First Results with a Cold Cesium Continuous Fountain Resonator

Gregor Dudle, Alain Joyet, Patrick Berthoud, Gaetano Mileti, and Pierre Thomann

***Abstract*—We report on the design, construction, and preliminary measurements on the resonator of a continuous Cs fountain frequency standard. The construction of the resonator is described, preliminary measurements of the available atomic flux, and of the beam temperature are presented, along with the first Ramsey fringes (width $\simeq$1 Hz) obtained in this new type of fountain. We discuss theoretical aspects of the interrogation scheme with a special view on how aliasing or intermodulation effects are suppressed in a continuous fountain.**

***Index Terms*—Atomic fountain, atomic frequency standards, Dick effect.**

I. INTRODUCTION

MOST prototypes of Cs fountain frequency standards rely on a pulsed mode of operation [1]: a cloud of cold atoms is first captured in an optical molasses or in a magnetooptic trap, cooled to low temperatures (a few microkelvin), sent in a vertical ballistic flight for microwave interrogation, and analyzed on its return in the source region. This process is repeated at a rate of roughly 1 Hz. As a result of the pulsed operation, the difference between the interrogating frequency and the atomic frequency, which is probed during the half-second near the apogee, is sampled with a duty cycle significantly smaller than one.

Cold atom fountains can lead to large improvements of both the short-term stability and the accuracy of Cs standards, as already demonstrated in at least two laboratories [2], [3]. However, their operation in a pulsed mode may introduce difficulties in achieving the ultimate short-term stability and accuracy that the use of cold atoms allow in principle. The best accuracy in Cs fountains is achieved for moderate atomic densities to limit the contribution of the collisional shift, which is proportional to the cold cloud density. The short-term stability, however, improves as the square-root of the number of atoms probed in each cycle, and its optimization would require as high an average atomic flux as possible. (The resulting compromise between stability and accuracy is almost completely relaxed in the case of ^{87}Rb, which shows a much lower collisional cross section than Cs [4]). Moreover, pulsed operation of passive frequency standards provides an undesirable aliasing mechanism through which the phase noise of the interrogation oscillator may severely limit the achievable short-term stability [5], [6].

Fig. 1. Basic configuration of the continuous fountain, showing the six cooling beams, the microwave cavity and the detection region.

This stability degradation may be overcome by using a very low noise cryogenic oscillator to produce the interrogation signal, as demonstrated in [7]. Several methods have also been suggested to circumvent this stability limitation, including the use of tandem pulsed resonators, or of multiple clouds sent in such a way that atoms are present in the interrogating region at all times [8], [9].

The continuous beam approach [10] provides an alternative way of reducing by about two orders of magnitude both the collisional shift and the aliasing effects tied to pulsed operation. Based on the experimental demonstration of a continuous beam

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of $2 \cdot 10^8$ atoms/s [11], the Allan deviation of a continuous fountain standard using the same initial atomic flux is expected to be $7 \cdot 10^{-14} \tau^{-1/2}$ and the potential for accuracy below 10^{-15} [12].

We report here on the design, construction, and preliminary operation of a continuous fountain as the first steps in the development of a primary standard for the Swiss Federal Office of Metrology (OFMET).

II. FOUNTAIN DESCRIPTION

A. Atomic Beam and Fountain

The basic principle of the continuous fountain is closely related to that of the now well-known pulsed fountain [1]. The main difference, illustrated in the simplified schematics of Fig. 1, lies in the parabolic—rather than linear vertical—shape of the average atomic path, which provides the required physical separation between atomic preparation and detection regions. Fig. 2 gives a more detailed picture of the fountain configuration.

