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LOW FREQUENCY ELECTROSTATIC INSTABILITIES
EXCITED BY INJECTION OF AN ELECTRON BEAM IN SPACE

By

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Low Frequency Electrostatic Instabilities
Excited by Injection of an Electron Beam in Space

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ABSTRACT

One-dimensional particle simulations have been carried out to study the low frequency broadband electrostatic noise that propagates almost perpendicularly from the magnetic field line when a nonrelativistic electron beam is injected into space from a spacecraft. For $T_e = T_i$ the electrostatic ion cyclotron waves appear as well as the waves near the lower hybrid frequency. When the magnetic field is reduced so that $\Omega_e \ll \omega_{pe}$ in a non-isothermal plasma, $T_e > T_i$, oblique ion acoustic instabilities appear to propagate almost perpendicular to the magnetic field. In addition, a very low frequency mode at $\omega \ll \Omega_i$ is found to be generated by the electrons flowing into the conductor. Both the injected beam electrons as well as the ambient electrons flowing into the spacecraft are responsible for generating those instabilities, which accelerate ions perpendicular to the magnetic field.

1. Introduction

Recent space experiments such as ARCS (Kaufmann et al., 1985), ECHO (Winckler et al., 1986), SEPAC (Neubert et al., 1986), and the Spacelab 2 mission (Gurnett et al., 1986 and 1988) show that an injected electron beam modified the ambient plasma significantly. Wave generation and particle acceleration are observed in the ambient plasma as the energy density of the beam electrons increases. In particular, excitation of low frequency broadband electrostatic noise has been observed. To understand the interactions between the beam electrons and the ambient plasma that lead to the excitation of various plasma waves and particle accelerations, numerical simulations are performed using a one-dimensional model, which can simulate waves propagating at an arbitrary angle with respect to the magnetic field.

Low frequency ion waves are considered to be excited by the ambient electrons carrying return currents to the spacecraft since the speed of the injected electrons is much larger than the phase velocity of the low frequency ion waves. The drift speed of the return current is generally much smaller than the beam injection speed so that the ambient electrons carrying the return current may be able to excite ion waves directly. Okuda and Ashour-Abdalla(1988) showed using a one-dimensional simulation that the ion acoustic waves are excited along the magnetic field.

In this paper, we study the activities of waves propagating almost perpendicular to the magnetic field. As expected from the cold plasma dispersion

relation, the lower hybrid instabilities are the dominant modes at higher frequencies, $\omega > \omega_{pi}$, which are excited directly by the injected beam. Here ω_{pi} is the ion plasma frequency defined by $\omega_{pi} = (4\pi n e^2 / m_i)^{1/2}$. When the finite electron temperature is considered, waves near the electron gyroharmonics as well as those near the upper-hybrid waves can be excited by the beam electrons. As shown in Sec. 3, we found that these high frequency electron modes saturate at low amplitude. At low frequencies, $\omega < \omega_{pi}$, the electrostatic ion cyclotron waves are destabilized for $T_e > T_i$. These ion cyclotron waves are generated by the ambient electrons returning to the spacecraft. When the magnetic field is reduced so that the electron gyrofrequency is much less than the plasma frequency, oblique ion acoustic instabilities are also excited in a non-isothermal plasma, $T_e > T_i$. In Sec. 2, the electrostatic dispersion relations are discussed emphasizing ion modes propagating nearly perpendicular to the magnetic field. Simulation results are given in Sec. 3. Electrostatic ion cyclotron waves, oblique ion acoustic waves, lower-hybrid waves and a very low frequency mode, $\omega < \Omega_i$, propagating almost perpendicular to the magnetic field, are excited. Significant ion accelerations perpendicular to the magnetic field are observed from these electrostatic instabilities. Section 4 summarizes these results and provides a comparison with data obtained from the spacecraft observations.

