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Dynamically excited single-component ion Coulomb crystals in linear Paul traps

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Abstract

This paper briefly discusses a few experiments regarding dynamically excited crystalline structures in a linear Paul trap. The dynamically excited structures are created either by applying a torque to an initially stationary crystal by utilizing the radiation pressure force from a near-resonant laser beam or by operating the trap at parameters where parametric resonances melt normal stationary crystals.

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1. Introduction

When trapped ions are cooled below a certain critical temperature (typically about 10 mK), they form spatially ordered structures often referred to as ion Coulomb crystals. Such crystals of various sizes containing single ion species have been investigated in various types of traps (see, e.g., Refs. [1–9] and references therein) in the past decade. In the present paper, we will present results showing that in linear Paul traps rotating crystals can be created by exerting a torque on an initially stationary crystal, and that dynamically excited ordered structures can be formed when trap parameters are chosen in such a way that stationary crystals will melt due to parametric resonances between the RF trap field and ion plasma modes.

2. The linear Paul trap

The central element of the experiments to be presented is a linear Paul trap situated in a vacuum chamber, which is operated at a pressure of $\sim 10^{-10}$ Torr. As sketched in Fig. 1, the trap consists of four sectioned cylindrical electrodes placed in a quadrupole configuration. The confinement of ions in the xy-plane is obtained by an

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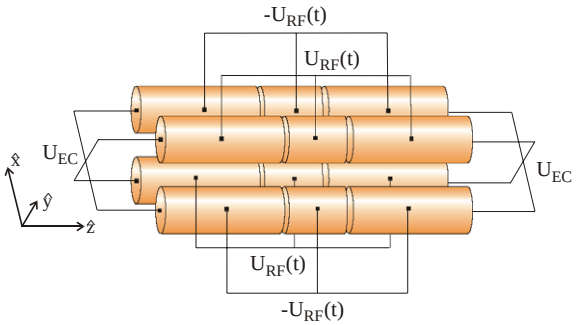

Fig. 1. Sketch of the linear Paul trap with indication of the applied potentials to the electrodes. For details see text and Ref. [10].

effective radial harmonic potential created by applying a time-varying potential $U_{RF}(t)$ in the form of either a sinusoidal RF-potential with an amplitude of typically a few hundred volts and a frequency $\Omega_{RF} = 2\pi \times 3.9$ MHz or in the form of a square pulse excitation with a periodicity of T with constant voltages applied for a time τT [10]. The radial confinement obtained by the latter operation of the trap is very similar to the quadrupole confinement in storage rings [10]. In all experiments, the confinement along the z-axis is made by adding a DC voltage U_{EC} to the eight end electrodes.

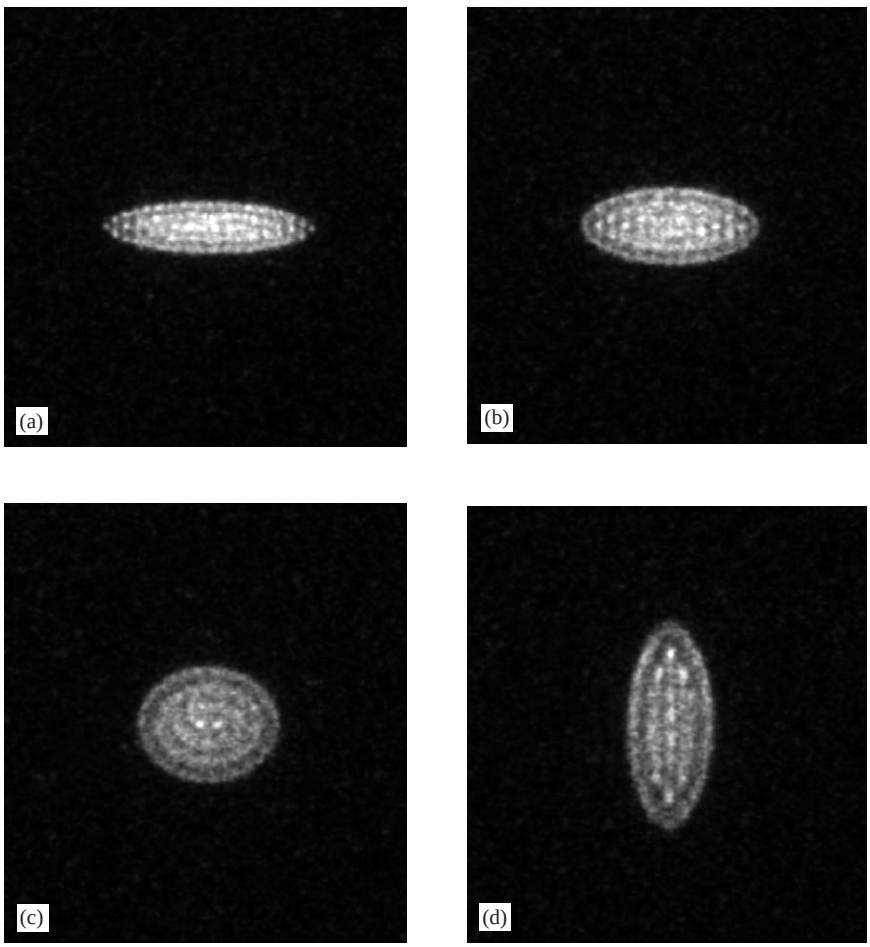

Fig. 2. Pictures of an ion crystal consisting of $\sim$200 ions at various rotation frequencies induced by the torque of a laser beam (see text for details). The width of each picture corresponds to a real length of 800 μm.

