An Alternative Cold Cesium Frequency Standard: The Continuous Fountain

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***Abstract*—We report on the primary frequency standard now under construction at the Observatoire de Neuchâtel (ON). The design is based on a continuous fountain of laser-cooled cesium atoms, which combines two advantages: the negligible contribution of collisions to the inaccuracy and the absence of stability degradation caused by aliasing effects encountered in pulsed operation. The design is reviewed with special emphasis on the specific features of a continuous fountain, namely the source, the microwave cavity (TE_{021} mode), and the microwave modulation scheme. The possible sources of frequency biases and their expected contributions to the error budget are discussed. Based on present data, an accuracy in the low 10^{-15} range and a short-term stability of $7 \cdot 10^{-14}$ are attainable simultaneously under the same operating conditions.**

I. Introduction

Laser cooling has made possible major improvements in frequency metrology. The gain in short-term stability and accuracy in pulsed fountains with respect to conventional thermal beam primary frequency standards has already exceeded a factor of three [1] and is likely to increase further. However, few devices are already operational, and most of the research work in this field is limited to schemes in which clouds of atoms are sequentially captured, launched, and interrogated. It has been recognized [2] that the pulsed character of the experiment imposes stringent conditions on the local oscillator. In addition, a high stability requires high density atomic clouds in which the collisional shift may be far from negligible. An alternative to solve both problems is the use of a continuous beam of laser-cooled atoms. Such a device is under construction at ON in collaboration with the Swiss Federal Office of Metrology (OFMET).

The purpose of this paper is to review the design of the so-called continuous fountain (Section II) and to address metrological considerations such as short-term stability, interrogation scheme, and frequency shifts with special emphasis on the continuous character.

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II. Description of the Design

This section gives a description of the continuous fountain presently under construction at ON. Fig. 1 shows a general view of the atomic resonator.

A. Vacuum System

The vacuum system is made of aluminum and can be divided into two parts. The lower part contains the source of the atomic beam and the detection region. Source and detection are in different compartments of the vacuum system. The chamber containing the source is filled with cesium vapour, and, in the detection part, graphite absorbs cesium atoms, ensuring a low background cesium pressure. The upper part houses the microwave interrogation and is surrounded by three layers of magnetic shielding. Ion pumps are connected to the upper and lower part of the system to achieve a working pressure in the 10^{-7} Pa range.

B. Optics

Previous investigations [3] have shown that the intensity of the atomic flux that can be obtained with an optical molasses is almost as good as the one achieved with an anisotropic magneto-optical trap. For the sake of simplicity, the source of the continuous fountain, therefore, will be an optical molasses formed by two pairs of counterpropagating beams in the vertical plane, mutually perpendicular and at 45° to the vertical (C; Fig. 1). A third pair (B; Fig. 1) is orthogonal to this plane and is retroreflected. Repumping light ($F = 3 \rightarrow F' = 4$) is mixed to the B beams. Each cooling beam has a $1/e^2$ diameter of 24 mm.

Further collimation of the launched atoms is achieved 50 mm above the center of the molasses in a region of 2-D transverse cooling. Beam diameters are 10 mm at $1/e^2$.

Two channels of detection are planned, thus allowing compensation for possible variations of the atomic flux by normalization. Both channels work with beams measuring 10 mm. The optics are entirely fiber-coupled, making the vacuum system independent of the preparation of the light on the optical bench. The main components are an extended cavity laser (ECL) as master laser whose output is amplified by a MOPA from which all cooling beams are derived. Repumping light is provided by a DBR laser, and the probing beam is the output of an additional ECL.

