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Improvement of the Frequency Stability Below the Dick Limit With a Continuous Atomic Fountain Clock

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***Abstract*—The frequency instability of a shot-noise limited atomic fountain clock is inversely proportional to its signal-to-noise ratio. Therefore, increasing the atomic flux is a direct way to improve the stability. Nevertheless, in pulsed operation, the local oscillator noise limits the performance via the Dick effect. We experimentally demonstrate here that a continuous atomic fountain allows one to overcome this limitation. In this work, we take advantage of two-laser optical pumping on a cold cesium beam to increase the useful fountain flux and, thus, to reduce the frequency instability below the Dick limit. A stability of $6 \cdot 10^{-14}\tau^{-1/2}$ has been measured with the continuous cesium fountain FOCS-2.**

I. Introduction

Since the redefinition of the second in 1967, the stability and the accuracy of cesium atomic clocks have been continuously improved. With the advent of laser cooling in the early nineties, thermal beams were replaced by cold atomic fountains [1] to contribute to International Atomic Time (TAI) as primary frequency standards [2]. Currently, state-of-the-art pulsed fountain clocks (atoms are sequentially laser-cooled, launched vertically upwards, and interrogated during their ballistic flight before the cycle starts over again [3]) are operated at an accuracy level below 10^{-15} in relative units. However, their short-term stability is degraded by the phase noise of the interrogation oscillator via the Dick effect [4], [5]. For example, with a state-of-the-art boîtier à vieillissement amélioré (BVA; enclosure with improved aging) quartz oscillator, the excess noise resulting from the Dick effect limits the frequency stability of a pulsed fountain clock to approximately $10^{-13}\tau^{-1/2}$ [6]. This limit has been overcome in a few laboratories, either by using a cryogenic sapphire ultra-stable oscillator [7], or by generating the microwave from an ultra-stable laser with the help of an optical frequency comb [8], [9].

Instead of making the effect negligible by employing an ultra-stable local oscillator, our alternative approach is to eliminate the dead times (time intervals without atoms in the free evolution region) by making use of a continuous beam of cold atoms. In this case, as shown in [10], the intermodulation effect[1] is negligible and the frequency stability is only limited by the fountain signal-to-noise ratio. Therefore, increasing the atomic flux is a direct way to improve the short-term stability and reduce the integration time necessary to reach a given statistical resolution. In this work, we use two-laser optical pumping on a continuous beam of cold atoms to increase the useful fountain flux and thus to achieve a better stability.

In Section II, we describe the continuous atomic fountain FOCS-2, its operation, and the state preparation with two-laser optical pumping. The experimental results will be presented in Section III and discussed in Section IV. Finally, we will conclude this work in Section V.

II. Description of the Continuous Atomic Fountain FOCS-2

A. Setup of the Fountain

A scheme of the continuous atomic fountain FOCS-2 is shown in Fig. 1 (a detailed description is given in [11]). Cesium atoms from a background thermal vapor are continuously slowed down in a two-dimensional magneto-optical trap (2D-MOT) to produce an intense beam of slow atoms (<25 m/s) [12]. This beam is then captured by a three-dimensional moving molasses which further cools and launches the atoms upward with a vertical velocity of 4 m/s [13]. This allows us to create a continuous beam of 10^9 atoms/s with a longitudinal temperature of about 75 μK [14]. The atomic beam is then collimated with Sisyphus cooling in the transverse directions to reduce the loss of flux resulting from thermal expansion during the free evolution time. Before entering the microwave cavity, the atoms are prepared into $|F = 3,\, m = 0\rangle$ with a state preparation scheme combining optical pumping and laser cooling. This is achieved in a 2-D-folded optical lattice situated 2.5 cm above the collimation stage. After these two steps, the transverse temperature is decreased to approximately 3 μK. Finally, one last retro-reflected laser

[1] The intermodulation effect refers to the down-conversion of the local oscillator frequency noise into the bandpass of the frequency control loop by aliasing. The Dick effect is an example of the intermodulation effect characteristic of pulsed operation.

