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Field-aligned and transverse plasma-potential structures induced by electron cyclotron waves

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It is demonstrated that potential structures of a magnetized plasma column can be controlled by electron cyclotron waves of azimuthal mode number $m=\pm 1$. A field-aligned plasma potential structure, i.e., an electric double layer with the potential jump corresponding to the ion flow energy is created around the electron cyclotron resonance point at the center and peripheral areas of the plasma column for $m=+1$ and -1 modes, respectively. As a result, transversely outward and inward electric fields are locally generated. Our experimental results show that the created potential structures are greatly relevant to the polarization profiles of the injected waves and the resultant heating profiles. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2827575]

Plasma-potential structures in magnetized plasmas have been studied for a long time. The potential structures are divided broadly into two types: one is the field-aligned potential structures including both an electric double layer (DL) due to charge separation phenomena and a potential gradient determined by a pressure gradient, i.e., following the Boltzmann's law. The studies on these structures have been progressed in connection with the energetic particle generation in space,[1,2] the ion acceleration for an electric thruster,[3,4] and the confinement of the fusion plasmas.[5] The other is a potential gradient in the direction perpendicular to the field lines, so-called radial electric-field shear. The radially sheared electric field is well known to induce the $\mathbf{E}\times\mathbf{B}$ drift flow shear and suppress the instabilities and turbulence driving the particle transport.[6]

As an application of the plasma-potential structures, in a tandem mirror fusion machine, the field-aligned potential jump (plug potential) for confining the energetic ions has been created applying an electron cyclotron resonance (ECR) heating and has been discussed using Cohen's and Pastukhov's theories basically following Boltzmann's law.[7] However, it is difficult to directly verify the structures because the axial profile of the plasma potential cannot be measured in the very large and high-density plasmas. Moreover, addressing the tandem mirror, it has recently been observed that the radial electric-field shear formed due to the high plug potential, or due to a cylindrical layer with energetic electrons created by localized off-axis ECR heating, suppresses the vortexlike turbulent structures and improves the plasma confinement.[8,9] Therefore, it is considered that the formations of the field-aligned and the transverse potential structures are of use to the plasma-confinement improvement.

A basic laboratory experiment simulating the tandem mirror situation was carried out in the past study,[10] where the potential jump near the ECR point could be generated as well as the tandem mirror and it was guessed that the potential height is determined by the ion flow energy in a Q-machine plasma. However, this experiment did not show the two or three-dimensional potential structures and was not correlated with the propagation of the waves relating to ECR, which would be relevant to the radial structure of the potential profile during ECR heating.

This letter shows plasma-potential structures created by electron cyclotron waves (ECWs) of azimuthal mode number $m=\pm 1$ in an inhomogeneously magnetized plasma with high-speed ion flow simulating the energetic ions in the tandem mirror. Our experiments demonstrate that the field-aligned potential structure, i.e., the DL, is selectively created at the center and peripheral areas by $m=+1$ and -1 mode waves, respectively. The spatially selective creation of the DL can drive the formation of the transverse potential structures, namely, the radially outward and inward electric fields.

Experiments are performed in Q_T-upgrade machine of Tohoku University, as shown in Fig. 1(a), where we mainly adopt converging magnetic-field configurations of types (I) and (II), presented in Fig. 1(b). A plasma source for controlling the field-aligned ion flow energy[11] under low argon gas pressures ($\sim$10 mPa) is set at the low magnetic-field side. In this case, the ion flow energy is confirmed to be proportional to an anode potential V_a in Fig. 1(a). The plasma column is terminated by an insulator plate and its radius is limited to about 3 cm by a limiter located at the same position as the anode. Microwaves (frequency: $\omega/2\pi=6$ GHz, power: $P_{\text{in}}=50$ W) with $m=+1$ and -1 modes are selectively launched from the high magnetic-field side using a horn antenna with a dielectric polarizer. It is also confirmed that an axial ratio of the circularly polarized wave radiated from the antenna is about 1.1. The ECR points of 6 GHz microwave are $z=26$ and 45.5 cm under configurations (I) and (II), respectively, since the ECR magnetic-field strength is 2.14 kG. Here, $z=0$ and each axis (x,y,z) is defined on the basis of the axial center of the machine and as indicated at the upper left of Fig. 1(a). Spatial profiles of plasma parameters are measured by two single-tipped Langmuir probes, which are movable in the x-z plane at $y=0$ and in the x-y plane at $z=26$ cm, respectively. Electric fields E_x, E_y, and E_z of the microwaves are measured using movable dipole antennas, where spatial profiles of wave phase are directly obtained using a network analyzer.

