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Formation of dc Potential Structure Due to Current-Driven Electrostatic Ion-Cyclotron Instability

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Abstract

Formation of dc potential structure due to current-driven electrostatic ion-cyclotron instabilities has been investigated by means of an open boundary two-and-a-half dimensional electrostatic particle in cell (PIC) simulation model. A dc potential difference is built up as a fluctuation associated with an ion-cyclotron wave induced by streaming electrons grows. A V-shaped dc potential structure is created for a bell-shaped electron stream, while the dc potential does not have a structure across the magnetic field for a uniform electron stream.

Keywords:

particle simulation, electrostatic ion-cyclotron instability, potential formation, aurora, kinetic-self-organization.

1. Introduction

Formation of electrostatic potential structures in magnetized plasmas is as yet a challenging problem for generating accelerated charged particles in a space plasma and controlling particle confinement in a fusion-oriented plasma device [1]. In particular, many space observations support the theory that auroral electrons are accelerated by an electric field above the ionosphere [2-4]. A current-driven electrostatic ion-cyclotron instability has been paid much attention as a candidate for formation mechanism [5,6]. In fact, it is reported that a V-shaped potential structure and an electrostatic ion-cyclotron wave are simultaneously present above the auroral ionosphere [7]. Although many computer simulations concerned with an ion-cyclotron instability have been performed [8,9], they did not succeed in demonstrating the creation of a dc potential difference along the magnetic filed by the instability.

In our previous papers [10,11] we have shown that the growth of an ion-cyclotron wave and creation of a dc potential difference along the magnetic field due to the current-driven instability in an open boundary simulation model. Furthermore, we have succeeded in demonstrating that a V-shaped dc potential structure is created by a current-driven electrostatic ion-cyclotron instability in the case of bell-shaped electron stream [11]. It is also interesting that the formation of dc potential structure due to a kinetic instability from the view point of the kinetic self-organization [12]. In this paper, we present the time evolutions of dc potential structure accompanied by current-driven electrostatic ion-cyclotron instability for the cases with a spatially uniform electron stream and a bell-shaped electron stream.

2. Simulation Model

We have employed a two-and-a-half dimensional particle in cell (PIC) simulation model with a self-consistent open boundaries [11,13]. A self-consistent

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open boundary condition is applied to the x direction, while a periodic boundary condition is applied to the y direction. An external uniform magnetic field is pointing into the x direction. The system is assumed to be divided in segments in the y direction where each segment is assumed to be connected to an external constant generator, and thus the particle influx at the $x = 0$ and $x = L_x$ boundaries is controlled in such a way that the net flux is kept constant in each time step in each segment. This procedure is applied for electrons, while the reflection boundary condition is applied for ions.

The ion motion is followed in the two dimensional real space and the three dimensional velocity space, whereas we adopt the drift kinetic approximation for electrons.

Simulation parameters are as follows: The system sizes are $L_x = 512\ \lambda_{De}$ and $L_y = 128\ \lambda_{De}$ and 512×128 spatial cells are used, where λ_{De} is the Debye length. The system is divided in 16 segments in the y direction. The ion to electron mass ratio is 400 and the temperature ratio is 1/2. The electron cyclotron frequency $\omega_{ce} = 5\ \omega_{pe}$ and the ion cyclotron frequency is $\omega_{ci} = 0.0125\ \omega_{pe}$, where ω_{pe} is the plasma frequency. At $t = 0$, 67108864 ions and electrons are uniformly distributed in the system. The ion velocity distribution is a Maxwellian, while the electron velocity distribution is a shifted Maxwellian with drifting into the x direction. In this paper we present the results of the cases with a uniform electron stream and a bell-shaped electron stream. For the uniform electron stream case, we have performed with the electron drift velocity $v_{de}/v_{te} = 0.8$, where v_{te} is the electron thermal velocity. For the bell-shaped electron stream case, electron drift velocity is given by $v_{de}(y)/v_{te} = 0.6 - 0.2 \cos (2\pi y/L_y)$.

It is to be noted that ion acoustic wave is not unstable and electrostatic ion-cyclotron wave is unstable in these plasma parameters.

3. Simulation Results

First of all, we present the results for the case of the spatially uniform electron stream with $v_{de}/v_{te} = 0.8$. Figure 1 shows the time evolution of the dc potential profile which is averaged over the period of the ion-cyclotron oscillation. We can see that the potential gradually goes up to the downstream region along the magnetic field. This potential difference along the magnetic field grows with time and the potential difference becomes $e\Delta\phi/T_e \simeq 0.05$ at $\omega_{pe}t = 2000$. It is to be noted that there is no significant potential structure across the magnetic field.

