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Controversies in Quasilinear Theory and Wave Structure Formation in Current-Carrying Plasma and at Beam-Plasma Interaction

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Abstract

The paper considers the development of a so called "bump-in-tail" and electric current instabilities in plasma. The process of turbulence excitation by "hot" electron beam in plasma-filled cylinder and by electric current in plasma is unstable concerning arising of correlations between an electric field and particles' movement, when the wave-particle correlation length becomes longer than the propagation distance of resonant electrons during the half-period of their oscillations in wave field. In this case a convective movement of particles on the phase space and ordered lattice or chain of packets in space (x, V_{ph}) appear. Packets of the lattice are transparent for electrons but packets of the chain reflect the resonant ones.

Keywords:
ordered wave packets, nonequilibrium plasma, solitary perturbation

1. Introduction

Phase V_{ph} and group V_{gr} velocities of plasma waves propagation in metallic magnetized plasma-filled cylinder [1] are limited from above and $V_{gr} \leq V_{ph} \leq V_c$, unlike V_{ph} of Langmuire waves. V_c is the maximum phase velocity. Such dispersion relation of plasma waves (and of ion-acoustic oscillations) leads to several differences of their packets evolution at "hot"-electron-beam-plasma instability (also at ion-acoustic instability) development in comparison with Langmuir waves, studied in [2-4].

This problem is considered here and is interesting because of the start of a new stage of beam relaxation as well as ion-acoustic instability development. This stage is characterized by increasing of correlation and by formation of structute of coherent packets. As many beam-plasma experiments are carried out in plasma waveguide, an investigation of the wave evolution in it and their interaction due to resonant particles is of practical interest as well as the evolution of ion-acoustic turbulence.

2. Formation of Ordered Structures of Wave Packets in Plasmas

Nonlinear particle dynamics in the wave field with $V_{ph} - V_{gr} > V_{tr}$ ($V_{tr} = 2\Omega_{tr}/k$ is the width of wave-particle resonance) is similar to dynamics in Langmuir waves. During the period of particle oscillations $2\pi/\Omega_{tr}$ ($\Omega_{tr} = k(e\varphi_k/m_e)^{1/2}$; ($\varphi_k$, is the amplitude) in wave fields the particles propagate on the distance $L = \pi(V_{ph} - V_{gr})/kV_{tr}$. For oscillations with $V_{ph} - V_{gr} > V_{tr}$ this distance is longer than wavelength $L > \lambda$ and hence the packet is transparent for particles. If the velocity distribution function f_o of particles, falling on packet, has positive inclination $\partial f_o/\partial V \geq 0$ then after packet $z > L$ in the

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resonant region $|V - V_{ph}| \le V_{tr}$ the derivative changes its sign $\partial f_o/\partial V \le 0$. Therefore particles damp oscillations in the resonant region at $z > L$, keeping up the length of packet equal to L. The latter provides that the area in phase space, occupied by one packet, does not change at a growing of packet's amplitude

$$2V_{tr}L \approx \lambda\left(V_{ph} - V_{gr}\right). \qquad (1)$$

Because after passing particles through packet derivative $\partial f_o/\partial V$ changes its sign in the resonant region and in the nonresonant region derivative remains previous, hence after packet steepenings on the distribution function are formed at velocities $V = |V_{ph} \pm V_{tr}|$. On these steepenings the growth rates of wave excitation are maximum. Therefore new packets with $V_{ph1,2} = |V_{ph} \pm V_{tr}(V_{ph})|$ are excited intensively after packet with V_{ph}. This phenomenon leads to ordering of wave fields. Hence if the propagation distance of resonant electrons during the half-period of their oscillations in wave fields L becomes shorter than correlation length $l_c = \pi(V_{ph} - V_{gr})/\gamma_k$ (γ_k is the linear growth rate of wave amplitude) the linear process turns out to be unstable concerning the arising of correlations of a particle movement and an electric field. This problem has been investigated in [5-11]. In this case the linear relaxation process turns into the ordered turbulent process which is characterized by a convective movement of particles on the phase space and by the appearance of the ordered structures of wave packets in space (z, V_{ph}).

Wave packets with V_{ph} near maximum one V_c at amplitude reaching values $V_{tr} \gg V_{ph} - V_{gr}$ reflect the main part of resonant electrons falling on the back front of packet and all resonant electrons falling on the first front of packet. It is determined by the fact that the propagation distance (relative to the packet's envelope) of resonant electrons during half-period of their oscillations in wave field $L = \pi(V_{ph} - V_{gr})/kV_{tr}$ becomes much shorter than the wavelength λ. Therefore after interaction with the packet the resonant electrons remain on its fronts, their velocities change on opposite ones and separatrix is not slammed behind them. Hence wave packets with $V_{ph} \approx V_c$ form a chain of packets reflecting resonant electrons. The width of this packet is approximately equal to the wavelength λ. At large amplitude this short packet is transformed into solitary electric potential well with potential shock in its vicinity

$$\Delta\varphi \approx \varphi_k\,(V_b - V_{ph})/\,V_{bth}, \qquad (2)$$

V_{bth} is the beam thermal velocity.

The growth rate of the well amplitude approximately equals

$$\gamma \approx \omega_{pe}\left(e\varphi_k\,/\,mV^2_{bth}\right)^{1/2}. \qquad (3)$$

The well is formed without a threshold in plasma with electron beam, with a threshold in current-carrying plasma and with a small threshold in current-carrying dusty plasma.

If the beam velocity V_b (or electron current velocity V_d in current-carrying plasma) is higher than $V_b > V_c + V_{tr}|_{Vph = Vc}$ then after the beam relaxation in resonant region $V_{ph}^{min} < V < V_c + V_{tr}$ the electron distribution function is nonequilibrium in the nonresonant region $V > V_c + V_{tr}$. Therefore the wave fields become unstable relative to modulation. Namely, the packets of the chain with $V_{ph} \approx V_c$ and with a large distance between them trap electrons with $V \approx V_c + V_{tr}$ with nonequilibrium distribution function and wave fields are excited further.

Similar behavior of wave turbulence is realized also in infinite plasma with electron beam in conditions $0 \le V_b/V_{bth} - (n_o/n_b)^{1/2} \le 1$. Here n_o, n_b are the densities of plasma and beam. It is determined by the fact that the high-frequency waves in infinite plasma have a dispersion relation similar to the waves in metallic magnetized plasma-filled cylinder if warm electron beam strongly influences on dispersion relation of waves. In latter case the frequencies of excited waves approximately equal $\omega \approx \omega_p$ for large wavevectors k and frequencies are proportional to k for small wavevectors if maximum phase velocity $V_{ph}^{max} = V_{bth}(n_o/n_b)^{1/2}$ satisfies $0 < V_b - V_{ph}^{max} < V_{bth}$.

The electron flow in nonequilibrium plasma can excite not only reflecting potential wells but also transparent potential humps, for example, Buneman potential hump in current-carrying plasma [12].

3. Conclusion

The formation of ordered structures of wave packets in plasma with electron beam and in current-carrying plasma has been investigated.

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