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Double layer created by electron cyclotron resonance heating in an inhomogeneously magnetized plasma with high-speed ion flow

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A potential jump, i.e., an electric double layer (DL) is formed near an electron cyclotron resonance (ECR) point when an electron cyclotron wave is injected into an inhomogeneously magnetized plasma with high-speed ion flow. A charge separation is caused by an electron reflection due to $-\mu \nabla B_z$ force enhanced by ECR heating and ion inertia. It is clearly demonstrated in the experiment that the potential height of the DL is almost proportional to the field-aligned ion flow energy; the DL is found to be self-consistently formed for maintaining charge neutrality by reflecting a part of the flowing ions. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2951997]

I. INTRODUCTION

Formations of field-aligned electric fields, i.e., plasma-potential structures, have attracted great interest for a long time in connection with particle accelerations and decelerations in space[1,2] and fusion-oriented plasmas.[3] The potential structures can be divided broadly into two types: one is an electric double layer (DL) due to charge separation phenomena, where the steady-state external forces would be applied to charged particles. Another is the potential gradient following the Boltzmann's law caused by the plasma-pressure gradient with keeping the charge neutrality. The investigations of the DL in laboratory plasmas have been progressed for clarifying the mechanism of the particle acceleration in auroral zones.[4–6] In recent years, direct observation of the field-aligned electric fields in space gives rise to the up-to-date argument about the DL.[7–9] More recently, a current-free DL in expanding helicon plasmas and a subsequent ion beam were discovered and the particle dynamics correlating with the DL has been studied.[10–14] In fusion plasmas, especially tandem mirror 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[15,16] with referring Cohen's and Pastukhov's theories[17,18] basically following the Boltzmann's law. In the tandem mirror fusion machines, however, it is difficult to directly verify the potential structures because the detailed potential structures cannot be measured in such very large and high-density plasmas.

A basic laboratory experiment simulating the tandem mirror situation was carried out in the past study, 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 of about 2 V would be determined by the ion flow energy in the Q-machine plasma.[19] However, no experimental verification of the effect of the ion flow energy on the potential structure was achieved, because there was no plasma source leading to control of the ion flow energy for this kind of experiment. In addition, the past experimental results showed neither the two or three-dimensional potential structures nor the correlation between the potential formation and the propagation of the waves relating to ECR. Concerning the electron cyclotron waves, the authors have investigated linear propagations of the waves with $m=0$ and ± 1 modes,[20–22] where m is an azimuthal mode number.

Based on the above-mentioned backgrounds, the purpose of the present work is to clarify the mechanisms of the potential structure formation triggered by ECR heating and to correlate the structure with the wave propagation. For achievement of the purpose, the authors have already developed the novel plasma source enabling the field-aligned ion flow energy to be controlled under strong magnetic fields.[23,24] In addition, we have briefly reported the DL formation near the ECR point and the wave propagation creating the potential structures.[25] In this paper, our attention is focused on the mechanisms of the DL formation near the ECR point and the effect of the ion flow energy on the analogy of energetic ion role in the fusion machine, under the situation that the $m=+1$ mode electron cyclotron wave is injected into the plasma with high-speed ion flow under a converging magnetic-field configuration. For the case of $m=+1$ mode wave injection, the authors have already shown the axisymmetric electron heating at the center of the plasma column.[25] Hence, the potential formation in this case can be treated as a one-dimensional problem on the axis.

II. EXPERIMENTAL SETUP

Experiments are performed in the Q_T-Upgrade Machine of Tohoku University shown in Fig. 1(a), which has a cylindrical stainless steel vacuum chamber of about 450 cm in length and 20.8 cm in diameter. The inhomogeneous magnetic-field configuration described in Fig. 1(c) can be created by two parties of the solenoidal coils, where $z=0$ is defined as the axial center of the vacuum chamber.