2. Electrostatic Dispersion Relation

Consider a beam-plasma system in which a nonrelativistic electron beam is drifting along a uniform magnetic field in a homogeneous background plasma. The perturbation is considered as electrostatic in the form of plasma waves

$$\exp i(kz + k_y y - \omega t), \quad (1)$$

where the parallel direction is along the magnetic field in the z direction. The electrostatic dispersion relation in a hot plasma is given by

$$1 - \epsilon_{pe} - \epsilon_{pi} - \epsilon_{pb} = 0, \quad (2)$$

where ϵ_{pe} and ϵ_{pi} are the susceptibilities of the electron and ion ambient plasma and ϵ_{pb} represents beam plasma, respectively. The susceptibility for the s species is defined by

$$\epsilon_{ps} = -\frac{\omega_{ps}^2}{k^2} \sum_{n=-\infty}^{\infty} \int_L \frac{2\pi v_{\perp} dv_{\perp} dv_{\parallel}}{\omega - n\Omega_s - k_{\parallel}v_{\parallel}} \left[J_n^2\left(\frac{k_{\perp}v_{\perp}}{\Omega_s}\right) \left(n\Omega_s \frac{\partial f_{ps}}{\partial(v_{\perp}^2/2)} + k_{\parallel} \frac{\partial f_{ps}}{\partial v_{\parallel}} \right) \right] \quad (3)$$

with the velocity distribution functions, $f_{ps}(v_{\parallel}, v_{\perp})$, the plasma frequencies, ω_{ps} , the cyclotron frequencies, Ω_s , and $k^2 = k_{\parallel}^2 + k_{\perp}^2$. The integration should be carried out along the Landau contour with respect to $v_{\parallel}$.

Assuming a Maxwellian velocity distribution for the ambient plasma, the plasma susceptibilities become

$$\epsilon_{ps} = \frac{2\omega_{ps}^2}{k^2 v_{Ts}^2} \left[1 - \frac{\omega}{k v_{Ts}} \sum_{n=-\infty}^{\infty} Z\left(\frac{\omega - n\Omega_s}{k_{\parallel} v_{Ts}}\right) \exp(-\lambda_s) I_n(\lambda_s) \right], \quad (4)$$

where $I_n(\lambda_s)$ are the modified Bessel functions with $\lambda_s = k_\perp^2 v_{Ts}^2 / 2\Omega_s^2$, and v_{Ts} is the thermal velocity of the s species. Z is the plasma dispersion function (Fried and Conte, 1961).

The distribution function of the beam electrons is assumed to be

$$f_{pb} = n_b f_M(v_\perp) \left(\frac{1}{\pi v_{Tb}^2} \right)^{1/2} \exp \left(- \frac{(v_\parallel - v_o)^2}{v_{Tb}^2} \right), \quad (5)$$

where the perpendicular velocity distribution is assumed to be a Maxwellian. If the beam drift velocity, v_o , is large compared to the beam electron thermal velocity, $k_\parallel v_{Tb} \ll \omega - m\Omega_e - k_\parallel v_o$, the beam electron susceptibility can be written by (Seidl, 1970)

$$\epsilon_{pb} = \frac{\omega_{pb}^2}{\Omega_e^2} \sum_{m=-\infty}^{+\infty} \left(\frac{S_m \Omega_r^2}{(\omega - m\Omega_e - k_\parallel v_o)^2 k_\perp^2} + \frac{m T_m \Omega_r}{\omega - m\Omega_e - k_\parallel v_o} \frac{k_\perp^2}{k_\perp^2} \right), \quad (6)$$

where ω_{pb} is the beam electron plasma frequency, and S_m and T_m are given by $S_m = \exp(-\lambda_b) I_m(\lambda_b)$ and $T_m = S_m / \lambda_b$ with $\lambda_b = k_\perp^2 v_{Tb}^2 / 2\Omega_e^2$.

