Three-Dimensional Double Layers Inducing Ion-Cyclotron Oscillations in a Collisionless Plasma

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Three-dimensional double layers are generated in a strongly magnetized collisionless plasma column. The position and shape of the double layers are controlled by the formation of mirror configurations of magnetic field, which simulate the magnetic field structure above the Earth's auroral oval. The double layers are found to induce electrostatic oscillations with frequencies above the ion-cyclotron frequency and its harmonics, in contrast to one-dimensional double layers. The oscillations are driven by the large inhomogeneous radial electric field and propagate azimuthally with mode number $m=1,2,3,\ldots$.

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Formation and control of electrostatic potentials in strongly magnetized plasmas are of current interest in conjunction with particle acceleration in space plasmas[1] and plasma confinement in fusion-oriented devices.[2] According to the observations above the Earth's auroral oval, the potential appears to have a three-dimensional (3D) profile with U- (or V-) shaped double-layer (DL) structure.[3] In addition, the electric field perpendicular to the magnetic field is accompanied with electrostatic fluctuations near the ion-cyclotron frequency.[4] A generation mechanism of the oscillations, however, has not yet been clarified definitely in spite of recent tentative predictions.[5] On the other hand, in open-ended fusion devices, efforts have been made to control potential profiles parallel and perpendicular to magnetic field.[6] And it is also of crucial importance to investigate plasma stability under a 3D potential structure.

To simulate the potential structure above the Earth's auroral oval, experiments have been carried out in laboratory magnetized plasmas. Coakley *et al.*[7] and Baker *et al.*[8] measured two-dimensional profiles of DL potentials in weakly ionized plasmas although the magnetic fields were so weak that only electrons were magnetized. A clear V-shaped DL was generated by Stenzel *et al.*[9] under a magnetic field increasing toward the high-potential side of the DL as in the region above the Earth's auroral oval. But the magnetic field, including a separatrix in the field geometry, was not strong enough to magnetize ions in all experimental regions. Jovanović *et al.*[10] realized a 3D well-shaped potential structure in a strongly magnetized plasma column. In their situation, ions were supplied from one end and passed through the potential well produced by an electron beam injection from the other end into a central region of the plasma cross section. In those experiments mentioned above, any ion-cyclotron oscillations were not detected. Recently, however, Merlino *et al.*[11] observed axisymmetric ion-cyclotron oscillations in the presence of DL in a weakly ionized plasma under a magnetic field decreasing toward the high-potential side of the DL. Their DL was generated by an additional discharge in front of a positively biased plate. These oscillations are well known[12] to be generated by biasing of a small plate positively in a magnetized plasma without such an additional discharge. If a virtual position of the plate is supposed at the DL position, the situation is the same as in the presence of the additional discharge.

Here we report measurements of electrostatic fluctuations with frequencies above the ion-cyclotron frequency and its harmonics, which are closely associated with a 3D U- (or V-) shaped structure of DL potentials in a nondischarge collisionless plasma under a strong magnetic field. The DL structure is controlled by the formation of mirror configurations of magnetic field, which have features in common with the magnetic field structure above the Earth's auroral oval. The fluctuations are induced by a large radial electric field provided by the 3D DL and propagate in the azimuthal direction with mode number $m=1,2,3,\ldots$, being completely different from the results in Ref. 11.

The experiment is performed on a plasma column produced by surface ionization in a double-ended Q machine[13] which has two plasma sources S_1 and S_2 under a strong magnetic field $B=1$–4 kG, as schematically shown in Fig. 1. Here, S_1 is a 3.5-cm-diam hot tantalum plate while S_2 consists of a 3.5-cm-diam hot tantalum plate and a cold plate with a 0.8-cm-diam hole just in front of it. The distance between S_1 and S_2 is 312 cm. The machine is operated under an electron-rich condition. The plasma density is around 10^9 cm^{-3}. The electron temperature ($\gtrsim$ ion temperature) is $\simeq 0.2$ eV. The ion Larmor radius is 0.7–2.8 cm. The background gas pressure is kept to below 1×10^{-6} Torr. Electron and ion collision mean free paths are much longer than the characteristic