In order to see the relation between the growth of the ion-cyclotron wave and the increase of the dc potential difference, we show the time evolutions of the ion density fluctuation of the mode with $k_{\parallel}\rho_i = 0.086$ and $k_{\perp}\rho_i = 0.55$ (a) , which is a typical unstable mode to the ion-cyclotron instability in our simulation parameters, and the potential difference along the magnetic field which is averaged over the y direction and four times of the plasma period (b) in Fig. 2. The ion density fluctuation rapidly grows in the initial stage. The potential difference goes up with an increase in the

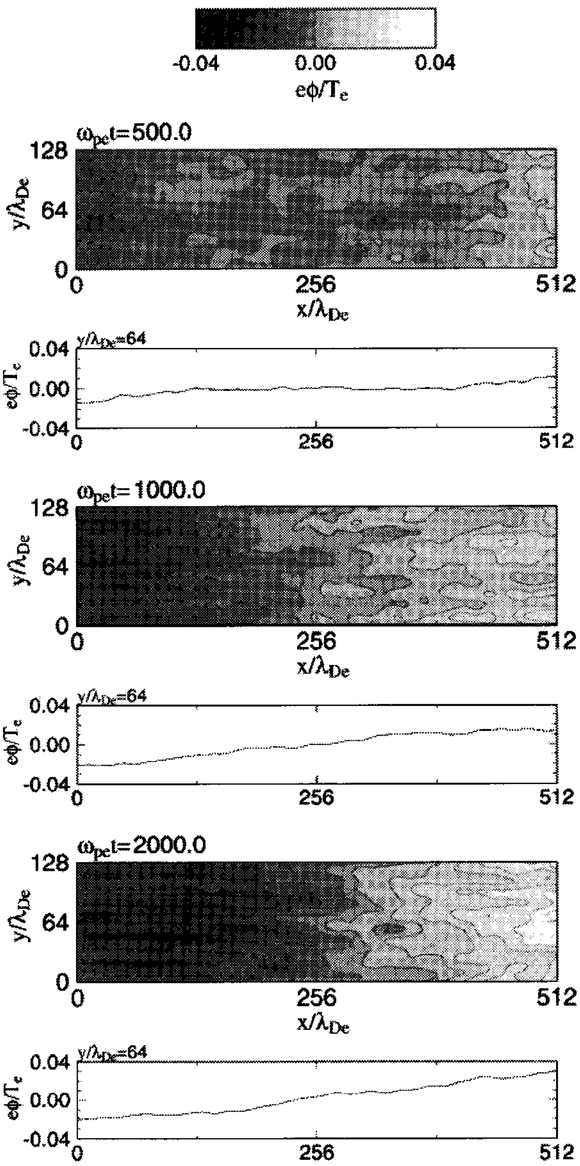

Fig. 1 Time evolution of dc potential profile for the case with a uniform electron stream.

fluctuation accompanied by the instability in the initial stage. At $\omega_{pe}t \simeq 2000$ the growth of the potential difference saturated, although the growth of the fluctuation level continues. The potential difference along the magnetic field lines across the system is about $e\Delta\phi/T_e \simeq 0.05$. Potential difference along the magnetic field lines may be created by the anomalous resistivity. The anomalous resistivity can be calculated from the relation $\eta = eE/n_0e^2\, v_{de} = e\,(\Delta\phi/L_x)/n_0e^2\, v_{de}$. Using the above results with $e\Delta\phi/T_e \simeq 0.05$, $L_x = 512\ \lambda_{De}$, $v_{de} = 0.8\ v_{te}$, one can get $\eta/\eta_0 \simeq 1 \times 10^{-4}$, where $\eta_0 = 4\pi/\omega_{pe}$.

Next, we show the time evolution of the dc potential profile for the case with the bell-shaped electron stream. Figure 3 shows the time evolution of the dc potential profile which is averaged over the period of the ion-cyclotron oscillation. A V-shaped potential structure which is vaguely seen in the upstream region at $\omega_{pe}t = 500$ grows with time, and then clearly formed at $\omega_{pe}t = 2000$. The potential difference along the magnetic field is $e\Delta\phi/T_e \simeq 0.04$. Potential well is also observed across the magnetic field. Its depth is $e\Delta\phi/T_e \simeq 0.02$ at $x \simeq 100\ \lambda_{De}$. In this case, the wave amplitude is larger in the fast electron stream region ($y \simeq L_y/2$) than in the slow electron stream region ($y \simeq 0, L_y$), and thus the potential difference along the magnetic field is larger in the fast electron stream region than in the slow electron stream region. The ion-cyclotron instability causes the ion perpendicular heating as well as the ion transport across the magnetic field. Since the instability is stronger in the fast electron stream region than in the slower electron stream region, the fast electron stream region becomes electron rich. As a result, the potential well across the magnetic field may be created.

