Progress on Ion Microwave Frequency Standards at Tsinghua University

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***Summary*—The ion microwave frequency standard is a candidate for the next generation of practical microwave frequency standards, which has a very wide application potential. Tsinghua University has continuously been working on the research and development of ion microwave frequency standards. A demonstration experiment of two laser-cooled cadmium ion microwave clocks with zero dead time shows a short-term stability of $\tau^{-0.95}$ averaging. Besides, a microwave frequency standard based on cadmium ions sympathetically cooled by ytterbium ions has been realized, and the clock signal has been obtained. In addition, two new laser-cooled ytterbium ion microwave clocks are also being built.**

Keywords—sympathetic cooling; ion trap; frequency standard Introduction

I. Introduction

Microwave frequency standards can be widely used in metrology, timekeeping and navigation[1]. Because of its high performance and the potential for miniaturization, microwave frequency standards based on trapped ions become a promising candidate for the next generation microwave atomic clocks.

At Tsinghua University, our group has continuously been working on the research and development of ion microwave frequency standards. The laser-cooled cadmium ion clock has a short-term stability of 4.2E-13$\tau^{-1/2}$(modified Allan deviation) and the fractional uncertainty is 1.8E-14[2]. The microwave frequency standard based on cadmium ions sympathetically cooled by calcium ions is the first sympathetic cooling clock in Paul trap, whose short-term stability is 3.5E-13$\tau^{-1/2}$ with the Ramsey free evolution time of 5 s[3]. The laser-cooled ytterbium ion clock has a short-term stability of 8.5E-13$\tau^{-1/2}$[4] and the fractional uncertainty is 6.3E-14[2].

II. Progress on zero-deadtime cadmium ion microwave clock

In our laser-cooled cadmium microwave frequency standard[2], deadtime accounted for more than 60% of the entire loop, which limited the short-term stability of the clock. Therefore, we introduce the zero deadtime (ZDT) method to the ion clock.

Based on two laser-cooled cadmium microwave clocks, a ZDT cadmium ion clock demonstration experiment was set up. The timing sequences of a single Cd^+ clock and the ZDT Cd^+ clock are shown in Fig. 1. ZDT clock consists of two sets of atomic clocks referenced on the same local oscillator. When one clock is in dead time, the other system is in the microwave interrogation process[6]. Therefore there is no dead time in the overall loop, and Allan deviation improves as τ^{-1} instead of $\tau^{-1/2}$[7]. ZDT clock has been realized in optical clocks[8-9], pulsed-optically-pumped clocks[10] and coherent-population-trapping clocks[11-12], and we have realized the ZDT clock in the ion microwave clock for the first time.

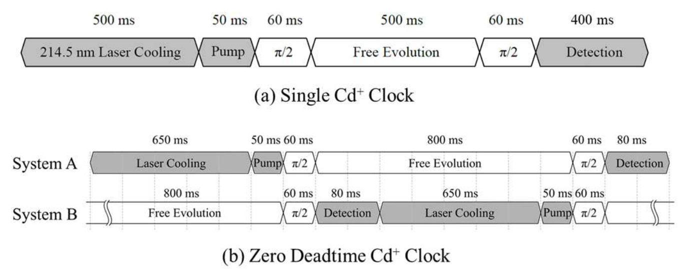

Fig. 1. The timing sequences of (a) a single Cd^+ clock and (b) the ZDT Cd^+ clock. Deadtime is indicated by a gray background.

The physical system of the ZDT clock demonstration experiment is shown in Fig. 2. In order to better observe τ^{-1} Allan deviation, we use a signal generator to generate noise to modulate the crystal oscillator (local oscillator), making its frequency stability worse from the 10^{-13} to 10^{-12} @ 1s.

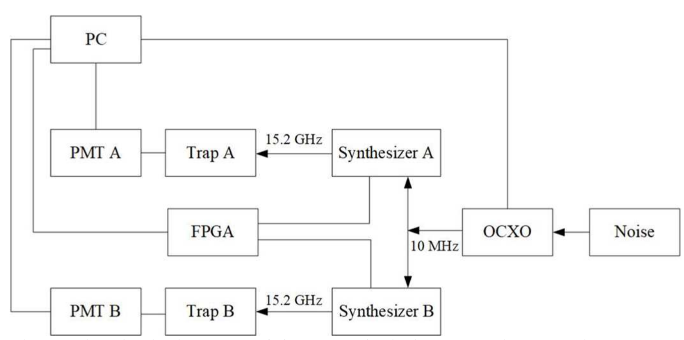

Fig. 2. The physical system of the ZDT clock demonstration experiment. Two identical laser-cooled cadmium-ion microwave clocks were used.

The local oscillator was locked at the ZDT Cd^+ clock for 4924 s, and the frequency stability results of the first 1500 s are shown in the purple line in Fig. 3. When the average time τ is in the range of 10 to 100 s, the slope of the Allan deviation is -0.95, which means frequency stability improves as $\tau^{-0.95}$. For comparison, the stability of a single set of Cd^+ clock is shown by the blue line. At average time τ =100 s, the Allan deviation of ZDT clock is only 2/3 of that of the single Cd^+ clock.