When the beam density, n_b , is much smaller than the ambient plasma density, n_p , the dispersion equation, Eq. (2), can be simplified to find the normal modes of the ambient plasma alone,

$$1 + \epsilon_{pe} + \epsilon_{pi} = 0. \quad (7)$$

In the presence of the beam electrons, these normal modes can become unstable when the beam electrons resonate with the normal modes of the ambient plasma satisfying

$$\omega - m\Omega_e - k_\parallel v_o \simeq 0. \quad (8)$$

The waves are most unstable for ω and $k = (k_{\perp}, k_{\parallel})$, satisfying Eq. (7) and Eq. (8), which correspond to the intersections of the plasma dispersion curves with the beam resonance lines.

To find the instabilities driven by the injected electron beam, the ambient and beam plasmas are assumed cold, i.e., $v_{Te} \ll \frac{c}{k} \frac{n\Omega_e}{k}$ and $\lambda_b \ll 1$. Then Eqs. (4) and (6) are combined with the dispersion relation as follows

$$1 - \frac{k_{\perp}^2}{k^2} \frac{\omega_{pe}^2}{\omega^2 - \Omega_e^2} - \frac{k_{\parallel}^2}{k^2} \frac{\omega_{pe}^2}{\omega^2} = \frac{k_{\perp}^2}{k^2} \frac{\omega_{pi}^2}{\omega^2 - \Omega_i^2} - \frac{k_{\parallel}^2}{k^2} \frac{\omega_{pi}^2}{\omega^2} - \frac{k_{\perp}^2}{k^2} \frac{\omega_{pb}^2}{(\omega - k v_o)^2 - \Omega_e^2} + \frac{k_{\parallel}^2}{k^2} \frac{\omega_{pb}^2}{(\omega - k v_o)^2}, \quad (9)$$

where only $m = 0$ and $m = \pm 1$ modes are taken from the beam ϵ_{pb} .

For an oblique propagation at $\omega \gg \Omega_i$, the ion contribution is negligible until the propagation angle becomes almost perpendicular to the magnetic field where

$$\frac{k_{\perp}^2}{k^2} \leq \frac{\omega_{pi}^2}{\omega_{pe}^2} = \frac{m_e}{m_i}. \quad (10)$$

At the perpendicular propagation, the electron plasma waves $\omega = (k/k)\omega_{pe}$ go over to the lower-hybrid wave $\omega^2 = \omega_{pi}^2/(1 - \omega_{pe}^2/\Omega_e^2)$ in the high density limit $\omega_{pi}^2/\Omega_i^2 \gg 1$, and the oblique electron cyclotron waves $\omega = (k/k)\Omega_e$ lead to the upper-hybrid wave $\omega^2 = \omega_{pe}^2 + \Omega_e^2$ for $\Omega_e > \omega_{pe}$. These lower- and upper-hybrid waves are destabilized by coupling with the negative energy waves of $m = 0$ and $m = -1$ on the beam electrons (Seidl, 1970). Each mode has two unstable waves with different wave numbers which are related to the Cerenkov interaction ($m = 0$) at $\omega = k(v_o - \omega_{pb}/k)$ around $\omega \approx k v_o$ and the anomalous Doppler effect ($m = -1$) at $\omega = k v_o - \Omega_e = k \omega_{pb}/k$

for $\omega \sim k v_m$. Near the ion cyclotron frequency, the third term in Eq. (9) becomes dominant and gives another wave branch,

$$\omega \simeq \frac{k}{k_*} \frac{\omega_{pe}}{\omega_{pi}} \Omega_i \quad (11)$$

in the limit of $\omega \ll \Omega_i$, which excites $m = 0$ and $m = -1$, which are two unstable modes driven by the injected beam in this frequency range. But these modes have a very small growth rate compared to the other modes in the cold plasma dispersion relation. Figure 1 from the cold plasma dispersion relation of Eq. (9) shows the frequencies and the growth rates for these instabilities as a function of the wavelength. Here only the $m = 0$ and $m = -1$ modes are unstable by the beam resonance given by Eq. (6).

