Development of Room Temperature and Cryogenic Strontium Ion Clocks With Low Uncertainties

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***Summary*—We are developing a transportable room temperature strontium ion clock at the National Research Council Canada (NRC) and a laboratory-based cryogenic strontium ion clock at the University of Toronto. These clocks are designed to minimize the systematic frequency shifts and meet the mandatory accuracy criteria for the redefinition of the SI second. The expected performances of the new optical clocks are compared to the well-characterized NRC strontium ion frequency standard that has been operational for more than a decade.**

Keywords*—*ion optical clock; transportable optical clock; cryogenic optical clock; systematic shifts

I. Introduction

The roadmap for the redefinition of the SI second, using either an optical transition from a single atomic species or optical transitions from an ensemble of atomic species, proposes to redefine the SI second in 2030, at the 29th meeting of the CGPM [1]. Mandatory criteria were established to ensure a significant improvement in accuracy compared to the current definition based on cesium and continuity with that definition [2].

The mandatory criteria related to clock accuracy are essentially validation that the optical standards are 100 times better than cesium fountain clocks. Practically, this means that clocks should demonstrate fractional frequency uncertainties of better than 2×10^{-18}. An additional requirement is that frequency ratio measurements between optical clocks are made with fractional uncertainties smaller than 5×10^{-18} [2].

The National Research Council Canada (NRC) optical clock based on the ${}^2S_{1/2}$–${}^2D_{5/2}$ transition of ${}^{88}\mathrm{Sr}^+$ has an evaluated uncertainty of 1.1×10^{-17}, limited primarily by the blackbody radiation (BBR) field evaluation and collisional frequency shifts [3]. A simplified uncertainty budget for this clock is shown in Table I under the heading *Current*. The reader is referred to [3] for a detailed discussion of the systematic shifts.

Work is underway to reduce the BBR shift uncertainty in the current NRC optical clock, but it is unlikely that the improved value will reduce the overall uncertainty to the level of the mandatory criteria.

Significant improvements to the uncertainty budget require a new design that mitigates the known limitations in the current system. New optical clocks under development at the NRC and the University of Toronto are expected to yield greatly improved systematic shifts as discussed below.

TABLE I
Comparison of the current NRC ${}^{88}\mathrm{Sr}^+$ ion clock with the expected uncertainty budget for the transportable ion clock. Uncertainties are given in units of 10^{-18} fractional frequency.

Source	**Fractional uncertainties**	
	Current	***Transportable***
BBR field evaluation	11	1
Collisional shift estimate	2.6	0.3
BBRS coefficient ($\Delta\alpha_0$)	0.83	0.8
Thermal motion	0.8	0.8
AOM chirps	0.2	0.2
Excess micromotion	0.2	0.2
Servo tracking errors	0.1	0.1
1092 nm ac Stark shift	0.07	0.07
Electric quadrupole shift	0.03	0.03
Total	11.4	1.6

II. Room-Temperature Strontium Ion Clock

A picture of the new ion trap that will be used in a room-temperature transportable ion clock is shown in Fig. 1. The C-shaped copper structure is made of a copper-chromium-zirconium alloy that has high thermal and electrical conductivity. This structure carries a 14.4 MHz rf voltage to the molybdenum endcap electrodes to create the ion-trap pseudo-potential. The spacing between the endcap electrodes is 0.84 mm. The shield electrodes (cone-shaped components) are also made of molybdenum. They are isolated from the rf-carrying structure with thick fused-silica and sapphire spacers to reduce capacitance and minimize heating. The shield electrodes are grounded at rf frequencies but independent dc voltages can be applied to them to minimize micromotion along the trap axis. Four extra trim electrodes (only two are visible in the foreground of the picture) will be used to minimize micromotion in the radial directions.

A preliminary measurement of the ion trap heating with a thermal imaging camera is shown in Fig. 2. When the trap is energized with a voltage of 450 V amplitude from a helical resonator to obtain a 2 MHz axial secular frequency, there is an approximately uniform temperature increase of less than 1°C of the trap components. In contrast, the temperature increases in the current trap when energized with a voltage that gives a

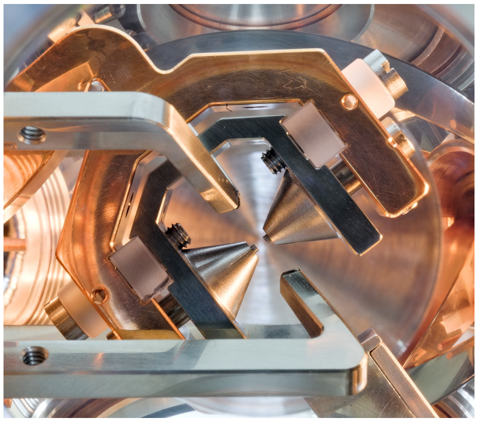

Fig. 1. Picture of the new ion trap in the vacuum chamber.

