Species of vacuum chamber design with cryogenic cooling for strontium optical clocks

M G Gurov¹, E G Gurova², S B Rozanov¹, S N Slyusarev¹

¹ FSUE «Russian metrological Institute of Technical Physics and Radio engineering», Mendeleev, Moscow reg., 141570, Russia
² Novosibirsk State Technical University, 20, Karl Marks av., Novosibirsk, 630073, Russia
³ Lebedev Physical Institute of the Russian Academy of Sciences, 53, Leninsky pr., Moscow, 119333, Russia

E-mail: goorovmg@mail.ru

Abstract. The paper briefly reviews the reasons for the optical clock resonance shift due to thermal radiation. The ways to decrease thermal radiation influence with modification of the spectroscopy by introducing of the cryogenic elements as an environment of the atoms from a cryogenic nozzle to create special internal chamber with the example of ⁸⁷Sr optical clocks are shown. The possibility and usefulness of using the double-circuit dual-mode cryogenic chamber to suppress thermal shift in a strontium optical clocks are considered. The selection of the each element material of the chamber is based on simulated thermal distributions and heat flows of these elements. The detailed concept of this double-circuit dual-mode chamber and calculation of the shifts from each element of this chamber are also presented.

1. Introduction

The use of optical clocks (spectroscopes) with alkaline-earth metals as an active substance for the development of new time and frequency standards with reduced uncertainty is increasingly taking place [1-6]. Modern optical clocks, working as a reference, show low levels of reproducible uncertainties lying in the range of 10⁻¹⁷⁻¹⁰⁻¹⁶ [7]. For greater improvement these values in practice, along with shifts, such as field shift and collision shift, it is necessary to reduce the shift of the clock resonance due to the action of thermal radiation of 10⁻¹⁸ by using accounting for amendments to the budget of uncertainties [9, 11] and the technology for moving atoms into a cryogenic chamber and back [3, 6].

The paper proposes another method for upgrading a strontium optical clock using a dual-circuit dual-mode cryogenic chamber. The construction uses two circuits of chambers surrounding the atomic cloud: an external vacuum chamber, which is a vacuum and it is at room temperature, and an internal chamber, which is a thermal insulator from external heat flows. The obvious reason for choosing this design of a dual-circuit chamber is to reduce the thermal radiation of the environment surrounding the working atoms by drastically lowering the temperature without introducing additional components into the budget of uncertainties [6, 7], for example, related to the forced displacement of the atoms.
2. Application of classical theory of thermal radiation effect on the clocks resonance shift of the optical clocks

In an optical clock, the physical interaction of the atoms of the frequency reference with the light and thermal fields occurs in the vacuum volume of a special chamber with glass windows. These windows have a maximum transmission in the band covering the entire wavelength range of the lasers involved in the cooling and detection processes, and for strontium optical clocks, for example, is 450-820 nm. While being at a non-zero (room) temperature, the chamber windows and the inner metal surface of the chamber are sources of thermal radiation. The flux density of this radiation is easily calculated from Planck’s equation, and at a temperature of \( \approx300 \) K it is 180–200 W/m\(^2\), which is one of the main obstacles to improving the uncertainty of the optical clock. The theoretical value of the thermal clock resonance shift of optical clock is the sum of the dynamic and static components. For example, at room temperature 300 K \( |\Delta \nu_{\text{stat}}| = 2.13 \) Hz and \( |\Delta \nu_{\text{dyn}}| = 0.147 \) Hz, i.e. \( |\Delta \nu_{\text{room}}| = |\Delta \nu_{\text{dyn}}^+ \Delta \nu_{\text{stat}}| = 2.27 \) Hz [2].

From the analysis of the dependence (1) of the shift, we can observe that the static part is proportional to the fourth degree of the temperature, and the dynamic component is proportional to the sixth degree of the temperature [6]. If all atoms are exposed to environmental radiation at a cryogenic temperature, i.e. below the temperature of liquid nitrogen, the thermal clock resonance shift in \(^{87}\text{Sr}\) is less than 0.01 Hz (see Figure 1). Provided, that the uniformity of the temperature distribution is equal to one degree, the uncertainty will be less than \( 10^{-16} \) [8, 9]. The behavior of the thermal resonance shift can be estimated as the sum of the weight shifts of the surfaces falling on the solid angle of the environment and taking into account the degree of the surface blackness falling on this angle (see Expression 1).

\[
\Delta \nu_{\text{BBR}}(T) = \frac{\Theta}{4\pi} \left[ \Delta \nu_{\text{stat}} \left( \frac{T}{T_0} \right)^4 + \Delta \nu_{\text{dyn}} \left( \frac{T}{T_0} \right)^6 + O \right]
\]

(1)

where \( \Theta \) is a part of the total solid angle from the visible cone with the tip in the center of the vacuum chamber or the center of the atomic cloud, \( \varepsilon \) is the degree of the blackness of the inner surface of the chamber.

