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Emission of Electromagnetic Waves from Langmuir Waves Generated by Cold Electron Beam Instability in Pair Plasmas

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Abstract

Using a two-dimensional electromagnetic and relativistic particle-in-cell (PIC) code, we show that high-frequency electromagnetic waves can be emitted by the plasma maser from Langmuir waves generated by cold electron beam instability in pair plasmas. It is confirmed that the presence of a magnetic field is essential for the plasma maser mechanism.

Keywords:

pair plasmas, plasma maser, beam instability, Langmuir wave, electromagnetic wave

1. Introduction

Plasma maser [1] is a new nonlinear process for generation of various kinds of waves in plasmas, among other processes like cyclotron maser instability [2], Cherenkov emission [3], free-electron laser [4], and parametric three-waves interaction [5]. The most important characteristics of the plasma maser process is that the process requires the external magnetic field. Recently Gyobu *et al.* [6] showed by using a 2-D EM PIC code that electromagnetic waves (R-mode) can be emitted from Langmuir waves generated by the electron beam ($T/T_b = 2$) instability in pair plasmas, where T is the background temperature and T_b is the beam temperature.

In the present paper we investigate by using a two-dimensional electromagnetic and relativistic PIC code whether electromagnetic waves can be generated by the plasma maser from Langmuir waves excited by cold electron beam ($T_b = 0$) instability [7] in pair plasmas.

2. Simulation Results

It is well known that an electron beam along a magnetic field in the y-direction becomes unstable to excite Langmuir waves. Solid lines in Figs. 1(a) and 1(b) show the time history of electric field energies E_x^2 and E_y^2 for a case of $\omega_{pe}/\Omega_c = 10$ with the beam of $v_b = 0.7c$, $n_b/n_o = 0.1$, while the dotted lines show the time history for a case without the electron beam. As seen in Figs. 1(a) and 1(b), both components of the electric fields are strongly excited due to the beam instability. The solid line in Fig. 1(c) shows the time history of the electric field energy E_z^2, while the dotted line shows the case without the beam. As seen in Fig. 1(c), the electric field E_z grows after the electric field energy associated with the beam instability becomes large.

The enhancement of the electric field E_z is related to the plasma maser mechanism. Before discussing this, we investigate the phase space $y - v_y$ for the beam electrons. Fig. 2 shows the phase space $y - v_y$ for the

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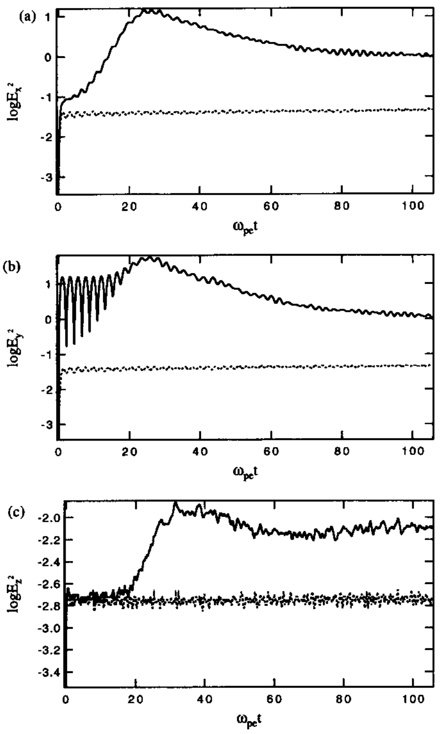

Fig. 1 Time history of electric field energies (a) E_x^2, (b) E_y^2, and (c) E_z^2. Solid lines show a case with $\omega_{pe}/\Omega_c = 10$, $v_b = 0.7c$, and $n_b/n_o = 0.1$. Dotted lines correspond to a case without the electron beam.

beam electrons at $\omega_{pe}t = 21.08$. The beam electrons are bunched in the phase space due to Langmuir waves generated by the electron beam instability.

To investigate the behavior of the electric field E_z, we perform a 2-D Fourier transformation in the direction parallel to a magnetic field. Fig. 3(a) shows the dispersion relations for Ez in the y-direction (ω vs $k_{\|}$). The results show that there appear two branches of electromangetic wave excitation. The first is seen near the frequency 2.5 ω_{pe} with maximum amplitude. The second excitation is seen around $\omega \simeq 1.0\ \omega_{pe}$ and $k_y c/\omega_{pe} = 2.0$. This is so-called Cherenkov emission due to

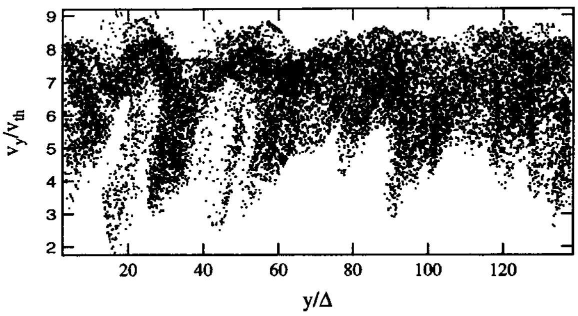

Fig. 2 The $(y - v_y)$ phase space distribution of beam particles at $\omega_{pe}t = 21.8$.

