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PROSPECTS OF RUSSIAN CESIUM FOUNTAIN

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Abstract – **We present the current state of things with the development of the Russian cesium fountain. Design of the physical parts, the laser system, and the optical system is briefly outlined. The preliminary results of the operation and detection with a magnetic-optical trap (MOT) and molasses regimes are described. We have made detailed temperature measurements on laser-cooled cesium atoms, exploring a wide range of laser intensity and detuning. The lowest measured temperature of about 20 μK for MOT and 2.2 μK for molasses are reached**.

***Keywords* - Optical cooling, cesium fountain, molasses**

I. INTRODUCTION

Russian State Time and Frequency Service relies on a group of H-masers and classical Cs-beam primary-frequency standard. H-masers are used as time keeper with a long- term stability near ~ 10^{-15}, while Cs standard is used for H-maser calibration and it has ~ 2×10^{-15} uncertainty. Recent advances in laser cooling, optical molasses, and various MOT constructions bring rapid progress in atomic frequency standards of the fountain type. These advances have shown an overwhelming advantage in getting better performances, compared to thermal beam devices. It is important to note, that a number of important characteristics of the frequency standards (second-order Doppler shift, cavity phase shift, etc.) can be considerably improved when using laser-cooled atoms. Presently, the best atomic clock candidate are isotopes of ^{87}Rb or ^{133}Cs atoms . For example, the accuracy of the BNM-SYRTE Paris Cs fountain clock is about 1.0×10^{-15} [1], and the PTB clock (Germany) reaches 1.4×10^{-15} [2]. At a moment, the fountains by BNM-SYRTE Paris group have been considerably upgraded in order to improve their accuracy to 8.0×10^{-16} for cesium and to 6.0×10^{-16} for rubidium atoms [3].

We started our Cs fountain project in the spring 1999, hoping to get an uncertainty at least one order less. The present paper is a brief review of the latest research data obtained at IMVP GP VNIIFTRI on this topic. The design of the fountain is briefly outlined in Section II, Section III gives a description of the optical setup. Some TOF temperature measurement results are presented in Section 5. Conclusions are given in Section VI.

II. MECHANICAL DESIGN

Physical package design of the Cs fountain of the IMVP GP VNIIFTRI is shown on Fig.1-3. A vacuum chamber (Fig.4) is made of stainless steel. It consists of five sections connected through copper gaskets. A bottom section is made of stainless steel. It consists of two ion getter pumps with 4

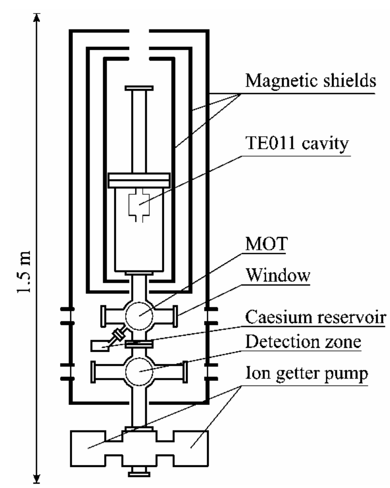

Fig.1. Mechanical design of CsFW.

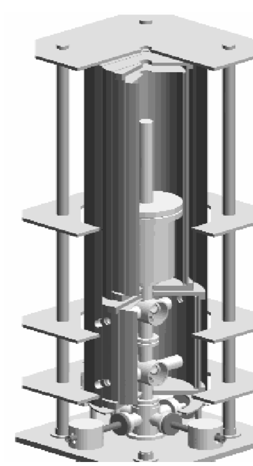

Fig. 2. Overview of the physical package of CsFW.

L/s total pumping rate, a partial pressure spectrum analyzer, a vacuum gauge and a vacuum sleeve. Other four sections (detection zone, MOT region, cavity zone and free flight zone) are made of titanium. There are eleven windows made of fused quartz. They are soldered by plumbum to the inner surface of titanium sleeve which in its turn is welded to the titanium vacuum flange.

