First dual mode operation of the Cs/Rb FO2 double fountain at SYRTE

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Abstract— This paper presents the achievement of the dual atom clock operation of the FO2 double fountain at LNE-SYRTE with both Cs and Rb atoms launched simultaneously. We describe how it works, metrological characteristics and results of the first Rb/Cs frequency measurement campaign performed with FO2 as a dual atom clock, among which a new absolute frequency determination of the ^{87}Rb hyperfine frequency.

I. Introduction

After the first Cs fountain FO1 was built at SYRTE, a first version of a Rb fountain was constructed by the end of the 1990's. The most notable result provided by this fountain was a measurement of the Rb hyperfine frequency that improved the accuracy by about 4 orders of magnitude over previous measurements [1]. The interest in a Rb fountain clock was clearly highlighted. It was soon considered as even more interesting to have the possibility of a direct comparison of Cs and Rb hyperfine frequencies by having the two species simultaneously captured in a single fountain set-up. This push forward the decision to transform the Rb fountain into a dual Cs/Rb fountain, dubbed FO2. Following longstanding developments of Rb and Cs subsystems independently [2], the FO2 fountain operating with either Cs or Rb as single species proved among the most accurate fountain clocks. Here we report on the first simultaneous dual mode operation of FO2 as a dual Rb/Cs clock.

II. Motivations

Since Rb and Cs have similar atomic structure and properties, and both are as easily laser cooled and manipulated, Rb was a natural candidate to extend the fountain principle initiated with Cs. Same concepts and techniques can be apply in a fountain clock set-up. A first application of the ^{87}Rb fountain was a measurement of the hyperfine frequency ν_{Rb} with considerably improved accuracy [3]. Several ν_{Cs}/ν_{Rb} measurements followed, which all involved FO2-Rb with Cs reference provided by SYRTE FO1 or FOM mobile fountain. The 2002 determination was chosen as secondary representation of the second by CCTF in 2004 [3]. The main interest of precise and repeated Rb/Cs comparisons is to provide a test of variation of fundamental constants [4]. Rb/Cs frequency ratio is sensitive to variations of the combination $\alpha^{0.49}(g_{Cs}/g_{Rb})$, where α is the fine structure constant and the g are the nuclear g-factors [5]. The dual operation of FO2 aims at pursuing this goal with improved accuracy expected from a truly simultaneous Rb/Cs data taking and possible elimination of common perturbations of the local environment (noise of local oscillator, magnetic field and temperature fluctuations, …).

Regarding systematic effects, a notable attractive feature of Rb is its reduced cold collision frequency shift when compared to Cs related effect, as first predicted by [6]. Indeed, the reduction from previous measurements, is by a factor larger than 30 [7] or 50 [8] .

Up to the end of 2008, FO2 had always run with a single species at a given time. The key elements and techniques for truly dual mode operation are described in Sect. III. Sect. IV deals with accuracy of the dual clock. The first measurements in dual mode, and associated results, are given in Sect. V.

III. Dual Fountain Set-up and Techniques

A. The dual atom fountain set-up

Figure 1 shows the scheme of the dual Rb/Cs FO2 fountain. The two atomic species are captured in the same region by a dual Rb/Cs optical molasses operating in a lin ⊥ lin configuration. The Rb/Cs optical molasses are overlapped using dedicated dichroic collimators. In each of these collimators, the laser lights at 780 nm and 852 nm for Rb and Cs are received from two optical fibers and combined on a dichroic beamsplitter. The resulting beam is collimated using a single achromat lens to a diameter of about 26 mm. More details concerning these collimators (mechanical and optical adjustments with severe constraints/requirements to ensure capture efficiency and correct launch direction for both Rb and Cs) and subsequent tests in-situ using the atoms as probes can be found in [9]. The six dual wavelength laser beams are aligned along the axes of a three-dimensional coordinate system, where the (111) direction is vertical. There are two

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separate optical benches generating light at 780 nm and 852 nm respectively, that is fed into the collimators *via* optical fibers. The optical molasses are loaded from $2D^+$-MOT presources for both Rb and Cs. Typical loading time is 500 ms for both Rb and Cs, with total optical power of ~ 200 mW using injected diodes for Cs, and ~ 300 mW using tapered optical amplifiers for Rb. The 2D-MOTs decrease consumption of Rb and Cs compared with previous chirped cooled atomic beams, yet at the price of decreased atomic beam fluxes. These presources also reduce the background pressure of atoms in the capture zone.