The plasma source yielding the ion-flow energy control is set at the low magnetic-field side. A barium oxide (BaO) cathode uniformly heated by a pyrolytic graphite-pyrolytic boron nitride heater and a tungsten mesh anode are placed as shown in Fig. 1(a). A tungsten mesh reflector and an electron emitter of mesh shape called mesh emitter are located in

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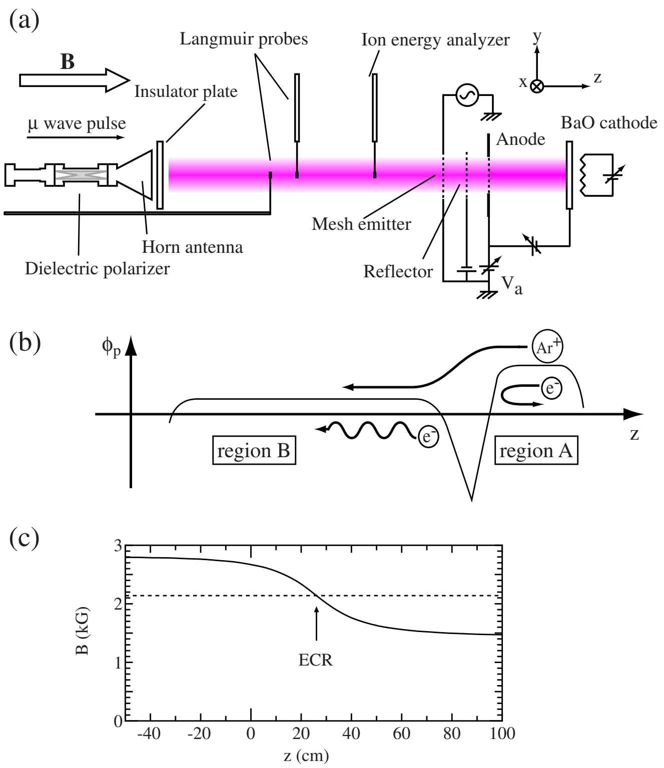

FIG. 1. (Color online) (a) Schematic diagram of the experimental setup. (b) The model of the potential profile in the plasma source. (c) External steady-state magnetic-field configuration.

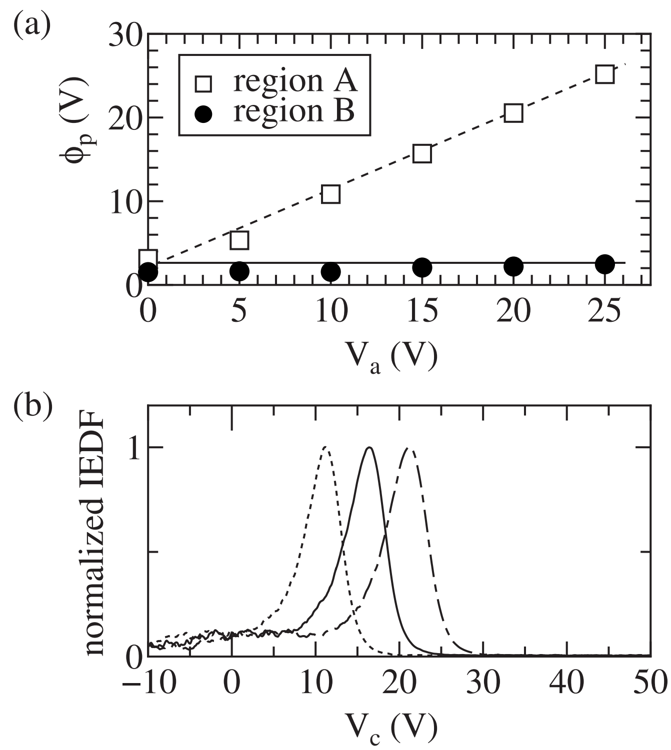

FIG. 2. (a) Plasma potential ϕ_p in regions A (open square) and B (closed circle) as a function of the anode potential V_a. (b) Normalized ion energy distribution functions (IEDFs) measured in region B for V_a=10 V (dotted line), 15 V (solid line), and 20 V (dotted-dashed line).