Figure 1 shows the dependence of the thermal shift of the clock transition position for \(^{87}\text{Sr}\).

Vacuum chambers with the suppression of thermal radiation have already been developed in many laboratories of the world [7-10]. These devices include cryogenic parts in one form or another. The main purpose of the development of this chamber is to reduce the value of the thermal shift to the level of mHz and to obtain the uncertainty of the position of the clock resonance at a negligible level (to \( 10^{-18} \)–\( 10^{-17} \)).

3. Methods of the temperature reducing of the working environment of the optical clocks

Since the consideration of the chamber concepts [8, 9], which make it possible to create an external environment for strontium atoms with thermal fields corresponding to ultralow temperatures, significant progress has been made in their creation and specific measurements. Three main areas of chamber development have been implemented or they are under development. The first type is a fixed cryogenic nozzle with a Stirling refrigerator [7]. Atoms trapped in the optical lattice are moved to this nozzle together with the lattice focus and back. A design of this nozzle is shown in Figure 2. This method allows reducing the thermal shift to few mHz [7] and obtaining uncertainty at the level of \( 2 \cdot 10^{-18} \) after two hours of measurements (\( 8 \cdot 10^{-18} \)@1000s). In this case, additional perturbation is introduced into the uncertainty budget at the level of 1.4 mHz, and the minimum time of the elementary measurement is increased in comparison with the methods without atomic displacements by approximately 1.5–2.0 times.
Figure 1. The dependence of the shift of the black-body radiation (BBR) in the full solid angle $4\pi$ on the temperature at $\varepsilon = 1$ for the case when the chamber material is a homogeneous black body. The upper graph is a behavior assessment of the optical resonance of a strontium optical clock before refinement, taking into account a larger number of weighting coefficients [1], and the lower one after [2]. Important values of the maximum BBR estimation are $\approx 10 \text{ mHz}$ at a liquid nitrogen temperature of $77 \text{ °K}$ and $2.354$ (new value $2.27$) Hz at room temperature.

Figure 2. Scheme of the moving atoms into a cryogenic, unmovable nozzle. The captured atoms move along with the focus of the optical lattice [7].

The second way to eliminate the impact of the thermal radiation relates to [10], in which it is supposed to maintain a sufficiently low, but not cryogenic temperature of the chamber, and at the same time, heat fluxes from different parts of the chamber are aligned technologically.

The third type is the fixed double chamber proposed in [8, 9]. The design is implemented as a small aluminum cryochamber with a characteristic diameter of $\approx 16$ cm inside a chamber with larger diameter of $\approx 30$ cm located at room temperature. Figure 3 shows the exterior of this dual-circuit chamber.
The aluminum internal chamber (see Figure 4) has a special internal fining to intercept most strontium atoms that are not trapped in the cooling process and prevent them from settling on the surface of windows at a low temperature, as well as a charge accumulation effect on the dielectric surface, described in [11]. In addition to simply cooling the environment surrounding the atoms, to provide an additional measurement scheme in this chamber, associated with the experiment on the movement of atoms together with the atomic lattice, two cavities, a cryo-nozzle, were introduced into the design of the internal chamber. These cryo-holes have the shape of an equilateral triangle with a side of ≈ 2.5 cm and an inlet of the lattice and atoms of ≈ 3 mm.

**Figure 3.** Modification image of the double cryogenic chamber given in the works [8, 9].

**Figure 4.** Image of a modified internal cryogenic chamber that combines the possibilities of still measuring the clock transition [8, 9] and the ability to move trapped atoms along with an optical lattice [7].

**4. Consideration of thermal shift of double-circuit dual-mode cryogenic chamber**

The given solution of the dual-circuit chamber contains windows, which are cooled to a cryogenic temperature like the metal parts. The temperature distribution including the surface pattern, i.e. emissivity, caused by external sources, has irregularities [8, 9]. They mainly appear due to low thermal conductivity and radiant thermal flux from the external chamber. The emission coefficients of the metal surface and the windows glass coating or the windows themselves at the same temperature should be technologically aligned due to the natural layer or artificial coating.
Figure 5. Results of the simulation of the heat flux and distribution of the temperature in the cross section of the quartz glass window.

