The Operation of the Atomic Fountains Developed at VNIIFTRI

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***Abstract*—We report on the operation of the cesium fountain primary frequency standard (SU-CsFO2), the rubidium fountain frequency standard (Rb5) and the pair of rubidium frequency standards (Rb1, Rb2) at the Russian metrological institute of technical physics and radio engineering (VNIIFTRI (SU)). We present measurements of their performance in long term frequency stability to be less than $2\cdot10^{-16}$. The frequency of SU-CsFO2 with total B uncertainty $2.2\cdot10^{-16}$ agreed well with other primary and secondary frequency standards within the uncertainty according to the Circular T data during the last 10 years.**

***Keywords*— time and frequency standard, atomic fountain, cold atom, cesium, rubidium**

I. Introduction

Until now, the unit of time, the second, is determined by the frequency of transition between two undisturbed ground states of the cesium-133 atom. Atomic fountains provide the best accuracy of this frequency. For this purpose, the CsFO2 cesium fountain was developed and is constantly being used at VNIIFTRI [1].

The Rb5 rubidium fountain was designed for a reproduction of the secondary definition of the second [2, 3, 4]. In addition, two rubidium fountains Rb1 and Rb2 have been developed for using in time and frequency keeping service [5]. We report on the performances of atomic fountains developed at VNIIFTRI.

II. THE PRIMARY FREQUENCY STANDARD SU-CSFO2

The Time and Frequency Division of the Russian metrological institute of technical physics and radio engineering in Mendeleevo (Russia) has operated SU-CsFO2 a laser-cooled cesium fountain primary frequency standard since 2012. Systematic biases and the associated uncertainties are shown in Table 1.

TABLE I. UNCERTAINTY BUDGET OF SU-CsFO2

Physical Effect	*Shifts (10^{-16})*	*Uncertainty (10^{-16})*
Second-order Zeeman effect	1066.0	0.1
Black-body radiation	-165.1	0.5
Gravitational shift	244.3	0.5
Resonator pulling	0	0.1
Purity of probe signal spectrum	0	0.1
Light shift	0	0.1
Tilting (DCP)	0	0.1
Collisions with residual gas	0	1
Microwave power dependence	0	1.8
Spin exchange shift	0.19*	0.19*
Total	1145.2	2.2

Currently, the type B fractional uncertainty in SU-CsFO2 is $2.2\cdot10^{-16}$.

The primary frequency standard SU-CsFO2 was used to measure the frequency of the H-maser CL45 identified by the BIPM clock code CL 403845. SU-CsFO2 has contributed 95 times to the TAI calibration process. The result of these evaluations is published in BIPM circulars and illustrated in Figures 1 and shows a good agreement between SU-CsFO2 and all others fountains participating to TAI used to steer its frequency.

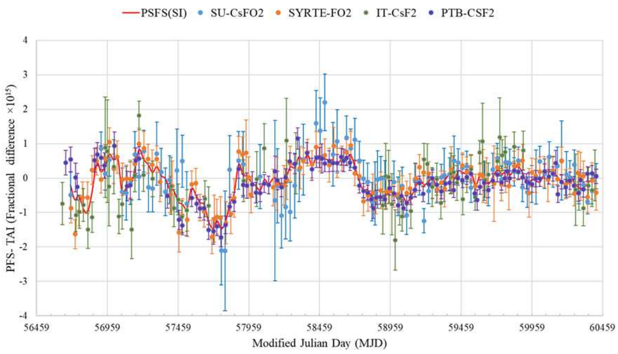

Fig. 1. Calibrations of the TAI by the CsFO2 fountains since February 2014 to May 2024. The data are from BIPM circular T. Each point is the fractional frequency difference between TAI and the SI second as measured by CsFO2 and corresponds to a formal monthly report to BIPM. The red curve is the difference between TAI and the PSFS(SI) second, as computed by BIPM from all available primary standards. For comparison, results from several others primary frequency standards are also shown.. Rb fountains for using in time and frequency keeping service

