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Simulation Studies of Buneman Instabilities in a Multi-Ion-Species Plasma

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Abstract

Buneman instabilities in a plasma consisting of hydrogen (H), helium (He) and electrons are studied by means of a two-dimensional, electrostatic, particle simulation code with full ion and electron dynamics. Electrons drift along a uniform magnetic field with an initial speed larger than the electron thermal speed. Simulations show that Buneman waves grow firstly and produce electric potential larger than the electron temperature. This potential traps some electrons, which causes the saturation of the Buneman waves. The potential reflects some H ions and accelerates them, while it does not reflect He ions with a smaller thermal speed. The electron trapping due to Buneman waves drastically changes the electron velocity distribution function $f_e(v_\parallel)$. This destabilizes H cyclotron waves which are almost stable in the initial state. These waves eventually grow to large amplitudes and heat He ions. As a result of the instabilities, $f_e(v_\parallel)$ is significantly broadened and finally has a plateau region much larger than the initial thermal speed.

Keywords:
buneman instability, ion cyclotron wave, energy transport, multi-ion-species plasma

1. Introduction

Nonlinear evolution of current-driven instabilities and energy transport in a multi-ion-species plasma are important problems in the heating and acceleration of ions in space plasmas [1-5]. Recently, with particle simulations, we have studied current-driven instabilities of ion acoustic and ion cyclotron waves in a plasma consisting of hydrogen (H) and helium (He) ions and electrons with the electron temperature higher than the ion temperatures [6]. It was demonstrated that ion acoustic waves quickly saturate to small amplitudes and that H cyclotron waves, which are only marginal in the initial state, eventually become dominant owing to the change in the electron parallel velocity distribution function, $f_e(v_\parallel)$. Those H cyclotron waves heat both H and He ions perpendicular to the magnetic field.

In that work, the electrons were assumed to drift along a uniform magnetic field with the initial speed equal to the thermal speed, $v_{d0} = v_{Te}$. In this paper, we numerically study the instabilities by stronger electron currents; the initial electron drift speed is taken to be larger than the electron thermal speed, $v_{d0} = 3v_{Te}$. It is found that, in the stronger current case, electric potential generated by Buneman waves becomes much larger than the electron temperature and strongly influences energy transport. Because some electrons are trapped by the potential, $f_e(v_\parallel)$ is deformed and broadened much more than in the smaller current case. The potential also reflects some H ions, which increases the parallel kinetic energy $K_\parallel$ more than the perpendicular energy $K_\perp$; in the smaller current case, the increase of $K_\parallel$ was quite small. Although He ions with a smaller thermal speed are not reflected by the potential, they are heated by H cy-

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clotron waves destabilized by the change in $f_e(v_\parallel)$. As a results of the instabilities of the Buneman waves and H cyclotron waves, $f_e(v_\parallel)$ finally has a flat region much larger than the initial thermal speed.

2. Simulation

We study the current-driven instabilities in a multi-ion-species plasma, using a two-dimensional (two space and three velocity components), electrostatic particle code with full ion and electron dynamics. The system size is $L_x \times L_y = 256\Delta_g \times 1024\Delta_g$, where Δ_g is the grid spacing. The code has three particle species; H, He and electrons. Their total particle numbers are $N_H = 27, 787, 264$, $N_{He} = 2, 883, 584$, and $N_e = 33, 554, 432$. The mass ratios are $m_H/m_e = 100$ and $m_{He}/m_H = 4$; the charge ratios are $q_H/|q_e| = 1$ and $q_{He}/q_H = 2$; the temperature ratios are $T_e/T_H = 5.0$ and $T_{He}/T_H = 1$; the electron cyclotron frequency is $|\Omega_e|/\omega_{pe} = 2.0$. The Debye length is $\lambda_{De} = \Delta_g$.The uniform external magnetic field is in the y direction.

We assume that the ions have isotropic Maxwellian velocity distribution functions at $t = 0$, and that the electrons drift along the magnetic field; the initial electron velocity distribution function is set to be

$$f_e(v_\parallel, v_\perp) = \frac{1}{(2\pi v_{Te}^2)^{3/2}} \exp\left(-\frac{v_\perp^2}{2v_{Te}^2}\right) \exp\left(-\frac{(v_\parallel - v_{d0})^2}{2v_{Te}^2}\right). \quad (1)$$

Here, the subscripts $\parallel$ and $\perp$ denote quantities parallel and perpendicular to the magnetic field, respectively. The initial drift speed is taken to be $v_{d0} = 3v_{Te}$. For these initial conditions and parameters, Buneman waves are unstable. Fundamental and second harmonic H cyclotron waves are also unstable. However, their growth rates are much smaller than those of Buneman waves. Ion acoustic waves and He cyclotron waves are stable.