front of the anode. The mesh emitter is constructed of the tungsten mesh covered with BaO for efficient electron emission. The mesh emitter is heated by directly passing alternative current through wires of the mesh and can uniformly emit electrons. A plasma is produced by a direct current discharge between the BaO cathode and the anode for the generation of argon ions, and this area is defined as "region A." The plasma potential in region A can be controlled by adjusting the anode potential V_a, and the reflector is negatively biased enough to reflect the electrons from region A. The ions produced in region A penetrate the reflector and are incorporated with the electrons emitted from the mesh emitter. Then the charged particles can flow downstream without the space-charge limitation, where the downstream side is defined as "region B." The plasma potential in region B is determined by the potential of the mesh emitter. As presented in Fig. 1(b), the ion flow with energy corresponding to the potential difference between regions A and B can be generated. The plasma in region B is terminated by an insulator plate located at the downstream of the synthesized plasma. The plasma potential ϕ_p measured in regions A and B under uniform magnetic field of 1.6 kG are plotted in Fig. 2(a) as open squares and closed circles; it is found that only the plasma potential in region A can be controlled by changing the anode potential V_a with keeping the constant potential in region B. The normalized ion energy distribution functions (IEDFs) in region B for V_a=10 V, 15 V, and 20 V are shown in Fig. 2(b) as dotted, solid, and dashed-dotted lines, respectively, where the local plasma potential measured at the same position is about 3 V for all cases and V_c is a collector voltage of an electrostatic ion energy analyzer. The IEDFs clearly show that the ions consist of only the flowing component and the beam energy increases with an increase in the anode potential V_a.

A microwave (frequency: $\omega/2\pi$=6 GHz) with m=+1 mode is injected from the high magnetic-field side using a horn antenna through a dielectric polarizer. The axial ratio of the circularly polarized wave radiated from the antenna is about 1.1 on the axis. The ECR point of 6 GHz microwave is z=26 cm as indicated in Fig. 1(c) because the ECR magnetic-field strength is 2.14 kG. Spatial profiles of the plasma parameters in region B are measured by single-tipped Langmuir probes movable on the axis.

III. EXPERIMENTAL RESULTS

Figures 3(a) and 3(b) show axial profiles of the plasma potential ϕ_p and the electron density n_e on the axis, respectively, for microwave power P_{in}=0 W (open circle) and for P_{in}=50 W (closed square), all of which are measured at t=30 μs after the wave injection for V_a=15 V. Here, the solid arrows in Figs. 3(a) and 3(b) represent the ECR point of the 6 GHz microwave and t=0 is defined as the moment of the wave injection. In the case of P_{in}=0 W, ϕ_p is spatially almost homogeneous and n_e increases in the high magnetic-field side due to the converging magnetic-field configuration, which would satisfy the flux conservation law of the charged particles during the spatial change of the plasma-column radius. On the other hand, a localized potential jump, i.e., the DL, is clearly observed near the ECR point for P_{in}=50 W,

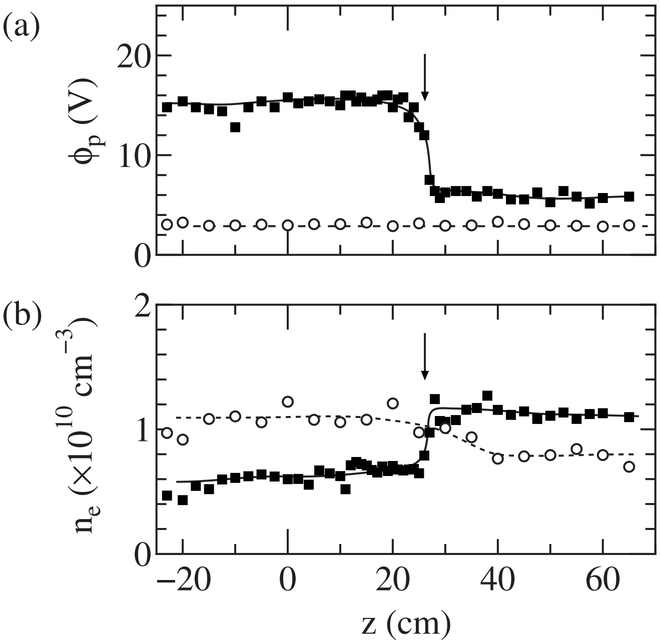

FIG. 3. Axial profile of (a) the plasma potential ϕ_p and (b) the electron density n_e at t=30 μs after the wave injection for P_{in}=0 W (open circle) and 50 W (closed square), where V_a is fixed at 15 V.