In a special visual programming environment, modelling was carried out using the finite element method of a situation where glass is cooled from the sides to a temperature of 77 K, but at the same time has boundary conditions from the top of an external chamber at 300 K. The situations with the distribution of thermal fluxes and temperatures were analyzed in the amount of three types of glasses: leucosapphire, BK-7 or K-8 and quartz glass. The best compromise of cost, technological reasons and temperature distribution showed quartz glass – the traditional material for the manufacture of windows in cryogenics. Uneven temperature distribution in quartz glass was no more than 2-3 K (see Figure 5). For a full assessment of the thermal shift the characteristic dimensions of the elements of the internal chamber were used, shown in Table 1.

| Item Name                  | Amount | Diameter, d, mm | Distance from chamber center, R, mm | Results of temperature modeling, K |
|----------------------------|--------|-----------------|------------------------------------|-----------------------------------|
| Window for the slower beam | 1      | 36              | 80                                 | 79                                |
| Ordinary windows           | 10     | 20              | 80                                 | 79                                |
| Side windows               | 2      | 20              | 15                                 | 79                                |
| The hole on the side of the furnace | 1 | 2             | 700                                 | 773                               |
| Window to the side of the furnace | 1 | 20             | 80                                 | 79                                |
Carrying out similar calculations in [8, 9] of the shift resonance values from the elements of the chamber, the following values of the shifts are obtained (see Table 2).

**Table 2.** Components of the shifts from the various elements of the cryogenic chamber.

| Item Name                          | Thermal shift per element or group of elements, Hz |
|-----------------------------------|----------------------------------------------------|
| Window for the slower beam        | 0.00015                                            |
| Ordinary windows                  | 0.00048                                            |
| Side windows (axes of which are parallel to the axis of symmetry of the chamber) | 0.00210                                            |
| The hole on the side of the furnace | 0.00012                                          |
| Window on the side of the furnace  | 0.00004                                            |

Therefore, the total shift from these elements listed in Table 1 does not exceed 0.003 K, which can reduce the thermal shift of the transition to the level of $2.8 \times 10^{-18}$ Hz and lead to an uncertainty of $6.7 \times 10^{-18}$.

### 5. Conclusions

The paper presents a review of the new development of a dual-mode cryogenic chamber for an optical clocks based on $^{87}$Sr. Direct theoretical studies allow considering quenching the thermal shift without introducing any new disturbances into the budget of uncertainties, only through a cryogenic environment [7, 8, 10]. The considered variants of realized or studied designs have their positive and negative properties. A variant of the vacuum cryogenic design is proposed [8, 9] where the thermal shift in the first approximation is reduced by a static, dual chamber with an intermediate screen. This design allows suppressing well the thermal shift to the level of $10^{-17}$ and with temperature near the temperature of the liquid nitrogen even down to $1.0 \times 10^{-18}$.

### Acknowledgments

Authors gratefully acknowledge department of the Lebedev Physical Institute of the Russian Academy of Sciences for the invaluable help and collaboration with spectroscopy. In addition, authors acknowledge the funding of the direction of Novosibirsk State Technical University.

### References

[1] Porsev S G, Derevianko A 2006 Multipolar theory of blackbody radiation shift of atomic energy levels and its implications for optical lattice clocks *Phys. Rev. A* **74** 020502

[2] Safronova M S, Porsev S G, Safronova U I et al. 2013 Blackbody radiation shift in the Sr optical atomic clock *Phys. Rev. A* **87** 012509

[3] Lisdat Ch, Middelmann T, St Falke et al. 2010 Tackling the blackbody shift in a strontium optical lattice clock *Precision Electromagnetic Measurements* **10** 48–49

[4] Gurov M G, McFerran J J, Nagorny B et al. 2013 Optical lattice clocks as candidates for a possible redefinition of the SI second, *IEEE Transactions on, Instrumentation and Measurement* **62** (6) 1568–1573

[5] Falke St., Schnatz H, Vellore J S R 2011 Winfred et al. The $^{87}$Sr optical frequency standard at PTB *Metrologia* **48** (5) p 399
[6] Middelmann T, Falke S, Lisdat C, Sterr U 2012 High accuracy correction of blackbody radiation shift in an optical lattice clock Phys. Rev. Lett. 109 263004

[7] Ushijima I, Takamoto M, Das M, Ohkubo T, and Katori H 2015 Cryogenic optical lattice clocks Nat. Photon 9 185-189

[8] Gurov M G, Gurova E G 2015 Effect of thermal fields on the shift of optical standards of frequency Russian physics journal 57 1709

[9] Gurov M G, Gurova E G 2014 Optical clocks and thermal fields impact Applied Mechanics and Materials 698 (2015) 561–565

[10] Ablewski P, Bober M and Zawada M 2018 Reducing Blackbody Radiation Shift Uncertainty in Optical Lattice Clocks Proceedings of the European Frequency and Time Forum (Torino, Italy) 352

[11] Lodewyck J, Zawada M, Lorini L et al. 2012 Observation and cancellation of a perturbing dc stark shift in strontium optical lattice clocks Ultrasonic, Ferroelectrics and Frequency Control (IEEE Transactions on) 59 (3) 411–415