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Nonlinear Plasma Maser Driven by Electron Beam in Magnetized Plasma

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Abstract

Simulations using a two dimensional electromagnetic and relativistic particle code show that high frequency electromagnetic waves with right-handed polarization (R-mode) can be generated by a plasma maser mechanism from electrostatic Langmuir waves excited by electron beam.

Keywords:

plasma maser, beam instability in magnetized plasma, Langmuir wave, right-handed polarized electromagnetic wave

1. Introduction

Plasma maser is a new nonlinear process in plasma turbulence which coexists with the quasilinear process between electrons and the resonant mode. Since the prediction of the process [1], it has attracted much attention because multi-modes turbulence which contains enhanced high frequency fluctuations in addition to low frequency turbulence are quite often observed in laboratory and astropysical plasmas [2]. Recently, the comparison between theory and simulation was reported for the plasma maser process for Langmuir waves [3] and electromagnetic waves [4] in the presence of whistler turbulence.

2. Numerical Simulation

By using TRISTAN code [4], we present the results of the numerical simulations on the generation of R-mode electromagnetic waves in the presence of Langmuir mode turbulence driven by electron beam ($T/T_b = 2$), where T is the backgound temperature and T_b is the beam temperature. Both the electron beam with a beam velocity T_b and a homogeneous external magnetic field are oriented in the z-direction. It is well known that an electron beam along a magnetic field in the z-direction becomes unstable to excite Langmuir waves. Solid lines in Figs. 1(a) and 1(c) show the time history of electric field energies E_x^2 and E_z^2 for a case of $\omega_{pe}/\Omega_e = 10$ with a beam of velocity $v_b = 0.7c$, density $n_b/n_0 = 1/30$, while the dotted lines show the time history for a case without the electron beam. Here, ω_{pe}, Ω_e, n_b, and n_0 are the electron plasma frequency, electron cyclotron frequency, electron beam density and background plasma density, respectively. As seen in Fig. 1(a) and Fig. 1(c), both components of the electric field are strongly excited due to the beam instability. This means that the Langmuir waves are propagating obliquely to the external magnetic field. In Fig. 1(b), the solid line shows the time history of the electric field energy E_y^2 in the presence of the beam, while the dotted line shows the case without the beam. As seen in Fig. 1(b), the electric field E_y grows after the electric field energy

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associated with the beam instability becomes large.

To investigate the behavior of the electric field E_y, we perform two-dimensional Fourier transformations in time and z which is parallel to the external magnetic field. The results show there appears two branches of electromagnetic waves. The first one has broad spectrum with maximum frequency lying around $2\omega_{pe}$ and $k_z \simeq K_z$. Here k_z and K_z are the wavenumbers parallel to the external magnetic field of Langmuir and electromagnetic waves, respectively. The second branch is observed around $\omega \simeq \omega_{pe}$ and $ck_z/\omega_{pe} \approx 1.7$. The second excited branch can be explained with the help of Cherenkov emission process by interaction with the electron beam [5]. But the first branch can not be explained by the usual emission mechanisms because here $\Omega/K_z \simeq 1.2c$ and $(\Omega - \Omega_e)/K_z \simeq 1.1c$. Here, Ω is the frequency of the electromagnetic wave. We cut the low frequency region ($\omega < 1.63\omega_{pe}$), as shown in Fig. 2(a), and then perform the inverse-Fourier transformation to obtain the time histories for the excited high-frequency waves. As seen from Fig. 2(b), the high-frequency electromagnetic waves with $\omega/\omega_{pe} \simeq 2.0$ along a magnetic field can be excited only after about $35\omega_{pe}t$. From the above observations we may conclude that electromagnetic waves propagating parallel to a magnetic field can be excited by the trigger of the Langmuir waves due to the electron beam instability.

