

STABILITY MEASUREMENTS BETWEEN Hg⁺ LITE 12-POLE CLOCKS

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Abstract- We describe frequency stability measurements of two Hg-ion clocks based upon linear 12-pole shuttle ion traps. The inter-comparison was carried out over several multi-day intervals with the short-term stability of each clock better than 2×10^{-13} at 1 second. Longer-term stability as good as 3×10^{-16} was demonstrated for these clocks.

Keywords- Atomic Clocks, Ion Traps, Mercury Ions

INTRODUCTION

One of the largest and often the most troublesome frequency pulling mechanism in linear ion trap atomic clocks with large ion clouds is the space-charge induced second-order Doppler shift. For large ion clouds with 10^6 to 10^7 ions, space-charge forces are balanced by the rf trapping electric fields to confine the charged cloud to a minimum of the rf field. For the classic Paul trap with a field node at a single point [1], the problem is most severe where the second-order Doppler shift from micro-motion can be ~ 10 times higher than that from secular thermal motion [2]. The linear trap was developed [3] to overcome this limitation so that space-charge Doppler shifts no larger than in a conventional Paul trap could be achieved with a 10-fold (or more) increase in ion number. The increased signal-to-noise in the detected clock resonance led to a 10-fold increase in short-term clock stability from $10^{-12} \tau^{-1/2}$ [4] for the Paul trap standard, to $10^{-13} \tau^{-1/2}$ and better [5,6] for the linear trap standard.

But the number dependent frequency shift is still non-negligible when large clouds are loaded into a linear trap and this sensitivity can degrade the longer-term clock performance or noise floor. The problem stems from tight rf confinement of the ion cloud since in a linear rf quadrupole geometry, the pseudo-potential grows as r^2 from the trap axis. We have recently developed a linear multipole ion trap [6] where ions are contained in an rf pseudo-potential of the form r^{10} .

This higher pole confining potential is beneficial to clock operation in two ways. The first is that the (radial) pseudo-potential approaches that of a square well and the ion cloud has a much larger diameter, determined largely by the trap diameter. Consequently, the density is reduced and less rf pseudo-force is required to overcome the reduced space-charge repulsion. Consequently, there will be less frequency pulling than in a linear quadrupolar confining field.

Another advantage of the multipole trap is that charged particles spend much less time in the confining rf fields. That is, the 12-pole r^{10} pseudo-potential is very small until the particle is near the walls of the trap. That is, an ion drifts through the trap interior in essentially rf-electric

field-free space. Specifically, by use of the virial theorem we have shown [6,7] that $KE_{\text{micro-motion}} = KE_{\text{secular}}/(k-1)$ (the 2k-pole rf trap is comprised of 2k electrodes) where KE denotes the kinetic energy in the transverse direction contained in micro-motion and in secular motion.

Rf-heating of the ion cloud reduces as the number of poles increases since the fractional time the ion spends in the rf-electric field diminishes as $1/(k-1)$.

II. CLOCK OVERVIEW

The 12-pole trap is closed from optical interrogation of the ions held inside as can be seen in Figure 1.

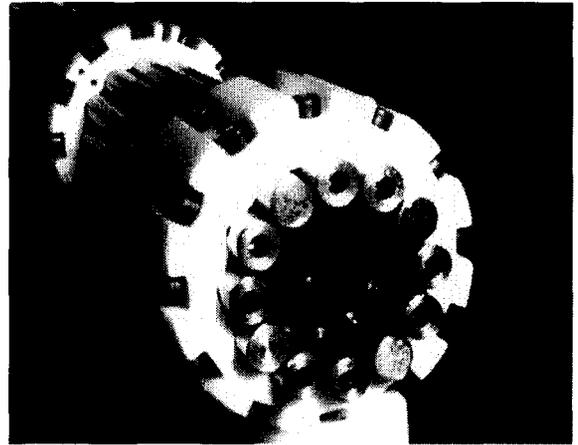


Fig.1 End view of the 12-rod linear ion trap. The inside diameter is ~ 1 cm.