The lower part of the vacuum vessel is separated in two compartments: source and detection. They are efficiently isolated from each other for stray light and Cs atoms by appropriate traps and getters while being connected to the same ion pump. Cold atoms are produced in the source region by capture and cooling from a thermal Cs vapor at the intersection of three pairs of mutually orthogonal laser beams. Each beam has a diameter of 25 mm (e^{-2}), a power of 15 mW, and a circular polarization opposite to that of the counterpropagating beam ($\sigma^+ - \sigma^-$ molasses). One pair is horizontal (Ox) and is retroreflected by a roof prism inside the vacuum system. The other two pairs are in the Oyz plane and propagate at 45° with respect to the vertical. The atomic beam is launched vertically upwards at an initial velocity v_0 by the moving molasses technique. To this end the frequency of the upward (downward) cooling beams is shifted by an amount $+\Delta f (-\Delta f)$ where $\Delta f = v_0/(\lambda\sqrt{2})$, with $\lambda = 852$ nm, the laser wavelength. Note that in the continuous fountain the frequencies of the lasers are fixed, which means that the capture and the launching of the atoms take place simultaneously.

B. Microwave Cavity

The microwave cavity (Fig. 3) is made from oxygen free, high conductivity (OFHC) copper. It is a cylindrical, coaxial cavity oscillating in a TE 021 mode. As shown in Fig. 4, the RF magnetic field in each interaction zone is vertical (i.e., axial), the field distribution in the (r, z) plane is independent of the azimuthal angle. The microwave radiation is coupled into and out of the cavity through two irises placed at equal distances from the atomic paths. The irises are in turn connected to waveguide-to-coaxial transition pieces. The upper and lower end plates are fitted with cutoff waveguides on each of the four atomic beam openings to reduce microwave leakage out of the cavity. The calculated attenuation for the dominant evanescent mode is more than 150 dB, neglecting the finite wall conductivity. The measured attenuation is >110 dB, presently limited by the measurement technique. All components of the cavity are assembled with indium seals. The electrical contact between body and end plates is ensured at the end of a quarter-wave section of narrow-gap coaxial cavity (choke). This feature efficiently shifts the frequency of the degenerate and unwanted TM mode and inhibits its oscillation (Fig. 5). The measured loaded Q is 11 500, and the measured temperature coefficient in vacuum (−140 kHz/K) is close to a calculated value based on the linear expansion coefficient of copper (−152 kHz/K).

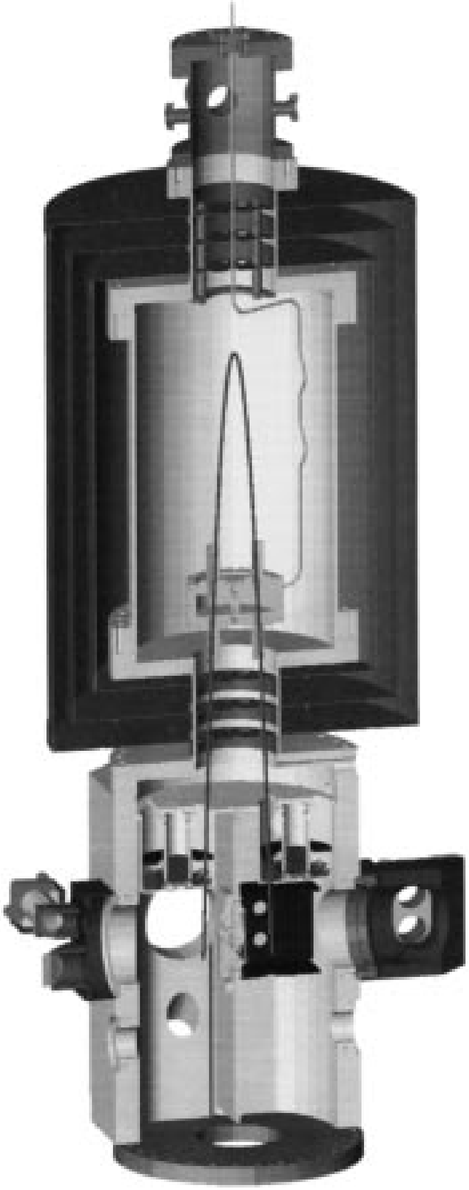

Fig. 2. Schematic view of the fountain resonator. The height of the drawn parabola is 75 cm.

III. INTERMODULATION EFFECTS

It has been predicted [5], [6] and demonstrated experimentally [13] that the frequency stability of passive frequency standards is particularly sensitive to the interrogation oscillator phase noise if their operating mode is pulsed. In this particular mode of operation, the frequency (FM) noise of the local oscillator (LO) around harmonics of the pulse rate is downconverted by aliasing into the bandpass of the frequency control loop.