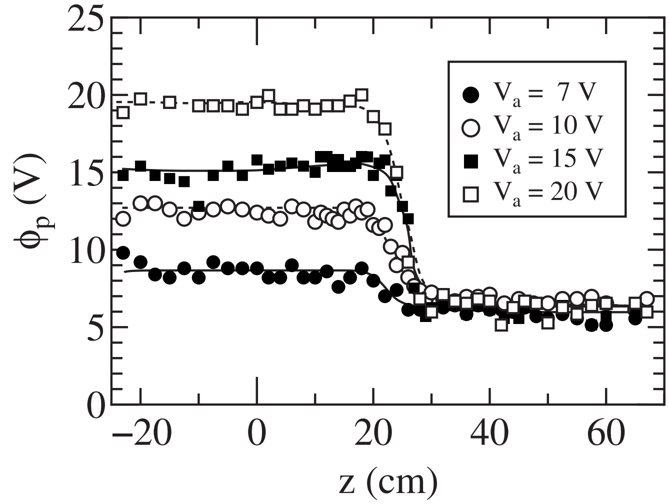

FIG. 4. Axial profiles of the plasma potential ϕ_p for P_{in}=50 W with the anode potential V_a as a parameter.

where the plasma potential in the high potential side is about 15 V and appears to almost correspond to the ion beam potential defined as V_c yielding the peak of the IEDF. It is found that the electron density n_e for P_{in}=50 W sharply drops in the high magnetic-field side and increases in the low magnetic-field side as shown in Fig. 3(b). The change of the density profile would be due to an electron reflection by a magnetic-mirror effect, i.e., $-\mu\nabla B_z$ force (μ: magnetic moment), which is markedly enhanced by ECR acceleration perpendicular to the magnetic-field lines. 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.

Concerning the elucidation of the physical mechanisms of the DL formation, the effect of the field-aligned ion flow energy is experimentally investigated. Figure 4 gives axial profiles of the plasma potential ϕ_p with the anode potential V_a as a parameter for the microwave power P_{in}=50 W. It is clearly demonstrated that the potential height of the DL relating to ECR increases with an increase in V_a, i.e., the ion flow energy, in spite of the constant microwave power.

In our experiments, the electrons are reflected by the $-\mu\nabla B_z$ force enhanced by ECR heating, while the ions are not affected by the microwave at all. Thus, it is expected that the ions are reflected by the potential structure of the DL and the charge neutrality is kept in the high magnetic-field side. Let us estimate a plasma potential ϕ_{pes} at the high magnetic-field side, which would satisfy the above-mentioned expectation, using the IEDF and an electron reflection ratio Γ_r. The IEDF for V_a=15 V and P_{in}=0 W is presented in Fig. 5 as a solid curve. Γ_r can be estimated as $\Gamma_r=(n_0-n_1)/n_0$, where n_0 and n_1 are the electron densities at the high magnetic-field side for P_{in}=0 and 50 W, respectively. The potential ϕ_{pes} at the high magnetic-field side is derived under the assumption that the same quantity of ions as the reflected electrons are reflected by the DL potential, satisfying the relation of

$$\Gamma_r = \frac{\int_V^{\phi_{pes}} \mathrm{IEDF}\, dV_c}{\int_V^{\infty} \mathrm{IEDF}\, dV_c}, \quad (1)$$

where V is V_c giving a rising edge at the low energy tail of IEDF. The numerator of the right-hand side of Eq. (1) and ϕ_{pes} estimated from Eq. (1) for V_a=15 V are indicated as a gray part and an arrow in Fig. 5, respectively.