An 'optically open' quadrupole trap where ions are concentrated along the centerline is also used so that ions can be optically pumped to into the desired initial state. In the quadrupole they are exposed to the UV 194 nm state selection light and imaged by fluorescence collection optics onto photomultiplier tubes. Figure 2 shows the quadrupole trap and the junction to the 12-pole. The imaging optical system on both the input, lamp side and the twin fluorescence collection imaging systems act as spatial filters to reduce stray light.

There is a dc break at the junction between the 4-rod and 12-rod traps so that each set of rod electrodes can be separately biased with dc voltage to prevent ions from entering either one of the two traps. For example, as the electron gun fires to load ions, the 12-rods are dc biased to ~ 3 volts so that ions are held in the 4-pole. Following

about 3-4 seconds exposure to light from the ^{202}Hg discharge lamp (194 nm) in the 4-pole trap, the dc voltage on the 12-rods is ramped down to zero and the ions expand into the 12-pole trap. To ensure they remain inside the 12-pole resonance trap, the 4-rod dc level is then ramped up to ~ 3 volts.

After the shuttling voltages have completed their ramping, there follows a ~ 0.5 second wait period to allow the ions to thermalize [2] to the conditions inside the resonance 12-pole trap where rf heating effects have decreased. A microwave pulse is then applied for ~ 6 seconds. A Rabi single pulse or alternatively, a Ramsey double pulse waveform is applied provided there is adequate microwave power [8].

As shown in Figure 4, the ions are then shuttled back into the 4-rod trap by reversing the dc voltage ramping used to move them into the 12-rod resonance trap. The population difference between the clock states established by the microwave pulse onto the ions in the resonance 12-pole trap is preserved during the shuttling procedure into the 4-rod trap. Changes in the measured fluorescence from the ions in the 4-rod trap are used to maintain a frequency lock to the center of the clock transition frequency as measured in the 12-rod trap [4]. Figure 5 shows Hg ion 194 nm fluorescence vs microwave frequency measured in the manner just described.

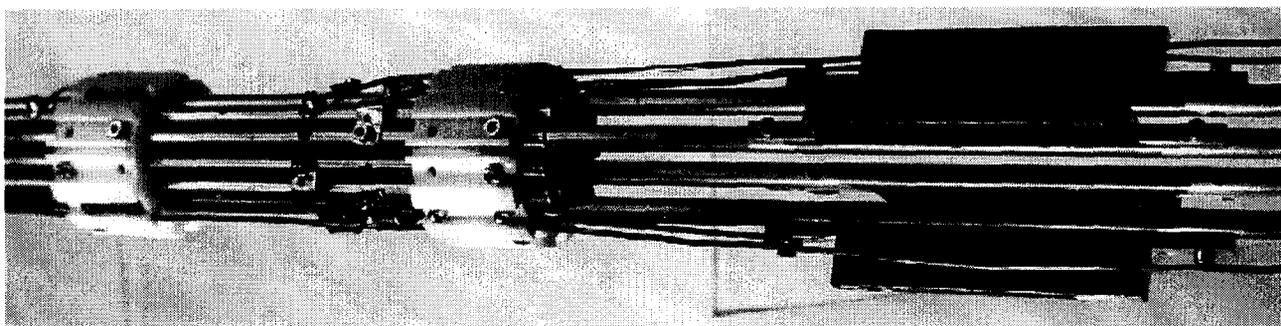


Fig. 3. The junction between the 4-rod trap and the 12-rod trap. The two traps are collinear with a dc break at the junction. Optical pumping into the $F=0$ clock level is done in the 4-pole trap. The microwave $^{199}\text{Hg}^+$ clock resonance is probed in the 12-pole trap interior.