The dependence of the whole electron distribution function f_{0e} on v_x, v_y and v_z, are shown by Fig. 3(a), (b) and (c), respectively. In Fig. 3, for example, $f_{0e}(v_x)$ shows the distribution function integrated over all particles with different v_y and v_z, i.e. $f_{0e}(v_x) = \int\int f_{0e}(v_x, v_y, v_z)dv_y dv_z$. The dotted and solid lines show the whole

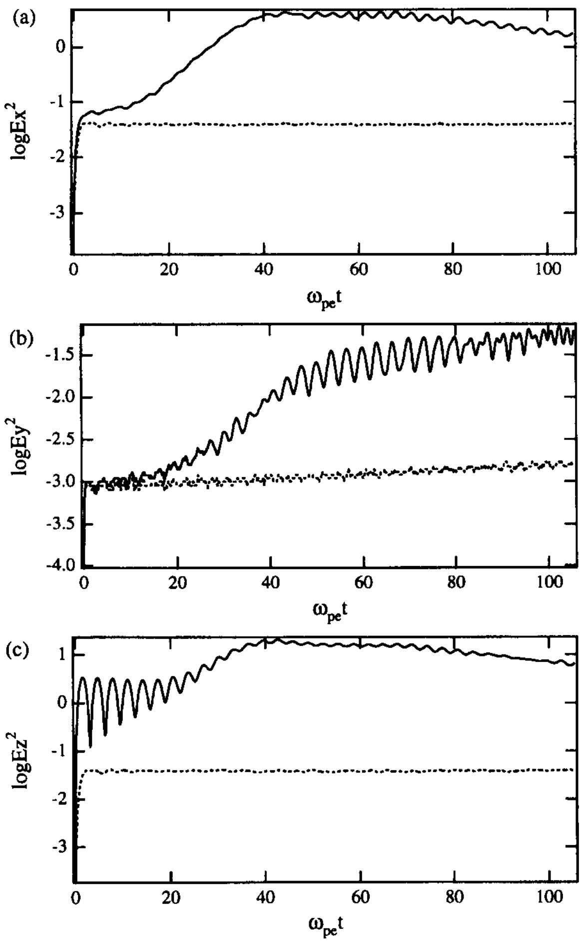

Fig. 1 Time history of electric field energies (a) E_x^2, (b) E_y^2, and (c) E_z^2. Solid lines show a case with $\omega_{pe}/\Omega_e = 10$, $v_b = 0.7c$, and $n_b/n_0 = 1/30$. Dotted lines correspond to a case without the electron beam.

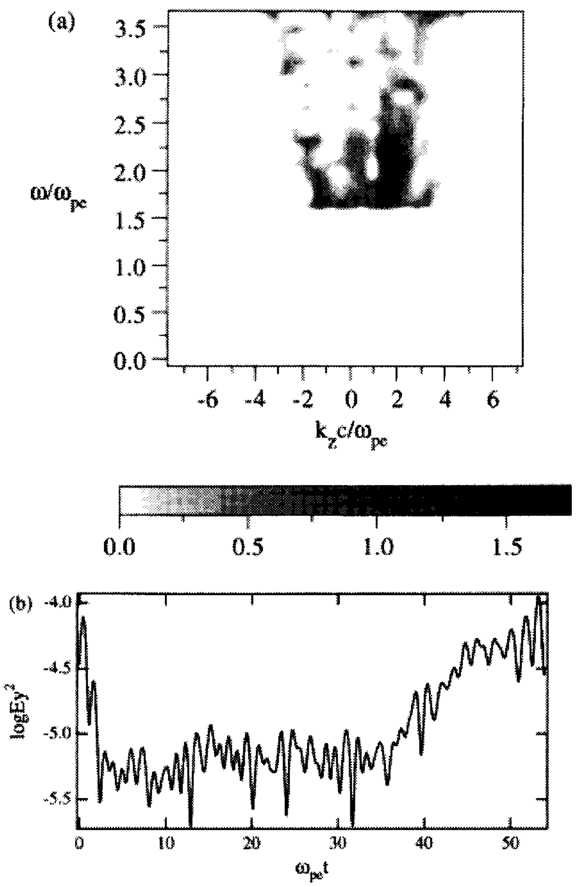

Fig. 2 (a) The dispersion relation (ω vs k) for E_y, cutting the low frequency region of $\omega < 1.63\omega_{pe}$. (b) Time history obtained by the inverse-Fourier transformation from (a).