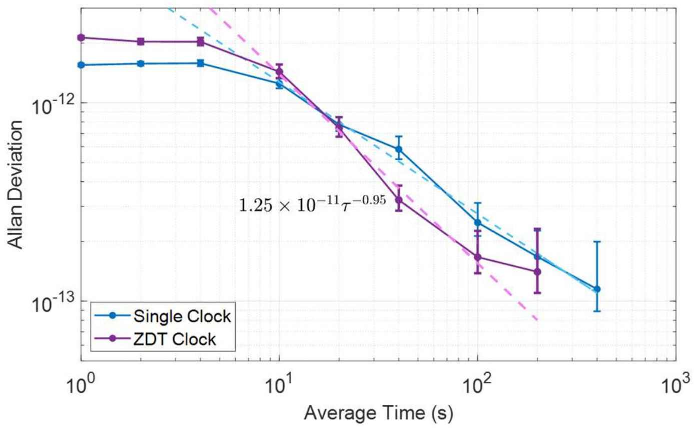

Fig. 3. The Allan deviation of the ZDT clock and single Cd^+ clock. The solid line is the measured data and the dashed line is the linear fit result.

Regrettably, we did not observe the turning point from τ^{-1} to $\tau^{-1/2}$ described in [7]. For the first 2300 s in total 4924 s, the Allan deviation improves as $\tau^{-0.81}$ in the range of 10 to 200 s; for all data in 4924 s, the Allan deviation improves as $\tau^{-0.78}$ in the range of 10 to 400 s. We haven't figured out the reason for this overall change in slope, and more experiments will be done in the future.

III. Progress on Sympathetically-Cooled Cadmium Ion Microwave Clock

Although the microwave clock based on cadmium ions sympathetically cooled by calcium ions has good frequency stability and frequency accuracy, it still faces a problem: in the two-component ion crystal, the cadmium ions are on the outside of calcium, which leads to a large second-order Doppler shift[13], limiting the signal-to-noise ratio for ion counts.

Therefore, we chose ytterbium ions as the coolant, which are more massive than cadmium ions, so that the cadmium ions are in the center of the ion crystal, suppressing the second-order Doppler shift. In previous articles, we reported the molecular dynamics simulation of the sympathetic cooling $^{174}Yb^+$-$^{113}Cd^+$ ion crystal[14-15].

We achieved the sympathetic cooling of the $^{174}Yb^+$-$^{113}Cd^+$ ion crystal, shown in the Fig. 4. We first cooled about 2800 ytterbium ions to about 10 mK, then turned on the cadmium oven and ionizing light. In our two-component ionic crystals, there are about 7000 cadmium ions, with a temperature of about 100 mK.

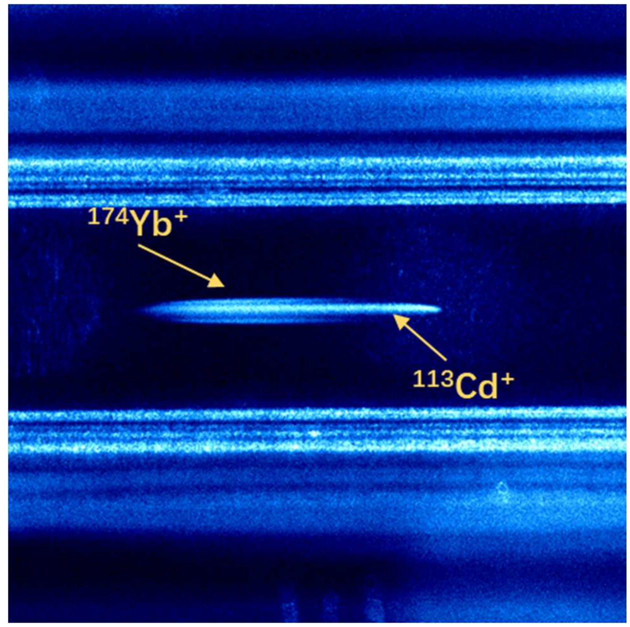

Fig. 4. The image of the sympathetic cooling ion on EMCCD. Cd^+ ions are in the center of the ion crystal, surrounded by Yb^+.

We thus obtain Ramsey clock transition signal, shown in Fig. 5. Probably because of decoherence, the Ramsey fringe has a large background. We are currently optimizing the clock signal for better performance of our sympathetically-cooled cadmium clocks.