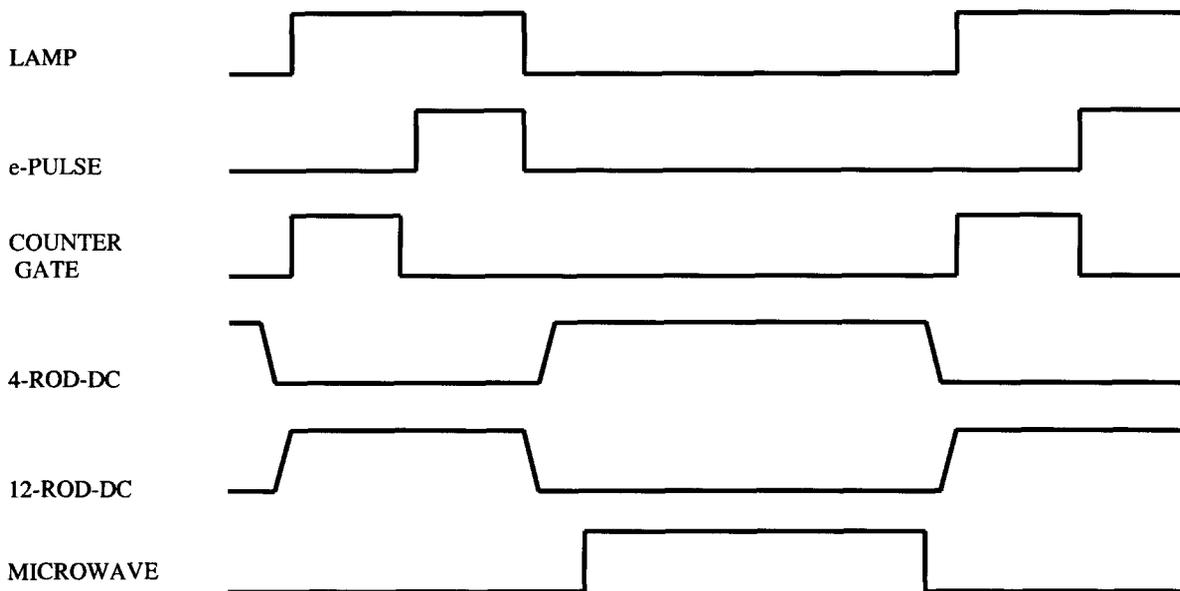


Fig. 4. The operation sequence used to measure the $^{199}\text{Hg}^+$ clock transition frequency at ~ 40.507 GHz. The clock frequency is measured while the ions are inside the 12-pole trap. The ions are shuttled from the 4-pole to the 12-pole for each frequency measurement. The ion cloud location is controlled by the 4-rod dc and 12-rod dc levels, ramped up and down as shown above. A Rabi microwave pulse shape is applied for ~ 6 seconds generating a ~ 0.13 Hz wide resonance curve as shown in figure 5.

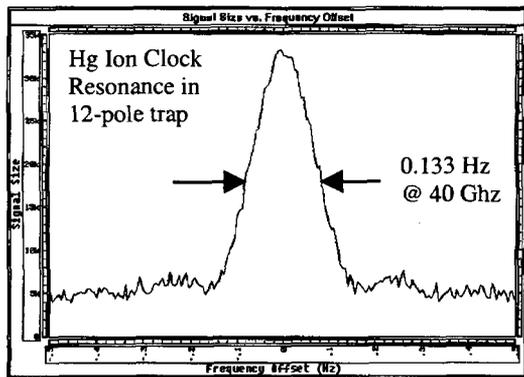


Fig. 5. Typical Rabi microwave resonance in the 12-pole trap. Fluorescence is measured after the ions have been electrically shuttled into the 4-rod quadrupole trap.

III. CLOCK STABILITY

Using a resonance curve similar to the one shown in Figure 5 we have measured the 12-pole Hg clock frequency stability vs a hydrogen maser in the Frequency Standards Lab at JPL. With short-term frequency stability $\sim 1 \times 10^{-13} \tau^{-1/2}$ the Hg clock will usually overtake the H-maser frequency stability at 10^4 seconds or longer averaging time intervals. This performance was demonstrated in the first tests of the 12-pole Hg ion clock operation [7].