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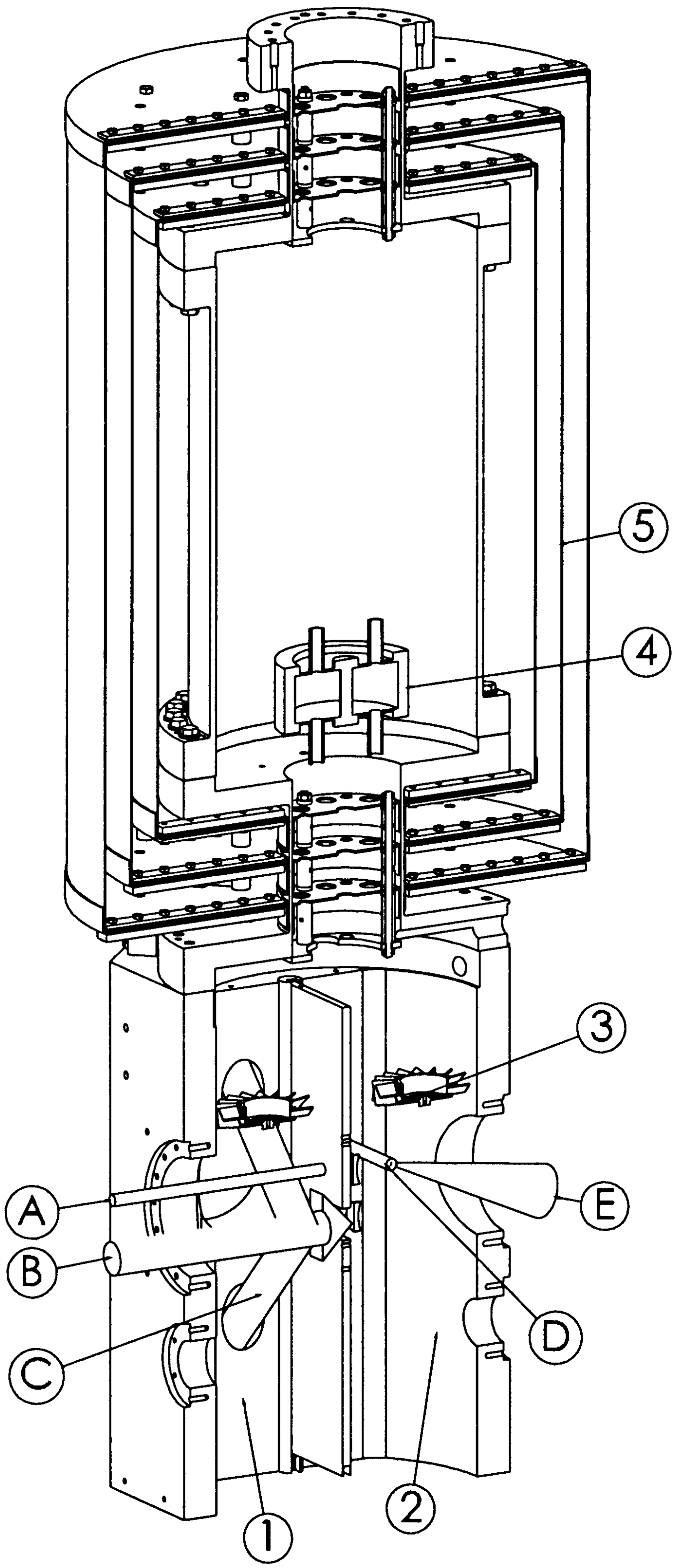

Fig. 1. General view of the atomic resonator under construction. 1) Source chamber, 2) detection chamber, 3) light trap (light shields not shown for clarity), 4) microwave cavity, and 5) magnetic shielding. A) Transverse cooling, B) and C) main cooling and launching, D) detection beam, and E) fluorescence.

C. Trajectory of Atoms

From the source, the atoms are launched at a small angle with respect to the vertical (30 mrad) by means of a moving molasses. The required horizontal velocity component is obtained by tilting the transverse cooling beam geometry (A; Fig. 1). For a 45° geometry, the launching velocity v_L is related to the difference in frequency between horizontal beams and up- and down-going beams ($+\Delta f$, $-\Delta f$, respectively) by

$$v_L = \sqrt{2}\lambda\Delta f. \tag{1}$$

With an initial velocity of approximately 3.8 m/s, the atoms describe a ballistic parabola with a maximum height of 750 mm. The horizontal distance between source and detection is 85 mm. The transit time between the first and second microwave interaction region is 0.5 s (atomic linewidth $Q = 10^{10}$).