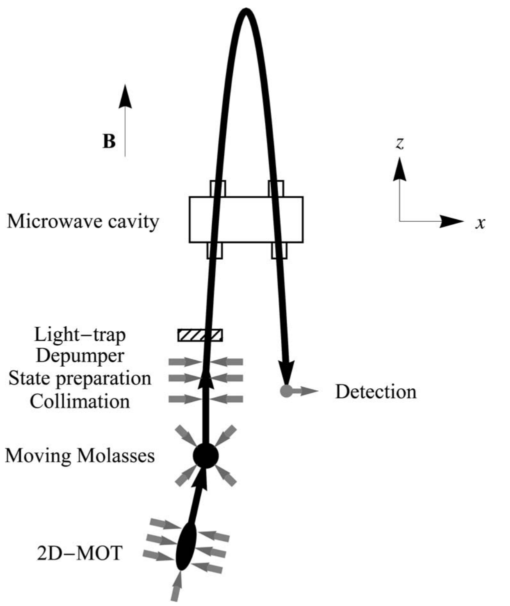

Fig. 1. Scheme of the continuous atomic fountain clock FOCS-2. The 2-D magneto-optical trap (2D-MOT) loads the 3-D moving molasses with an intense beam of pre-cooled atoms. There, the atoms are further cooled to 75 μK and launched vertically at a speed of 4 m/s. Then, the atomic beam is collimated by transverse Sisyphus cooling before the atoms are pumped into $|F=3, m=0\rangle$ in the state preparation stage, and a depumper laser is used to empty the $F=4$ clock state. Through the microwave cavity, the atoms experience a first $\pi/2$-pulse, thereby creating a superposition state that evolves freely for approximately 0.52 s in a constant vertical magnetic field before the atoms undergo a second $\pi/2$-pulse during the second passage. Finally, the transition probability between $|F=3, m=0\rangle$ and $|F=4, m=0\rangle$ is measured by fluorescence detection of the atoms in $F=4$. The light-trap prevents the stray light from the atomic beam source from reaching the free evolution zone situated above it.

beam (depumper) tuned to the $F=4 \rightarrow F'=4$ transition is used to depump the atoms remaining in the $F=4$ clock state.

In a continuous fountain, the two microwave interactions must be spatially separated. To this end, both the transverse cooling lattice and atomic state preparation stage are tilted by 1.6° from the horizontal to bend the atomic trajectory. The atoms pass through the microwave cavity in the upward direction, undergoing a first $\pi/2$-pulse, freely evolve for 0.52 s, and turn back into the second microwave zone, where they experience a second $\pi/2$-pulse. The transit time in each Ramsey zone is of the order of 10 ms. To define a vertical quantization axis and thus lift the degeneracy of the $|F=3, m\rangle \rightarrow |F=4, m\rangle$ microwave transitions, a vertical magnetic field is applied throughout the free evolution region. The experimental value of 73 nT shifts the seven resonances by $m \times 513$ Hz away from the $|F=3, m=0\rangle \rightarrow |F=4, m=0\rangle$ clock transition frequency. The atomic populations can be probed by fluorescence detection of the $F=4$ atomic flux, while scanning the microwave frequency around each transition. To this end, we send a retroreflected probed laser beam (14 mm diameter and 1 mW of power) tuned 2 to 5 MHz below the $F=4 \rightarrow F'=5$ transition through the atomic beam, and we collect and measure the fluorescence light with a low-noise photodetector (noise spectral density: 10^{-14} A/$\sqrt{\text{Hz}}$ between 0.1 and 20 Hz).[2]

B. State Preparation

As mentioned in the introduction, we make use of two-laser optical pumping to improve the short-term stability of the clock. This pumping process was described in [15] and we briefly recall the main principle. A first laser is used to excite the $F=4$ cesium ground state to pump the atoms into $F=3$, while a second π-polarized laser beam excites the $F=3 \rightarrow F'=3$ transition. Because of selection rules, $|F=3, m=0\rangle$ is the only ground-state sublevel which is not coupled to laser light; therefore, all of the atoms will accumulate into this state. Basically, Zeeman pumping toward $m=0$ is performed by the second laser, while the first acts as a hyperfine repumper. Every spontaneous emission event transfers a random recoil to the atom, thereby heating the cold atomic beam. As explained in [15], we adjust the frequency, polarization, and geometry of the laser beams to produce Sisyphus cooling simultaneously with the optical pumping to compensate this heating process.