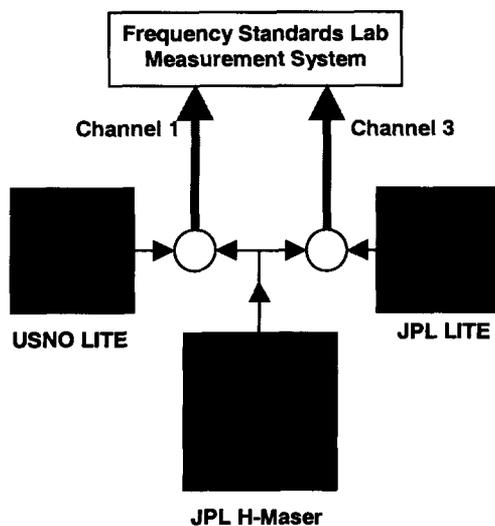


Fig. 6. The method used to compare the two 12-pole based ion clocks. In this figure, the ion clocks are the USNO LITE and the JPL LITE and are each simultaneously compared to the JPL H-maser via the measurement system. Simultaneous frequency differences with the maser are subtracted yielding a sequence of frequency differences between ion clocks. All 3 clocks were located at the JPL Frequency Standards Lab for these measurements.

Since then we have built a second 12-pole based ion clock so that we can measure stability below the 10^{-15} maser limit in each ion clock. We expect a noise floor well below 10^{-15} since the 12-pole clock is ~ 20 times less sensitive to variations in the number of trapped ions and to the resulting space charge induced second order Doppler frequency pulling as discussed in Section I. During this measurement, the 12-pole clocks were each in separate environmental chambers at JPL where temperature was independently held constant to ± 0.05 C. The JPL H-maser was similarly isolated in a temperature controlled and magnetic shielded chamber. (The ion clock's magnetic shielding and related issues are discussed in Burt et. al. in this same proceedings.)

In order to compare the frequencies of the two 12-pole ion clocks, we reference each to a common hydrogen maser and generate a long-term frequency comparison of each vs the maser.

By measuring simultaneous ion clock frequencies against the maser and subtracting ion clock 1 (called JPL LITE) frequency from ion clock 2 (called USNO LITE) frequency, we form a series of frequency comparisons of the two ion clocks. This differencing procedure is shown schematically in Figure 6.

Figure 7 shows the results of a 3-day comparison of the each ion clock vs a maser and the extracted comparison of the two ion clocks. Channels 1 and 3 each show a frequency variation of $\sim 5 \times 10^{-14}$ at about 1.5×10^5 seconds into the measurement. The difference frequency between the two ion clocks shows no such frequency change thus identifying the maser as the source of the frequency change.

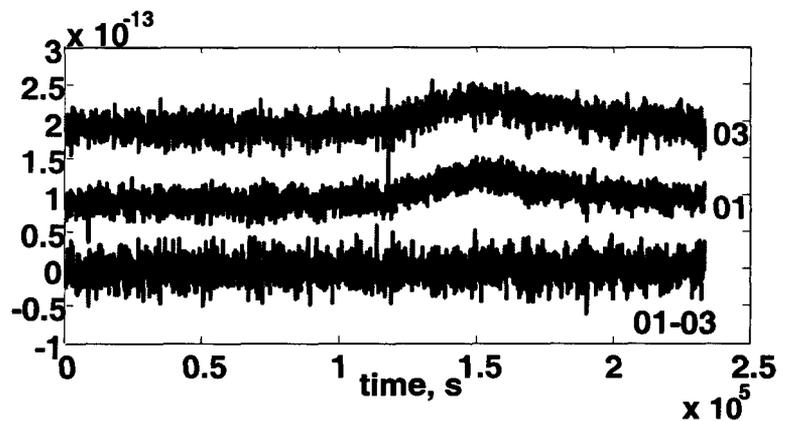


Fig. 7. Time series of frequency measurements of two ion clocks vs a common H-maser (03 and 01) and the inferred frequency measurements of the two ion clocks relative to one another (01-03).

The Allan deviation of the relative frequencies of the two 12-pole ion clocks is shown in Figure 8. The ultra-high stability of 4×10^{-16} reached for each clock demonstrates the viability of linear multi-pole ion traps as excellent clocks.