Figures 1(c) and 1(d) show axial profiles of a plasma potential ϕ_p and an electron density n_e at the radial center of the plasma column, respectively, for $P_{\text{in}}=0$ W (open circle) under configuration (I), and for $P_{\text{in}}=50$ W of $m=+1$ mode

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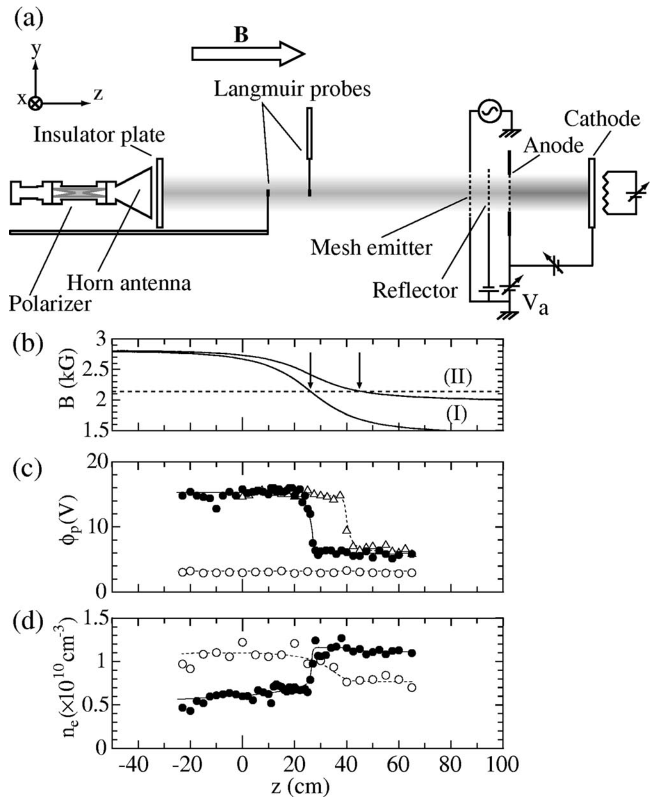

FIG. 1. (a) Schematic of experimental setup. (b) Magnetic-field configurations (I) and (II). (c) z profiles of the plasma potential for $P_{in}=0$ W (open circle) under configuration (I) and for $P_{in}=50$ W of $m=+1$ mode under configurations (I) (closed circle) and (II) (open triangle). (d) z profiles of the electron density for $P_{in}=0$ W (open circle) and $P_{in}=50$ W (closed circle) under configuration (I).