Practical realization of the atomic state preparation on the cold atomic beam is achieved with a 2-D phase-stable optical lattice [16] and a 1-D retro-reflected Zeeman pump beam. On the one hand, the frequency (125 MHz above the $F=4 \rightarrow F'=4$ transition) and the strong polarization gradient resulting from subsequent multiple reflections of the incoming 45°-linear polarization of the lattice allow the combination of Sisyphus cooling with the hyperfine pumping for state preparation. On the other hand, the second laser used for Zeeman pumping toward $|F=3, m=0\rangle$ is tuned to the $F=3 \rightarrow F'=3$ transition and thus acts also as a repumper for the cooling process. Thereby, the atoms are either pumped toward $m=0$ when they are in $F=3$, or laser-cooled in the optical lattice when they are in $F=4$. With an atomic beam velocity of 3.6 m/s through the state-preparation region and with a Gaussian waist of 5.7 mm, truncated at a diameter of 11 mm for both optical lattice and Zeeman pump laser beams, the transit time of 3 ms is sufficient to produce an efficient pumping to the $|F=3, m=0\rangle$ ground-state.

C. Operation of the Fountain

A block diagram of the frequency control loop is shown in Fig. 2. The microwave interrogating the atoms is generated with a synthesizer (SDI CS-1, Spectra Dynamics Inc., Louisville, CO). Four internal phase-locked loops are successively locked on the reference hydrogen maser: a 5-MHz voltage-controlled crystal oscillator (VCXO), a 100-MHz VCXO, a 9.2-GHz dielectric resonator oscillator (DRO), and a 7.36823-MHz signal from a direct digital synthesizer (DDS). The last two signals are mixed together to

[2] This corresponds to 300 atoms/s when integrated within a bandwidth of 1 Hz.

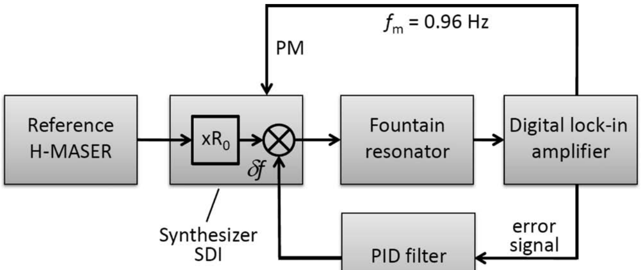

Fig. 2. Block diagram of the frequency servo-loop. The microwave synthesizer (SDI) is referenced to the hydrogen maser while the 9 192 631 770 Hz output is square-wave phase modulated (PM) at 0.96 Hz to interrogate the atoms. The error signal is obtained via synchronous detection of the fountain transition probability and it is then integrated by the loop filter (PID) to produce the frequency correction applied to the synthesizer with 1 μHz of resolution. The modulator, the synchronous detector, and the loop filter are all implemented in software using real-time Labview routines.

generate the 9 192 631 770 Hz clock transition frequency. The amplitude of the field is adjusted such that the atoms experience a $\pi/2$-pulse for each passage in the microwave cavity. To produce an error signal, the phase of the 9 192 631 770 Hz is square-wave modulated with a peak-to-peak amplitude of $\pi/2$. The frequency[3] $f_m = 0.96$ Hz of the phase modulation is controlled by the reference output of a digital lock-in amplifier (DLA). The fluorescence signal from the photodetector is square-wave demodulated in the DLA to produce the servo-loop error signal. Then, the error is integrated with a PID filter and frequency corrections δf are directly applied, with a resolution of 1 μHz, to the SDI synthesizer through the DDS via a Labview software routine (National Instruments Corp., Austin, TX).

