavity aperture is the bottleneck for getting atoms through the system. As Equation (2) shows large cavity openings are desirable from the standpoint of stability as is the lowest possible atom temperature, also the clock stability is, in this approximation, not a function of the Ramsey time. This behavior is a result of the fact that atoms are being lost at longer interrogation times at a rate which compensates for the gain in interrogation time. This atom loss mechanism can be seen in the experimental data shown in Fig. (4), the atom number drops off sharply as a function of atom toss height.



**Figure 5 - Detected atom number (arbitrary units) as a function of flight time. These data were collected using a MOT followed by optical molasses.**



**Figure 5 - The central Ramsey fringe on the  $|4,0\rangle - |3,0\rangle$  transition. The data shown are simply the detected signal (arbitrary units) in the  $|3,0\rangle$  state plotted as a function of detuning in Hz away from 9.192 631 770 GHz.**



**Figure 6 - The raw signal over the entire Rabi pedestal on the  $m=0$ ,  $\Delta m=0$  transition. The vertical axis is atoms detected in the  $F=3$  state divided by detected atoms in  $F=3 + F=4$ . No state selection or further normalization has been applied.**

### Ramsey Fringes

Experimental Ramsey fringes on the  $|4,0\rangle \rightarrow |3,0\rangle$  clock transition can be seen in Figs. 5 and 6 showing the central fringe and the entire Rabi pedestal with fringes respectively.

These data were obtained with relatively crude control over temperature, microwave power and C-field strength. Still, one can observe the expected Ramsey fringe pattern as well as the underlying Rabi pedestal. The offset on the central fringe is due to an uncorrected offset in the Hydrogen maser which serves as the reference for the 9.192 GHz synthesizer. Work is in progress to systematically control the above mentioned variables in order to begin investigating systematic shifts to the clock transition.

### Conclusions

We have presented here the first results from the NIST time and frequency laser-cooled cesium fountain. The major subassemblies of the fountain have been discussed including a novel method for mapping the C-field region. Preliminary experimental results including Ramsey fringes on the cesium clock transition have been presented.

### Acknowledgments

The authors would like to thank M. Young, D. B. Sullivan, T. P. Heavner and H.G. Robinson for many helpful suggestions.

### References

[1] N.F. Ramsey, *Molecular Beams*. Oxford, U.K.: Oxford Univ. Press, 1956, sect. V .5.2, pp. 139.

[2] Selma Zina Ghezali, et al., "The accuracy evaluation of the LPTF cesium fountain frequency standard at the  $10^{-15}$  level and future prospects," to be published in Proc. 12<sup>th</sup> European Frequency and Time Forum.

[3] S. R. Jefferts, R.E. Drullinger, A. DeMarchi, "Design and Realization of the NIST Fountain Cavity," in these proceedings.

[4] H. G. Robinson et al., "Design Studies for a Laser-Cooled Space Clock," in these proceedings.

\* - Permanent address - Istituto Elettrotecnico Nazionale "G. Ferraris" Str. Delle Cacce 91, 10135 Torino It.