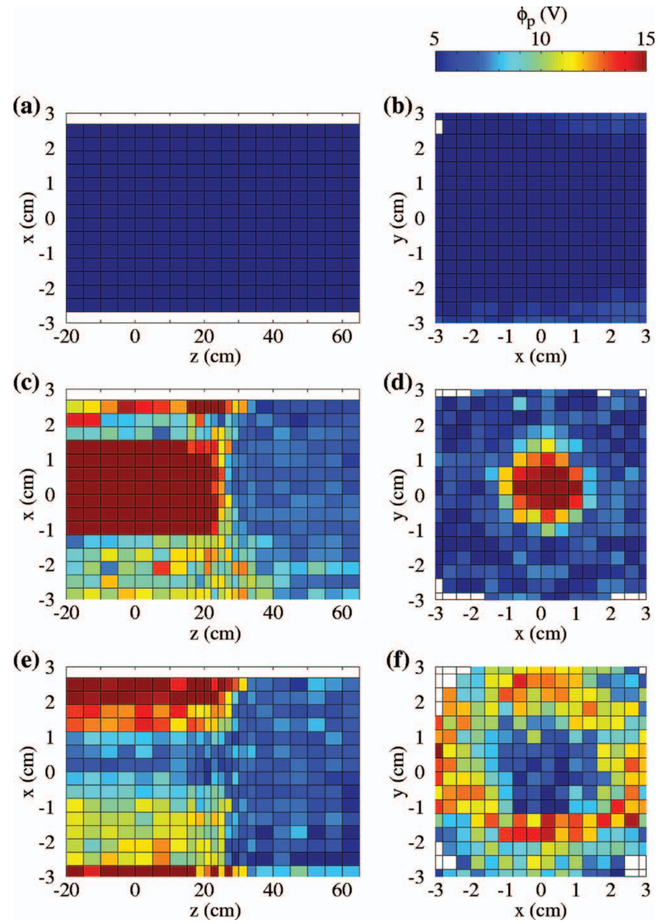

FIG. 2. (Color) x-z and x-y profiles of the plasma potential ϕ_p for [(a) and (b)] $P_{in}=0$ W, [(c) and (d)] $P_{in}=50$ W with $m=+1$ mode, and [(e) and (f)] $P_{in}=50$ W with $m=-1$ mode, where the anode potential is fixed at $V_a=15$ V. (a), (c), and (e) are measured at $y=0$ cm under configuration (I), while (b), (d), and (f) are obtained at $z=26$ cm under configuration (II), i.e., the higher magnetic-field side than the ECR point.

under configurations (I) (closed circle) and (II) (open triangle), all of which are measured at 30 μs after the wave injection for $V_a=15$ V. In the case of $P_{in}=0$ W, ϕ_p is almost homogeneous and n_e increases in the high magnetic-field side due to the converging magnetic-field configuration. On the other hand, a localized potential jump corresponding to the ion flow energy, i.e., a DL, is clearly observed near the ECR point when the microwave of $m=+1$ is launched. Here, we mention the potential height tracks the ion flow energy changeable by V_a. In our experiments, DL is observed for 15–50 μs after the wave injection. The electron density n_e sharply drops in the high magnetic-field side due to an electron reflection by a magnetic-mirror effect, i.e., $-\mu\nabla B$ force (μ: magnetic moment), which is markedly enhanced by ECR acceleration perpendicular to the magnetic-field lines and yields the increase in n_e in the low magnetic-field side, as presented in Fig. 1(d). That is to say, the electrons lying within the loss cone transit to the outside of the loss cone by ECR heating, and are axially reflected in the converging magnetic-field configurations. Since the electrons decelerated by the $-\mu\nabla B$ force congest near the ECR point, a localized electron-rich area (negative charge) would be formed. The ions can penetrate there because of their inertia and reach the low electron density area in the downstream region of the electron-density drop. Hence, a localized ion-rich area (positive charge) would be formed at the high magnetic-field side of the electron-rich area. This is so called the electric double layer, and its potential height is self-consistently determined for satisfying the charge neutrality by reflecting a part of energetic ions.

Figure 2 gives two dimensional profiles of the plasma potential ϕ_p in the x-z plane and the x-y plane for [(a) and (b)] $P_{in}=0$ W, for [(c) and (d)] $P_{in}=50$ W of $m=+1$ mode, and for [(e) and (f)] $P_{in}=50$ W of $m=-1$ mode under the condition of $V_a=15$ V. ϕ_p for $P_{in}=0$ W is homogeneous, as shown in Figs. 2(a) and 2(b). In the case of $m=+1$ mode shown in Figs. 2(c) and 2(d), the DL, i.e., the field-aligned potential jump, is found to be formed around the center area of the cross section of the plasma column. In the case of $m=-1$ mode, on the other hand, the DL is formed around the peripheral area, as presented in Figs. 2(e) and 2(f). The selective formation of the DL in the center and peripheral areas can generate the radial potential structures in the higher magnetic-field side, as presented in Figs. 2(c)–2(f). These results indicate that the potential structure in the radial direction can actively be controlled by just selecting the azimuthal mode number m of the launched ECW. Here, it is clearly shown that the transversely inward and outward electric fields are formed in the high magnetic-field side for $m=+1$ and -1 modes, respectively.