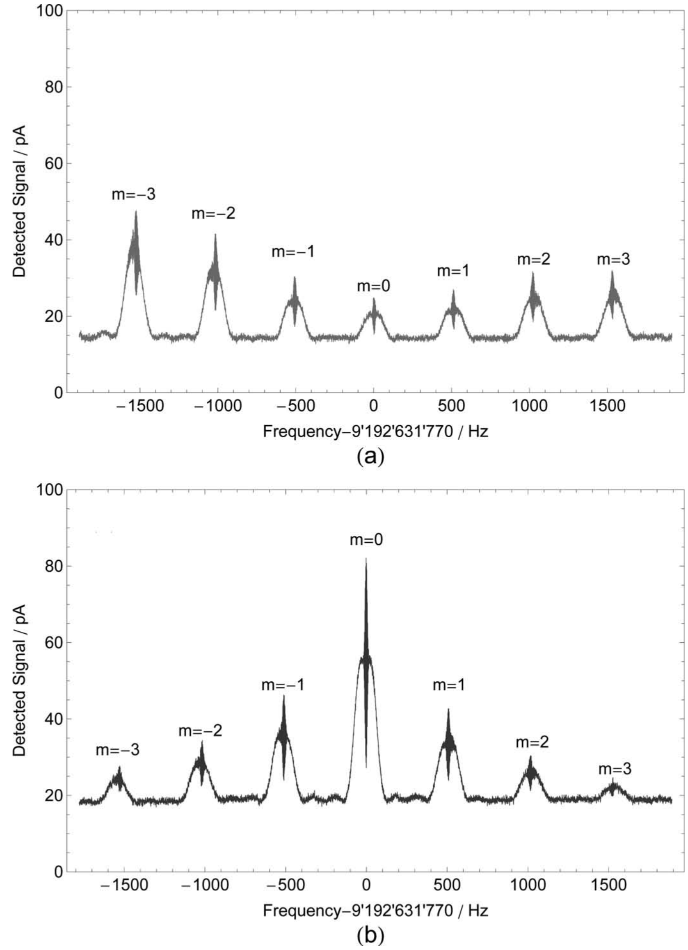

Fig. 3. Microwave spectra measured (a) without state preparation and (b) with state preparation. The number of atoms detected in $F = 4$ is represented as a function of the microwave frequency. We measured the fluorescence light of atoms transferred in $F = 4$ when the microwave is resonant with one Zeeman component ($|F = 3, m\rangle \rightarrow |F = 4, m\rangle$). Note that we used the same scale for both graphs to facilitate the comparison.

III. Experimental Results

A. Microwave Spectra

The efficiency of the state preparation is illustrated through the microwave spectra measured with and without atomic state preparation and shown in Fig. 3. They have been obtained by scanning the microwave frequency and by measuring the number of atoms in $F = 4$. As explained in Section II, in both cases, we use a depumper laser to depopulate the $F = 4$ ground state before the microwave interrogation and we detect fluorescence light of the atoms at the detection region. In Fig. 3(a), without optical pumping, we observe that the population distribution over the seven Zeeman sublevels of $F = 3$ is clearly not symmetrical and only 8% of the atoms are in $m = 0$. For a primary frequency standard, both features are undesirable for stability and accuracy. Indeed, the asymmetry may produce Rabi pulling [17], and the small atom number in the $|F = 3, m = 0\rangle$ ground-state affects the signal-to-noise ratio and thus degrades the clock stability. The same measurement with optical pumping is shown in Fig. 3(b). The population distribution is now quite symmetrical and about 40% of the atoms accumulated in $m = 0$. Even if the purity of state preparation is limited by a residual magnetic field inhomogeneity, this process increases the useful flux by a factor of 6.5.

[3] It was shown in [10] that choosing $f_m = 1/2T$, where T is the average transit time, cancels the intermodulation noise. In FOCS-2 we have $T = 0.52$ s.

B. Signal-to-Noise Ratio

The short-term instability of the continuous fountain is directly linked to the signal-to-noise ratio of the $|F = 3, m = 0\rangle$ flux, which itself scales with the square root of this flux if all technical noise is sufficiently suppressed (atomic shot-noise limit). Therefore, increasing the $|F = 3, m = 0\rangle$ flux is a direct way to improve the clock stability. In 1991, state preparation with two-laser optical pumping was already implemented in a thermal cesium beam resonator. However, despite a 6.6-fold improvement of the $|F = 3, m = 0\rangle$ flux, a degradation of the signal-to-noise ratio was

TABLE I. Signal-to-Noise Ratio Measured and Relative Frequency Stability Calculated and Measured With and Without State Preparation (SP).

