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Thermal effects in the dissipative instability of the electron beam-plasma systems

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Abstract

The effects of the thermal motion of the charged particles in the dissipative instability of the under and over-limiting currents of a relativistic electron beam in a fully magnetized beam-plasma waveguide is investigated. It is shown that by increasing the temperature of the plasma electrons, the resonant frequency of the waveguide slightly increases and the growth rates of the instability development decreases. In addition, an increase of the temperature of the plasma electron can change the dissipative hydrodynamic instability to the collisionless kinetic instability. Furthermore, the dissipative instability of the overlimiting electron beam is shown to be more sensitive with respect to the electron plasma temperature compared to the underlimiting electron beam case.

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1. Introduction

The electron beam in a plasma is one of the most colorful phenomena in plasma physics. The problem of electron beam propagation in a plasma is an essential issue for astrophysical, particle acceleration, microwave generation, and plasma heating [1–5]. Recently, most of the beam-plasma interaction experiments are gradually changed over to more and more high-current electron beams [6–8]. Electron beams propagation in plasma-filled structures has been studied. Originally, the idea was to develop microwave sources based on the excitation of slow plasma waves by fast beam electrons under the Cherenkov resonance condition. The instability of an overlimiting electron beam is due to the excitation of the beam wave with negative energy, or to the aperiodic modulation of the beam space charge in a medium with negative dielectric constant [7–9]. Along with the increase of the beam current, dissipation can play an important role in the dynamics of beam-plasma instability development [10–12]. because dissipation may also lead to the excitation of the beam wave with negative energy. The influence of dissipation on the interaction of an overlimiting electron beam with a plasma is an important issue in particle acceleration [13], microwave generation, and plasma heating [14,15]. The processes of dissipative phenomena and their instabilities are investigated in many papers by hydrodynamic description [16–21]. The effect of dissipation on the instability of the underlimiting and overlimiting electron beam wave with negative energy and the transition of this instability to the dissipative type when the level of dissipation increases have been investigated in the cold beam-plasma waveguides [21].

In the present Letter we investigate the effect of the thermal motion of the plasma electron on the development of the dissipative instabilities of under and over-limiting electron beam by the kinetic description. A fully magnetized beam-plasma waveguide is considered. Along with the growth rates in two

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different cases, the influence of the temperature of the plasma electrons on the mode structure of the instability is investigated. The effect of the thermal motion of the charged particles on the transition of dissipation of the under-limiting and over-limiting beam instabilities is treated in details. This shows that when the temperature of the electron plasma increases, the transition from the dissipative hydrodynamic instability to the collisionless kinetic instability can be seen. On the other hand, the increase of the temperature of the plasma electrons can change the nature of the dissipative beam instability. In addition, a comparison of the underlimiting and overlimiting electron beam cases is carried out.

This Letter is presented in three sections. In Section 2, we formulate the problem and the effects of the thermal motion of charged particles on the dissipative instability of the electron beam is studied. Finally, in Section 3, a summary and conclusion is presented.

2. Formulation and dissipative instability of the electron beam

We now consider a cylindrical waveguide fully filled with a warm plasma. A monoenergetic relativistic electron beams is injected into it. Furthermore, we suppose that the beam and plasma radii coincides with the waveguide radius. For simplicity, we assume that the external longitudinal magnetic field is to be strong enough and consider only the symmetrical E modes with nonzero components E_r, E_z, and B_φ. We assume that both the electron of the plasma and beam, in their intrinsic frame, have the Maxwellian distribution with nonrelativistic temperature.

It is well known that the interaction of an electron beam with a plasma is strong when the Cherenkov resonance condition is fulfilled, i.e., [22–25] when the beam has only a directed velocity component longitudinal to the external magnetic field. Now, we begin the analysis of the interaction of a straight mono-energetic electron beam with a plasma when the external longitudinal magnetic field is assumed to be strong enough to freeze the transversal motion of the beam and the plasma electrons. When the relativistic electron beam penetrates into a plasma, it is evident that such a beam must be directed strictly parallel to the external magnetic field. The validity of this model is restricted to the fast processes with characteristic velocities exceeding the thermal velocities of the charged particles. The dispersion relation of electromagnetics waves in such a beam-plasma system is written as follows [22–26]

$$k_\perp^2\varepsilon_{xx}+\left(k^2-\frac{\omega^2}{c^2}\varepsilon_{xx}\right)\varepsilon_{zz}=0, \tag{1}$$

