Research Progress on Mercury Ion Microwave Clock for Time Keeping

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Abstract. Mercury ion microwave clock has great prospect in timekeeping and space applications for its excellent frequency stability and very low drift rate. In recent years, we have been studying the method to maintain the sealed vacuum system with getters for mercury ion microwave clock. This technology, which can reduce the size, weight and power consumption (SWaP) and greatly improve the reliability of the vacuum system, plays the key role in developing the mercury ion microwave clock from laboratory to practical application. In this letter, we present a multipole trap mercury ion clock developed for ground timekeeping applications using sealed vacuum system. Based on the ion shuttling between the quadrupole and 12-pole trap, the sensitivity of ion number dependence effect and external magnetic field could be effectively suppressed, which promising a better long-term stability than conventional single quadrupole trap system. The optical system is also optimized to enhance the signal to noise ratio (SNR) of the clock spectral line. To date, the ion clock physical package has been built. The clock transition spectral is measured in quadrupole trap region firstly. That shows a stability limit of 7.29×10^{-14} at 1s according to the shot noise. The signal of ions shuttling between the two traps is also observed. The near 100% shuttling efficiency has been demonstrated even after 50 times ion shuttling.

Keywords: Mercury ion microwave clock · Timekeeping clock · Sealed vacuum system · Multi-pole ion trap

1 Introduction

In traditional atomic clocks based on atomic beams and cells, the frequency stability are mainly limited by finite coherence time and wall collisions. Mercury ion microwave clock could solve these effects by using ion trapping technology, which permits a much better performance on frequency stability and drift rate. Furthermore, no lasers, cryogenics, and microwave cavity required make this kind of clock suitable for long-term continuous operation and space applications [1]. With these advantages, mercury ion microwave

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clock has attracted wide interest over the past 40 years. In 2019, Jet Propulsion Laboratory (JPL) had launched a compact prototype, namely Deep Space Atomic Clock, into the earth orbit and demonstrated the excellent performance that exceeds current space clock by up to an order of magnitude [2]. Moreover, the long-term test of the JPL's ultra-stable mercury ion clock LITS-9 had shown the long-term stability comparable to the laser-cooled cesium fountain [3]. It is an invaluable stand-alone continuous running unsteered standard representation of UTC. The research programs of mercury ion microwave clock are also under way in Europe and Russia [4, 5]. It can be predicted that the mercury ion microwave clock will play an important role in future precision measurement, time keeping application, satellite navigation and deep space exploration [2, 3, 6].

In recent years our group has made a lot of progress in the key technology of mercury ion microwave clock, such as sealed vacuum system, miniaturized Mercury isotope lamp and low-noise microwave synthesizer. A compact prototype towards the space-borne applications has been realized [7]. Recently, we are developing a high performance mercury ion microwave clock employing the sealed vacuum maintain method aims to long-term time keeping. This paper mainly introduces the design, development and preliminary experimental progress of this clock.

2 Sealed Vacuum System

The charge exchange and spin exchange reactions caused by the frequent collisions between trapped ions and gas molecules severely restrict the ion confinement time, and lead to significant relaxation and frequency shift of clock transition spectrum. Therefore, the mercury ion microwave clock needs a much higher vacuum environment than the beam and cell type frequency standards. In addition, due to the using of buffer gas, it must be keeping ultra-high vacuum background and simultaneously injecting the inert gas for cooling ions, which makes the vacuum system much more complicated.

In the laboratory, the mercury ion microwave clock could use a "flow-through" vacuum system, which uses molecular pump group to suppress the unwanted background gas, while continuously filling the vacuum chamber with buffer gas to keep the pressure constant [8]. However, the "flow-through" vacuum system is hard to work uninterruptedly for a long period due to the regular maintenance and limited in many practical scenarios critical to the system SWaP and reliability [9].

Sealed vacuum system pumped by getter pump is a superior alternative scheme. With physical adsorption and chemical reaction to getterable gas, the getter does not need power supply once activated, and there is no magnetic and moving parts, no necessary to maintenance in whole lifetime. It is very suitable for holding the vacuum system required high reliability, long service life and small SWaP, especially in the vacuum electronic devices such as Travelling Wave Tube Amplifier [10]. The getter has a high pumping speed for the background gas such as hydrogen, but no pumping the inert gas which are used as buffer gas. In consequence, the buffer gas could be sealed in the vacuum system after the getter activation.

Compared with the flow-through vacuum system, the sealed vacuum system has a higher vacuum background and longer ion trapping time [7]. The system's SWaP are greatly reduced and reliability is also greatly improved. The sealed vacuum maintenance technology is the key to the mercury ion microwave clock application outside of the laboratory.

In previous works, we have built a 16.4 L compact mercury ion microwave clock with a 0.5 L sealed vacuum system which has a life expectancy about 30 years [7]. There is no degradation on the ion trapping time and clock transition signal intensity since the vacuum sealed 4 years ago. Recently, we use this technique to develop a high performance mercury ion microwave clock prototype towards the time keeping applications.