In order to interpret the above-mentioned difference in the potential structures, related characteristics of the ECWs have to be revealed. x profiles of a phase difference $\Delta\theta$ between E_x and E_y of the wave electric fields for $m=\pm 1$ modes are plotted as open circle in Fig. 3, where the right- and left-handed polarizations are represented by $-180°$

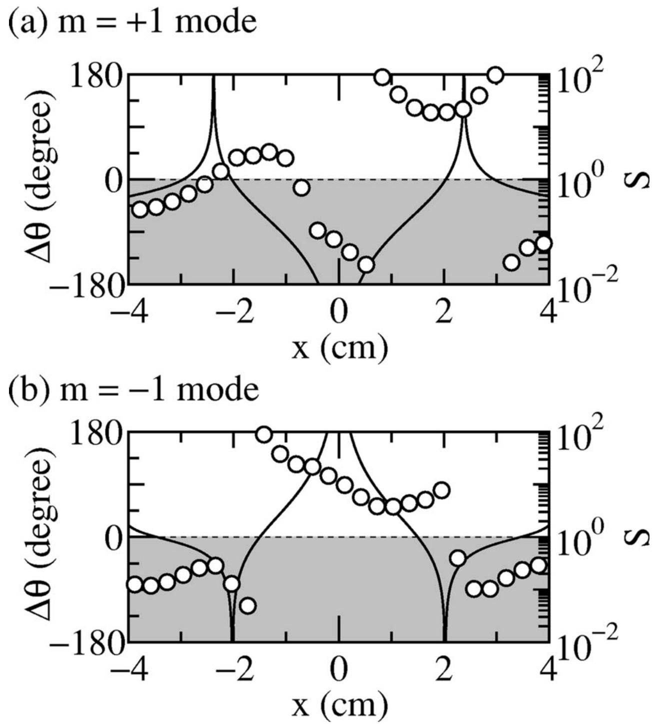

FIG. 3. x profiles of the theoretical polarization index S (solid line) and the experimentally obtained phase difference $\Delta\theta$ between E_x and E_y of the microwaves for (a) $m=+1$ and (b) $m=-1$ modes at $z=15$ cm under configuration (I).

$<\Delta\theta<0°$ and $0°<\Delta\theta<180°$, respectively. It is found in Fig. 3(a) that the polarization for $m=+1$ is right handed around the center area and left handed around the peripheral area, i.e., the polarization is reversed along the radial axis. In contrast, the left- and right-handed polarizations are observed around the center and peripheral areas for the case of $m=-1$, as plotted in Fig. 3(b). The theoretical polarization index S (solid line) for $m=\pm 1$ modes is compared with the experimentally observed polarization direction in Fig. 3, where S is defined as $S \equiv |E_r + iE_\theta| / |E_r - iE_\theta|$ and is derived with the dispersion theory of electromagnetic waves in bounded plasmas.[12] The right-handed and left-handed polarizations correspond to $S<1$ and $S>1$, respectively. In the calculation of S, the perpendicular wavenumbers $k_\perp = 1.02$ and 1.20 cm^{-1} measured in the experiments are used for $m=+1$ and -1 modes, respectively. The theoretical S in Fig. 3 also shows that the wave polarization for $m=+1$ ($m=-1$) mode is right handed (left handed) around the center area and left handed (right handed) around the peripheral area, i.e., the observed polarization profiles are well explained by the dispersion theory in bounded plasmas. We could observe in the experiments and confirm in the simulation (not shown here) that the waves are absorbed around the center and the peripheral areas for $m=+1$ and -1 modes, respectively. Thus, it is clarified that the wave is absorbed around the area where the polarization is right handed. As a result, the radial location of the DL can be changed by selecting the azimuthal mode number m. It is demonstrated that the direction of the transverse electric field can be easily changed by the microwave-antenna operation.

In summary, it is demonstrated that the plasma-potential structures can be controlled by just selecting the excited azimuthal mode number of the ECW. In our experiments, $m=+1$ and -1 mode ECWs can heat the electrons and create the field-aligned DL near the ECR point in the center and peripheral areas, respectively, where the potential height of the DL becomes the same as the ion flow energy simulating the energetic ions in the tandem mirror. It is clearly evidenced that the the wave polarization is reversed along the radial axis and the electrons are heated only in the position of the right-handed polarization. These results suggest a method of the plasma-potential-structure control for suppressing instabilities in magnetized plasmas.

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