Figure 1 shows time variations of the electron drift speed (parallel velocity averaged over all electrons) and amplitudes of two typical modes. Here, the drift speed is normalized to its initial value. The electric field energy $|E_k|^2$ is normalized to $m_e v_{Te}^2$. The solid line (a) in the lower panel represents a Buneman wave with the wave number $(k_\parallel\lambda_{De}, k_\perp\lambda_{De}) = (0.39, 0)$. The dashed line (b) shows a second harmonic H cyclotron wave with $(k_\parallel\lambda_{De}, k_\perp\lambda_{De}) = (0.018, 0.17)$. We will refer to these modes as mode (a) and (b), respectively. The theoretical initial growth rate γ and frequency ω of mode (a) are $\gamma = 0.088\omega_{pe}$ and $\omega = 0.12\omega_{pe}$. On the other hand, mode (b)

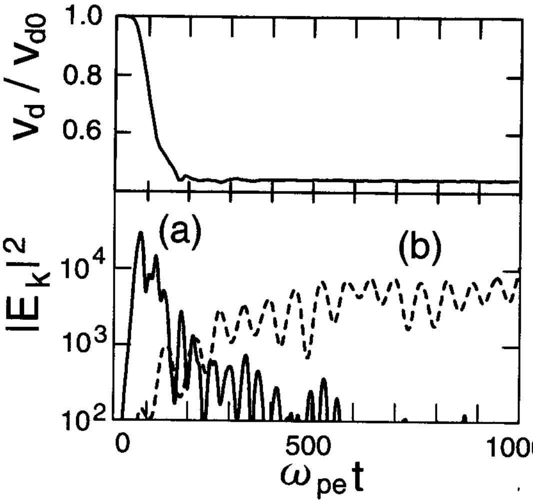

Fig. 1 Time variations of amplitudes of two typical modes. Solid line (a) and dashed line (b) represent a Buneman wave and second harmonic H cyclotron wave, respectively.

is initially almost stable. In the early stage, the electron drift speed quickly decays with time, and mode (a) rapidly grows. The observed initial growth rate of mode (a), $\gamma = 0.085\omega_{pe}$, is in good agreement with the theoretical value. However, it soon saturates and is damped after the time $\omega_{pe}t \simeq 100$. Although mode (b) is almost stable in the initial state, it is destabilized at $\omega_{pe}t \simeq 100$. Its amplitude eventually becomes the same order of magnitude as that of the early stage of mode (a).

Buneman instabilities produce electric potential larger than the electron temperature. Figure 2 shows a contour map of electric potential, $e\phi$, in the (x, y) plane at $\omega_{pe}t = 75$. Here, the lengths and potential are normalized to λ_{De} and electron temperature T_e, respectively. The potential difference along the magnetic field in the y direction is much larger than T_e; $\Delta(e\phi) \simeq 4T_e$.

Saturation of Buneman waves is caused by the electron trapping by the potential difference along the magnetic field. Figure 3 shows a potential profile as a function of y (along the line $x = 1$) and phase space plot of electrons (y, v_y) at $\omega_{pe}t = 100$. In the phase space, particles in the region $0.5 < x < 1.5$ are plotted. Some electrons are trapped by the positive potential and form vortices in the phase space.

The energies of the Bunaman waves are gradually transferred to H ions, because the electric potential can reflect some H ions and accelerate them. Figure 4 shows a potential profile and phase space plots (y, v_y) of H and He ions at $\omega_{pe}t = 200$. We observe that some H ions are

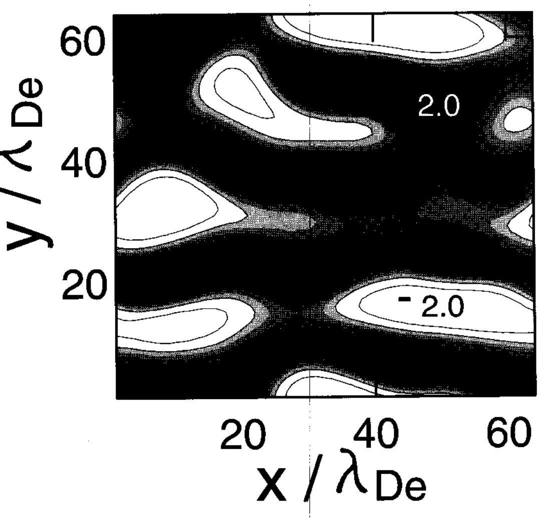

Fig. 2 Contour map of electric potential, $e\phi$, at $\omega_{pe}t = 75$.

