Paul Trap for Optical Frequency Standards

S. R. Jefferts, C. Monroe, A. S. Barton, and D. J. Wineland

***Abstract*— We describe a variant of the quadrupole rf (Paul) ion trap capable of localization of a trapped ion within much less than an optical wavelength (Lamb–Dicke regime). Attainment of the Lamb–Dicke regime reduces the sensitivity of the central absorption feature to atomic motion, thereby reducing an important source of noise in an optical frequency standard. The trapping potentials are generated by a high-Q, vacuum-compatible, quarter-wave resonator driven at about 240 MHz. Secular frequencies of tens of megahertz have been achieved for trapped magnesium and beryllium ions.**

I. Introduction

We describe an ion trap capable of very strong confinement. Ion traps with strong confinement are important in several applications. In optical atomic spectroscopy, strong confinement allows the attainment of the Lamb–Dicke condition whereby the extent of the atom's motion is less than $\lambda/2\pi$ where λ is the wavelength of the exciting radiation [1]. This is important because it suppresses the effects of Doppler broadening which, in the case of harmonically bound atoms, takes the form of motion-induced sidebands [2]–[5]. It is also important because it suppresses the fluctuations of the "carrier" from measurement to measurement [6]. Suppression of these effects will be important in any optical frequency standard based on trapped atoms.

With strong confinement, it should also be possible to achieve resolved sideband cooling [7], [8] using allowed electric-dipole transitions. Here, we require that the trap is made deep enough that the atom oscillation frequencies (ω_i, $i = x, y, z$) satisfy $\omega_i \gg \gamma$, where γ is the linewidth of the transition. This has the potential advantage that cooling to the ground state of motion can be achieved very rapidly.

For a single ion bound in a quadrupole rf trap [9]–[12], the axial or z frequency ω_z must satisfy $\omega_z \leq \Omega/2$ where Ω is the rf drive frequency. If we assume zero static potential applied between the electrodes, then at the Mathieu stability limit ($q_z = 0.908$) [9]–[12] in an axially symmetric trap, $\omega_z(\max) = \Omega/2$ and the radial secular frequency is $\omega_r(\max) \simeq 0.35\,\omega_z(\max)$. The maximum secular frequency can then be expressed as [9]–[12]

$$\nu_z(\max) = \frac{\Omega}{4\pi} = \frac{1}{2\pi d_o}\sqrt{\frac{QV_o}{0.908M}} \qquad (1)$$

where Q is the ion charge, V_o is the peak rf potential applied between the ring and endcaps, M is the ion mass, and d_o is the characteristic trap dimension. For a trap with hyperbolic electrodes, $2d_o^2 \equiv r_o^2 + 2z_o^2$, where r_o is the inner radius of the ring electrode and $2z_o$ is the inner endcap-to-endcap distance. Using $Q = 1e$, $M = 9u$, $V_o = 2$ kV, and $d_o = 0.15$ mm, we find $\nu_z(\max) \simeq 164$ MHz, and $\nu_r(\max) \simeq 58$ MHz.

According to (1), to achieve strong confinement, we require large values of V_o and small values of d_o. Implicitly, we assume Ω is adjusted to give stable trapping; that is, $\Omega > 2\omega_z$. Large values of V_o can be limited by electric field breakdown or arcing. Also, if the high voltage is generated external to the required vacuum enclosure for the trap, the voltage is reduced by the capacitance of the vacuum feedthroughs. This problem becomes more difficult for the required high values of Ω.

As the trap dimensions are reduced in size, it becomes more difficult to machine the desired electrode shapes. This problem can be minimized by choosing simpler electrode shapes where the leading anharmonic terms in the trap potential can be nulled for appropriate choices relative dimensions. For example, nominally quadrupolar electrodes with simple conical surfaces can be used [13]. "Planar" traps formed with holes in parallel plates [14]–[16] or with conducting rings [16] simplify construction even further. These electrodes can be made extremely small using lithographic techniques [16].

As multielectrode traps (such as the conventional quadrupole trap) become smaller, the relative electrode positions also become more difficult to maintain. One way to eliminate this problem is to keep either the ring or the endcap electrodes small and let the complementary electrode(s) recede to large distances. For example, the Paul–Straubel or "ring" trap is essentially a ring electrode with the endcaps at large distances. This trap has been analyzed [15]–[17] and demonstrated for Ba^+ ions [15] and In^+ ions [17]. For this kind of trap, an efficiency ϵ can be defined as the ratio of the rf-voltage required in a quadrupole trap with hyperbolic electrodes to the voltage required in the ring trap (of the same internal ring diameter) which gives the same secular frequency. References [16]–[18] find ϵ in the range of 0.1 to 0.2.