This comparison was carried out over a 4 day time

IV. CONCLUSIONS

We have developed the first trapped ion clocks based upon a linear multi-pole rf trap. The reduction in clock frequency sensitivity to variations in the number of trapped ions has enabled excellent long-term stability and an ultra-low noise floor.

Improvements in the UV optical systems will allow better short-term stability and a faster measurement of the noise floor which may be as low as 1×10^{-16} .

ACKNOWLEDGMENTS

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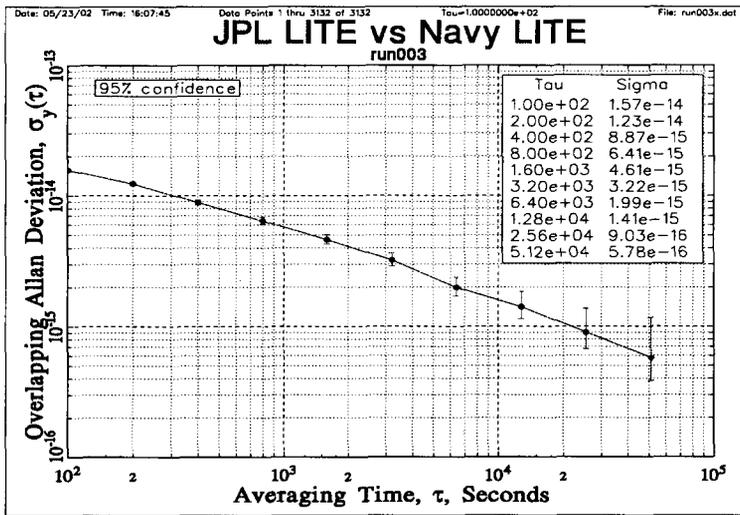


Fig. 8. The Allan Deviation of the frequency sequence of JPL LITE ion clock vs USNO LITE Ion clock from data included in Fig. 7 totaling ~ 4 days. Note that the data represents the sum of the noise in the two ion clocks so that each clock shows noise of $\sim 4 \times 10^{-16}$ at 51,200 seconds.

period and the channel 1 to channel 3 differencing was analyzed to form the Allan deviation shown. Note that there has been no linear drift removal between the two ion clocks in any of the data presented in this paper.

The results of an 8.5 day run are shown in Figure 9. During this measurement, the short-term noise of one of the clocks was degraded slightly from the measurements shown in Figures 8. Nevertheless, each clock reached a stability of $\sim 5.5 \times 10^{-16}$ over this longer run.

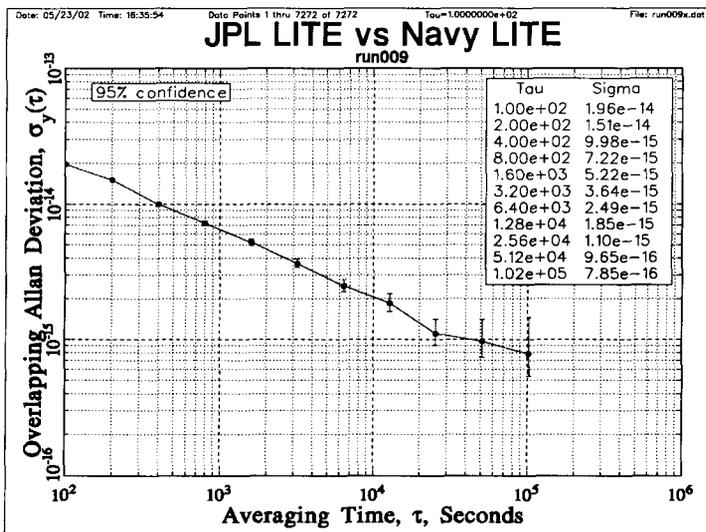


Fig.9. Results of a ~8.5 day comparison of the stability of the two ion clocks. Short-term stability is slightly worse than in the data of Fig. 8 so that at $\tau = 10^3$ seconds each clock shows $\sim 5.5 \times 10^{-16}$. Again, no linear drift has been removed.