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Radial Compression of Density Profile of a Pure Electron Plasma by Application of External Torque

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Abstract

We report a preliminary experimental study focused on controlling the density distribution of a pure electron plasma confined in the Malmberg-Penning trap by application of external torque. Substantial radial compression of the density distribution is observed by application of a properly controlled rotating electric field. Preliminary analyses of the wave propagating in the plasma in terms of the frequency spectra and correlation function indicate that plasma selectively absorbs the energy of the driver field to support a wave that fits the profile of the plasma and that the excited wave shows a spectrum which occasionally shifts from the driver wave by 40 kHz.

Keywords:

nonneutral plasma, rotating wall, wave torque, plasma compression

1. Introduction

Non-neutral plasmas confined in Malmberg-Penning traps show long confinement time that is attributed to the conservation of the total angular momentum supported by the cylindrical symmetry. In practice, however, slight asymmetries of the electric and magnetic fields inherent to a trap and background neutral gases generate an external torque to reduce the angular momentum. The reduction of the angular momentum causes radial expansion and eventual particle losses that eventually limit confinement time. A technique has been developed by the UCSD group that substantially improves confinement by counteracting the loss of momentum [1,2]. The "rotating wall" technique consists of exerting an external torque to the plasma through plasma waves. The transfer process for the angular momentum from plasma wave to each particle is interpreted as being due to Landau damping [3].

This paper reports a preliminary experimental study focused on radial compression of the density distribution of a pure electron plasma under the application of external torque. There are two motivations for us to pay attention to the established technique afresh. One is to acquire an extra technique for the precise control of the initial distribution of the electron density for two-dimensional (2D) vortex experiments [4]. The other is to obtain an extra knob of external driving plasma in its relaxation process and examine self-organization processes of an "open" system. Processes in the plasma spontaneously generating new structure under the effects of externally excited waves are worth studying synthetically with our highly accurate imaging diagnostic in terms of energy and momentum transfers from waves to the particles [5].

2. Experimental setup

This experiment is performed by applying rotating electric field at the one end of a pure electron plasma confined in the Malmberg-Penning trap under a homogeneous magnetic field $B_0 = 0.048$ T as schematically shown in Fig. 1 [6]. A rotating electric field ($m = \pm 1$) is applied across the plasma by transmitting 90-degree-shifted sinusoidal voltages with variable frequency to four wall segments azimuthally-separated at the axial locations labeled with No.12, 14, 16. The measurements of the density distribution are made by spilling out the whole electrons along the magnetic field line onto a phosphor screen to record the luminosity distribution with a CCD camera. We have confirmed a linear relationship between the electron number and the luminosity.

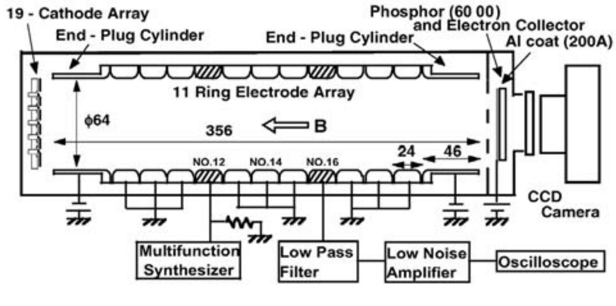

Fig. 1 The schematic configuration of the plasma trap.

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3. Radial compression by frequency ramp-up

Figure 2 shows time evolution of the 2D density distributions of electrons confined for a variable period up to 1 s. The initial density distribution at 0 ms is broad and axisymmetric, peaking slightly on the axis. In the upper panels showing the case with no external electric field, the slight peak disappears by 100 ms and particles at the periphery of the distribution escape radially by 800 ms. On the lower panels, with the addition of a rotating electric field (m = 1) under the phase-locked frequency ramp-up, the density peak on axis is lost and the convex density profile with a mild gradient is observed at 100 ms. The particles begin to contract radially at 200 ms and the peak density is maximized at 500 ms.