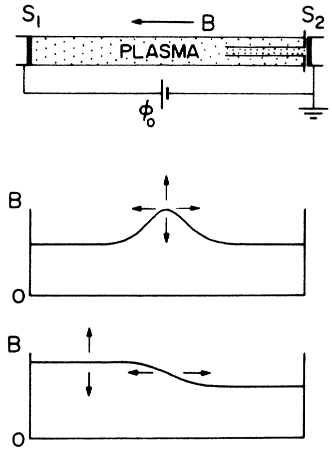

FIG. 1. Schematic of setup with plasma sources, S_1 and S_2, and two configurations of applied magnetic field B.

lengths of potential slopes measured. The DL is known to be generated by application of a potential difference between S_1 and S_2, as described in Ref. 13, where, however, S_1 and S_2 (with no cold plate in front of the tantalum plate) supplied plasmas of the same diameter and the DL had one-dimensional (1D) potential structure in the plasma. In this work, two plasmas supplied by S_1 and S_2 have different diameters, 3.5 and 0.8 cm, respectively, yielding the DL with 3D potential structure.[14] A potential ϕ_0 is applied to S_1 with respect to the hot plate of S_2, which is grounded together with the 15.7-cm-diam vacuum chamber. The potential structure and associated fluctuations are controlled by two types of mirror configurations of B. Measurements of plasma potential ϕ are made by use of small emissive probes. Other plasma parameters are measured by Langmuir probes.

At first, the ϕ structures of the DL are measured under a magnetic field with magnetic bump somewhere between S_1 and S_2. Figure 2 demonstrates typical results of axial ϕ profiles and equipotential lines in the r-2 (radial-axial) plane. A clear U-shaped ϕ structure is found to be formed under a strong magnetic field. This structure is confirmed to be symmetric with respect to the plasma-column axis. The 3D structure is characterized by a strong radial electric field E_r on the low-potential side. E_r appears around the region of radial boundary of the two plasmas with different potential and diameter. As reported for the 1D DL under a uniform magnetic field,[13,15] the DL width is larger than the predicted value because the low-potential tail fluctuates "back and forth." In the presence of the magnetic bump near the DL position, this back and forth motion is limited in the region around the bump,[16] because the magnetic bump provides the plasma constriction accompanied with particle reflection. Thus, the DL is localized there, with a smaller width, resulting in an enhancement of the U-shaped structure. Moreover, the DL moves when the bump shifts.

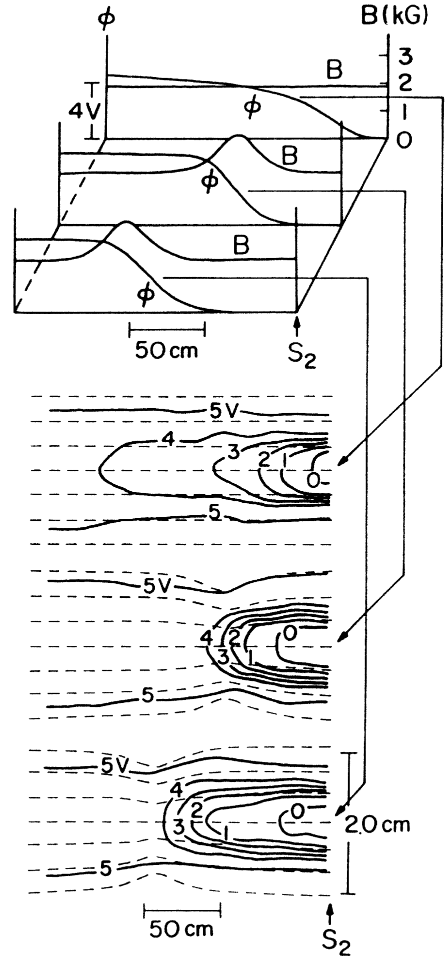

FIG. 2. Potential (ϕ) structures of U-shaped DL at $\phi_0 = 5$ V under magnetic fields with bump. Upper: Axial profiles of ϕ and B. Lower: Equipotential lines and magnetic field lines (dotted lines) in the r-z plane.

