Demonstration and Observation of a Frequency Standard based on an Expanding Cold Atoms Cloud of Cesium

Stella Torres Müller, Daniel Varela Magalhães, Aida Bebeachibuli, Mônica Silva Santos and Vanderlei Salvador Bagnato
Instituto de Física de São Carlos
Universidade de São Paulo
São Carlos – SP, Brazil
dvarela@if.sc.usp.br

***Abstract*— This work reports the first results obtained in a laboratory system implemented to be a primary standard based on an expanding cloud of cold 133Cs. An atomic sample is prepared through the magneto-optical trapping technique, and after the loading procedure the atomic cloud is left to freely expand. A microwave interrogation signal is applied to the atoms, probing them in the ground state transition $6S_{1/2}(F=3) - 6S_{1/2}(F=4)$. The microwave interrogation was applied either in one or two pulses methods. The system could be also locked in a commercial standard to perform its stability evaluation. The first results showed a stability of $9\times10^{-11}\tau^{-1/2}$, promising for such use of simple type of frequency standard.**

I. Introduction

The use of cold neutral atoms for precision measurements on the microwave range of clock transition has always been of great interest. Since the first steps of development in cooling and trapping techniques many authors have demonstrated the potentiality of using cold atoms as good candidates to be employed in the construction of compact high-performance atomic clocks. Clock transitions in laser cooled Cs [1] and in laser cooled Na [2] have early been demonstrated. After the seminal demonstrations, the main interest was focused towards the atomic fountains [3] , where atoms are launched upwards and pass twice through the same interaction region, once on the way up, and once on the way down, producing the Ramsey fringes with resolution mainly determined by the time between interactions. Atomic fountains of Cs are now operational in many laboratories around the world [LPTF, NIST, PTB, etc] and typical stability has been demonstrated to be $\approx 10^{-13}\tau^{-1/2}$ [4] or even better, depending on the macroscopic oscillator used [5].

Recently, attention has been focused on the use of cold atoms to produce compact clocks, where a trade-off between size and performance is been taken into account. A good example of such efforts is the HORACE project (Horloge à Refroidissement d´Atomes en Cellule) [6], where direct cooling of Cesium atoms inside the microwave cavity using isotropic laser light is performed. The trapped cloud is prepared and interrogated within the cavity using a sequence of microwave pulses, generating a Ramsey fringe set where the central fringe width measured is *14Hz*. For such system a stability of $\approx 10^{-12}\tau^{-1/2}$ was projected.

In this work we demonstrate an equivalent clock, but based only on a Rabi profile, obtained for a free expanding cloud of cold Cs atoms where a microwave antenna provides the radiation for the transition, which is optically detected by fluorescence using interaction with excited levels. The obtained clock transition is used to lock a microwave chain and the overall system stability is evaluated, revealing an acceptable value which we believe can be considerably improved as will be discussed. The implications of demonstrating simple cold atoms clocks of compact sizes are discussed.

II. Experimental Set-up

As shown in the simplified scheme of figure 1, a glass cell stores a cesium vapor at a background pressure better than 10^{-9} torr, maintained by an ion pump. A temperature controlled Cs reservoir allows regulating the amount of Cs atoms into the glass cell. Around the glass cell we have two main coils to produce the magnetic field for magneto-optical trapping of the atoms and a set of compensation coils to guarantee a field free environment for the atomic cloud expansion. Atomic densities on the order of $10^{10}\,cm^{-3}$ are typically evaluated by fluorescence. Two stabilized diode lasers provide the frequencies necessary to produce trapping and repumping light. The relevant transitions excited by the lasers are the $6S_{1/2}(F=4)\rightarrow 6P_{3/2}(F'=5)$ cycling trapping transition and the $6S_{1/2}(F=3)\rightarrow 6P_{3/2}(F'=4)$ repumping, which prevents atoms from accumulating in the $F=3$ ground state during the trapping phase of the experiment. Each laser beam carries about *12 mW* of power