The vacuum chamber is baked during 200 h at 250^{o} C. At present, we have a 10^{-6} residual pressure, which is mainly due to the hydrogen partial pressure. Microwave cylindrical cavity made of copper oscillates in TE011 mode. The unloaded cavity quality factor is 20000, while at chosen coupling strength, the loaded cavity quality factor is about

Fig.3. Photo of the physical package of CsFW

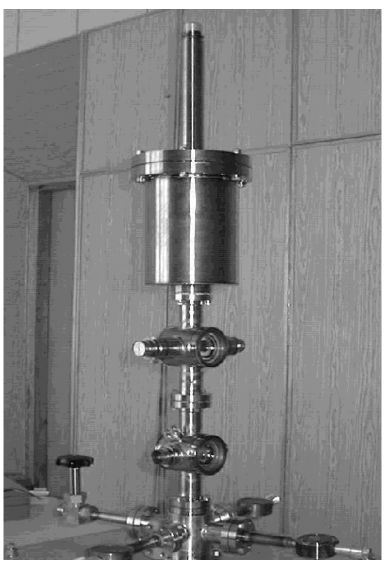

Fig.4. Vacuum part of CsFW (photo).

3000. Cut-off tubes 60 mm in length and 11 mm in diameter are soldered to the entrance and exit holes of the cavity to avoid microwave leakage into free flight region. The cavity and free flight sections are surrounded by three cylindrical Permalloy magnetic shields.

A thermocontrol solenoid wound on a cylindrical aluminium tube is installed in space between two inner shields. The inhomogeneity of the axial magnetic flux density ("C-field") in the interaction zone was evaluated by using ferrosensor as a measurement tool. Given that all compensating coils are switched on the homogeneity does not exceed 1.4 nT (rms) for mean magnetic-flux densities in the range 100nT-1000nT . Detection and MOT sections share the same magnetic shield with upper two sections and have their own cylindrical solenoid creating a weak magnetic flux in the direction of the C-field. The design rigidify is ensured by four vertical carrier rods and by five horizontal square plates mounted on the rods. The plates are also used as the base plates for the necessary optical parts. The final alignment is carried out by monitoring and optimizing the detection signal. Fig.1 and Fig.2 illustrate fountain's mechanical design.

III. OPTICAL SETUP

The laser system for cooling and detecting the Cs atoms consists of four laser diodes (Fig 5).

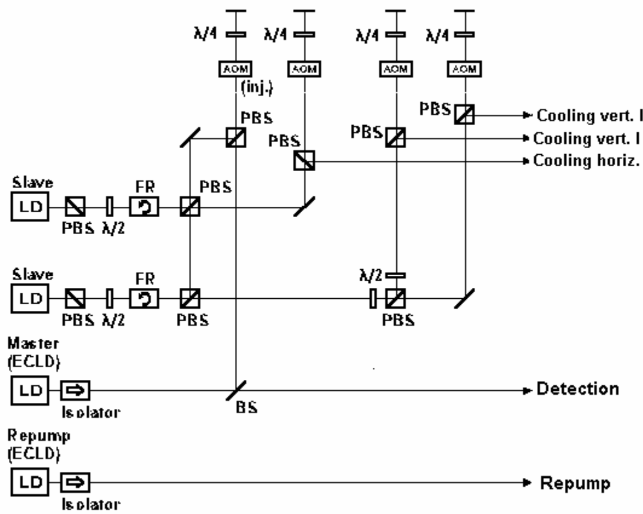

Fig.5. General scheme of the laser system for cesium fountain: AOM-acousto-optical modulator, PBS-polarizing beam splitter.

Two of them master and repumping lasers, are extended cavity laser diodes (ECLD) and other two are injected slave lasers. The lock-in technique for master and repumping lasers resembles that described in [4] except for the laser current modulation frequency, which is 10 kHz in our case instead of about 80 kHz given in [4]. The master laser is frequency locked to the inverted F=4- F'=5 transition signal (Fig. 6 and Fig. 7) and the repumping laser is locked to the inverted F=3-F'=2 absorption signal [5]. After double pass via acousto-optical modulator (AOM) the repumping laser frequency is shifted to the vicinity of the F=3- F'=3 transition. An application of the inverted picks in lasers frequency stabilization system simplifies the operation of AFC and improves its reliability.