The two atoms are launched upward at same instant with a slightly different velocity of 4.33 $m.s^{-1}$ (apogee 0.96 m) for Cs and 4.16 $m.s^{-1}$ (apogee 0.88 m) for Rb, then cooled to ~ 0.9 µK and 1.5 µK repectively. There are two state selection microwave cavities (heights 64 mm and 139 mm above capture region for Cs and Rb cavity respectively). For Cs the F=3 m_F=0 initial state is selected with atom number adjusted by adiabatic population transfer [9]. Radiation pressure beams (push beams in Fig. 1) throw out Rb/Cs atoms in the unwanted atomic states (F=4 for Cs and F=2 for Rb).

The Ramsey interrogation region to probe the hyperfine transitions (F=3–F=4 at 9.192 GHz and F=1–F=2 at 6.834 GHz for ^{133}Cs and ^{87}Rb respectively) is nearly the same for both atoms. The Rabi interactions at upward and downward passages take place in a special double microwave cavity comprising two resonators on top of each other. Centre resonator heights above the capture zone are 0.442 m for Rb and 0.518 for Cs. The Rb/Cs resonators are machined out of a single copper assembly to save place and achieve temperature

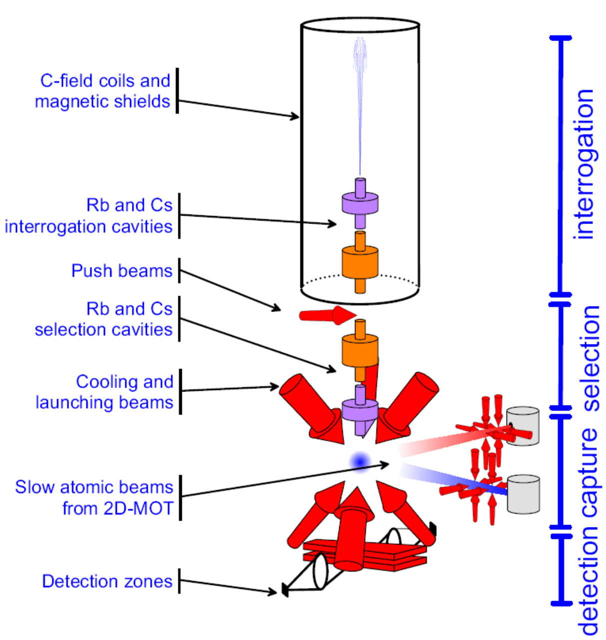

Figure 1. Scheme of the dual fountain set-up.

tuning for each atom at same temperature. Tuning for both cavities simultaneously to within 40 kHz occurs near 300 °K. The resonators are TE_{001} cylindrical cavities with quality factors of 6600 for Cs and 6000 for Rb. Each resonator can be fed either symmetrically or asymmetrically using two opposite microwave feedthroughs to study and reduce first Doppler effects (related to phase gradients).

B. Dual detection technique

The detection of the two clock states, for each atom, is by induced fluorescence using same photodetectors. The detection zone located below the capture zone consists of two dual wavelength standing waves of resonant light allowing calculation of the transition probabilities for Rb and Cs. Selection between the two atoms is temporal. We choose the launch velocities so that there are no collision between the two clouds during all interactions (microwave state selection and Ramsey interrogation) and then we finely adjust the launch times so that there is no overlap between the two times of flight. Difference in Rb/Cs launch times is by a fraction of ms. A plot of the dual Rb/Cs ballistic flight is given in Fig. 2 with the time sequences adjusted for dual clock operation. There are two synchronized computers, Cs computer being the master clock. Typical dual clock cycle is 1.5 s. Note that the Ramsey interrogation times, and hence Ramsey fringe widths, are equal for Rb and Cs (T = 598 ms, Ramsey fringe FWHM ≅ 0.82 Hz).