3. Dynamically-excited crystalline structures

3.1. Torque-induced rotating crystals

While the torque produced by the radiation pressure force of a near-resonant laser beam for many years has been applied to control the plasma rotation frequency in Penning traps [11], the same technique has only recently been demonstrated on cold ion ensembles in RF traps [9]. In these experiments, first a non-rotating ion crystal was formed by laser cooling $^{40}Ca^{+}$ ions along the RF field-free axis (the z-axis) of a linear Paul trap. An example of such a non-rotating crystal consisting of ~ 200 ions is shown in Fig. 2(a). Next, a "torque" beam with a power ~ 1 mW is focused to a spot size of about 100 μm, where it crosses the ion crystal in a direction perpendicular to the cooling beams. By either changing the offset position of the torque beam with respect to the central RF field-free axis, the detuning of the laser or the laser power, stable rotating crystals with significantly changed crystal aspect ratios could be formed. A series of such rotating crystals obtained by only changing the offset position of the torque laser are shown in Figs. 2(b)–(d). The rotation frequencies in the three cases are: (b) 0.4 $\omega_{r,trap}$, (c) 0.7 $\omega_{r,trap}$, (d) 0.9 $\omega_{r,trap}$, where $\omega_{r,trap} = 2\pi \times 180$ kHz is the radial trap frequency. In most extreme cases, rotational frequencies of up to 0.98 $\omega_{r,trap}$ have been achieved. For reference, the axial trap frequency was $\omega_z = 2\pi \times 86$ kHz in all the experiments. Rotating crystals might be used to quantify sympathetic cooling of the radial degrees of freedom of an ion plasma when applying laser cooling only along the RF field-free axis as done in many experiments. By monitoring the relaxation of the rotational energy after the torque-inducing laser has been switched off, we find that the typical time scale for indirect rotational cooling is ~ 100 ms. More details about experiments on such rotating crystals can be found in Ref. [9].

4. Parametric-resonance-induced crystalline structures

Another type of "dynamically stable" crystal structure is apparently related to parametric resonances between the frequency of the radial confining trap field and plasma modes of the ion crystals. The dynamically excited structures are obtained whenever the plasma frequency ω_{plasma} slightly exceeds $\omega_{RF}/2$, which means that parametric resonances will be present for larger crystals [12]. The structures are particularly easily observed when operating the linear Paul trap by a periodic sequence of square pulses [9,10]. In Figs. 3(a) and (b) crystalline structures are shown in the absence and presence of parametric resonances, respectively, for $T = 10^{-6}$ s and $\tau = 0.1$. The axial ordered structure in Fig. 3(b) might very well be stable due to rotation around the z-axis as argued in Ref. [13]. Since rotating crystals have lower densities than stationary ones (see Fig. 2), and the plasma frequency ω_{plasma} scales as the square root of the ion density, parametric resonances can in fact be avoided by rotation. The extreme axial ordering is not simply explained and certainly deviates from the structures of the rotating crystals of Fig. 2. However, similar ordered structures sometimes also appear for cold stationary (or nearly stationary) ion samples under trapping conditions where resonant parametric excitations are not possible. In Fig. 4, two pictures of a small cold ion sample of ~ 70

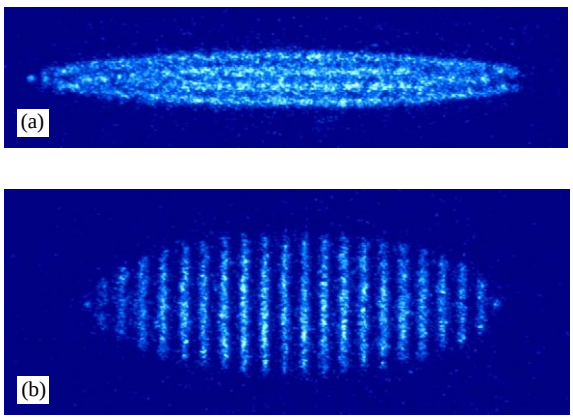

Fig. 3. Two images of the same ion crystal observed in the absence (a) and in the presence (b) of parametric resonances, respectively. Note the very different shape and ordering of these two crystals.

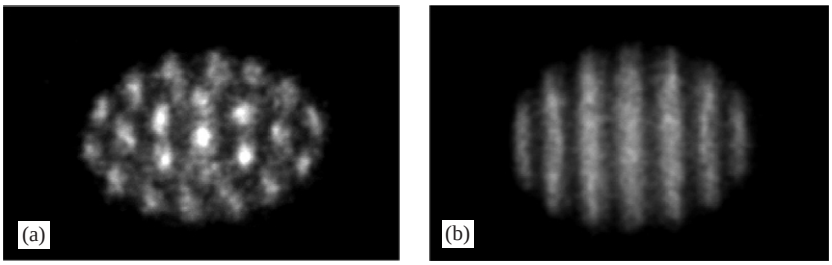

Fig. 4. Two images of the same cold ion sample of ~70 ions under trapping conditions with no parametric resonances observed at two different moments in time.

ions monitored at two different moments are presented. While a normal stationary crystal structure is observed in Fig. 4(a), a pronounced axial ordered structure is clearly observed in Fig. 4(b). The similar spatial extension of the two structures indicates that the ordered structure of Fig. 4(b) must be at least quasi-stationary. It should be noted that the observed "dynamically stable" structures might very well be interesting in connection with crystallization experiments in storage rings, where the radial confinement is equivalent to that of a pulsed operated linear Paul trap [10].

5. Conclusion

It has been shown that dynamically excited ion Coulomb crystals can be formed in linear Paul traps either by applying a torque induced by a near-resonant laser beam or through a parametric coupling of the ion plasma to the RF field applied to the trap electrodes. The crystal structures in the first case resemble those of stationary crystals, while in the latter a strong axial ordering always seems to exist.

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