3 Design of Time Keeping Ion Clock Prototype

3.1 Extended Linear Ion Trap

The goal of this research is to achieve a high level performance mercury ion microwave clock which could be operated reliably and continuously. Therefore, the vacuum system is designed for long-term sealed operation with getter pump. We use the extended linear ion trap (ELIT) to reduce the ion number dependent shift, which is the major bottleneck of long-term stability in the conventional linear trap.

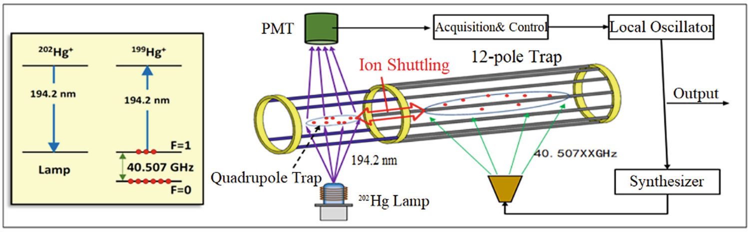

Fig. 1. Schematic diagram of mercury ion microwave clock for time keeping

As shown in Fig. 1, this ELIT is consists of a quadrupole trap and a 12-pole trap, respectively for the ion state preparation/readout and clock transition interrogation. This architecture allows the unique benefits of both traps to be used in the same clock. In quadrupole trap, the ions would concentrate on the trap axis, which helps to increase the efficiency of optical pumping and fluorescence detection. In 12-pole trap, the ions' distribution is more uniform which greatly weakens the space charge effect of the trapped ions [11]. This property helps to reduce the ion number dependent shift of the clock transition. By manipulating the DC bias applied on trap electrodes, the mercury ions shuttle back and forth between the two trap regions, the processes of optical pumping and microwave resonance are separated into two independent spaces, which is beneficial to optimal design of magnetic field device and optical system.

3.2 Magnetic Field Set

The magnetic field set includes a four layers magnetic shield and C field coils, which provides a quite uniform magnetic field environment for clock transition interrogation.

Because of the spatially separated optical and microwave interaction, there is no more necessary to open optical paths on magnetic fields. Therefore, magnetic shielding efficient could be greatly improved compared with the former single quadrupole trap system. The magnetic shield is made of the Permalloy with very high permeability, including three concentric magnetic shield cylinders covering the 12-pole trap region and a fourth outermost shield box composed of six shielding plates enclosing the whole ion trap region. The shielding factor in ion trap's radial direction can reach up to 10^6, and the axial shielding factor is smaller, about 5×10^4.

A solenoid is used to generate a uniform weak magnetic field in the 12-pole trap region. A pair of auxiliary coil is employed to compensate the rapid field decrease on both edges of the solenoid which introduces the decoherence and ion number dependent shift [12]. By optimizing the coil design, the designed magnetic field inhomogeneity of the whole axial ion trapping region in 12-pole trap is less than 0.5% (see Fig. 2).

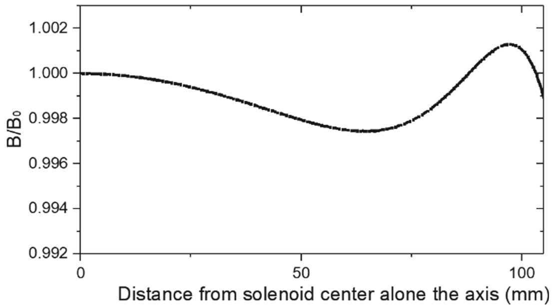

Fig. 2. Simulation result of relative magnetic intensity in the axial direction. B_0 is the magnetic field intensity at the solenoid center.

3.3 Optical System

In previous quadrupole trap ion frequency standard system, the optical system is mainly limited by the structure and size of magnetic shielding and C-field coils. As a contrast, The structure of the optical system can be further optimized with the ELIT architecture. A couple of fluorescence collecting arms are arranged on the symmetrical position of both sides of the trap, which could increase the SNR by a factor of $\sqrt{2}$. In our previous quadrupole ion frequency standard system, after the optical pumping of $^{199}Hg^+$, the ^{202}Hg discharge lamp needs to be transformed into dim state to enable the ions to carry out microwave resonance. In the extended ion trap system, the microwave resonance region is far away from the quadrupole optical window, which further reduces the optical frequency shift. In practical operation, this structure can make the lamp keep bright state in the process of microwave resonance. The lamp operating at an optimized duty cycle would increase the light intensity and its stability. The optical lenses are also well designed to suppress stray light and reduce background noise of fluorescence collection.

3.4 Integrated Design

In order to carry on the overall temperature control and transportable comparison tests, the whole physical package and circuit part are designed to integrate in a chamber assembled by a thermal control cover and platform. That has a scale of 1 m in length, 0.6 m in width and 0.3 m in height. The sealing structure between the temperature-controlled cover and platform can reduce the thermal convection with air flow, which can further enhance the temperature control accuracy of the whole set.