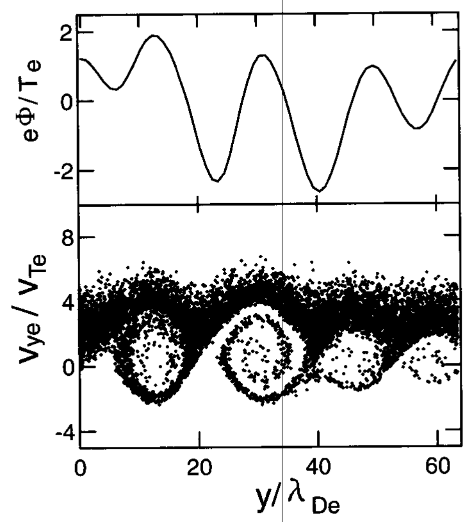

Fig. 3 Potential profile as a function of y (along the line x = 1) and electron phase space plot (y, v_y) at $\omega_{pe}t$ = 100.

being reflected at $y \simeq 10$, around which the potential takes large positive values. The maximum velocity of accelerated H ions reaches a value $v_y \sim 15v_{TH}$. Their energies do not decay, even after the Buneman waves are damped. On the other hand, He ions are not reflected by the potential, because they have a smaller thermal speed. As we will see later in Fig. 6, the parallel energy of He ions decays, as the Buneman waves are damped.

We now discuss the change of the electron parallel velocity distribution function, $f_e(v_{\parallel})$, and its effect on the energy transport. Because of the electron trapping due to Buneman instabilities, $f_e(v_{\parallel})$ is drastically deformed.

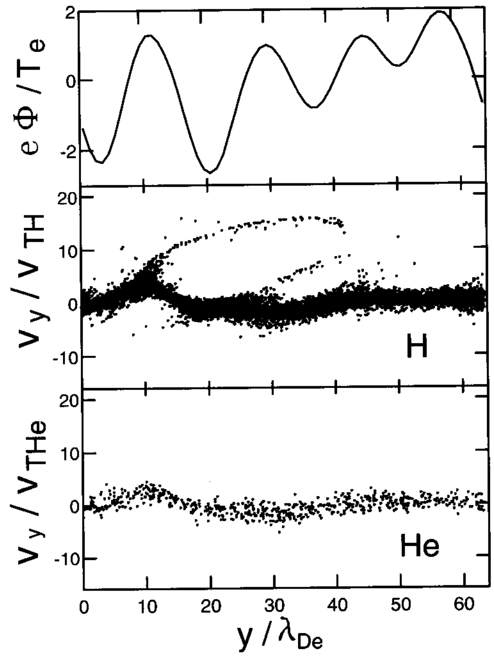

Fig. 4 Potential profile (top panel) and phase space plots (y, v_y) of H and He ions (lower panels) at $\omega_{pe}t$ = 200.

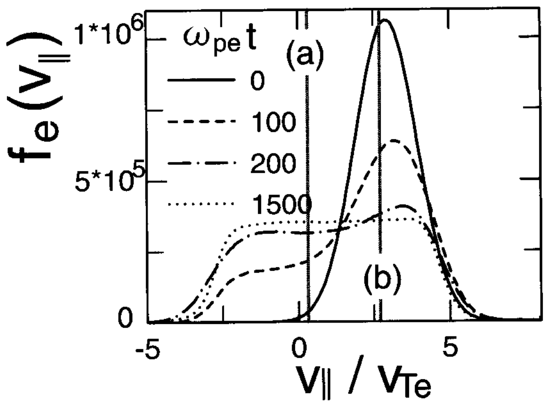

Fig. 5 Evolution of electron parallel velocity distribution function, $f_e(v_{\parallel})$. Vertical lines (a) and (b) show parallel phase velocities of Buneman wave and second harmonic H cyclotron wave, respectively.