The master laser emission is used to injection-lock two 150 mW slave lasers which provide six cooling light beams. A portion of the master laser lights used to detect of the atoms. To avoid problems with the detrimental frequency noise introduced by direct frequency modulation of the diode laser current a common FM spectroscopy (Pound-Drever) method will be applied. This method will also enhance the loop bandwidth so as to make a narrower laser emission spectrum. But instead of electro-optical modulator (EOM),

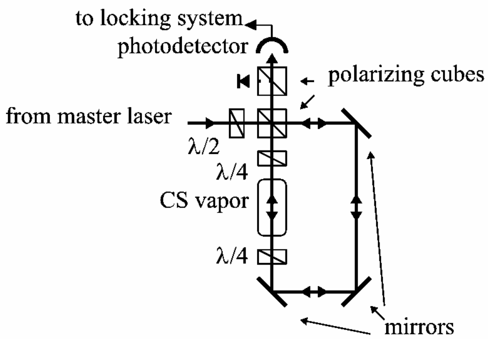

Fig.6. Experimental scheme of the laser-frequency stabilization system.

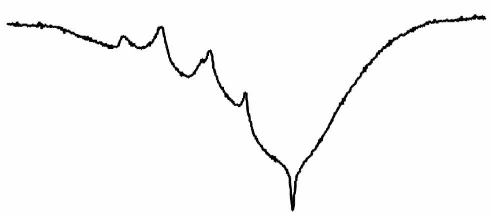

Fig.7. The saturated absorption signal with an inverted F=4-F'=5 pick used for the laser-frequency stabilization. The left pick corresponds to the principal line F=4-F'=3 transition, the right pick is the principal line of F=4-F'=5 transition. All cross-over picks in between.

we plan to use an acousto-optical modulator (AOM) in Raman-low frequency mode will be used for preparation FM sidebands. Polarization-maintaining fibers are used to spatially filter the beams and to deliver each of them from optical table to the base plates surrounding physical apparatus. The fiber-coupling efficiency is about 50% .

To properly manipulate the frequency and intensity of the laser beams involved in cooling, launching, post-cooling and detection processes the microcontroller system (MCS) has been developed. The master laser emission tuned on F=4- F'=5 transition is shifted down by 140-200 MHz after double pass through AOM. The 70-100 MHz signal of voltage controlled oscillator (VCO) to drive the AOM's is produced by the f MCS. The frequency-shifted beam injects two slave lasers one of which forms horizontal cooling beams and second one forms couple of vertical beams after double passing three other AOMs. Their emission frequencies are shifted relative to the F=4- F'=5 transition frequency in the range 0 -60 MHz. These three AOMs control the intensity and shift equally, and the frequencies of the vertical beams up and down by Δf for the launching phase.

The multiple frequency synthesis system (FSS) forms 70 MHz, 70+Δf/2, 70-Δf/2 signals that drive the AOMs. FSS consists of 50, 70 and 90 MHz oscillators phase locked to 5MHz oscillator. For vertical beams the 50 and 90 MHz signals are mixed with 20 MHz +Δf/2 signal from MCS. For horizontal beams an unshifted 70 MHz signal is used. All AOMs driving sign70+Δf/2als are controlled in amplitude by MCS low frequency signals.

IV. Synthesis System for Microwave Interrogation Signal

At present the microwave-interrogation-signal synthesis system is in construction phase. A 1.44GHz oscillator is phase locked to the hydrogen maser as to local oscillator. The 9192631770 Hz output signal of the second oscillator is phase locked to the 6^{th} harmonic of the local oscillator. This output signal is used as a fountain microwave-interrogation signal. Phase modulation by (±π/2) is used for AFC. The error signal is led to the maser cavity varactor. Thus, the frequency of 1.44 GHz oscillator for a closed loop condition is equal to:

$$f = 1.440\left(1 + \sum_{i} \sigma_i\right) GHz,$$

where σ_i are systematic relative-frequency shifts such as "C-field" shift, gravitational shift, black body radiation shift etc. At present a hydrogen maser with increased output power (2×10^{-12}) and with a line Q-factor of (2×10^{9}) is already in operation [6]. A 1.4 GHz oscillator has been manufactured as well. Its frequency variations for open-loop condition are (2-5)$\times10^{-10}$ et at 1 - 10s measurement intervals. Finally, the MCS system controls finally the l. 9192.. GHz microwave oscillator through the serial interface.

V. Preliminary Results and Discussions

The preliminary investigation of a prototype fountain system have recently been carried out [7]. Firstly, the operation in a MOT regime was investigated. Two 80 mm in diameter anti--Helmholtz coils were installed on a MOT section. The distance between them was 60 mm. The magnetic-flux-density gradient value could exceed 10 G/cm. Unbalanced horizontal beams were used.

The current in the coils is switched off during the last 80-100 ms to let the gradient magnetic field decrease to zero. The beams in X and Y directions were retroreflected by mirrors in -X and -Y directions, respectively (in future it is planned to get balanced horizontal beams by using optical scheme shown on Fig.8).