When the effects of the finite thermal speed of the ambient plasma are considered, the upper-hybrid branch is decomposed into an infinite set of electron cyclotron harmonic branches. Also, the ion cyclotron harmonic waves appear as described by the dispersion relation of Eq. (2). Any of these waves can be excited by the beam, but most of these waves are strongly damped by the cyclotron damping at phase velocities satisfying the resonance condition of Eq. (8). If T_i/T_e is near unity, the most unstable ion cyclotron waves occur at $\omega \simeq 1.2\Omega_i$ and $\lambda_i \leq 1$. As T_i/T_e decreases below 1, the low-order ion cyclotron harmonics become unstable at frequencies $\omega \simeq (m + 1/2)\Omega_i$ and propagate more parallel to the magnetic field and, hence, more like ion acoustic waves propagating nearly perpendicular to the magnetic field. This ion acoustic wave at $\omega \geq \Omega_i$ is damped by ion Landau damping as T_i increases

so that ion acoustic wave instabilities can exist only for $T_i \ll T_e$ (Kindel and Kennel, 1971).

3. One-dimensional Simulation Results

Numerical simulations have been carried out in order to test the excitation of ion waves and ion acceleration perpendicular to the magnetic field. The simulation model developed earlier (Okuda et al., 1987) is modified so that the magnetic field is taken almost parallel to the surface of the conducting plate. In this model the waves propagate almost perpendicular to the magnetic field. The motions of ions and electrons become three dimensional, spiraling across the magnetic field while streaming along the magnetic field in the present model. The beam electrons are continuously injected along the magnetic field from a conducting plate into a semi-infinite uniform plasma with a given density ratio of $n_b/n_p = 1/8$. The system length is $L_x = 1024\Delta$ where Δ is the grid size which is equal to the Debye length $\lambda_{de} = v_{Te}/\omega_{pe}$ of the ambient electrons. The system length is divided into eight bins for the diagnostic purposes whose length is 128Δ . Each grid contains forty electrons and ions initially. Beam injection velocity is $v_o = 20v_{Te}$, and the mass ratio, $m_i/m_e = 100$, is chosen. The ambient electron Debye length is chosen equal to the grid size and about 80 particles per grid have been used. Ion instabilities propagating perpendicular to the magnetic field become apparent when the angle between the magnetic field and wave propagation, θ , is

nearly perpendicular so that the condition of Eq. (10) is satisfied. Here we chose $\theta = 1.52$ in the simulations. In this case the magnetic field is almost parallel to the surface of a conductor so that some of the beam electrons are lost to the conductor when injected. This will be discussed more later. The magnetic field strength is changed for three cases: $\Omega_e > \omega_{pe}$, $\Omega_e \approx \omega_{pe}$, and $\Omega_e < \omega_{pe}$. We ran the simulations long enough so that the ion response can be fully represented.

Let us first study the case where $\Omega_e = \omega_{pe}$ and $T_e = T_i$. Figures 2(a)-(b) show the phase space plots along the magnetic field for the beam electrons at $\omega_{pe}t = 100$ and $\omega_{pe}t = 800$, respectively. The beam electrons are strongly accelerated by the electric field caused by the beam-plasma instabilities so that the phase space structure shows an apparent periodicity corresponding to the wavelength of the most unstable lower-hybrid instability, $k_\perp \rho_i \approx 1$. Some of the beam electrons attain energy beyond the injection energy. As the instabilities grow further, the beam electrons in the phase space show strong diffusion with stochastic behavior as shown in Fig. 2(b). This can happen when the wave amplitudes become large. Also, we found several different k-modes grow at the later stage of the instability. The overall drift speed is reduced to about $15v_{Te}$, considerably smaller than the injection speed. The average velocity of the ambient electrons near the conducting plate is found to remain negative suggesting the flow of the ambient electrons to the conductor carrying a return current. We discuss in more detail the return current along with the parallel velocity distribution functions of the electrons and the ions.