	Without SP	With SP
S/N measured	238 $s^{-1/2}$	948 $s^{-1/2}$
σ_y ($\tau = 1$ s) calculated	$2.3 \cdot 10^{-13}$	$5.7 \cdot 10^{-14}$
σ_y ($\tau = 1$ s) measured	$2.8 \cdot 10^{-13}$	$6.0 \cdot 10^{-14}$

observed because of the presence of excess noise on the fluorescence signal [18]. The origin of this additional noise was later attributed to the presence of residual unpumped atoms combined with frequency fluctuations of the pumping laser [19].

Because our experimental conditions are different (slower atoms, longer interaction time, and lower laser frequency noise), we expect to observe an improvement of the signal-to-noise ratio corresponding to the 6.5-fold gain of $|F = 3, m = 0\rangle$ flux obtained in our experiment using state preparation. To check this, we simultaneously measured the peak-valley signal S (see Fig. 4) resulting from $|F = 3, m = 0\rangle$ and the noise spectral density N at the top of the central Ramsey fringe with the square-wave phase modulation, both measurements were made with and without state preparation. More precisely, the signal S in amps was obtained from the dc current of the fluorescence detection low noise photodetector, and the noise N in amps per root hertz from the linear spectral density of the photodiode current at 0.96 Hz (modulation frequency). The achievable stability can then be calculated from the following expression for the Allan deviation [20]:

$$\sigma_y(\tau) = \frac{\sqrt{2} \cdot \beta}{\pi} \frac{\tau^{-1/2}}{Q_{\rm at}({\rm S/N})}, \qquad (1)$$

where $Q_{\rm at} = f_0/\Delta f$ is the atomic quality factor, $f_0 = 9\,192\,631\,770$ Hz is the clock frequency, $\Delta f = 0.96$ Hz is the width of the central Ramsey fringe, τ is the measurement time in seconds, $\beta \cong 1.1$ is a numerical factor which depends on the details of the modulation-demodulation parameters [20] and S/N is the signal-to-noise ratio.

In Table I, we summarize the measurements [with and without state preparation (SP)] of the signal-to-noise ratio and the theoretical impact on the frequency stability of the fountain. In contrast with the result of [18], the signal-to-noise ratio with state preparation is better than without. We get a 4-fold factor of improvement, which directly impacts on the frequency stability of the clock. These results will be discussed in Section IV.

C. Clock Stability

We measured the Allan deviation of the fountain FOCS-2 compared with a reference hydrogen maser for both situations with and without state preparation. The results are shown in Fig. 5. These measurements were acquired over 17 000 s, which is clearly sufficient to highlight the $\tau^{-1/2}$ behavior characteristic with a good statistics.

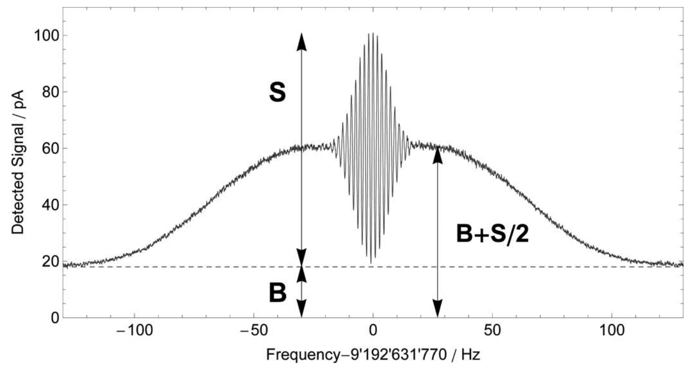

Fig. 4. Microwave spectrum of $|F = 3, m = 0\rangle$ Rabi pedestal and Ramsey fringes, obtained with state preparation. Important experimental parameters for the signal-to-noise ratio analysis are the peak-valley signal S and the background of $F = 4$ atoms B.