Figure 3(a)-1 quantitatively displays the radial density profiles corresponding to the images in Fig. 2. Without external field the density at t = 800 ms decreases over the whole region of the profile. Addition of the rotating field, however, leads to more than five times increase of the on-axis density during the period from 100 ms to 500 ms. In this process the particles around the periphery of the distribution converge to the center. The on-axis density is plotted against the external driver frequency in Fig. 3(a)-2. The rapid increase of the on-axis density is observed in the driver frequency range of 0.5 to 1.2 MHz (between dashed lines) and the steepest rise is observed during 0.72 to 0.93 MHz (between solid lines).

In Fig. 3(b), when the driver frequency is swept over 0.1 to 1.8 MHz, the on-axis density does not exceed 60 % of that

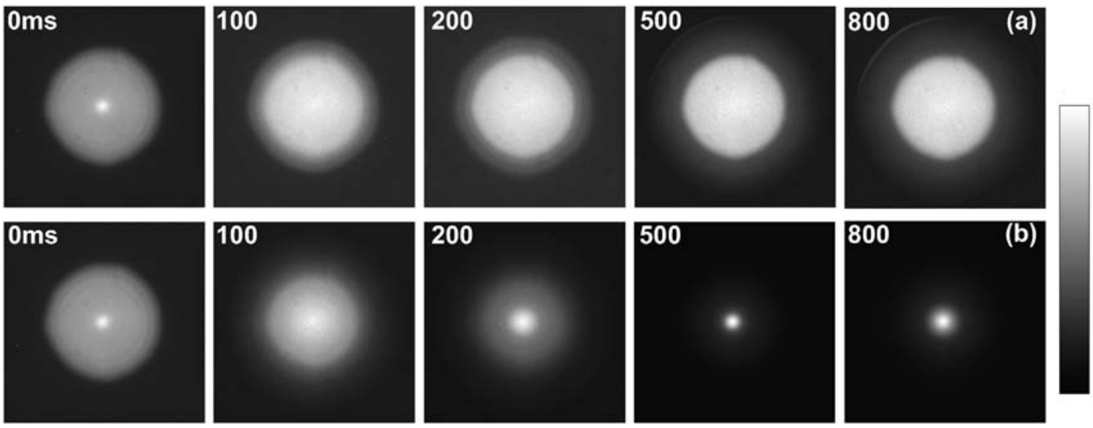

Fig. 2 Time evolution of the density distributions without external field (a) and with a rotating field (b). The frequency of the driver wave is swept linearly from 0.3 to 2.0 MHz for 800 ms with the amplitude $V_{p\text{-}p}$ = 2 V.