Figure 3 shows the U-shaped DL generated when the magnetic field lines converge toward S_1. The axial ϕ drop is found to be localized around the converging region. The DL moves if this region shifts. The results are almost the same as in the case of the magnetic bump. In this case, however, B is stronger on the high-potential side than that on the low-potential side of the DL. The U-shaped ϕ structure and this B configuration should be remarked to have features in common with those above the Earth's auroral oval.

In the presence of the U-shaped DL, local density and potential fluctuations, $\tilde{n}$ and $\tilde{\phi}$, respectively, are measured. Electrostatic fluctuations with frequencies $\omega/2\pi$ above the ion-cyclotron frequency $\omega_{ci}/2\pi$ and its

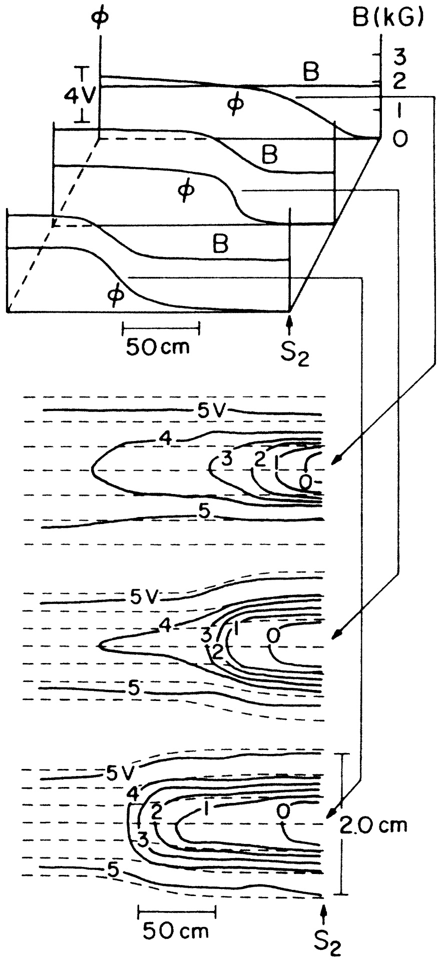

FIG. 3. Potential structures of U-shaped DL at $\phi_0 = 5$ V under magnetic fields increasing toward S_1.

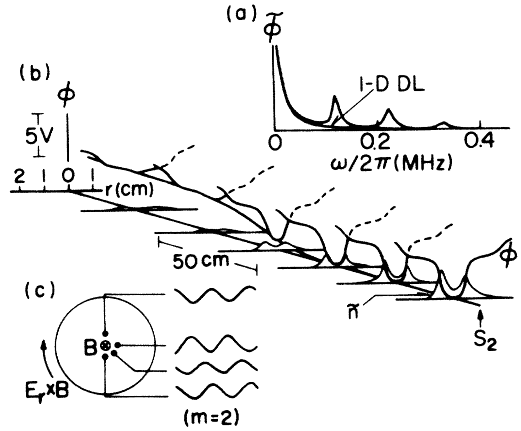

FIG. 4. Fluctuations ($\tilde{n}$) associated with U-shaped DL at $\phi_0 = 5$ V. (a) Frequency spectrum at $B = 2.4$ kG ($\omega_{ci}/2\pi = 0.094$ MHz), together with that in case of the 1D DL. (b) Amplitudes at various positions (thin lines), together with ϕ profiles, in the lowest configurations of ϕ and B in Fig. 3 ($\tilde{n}/n \lesssim 8\%$). (c) Phase change yielding azimuthal propagation with mode number $m = 2$ at $B = 1.9$ kG, where this mode is dominantly generated.