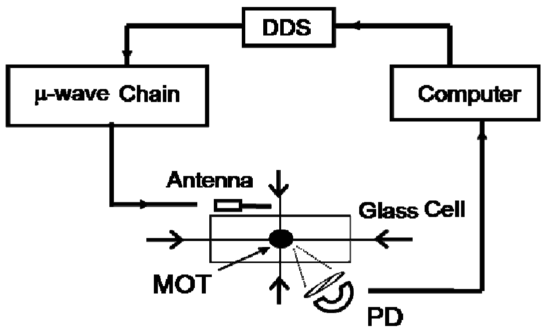

Figure 1. Schematic of the experimental setup.

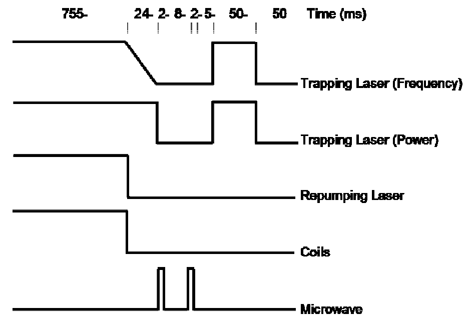

Figure 2. Temporal sequence applied to the experiment.

in a Gaussian beam of *2.5 cm* waist. Fluorescence light from the intersection laser beam region is imaged onto a calibrated detector located at *10 cm* from the cell center. A microwave antenna of quarter–wave is positioned perpendicular to the vertical axis, outside the glass cell and about *5 cm* from the atoms.

The irradiation pattern of the antenna was investigated such that it was positioned to have the atoms located on the high intensity region. The antenna was coupled to a microwave chain [7], generating *9.192 GHz* after a sequence of multiplication. About 2×10^{8} atoms are captured in the MOT and correspond to the sample for performing the microwave transition and to lock the oscillator chain.

The time sequence used to observe the microwave resonance is the following: for about *800 ms*, the magnetic field of the MOT, as well as the lasers, are on, allowing capture and accumulation of atoms. The repumping laser and the MOT coils are then turned off, and they will remain so until the end of the sequence. For the next *23.9 ms* the trapping laser still on will promote optical pumping of the atoms to the $6S_{1/2}(F=3)$ state, after which it is turned off. At this stage, the atomic cloud is in free expansion and remains that way for the next few ms, when the first pulse of microwave with Δt_p of length is applied. After Δt_b, a second pulse of microwave can be applied or not. At the end, the trapping laser is turned back on for *50 ms* and the fluorescence of atoms at $6S_{1/2}(F=4)$ is detected.

The atoms originally at $6S_{1/2}(F=3)$ are transferred to $6S_{1/2}(F=4)$ by the microwave field. A variable attenuator is placed on the microwave source such that a π-pulse is applied during the Δt_p period (Rabi method). In the case of two consecutive pulses Δt_p, the microwave power is regulated to produce two $\pi/2$-pulses (Ramsey method). The temporal sequence for the experiment is illustrated in figure 2. The fluorescence detection system is composed of a collecting lens set which images the cloud onto a calibrated photodetector.

Once the resonance line is obtained, a modulation of the microwave frequency allows obtaining the error signal used to lock the oscillator on the atomic resonance. The microwave chain is phase locked (PLL) to the *10 MHz* output of the commercial standard (Agilent model 5071A).

The modulation central frequency is supplied by the control computer, and it means the correction applied to the modulation signal to maintain the interrogation signal in the peak of the Cs resonance (*9192631770 Hz*). The correction signal is computed and used to evaluate the stability of the standard obtained from the expanding cloud signal. The comparison scheme is showed in figure 3.

