Electrostatic Oscillations Observed in Non-Neutral Electron Plasmas Confined in a Magnetic Field Gradient

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Non-neutral electron plasmas were confined in an axisymmetric magnetic mirror field of the mirror ratio $R \sim 3$. Axial plasma oscillations (Trivelpiece-Gould modes), diocotron oscillations with the azimuthal mode number $m = 2$, and solitary waves were investigated experimentally. It was observed that the velocities of an electron soliton and an electron hole decreased at high field side in a magnetic mirror confinement.

Keywords: non-neutral plasma, magnetic mirror confinement, electrostatic oscillation, electron solitary wave

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A wide variety of non-neutral plasmas (NNPs) have been confined in various devices and their properties have been investigated both theoretically and experimentally [1]. In a uniform magnetic field, NNPs have been studied extensively by San Diego Group. Laser cooled strongly coupled NNPs in Penning traps and linear Paul traps were investigated by National Institute of Standards and Technology and Aarhus Group. Also, NNPs in a magnetic mirror field [2] and toroidal magnetic field are expected to provide interesting phenomena to be studied. Reported here are axial plasma oscillations, diocotron oscillations with $m = 2$, and solitary waves in non-neutral electron plasmas confined in an axisymmetric magnetic field gradient.

The experimental setup is composed of two sets of magnetic coils, an electron gun, 45 ring electrodes with the inner diameter of 7 cm and the thickness of 1.2 cm for applying the electrostatic potential, and a phosphor screen (PS) with a charge coupled device camera. Shown in Fig. 1 (a) are examples of a measured magnetic field and an electrostatic potential applied to ring electrodes. Here, coil currents of 30 A and 120 A for the low field and high field, respectively, resulted in $R \sim 3$. Ring electrodes can be used to excite or detect axial oscillations of a plasma. In addition, five ring electrodes at z = 9.3, 18.9, 28.5, 38.1, and 47.7 cm are azimuthally segmented into four pieces, so that an azimuthal motion of a plasma can be excited or detected. The vacuum chamber pressure was $\sim 1 \times 10^{-8}$ torr.

The experimental procedure was as follows. At first, electrons were injected and confined axially with electrostatic potentials on both ends. The number of electrons reached 10^9 at most. After 150 msec, the electron temperature was about 1 eV and the density n_e was in the order of 10^6 cm^{-3} with the Debye length less than 0.7 cm. Then the potential V_H at high field side was grounded to start a magnetic mirror confinement. After holding electrons for 5 ms, the potential V_L in front of PS was grounded for profile measurement. When oscillations were observed, RF bursts were applied to a ring electrode at low field side and signals from other electrodes were detected through broadband (0.01 - 2000 MHz) amplifiers with +40 dB gain.

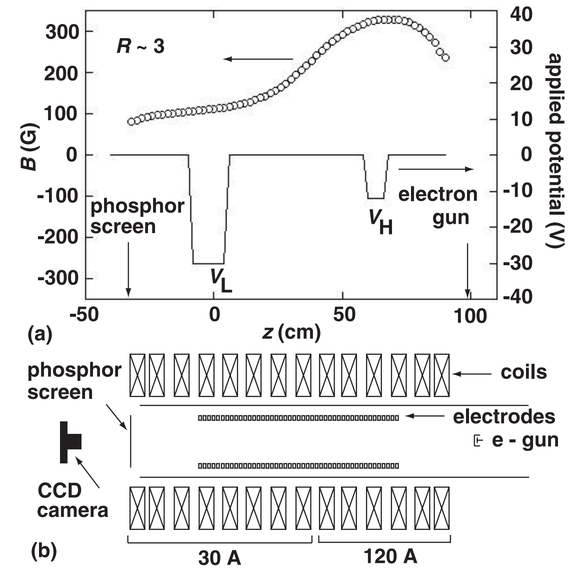

Fig. 1 Open circles denote the measured magnetic field strength along the axis of symmetry. The thin solid line corresponds to the applied electrostatic potential (a). A schematic drawing of the experimental setup (b).