III. Rb FOUNTAINS FOR USING IN TIME AND FREQUENCY KEEPING SERVICE

In 2016 VNIIFTRI were made operational Rb87 frequency standards (Figure 2). These were neither instruments intended for secondary presentation of the SI second, nor clocks. One may treat these instruments as a keeper of frequency value. These standards have been calibrated against operational SU-CsFO2 primary fountain frequency standard and have been used as time and frequency keepers. All these instruments were fed by 5 MHz signal of H-maser CL53 (BIPM clock code CL 403853 (CL53). This H-maser was chosen from the whole ensemble of masers because of its high short term frequency stability ($\sigma_y(\tau) \sim 6\cdot10^{-14}$, τ =1 s) and high spectral purity of 5 MHz signal [6].

Allan deviations of the frequency differences between the fountain Rb1, Rb2 and the hydrogen maser CL 403853 are shown in Figure 3 and Figure 4: the instability of less than $8 \cdot 10^{-16}$ at the interval of 24 hours and less than $2 \cdot 10^{-16}$ at the interval of 16 days.

Fig. 2. Rubidium atomic fountain (Rb2)

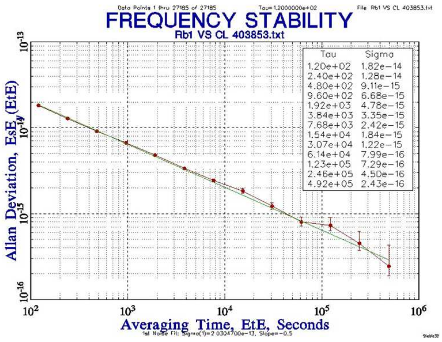

Fig. 3. Allan deviation of the frequency difference between the fountain Rb1 and the hydrogen maser CL 403853. Drift is not removed

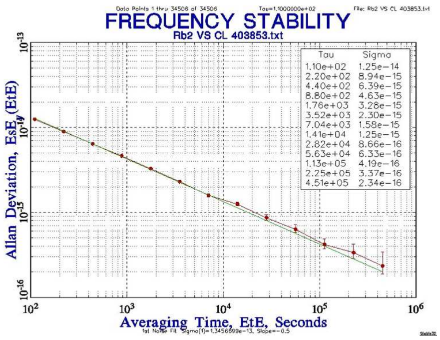

Fig. 4. Allan deviation of the frequency difference between the fountain Rb2 and the hydrogen maser CL 403853. Drift is not removed

Allan deviation of the frequency difference between the fountain Rb1 and fountain Rb2 is shown in Figure 5.

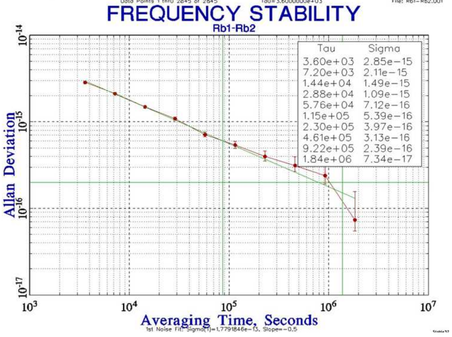

Fig. 5. Allan deviation of the frequency difference between the fountain Rb1 and the fountain Rb2

IV. Rb5 FOR A REPRODUCTION OF THE SECONDARY DEFINITION OF THE SECOND

In Figure 6 are shown the main functional parts of Rb5.