III. Results and Discussion

In a first experiment the microwave power was fixed to have about $30\mu G$ of average field amplitude at the atoms site. The pulse duration (Δt_p) was varied from *2* to *20 ms* and the growing production of $6S_{1/2}(F=4)$ atoms could be observed, reaching a maximum and then decreasing definitively. This is the first cycle of the Rabi oscillation. The pulse time Δt_p has been fixed to produce the maximum transference to $6S_{1/2}(F=4)$ level, which corresponds to a π-pulse. For the used microwave amplitude. $\Delta t_p \approx 12ms$ Fixing the pulse duration, the microwave frequency was swept, generating the resonance curve shown in figure 4.

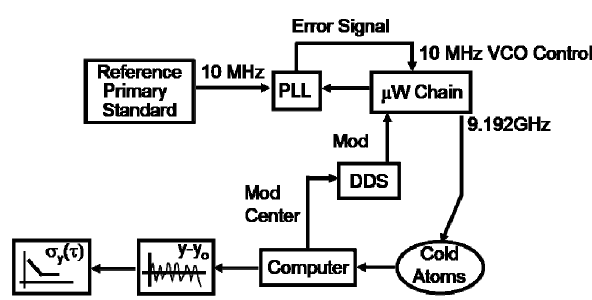

Figure 3. Scheme used for stability evaluation.

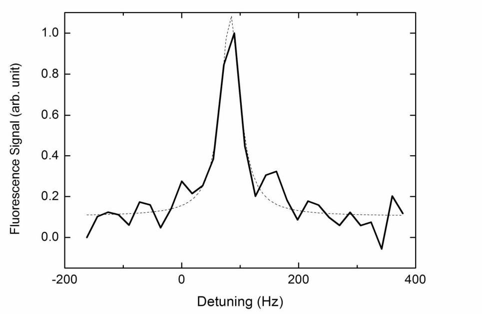

Figure 4. Resonance observed for the clock transition using a Rabi pulse for interrogation.

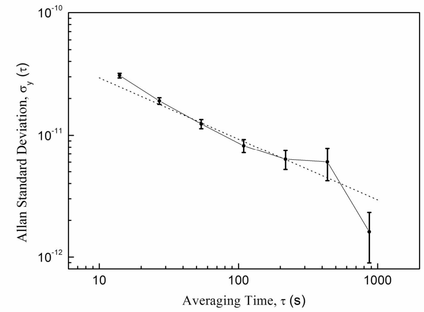

Figure 5. Allan standard deviation of the system when locked to an Agilent 5071A primary standard.

Fitting the resonance curve with a Lorentzian shape we obtain a half-maximum full width (FWHM) of *39Hz*. Comparing with the results reported by Guillot and collaborators [8] for the first evaluation of the atomic clock with cooled atoms in a cell, a factor of 6 improvement is obtained with a free expanding cold atomic cloud. Our results are however compatible with the results by Sesko and Weiman [1] where *44Hz* FWHM was observed in an experiment similar to the one here presented.

If our obtained line width of *39Hz* is compared with NIST-6 (NBS-6) atomic clock, *26Hz*, which is based on a Cs beam with a *4m* long transition region [9], we can realize the great potentiality of the use of cold atoms Rabi interrogation method as a clock transition. In terms of linewidth/length of transition region, we are a factor of *1000* better than conventional beam clocks. Comparing with atomic fountains, whose typical line width is *1Hz*, means a great deal of capacity to obtain narrow transitions within small length of transition, when just a cloud of cold atoms is used.

The resonance observed on figure 4 was used as a clock transition to lock a local oscillator. The generated error signal was used to evaluate the comparison obtaining the Allan variance. The frequency stability of the produced clock is presented in figure 5, resulting in an Allan standard deviation of $\sigma(\tau) = (9 \pm 1)10^{-11}\tau^{-1/2}$, which is already a good stability considering the simplicity of the device. There is still a lot of room for improvements, but it should be emphasized that with the main characteristics of our device, we should obtain a result estimated to be one order of magnitude better for the short term stability.