This return current is considered to induce ion wave instabilities since the velocity of electrons carrying the return current is small compared to the injection velocity (Okuda and Ashour-Abdalla, 1988).

The local electron velocity distributions at $\omega_{pe}t = 800$ for those electrons located at $128\Delta \leq x \leq 256\Delta$ are given in Fig. 3. The beam electrons in parallel velocity distribution show broad spread in energy. While most of the beam electrons slowed down losing their energy, some of them gained energy extending beyond the initial injection energy as shown in Fig. 3(a). The ambient electron distribution shows a net drift toward the conductor representing a return flow and it has a negative slope, $\partial f / \partial v_{\parallel} < 0$ for $-2.5 \leq v_{\parallel}/v_{Te} \leq 2.0$ so that it is possible for this electron distribution to excite waves whose phase velocity v_{ph} lies $-2.5 \leq v_{ph}/v_{Te} \leq 0$ (Okuda and Ashour-Abdalla, 1988). The average ambient electron drift speed is negative and the drift speed in this bin is close to the estimated velocity of the return current, $v_r = v_0 n_b / n_p$, based on the charge neutrality. But the average drift speed of the other bins is found generally smaller than the estimated speed based on the charge neutrality. High frequency electron waves such as upper-hybrid waves and electron cyclotron waves propagating perpendicular to the magnetic field saturate at such a small amplitude that perpendicular velocity distribution $f_{\perp}^e$ shown in Fig. 3(b) does not indicate any appreciable acceleration of the electrons. The parallel velocity distribution of ions shown in Fig. 3(c) does not show any net drift so that the return current is carried by the electrons alone. On the other hand, the perpendicular distribution of

ions in Fig. 3(d) shows strong acceleration, resulting in the high energy tail formation, which is due to the instabilities propagating perpendicular to the magnetic field.

In order to identify the plasma instabilities propagating nearly perpendicular to the magnetic field, frequency spectra for the electric field E and the ion density perturbation $\delta n_i = n_i - \bar{n}_i$ at a fixed position of $x = 104\Delta$ have been plotted in Figs. 4(a) and (b), respectively. The frequency spectrum of the electric field shows the most prominent peak around the lower-hybrid frequency at $\omega \approx 0.07\omega_{pe}$. The corresponding wavelength spectrum of the electric field at a fixed time $\omega_{pe}t = 400$ given by Fig. 4(c) shows a sharp peak at $k_\perp \rho_i \approx 1$ where ρ_i is the ion Larmor radius. From this observation, we find $kv_e \approx 0.1\omega_{pe}$, suggesting that this mode is the lower-hybrid instability driven by the $m = 0$ beam mode given by the resonance condition, Eq. (8). The frequency spectrum of the ion density perturbation in Fig. 4(b) shows the dominant peak at the lower hybrid frequency and a smaller peak at $\omega \approx \Omega_i$ and another very small peak near the higher harmonics. These modes near the ion cyclotron harmonics correspond to the ion cyclotron instabilities.

When the magnetic field strength is reduced to $\Omega_e = 0.2\omega_{pe}$ and the mass ratio is changed to $m_i/m_e = 400$, the wave spectra of this simulation are given in Figs. 5. To reduce ion Landau damping, a non-isothermal plasma with $T_i/T_e = 0.1$ is considered. In this case the ion cyclotron frequency becomes so small, $\Omega_i \approx 1/2000\omega_{pe}$, that these ion cyclotron instabilities can be negligible for our simulation period, $\omega_{pe}t = 800$. Since the large Larmor

