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Collisional effects on the current-filamentation instability in a dense plasma*

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Abstract The collisional current-filamentation instability (CFI) is studied for a nonrelativistic electron beam penetrating an infinite uniform plasma. It is analytically shown that the CFI is driven by the drift-anisotropy rather than the classical anisotropy of the beam and the background plasma. Therefore, collisional effects can either attenuate or enhance the CFI depending on the drift-anisotropy of the beam-plasma system. Numerical results are given for some typical parameters, which show that collisional effects cannot stabilize but enhance the CFI in a dense plasma. Thus, the CFI may play a dominant role in the fast electron transport and deposition relevant to the fast ignition scenario (FIS).

Key words current-filamentation instability, weibel instability, collision, beam plasma interaction

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1 Introduction

It is generally thought that collisional effects on current-filamentation instability (CFI)[1] or Weibel instability as sometimes called[2, 3] are very important if the collision frequency is comparable with the CFI growth rate. In the fast ignition scenario (FIS) concept of laser fusion[4], the electron beam has to propagate through a cold dense plasma with the density up to $10^{21}\text{cm}^{-3} \sim 10^{26}\text{cm}^{-3}$. Under such conditions the collisional effects cannot be ignored any more. Therefore, the collisional CFI attracts renewed interest recently[5—8].

However, since the beginning, contrary results have been obtained for collisional effects on the CFI. Some support that they enhance the instability[5, 9, 10], while others show that they attenuate it[6—8, 11], making the problem rather confused. In the present paper, we clarify that the collisional effects can either enhance or attenuate the CFI depending on the drift-anisotropy of the beam and the background plasma. Moreover, the largest increment can be obtained in the case of a hot electron beam penetrating a cold dense plasma. This is very important because it strongly suggests that collisional effects probably cannot stabilize the CFI in the fast ignition scenario. Therefore, anomalous kinetic heating[12] may be dominant in the target heating. In Sect. 2, we briefly introduce the kinetic physic description of the CFI and obtain the corresponding dispersion equation. In Sect. 3, we mainly focus on some typical numerical solutions of the dispersion equation obtained in the former section and discuss the present predictions. Finally, summary and conclusions are presented in Sect. 4.

2 Collisional CFI dispersion equation

We start with the Vlasov-Krook equation[10, 13] for the electron distribution function f_α,

$$\frac{\partial f_\alpha}{\partial t}+\vec{v}_\alpha\frac{\partial f_\alpha}{\partial \vec{r}}+q_\alpha\left(\vec{E}+\frac{\vec{v}_\alpha\times\vec{B}}{c}\right)\frac{\partial f_\alpha}{\partial \vec{p}_\alpha}=-\nu_\alpha(f_\alpha-f_{\alpha 0}), \tag{1}$$

where q_α is the electron charge, ν_α is the effective collision frequency, and $f_{0\alpha}$ is the equilibrium distri-

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bution function.

Since we consider a homogeneous, spatially infinite, and unmagnetized plasma, where the ions are deuterium or tritium at rest to form a charge neutralized background, the distribution function for the electrons is approximated by

$$f_{0\alpha}(\vec{v}_\alpha)=\frac{n_{0\alpha}}{2\pi v_{t\alpha}v_{l\alpha}}e^{-v_x^2/2v_{t\alpha}^2}e^{-(v_z-v_{d\alpha})^2/2v_{l\alpha}^2}, \quad (2)$$

where α=b, p labels the beam electrons and the background electrons, respectively, and $n_{0\alpha}$, $v_{t\alpha}$, $v_{l\alpha}$, $v_{d\alpha}$ correspond to density, transverse thermal velocity, longitudinal thermal velocity and drift velocity of the α-type electrons, respectively. As for the collision frequency, we use an average temperature $\bar{T}_\alpha=(T_{t\alpha}+T_{l\alpha}+T_{d\alpha})/2$ to replace the isotropic thermal temperature T_α, where $T_{t\alpha}$, $T_{l\alpha}$ and $T_{d\alpha}$ represent the transverse thermal temperature, longitudinal thermal temperature, and the equivalently drift temperature caused by the drift velocity, respectively. We also take into account intra-beam collisions[14], where we have $\nu_b=\nu_{bb}+\nu_{bp}+\nu_{bi}$ for the beam electrons and $\nu_p=\nu_{pp}+\nu_{pb}+\nu_{pi}$ for the background electrons.

If we add Maxwellian equations to the system and linearize them, we can get the dispersion equation for the system:

$$\omega^2-\sum_\alpha\omega_\alpha^2-c^2k_x^2-\sum_\alpha\omega_\alpha^2\frac{v_{d\alpha}^2+v_{l\alpha}^2}{2v_{t\alpha}^2}Z'_\alpha-\mathrm{i}\sum_\alpha\omega_\alpha^2\frac{\nu_\alpha}{\sqrt{2}k_x v_{t\alpha}}Z_\alpha=0, \quad (3)$$

where

$$Z_\alpha=\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty}dt\frac{e^{-t^2}}{t-\xi_\alpha},$$

and

$$\xi_\alpha=\frac{\omega+\mathrm{i}\nu_\alpha}{\sqrt{2}k_x v_{t\alpha}}.$$

From Eq. (3) we can see that the classical anisotropic term v_{lb}^2/v_{tb}^2 driving the classical Weibel instability[2] is replaced by the drift-anisotropic term $(v_{lb}^2+v_{db}^2)/v_{tb}^2$. Thus, the CFI is determined by the drift-anisotropy of the beam and the background plasma.