On their trajectory, the atoms pass, after having left the source, a zone of transverse cooling [3]. In a further step, complete population inversion is obtained in the atomic beam by means of a depumping laser tuned to the $4 \rightarrow 4'$ transition, which transfers all atoms into the $F = 3$ ground state. There is no provision in the present scheme to change the existing population distribution in the m_F sublevels.

Before entering the upper part of the vacuum system, the atoms pass a light trap based on velocity selection. The trap consists of turbine wheels whose blades, made of thin absorbing glass sheet, are mounted at 45° with respect to its vertical rotation axis. If the tangential speed matches the atomic velocity, the atomic beam is transmitted with little (10%) attenuation, and the light is absorbed or specularly reflected toward a fixed light trap. A discussion on the performance of the light trap and considerations on the expected relative frequency offset caused by light shift is given in Section III.

Beyond the light trap, the atoms continue their parabola and are subjected to the two consecutive 10-ms microwave pulses spaced in time by typically $T_L \simeq 0.5$ s. On the detector side, another light trap prevents scattered light from reaching the interaction region. Finally, the internal state of the atoms is probed optically.

D. Microwave Cavity

A continuous beam of atoms requires two separate interaction zones in the microwave cavity. With a narrow parabolic flight, however, the two zones can be separated by a few centimeters only. The atoms will pass through a coaxial TE_{021} cavity on opposite sides of its axis but at the same radius r_p. The proposed cavity mode shows no azimuthal dependence of the H-field and has a maximum z-component at r_p. The longitudinal dependence of the H_z-component at r_p is sinusoidal, as in a TE_{011} cavity. A sketch of the field lines is given in Fig. 2.

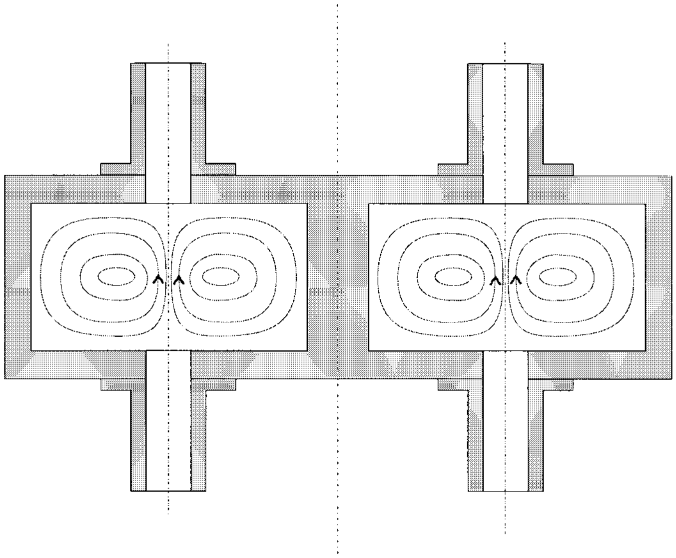

Fig. 2. Vertical section on the cavity. Schematically drawn are the H field lines.

III. Metrological Issues

A. Short-Term Stability

On the basis of the continuous atomic flux deduced from atomic shot noise measurements in the demonstration experiment, we anticipate a flux of atoms contributing to the Ramsey signal equal to $\phi_s = 5 \cdot 10^5$ at/s. For an atomic quality factor $Q \approx 10^{10}$, the short-term Allan deviation is given by

$$\sigma_y(\tau) = \frac{\tau^{-1/2}}{2Q\phi_s^{1/2}} \tag{2}$$

yielding $\sigma_y(\tau) = 7 \cdot 10^{-14}\tau^{-1/2}$.

B. Local Oscillator Effects

The development of new atomic frequency standards based on ion traps, optically pumped Cs beam, and laser pumped Rb gas cells triggered great effort to predict, study, and diminish the degradation of the stability caused by the phase noise of the local oscillator (LO). One of the studied mechanisms—known as the Dick effect—appears to be a major limitation also in pulsed fountains of cold neutral atoms [2]. As other researchers have demonstrated [4], the Dick effect will play a minor role in continuous fountains, provided that an adequate interrogation scheme is chosen.