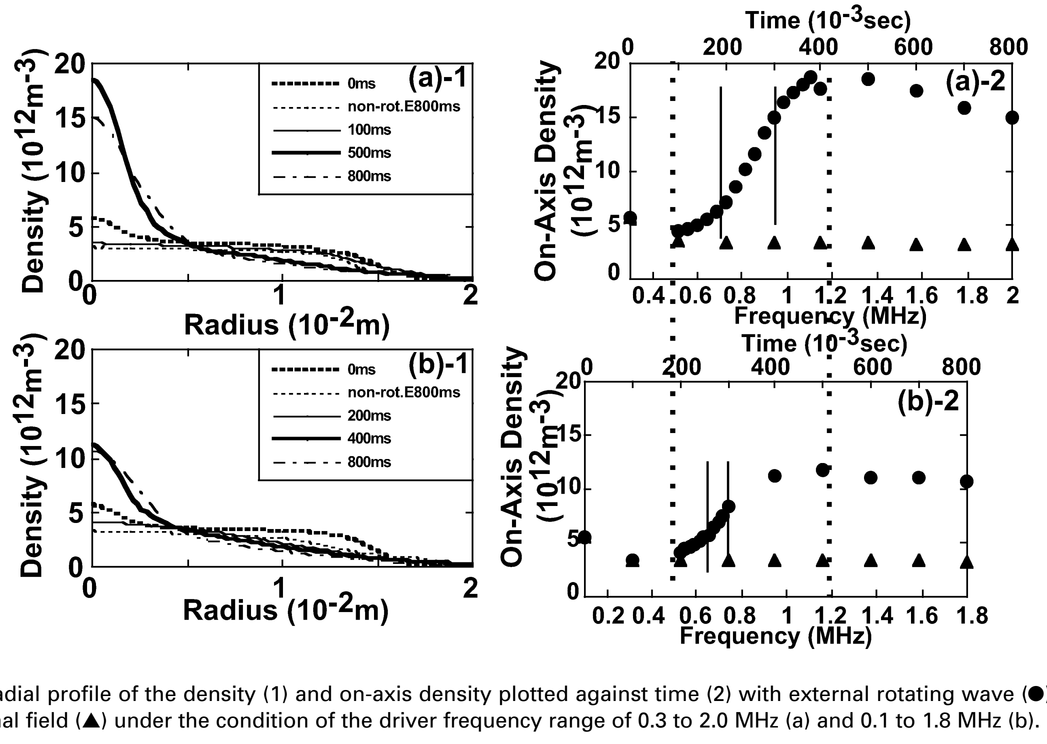

Fig. 3 The radial profile of the density (1) and on-axis density plotted against time (2) with external rotating wave (●) and without external field (▲) under the condition of the driver frequency range of 0.3 to 2.0 MHz (a) and 0.1 to 1.8 MHz (b).

attained in the case of Fig. 3(a)-1. Because the two cases are examined from the same initial distributions, the increasing rate of the on-axis density is considered to depend primarily on the range of the driver frequency. The frequency in Fig. 3(b)-2 associated with the on-axis density increase is in the range 0.5 to 1.2 MHz as indicated by dashed lines. The frequency range is similar to the case of Fig. 3(a)-2. But the optimum band with the maximum rate of increase lies in a narrower range from 0.65 to 0.75 MHz (between solid lines). This is attributed to the observation that the particle loss is substantially large before the compression of the density starts at 0.5 MHz. The coupling of the plasma wave to the plasma can be different as a result of changes in the density profile. We try to detect signals from the plasma during the evolution of the density profile and analyze the propagation properties of the waves excited in the plasma.

4. Analyses of wave signal detected from the plasma

Electrostatic waves propagating in the plasma induce a distribution of image charges on the surface of the conducting wall. The time variations of the image charge distribution are integrated over a sector probe and detected as electronic signals.

Figure 4(a) shows the signals detected on a sector probe at No.16 that is 9.6 cm apart axially from the driver sectors at No.12. The frequency of the driver wave of $m = 1$ mode is swept linearly from 0.01 to 1.4 MHz for 600 ms with the amplitude $V_{p\text{-}p} = 36$ mV. Images of the density distribution at consecutive times are shown in Figs. 4(b)–(e). There is a marked increase in the amplitude of the received signal during the initial 50 ms, while the frequency is less than 125 kHz. But we do not see any appreciable changes in the density distribution, (b) and (c).

The density profile is compressed during the period from $t = (150–600)$ ms as seen in Figs. 4(c) and 4(e). The radial distributions replotted in Fig. 4(f) exhibit steepening of the profile and the increase of the on-axis density by a factor of more than 5. The particle loss during this period is less than 5 %. During the compression period of 450 ms strong intermittent enhancements are observed in the received signals. The corresponding frequency of the driver wave is being swept from 1.16 MHz to 1.3 MHz. The waves propagating in the plasma at these frequencies belong to Trivelpiece–Gould (TG) mode [7]. The theoretical expression under the present experimental condition evaluates the characteristic TG mode frequency to be $f_{TG} \approx (k_{\|}/k_{\perp})f_p \approx$ 1 MHz, where f_p is the plasma frequency on axis, $k_{\|}$ and $k_{\perp}$ are the wave numbers parallel and perpendicular to B_0 respectively.