3 Numerical calculations and results

There are usually no simple analytic solutions to Eq. (3), thus we mainly focus on numerical solutions here. Since the system can be described by hydrodynamic equations if the thermal effect is weak, we divide the plasmas into three configurations: the kinetic domain, the hydrodynamic domain, and the hybrid domain with one in kinetic and the other in hydrodynamic domain, which correspond to $|\xi_\alpha|\ll 1$, $|\xi_\alpha|\gg 1$, and $|\xi_b|\ll 1$, $|\xi_p|\gg 1$, respectively. For the Hybrid domain we also have another case where $|\xi_p|\ll 1$, $|\xi_b|\gg 1$. Since it is similar to the former case under the nonrelativistic constraint, we do not argue it here. Although we have artificially distribute the plasmas into three configurations for physical concept convenience, our numerical calculations indeed include regions $|\xi_\alpha|\sim 1$, where the beam-plasma system should be described by kinetic equations. The filamentation mode is found to be purely growing if we use the two-pole approximation for the plasma dispersion function[15] here, thus it does not undergo Landau damping.

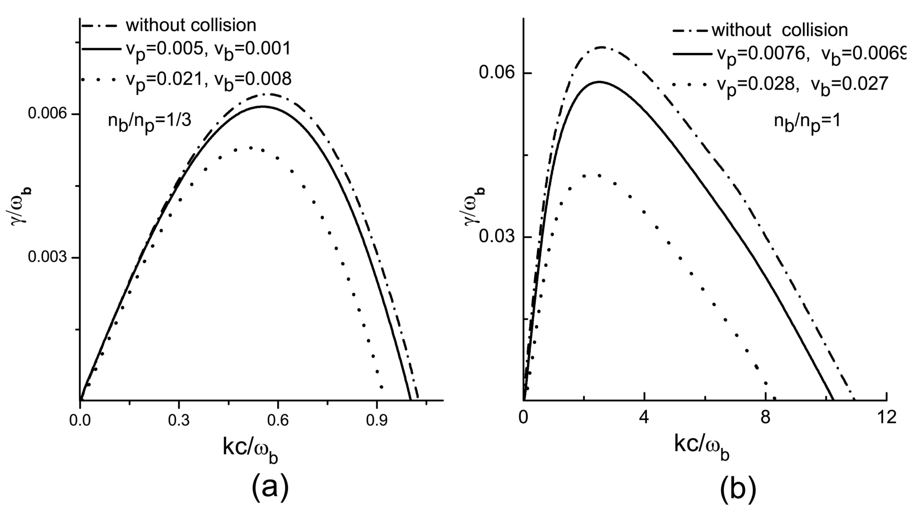

Fig. 1. The linear growth rate of the CFI versus the wave number k for symmetric or quasi-symmetric counter-streaming. The collision frequency is normalized to ω_b. The parameters are: case (a), $n_p/n_b=3$, $T_{tb}=T_{lb}$=10 keV, T_{db}=5 keV, $T_{tp}=T_{lp}$=3 keV, and case (b), $n_p/n_b=1$, $T_{tb}=T_{lb}$=100 eV, T_{db}=2 keV, $T_{tp}=T_{lp}$=20 eV.

Figures 1 (a) and (b) show the numerical growth rate of the CFI for the quasi-symmetric and symmetric counter-streaming in the kinetic and the hydrodynamic domain, respectively, from which attenuated CFI is identified. Usually, collisional effects change ω to $\omega+\mathrm{i}\nu_\alpha$, which cancels the growth rate in the order of ν_α. It is often the case in the hydrodynamic domain. For the kinetic domain, the background electron collision usually shifts the electron from kinetic domain to hydrodynamic domain, leading to increment of the CFI. Usually, the attenuating effects excess the enhancing effects for the symmetric or quasi-symmetric counter-streaming, and the CFI is still decreased. However, the net reduction in the kinetic domain is much less than the collision frequency. This is shown clearly in Fig. 1 (a).