The response of a Ramsey resonator to usual modulation schemes (e.g., square-wave frequency modulation) exhibits transients in the response of the atomic resonator of the order of T_L, the time between the two microwave pulses. If these transients are to be blanked out, the duty cycle will decrease, and, in the worst case, the resulting Dick effect will become comparable with the value in a pulsed fountain. Lowering the modulation frequency would help maintain a high duty cycle but would impose too stringent requirements on the low frequency part of the LO phase noise specification. The advantage of a continuous fountain would be lost as far as the Dick effect is concerned.

On the other hand, the response of a Ramsey resonator to square-wave phase modulation is essentially immune both to aliasing effects caused by blanking periods (if any) and to intermodulation effects caused by non-linearities of the resonator response [5]. Indeed, it can be shown that if the modulation period T_m is equal to $2T_L$, the transient duration reduces to T_R, the transit time across each interaction region. This transient originates from the small fraction of atoms ($\approx 2\%$), which experience the phase switch during their passage in the RF cavity. For all other atoms, the sensitivity of the resonator response to phase fluctuations of the LO is independent of time but only changes sign each half-period of the modulation. After square-wave demodulation and low-pass filtering, the correction signal applied to the LO corresponds exactly to the moving average (over T_L) of the LO frequency noise, but at no point are high frequency components of the LO noise spectrum translated down into the baseband. The linearity and time-independence of the resonator response are the essential elements for the overall immunity of this interrogation scheme to aliasing and intermodulation effects. The stability will still be limited by the residual contribution of the short transients for which the response is time-dependent, through a Dick effect or an intermodulation effect depending on whether the transients are blanked or not. (This effect, as well as the influence of the atomic velocity distribution, are presently being studied). In both cases, the remaining degradation of the short-term stability is expected to remain in the low 10^{-14} range with state-of-the-art quartz oscillator and synthesizer schemes. This is an asset of the continuous beam technique for both ground and space applications.

C. Collisional Shift

One advantage of the continuous beam is that the atomic density corresponding to a given average atomic flux and, consequently, to a given short-term stability is considerably lower than that in pulsed operation. A preliminary calculation of the collisional shift for a continuous beam has been made with the following assumption: collisions are caused by all atoms emitted from a source entering the cavity in any one of the $|3; m_F\rangle$ substates (total flux ϕ), and the signal is produced only by the flux ϕ_s of atoms initially in $|3; 0\rangle$ substate that reaches the detection region after passing through both cavity holes (area S_c). The continuous beam is characterized by its launching velocity $\bar{v}_L$, its velocity at the cavity level v_c, and its longitudinal temperature T_l. For $T_l < 200\ \mu$K, the position-dependent atomic density is sharply peaked near the apogee. Using this position-dependent density, the time-averaged density $\bar{n}$ experienced by the atoms in the beam center along their trajectory is readily evaluated:

$$\bar{n} = 7\frac{\Phi_s}{2v_c S_c}\left(1+\frac{v_c}{\bar{v}_L}\right)^2\left\{1+\ln\left(\frac{v_c^2}{\bar{v}_L}\sqrt{\frac{\pi m_{Cs}}{2k_B T_l}}\right)\right\}. \tag{3}$$

The collisional shift $\Delta\nu_c/\nu_{Cs}$ is then predicted using $\Delta\nu_c/\nu_{Cs} = -K\bar{n}$, where ν_{Cs} is the cesium clock frequency and $K = 6\cdot 10^{-22}$ cm^3 [1]. For a continuous fountain operating with 10^6 at s, $\bar{n} = 2.4\cdot 10^5$ at cm^{-3}, and the expected collisional shift amounts to $1.4\cdot 10^{-16}$. It will even be lower with a molasses as an atomic source. The associated uncertainty will lie in the low 10^{-17} range.