electron distribution function at $\omega_{pe}t = 0$ and $\omega_{pe}t = 105.4$, respectively. The electron distribution function changes according to the development of the Langmuir turbulence. At the final stage of the simulation study ($\omega_{pe}t = 105.4$), the plateau formation in quasilinear diffusion is observed by Fig. 3(c). This means that the resonant interaction between electrons and the Langmuir turbulence generated by the electron beam occurs quite effectively during the simulation study.

We study the growth rate of the instability with different parameters. Fig. 4(a) shows the growth rate measured in the simulations with different values of electron beam density, n_b/n_0, (1) 1/50, (2) 1/40, (3) 1/35, (4) 1/30, (5) 1/25, (6) 1/20. The growth rate is computed by making use of exponential curve fitting at $\omega_{pe}t = 30$.

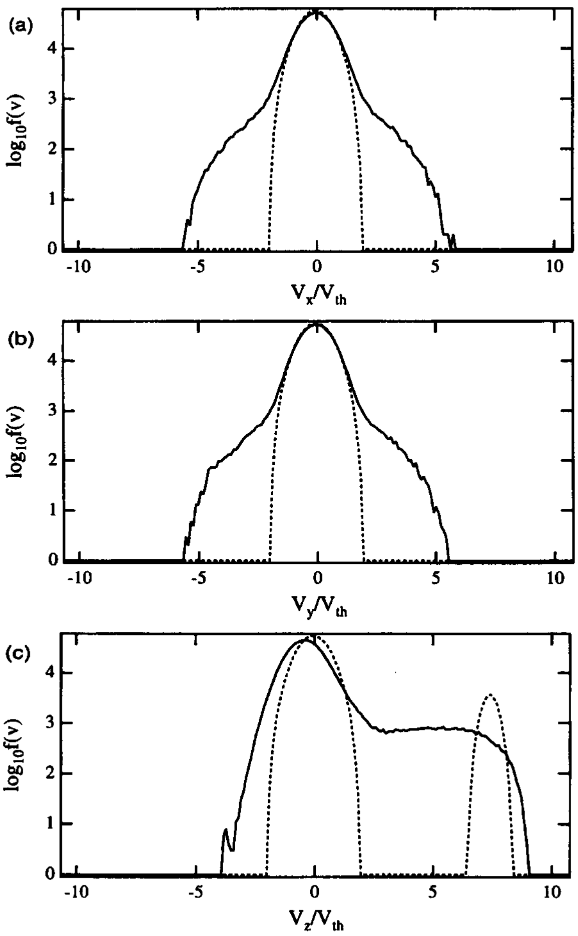

Fig. 3 (a) Dependence of the whole electron distribution function f_{0e} on (a) v_x, (b) v_y and (c) v_z, respectively. The dotted and solid lines show the whole electron distribution function at $\omega_{pe}t = 0$ and $\omega_{pe}t = 105.4$, respectively.

From Fig. 4(a) we find that the growth rate increaes with incresing beam density.

Furthermore, we study the effect of the external magnetic field on the growth of the electromagnetic wave emission. Fig. 4(b) shows the time history of E_y^2 in the presence of an electron beam with $n_b/n_0 = 1/30$ and $v_b = 0.7c$ for (1) zero magnetic field, (2) weak magnetic field $\omega_{pe}/\Omega_e = 10$), and (3) strong magnetic field ($\omega_{pe}/\Omega_e = 3$). From Fig. 4(b), it can be seen that there is no enhancement of the electric field E_y for unmagnetized plasma (case (1)), compared with magnetized plasma (cases (2) and (3)).

The presence of strong magnetic field results in more effective electromagnetic emission.