Moreover, because of the servo-loop time constant, the data points below 30 s are not significant for the stability. In this figure, the dots are measurements of the fountain stability without state preparation, whereas the squares are the results with state preparation. The dashed lines indicate $2.8 \cdot 10^{-13}\tau^{-1/2}$ without state preparation and $6 \cdot 10^{-14}\tau^{-1/2}$ with state preparation. This 4.7-fold improvement of the stability is in good agreement with the signal-to-noise measurement and thus confirms the absence of Dick effect in the continuous fountain (see also the discussion below Section IV-B). Finally, we note that the bump at 300 s, present on both experimental data sets, is due to temperature fluctuations of our laboratory ($\pm$1K) and should disappear in a better stabilized environment.

IV. Discussion

A. Cancellation of the Dick Effect by the Continuous Approach

Fig. 6 shows the Allan deviation with state preparation, together with the calculated Dick effect theoretical limit for pulsed fountains and the intermodulation noise limit for the continuous approach. These latter were calculated using the phase noise measurement of the synthesizer and with the same average atomic flux [10]. The square-wave phase modulation frequency is 0.96 Hz for the continuous method, while repetition rates between 1 and 1.2 Hz were considered for the pulsed operation with one cold atomic cloud per cycle. We observe here that the Allan deviation of FOCS-2 is below the Dick effect limit imposed for pulsed fountains. This result allows us to confirm the measurements of [21] in conditions where there is no need to artificially degrade the oscillator phase-noise to highlight the effect. In principle, a cancellation of the intermodulation noise at a level close to $3 \cdot 10^{-16}\tau^{-1/2}$ is possible for the continuous case, whereas for the pulsed mode, the limitation is between $1 \cdot 10^{-13}\tau^{-1/2}$ and $2 \cdot 10^{-13}\tau^{-1/2}$. Hence, we show here the potential for improvement of the frequency stability by further increasing the atomic flux in the continuous case.

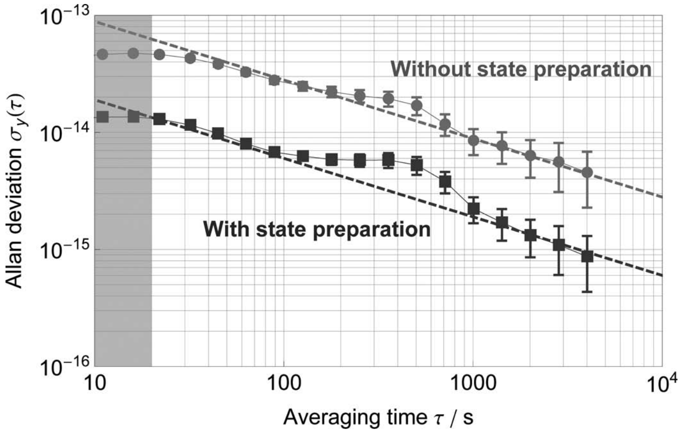

Fig. 5. Allan deviation, σ_y, of the frequency difference between the fountain FOCS-2 and the hydrogen maser as a function of the averaging time. The dots were obtained without state preparation and the squares with state preparation. The dashed line indicates $2.8 \cdot 10^{-13}\tau^{-1/2}$ for the dots and $6 \cdot 10^{-14}\tau^{-1/2}$ for the squares. The tinted area highlights the points that lie outside of the servo loop bandwidth. The bump in the data sets at 300 s is due to ±1K thermal fluctuations of our laboratory. The measurements with state preparation were made in more stable conditions.

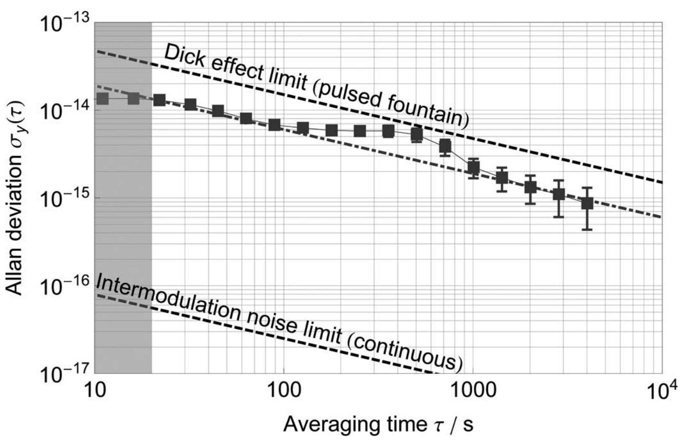

Fig. 6. The squares represent the Allan deviation, σ_y, of the fountain obtained with atomic state preparation. The upper dashed line gives the limit of the Dick effect for a pulsed fountain, calculated with the same interrogation oscillator and with the same average flux. The lower dashed line gives the intermodulation noise limit valid for the continuous approach. See Section IV-A for details.