radius of the beam electrons, $\rho_b \simeq 5\Delta$, causes the loss of the beam particles near the injection point, the injection current is reduced so that the resultant instabilities and accelerations become weaker. The frequency spectrum of the ion density perturbation in Fig. 5(a) shows a peak at $\omega \approx 0.06\omega_{pe}$ near ω_{pi} as well as near the lower-hybrid frequency, $\omega_{LH} \simeq 0.01\omega_{pe}$. The wavelength spectrum for the fixed frequency at $\omega = 0.015\omega_{pe} \simeq \omega_{LH}$ is given in Fig. 5(b). This spectrum shows a large peak at $k \cdot \rho_i \simeq 1$ corresponding to $kv_o = 0.015\omega_{pe}$. This wave is the lower-hybrid instability propagating away from the spacecraft corresponding to the $m = 0$ in Eq. (8) excited by the injected beam directly. When the frequency is fixed at $\omega = 0.06\omega_{pe}$, the corresponding wavelength spectrum is shown in Fig. 5(c). This spectrum shows a broadband spectrum at negative k values indicating that these modes are propagating toward the spacecraft which are driven by the ambient electrons flowing into the conductor. We found the average k value satisfies $\omega = kc_s \simeq \omega_{pi}$ where c_s is the sound speed. Therefore, this backward propagating wave can be identified as the oblique ion acoustic instability driven by the return current.

When the magnetic field strength is increased to $\Omega_e = 4\omega_{pe}$, the electron Larmor radius becomes so small that the beam electrons can be injected almost perpendicularly into plasmas without suffering loss near the injecting point. Thus, the beam electron density is not reduced, so it can excite stronger beam plasma instabilities along the magnetic field. Results of this simulation are shown in Figs. 6 and 7 using $T_e = T_i$, $v_o = 20v_{Te}$, and $m_i/m_e = 100$. Phase space plots along the magnetic field shown in Figs. 6(a)-(b)

indicate large parallel acceleration of the ambient electrons as well as the beam electrons. Large density fluctuations of both the beam and ambient plasmas shown in Figs. 6(c)-(d) can result in a widely varying drift speed of the electrons carrying return currents for each bin.

In the second bin, for example, the ratio of the beam to the ambient plasma densities becomes so large that the ambient electrons drift as fast as $v_e \approx 7.7\tau_e$, as shown in Fig. 7(a). In addition to the return current carried by the ambient electrons, ions also are found to carry return current in the region where a large beam density is found, although the ion drift is relatively small compared to electron drift as shown in Fig. 7(b). On the other hand, in the fourth bin shown in Figs. 7(c) and (d) the drift speed of the electrons remains small and almost no drift of ions is found, which can be expected from the density distribution shown in Figs. 6(c)-(d). The ratio between the beam density and the ambient plasmas' density in the fourth bin is so small that the ambient electrons drift slower.

The electron perpendicular velocity distribution given by Fig. 8(a) shows no appreciable acceleration in the perpendicular direction, but very strong perpendicular ion accelerations are observed in Fig. 8(b). This perpendicular acceleration of ions can heat the plasmas outside the injected beam by gyrating out of the pass along the initial beam electrons.

Since the magnetic field strength is increased, the growth rate of the ion cyclotron instabilities is found to become larger. In addition, the net beam current is not reduced because of its small Larmor radius, so the waves can

grow to larger amplitude. The wave spectrum of the ion density perturbations for $\Omega_i \approx 4\omega_{pe}$ measured at $x = -4.4\Delta$ is shown in Fig. 9 which shows the apparent ion cyclotron harmonics as well as the lower-hybrid instabilities. Also, the very low frequency mode satisfying Eq. (11) is observed as expected from the cold plasma dispersion relation.

4. Conclusions

One-dimensional particle simulations have shown that the low frequency ion waves propagating almost perpendicular to the magnetic field can be excited by the injection of a nonrelativistic electron beam into a plasma from a conducting spacecraft. Since the drift speed of the ambient electrons carrying return currents is much smaller than the beam injection speed, low frequency ion modes are excited by the return flow of the ambient electrons accelerating ions significantly perpendicular to the magnetic field. While the lower-hybrid instability is the strongest mode among the ion modes excited directly by the injected beam, lower frequency electrostatic ion cyclotron waves and oblique ion acoustic waves are also excited by the ambient electrons carrying return currents. In addition, the very low frequency mode $\omega \approx (k_{\parallel}\omega_{pe}/k_{\perp}\omega_{pi})\Omega_i$ is also found to be excited.