The measured electron reflection ratio Γ_r depending on V_a for P_{in}=50 W is plotted in Fig. 6(a). It is found that Γ_r decreases with an increase in V_a in spite of the constant microwave power because of the effect of the axial electric field of the DL. The electric field of the DL accelerates the electrons to the high potential side, i.e., prevents $-\mu\nabla B$ force from reflecting the electrons. The plasma potential ϕ_p measured in the high potential side and the estimated potential ϕ_{pes} are plotted in Fig. 6(b) as closed squares and open circles, respectively. The estimated potential ϕ_{pes} also

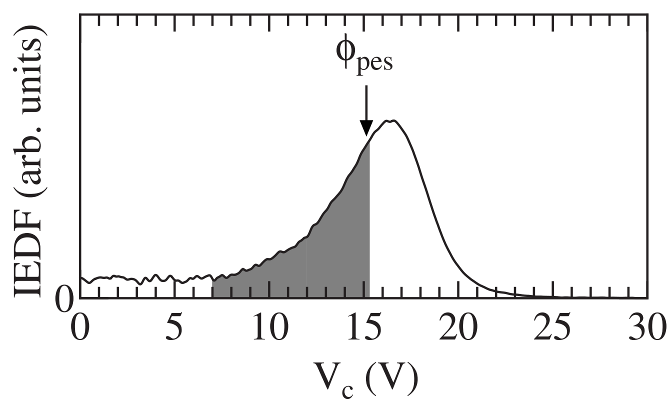

FIG. 5. The IEDF for V_a=15 V and P_{in}=0 W (solid curve). The gray part and the arrow show the numerator of the right-hand side of Eq. (1) and the estimated plasma potential ϕ_{pes} from Eq. (1), respectively.

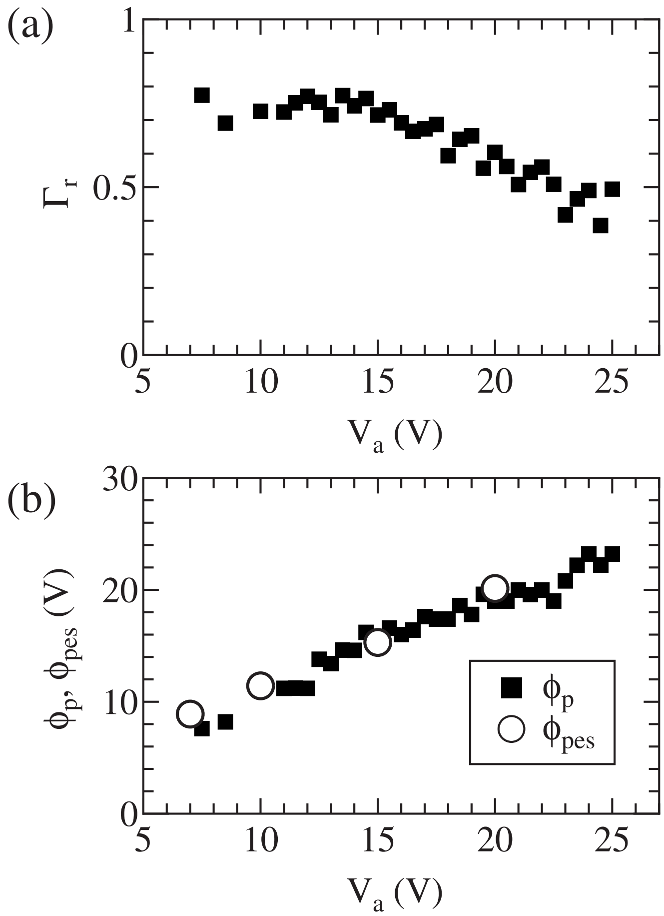

FIG. 6. (a) Electron reflection ratio Γ_r, and (b) plasma potentials ϕ_p (closed square) measured by the Langmuir probe at the high-potential side and ϕ_{pes} (open circle) estimated using Eq. (1) as a function of the anode potential V_a.