B. Improvement of the Signal-to-Noise Ratio: Effect of the Background

In Section III, as a result of state preparation, we have seen both an increase of the $|F = 3, m = 0\rangle$ clock signal as well as an improvement of the signal-to-noise ratio and the stability of the clock. A careful inspection of these results, with and without state preparation, shows that the improvement of the signal-to-noise ratio (4-fold factor) is larger than the square root of the improvement of the flux ($\sqrt{6.5}$-fold factor). We attribute this difference to the reduction of the relative importance of the background level B (see Fig. 4) due to $F = 4$ unpumped atoms as a result of state preparation. Indeed, the ratio between the background atoms B and the inversion signal (peak-valley) S is about 5 times smaller with state preparation than without, whereas the signal increases by a 6.5-fold factor. In Table II, we summarize the typical signal values measured on the central fringe of $|F = 3, m = 0\rangle$ with and without state preparation (see Fig. 4) together with the noise N measured as explained in Section III. The last column displays the ratio between the data with state preparation and without state preparation. It shows that the increase of the square of the measured noise level, N^2, is approximately equal to the increase of $B + S/2$. This indicates that N has an atomic shot-noise origin. Moreover, the increase of the signal-to-noise ratio by a factor of $6.5/\sqrt{2.7} \approx 4$ is explained by state preparation. In our experiment, two-laser optical pumping reduces the importance of $F = 4$ background relative to the number of atoms in $|F = 3, m = 0\rangle$. Therefore, the stability of the clock increases more than expected from the signal increase alone.

TABLE II. Signal-to-Noise Ratio Analysis.*

	Without SP	With SP	Ratio
Peak-valley S (pA)	12.6	82.1	6.5
Background B (pA)	14.3	18.9	1.3
$B + S/2$ (pA)	20.6	60	2.9
Noise N^2 ($A^2 \cdot Hz^{-1}$)	$2.8 \cdot 10^{-27}$	$7.5 \cdot 10^{-27}$	2.7

*The second column was measured without state preparation (SP) and the third column with SP. The last column gives the ratio between the values with SP and without SP.

V. Conclusion

We demonstrated that the frequency instability of the continuous fountain clock FOCS-2 can be reduced below the Dick limit by making use of atomic state preparation combined with laser cooling. More precisely, two-laser optical pumping is used to increase the number of cold cesium atoms in $|F = 3, m = 0\rangle$. A first σ-polarized laser in a 2-D-optical lattice configuration couples to the $F = 4$ ground state and transfers the atoms in $F = 3$, while a second π-polarized laser excites the $F = 3 \rightarrow F' = 3$ transition to pump the atoms toward $m = 0$.

Using this technique, we are able to prepare 40% of the atoms in $|F = 3, m = 0\rangle$, resulting in a 6.5-fold increase of the fountain clock signal. Moreover, atomic state preparation reduces the relative importance of the atomic background noise; therefore, an improvement of the signal-to-noise ratio by a 4-fold factor has been measured.

As a result, a frequency instability of $6 \cdot 10^{-14}\tau^{-1/2}$ has been obtained with the fountain clock FOCS-2. This is below the Dick limit affecting pulsed fountains of $2 \cdot 10^{-13}\tau^{-1/2}$ calculated with the same average flux and interrogation oscillator. By comparison of measurements and theoretical computations, we have seen that this stability is limited only by the signal-to-noise ratio of the flux and there is no limitation resulting from the intermodulation effect for continuous operation above $3 \cdot 10^{-16}$ at

1 s. The improvement of the Allan deviation has a direct impact on the evaluation of the fountain by reducing the measurement time by a factor of 16.

Acknowledgments

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