For further investigation of the waves we expand the wave form in the time domain $t = (0–40)$ ms in Fig. 5(a). Here the driver frequency f_{dr} is swept from 10 kHz to 90 kHz. A steep rise is observed in the amplitude of the received signal at $t = 4$ ms. Figure 5(b) shows the correlation function between driver wave and received wave during the period from $t = (2–8)$ ms. The correlation function starts to rise at $t = 3.5$ ms and be maximized at 4 ms. In Fig. 5(c) frequency spectra of the driver wave (dashed curve) and the received wave (solid curve) are plotted at consecutive times. The amplitude of the received wave increases sharply at f_{re} = 17.5 kHz when f_{dr} reaches there at $t = 3.5$ ms. The density distribution shows no appreciable change in its shape but the location of its peak. The frequency spectra and the motion of the density profile indicate that the diocotron mode is excited resonantly when f_{dr} = 17.5 kHz = f_{re}. The frequency of the diocotron mode is evaluated as $f_{diocotron} \approx f_p^2/f_c \approx$ 10–66 kHz, where f_c is the cyclotron frequency [7]. The oscillation frequency f_{cor} in the correlation function in Fig. 5(b) between the driver and the received signals indicates that the frequency f_{re} of the diocotron mode remains unchanged while f_{dr} goes up further.

Some spiky oscillations are observed in the amplitude of the received wave when f_{dr} reaches around 1 MHz which corresponds to the characteristic frequency of TG mode. On-axis density sharply increases around this frequency as shown in Fig. 4. The observation indicates that the plasma absorbs the energy of the driver field. Figure 6(a) shows a typical

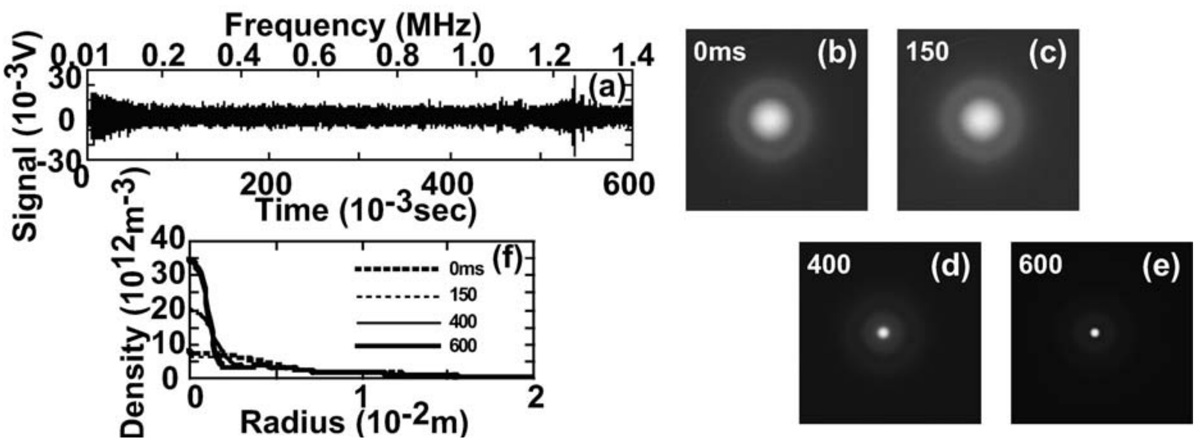

Fig. 4 (a) The received signal detected on a sector probe at No.16. (b)~(f) Snapshots of the density distributions with $N/10^8$ = 3.2 (b), 3.1 (c), 3.0 (d), 2.9 (e) and the radial profiles (f).