It should be straightforward to extend the present demonstration technology to make a compact high performance atomic clock, which will be fully optically operated and with long lifetime of Cs supply compared to present Cs tubes lifetime.

In a second experiment, a sequence of two pulses during the interrogation time was used in an attempt to use the Ramsey method. In this case we have used $\Delta t_p \approx 2ms$ and $\Delta t_b \approx 8ms$, with a power level such that a $\pi / 2$-pulse for each interrogation is applied. For this case, the presence of the Ramsey fringes superimposed to a broad Rabi profile was observed. The central fringe presents a FHMW of about *30Hz*, not much an improvement with respect to the Rabi resonance method. That was surprised to us compared with the results presented by C. Monroe et al [10] where fringes with good contrast are obtained. We associated our poor Ramsey Fringes contrast to the phase variation between pulses as well as to the field amplitude variation filled by the atoms for the two time pulses. Also, being a traveling wave coming out of the antenna, the system is more sensitive to residual Doppler profile. At the present experimental conditions an equivalent stability were obtained using the Ramsey method when compared to the Rabi method.

IV. CONCLUSIONS

With this work we have shown the first step concerning the development of a frequency standard based in an expanding atomic cloud of cold 133Cs. Despite the poor SNR we observed a stability of $\sigma(\tau) = (9 \pm 1)10^{-11}\tau^{-1/2}$, indicating a good direction to be followed. Our next steps have to be concentrated on improving the observation of the clock transition, with an interrogation cavity instead of an antenna. The challenge will be to place the cavity without sacrificing the MOT quality. Once in a cavity the Ramsey method should produce better results, due to the better homogeneity of the interrogation field.

ACKNOWLEDGMENT

The authors are pleased to acknowledge A. Clairon, S. Bize and G. Santarelli, from Observatoire de Paris, for all the fruitfull discussions and advices. This research is supported by FAPESP, Programa TIB (CNPq) and CAPES.

REFERENCES

[1] D. W. Sesko and C. E. Wieman, Opt. Lett. 14, 269 (1989).

[2] M. A. Kasevich, E. Riis, S. Chu and R. G. DeVoe, Phys. Rev. Lett. 63, 612 (1989).

[3] A. Clairon, P. Laurent, G. Santarelli, S. Ghezali, S. N. Lea and M. Bahoura, IEEE Trans. Instrum. Meas. 44, 128 (1995).

[4] S. R. Jefferts, J. H. Shirley, T. E. Parker, T. P. Heavner, D. M. Meekhof, C. W. Nelson, F. Levi, G. Costanzo, A. DeMarchi, R. E. Drullinger, L. Hollberg, W. D. Lee and F. L. Walls, Metrologia 39, 321 (2002).

[5] Y. Sortais, S. Bize, M. Abgrall, S. Zhang, C. Nicolas, C. Mandache, P. Lemonde, P. Laurent, G. Santarelli, N. Dimarcq, P. Petit, A. Clairon, A. Mann, A. Luiten, S. Chang and C. Salomon, Phys. Scr. T95, 50 (2001).

[6] S. Trémine, S. Guérandel, D. Holleville, A. Clairon and N. Dimarcq, 2004 IEEE International Ultrasonics, Ferroelectrics and Frequency Control Joint 50th Anniversary Conference, 65, (2004).

[7] J. F. Garcia Nava, F. L. Walls, J. H. Shirley, W. D. Lee and M. C. Delgado Aramburo, 1996 IEEE International Frequency Control Symposium, 973, (1996).

[8] E. Guillot, P. E. Pottie, C. Valentin, P. Petit and N. Dimarcq, 1999 Joint Meeting EFTF - IEEE IFCS, V1, 81, (1999).

[9] D. J. Glaze, H. Hellwig, D. W. Allan and S. Jarvis, Metrologia 13, 17 (1977).

[10] C. Monroe, H. Robinson and C. Wieman, Opt. Lett. 16, 50 (1991).