Structure and control of Coulomb crystals in a Penning trap *

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We apply rotating electric fields to ion plasmas in a Penning trap to obtain phase-locked rotation about the magnetic field axis. These plasmas, containing up to 10^6 $^9Be^+$ ions, are laser-cooled to millikelvin temperatures so that they freeze into solids. Single body-centered cubic (bcc) crystals have been observed by Bragg scattering in nearly spherical plasmas with $\gtrsim 2 \times 10^5$ ions. The detection of the Bragg patterns is synchronized with the plasma rotation, so individual peaks are observed. With phase-locked rotation, the crystal lattice and its orientation can be stable for longer than 30 min or $\sim 10^8$ rotations.

Keywords: Penning trap, Coulomb crystals, Bragg diffraction

1. Introduction

Highly charged ions such as bare uranium nucleus U^{92+} have been created and trapped in several laboratories, providing opportunities for testing physics in very strong electric fields [1]. In Penning traps, which use static electric and magnetic fields for confinement, these trapped plasmas can relax to a global thermal equilibrium which undergoes a rigid-body rotation about the magnetic field axis [2]. Active control of the rotation frequency prevents plasmas from spinning down under the ambient drag from static field errors and background neutral molecules, and allows variation of the plasma density and shape [2,3].

Plasmas consisting of one charged particle species provide an experimental realization of a classical one-component plasma (OCP) [4]. With Doppler laser cooling, pure ion plasmas such as $^9Be^+$ and $^{24}Mg^+$ with density n_0 greater than 10^8 cm^{-3} and temperature T less than 5 mK can be routinely obtained [2], resulting in a Coulomb coupling parameter $\Gamma \equiv (Z^2e^2/4\pi\varepsilon_0 a_{\rm WS})(k_{\rm B}T)^{-1}$ greater than 200. Here, Ze is the ion charge and $a_{\rm WS}$ is the Wigner–Seitz radius defined by $4\pi a_{\rm WS}^3/3 \equiv 1/n_0$. For highly charged ions, the same Γ value can be obtained with much higher temperatures because of the high Z. A classical, infinite OCP freezes into a bcc lattice at $\Gamma \approx 172$ [5]. However, this result does not strictly apply to the trapped plasmas because of the sur-

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face effects associated with their finite size. Both simulations [6] and experiments [7] show that a structure of concentric shells forms for nearly spherical plasmas with 10^3 to 10^4 ions. For plasmas with $\gtrsim 2\times10^5$ ions or $\gtrsim$30 shells, time-averaged Bragg scattering patterns are consistent with bcc crystals (presumably located near the plasma center) [8], in agreement with a theoretical estimate [9]. But this measurement cannot determine whether the Bragg patterns come from single crystals or polycrystals.

In this report, we demonstrate that azimuthally asymmetric electric fields rotating in the same sense as the plasma can phase-lock the rotation of crystallized plasmas without slip, therefore precisely controlling the plasma rotation frequency, density, and surface shape [10]. We synchronize the detection of Bragg-scattered light either with this active rotation control or using the time dependence of the scattered light itself measured by a fast photomultiplier tube. Time-resolved (stroboscopic) Bragg diffraction patterns are obtained, effectively removing the plasma rotation [11]. Patterns from single bcc lattices are observed most of the time in these plasmas [11], in agreement with the theoretically predicted bulk structure of a solid one-component plasma [5]. With phase-locked rotation, the lattice and its orientation can be stable for longer than 30 min, compared to an observed ~ 1 min lifetime without the active rotation control.

2. Experimental setup

Figure 1 shows the apparatus and the asymmetric rotating field. The trap consists of a 127 mm long stack of cylindrical electrodes at room temperature with an inner diameter of 40.6 mm, enclosed in a 10^{-8} Pa vacuum chamber. An axisymmetric potential $\propto [z^2 - (x^2 + y^2)/2]$ is generated by biasing the central electrodes to $-V_0$, giving axial particle confinement. A uniform magnetic field $B_0 = 4.46$ T from a superconducting magnet is aligned parallel to the trap axis, resulting in global rotation and radial trapping. As shown in the inset, a rotating quadrupole field (rotation frequency ω_w) with a potential $\propto (y^2 - x^2)\cos(2\omega_w t) + 2xy\sin(2\omega_w t)$ is generated by applying properly phased sinusoidal voltages to the 6-fold azimuthal sectors of the compensation electrodes [3,10].

We create $^9Be^+$ plasmas by ionizing neutral Be atoms in a separate trap (not shown) and transferring the ions to the main trap for experimentation. This procedure can be repeated several times to accumulate up to 10^6 ions. The trapped $^9Be^+$ ions are then cooled to temperatures T somewhat higher than the limit of 0.5 mK by a laser beam propagating parallel to B_0 at wavelength $\lambda \approx 313.11$ nm [2]. In thermal equilibrium, the plasma takes the shape of a spheroid with uniform density and a rigid-body rotation frequency ω_r. The density and aspect ratio of the spheroid are determined by ω_r, for given B_0 and V_0 [2]. An $f/5$ imaging system detects resonantly scattered photons from the axial cooling beam (diameter ≈ 0.4 mm, power ≈ 50 μW) to produce a side-view image of the plasma, from which we measure ω_r (and n_0) with an uncertainty of about 5%. Bragg-scattered light is detected by a CCD camera with a gateable image intensifier near the forward-scattering direction ($< 5.4°$) since