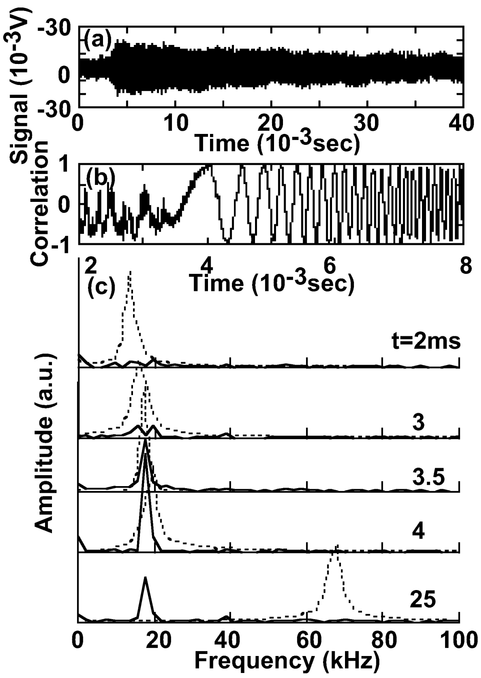

Fig. 5 (a) The received wave in the time domain 0–40 ms. (b) The correlation function between driver wave and received wave. (c) Frequency spectra of driver wave (dashed curve) and received wave (solid curve).

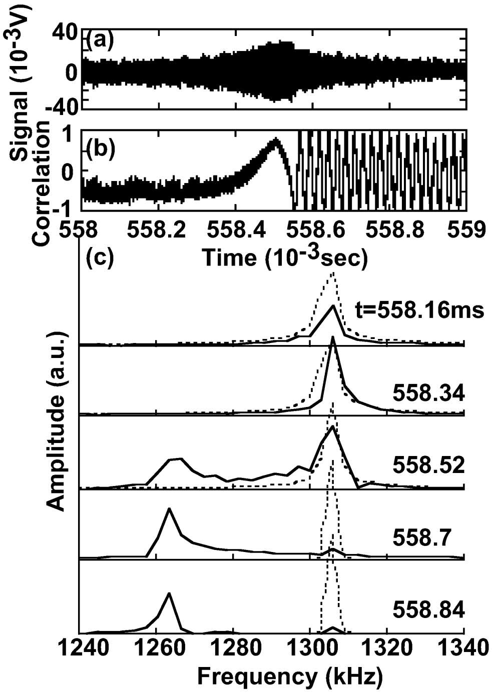

Fig. 6 (a) The received wave during the period of 1 ms starting from 558 ms. (b) The correlation function between driver wave and received wave. (c) Frequency spectra of driver wave (dashed curve) and received wave (solid curve).

waveform of the received signal recorded during the period of 1 ms starting from t = 558 ms. An enhancement is observed in the wave amplitude at t = 558.5 ms. The sweep width of the driver frequency is Δf_{dr} = 2.31 kHz during this period. The correlation function in this period between the driver and receiver wave is shown in Fig. 6(b). The correlation increases and an oscillatory phase shift appears between the two waves as the wave amplitude starts to increase around t = 558.3 ms.

The frequency spectra of the received wave are plotted in Fig. 6(c). The spectra indicate that the wave growth starting at t = 558.3 ms corresponds to the matching between f_{dr} and the dispersion characteristics of the plasma at 1305 kHz. When f_{dr} goes up further, the signal of the plasma wave decreases at 1305 kHz, and we observe subsequent enhancement around the frequency of f_{re} = 1265 kHz at t = 558.7 ms. The emergence of the wave at 40 kHz below the driver frequency f_{dr} is associated with the appearance of the oscillation at the same frequency f_{cor} in the correlation function.

These observations indicate that the wave is coupled to the plasma and propagating at particular frequency while the frequency of the external electric wave changes in a narrow range. The resonant frequency may be selected from a frequency band that properly fits the density profile. The dominant component of the wave can continue to absorb the external energy as far as the width of the dispersion and that of the time varying external field over lap.

In summary, we have observed substantial radial compression of the density distribution of a pure electron plasma and associated increase of the on-axis density by application of a properly controlled rotating electric field. Preliminary analyses of the waves propagating in the plasma in terms of the frequency spectra and correlation function indicate that plasma absorbs the energy of the driver field to support a wave that fits the profile of the plasma but propagates with a frequency with a finite shift from the driver. These observations could offer a key to better understanding the mechanism of the generation of new structures in plasmas under external forces.

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