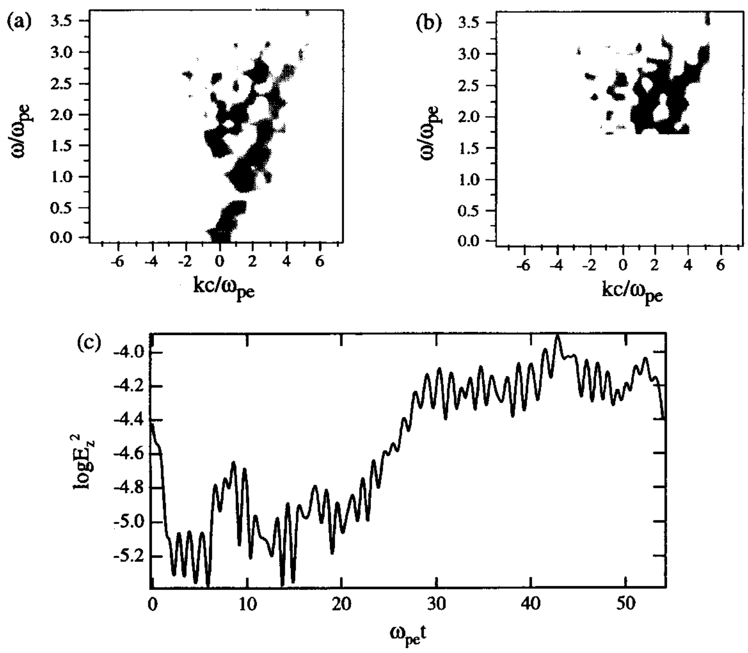

Fig. 3 (a) The dispersion relation for E_z (ω vs $k_{\|}$). (b) The dispersion relation (ω vs $k_{\|}$) for E_z, cutting the low frequency region of $\omega < 1.74\ \omega_{pe}$. (c) Time history obtained by the inverse-Fourier transformation from (b).

the resonance with electron beam. But the first branch could not be explained by the usual emission mechanisms. We cut the low frequency = region of $\omega < 1.746\ \omega_{pe}$ from Fig. 3(a), as seen in Fig. 3(b) and 3(c), then we perform the inverse-Fourier transformation to obtain the time histories for the excited high-frequency waves. As seen in Fig. 3(c), the high-frequency electromagnetic waves with $\omega/\omega_{pe} \simeq 2.5$ along a magnetic field can be excited only after about 20 $\omega_{pe}t$. We may conclude from the above observations that the electromagnetic waves parallel to a magnetic field can be excited by the trigger of the Langmuir waves due to the cold electron beam instability. We investigate further the characteristics of the excited electromagnetic waves. Fig. 4 shows the hodograph of the electric field $E_x - E_z$ associated with the excited electromagnetic waves. From Fig.4 we conclude that the excited electromagnetic waves along a magnetic field show almost linear-polarization.

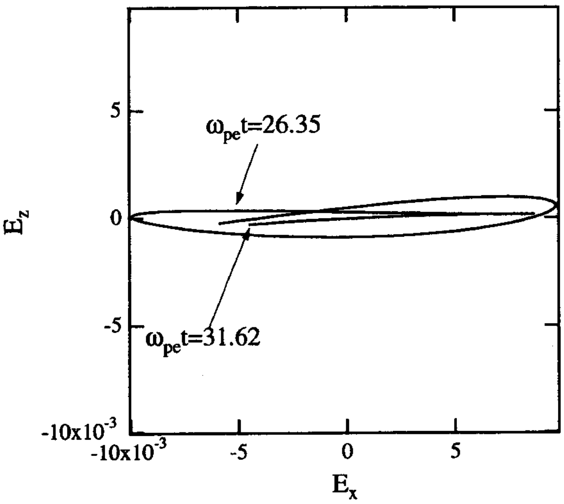

Fig. 4 Hodograph of ($E_x - E_z$) for high-frequency (ω > 1.74 ω_{pe}) electromagnetic waves propagating along a magnetic field.