D. Light-Shift

If exposed to the fluorescence emitted from the continuous source, atoms entering the microwave interaction region would experience a light-shift $\Delta\nu_{\rm LS}/\nu_{\rm Cs} = 10^{-12}$, which might be difficult to measure or extrapolate to the required 10^{-15} level. To prevent that, light traps will be placed between the atomic resonator and both the source and the detection region. The efficiency of such a device has been tested on a prototype to be better than 10^5 in various conditions of illumination. Thus, the light-shift is safely expected to be lower than 10^{-16}.

E. Cavity Phase Shifts

An important issue of the cavity design, namely in contrast to the cylindrical cavity in use in a pulsed fountain, is the phase shift. The relative frequency offset related to an end-to-end phase shift $\Delta\varphi$ is given by

$$\frac{\Delta\nu_\varphi}{\nu_{Cs}} = \frac{\Delta\varphi}{\pi Q}. \tag{4}$$

For $Q \approx 10^{10}$, the relative frequency offset is thus roughly $3\cdot 10^{-17}/\mu$rad. A conservative estimate of this relative frequency offset is $5\cdot 10^{-16}$ if the coupling holes are offset by as much as 0.1 mm from cavity apertures. Moreover, it should be noted that the small size of the cavity allows a true cavity reversal (as opposed to beam reversal), thus reducing even further the uncertainty associated with end-to-end phase shift.

An estimate of the distributed phase shift in the radial direction has been computed by techniques similar to those described in [6]. For this 1-D computation, only the losses in the cylindrical walls are taken into account. The effect of the feeding holes, as well as that of the apertures for the atoms, are neglected. The peak-to-peak variation of the phase across an 8-mm aperture is of the order of 12 μrad and would thus yield a relative frequency offset of $4\cdot 10^{-16}$ in the worst case. More details on the evaluation of the distributed phase shift can be found in [7]. In conclusion, this coaxial cavity is perfectly suitable for a primary frequency standard below the 10^{-15} accuracy level.

IV. Conclusion

A primary frequency standard based on a continuous beam of laser-cooled atoms is presently under construction at ON. In this device, atoms are extracted from an optical molasses and launched at a small angle with respect to the vertical. A demonstration experiment indicates that the expected atomic flux combined with the atomic line Q of 10^{10} is sufficient to achieve a short-term stability of $7\cdot 10^{-14}\tau^{-1/2}$. To not degrade this short-term stability, care must be taken for the selection of the interrogation scheme. Square wave phase modulation with square demodulation is promising because the intermodulation effect and the Dick effect are suppressed to a large extend. Among the advantages, one must also mention the reduced collisonal shift that is expected to be in the 10^{-16} range. Light shift and phase gradient are specific problems of the continuous fountain. The former is addressed by a rotating light trap capable of lowering the relative frequency offset down to the 10^{-16} range. An estimate of the phase gradient indicates that the related shift is of the order of $4\cdot 10^{-16}$ and thus compatible with the accuracy goal of 10^{-15}. As for the end-to-end phase shift, a cavity reversal should allow the cancellation of this effect. Finally, the possibility of operating the standard simultaneously at optimum accuracy and stability is inherent to the continuous beam design. This is discussed here in a fountain geometry for ground-based clocks but will equally apply to space versions in which linear beams will be used.

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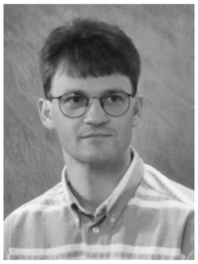

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Pierre Thomann (M'90) received a degree in physics engineering and a Ph.D. degree in physics in 1978, both from the Swiss Federal Institute of Technology in Lausanne, Switzerland. He worked as postdoctoral research assistant one year at Oregon State University and one year at JILA, University of Colorado. From 1980 to 1991, he led several industrial developments in the field of atomic clocks (Rb, H-maser, and cesium). He then joined the Observatoire de Neuchâtel as head of the Cesium group, where his current interests are applications of the laser cooling of atoms, mostly in the field of time and frequency metrology.