Self-excited mono-ion oscillator

(trapped single ion/anharmonic axial oscillation/excitation always resonant/thermal noise compensated)

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Contributed by Hans Dehmelt, April 4, 1986

ABSTRACT We propose self-excitation as a potentially more sensitive technique for studying a mono-ion oscillator of frequency $\nu_z \approx 0.1$ –100 MHz. This technique also makes only low demands on the harmonicity of the ion oscillation. It should therefore work with inexpensive, easily constructed rf traps. In our analysis, the bound ion between the trap electrodes is represented by an effective circuit resembling that of a piezoelectric quartz crystal. The feedback circuit developed, when operated below self-excitation threshold, may also make efficient electronic cooling of the ion possible, particularly in conjunction with a heterodyne feedback scheme. In the super-regenerative mode, the apparatus might function as a powerful atomic amplifier of the ion oscillation for an energy as low as a fraction of $h\nu_z$. These techniques may prove especially useful in conjunction with attempts to synthesize in an rf trap a loosely bound anti-hydrogen atom from a positron and antiproton.

In the past the axial oscillation of an individual ion (electron) confined in a trap has been detected by employing an external drive of fixed frequency (1). The optimum signal current realized then was only about 10% of the maximum possible signal

$$i_{d\max} = e\omega_z/2.$$

Even so, the large anharmonicity of the ion oscillator called for very large off-resonance drive amplitudes and complex compensation and modulation schemes, in order not to swamp the weak ion signal by feedthrough of the drive. An alternative way to effectively drive a bistable anharmonic oscillator based on a trapped ion undergoing occasional collisions is by self-excitation. This ensures that the drive is always on exact resonance. Considerable effort was devoted to self-excitation schemes at the time, but the external drive approach succeeded first. Renewed attempts are now proposed, because self-excitation promises to work with very simply constructed rf traps for an electron or atomic ion of correspondingly large and probably not even monotonic anharmonicity.

The ion oscillating at ω_z in the trap may be represented by the equivalent circuit (2) shown in Fig. 1, which resembles that of a piezoelectric quartz crystal (3) in a metal can. The lc circuit with

$$lc\omega_z^2 = 1$$

represents the ion, while C_e and C'_e are interelectrode capacities. By connecting a coil of inductance L and shunt resistance R to the terminals 0 and 1 with

$$LC_e\omega_z^2 = 1$$

the capacity C_e may be tuned out. Also by connecting the

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FIG. 1. Electrical equivalent of harmonically bound ion in trap; C_e and C'_e are interelectrode capacities.

zero-impedance output of the first amplifier to terminals 0 and 2 the capacity C'_e is short-circuited. Both of these steps have been used to arrive at the front end of the circuit shown in Fig. 2. This front end is parallel resonant at ω_z because l , c , R , and the zero output impedance of the amplifier, assumed as ideal, form a closed loop. When the ion is oscillating and a current i_s is circulating in the loop, the voltage

$$u_s = i_s R$$

is developed as input voltage between the terminals 0 and 1. For a gain G adjusted to

$$G = 1$$

the same voltage u_s appears between the terminals 0 and 2. As there is no net voltage drop between terminals 2 and 1, no work is extracted from the ion, and the ion oscillation persists indefinitely. This is the condition for self-excitation. The "atomic" oscillator (4) realized in this fashion obviously depends for its function on the presence of the ion in a crucial way. The corresponding input signal u_s at ω_z is greatly amplified, filtered, and finally rectified. This dc signal, proportional to the ion amplitude, may then be displayed on a milliammeter.

