Performance of micro mercury trapped ion clock

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***Abstract*— Trapped mercury ion is a promising candidate for portable and operational atomic clocks. It operates at the 40.5-GHz ground state hyperfine transition of ^{199}Hg ions. Mercury ions are confined in a linear RF trap, buffer-gas cooled, with a long ion storage lifetime in an ultra-high vacuum enclosure without an active pump. The clock transition is optically-pumped and detected with a Hg discharge lamp without need of a laser light source. This approach has proven to provide simplicity in design and implementation and robustness in operation. In this paper, we report our recently effort on developing a micro and low-power mercury trapped ion clock in the DARPA ACES program. In a 5 mm x 10 mm linear trap (0.25 cc), we have achieved the clock fractional frequency stability of $1.7 \times 10^{-12}\tau^{-1/2}$ and reached down to 7×10^{-14} after 1000 seconds of averaging. We will discuss the clock performance under different conditions and implications toward a micro mercury trapped ion clock with low power and high stability.**

Keywords—atomic frequency standard; mercury ion;

I. Introduction

There are a number of different approaches to miniaturize the atomic clock such as free space atoms in a vapor cell, laser cooled atoms, and trapped ions [1][2][3]. Our clock is operated using the 40.5 GHz ground state hyperfine transition of trapped $^{199}Hg^+$ ions [4][5][6]. The mercury ion microwave clock has a high clock transition (~40.507,347,996 GHz) and a low second order Zeeman shift (~100 Hz/G^2) compared to other microwave clocks, which significantly reduces the magnetic field sensitivity of the clock performance. The trapped ions are optically pumped by a 194-nm discharge lamp, and the ion signal is detected through 194-nm fluorescence photons. Using the 194-nm discharge lamp eliminates the complexity of a laser development for a miniaturized mercury ion microwave clock. Recently, the mercury ion microwave clock has been used to develop a deep space atomic clock (DSAC) for the National Aeronautics and Space Administration (NASA) [7][7]. Here we report our recent progress on developing a miniaturized and low power mercury ion microwave clock. We aim to develop a clock with a volume below 50 cm^3, a power consumption below 250 mW, a short-term instability below $10^{-11}/\tau^{-1/2}$, and a long-term instability of 10^{-13}.

II. Experimental Setup

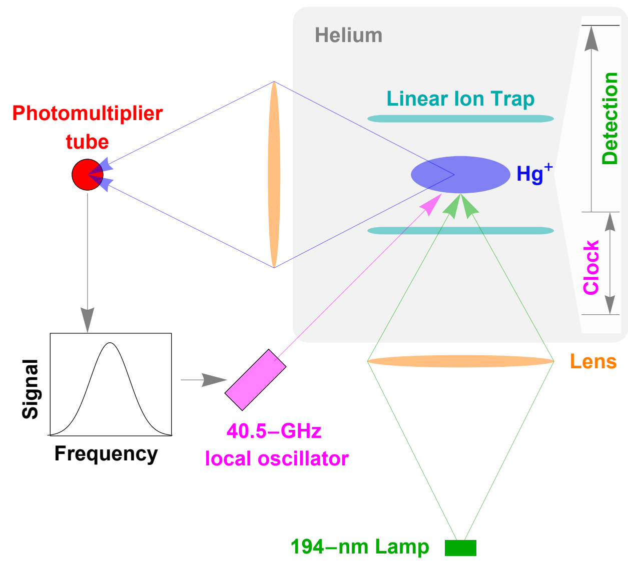

Fig. 1. Experimental diagram. The $^{199}Hg^+$ ions (blue dot) are trapped in a quadrupole linear ion trap. The $^{199}Hg^+$ ions are cooled by helium buffer gas (gray box). The waveguide deliveries the 40.5-GHz microwave radition from a frequency synthesizer to the ions. The trapped ions are illuminated by the 194-nm light emitted from the lamp (green rectangle with arrows). The 194-nm lamp light is projected onto the ion location by a focus lens. The 194-nm fluorescence photons of the trapped ions are collected by the photomultiplier tube (red circle). The 194-nm fluorescence signal strength depends on the 40.5 GHz frequency (signal vs. frequency rectangle) and is used to lock the local oscillator to the clock transition of the $^{199}Hg^+$ ions (gray arrows).