We investigate further the emission process of electromagnetic waves by Langmuir waves. The plasma maser theory predicts that there appears no plasma maser mechanism when external magnetic field is absent. Fig. 5 shows three different simulations: (1) thermal noise case with no electron beam and no magnetic field, (2) the case with beam ($v_o = 0.7c$, $n_b/n_o = 0.1$) and no magnetic field, (3) case with beam ($v_o = 0.7c$, $n_b/n_o = 0.1$) and with magnetic field ($\omega_{pe}/\omega_{ce} = 0.1$). As seen in Fig. 5, there is no strong enhancement of the electric field Ez for the case (2), compared with the case (3). Therefore, we conclude that the present emission mechanism is the plasma maser process, because it is essential for the presence of the external magnetic field as predicted by the plasma maser theory.

There are many emission mechanisms of electromagnetic waves from Langmuir waves. We try to explain the characteristics of the electromagnetic radiation around $\Omega/\omega_{pe} \approx 2.5$ observed in the present simulation. The cyclotron maser originates from the relativistic electron mass change and the free energy for the electromagnetic radiation exists in the direction perpendicular to a magnetic field. On the other hand, in

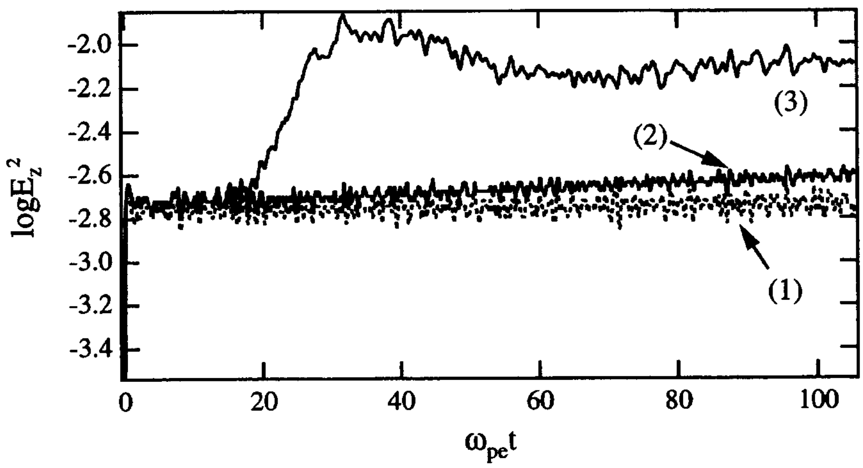

Fig. 5 Time history of electric field energy E_z^2 on effect of external magnetic field. (1) Thermal noise case with no electron beam and no magnetic field. (2) Case with cold beam ($v_b = 0.7c$, $n_b/n_o = 0.1$) and no magnetic field. (3) Case with cold beam ($v_b = 0.7c$, $n_b/n_o = 0.1$) and with magnetic field ($\omega_{pe}/\omega_{ce} = 10$).

the present simulation, the free energy exists in the electron beam parallel to a magnetic field. Thus, we can rule out the cyclotron maser mechanism. Next, the Cherenkov maser satisfies the Cherenkov condition between electrons and electromagnetic waves $\Omega = \vec{K} \cdot \vec{v}$, where Ω and $\vec{K}$ represents the frequency and wavenumber for electromagnetic waves. As is shown by Fig. 3(a) in the present simulation, it is difficult to satisfy the Cherenkov condition because $\Omega/k_{\parallel} = 1.2c \gg v_e$, where c, v_e are light velocity, electron thermal velocity, respectively. Accordingly, the Cherenkov emission mechanism is not likely to operate in our simulation. The third possibility is the free electron laser including the Langmuir waves driven by electron beam. This requires several matching conditions to be satisfied among the frequencies and wavenumbers of Langmuir and electromagnetic waves. However, the simulation results does not satisfy these matching conditions. Finally, the standard three-wave interaction requires the matching conditions $\Omega \pm \omega = \Omega'$, $\vec{K} + \vec{k} = \vec{K}'$, where ω, $\vec{k}$ shows the frequency, wavenumber of Langmuir waves, respectively. We may rule out the three-wave interaction because the above conditions are not satisfied in the simulation. Accordingly, we must conclude that the standard emission mechanisms can not explain the generation of high-frequency electromagnetic radiation around $\Omega/\omega_{pe} \approx 2.5$ observed in the present simulation.

3. Conclusions

We found that high-frequency electromagnetic waves can be excited for both directions parallel and perpendicular to a magnetic field. We confirmed that these electromagnetic waves can be generated by the plasma maser from Langmuir waves excited by the cold electron beam instability.

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