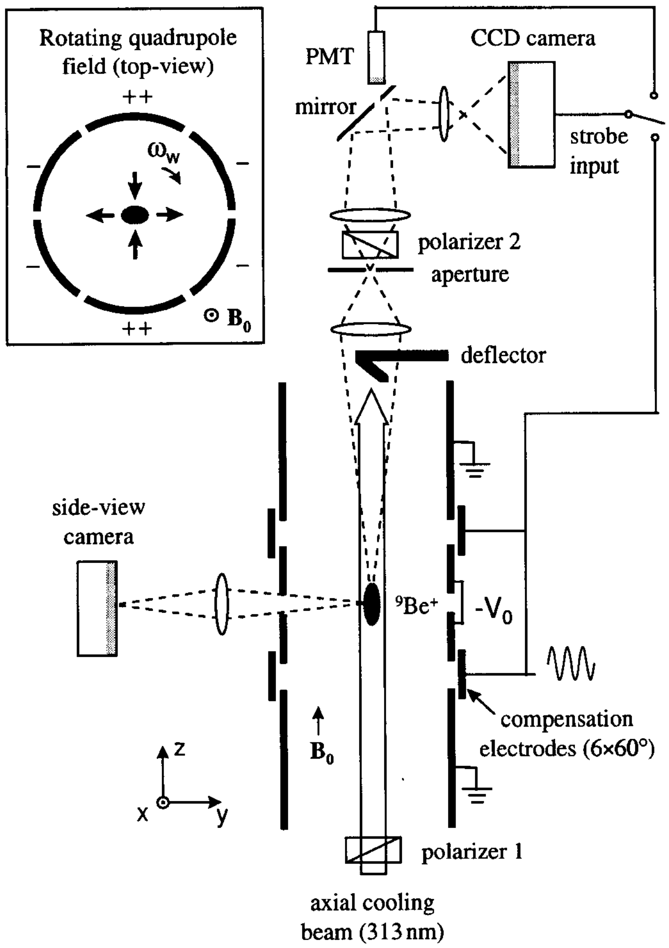

Figure 1. Schematic of the experimental setup.

$\lambda \ll a_{WS}$ [8]. Time-resolved Bragg diffraction patterns are obtained by strobing the camera with either one of the two timing signals [11].

3. Results and discussions

Figure 2(a) shows a time-averaged diffraction pattern of concentric rings from a nearly spherical plasma with 7.5×10^5 ions. When the pattern is time-averaged, even single crystals produce rings because of the plasma rotation about the axial laser beam [8]. With the rotating field controlling the plasma rotation, we trigger the intensifier synchronously with the rotating field to open the camera for 50 ns each $2\pi/\omega_w$ period. This enables the camera to record the diffraction pattern in the frame rotating with the quadrupole field. Figure 2(b) shows such a time-resolved pattern taken nearly simultaneously with figure 2(a) and accumulated over $\sim 10^6$ plasma rotations.

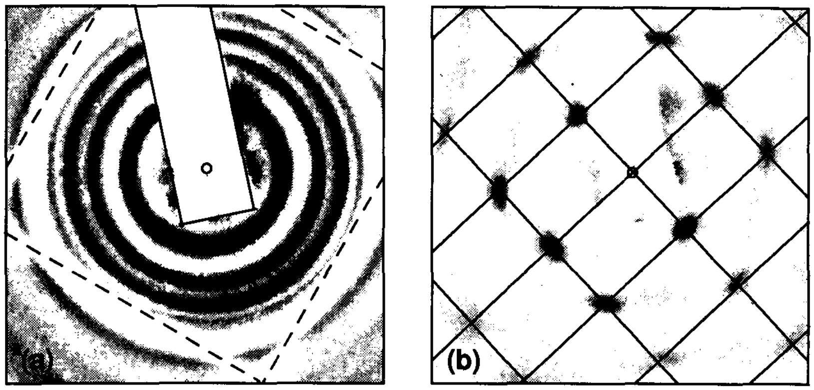

Figure 2. Bragg diffraction from a plasma phase-locked to the rotating field ($\omega_r = \omega_w = 2\pi \times 140$ kHz, $n_0 = 4.26 \times 10^8$ cm^{-3}). (a) 1 s time-averaged pattern. The long rectangular shadow is from the beam deflector; four dashed line shadows that form a square are due to a wire mesh. (b) Time-resolved pattern obtained by strobing the camera with the rotating field (integration time ≈ 5 s). For a bcc $\langle 1\,1\,0 \rangle$ crystal, a spot is predicted at each intersection of the rectangular grid lines whose separations are not adjusted.

The well-defined rectangular dot pattern demonstrates that the crystal is phase-locked to the rotating field with $\omega_r = \omega_w$ [10]. With this phase-locked rotation, the crystalline lattice and its orientation with respect to the laser beam can last longer than 30 min ($\sim 10^8$ rotations).

The diffraction pattern in figure 2 corresponds to a single bcc crystal with a $\langle 1\,1\,0 \rangle$ axis aligned parallel to the laser beam. The theoretically predicted pattern agrees well with the observation within about 1%. This rectangular grid pattern is essentially a plane of the reciprocal lattice, as can be seen from the Ewald construction in the forward-scattering limit [11]. From the widths and intensities of the Bragg peaks, we estimate that the crystals consist of at least 10 lattice planes [8].

In the future, we plan to directly image individual ions in crystallized plasmas with phase-locked rotation. In addition, with the improved stability of the crystal lattices obtained by the rotating field, we hope to observe the melting phase transition of the system.

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