PRELIMINARY EVALUATION OF THE ON-METAS CONTINUOUS FOUNTAIN STANDARD

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Abstract

We report on the preliminary evaluation of a primary standard based on a continuous fountain of laser-cooled cesium atoms. In its present configuration, the continuous fountain operates at a short-term stability of $2.5 \cdot 10^{-13}\tau^{-1/2}$, the flicker-floor is reached at $2 \cdot 10^{-15}$ after 10'000 s, which allows precision measurements to be conducted in relatively short periods. The light-shift has been measured and has been assigned almost exclusively to fluorescence from the cold atoms leaving the source. The evaluation of the second-order Zeeman bias relies on the measurement of the average field using the field dependent transitions ($m_F \neq 0$, $\Delta m_F = 0$). Magnetic homogeneity requirements are more severe in a continuous fountain because the unambiguous identification of the central fringe of the Ramsey pattern for the determination of the average magnetic field requires a highly homogeneous field. We have developed a model which makes use of fringe contrast and envelope asymmetry measurements as complementary diagnostic methods to evaluate the relevant parameters of the field profile.

1 INTRODUCTION

In a common effort the Swiss Federal Office of Metrology (METAS) and the Observatory of Neuchâtel (ON) have designed and built a primary frequency standard based on a fountain of laser cooled cesium atoms. In contrast to most other atomic fountains the ON/METAS development utilises a continuous beam of cold atoms rather than cold clouds of cesium in a pulsed way([1, 2, 3]. Details of the device have been presented at previous fora and can be found in their proceedings [4].

In this communication we present recent results obtained with the fountain. Over the last months several accuracy and stability issues have been investigated. A special emphasis was therein given to topics that are specific to the continuous character of the fountain. An obvious potential problem of a continuous fountain is the stray light of the source of atoms if it reaches the region where the atoms are interrogated. The resulting light shift at maximum brightness of the source has been measured to be $1.4 \cdot 10^{-12}$ and is entirely caused by the fluorescence from the cold atoms in the source. As a solution, we propose a rotating light trap, a device shown in figure 1 and already presented at the EFTF 2001 [4]. Such a light trap is now being installed in the fountain, after several reliability tests and checks of optical efficiency. In a separate experiment the blades of the light trap have attenuated the stray light by a factor 10^5 which is more than sufficient to bring the light shift down to a negligible level.

Figure 1: Picture of the wheel of the rotating light trap.

Besides, the determination of the mean magnetic C-field and of its homogeneity is another important point in the uncertainty budget where the approach differs considerably from the pulsed fountain. In section 2 we discuss the mapping of the C-field in a continuous fountain. Section 3 is devoted to a partial uncertainty budget: the effects that have been addressed so far are listed. Finally, conclusions are presented in section 4.

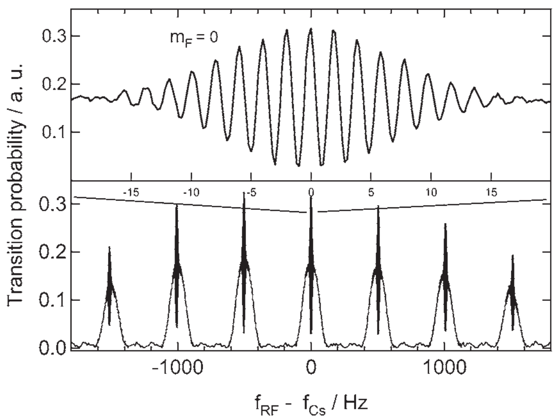

Figure 2: Scan over all $|F = 3, m_F > \rightarrow |F = 4, m_F >$ transitions.

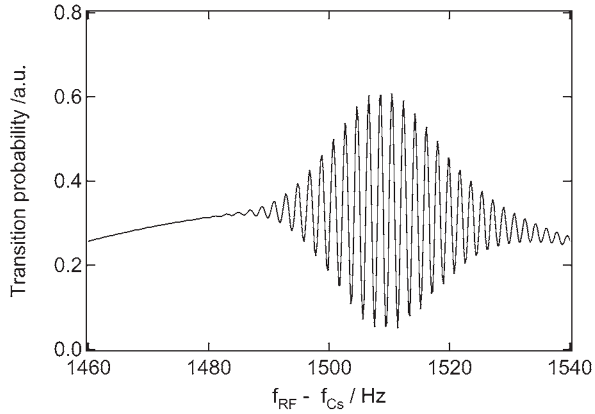

Figure 3: Simulated Ramsey fringes for the $m_F = 3$ transition. Light gray shows the calculation with a perfect C-field, the black fringes are computed with a small magnetic gradient in the apogee region.

2 ACCURACY ISSUES: MAGNETIC FIELD MAPPING

The homogeneity and stability of the C-field inside the resonator are of highest importance for the accuracy and the stability of a primary frequency standard. Its evaluation in a continuous fountain is, however, different from the way it is obtained in a pulsed fountain.

Figure 2 shows a scan over all $|F = 3, m_F > \rightarrow |F = 4, m_F >$ transitions. It can be seen that Ramsey fringes are visible up to $m_F = \pm 3$. However, for the linearly dependent transitions $m_F \neq 0$ and especially for $m_F = \pm 3$, there is a loss of contrast of the fringes. Among the evaluation of the different frequency shifts, the second order Zeeman shift requires an accurate knowledge of the residual inhomogeneity of the static magnetic field B along the atom's trajectories. As a matter of fact, the calculation of this shift depends on the mean square value $< B^2 >$ of the magnetic field over all trajectories of the detected atoms.