Finally, the dependence of the normalized growth rate $[\gamma/\omega_{pe}]$ on plasma parameter $[\Omega_e/\omega_{pe}]$ is shown in Fig. 5. The dotted line represents a curve from the equation, $0.063 + 0.334x - 0.272\,x^2$, where $x = \Omega_e/\omega_{pe}$

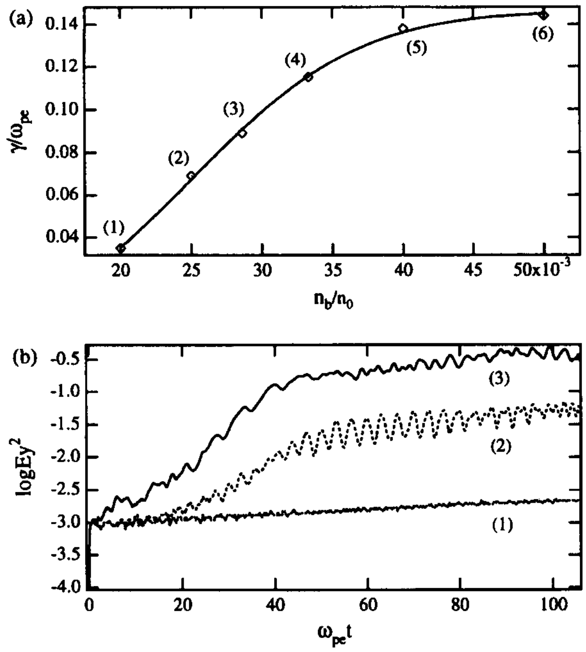

Fig. 4 (a) Growth rates vs beam density for cases with E_y parallel to the magnetic field ($v_b = 0.7c$, $\omega_{pe}/\Omega_e = 10$). (1) $n_b/n_0 = 1/50$, (2) $n_b/n_0 = 1/40$, (3) $n_b/n_0 = 1/35$, (4) $n_b/n_0 = 1/30$, (5) $n_b/n_0 = 1/25$, and (6) $n_b/n_0 = 1/20$. (b) Time history of electric field energy E_y^2 for different external magnetic field strength. (1) Thermal noise case with electron beam ($v_b = 0.7c$, $n_b/n_0 = 1/30$) and no magnetic field. (2) Case with beam ($v_b = 0.7c$, $n_b/n_0 = 1/30$) and weak magnetic field ($\omega_{pe}/\Omega_e = 10$). (3) Case with beam ($v_b = 0.7c$, $n_b/n_0 = 1/30$) and strong magnetic field ($\omega_{pe}/\Omega_e = 3$).

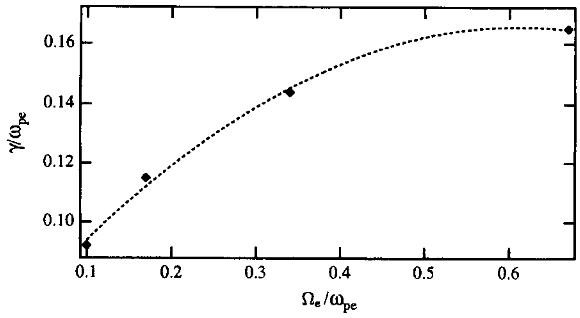

Fig. 5 Dependence of the normalized growth rate [γ/ω_{pe}] on plasma parameter [Ω_e/ω_{pe}]. The dotted line shows a curve from the equation obtained by a least squares method.

obtained by a least squares method. The growth rate enhances with the increase of the magnetic field.

According to the detailed calculations [6], the growth rate obtained from theory is found to be $\gamma/\omega_{pe} = 3.83 \times 10^{-2}$, while the simulations show $\gamma/\omega_{pe} = 1.15 \times 10^{-1}$. The difference may be attributed to the difference in situations between theory and simulations. In simulations, Langmuir waves are propagating obliquely to the ambient magnetic field, whereas in the theoretical model they are propagating along the magnetic field.

3. Conclusions

Numerical simulations show that the EM R-mode wave is amplified by Langmuir turbulence driven by electron beam. The results of the numerical simulations agree well with those of the theoretical analysis [6].

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