where ω is frequency, $k_\perp, k$ are components of the wave vector perpendicular and parallel to the external magnetic field, respectively, and c is light speed. In the high-frequency range of a weakly ionized plasmas, i.e., $\omega \gg kv_{T_e}, \nu$, the dielectric permittivity tensor of this system under the aforementioned conditions, in the laboratory frame can be written as follows [22–26]

$$\begin{aligned}
&\varepsilon_{xx}=1,\\
&\varepsilon_{zz}=1-\frac{\omega_{pe}^2}{\omega^2}+\frac{i\nu\omega_{pe}^2}{\omega^3}-\frac{3\omega_{pe}^2k^2v_{T_e}^2}{\omega^4}\\
&\qquad+i\sqrt{\frac{\pi}{2}}\frac{\omega_{pe}^2\omega}{k^3v_{T_e}^3}\exp\left(-\frac{\omega^2}{2k^2v_{T_e}^2}\right)-\frac{\omega_b^2}{\gamma^3(\omega-ku)^2},
\end{aligned} \tag{2}$$

where ω_{pe} and ω_b are the Langmuir frequency of plasma and beam, respectively; u is the velocity of the electron beam in the direction of the external magnetic field, and v_{Te} is thermal velocity of the electrons in the plasma. Substituting Eq. (2) into Eq. (1), the dispersion equation of this system is obtained as follows:

$$\begin{aligned}
&k_\perp^2+\left(k^2-\frac{\omega^2}{c^2}\right)\left(1-\frac{\omega_{pe}^2}{\omega^2}+\frac{i\nu\omega_{pe}^2}{\omega^3}-\frac{3\omega_{pe}^2k^2v_{T_e}^2}{\omega^4}\right.\\
&\qquad\left.+i\sqrt{\frac{\pi}{2}}\frac{\omega_{pe}^2\omega}{k^3v_{T_e}^3}\exp\left(-\frac{\omega^2}{2k^2v_{T_e}^2}\right)-\frac{\omega_b^2}{\gamma^3(\omega-ku)^2}\right)=0,
\end{aligned} \tag{3}$$

where ω is the frequency at resonance, k is the component of the wave vector along z axis, $k_\perp=\mu_{0s}/R$, R is the waveguide's radius, μ_{0s} are the roots of zero order Bessel function, i.e., $J_0(\mu_{0s})=0$, $s=1,2,3,\ldots$, and $\gamma=(1-u^2/c^2)^{-1/2}$. The comparison of Eq. (3) with the dispersion equation of the cold beam-plasma system (see for example Ref. [22]), shows that an additional real and imaginary term appears which corresponds to the thermal motion of the plasma electrons. When the Cherenkov resonance takes place between the electron beam and plasma, the dispersion (3) determines the growth rates of the beam-plasma instability in the aforementioned plasma-filled waveguide. Then, the solution of the Eq. (3), can be written as

$$\omega=\omega_0+\delta=ku+\delta\quad\bigl(|\gamma|\ll\omega_0\bigr), \tag{4}$$

where $\omega_0=ku$, the resonant condition of the warm plasma waveguide, is the solution Eq. (3) without the electron beam contribution

$$\omega_0^2=\omega_{pe}^2+\frac{3\omega_{pe}^2k^2v_{Te}^2}{\omega_0^2}-k_\perp^2u^2\gamma^2. \tag{5}$$

The resonant condition of the cold plasma waveguide [22], is

$$\omega_0^2=\omega_{pe}^2-k_\perp^2u^2\gamma^2. \tag{6}$$

We can see from Eqs. (5)–(6) that the thermal motion of the electron plasma slightly increases at the resonant frequency of the waveguide. The electron beam can resonantly interact with the plasma only under the condition

$$\omega_{pe}^2+\frac{3\omega_{pe}^2k^2v_{T_e}^2}{\omega_0^2}>k_\perp^2u^2\gamma^2. \tag{7}$$