harmonics are always observed as presented in Fig. 4(a). As already noted,[17] this kind of instability is not detected in the case of the 1D DL. This means that E_r provided by the 3D ϕ structure is responsible for these fluctuations. In fact, a peak of the fluctuations is found at the position of the maximum radial ϕ slope on the low-potential side, as demonstrated in Fig. 4(b). On the other hand, the fluctuations are negligibly small on the high-potential side. No phase change is observed along the magnetic field. The fluctuations, however, propagate azimuthally with mode number $m = 1, 2, 3, \ldots$ in the direction of $\mathbf{E}_r \times \mathbf{B}$, as shown for $m = 2$ in Fig. 4(c). The phase difference between $\tilde{n}$ and $\tilde{\phi}$ is about 180°, suggesting a flute-type instability. By our varying B on the high-potential side and/or on the low-potential side of the DL, $\omega/2\pi$ is found to depend only on B on the low-potential side where E_r is formed in the plasma. In Fig. 5(a), the observed frequencies normalized by m are plotted as a function of B on the low-potential side at $\phi_0 = 10$ V. In this case, $\omega/2\pi$ is a little above $m\omega_{ci}/2\pi$. With an increase in ϕ_0, however, $\omega/2\pi$ increases linearly with ϕ_0, as found in Fig. 5(b). Roughly speaking, $E_r \propto \phi_0$ and thus $\omega/2\pi$ increases linearly with E_r. All these features are almost independent of the plasma density in the range $(0.5\text{–}5.0) \times 10^9$ cm^{-3}.

The oscillations observed are similar in many points to the one branch of fluctuations reported by Jassby,[18] which appeared for $E_r \lesssim 18.5$ V/cm $[(E_r/B)/v_i \lesssim 5.0$, where v_i is the ion thermal speed]. In his work, E_r was changed by application of a potential difference between two concentric sections of a segmented hot plate for surface ionization and was uniform axially in contrast to the DL structure. In our case, $E_r = 8.0\text{–}100$ V/cm and $\omega/2\pi \gtrsim m\omega_{ci}/2\pi$, depending on E_r. The other branch with lower frequencies in his paper, which was observed for $E_r < 14.0$ V/cm $[(E_r/B)/v_i < 3.5]$ and was investigated with much more interest, are not generated in our experiment. These differences might be due to the different axial ϕ structure. In the work of Ganguli *et al.*,[5] an electrostatic instability with frequencies $\gtrsim m\omega_{ci}/2\pi$ was predicted to be driven by an inhomogeneous electric field perpendicular to magnetic field. But their theory yields the instability only for $(E_r/B)/v_i = 2.8\text{–}3.2$, being different from our observations of the fluctuations in the wide range of $(E_r/B)/v_i = 2.9\text{–}81.0$, where the radial ion motion is quite important.

In summary, a generation of 3D U-shaped DL is demonstrated in a collisionless plasma column under

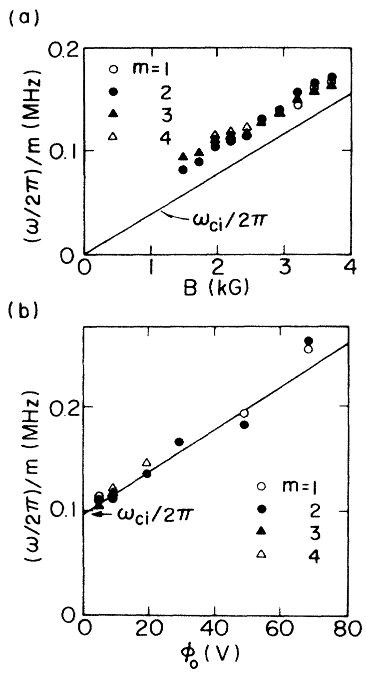

FIG. 5. Fluctuation frequencies $\omega/2\pi$ normalized by m as a function of (a) B on the low-potential side of the DL at $\phi_0 = 10$ V and of (b) ϕ_0 at $B = 2.5$ kG.

mirror configurations of magnetic field, yielding features in common with the potential and magnetic field structures above the Earth's auroral oval. Electrostatic oscillations with frequencies $\gtrsim m\omega_{ci}/2\pi$ appear on the low-potential side of the DL, where a large inhomogeneous radial electric field is formed in the plasma. Finally, our work is a clear laboratory demonstration for such electrostatic ion-cyclotron oscillations to be induced by a radial electric field provided by 3D U- (or V-) shaped DL. Although the process of the potential formation is not necessarily the same as in the region above the Earth's auroral oval, our results are of great importance in order to understand the ion-cyclotron oscillations observed there.

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