As usual in frequency standards, the evaluation of $< B^2 >$ requires a knowledge of $< B >$ and some information on the departure from the ideal situation B = constant. $< B >$ is in principle obtained from the position of the 'central' fringe of the Ramsey pattern of a linearly field-dependent transition ($m_F \neq 0$). The identification of the central fringe is a problem in itself which can be solved in a pulsed fountain by tossing atoms at different heights. In a continuous fountain this procedure is not possible due to the geometrical constraints on the atomic beam. The combination of inhomogeneities of the magnetic field and the velocity distribution has two effects on $m_F \neq 0$ transitions. First, to displace the central fringe with respect to the fringe envelope and second, to reduce the contrast and to affect the symmetry of the envelope.

The first effect makes it difficult to identify which fringe should be used to determine the mean value of the magnetic field. However, in the present configuration where a C-field of 71 nT is used (corresponding to a splitting of the Zeeman sub-levels of 500 Hz), the central fringe must be determined unambiguously in order to make sure that this contribution to the uncertainty budget is negligible at the 10^{-15} level. Indeed, an uncertainty of 1.5 nT on the mean magnetic field (*i.e.* roughly 10 Hz on the $m_F = \pm 1$ transitions) corresponds to a frequency uncertainty of 10^{-15}.

The second effect can be used for this determination. We have developed a simple theoretical model which allows us to estimate the value of the spurious field around the apogee of the atom's trajectories based on the loss of contrast and the symmetry of the Ramsey pattern on the $m_F = \pm 3$ transitions. In the model we assume that the C-field is the sum of a constant term B_0 and a z-dependent perturbation $B(z) = b \exp(\gamma(z - z_0))$ where z_0 is the mean apogee of the atomic beam, b is equal the spurious field at the apogee $z = z_0$ with a slope γb. This dependence of $B(z)$ is justified by the openings at the end of the magnetic shielding, near the apogee of the parabola. As the atoms spend an important part of the interaction time in this region, inhomogeneities in the lower part of the parabola are neglected.

We have used the model to estimate the b and γ of our present C-field. Figure 3 shows simulated Ramsey fringes on the linearly field dependent transition $m_F = 3$ with a perfectly homogeneous C-field (light gray line) and with a C-field showing a small departure from the ideal case as described above. The two parameters of the model b and γ are obtained by fitting simulated Ramsey fringes to experimental data. We find that $b < 0.1$ nT at the apogee of the mean trajectory and $\gamma b < 2$ nT/m.

Effect		*Shift* 10^{-15}	*Uncert.* 10^{-15}
C-field	m	23.7	1
Light-shift w/o trap	m	1400	
Light-shift w trap	e	< 1	< 0.1
Collisional shift	e	–	< 0.1
Cavity phase shift	e	–	< 1
Cavity feeding	m	–	< 10

Table 1: Summary of the already addressed shifts and the corresponding uncertainties. e stands for estimated, m for measured

Albeit weak, this residual field still leads to a frequency offset of about 5 Hz ($\sim$ 3 fringes) between the central fringe and the fringe having the maximum contrast on the transitions $m_F = \pm 1$. This value corresponds to an uncertainty below 10^{-15} on the second order Zeeman shift, but is not negligible in the uncertainty budget and more work on the C-field is thus needed.

The usual main contribution to the uncertainty of the second order Zeeman shift stems from the use of $< B >^2$, rather than $< B^2 >$. However, the stringent condition that the magnetic field must fulfill to allow an unambiguous identification of the central fringe ensures at the same time that the contribution due to $\delta B^2 =< B^2 > - < B >^2$ is made negligible.

3 PARTIAL UNCERTAINTY BUDGET

Table 1 summarizes all accuracy issues addressed so far. The values for shift due to the C-field is explained in details in the previous section. As for the light shift, the values reported here are exposed in [4]. The estimated value with the light trap in place reflects the measured value, divided by the attenuation of the rotating light-trap as obtained in a separate experiment. The collisional shift, an important contribution in a pulsed fountain, can be neglected in a continuous fountain. Indeed, the estimated value given here is the typical value of a pulsed fountain [5] multiplied by the ratio of the densities between continuous and pulsed fountain. The cavity phase shift, investigated earlier is a theoretical estimate of the distributed and end-to-end phase shift [6]. Finally, we checked the influence of the feeding of the cavity from opposite ports. No effect was visible at the level of 10^{-14}.

4 CONCLUSION

The ON/METAS frequency standard based on a continuous beam of laser cooled cesium atoms is now operational. Ramsey fringes can be obtained routinely and tentative stability measurements are performed with a commercially available frequency multiplier. Among the efforts towards a complete accuracy evaluation, the mapping of the C-field takes an important place. We have shown how to evaluate and put an upper limit to the imhomogeneities of the magnetic field—and thus to the uncertainty of the second order Zeeman shift— even though a detailed mapping by tossing atoms to different heights is not possible. In the present configuration the uncertainty ascribed to the C-field amounts to $1 \cdot 10^{-15}$ a value that has to be decreased if the goal of an overall uncertainty of 10^{-15} is to be met. Further improvements on the quality of the C-field can be expected from the installation of compensation coils near the openings of the magnetic shielding.

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