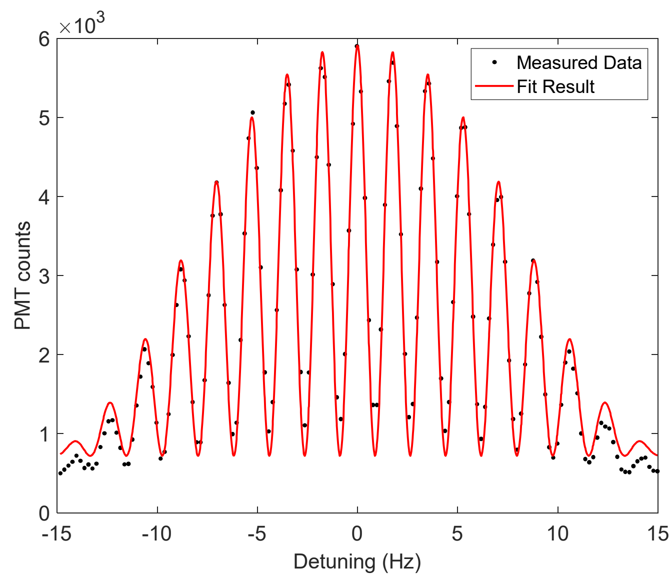

Fig. 5. A typical Ramesy fringe of the clock transition (15.2 GHz) with a free evolution time of 500 ms.

IV. Progress on Laser-Cooled Ytterbium Ion Microwave Clock

For the ytterbium ion microwave clock, we also have two improvement routes. In the first scheme, we improved the quadrupole ion trap into a combinatorial trap combined with a quadrupole and a twelve-pole trap. Multi-pole traps are often used in buffer-gas-cooled mercury ion microwave clocks[16-17], and we apply them to laser-cooled ytterbium ion microwave clocks for the first time. We designed and assembled our combinatorial well, the structure of which is shown in Fig. 6. The experimental apparatus of the multi-pole trap clock is preparing a vacuum and will be put into use soon.

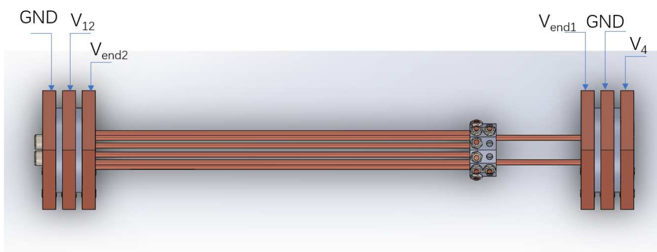

Fig. 6. The assembled combinatorial trap combined with a quadrupole and a twelve-pole trap. The voltages connected to different electrodes are also shown.

The other route is the miniaturization of the physical package. In our new design, the total physical package, including a 3-layer magnetic shield barrel, has a total volume of 50 L, which is 20 times smaller than the laser-cooled ytterbium clock in our lab before[4-5]. The physics package is shown in Fig. 7. We use two miniaturized non-evaporable getter combination ion pumps to maintain the vacuum so that The vacuum of the system is expected to reach 10^{-9} mbar.

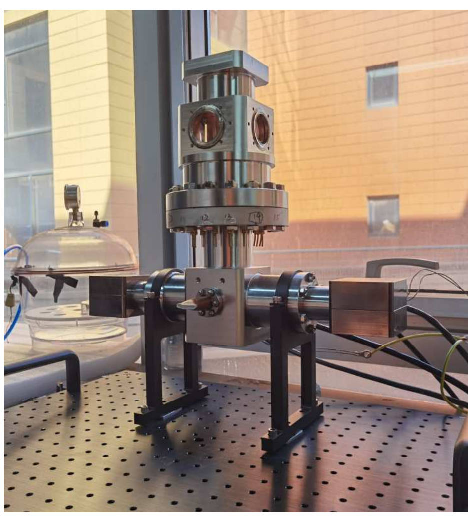

Fig. 7. The physics package (without magnetic shield) of the miniaturized ytterbium ion microwave clock. A linear Paul trap is set vertically inside the cube vacuum chamber.

We achieved laser cooling of ytterbium ions in the new miniaturized clock. About 2.3E4 ytterbium ions are trapped and cooled to 14 K. Ramsey fringe of the clock signal of 12.6 GHz was achieved and more experiments are still in progress.

V. Conclusions and Expectations

Based on the laser-cooled cadmium ion clock[2], a zero-deadtime laser-cooled cadmium ion clock is built. The frequency stability depends on $\tau^{-0.95}$ and the Allan deviation of ZDT clock is also smaller than that of the single Cd^+ clock. To reduce the frequency uncertainty of the sympathetically-cooled cadmium ion clock, we replaced the coolant ions with ytterbium ions. We achieved the sympathetic cooling of $^{113}Cd^+$ by $^{174}Yb^+$ ion for the first time and Ramsey fringe of the clock signal is obtained. Besides, we are building two sets of laser-cooled Yb^+ clocks. One is a miniaturized clock with the size of 50 L and the other is a multi-pole-trap clock to reduce the Doppler shift.

Among these new ion microwave clocks mentioned above, some are being assembled, and some have completed some preliminary experiments. We expect them to get better performance and achieve wider applications.

Acknowledgment

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