In the work described below [18], we discuss a strategy for achieving large values of V_o and Ω, and small values of d_o in a trap with nominal quadrupolar geometry where $\epsilon \simeq 1$.

II. Description

The trap described here is very simple, consisting of two thin sheets of metal; one has a hole (the ring) and the second, perpendicular to the first, is slit and acts as the endcaps. The arrangement is illustrated in Fig. 1. One trap constructed with this geometry, used for trapping $^{24}Mg^+$ ions, had a ring inner diameter $2r_o$ of 0.43 mm, and the endcap slit width $2z_o$ was 0.32 mm. The molybdenum sheet from which the

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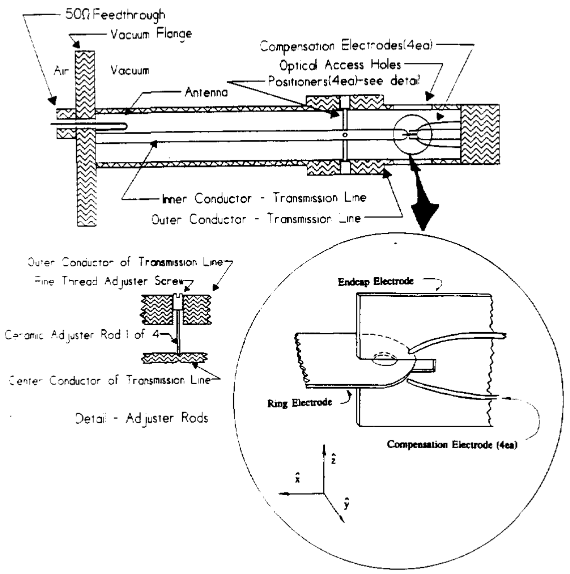

Fig. 1. Approximately scale drawing of the coaxial resonator and rf trap electrodes (shown in an expanded view in the lower right of the figure). The ring electrode is attached to the inner conductor at the position of the antinode of the $\frac{1}{4}$-wave line. The endcaps electrode is held near rf ground by the short section of center conductor at the right-hand side of the resonator. The resonator is driven by a coaxial line external to the vacuum system shown at the left. The area of the loop antenna is adjusted so the resonator (on resonance) presents a matched load (50 Ω) to the input line. The resonator is surrounded by a vacuum envelope (not shown in the figure) which has quartz windows to allow the passage of U.V. laser beams and fluorescence light. The position of the ring electrode relative to the endcaps electrode is maintained by four adjustable ceramic rods (alumina) shown in the detail in the lower left of the figure. Static potentials are applied to four compensation electrodes to compensate for stray electric fields due to contact potentials and charge buildup on the trap electrodes. For a proper selection of compensation potentials, the average position of the ion coincides with the position of zero rf electric field. The two compensation electrodes in front of the endcaps electrode are shown in the expanded view in the lower right of the figure. Two more compensation electrodes (behind the endcaps electrode) are not shown in the figure.

trap was constructed was 0.13 mm thick. As shown in Fig. 1, the relative positions of the trap electrodes are maintained by ceramic positioning rods.

The trap is mounted at the end of an ultra-high vacuum-compatible coaxial 1/4-wave resonant transmission line. This OFHC copper 1/4-wave line is installed inside a vacuum enclosure with silica windows to allow the passage of U.V. laser beams for cooling and probing the ions and resonance fluorescence light from the ions. The transmission line is resonant at a frequency of approximately 240 MHz and has an unloaded quality factor (Q_u) on the order of 2000. The transmission line is excited with a small loop antenna at the base of the transmission line. The area of the loop is adjusted so that, on resonance, the antenna and the resonator present a 50 Ω load to the driving amplifier. With some care in adjusting the coupling, VSWR's of less than 1.05 can be achieved.

One advantage of this type of design results from the fact that the rf voltage at the vacuum feedthrough is small, thus minimizing problems associated with high voltage breakdown at or before the feedthrough and reducing of the resonator Q by the vacuum feedthrough.