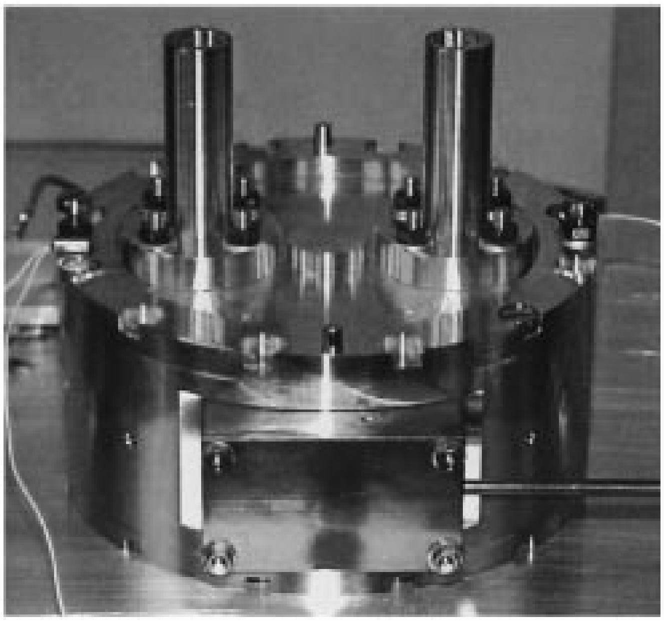

Fig. 3. Photograph of the cavity. The two tubes on top of the cavity are the cutoffs through which the atoms perform their parabolic flight. The separation of the two holes is 56 mm.

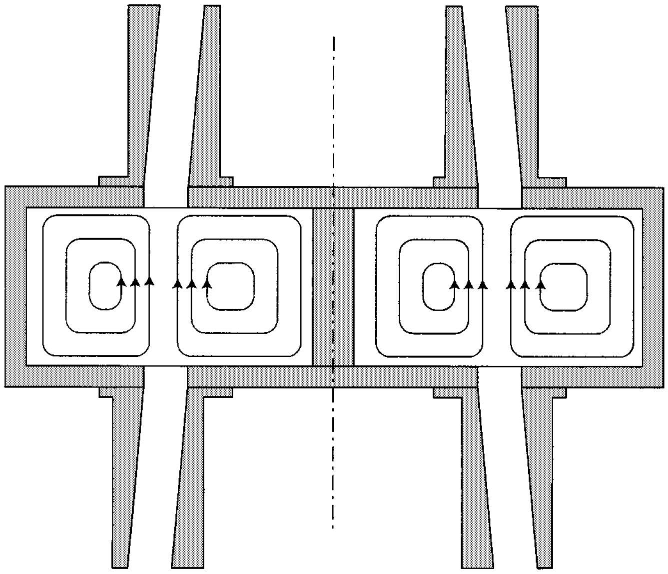

Fig. 4. Cut through the microwave cavity in the $(r,\ z)$ plane of the parabola. The lines inside the resonator indicate the H-field lines. The cutoffs are tilted to minimize the loss of atoms due to geometrical reasons. The central post is on the axis of rotational symmetry for the field mode (Oz).

In continuously operated frequency standards, a similar degradation of the frequency stability may arise as well. It depends, however, on the scheme of modulation–demodulation used to generate the error signal which controls the LO and on the value of the modulation frequency. This mechanism, the so-called intermodulation effect was first pointed out by Kramer [14], then described in detail by Audoin [15] in the case of a passive cell standard in the quasistatic approximation (interrogation frequency much smaller than atomic resonance linewidth).