Our experiments are carried out using trapped $^{199}Hg^+$ ions in a 30 cm^3 vacuum package. A 420 Vrms at 1.6 MHz is applied between adjacent trap rods, and a potential difference of 20 V is applied between trap rods and the end caps. The vacuum package is filled with 3×10^{-6} torr of helium to provide buffer gas cooling for the ions. The experimental setup is illustrated in Fig. 1. A more detailed description is provided in Ref. [6]. The trapped ions are interrogated by the microwave radition from a frequency synthesizer. The microwave radition drives the trapped ions from the lower $|S_{1/2}, F=0\rangle$ hyperfine state to the upper $|S_{1/2}, F=1\rangle$ hyperfine state. The hyperfine splitting of mercury ions is about 40.5 GHz and is used for the clock frequency. The 194-nm ultraviolet light of a mercury discharge lamp optically pumps the ions from the $|S_{1/2}, F=1\rangle$ state to the $|P_{1/2}\rangle$ state. A photonmultiplier tube collects the

194-nm photons emitted from the trapped ions due to the $|P_{1/2}\rangle \rightarrow |S_{1/2}\rangle$ sponteneous emission. This 194-nm signal is used to detect the ion hyperfine state and to lock the frequency synthesizer to the 40.5-GHz clock transition of the $^{199}Hg^{+}$ ions.

III. RESULTS

Our mercury clock is operated in the pulse mode, where each clock cycle composes of a 40.5- GHz microwave pulse following by a 194-nm optical pulse. In the previous study [6], we operated the clock with a 11 second cycle time, which yields an Allan deviation of $6 \times 10^{-12}\tau^{-1/2}$ and reaches 2×10^{-13} after the integration time of 1000 seconds. It is a challenging task to improve the clock stability and shorten the cycle time while maintaining a small size and low power consumption for our physics package.

To achieve a high-level stability, it is important to have a high signal-to-noise ratio (SNR). To increase the SNR, one can increase the 194-nm optical power. However, our mercury discharge lamp is already operating at its maximum capacity. Currently, we are developing a new mercury discharge lamp which can provide a stronger 194-nm optical power. A high 194-nm power will also reduce the optical pumping time and consequently shorten the clock cycle time.

Another way to improve the SNR is to increase the ion number. After we modified the trap rods configuration to increase the trapping potential, the ion signal was significantly higher. This indicates that we can improve the ion number by optimizing the trap design. The higher ion signal yields a higher SNR. As a result, the Allan deviation of the clock is significantly improved. Figure 2 shows that the clock Allan deviation is $1.7 \times 10^{-12}\tau^{-1/2}$ and reaches 7×10^{-14} after 1000 seconds without a magnetic shield for a 6.2 second cycle time. Here the microwave pulse is 1 second and the optical pulse is 5 seconds. The microwave power is optimized to give the maximum ion signal after the microwave pulse. The higher SNR allows us to shorten the clock cycle time to 1.8 second while the short-term stability of the clock still meets the Atomic Clock with Enhanced Stability program requirement (ACES). For a 1.8 second cycle time, the Allan deviation is $5.5 \times 10^{-12}\tau^{-1/2}$ and reaches 2×10^{-13} after 1000 seconds without a magnetic shield. Here the microwave pulse is 0.5 second and the optical pulse is 1 second.

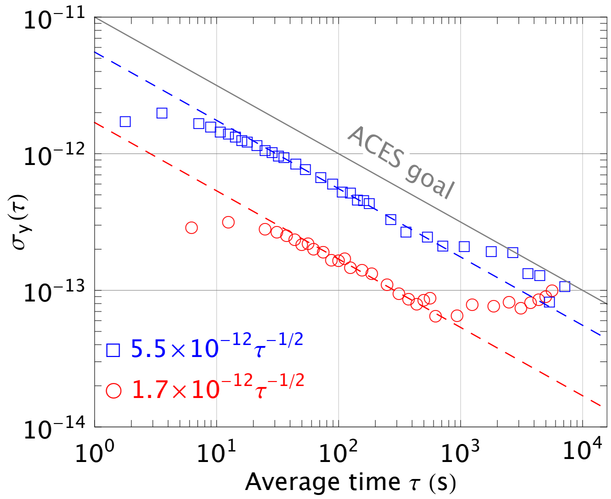

Fig. 2. Allan deviation for different cycle times. The experimental data for a 1.8 second cycle time and a 6.2 second cycle time are shown in blue square and red circle, respectively. The data are fitted to the $\tau^{-1/2}$ function (blue and red dashed lines) to determine the short term stability. For the 1.8 second cycle time and the 6.2 second cycle time, the short term stability is $5.5 \times 10^{-12}\,\tau^{-1/2}$ and $1.7 \times 10^{-12}\,\tau^{-1/2}$, respectively. The gray solid line represents the goal of the Atomic Clock with Enhanced Stability program (ACES).

IV. CONCLUSIONS

We have demonstrated significant improvements on a miniaturized mercury ion microwave clock. We have achieved the clock fractional frequency stability of $1.7 \times 10^{-12}\tau^{-1/2}$ and reached down to 7×10^{-14} after 1000 seconds of averaging. We have shorten the clock cycle time from 11 seconds to 1.8 second.

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