The potential difference obtained in this simulation is quite small. However, the potential jump increases as propagating in the downstream region. Thus it is likely that a larger potential difference may be created for a larger and longer system. If we assume that the potential difference is proportional to the system length, one can get kV potential difference for $T_e = 1$ eV, $n_e = 10^2$ cm^{-3}, and several thousand kilometers anomalous resistivity

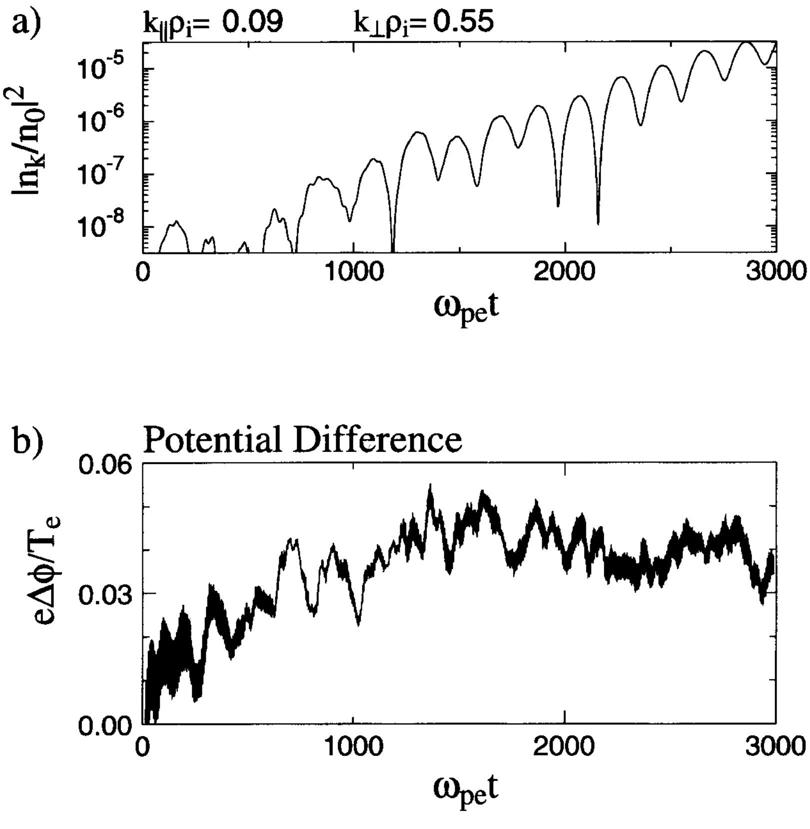

Fig. 2 Time history of ion density fluctuation (a) and potential difference along the magnetic field (b) for the case with a uniform electron stream.

region [14], which is consistent with the auroral electron acceleration.

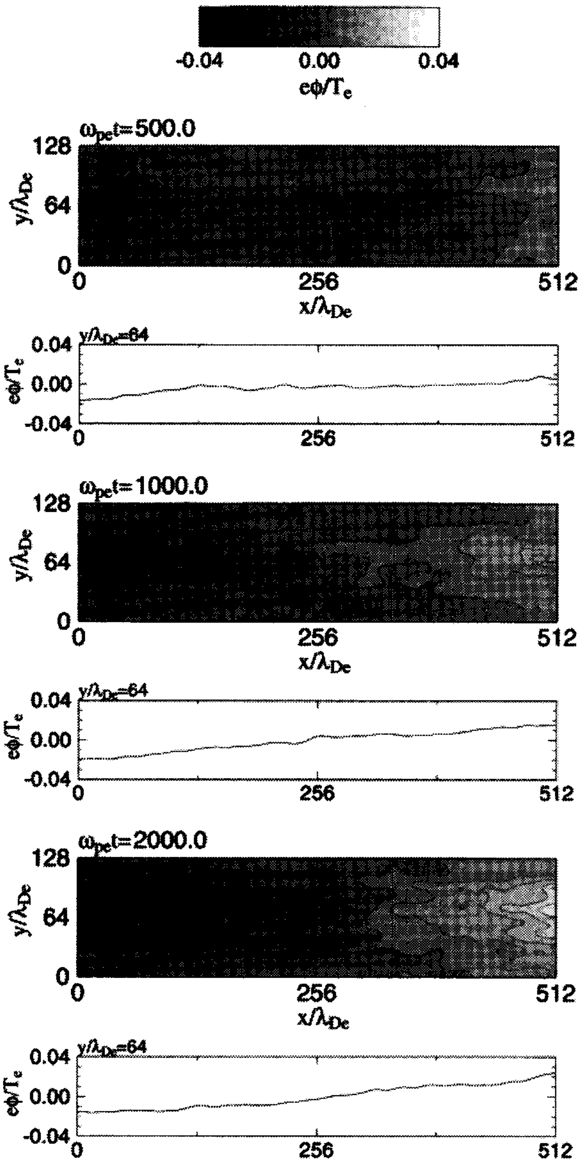

Fig. 3 Time evolution of dc potential profile for the case with a bell-shaped electron stream.

4. Summary

We have investigated that the time evolutions of dc potential structure created by current-driven electrostatic ion-cyclotron instabilities by means of an open boundary two-and-a-half dimensional electrostatic particle in cell (PIC) simulation where the simulation system is connected to constant current generators. It is shown that the dc potential difference along the magnetic field gradually increases with an increase in the fluctuation accompanied by electrostatic ion-cyclotron waves due to the instability. The electrostatic potential increases from the upstream boundary to the downstream boundary. While there is no significant potential structure across the magnetic field for the case with the uniform electron stream, a V shaped potential structure is observed to grow with time for the bell-shaped electron stream.

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