The oscillations were measured for two types of plasmas. The first one was a plasma confined with a magnetic mirror field at high field side and an electrostatic field at low field side. Shown in Fig. 2 (a) is an example of a 100

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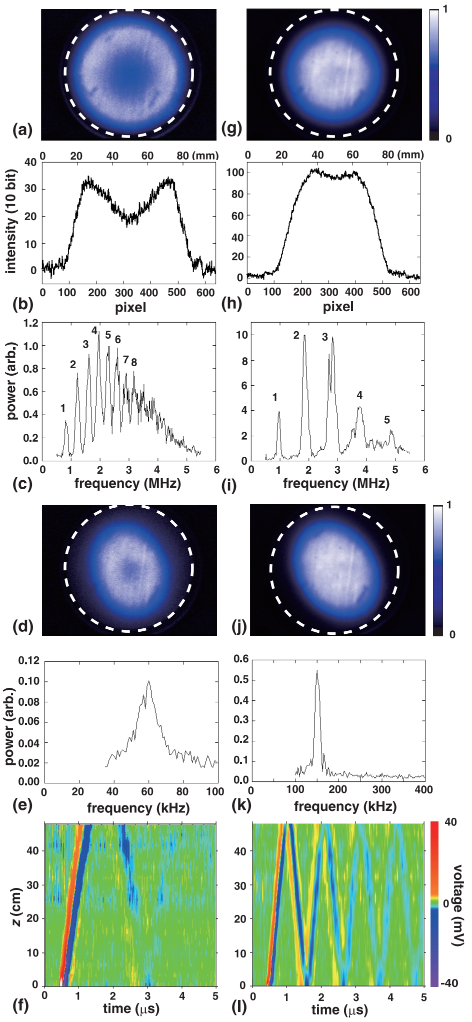

Fig. 2 A PS image (a) and its radial density profile (b), an axial oscillation spectrum (c), a PS image with $m = 2$ diocotron oscillation (d) and its spectrum (e), contour plot of the signals from electrodes, which shows propagation of solitary waves (f), for a plasma with the MMC. The same data set for the ESC (g)-(l).

shots averaged image of such a plasma. The color gradient is normalized to its peak intensity. Here, unit intensity corresponds to about 100 electrons per pixel or 4.4×10^5 electrons per cm^2. This quntity is an electron density integrated along a curved magnetic field. And it is seen from Fig. 2 (b) that the confined plasma had a hollow profile as reported previously [2, 3]. This is referred to as a magnetic mirror confinement (MMC). The second one was a plasma confined with electrostatic potentials on both sides of a magnetic field gradient, which is obtained without grounding V_{H}. Figures 2 (g) and (h) show an image of a plasma with a bell shaped profile and its radial density profile. This is referred to as an electrostatic confinement (ESC).

Shown in Figs. 2 (c) and (i) are spectra of the axial electrostatic oscillations observed in MMC and ESC, respectively. These oscillations correspond to the Trivelpiece-Gould modes. Therefore, resonance frequencies become higher as the plasma density and/or temperature becomes higher. Digits in the figures denote the axial mode number. As in the case of spheroidal NNPs, these oscillations can be used to diagnose the plasma density qualitatively.

When large amplitude RF bursts are applied to plasmas through azimuthally segmented electrodes, $m = 2$ diocotron oscillations can be excited. Figures 2 (d) and (j) are images of plasmas with $m = 2$ diocotron oscillation in a magnetic field gradient, which clearly show oval profiles. In case of NNPs in a uniform magnetic field, the resonance frequency is almost proportional to n_{e} and the oscillation phase is uniform along the field in an azimuthal direction. However, in a magnetic mirror confinement, n_{e} changes along a magnetic field line [3]. In experiments, the signals observed with five azimuthally segmented electrodes along a curved magnetic field were almost in phase with each other. Shown in Figs. 2 (e) and (k) are the spectra for the diocotron oscillations, which have smaller Q value (≤ 10). The density gradient in the plasma might result in the broader spectra because a diocotron frequency is a linear function of n_{e}.

So far, solitary waves of NNPs were observed only in a uniform magnetic field [4–6]. Measurement of the solitary waves in NNPs with a magnetic field gradient was conducted for the first time. Signals from 16 ring electrodes were used for contour plots of the measured voltages as functions of time and position, which are shown in Figs. 2 (f) and (l). Here, an electron soliton was excited from low field side near $z = 0$ by applying a negative voltage of -10 V to a ring electrode with the rise time of 50 ns. At the moment, both electron soliton and hole are excited simultaneously due to an induction to the nearby electrodes. In case of MMC, it is seen that the velocities of soliton and hole decreased at high field side and that the peak voltages decay quickly. In the ESC, both the soliton and hole propagate back and forth many times.

In summary, spectra of axial electrostatic oscillations in NNPs were obtained for both magnetic mirror and electrostatic confinement. Diocotron oscillations with $m = 2$ and solitary waves were observed for the first time in non-neutral electron plasmas in a magnetic field gradient. Since the nonlinear oscillations in a mirror confined plasma contain interesting topics to be studied [7], details will be investigated more in future experiments.

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