This destabilizes H cyclotron waves which are almost stable in the initial state. These waves can strongly influence energy transport to He ions.

Figure 5 shows the evolution of $f_e(v_{\parallel})$. The vertical lines (a) and (b) represent parallel phase velocities, $\omega/k_{\parallel}$, of the Buneman wave ($\omega/k_{\parallel}$ = 0.31) and the second harmonic H cyclotron wave ($\omega/k_{\parallel} = 2.7v_{Te}$), respectively. Time variations of these waves were

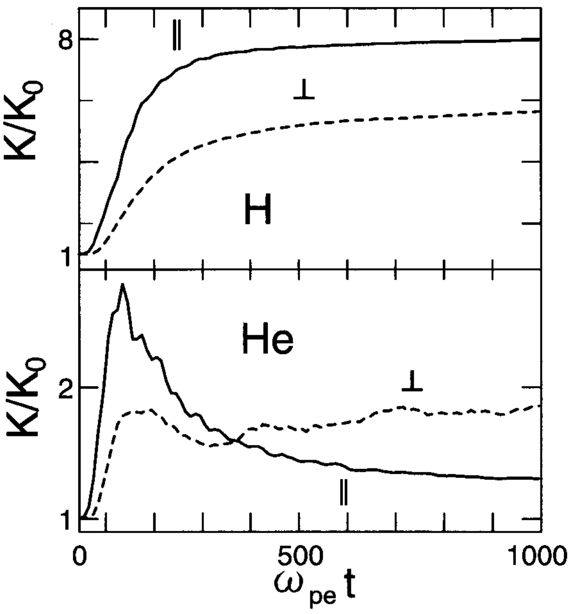

Fig. 6 Time variations of kinetic energies of H and He ions. The solid and dashed lines show parallel and perpendicular energies, respectively. Energies are normalized to their initial values.

already shown in Fig. 1. Initially, $f_e(v_\parallel)$ is a shifted Maxwellian. However, the electron trapping due to the Buneman waves quickly broadens $f_e(v_\parallel)$. Furthermore, it flattens $f_e(v_\parallel)$ over a large region with its center at line (a), and makes the slope of $f_e(v_\parallel)$ steep around line (b). Then, the second harmonic H cyclotron waves are destabilized; their growth rates are proportional to $\partial f_e(v_\parallel)/\partial v_\parallel$ at their parallel phase velocities. The second harmonic waves make $f_e(v_\parallel)$ flat around line (b). As a result of the instabilities of the Buneman waves and H cyclotron waves, $f_e(v_\parallel)$ eventually has a plateau region which is much larger than the initial thermal speed, $-3v_{Te} \lesssim v_\parallel \lesssim 4v_{Te}$.

We plot in Fig. 6 time variations of kinetic energies of H and He ions. The solid and dashed lines represent parallel energy $K_\parallel$ and perpendicular energy $K_\perp$, respectively. They are normalized to their initial values. Note that the vertical axis for H ions is larger than that for He ions. In H ions, the increase in $K_\parallel$ is greater than that in $K_\perp$. This is because the Buneman waves accelerate some H ions in the direction parallel to the magnetic field, as shown in Fig. 4. The increase in $K_\perp$ is mainly due to the collective motions forming H cyclotron waves. On the other hand, in He ions, $K_\perp$ eventually becomes larger than $K_\parallel$. In the early stage, $\omega_{pe}t \leq 150$, $K_\parallel$ and $K_\perp$ rapidly increase, as the Buneman waves grow. After $\omega_{pe}t \sim 150$, both of them decrease, as the Buneman waves are damped. However, at $\omega_{pe}t \sim 300$, $K_\perp$ starts to gradually increase owing to cyclotron resonances with H cyclotron waves.

3. Summary

Nonlinear evolution of Buneman instabilities and energy transport among different particle species are studied by means of a two-dimensional, electrostatic, particle simulation code. Simulations show that Buneman waves grow in the early stage and generate electric potential larger than the electron temperature. The potential traps some electrons, which causes the saturation of the Buneman waves. The wave energies are transferred to H ions, because the potential reflects some H ions and accelerates them. The electron trapping due to Buneman waves drastically deforms $f_e(v_\parallel)$, which destabilizes H cyclotron waves. Although H cyclotron waves are almost stable in the initial state, they eventually grow to large amplitudes and heat He ions. Because of the instabilities, $f_e(v_\parallel)$ finally has a plateau region much larger than v_{Te}.

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