These simulation results may be used to understand the data obtained from spacecraft experiments. Broadband electrostatic noise at low frequencies in Spacelab 2 (Gurnett et al., 1986), and a quasi-dc component and large

superposed low frequency components as well as the ion gyroharmonic waves in the ECHO 6 experiment (Winckler et al., 1986) have been detected. These low frequency waves seem to correspond to the ion modes found in our one-dimensional simulation model. These ion modes propagating perpendicular to the magnetic field cause significant ion accelerations. This perpendicular acceleration of ions as well as the anomalous beam diffusion (Okuda et al., 1988) may be able to explain the hot plasma produced in the region exterior to the beams in ECHO 6 experiments (Winckler et al., 1986).

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Figures

FIG. 1. Cold plasma dispersion relations with $\theta = 0.05$, $m_i/m_e = 100$ and $\Omega_e = \omega_{pe}$. Solid lines represent frequencies $\text{Re } \omega$ and dotted lines are growth rates $\text{Im } \omega$.

FIG. 2. Phase space plots from the simulation with $\Omega_e = \omega_{pe}$, $m_i/m_e = 100$ and $T_e = T_i$ of the beam electrons at (a) $\omega_{pe}t = 400$ and (b) $\omega_{pe}t = 800$.

FIG. 3. Local electron velocity distributions of the second bin($128\Delta \leq x < 256\Delta$) at $\omega_{pe}t = 800$.

- (a) Electron parallel velocity distribution.
- (b) Electron perpendicular velocity distribution.
- (c) Ion parallel velocity distribution.
- (d) Ion perpendicular velocity distribution.

FIG. 4. Frequency and wavelength spectra of the simulation with $\omega_{LH} \simeq 0.07$ and $\Omega_i = 0.01$.

- (a-b) The frequency spectra of the electric field(a) and the ion density perturbation(b) at the fixed point $x = 104\Delta$.
- (c) The wavelength spectrum of the electric field at the fixed time $\omega_{pe}t = 400$.

FIG. 5. Frequency and wavelength spectra of the ion density perturbations of the simulation with $\Omega_e = 0.2\omega_{pe}$, $T_i = 0.1T_e$, and $m_i/m_e = 400$.

- (a) The frequency spectrum at the fixed point $x = 64\Delta$ with $\omega_{LH} = 0.01\omega_{pe}$, $\omega_{pi} = 0.05\omega_{pe}$ and $\Omega_i = 0.0005\omega_{pe}$.
- (b) The wavelength spectrum for the fixed frequency $\omega = 0.015\omega_{pe} \sim \omega_{LH}$.
- (c) The wavelength spectrum for the fixed frequency $\omega = 0.06\omega_{pe}$.

FIG. 6. Results of the simulation at $\omega_{pe}t = 800$ when $T_e = T_i$, $m_i/m_e = 100$ and $\Omega_e = 4\omega_{pe}$.

- (a) Phase space plots of the ambient plasmas and
- (b) of the beam electrons.
- (c) The density distributions in x space of the beam electrons and
- (d) of the ambient plasmas.

FIG. 7. The parallel velocity distributions

- (a) of the electrons at the second bin ($128\Delta \leq x \leq 256\Delta$),
- (b) of the ions at the second bin,
- (c) of the electrons at the fourth bin ($512\Delta \leq x \leq 640\Delta$) and
- (d) of the ions at the fourth bin.

FIG. 8. The perpendicular velocity distributions at the second bin of the electrons(a) and the ions(b).

FIG. 9. The frequency spectrum at the fixed point $x = 44\Delta$ with $\omega_{LH} = 0.1\omega_{pe}$ and $\Omega_i = 0.04\omega_{pe}$.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

(Top) Fig. 8(a) & 8(b)
(Bottom) Fig. 9

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