Uncontrolled static electric fields arising from contact potentials or charged patches, can cause significant problems in miniature rf-traps. These fields displace ions from the zero of the rf trapping fields, thereby leading to undesirable increases in the micromotion amplitude [15]. A common scheme for dealing with these problems is the introduction of compensation electrodes which are used to cancel the stray electric fields in the trapping regions. We have included compensation electrodes, similar to those used by the University of Washington group, in the manner shown in Fig. 1. Static potentials applied to various combinations of the compensation electrodes allow for cancellation of static electric fields in an arbitrary direction in the trapping region.

With zero static potential between the electrodes and in the pseudopotential approximation, the secular (motional) frequencies of a trapped ion can be expressed as

$$\omega_i = \alpha_i \left\{ \frac{\sqrt{2} Q V_o}{m d_o^2 \Omega} \right\} \tag{2}$$

where α_i is a numerical constant for ion motion along the ith axis ($i = x, y, z$; see Fig. 1). For a quadrupolar hyperbolic ion trap, the constant α_i is one half for the x and y directions, and unity for the z direction. The trap described here breaks the symmetry about the z direction, causing $\omega_x < \omega_y$. In the pseudopotential approximation, with zero static electric field between the trap electrodes, $\omega_x + \omega_y = \omega_z$. Measured ion motional frequencies for this trap fall in the ratios of $\omega_x/\omega_z = 0.40$ and $\omega_y/\omega_z = 0.60$. The secular frequencies of trapped $^{24}Mg^+$ ions were measured by monitoring the intensity of the scattered laser-cooling light ($\lambda \simeq 280$ nm) while a rf drive, applied to one of the compensation electrodes, was swept over the frequency range which included the secular motion frequencies. Data taken with a single trapped $^{24}Mg^+$ ion and $V_o \simeq 450$ V peak at Ω are shown in Fig. 2; voltages in excess of 1000 V peak have been achieved. The measurements of ion secular frequencies at a given rf power in Ω (and calculated rf voltage at the trap) also yield the efficiency of this trap relative to the normal hyperbolic rf-trap. From these measurements, we can assign a trap efficiency factor ϵ of about 0.9 for the axial (z) direction of this trap. This compares favorably with the efficiency factor of about 0.13 for the single ring trap [15] and about 0.5 for the multiring trap [16], or endcap trap [17].

We have constructed a similar, but slightly smaller, trap ($2r_o = 0.30$ mm, $2z_o = 0.20$ mm) for $^9Be^+$ ions which has demonstrated confinement with secular axial frequencies in excess of 50 MHz ($\Omega/2\pi = 230$ MHz), the largest secular frequency reported to date. The secular frequencies in this trap will be limited by the requirement that $\omega_z < \Omega/2$ for stable trapping. A method of increasing the range of possible values of ω_z is to increase Ω; one way this can be accomplished with no change to the apparatus is by driving the transmission line at the first overtone, thereby raising Ω and hence the limit on ω_z by a factor of 3.

III. Conclusions

We have reported a simple Paul trap capable of good localization of trapped ions. This trap has demonstrated the

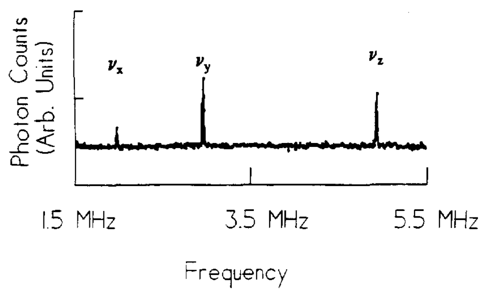

Fig. 2. Response of a single $^{24}Mg^+$ ion to an oscillating potential applied to one of the compensation electrodes shown in Fig. 1. The cooling laser for $^{24}Mg^+$ ions is tuned several linewidths to the red of the $^2S_{1/2} \rightarrow {}^2P_{3/2}$ transition. When the ion motion is excited by the oscillating electric field, the Doppler shift caused by its increased velocity leads to an increase in fluorescence scattering. The three resonances shown correspond to excitation of the three secular frequencies ω_x, ω_y, and ω_z.

highest secular frequencies for trapped ions reported to date. Unlike some other designs, it retains the trapping efficiency of conventional hyperbolic quadrupolar designs, thereby allowing larger traps to be built to achieve a given secular frequency and relaxing dimensional tolerance requirements. Use of a coaxial-resonator-based design minimizes problems associated with high-voltage breakdown and facilitates the attainment of high values of the drive frequency Ω.

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