A dual detected time of flight is shown in Fig. 3. Despite the non gaussian wings of the cold atom velocity distributions (especially for Rb), overlap is made insignificant. We choose to apply the detection beams for about 100 ms (and correspondlingly acquisition times) for the two atoms in contiguity without any temporal overlap. In these conditions signal-to-noise ratio, and hence frequency stability, for each atomic clock alone is preserved. The short term instabilities, limited by atom numbers, are at present about 3×10^{-14} at 1 s for Cs at high density and 5×10^{-14} for Rb.

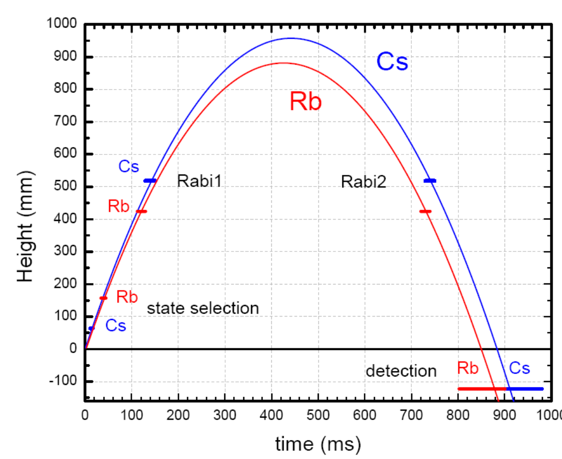

Figure 2. Rb/Cs ballistic flights in dual clock configuration. Time origin is launch time and height origin is capture height.

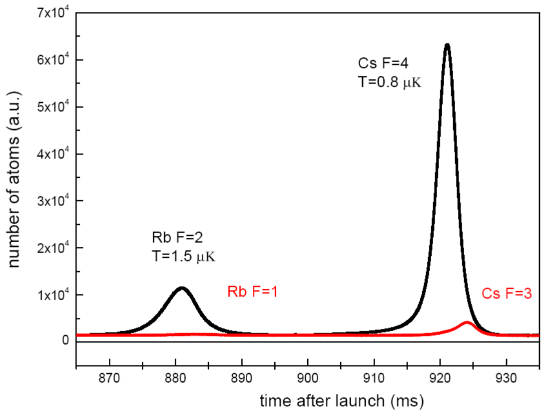

Figure 3. Example of a dual time of flight detected with time sequence as in Fig. 2. The interrogation signals for both Rb and Cs are at Ramsey centre fringe resonance of the respective clock transitions, while for clock operation the interrogation frequency alternates between the two sides of the fringe.

C. Cs/Rb Synthesizers

The stability requirements of the frequency synthesizers driving the atomic fountains is quite stringent, and a variety of different designs have been implemented already. At LNE-SYRTE, the heart of the frequency synthesis is a cryogenic sapphire oscillator (CSO) operating near 11.932 GHz. A frequency offset stage already described in [11] shifts its output signal to 11.98 GHz with provision for tunability using a direct digital synthesizer (DDS). The 11.98 GHz signal reproduces the low phase noise and high short-term frequency stability of the CSO. This ultrahigh stable signal is down converted to 1 GHz and to 100 MHz for distribution purposes [12]. To compensate the drift of the CSO, the signal at 11.98 GHz is weakly phase-locked to the 100 MHz output signal of a H-maser (time constant of 1000 s). The three signals at 11.98 GHz, 100 MHz, and 1 GHz are phase coherent with the H-maser while having the short term phase stability of the CSO.

In the present configuration, FO2-Cs uses the 11.98 GHz signal to generate 9.192 GHz in a home-built frequency chain while the 1 GHz signal is up-converted to 6.384 GHz for FO2-Rb. Each frequency chain incorporates a computer-controlled high-resolution DDS digital synthesizer to tune the interrogation signal to the clock transition based on the detected atomic transition probability. The corrections applied to the DDSs are the basis for evaluating frequency stability and measuring frequency shifts. Each synthesizer includes a Mach-Zender interferometer RF switch at 400 MHz or 200 MHz to reduce potential microwave leakages [13]. Each synthesizer has two outputs with power and phase adjustments on one channel to provide symmetrical feeding of the Ramsey resonators. The FO1-Cs single fountain located 150 m away from FO2/CSO labs uses the 100 MHz ultrastable signal distributed with a high-stability RF cable and there up-converted to 9.192 GHz. The FO1-Cs synthesis has other common features with FO2 synthesizers (RF switch, and dual outputs).