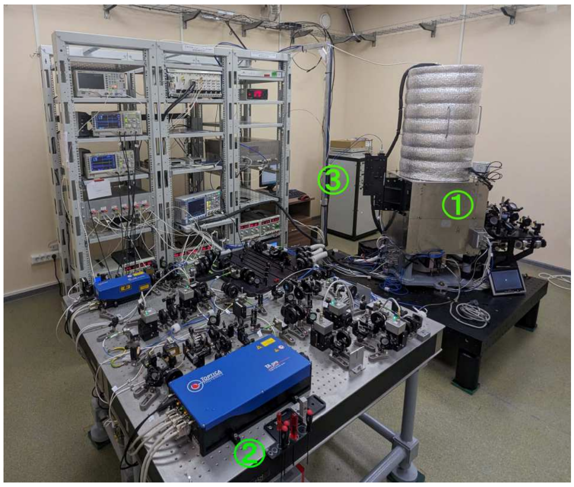

Fig. 6. Rubidium atomic fountain (Rb5): 1 – physical package, 2 – laser system, 3 – microwave source

A. The physical package

The Rb5 vacuum system is made of titanium, except the microwave cavity and flight tube. The system is pumped by ion pump (20 l/s) and two getter pumps, which are placed in the bottom of physical package. The vacuum pressure is lower than $1 \cdot 10^{-10}$ mbar. Rubidium atoms are collected from low velocity intense source in the (1, 1, 1) configuration optical molasses. To form six cooling laser beams with proper lin _|_ lin polarization and diameter 25 mm at the $1/e^2$ intensity level, adjustable collimators are mounted on the trapping chamber. There are two additional windows for the repump beam and CCD camera for monitoring the atomic cloud.

A state-selection cavity with a Q factor ~ 850 is located above the trapping chamber. The microwave cavity and the flight tube are surrounded by C-field cylinder made of aluminum alloy and five layers of μ-metal magnetic shields. The total shield factor is about $2 \cdot 10^5$. The cylindrical TE011 microwave cavity, made of oxygen-free copper, is located at the height of 0.48 m above the trapping chamber center. Two symmetrical rectangular TE101 waveguides excite microwave field inside cavity. Waveguides are weakly coupled to the cavity through two round holes, positioned on opposite sides of the cavity cylindrical body. The cavity loaded quality factor is Qc ~ 28 600.

B. The laser system

The laser system of Rb5 consists of two lasers. The light for cooling and detection beams is provided by Toptica TA pro diode laser with a tapered amplifier and a total output power of about 0,7 W. The laser frequency is locked to the F=2 - F=3 optical cycling transition of 87Rb D2 line by modulation transfer spectroscopy.

The repump light is provided by Toptica DL 100 pro design diode laser. The laser frequency is locked to the F=1 - F′ =1,2 crossover transition by frequency modulation (FM) spectroscopy and shifted to frequency transition by double-pass AOM. Mechanical shutters with stepper motors are used in laser system to prevent any penetration of laser radiation into the fountain during interrogation of the atoms. The light from optical bench is coupled to the vacuum system with polarization maintaining optical fibers and collimators.

C. The microwave source

The commercial synthesizer RB-1 (SpectraDynamics, Inc.) with frequencies locked to the reference H-maser («Vremya-Ch», $\sigma_y(\tau) \sim 6{\cdot}10^{-14}$ τ =1 s) forms microwave signals for state selection and Ramsey interrogation. There are splitter, phase shifter and attenuator for symmetrical exciting the microwave field inside the cavity.

Table 2 contains a list of systematic effects identified for Rb5 with current estimates of the type B uncertainties of the related frequency shifts.

TABLE II. UNCERTAINTY BUDGET OF RB5

Physical Effect	***Shifts (10^{-16})***	***Uncertainty (10^{-16})***
Second-order Zeeman effect	1231.5	0.1
Black-body radiation	-121.5	0.7
Gravitational shift	225.1	0.5
Resonator pulling	0	0.1
Purity of probe signal spectrum	0	0.1
Light shift	0	0.1
Tilting (DCP)	0	1
Collisions with residual gas	0	1
Microwave power dependence	0	1.8
Spin exchange shift (under research)	-3	2
Total	1332.1	3.2

Figure 7 shows Allan deviation of the frequency difference between the fountain Rb5 and hydrogen maser H03.