In the dissipative case, i.e., $\nu\gg\delta$, from Eqs. (3)–(6), we obtain

$$\begin{aligned}
&i\left(\frac{\nu\omega_{pe}^2}{\omega_0}+\sqrt{\frac{\pi}{2}}\frac{\omega_{pe}^2\omega_0^3}{k^3v_{T_e}^3}\exp\left(-\frac{\omega_0^2}{2k^2v_{T_e}^2}\right)\right)x^2+\frac{2\omega_b^2(\gamma^2-1)}{\gamma^3}x\\
&\quad=-\frac{\omega_b^2}{\gamma^3},
\end{aligned} \tag{8}$$

where $x = \delta/\omega_0$. The factor $[2(\gamma^2 - 1)]^{-1}$ corresponds to the ratio of the beam current to the limiting current in the vacuum waveguide [21]. This factor actually serves as a parameter that determines the beam current value and the character of the beam-plasma interaction. The solutions of Eq. (8), essentially depend on the value of δ/ω_0, and the factor $[2(\gamma^2 - 1)]^{-1}$. Comparing the values δ/ω_0, with factor $[2(\gamma^2 - 1)]^{-1}$ under the Cherenkov resonance interaction of the electron beam with the plasma, and analyzing Eq. (8), we obtain the following results.

2.1. *The underlimiting electron beam case*

When $(\delta/\omega_0) \ll [2(\gamma^2 - 1)]^{-1}$, corresponding to the dissipative underlimiting beam current, and assuming $\nu \gg \delta$, by neglecting the second term in the left-hand side of Eq. (8), we obtain the spatial growth rate of the beam instability in the warm plasma filled waveguide

$$\delta^{(\nu)}_{\text{unde}} = \frac{\sqrt{2}}{2}(1+i)\frac{\omega_0}{\gamma}\left(\frac{\omega_b^2}{\gamma\omega_{pe}^2}\right)^{1/2} \times \left(\frac{\nu}{\omega_0} + \sqrt{\frac{\pi}{2}}\frac{\omega_0^3}{k^3 v_{T_e}^3}\exp\left(-\frac{\omega_0^2}{2k^2 v_{T_e}^2}\right)\right)^{-1/2}. \tag{9}$$

This result corresponds to an unstable oscillation, $\text{Im}(\delta) > 0$. The instability in this case is named as dissipative underlimiting electron beam instability. This instability is caused by the induced radiation of the proper waves of the system. Since $\text{Re}(\delta) < 0$, and $\text{Im}(\delta) > 0$, we have $u > \omega/k$. Consequently, the beam electrons are faster than the wave and transfer a part of energy to it. We can see from Eq. (9), that the dependence of the growth rate on the resonant frequency and beam and plasma frequencies is $\omega_0^{3/2}$, ω_b, and ω_{pe}^{-1}, respectively.

2.2. *The overlimiting electron beam case*

When electron beam current increases and becomes comparable or higher than the limiting vacuum current $(\delta/\omega_0) \gg [2(\gamma^2 - 1)]^{-1}$, corresponding to the overlimiting beam current, the effect of the beam space charge changes the physical nature of the instability in the magnetized plasma-filled waveguide. It becomes similar to the instability in a medium with negative dielectric constant [22]. When this takes place, under the aforementioned conditions, neglecting the right-hand side term of Eq. (9), we obtain

$$\delta^{(\nu)}_{\text{ove}} = i\frac{\omega_0}{\gamma}\left(\frac{\omega_b^2}{\gamma^2\omega_{pe}^2}\right)\left(\frac{\nu}{\omega_0} + \sqrt{\frac{\pi}{2}}\frac{\omega_0^3}{k^3 v_{T_e}^3}\exp\left(-\frac{\omega_0^2}{2k^2 v_{T_e}^2}\right)\right)^{-1} \times \left[\frac{2(\gamma^2-1)}{\gamma}\right]^{1/2}, \tag{10}$$

corresponding to an unstable oscillation. We can see from Eq. (10), that the dependence of the growth rate on the resonant frequency, beam and plasma frequencies, is ω_0^2, ω_b^2, and ω_p^{-2}, respectively. By comparing Eq. (9), with (10), it is easily seen that the growth rate decreases by increasing the plasma frequency and increases by increasing the plasma and resonant frequencies. In addition, the dependence of the growth rate of the overlimiting electron beam case is more sensitive with respect to the electron plasma temperature compared to the underlimiting electron beam case.

3. Discussion

By using the total dielectric permittivity tensor in the laboratory frame, the dispersion relation of a fully magnetized beam-plasma waveguide system was obtained. Analyzing the dispersion relation, the growth rates of the various instabilities of the electron beam flowing in a warm plasma are investigated. The effects of the thermal motion of the charged particle in dissipative underlimiting and overlimiting electron beam current in the aforementioned system in the presence of a strong external magnetic field are studied.