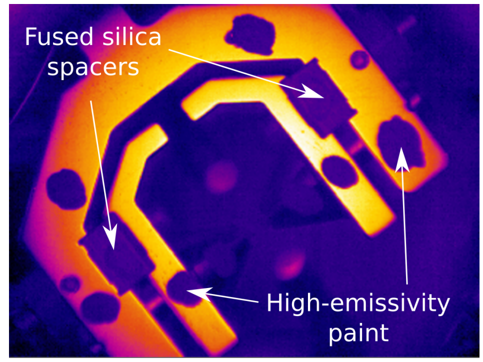

Fig. 2. Thermal imaging of the energized ion trap. The bright surfaces are caused by the reflection of the blackbody radiation emitted by the thermal imaging camera sensor onto the polished metal components. The temperatures are measured using a high-emissivity paint applied at a few test points. The trim electrodes were removed to capture this image.

2 MHz axial secular frequency are non-uniform and can exceed 10°C. The trap heating effects in the new system will be further reduced with temperature control of the electrical conductor between the helical resonator and the ion trap. The observed small and well-behaved temperature increases, combined with finite-element simulations of the thermal field are expected to reduce the BBR shift uncertainty by more than one order of magnitude compared to the current trap design, to below the 10^{-18} level.

The next most important frequency shift is caused by collisions with background gas molecules, especially H_2. The vacuum system of the new optical clock is designed to optimize the gas conductance between the trapping region and the vacuum pumps. A Monte-Carlo simulation of molecular flow in the vacuum system [4] indicates that the pressure and collisional frequency shifts (CFS) in the transportable clock should be about an order of magnitude smaller compared to the current system. The uncertainty budget for the transportable ion optical clock, taking into account the above discussion, is summarized in Table I under the heading *Transportable*. The overall fractional frequency uncertainty of the transportable room-temperature ion clock is expected to be around 1.6×10^{-18}.

III. Cryogenic Strontium Ion Clock

A cryogenic $^{88}Sr^+$ optical clock (cryoclock) is being developed at the University of Toronto in collaboration with the NRC. The cryoclock consists of an outer room-temperature vacuum chamber and an inner vacuum chamber cooled to 4 K. The inner vacuum chamber is made with C101 copper, a material selected for its excellent thermal conductivity at cryogenic temperatures. The trap structure and electrodes will have the same geometry as in the room-temperature clock, and will be made from a thermally conductive copper alloy in order to present a uniform low-temperature blackbody environment to the ion.

A simple analysis shows that the BBR shift fractional frequency uncertainty is only 1.9×10^{-23} for a 1 K uncertainty at 4 K and that the differential scalar polarizability ($\Delta\alpha_0$) contribution to the uncertainty is reduced to 2.6×10^{-26} [5]. At a 4 K temperature, the background pressure routinely reaches 10^{-12} Pa [6] which is about 4 orders of magnitude lower than in our current vacuum system [3]. Assuming that the other systematic shifts have uncertainties similar to the room-temperature clocks, the cryoclock total uncertainty reaches a level of 8.6×10^{-19}.

IV. Conclusions

We presented two new $^{88}Sr^+$ ion clocks that are being developed to reduce the dominant systematic shifts that are limiting the accuracy of the current system. Both optical clocks use a similar ion trap design that minimizes heating effects when an rf voltage is applied to the ion trap. Preliminary measurements of trap heating and simulations of the vacuum background pressure indicate that the new traps are expected to have systematic frequency shifts below 2×10^{-18}, one of the mandatory criteria for the redefinition of the SI second.

The cryoclock can potentially reach the low 10^{-19} fractional uncertainty with the implementation of sideband cooling and other technical improvements to clock operation. The cryoclock is expected to play a key role in the study of systematic frequency shifts and the validation of the room-temperature clock's uncertainty budget.

References

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