4 Initial Result

4.1 Clock Transition in Quadrupole Trap

After the ultra-high vacuum preparation and buffer gas injection, the valve connected to the turbo pump was turned off, only leaving the getter pump to maintain the sealed vacuum. Then the ions are loaded in the quadrupole trap region. Figure 3 shows the Rabi spectra of clock transition measured in the quadrupole trap with line width of 0.38 Hz. The detection SNR is 93.5, which is much better than any our former quadrupole trap system [7, 8].

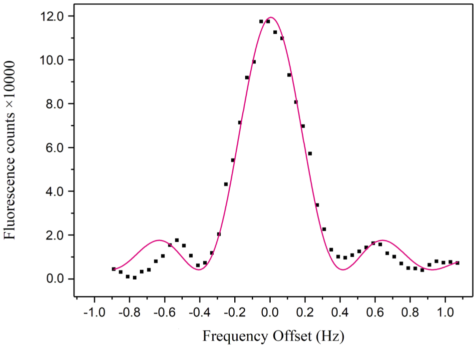

Fig. 3. The Rabi spectrum of the clock transition.

The theoretical stability limit by shot noise could be evaluated with follwing the formula:

$$\sigma = \frac{1}{\pi(\mathrm{SNR})Q}\sqrt{\frac{\mathrm{T}_c}{\tau}}$$

where Tc is the clock cycle time, τ is the measurement time, Q is quality factor of the transition line. According to the measured result and the clock cycle time of 5.2 s, the shot noise that contributes to the frequency stability is $7.29 \times 10^{-14}/\tau^{1/2}$。

4.2 Ion Shuttling

Ion shuttling is the key process of ELIT system. Because of the discontinuous radial trapped potential at the gap between the two trap regions, the ions tend to escape from the gap during the shuttling process, resulting in the loss of the trapped ions. According to modeling and simulation, we found that the maximum shuttling efficiency can be achieved when the phase-opposite trapping potential is applied on the co-axial electrodes of the quadrupole and 12-pole traps [13].

In the experiment, the ion shuttling is realized by manipulating the DC bias on the two traps. As shown in Fig. 4, after a 100s-ion-loading, the fluorescence intensity no longer increases, which means the ion loading reaches saturation. After that, the emitter is turned off and ion shuttling process began. The DC bias level on quadrupole trap is lifted higher than that on multipole trap. Then the ions are dumped into the multipole trap, hence the ions' fluorescence disappears. When the level flips, the ions come back into quadrupole trap, and fluorescence signal recovers. After 50 cycles of ion shuttling, there is no degradation observed on the ion fluorescence, indicating that the ions can be moved back and forth with nearly 100% efficiency.

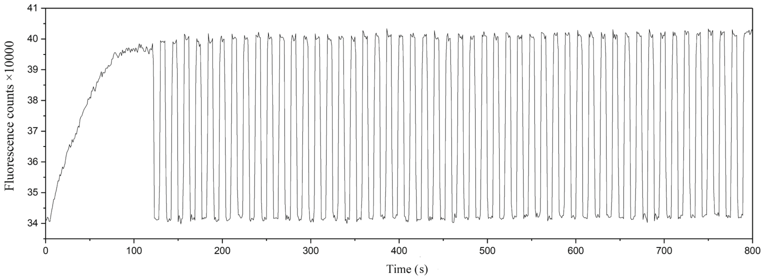

Fig. 4. Fluorescence measurement vs time as ions are shuttled back and forth between the two trap regions.

5 Discussion and Conclusion

We report the progress of a new designed mercury ion microwave clock based on ELIT. The clock transition spectral has been measured in quadrupole trap. The ions shuttling in ELIT has been realized with efficiency near 100% as well. These initial experimental results verify the availability of the sealed vacuum maintain strategy and the enhancement of SNR by optics optimizing.

The measured clock transition line implies a SNR*Q limited stability of $7.29 \times 10^{-14}/\tau^{1/2}$. With the second collection arm, the $\surd 2$ improvement on SNR would give a performance of $5.15 \times 10^{-14}/\tau^{1/2}$. According to our previous study [14], while using the current time sequence and local oscillator (OCXO 8607), the Dick effect of this system is about $1 - 2 \times 10^{-13}/\tau^{1/2}$, which will be the major limitation to realize the short-term stability of magnitude 10^{-14}. In addition to using higher performance local oscillators, such as H-maser, cryogenic sapphire oscillator and optically generated microwave oscillator, Dick effect is usually reduced by increasing the ratio of interrogation time to dead time. In ELIT, the microwave interrogation time could be increased conveniently without compromising to the line SNR. Furthermore, since the physical system could be dramatically simplified with sealed vacuum operation, it becomes simple and practical to build the dual-trap mercury ion clock proposed by G. J. Dick [15], which could suppress the Dick effect by interleaving lock.

In the next step, these methods will be tried to reduce the Dick effect for enhancing the short-term stability into 10^{-14}. Besides that, more efforts will be taken on the optimization of the clock transition in 12-pole trap. All these work contributes to realize ultra stable mercury ion microwave clock with long-term stability of magnitude 10^{-16}.

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