In the weakly ionized plasma, the dependence of the dissipative parameter ν on the temperature of the plasma electron is as follows [27]

$$\nu \propto T^{5/6}. \tag{11}$$

When the temperature increases, the dissipative parameter ν of the plasma electron increases too. Indeed, in the fully ionized plasma this dependency will be as follows [22]

$$\nu \propto T^{-3/2}. \tag{12}$$

When the temperature increases, the dissipative parameter ν of the plasma electron decreases too.

The dependence of the growth rates on the thermal motion of the charged particle and dissipation, for various cases (a), (b), (weakly/fully ionized plasma) and various $(\omega_b/\omega_{pe}) = 0.2$, and $\gamma = 3$ with considers Eqs. (11)–(12) is plotted in Fig. 1.

By considering the growth rate of various cases (a), (b), (weakly/fully ionized plasma), illustrated in Fig. 1, the following results are obtained:

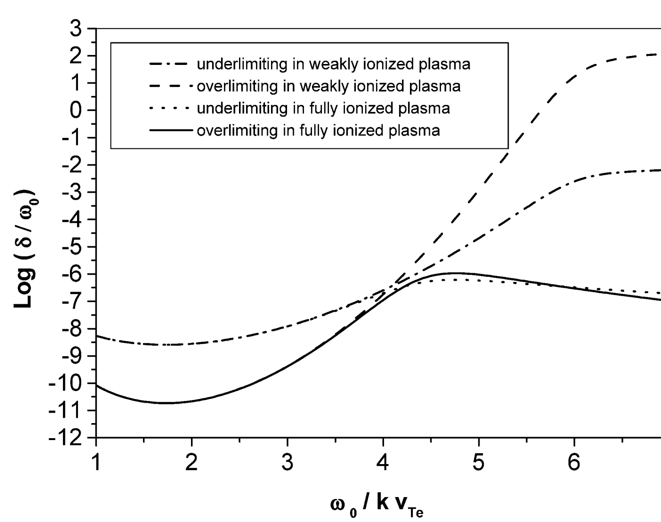

Fig. 1. Dependence of the growth rates on the thermal motion of the plasma electrons for the underlimiting and overlimiting electron beam propagation in the weakly and fully ionized plasmas when $\omega_b/\omega_{pe} = 0.3$, $\gamma = 3$ and $(\nu_0/\omega_0) = 0.1$. (ν_0) is dissipative parameter in the cold plasma.

(1) The thermal motion of the electron plasma slightly increases the resonant frequency of the beam-plasma waveguide system.

(2) Comparison of Eqs. (9), and (10), with the cold plasma case, shows that a collisionless Cherenkov wave absorption correction appears, which reduces the growth rates. In the range of long wavelengths when

$$\frac{\nu}{\omega_0} > \sqrt{\frac{\pi}{2}}\frac{\omega_0^3}{k^3 v_{T_e}^3}\exp\left(-\frac{\omega_0^2}{2k^2 v_{T_e}^2}\right), \tag{13}$$

or $(\omega_0/kv_{T_e}) > 4$ (decrease of the temperature of plasma electron), (Fig. 1), the collisionless Landau damping is negligibly small as compared to the collisional damping. In this case, dissipative beam instability can be developed and instability has dissipative collisional hydrodynamic beam instability character. In the opposite limit of short wavelengths when

$$\frac{\nu}{\omega_0} < \sqrt{\frac{\pi}{2}}\frac{\omega_0^3}{k^3 v_{T_e}^3}\exp\left(-\frac{\omega_0^2}{2k^2 v_{T_e}^2}\right), \tag{14}$$

or $(\omega_0/kv_{T_e}) < 4$, (increase of the temperature of plasma electron), (Fig. 1), the collisional damping is negligibly small compared to the collisionless Landau damping. In the other hand, increasing the temperature of the plasma electron or decreasing (ω_0/kv_{T_e}) the growth rate decreases. In this case, the dissipative beam instability cannot be developed and the instability has collisionless kinetic beam instability character. This shows that when the temperature of the electron plasma increases, the dissipative hydrodynamic instability changes to the collisionless kinetic instability. In the other hand, when the temperature of the electron plasma increases, the continuous transition from the hydrodynamic instability to the kinetic instability takes place.

(3) In the absence of dissipation, when $(\omega_0/kv_{T_e}) > 4$, the overlimiting electron beam case depends more sensitively on the thermal motion of the electrons plasma compared with the underlimiting electron beam case presented in Fig. 1. The growth rates decreases when the temperature of the plasma electrons increases. In the other hand, the growth rates of the dissipative instability of the overlimiting electron beam is more sensitive with respect to the electron plasma temperature compared to the underlimiting electron beam case.

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