IV. SYSTEMATICS/ACCURACY BUDGETS

Table 1 gives the budget of systematic effects and their associated uncertainties for FO2-Cs/ FO2-Rb during the dual clock measurements presented in Sect. V. These budgets are almost the same as for each clock when operated alone. By far the largest systematic effect is the quadratic Zeeman shift and Rb is twice more sensitive than Cs. Great care has to be taken to measure the C-field value needed for the corrections. To this purpose we use Ramsey spectroscopy on the first order Zeeman sensitive transitions for both Cs and Rb. Fig. 4 shows the C-field maps obtained with Rb and Cs consecutively. Note that each point in this figure is the integral of the magnetic field over the height launch, and hence we cannot expect perfectly identical maps since the interrogation regions do not exactly coincide. The remaining field gradient could be further improved by better adjustment of the currents in the four dedicated compensating coils. During clock operation at standard apogees (of 0.88 m for Rb and 0.96 m for Cs) we repeatedly check the stability of the C-field.

TABLE I. ACCURACY BUDGET FOR SYRTE FO2-CS/RB AND FO1 FOUNTAINS

	FO2-Cs corr. ± unc. ($x10^{-16}$)	FO2-Rb corr. ± unc. ($x10^{-16}$)	FO1-Cs corr. ± unc. ($x10^{-16}$)
Quadratic Zeeman effect	- 1914.3 ± 0.3	- 3468 ± 0.7	-1276.7± 0.2
Blackbody radiation	167.2 ± 0.6	120.6 ± 1.6	1652 ± 0.6
Cold collisions and cavity pulling	246 ± 2.5	8.4 ± 2.6	81 ± 2.2
First order Doppler effect	< 3.0	< 2.5	< 3.2
Microwave leakage & spectral purity	< 0.5	< 0.5	< 1.0
Others (quantum motion, Background gas collisions, Ramsey & Rabi pulling, ..)	< 2.0	< 2.0	< 1.7
Gravitational redshift	-65.4 ± 1	-65.5 ± 1	-69.3 ± 1.0
Total uncertainty	**4.5**	**4.6**	**4.5**

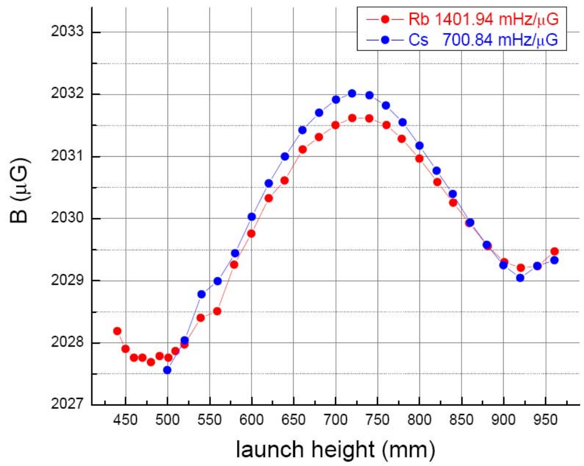

Figure 4. C-field map in the interrogation region probed by the FO2-Rb and FO2-Cs atoms on 1-1 Zeeman transitions.

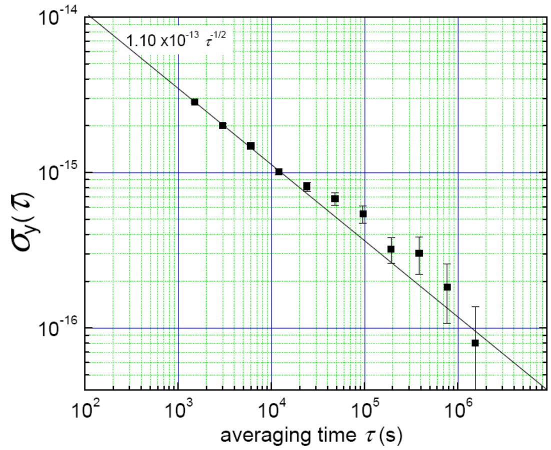

Figure 5. Allan standard deviation for the relative frequency differences between FO2-Rb and FO2-Cs (MJD period 54789-54862) .