In the case of a much denser background plasma, i.e., the asymmetric counter-streaming case, the collisional effects can enhance the CFI a lot, especially in the long wavelength region. Usually, a dense background is much less drift-anisotropic than the beam under current neutralization condition[16] $v_{\mathrm{dp}}=-n_{\mathrm{b}}v_{\mathrm{db}}/n_{\mathrm{p}}$. Therefore the CFI of the beam-plasma system is mainly driven by the beam. The dense background, however, usually stabilize the CFI of the beam-plasma system, which is approved by the comparison of case I and II in Fig. 2 (b). When collisions are taken into account, the beam electron collision frequency is usually much smaller than the CFI growth rate, which can hardly decrease the CFI. As for the background electron collision, although it causes detuning between the background electron perturbations and its corresponding reactive fields, resulting in reduction in the contribution of the background electron to the beam-plasma CFI. But since the dense background electron's contribution to the CFI is little, the background electron collision can reduce the CFI little. Instead, it spoils the ordered collective movement of the background electron and greatly decreases the stabilization effect of the background plasma to the beam-plasma system, leading to increment of the CFI. For the asymmetric counter-streaming where the background is much denser than the beam, the enhancing effects excess the attenuating effects, so the CFI is increased finally. This is shown in Fig. 2.

In Fig. 2 (a), the collisional effects shift the beam-plasma system from the kinetic domain to the hybrid domain in the long wavelength region, where we can see the CFI is improved significantly. For short wavelength region $kc/\omega_{\mathrm{b}}\geqslant 1$ where the wave frequency is much larger than the collision frequency and the system is still in the kinetic domain, the CFI is still attenuated a little. That is because thermal effect is still significant for the region. In Fig. 2 (b), especially for case II, the collisional effects even shift the whole system from the kinetic domain to the hydrodynamic domain, where we can see the CFI growth rate is enhanced for a factor.

4 Summary and concluding remarks

We have kinetically investigated the collisional effects on the current-filamentation instability (CFI), using general drifting Maxwellian distribution func-

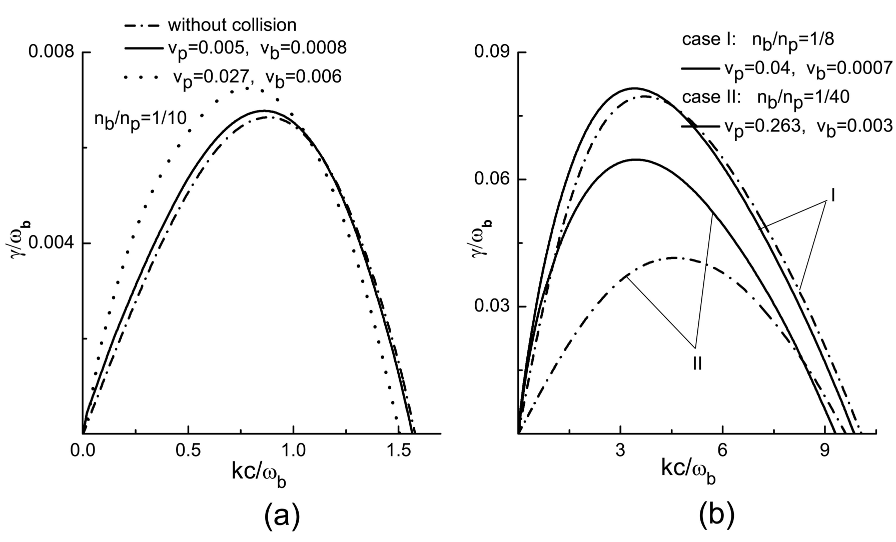

Fig. 2. The linear growth rate of the CFI versus the wave number k for asymmetric counter-streaming. The parameters are: case (a), $n_{\mathrm{p}}/n_{\mathrm{b}}=10$, $T_{\mathrm{tb}}=T_{\mathrm{lb}}$=5 kev, T_{db}=10 keV, $T_{\mathrm{tp}}=T_{\mathrm{lp}}$=2 keV, and case (b), $T_{\mathrm{tb}}=T_{\mathrm{lb}}$=100 eV, T_{db} =9 keV, $T_{\mathrm{tp}}=T_{\mathrm{lp}}$=100 eV.

tions and the Vlasov-Krook-Maxwell equations. For simplicity we constrain our study to the nonrelativistic case. Generally, the Krook collisional operator[13] cannot conserve the particle number, the momentum and the energy. As a result we confine our analysis to the weakly collisional plasmas. The largest collision frequency in this manuscript is only 0.04 (normalized to the corresponding plasma frequency), which not only makes the Vlasov-BGK equation an appropriate approach, but also ensures the assumption of zero-order fields reasonable.

Under the above considerations, we find analytically that the CFI is driven by the drift-anisotropy of the beam-plasma system. Therefore, collisional effects can decrease the CFI for symmetric or quasi-symmetric counter-streaming but enhance it for asymmetric counter-streaming. Our numerical solutions show that the increment can be significant especially for a hot beam penetrating a cold dense background plasma.

Although we obtain the above results in the non-relativistic case, similar results could be expected in the relativistic case. Thus our investigations are helpful to understand the beam-plasma interactions associated with plasma astrophysics, and especially the FIS, where a hot relativistic electron beam has to penetrate into a cold dense plasma. Since our results show that the CFI is enhanced for the ultra asymmetric counter-streaming, it suggests that anomalous kinetic heating might be a hopeful candidate for the heating mechanism in the FIS.

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