A closer look shows that the circuit has very desirable low-noise properties: the thermal noise voltage u_n associated with the resistance R at temperature T_R is compensated to zero, as is R . In other words, the effective total noise voltage and the effective net resistance seen by the ion both vanish,

$$u_{\text{neff}} = 0$$

and

$$R_{\text{eff}} = 0.$$

Analogously, when the gain G is reduced to <1 and the ion is not self-excited, the effective damping resistance is reduced to

$$R_{\text{eff}} = (1 - G)R$$

FIG. 2. Block diagram of self-excited mono-ion oscillator. The highly selective second amplifier plus detector combination is conveniently realized by a commercial communications receiver supplemented by circuitry for phase locking the intermediate-frequency (if) signal to a stable reference and for rectifying the if signal in a narrow-band phase-sensitive detector.

and the ion temperature to

$$T_i = (1 - G)T_R.$$

Also, the damping time of the axial oscillation increases by $(1 - G)^{-1}$. Conversely, when the phase of the fed-back amplified signal is reversed and the amplification is increased to

$$G > 1$$

the damping time τ_i drops to

$$\tau_i = \tau_{i0}/(1 + G),$$

a fraction of the value τ_{i0} without feedback. However, the ion temperature increases by a factor of $1 + G$ over that without feedback,

$$T_i = (1 + G)T_R.$$

These types of electronic ion cooling (5, 6) will be discussed more fully in another paper.

The self-excited mono-ion oscillator also may function as an extremely high gain atomic amplifier, when operated in the super-regenerative mode. In this mode, when an average is taken over many identical measurements, an initial excitation to even a fraction of the first axial oscillation quantum level may be inferred from the time it takes the amplitude to grow exponentially to the preset maximum value, after a feedback gain >1 is suddenly turned on. This mode opens the way to

“bolometric” detection (7), when the sidebands of optical transitions of the ion are excited by a laser beam and energy is transferred by this route into the axial oscillation. So far nothing has been said with reference to the amplitude of the oscillation assumed by the ion. To stabilize the amplitude at, say, 80% of the electrode separation, some control mechanism is necessary that reduces the gain to <1 whenever the limit is exceeded. This may be achieved by the special trap design shown in Fig. 3. Shown here is a Paul rf quadrupole trap with five hyperbolic electrodes. For terminals 1 and 2 both grounded, the two rf voltages at frequency Ω are adjusted such that a smooth rf parabolic potential is produced by the electrodes. The resulting effective trapping potential (6, 8) is also parabolic and the axial ion oscillation is harmonic. However, the ratio of the amplitude of the displacement current circulating in the signal loop 0–1–2–0 to the ion amplitude decreases with amplitude, because with increasing amplitude a larger fraction of the displacement current is carried by the lead that connects the outer electrodes E_2 and E'_2 . This lead is grounded by the zero impedance of the Ω drive.

We have neglected the capacity between the electrodes E_1 and E'_1 , because it is small. Also at the frequency ω_z the lc -circuit equivalent of the ion short-circuits it. Should there be difficulties with wild oscillations, the interelectrode capacity may be neutralized or, even better, a heterodyne scheme may be incorporated into the feedback loop. In such a scheme, after amplification, the ω_z signal voltage produced by the ion would first be mixed with a Ω signal. After filtering the, say $\Omega - \omega_z$, sideband would be fed back to terminal 2 to excite (9, 10) the ion. An analogous side band (1) scheme should work with a Penning trap.

In conclusion, we have proposed a self-excited *atomic* oscillator, whose function clearly depends on the presence of an ion (or electron) in the trap. Such a device should function with cheap traps, as it tolerates large and amplitude-dependent anharmonicities due to fourth- and higher-order terms in the trapping potential. Further, it may be capable of an axial oscillation signal/noise performance an order of magnitude better than the best *generator-driven* mono-ion oscillators currently in use (1). Such techniques may be particularly useful in the synthesis of a trapped, very loosely bound, anti-hydrogen Rydberg atom (11), which on demand may be deexcited to a very slow, free, ground state anti-hydrogen atom by suitable electromagnetic wavepulses.

We thank our colleagues Robert Van Dyck, Jr., Paul Schwinberg, and Gerald Gabrielse for discussions. Diana Dundore read the manuscript. The work was supported under the SAPARIS Project (PHY-8506028) by the National Science Foundation.

FIG. 3. Design of five-electrode rf quadrupole trap; the additional electrodes are used to stabilize the amplitude of the axial oscillation of the trapped ion.

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