The cold collisions shift is extrapolated for Cs in real time exploiting interleaved measurements at high/low Cs density using adiabatic passage. The technique is not implemented for Rb since the related effect is expected to be much smaller. Instead, by the end of the dual clock campaign presented below, we performed clock measurements alternating between two loading times (600 ms and 300 ms) for Rb to extrapolate the shift due to Rb atom number. Note that this shift includes contributions from cold collisions and from cavity pulling due to small cavity temperature detuning. The associated uncertainty is mainly statistical. In the future we plan to systematically perform such interleaved measurements for Rb, just as for Cs. This will be all the more desirable if, as planned, we increase the Rb atom number (by increasing optical power) to improve clock stability.

In Table 1 the overall accuracy is the quadratic sum of all systematic uncertainties. The budget for FO1-Cs fountain is also given since this fountain was involved in the measurements presented below.

V. First Rb/Cs Frequency Measurements with Dual Atom Clock FO2

A. Rb-Cs differential frequency fluctuations

The first measurement campaign with FO2 operating as a dual atom clock took place from 19/11/2008 to 31/01/2009, covering 48 effective days of data. Fig. 4 presents the Allan standard deviation for the relative frequency difference between FO2-Cs and FO2-Rb. Data are corrected for all systematic effects except for the shift dependent on Rb atom number which is corrected in post data processing. Assuming white noise the statistical resolution of about 10^{-16} is reached in 20 days. These results indicate a good rejection of the local oscillator noise.

During the same period, FO1-Cs fountain was also running. Comparison has been made between FO2-Rb and FO1-Cs over synchronous data (36 effective days of data) to provide cross-check against FO2-Rb/FO2-Cs comparison.

B. New ^{87}Rb hyperfine frequency determination.

The present Rb-Cs double campaign provides a new value for the ^{87}Rb hyperfine frequency. We take as reference the value recommended by the CCTF in 2004 [3], which is the value measured at LNE-SYRTE in 2002. Then we obtain for the mean relative Rb-Cs hyperfine frequency differences:

$$\nu(\text{FO2-Rb})(2009)/\nu_{\text{Rb}}(\text{CCTF}) - 1 = (-1.68 \pm 0.65) \times 10^{-15}$$

from the FO2-Rb/FO2-Cs comparison, and

$$\nu(\text{FO2-Rb})(2009)/\nu_{\text{Rb}}(\text{CCTF}) - 1 = (-1.23 \pm 0.65) \times 10^{-15}$$

from the FO2-Rb/FO1-Cs comparison. The two results are consistent within the error bars which are dominated by systematic uncertainties. We choose to average them with equal weights. Then we obtain for the ^{87}Rb hyperfine frequency

$$\nu(\text{ FO2-Rb})(2009) = 6\,834\,682\,610.904\,314\,(4.4)\text{ Hz}.$$

The recommended value

$$\nu_{\text{Rb}}(\text{CCTF, }2004) = 6\,834\,682\,610.904\,324\,(21)\text{ Hz}$$

which is assigned a relative uncertainty of $3\text{x}10^{-15}$ is consistent with the new determination.

VI. Conclusion and Outlooks

At present the FO2 fountain is routinely working as a dual Rb/Cs atomic clock, with the two species simultaneously interrogated on a cycle basis. In dual mode operation independency of each clock alone is preserved. The simultaneous mode also preserves the stability and accuracy of each clock when operated singly.

Clearly the dual operation of FO2 opens new possibilities and perspectives. One possibility that we currently exploit is to use one atom as reference, without resort to another fountain, while performing some test with the other atom. From the fundamental side, previous physics tests can be improved. For example, the Lorentz invariance test carried out with FO2-Cs, consisting to look for a dependence of the clock frequency with the atomic orientation, was limited by magnetic noise [14]. This test could benefit from a similar test performed this time with Cs and Rb in simultaneity. In addition, sensitivity to model parameters is different for the two atoms. Up to now the dual operation of FO2 has been exploited for the metrological clock application only. However, the FO2 fountain set-up offers flexibility in the Rb/Cs time sequences. With a view to study Rb/Cs cold collisions, for example, parameters could be adjusted to finely tune collision energy.

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