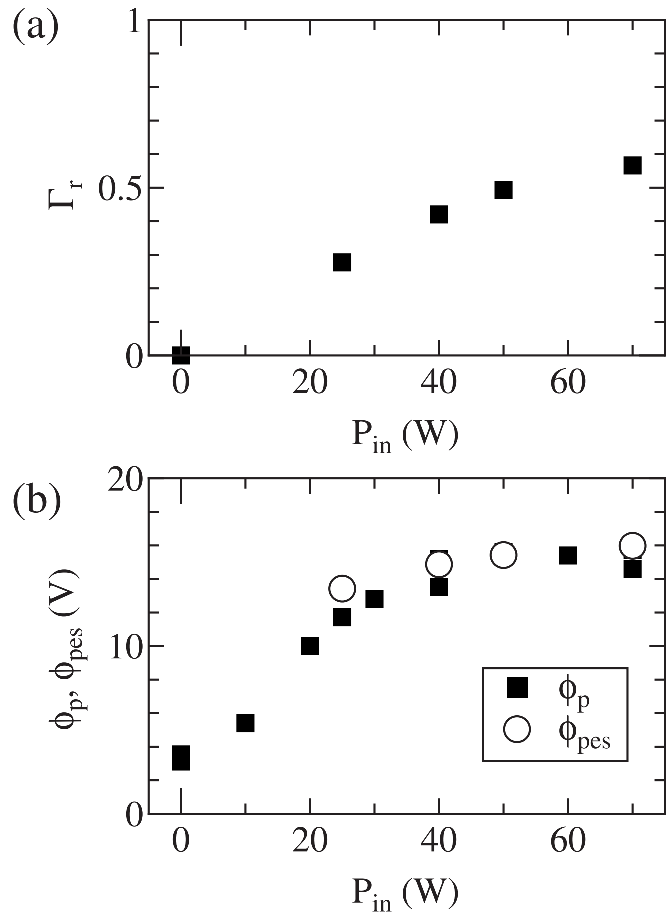

FIG. 7. (a) Electron reflection ratio Γ_r, and (b) plasma potentials ϕ_p (closed square) measured by the Langmuir probe at the high-potential side and ϕ_{pes} (open circle) estimated using Eq. (1) as a function of the microwave power P_{in}.

linearly increases with an increase in V_a and is in agreement with the measured potential ϕ_p. The same data set as Fig. 6 is described in Fig. 7 as a function of the microwave power P_{in}. Γ_r is found to increase with an increase in P_{in} because of the enhancement of the $-\mu\nabla B_z$ force by the electric field of the microwave. The estimated ϕ_{pes} as a function of P_{in} is also in good agreement with the measured potential ϕ_p. Therefore, the assumption that the ions are reflected by the DL and the charge neutrality is kept, gives a good explanation for the behavior of the DL created by ECR heating.

Based on the above-described experimental data set, we can deduce the physical mechanisms of the DL formation triggered by ECR heating in an inhomogeneously magnetized plasma with high-speed ion flow as follows. The electrons decelerated in the axial direction by the $-\mu\nabla B_z$ force, which is enhanced by ECR heating, congest near the ECR point and are finally reflected to the low magnetic-field side. Hence, a localized electron-rich area (negative charge) and a rapid electron-density drop are formed near the ECR point. The ions can penetrate the electron-rich area because of their inertia and reach the low electron-density area downstream of the electron-density drop. As a result, a localized ion-rich area (positive charge) is formed at the high magnetic-field side of the electron-rich area. This is so called the electric double layer and the charge profile can create the rapid potential jump; the potential height is self-consistently determined for satisfying the charge neutrality by reflecting a part of energetic ions.

IV. CONCLUSION

The plasma-potential structures on the axis are investigated when the electron cyclotron wave of azimuthal mode number $m=+1$ mode is injected into the inhomogeneously magnetized plasma with high-speed ion flow. The electric double layer (DL) with the rapid potential jump corresponding to the ion flow energy is formed near the ECR point due to the electron reflection by the magnetic-mirror effect ($-\mu\nabla B_z$ force) enhanced by ECR heating and the ion inertia. It is experimentally demonstrated that the potential height of the DL is almost proportional to the field-aligned ion flow energy. The verification of the potential height using the ion energy distribution function and the electron reflection ratio shows evidence that the potential height of the DL can reflect a part of the ions flowing from the low magnetic-field side and keep the charge neutrality in the high magnetic-field side.

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