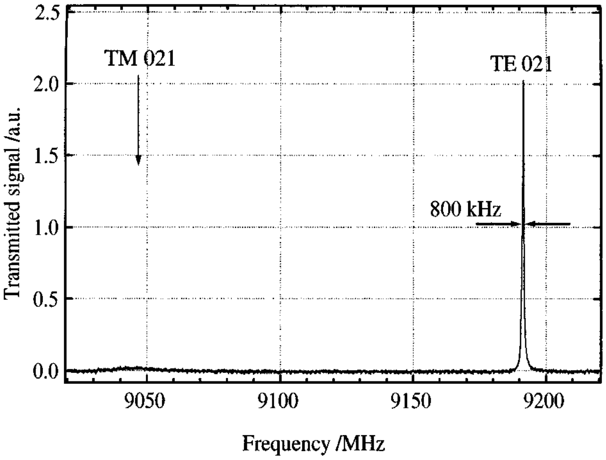

Fig. 5. Transmission spectrum of the cavity. In addition to the TE_{021} mode one makes out the TM_{021} mode, 140 MHz below the Cs resonance.

To evaluate to what extent aliasing or intermodulation effects will degrade the frequency stability of a continuous fountain we have developed a formalism which applies to all Ramsey type resonators. This formalism uses the autocorrelation of the time dependent signal from the resonator to calculate the power spectral density of the locked local oscillator (LLO). This approach can be applied to any modulation-demodulation scheme and to any time dependence of the atomic beam.

If the microwave interaction duration is negligible compared to the separation of the pulses, it can be shown [16] that the additional contribution $S_{y,\,al.}^{\mathrm{LLO}}$ to the fractional power spectral density of an LLO S_y^{LLO} due to intermodulation and aliasing effects is given by

$$S_{y,\,al.}^{\mathrm{LLO}} = 2\sum_k c_k^2 R(T/T_m) S_y^{\mathrm{LO}}(2kf_m) \tag{1}$$

where

$S_y^{\mathrm{LO}}(f)$	fractional power spectral density of the unlocked oscillator;
c_k^2	coefficients depending on the modulation–demodulation scheme;
$R(T/T_m)$	function describing the atom-field interaction;
T	time between the two microwave pulses of the Ramsey interrogation;
T_m	period of the interrogation modulation ($f_m = 1/T_m$).

In [16] it is shown that for a monokinetic beam, $R(T/T_m)$ takes the form

$$R(T/T_m) = \mathrm{sinc}^2\left(2k\pi\frac{T}{T_m}\right) \tag{2}$$

where $\mathrm{sinc}(x) = \sin(x)/x$. This means that (1) equals zero for all modulation–demodulation schemes if the modulation period T_m is twice the time between the two microwave pulses T $(2T = T_m)$. In a continuous resonator, T_m is a free parameter that can be selected to cancel expression (1). This result has already been obtained by Makdissi [17] in a different context, namely that of an extension of the sensitivity function introduced by Dick [5], [6] to the continuous case.

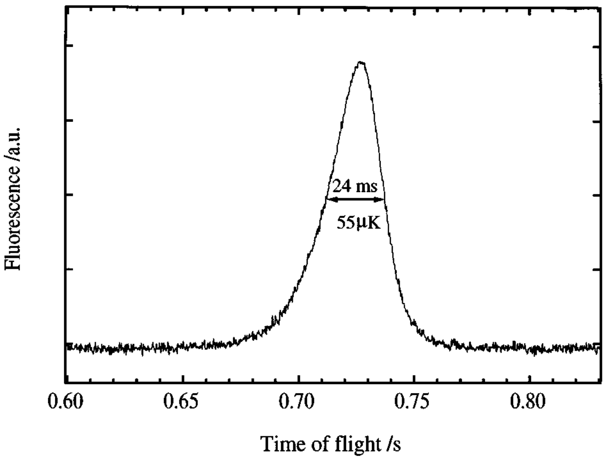

Fig. 6. Time of flight spectrum of the continuous fountain. Small slices are cut out of the continuous beam by means of a pusher laser. The fluorescence in the detection region allows one to infer the longitudinal temperature of the atomic beam.