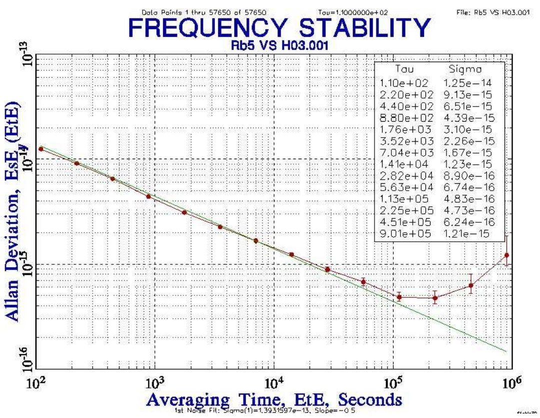

Fig. 7. Allan deviation of the frequency difference between the fountain Rb5 and the hydrogen maser H03. Drift is not removed

The currently used scheme for comparing Rb5 with Rb1, Rb2 and cesium fountain primary frequency standard is presented in Figure 8 [7].

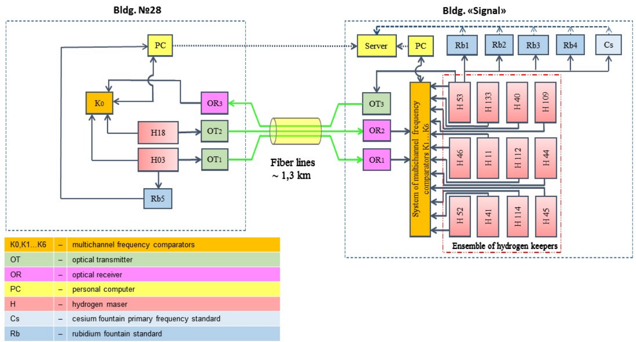

Fig. 8. Comparison scheme

V. CONCLUSION

The primary frequency standard SU-CsFO2 has been operational since February 2014 for external use and long periods of reliable operation have been achieved.

The pair of rubidium fountains (Rb1 and Rb2) at the Russian metrological institute of technical physics and radio engineering have been in operation for about 6 years. These device have been used as time and frequency keepers. Each fountain has demonstrated periods of stability at the level below $2{\cdot}10^{-16}$.

It is planned that the comparison data of the rubidium fountain frequency standard Rb5 will be sent to the BIPM to contribute to TAI.

REFERENCES

1. Domnin, Y.S., Baryshev, V.N., Boyko, A.I. *et al.* The MTsR-F2 fountain-type cesium frequency standard. *Meas Tech* 55, 1155–1162 (2013) (DOI: 10.1007/s11018-012-0102-0).
2. 2007 International Committee for Weights and Measures 2006, Recommendations adopted by the CIPM, Proc`es-Verbaux des S´eances du Comit´e International des Poids et Mesures, 95th meeting (2006) p 249.
3. D. S. Kupalov *et al.*, "First results on Rb fountain Rb304 frequency standard developed at VNIIFTRI," *2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, Besancon, France, 2017, pp. 633-635. (DOI: 10.1109/FCS.2017.8088983).
4. Kupalov D.S., Baryshev, V.N., Blinov, I.Y. *et al.* Uncertainty Budget of Rubidium Fountain: Preliminary Results. *Meas Tech* 64, 817–823 (2022).(DOI: 10.1007/s11018-022-02009-4).
5. Купалов Д.С., Барышев В.Н., Блинов И.Ю., Бойко А.И., Домнин Ю.С., Копылов Л.Н., Купалова О.В., Новоселов А.В., Хромов М.Н., Хранитель единиц времени и частоты на основе «фонтана» атомов рубидия, Альманах современной метрологии. 2018. № 15. С. 31-41.
6. I. Blinov, A. Boiko, N. Kosheliaevskii, O. Kupalova and O. Sokolova, "First experiments on application of Rb fountain frequency standards for TA(SU) time scale maintenance," *2018 European Frequency and Time Forum (EFTF)*, Turin, Italy, 2018, pp. 257-262. (DOI: 10.1109/EFTF.2018.8409045).
7. D.V. Sutyrin *et al* 2019 *Quantum Electron.* 49 199. (DOI: 10.1070/QEL16885).