After the MOT magnetic fields were switched off, the atoms were further cooled in a (1-3)ms phase when the lasers changed their frequency from 6MHz to 60 MHz bellow the F=4-F'=5 resonance frequency. The intensity of the beams did not change at the time. In 0.2 s after atoms released a TOF signal that was obtained in the in the detection zone and is shown in Fig.9. The probe beam is derived from a diode laser, which has an intensity of 1mW/ cm^2, is linearly polarized. According to Its 7 ms width the evaluated temperature of the cold atoms is about 20 μK ms.

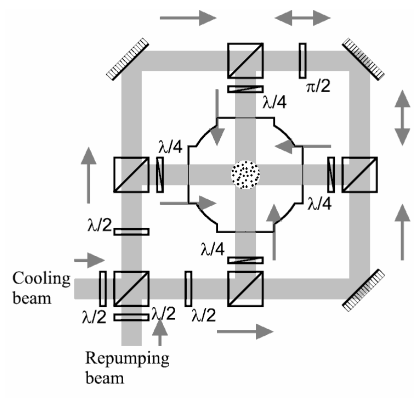

Fig.8. The distribution of cooling and repumper light beams in the horizontal plane.

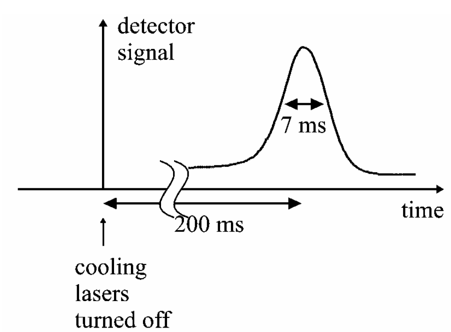

Fig.9. Time-of-flight signal recorded on the detector (MOT regime).

To check operation in molasses phase, we surrounded the MOT and detection zones by a single layer of the magnetic shield. We obtained a molasses operation, and the cold atom temperature is determined by measuring the optical thickness of the ballistically travelling sample cold atoms as a function of the time. The time-of-flight detection pulse width was measured and the pulse width was found to be about the same for MOT and molasses phases. Two vertical beams have the same intensity (about 1mW/ cm^2) and create a moving standing wave at a velocity $V=\lambda\Delta\nu$, where $\Delta\nu$ is the frequency detuning. If the acceleration of $\Delta\nu$ on time (from 6MHz to 60 MHz bellow the F=4-F'=5 resonance frequency for additional cooling purpose) is not too large, the temperature of the atoms, which is initially at equilibrium in the molasses, will stay nearly at equilibrium during the acceleration phase. The intensity of the beams is changed up to 10% at the time acceleration phase of $\Delta\nu$. The evaluated molasses temperature was about 2-3 μK (Fig.10). This values are in the reasonable agreement with an important prediction of the theory [8].

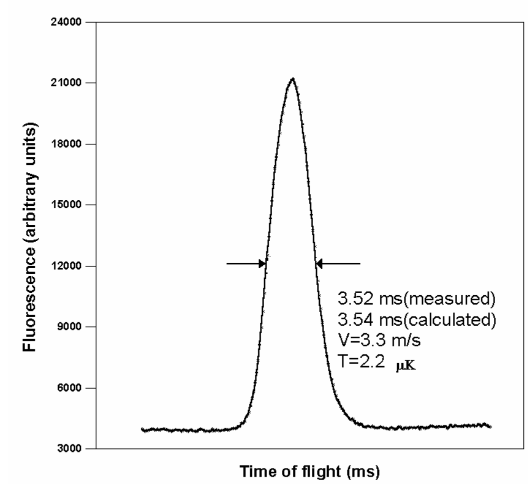

Fig.10. Time-of-flight signal recorded on the detector (molasses regime).

VI. Conclusions

The results of the paper are in following:

1. A prototype of the fountain apparatus has been designed and manufactured. A necessary vacuum level to cool the atoms in the molasses phase was obtained.
2. A laser system allowing frequency and intensity control of all laser beams involved in cooling process was designed and realized.
3. The preliminary investigation of the cold atoms for the MOT and molasses phases was carried out.

Presently, the installed experimental device is used to obtain cold-fountain-atom Ramsey fringes for the hyperfine-structure components of Cs atoms in the ground state (in progress).

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