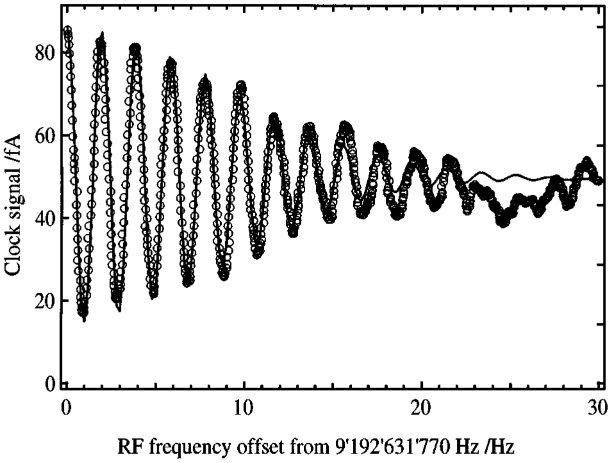

Fig. 7. Ramsey fringes of the clock transition ($F = 3$; $m_F = 0 \leftrightarrow F = 4$; $m_F = 0$) in the continuous fountain. Circles represent experimental values, the plain line is a numerical simulation with an atomic beam at 50 μK. The spacing between fringes is 1 Hz. The decreasing contrast with the increasing detuning may be used to estimate the temperature of the atomic beam. The experimental curve results from the accumulation of ten scans of 1000 s duration each. The dominant noise contribution is thermal noise from the detector.

Moreover, one can easily demonstrate that for square wave phase modulation (still with $2T = T_m$) all coefficients $c_k^2 = 0$ leading to an even stronger cancellation of the added noise expressed by (1).

It has to be mentioned that these results are valid for a monokinetic beam, i.e., if all atoms spend the same time between the two microwave pulses. This is obviously not the case for a beam with a finite temperature. The aim of the current work is to extend these results to beams of finite temperature and nonvanishing interaction durations.

Let us finally note that a simple connection can be made with Dick's description for pulsed Ramsey resonators. The pulsed nature can be taken into account in our approach by a gated demodulation function in which case (1) reduces to the familiar Dick formula.

IV. PRELIMINARY MEASUREMENTS

A. Flux Measurements

Preliminary flux measurements without the microwave cavity have been performed on the fountain. Two different methods, one based on the optical calibration of the detection system, the other on the measurement of the atomic shot noise [12], lead to a total flux of $>10^5$ atoms/s (all m_F values) in the detection region, which is less than expected by an order of magnitude. A pusher laser beam tuned to the $F = 4 \rightarrow F' = 5$ transition has been implemented to cut thin slices (9.5 ms) of the continuous atomic beam. The time-of-flight (TOF) distribution is recorded using the fluorescence in the probe beam and the longitudinal temperature of the beam can be inferred. A typical TOF spectrum is shown in Fig. 6 and indicates a temperature of 55 μK.

B. Ramsey Fringes

Although most efforts are now concentrated toward optimization of the atomic flux, it has been possible under the present operating conditions to obtain preliminary Ramsey fringes near the clock transition frequency (C-field = 1 μT) by scanning the frequency of the microwave radiation in the cavity. Fig. 7 shows a scan near the nominal Cs clock frequency. The 9.2 GHz signal was generated by using a quartz oscillator locked to an H-maser and a frequency multiplier from a commercial Cs standard. The S/N ratio does not yet allow a detailed analysis of the fringes. However, their width (1 Hz) is as expected and the decreasing contrast far from the central fringe is explained by the beam temperature, as demonstrated by the theoretical Ramsey pattern in a 50 μK fountain represented in the same figure. This temperature is consistent with the value obtained by the TOF measurement.

V. CONCLUSION

An atomic fountain resonator based on a continuous beam of laser cooled Cs atoms has been constructed. Although the flux of cold atoms needs to be optimized to increase the signal to noise ratio, it has been possible to record the first Ramsey fringes with a continuous fountain. The spacing of the fringes is 1 Hz. The longitudinal temperature of the beam measured by the TOF technique agrees well with the value deduced from the reduction of the contrast of the Ramsey fringes (50 μK). Work is continuing on the construction of a frequency standard.

A formalism has been developed to calculate the additional noise contribution to the power spectral density due to aliasing or intermodulation effects. No degradation of the frequency stability is expected for a Ramsey type resonator if the modulation period is twice the time between the two microwave pulses. This condition can easily be met in a continuous fountain. Square wave phase modulation is especially promising as the cancellation of the additional noise is even stronger for this particular type of modulation.

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