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Turbulence Effect on the Growth of the Electromagnetic Instability Modes in the Fast Ignition Scheme

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Abstract

In the fast ignition scheme of the inertial confinement fusion process, turbulence plays a significant role in the energy deposition mechanism and the implosion of the target plasma. In this paper, the growth of electromagnetic modes observation in the turbulent plasma that formed as the result of power laser beam interaction with fusion fuel is analyzed. The results show that the body stress threshold for the instability of the purely transverse mode is 1.5 times the shear stress threshold. The body stress threshold for the instability of the transverse-longitudinal coupled mode is 0.83 times the shear stress threshold. The instability growth rate maximum for the purely transverse mode is about 0.01 times higher than that of the transverse-longitudinal coupled mode. By decreasing the density gradient of plasma twoard fuel core, the stress threshold is increasing, and the range of the propagation angles of growing modes is limited. Increasing steps of the density gradient of the fuel in the low-density corona, the electromagnetic instability occurs at a higher stress flow.

Keywords: Plasma turbulence; Stress flow; Electromagnetic modes; Fast ignition scheme; Density gradient.

Introduction

When ultra-intense lasers (>1018 W/cm2) interact with fuel fusion, the electron beams are produced at the critical density surface. The return cold electron currents are concurrently produced in the background for the requirement of charge neutrality in plasma [1]. The equilibrium between a fast electron beam and the return currents is unstable, which will produce strong electromagnetic perturbation and filaments of the fast electron beam. It makes the energy transport effectiveness very poor and the intense fast electrons cannot transport beyond the filament length [2–4]. The crossed gradients of electron pressure and plasma density are generated magnetic fields (~ 0.1 MG), which arise in the turbulent zone and increase with its development. The stress and viscosity affect convective flow in heat losses that lead to increasing anisotropic temperatures. In this condition, turbulence and steers flow must play an important role in the context of the dispersion relation for the transverse waves. The laser-plasma interactions and resultant instabilities in the fast ignition process have been studied by many researchers experimentally and theoretically in the past few decades[5-7]. The effect of such stress has been often neglected in the calculation of the instability growth rate of the electromagnetic modes. In this paper, the role of turbulence and stress flow on the instability growth of the electromagnetic modes in the density gradient of fusion fuel is explored.

Theoretical model

We consider a dense plasma composed of immobile ions and electrons where the electronic density varies along the x-axis. The distribution function is rotationally symmetric around the x-axis. The wave vector k chose in the x-y plane without loss of generality. The deformation distribution f_0 is quasi-Maxwellian, expressed in terms of the stress and velocity anisotropy that is expressed by

$$f_0(v)=\sqrt{\eta}\left(\sqrt{2\pi}v_T\right)^{-3}\exp\left((-\eta v_x^2+v_y^2+v_z^2)/2v_T^2\right)[1+\frac{p_{xy}}{v_T^2}\left(\sqrt{\eta}v_x v_y\cos 2\theta+\frac{\eta}{2}v_x^2\sin 2\theta-\frac{1}{2}v_y^2\sin 2\theta\right)$$
$$+\frac{p_{xx}}{4v_T^2}\left(\eta v_x^2(2\cos^2\theta-\sin^2\theta)-v_y^2(2\sin^2\theta-\cos^2\theta)-6\sqrt{\eta}v_x v_y\sin\theta\cos\theta-v_z^2\right)+v_y^2(2\sin^2\theta-\cos^2\theta))] \quad (1)$$

where P_{xx} and P_{xy} respectively are the body stress and shear stress normalized by $n_e m v_T^2$, θ is the angle between the wave vector and the x-axis, $\eta(x, t) = n_0/n_e(x, t)$ is the density gradient in the x-direction by the temperature anisotropy of the distribution function. For variation modes of electromagnetic perturbations propagating in plasma, the linear dispersion relation by solving the linearized Vlasov equation as given below:

$$\frac{\partial f_1}{\partial t}+v\frac{\partial f_1}{\partial \vec{r}}+\frac{q}{m}(E_1+\frac{\vec{v}}{c}\times B_1)\frac{\partial f_0}{\partial v}=0 \quad (2)$$

Substitution of the distribution function into the Vlasov equation yields the dielectric tensor as follows

$$\left|((k_\alpha k_\beta/k^2)-\delta_{\alpha\beta})(kc/\omega)^2+\varepsilon_{\alpha\beta}(k,\omega)\right|=0 \quad (3)$$

The dispersion relation for purely transverse mode is given by:

$$\varepsilon_{zz}-(kc/\omega)^2=0 \quad (4)$$

The growth rate of the electromagnetic purely transverse mode is given by:

$$\delta=\frac{kv_T}{\eta\sqrt{\pi\eta/2}}\frac{\eta-1-\eta p_{xy}\sin 2\theta-\frac{3}{2}\eta p_{xx}\cos^2\theta-\left(\frac{kc}{\omega}\right)^2}{1-\frac{3}{2}\eta p_{xy}\sin 2\theta-\frac{1}{4}p_{xx}(9\cos^2\theta-1)} \quad (5)$$

For the transverse-longitudinal coupled mode, the dispersion relation is given by:

$$\varepsilon_{xy}{}^2 - \varepsilon_{xx}\varepsilon_{yy} + \varepsilon_{xx}(kc/\omega)^2 = 0 \qquad (6)$$

The growth rate of the electromagnetic transverse-longitudinal coupled mode is determined by

$$\delta = \frac{kv_T}{\sqrt{\pi/2}} \frac{\eta - 1 + \frac{\pi}{2}Q + 2\eta p_{xy}\sin 2\theta - \frac{3}{2}\eta p_{xx}(1-2\sin^2\theta) - \left(\frac{kc}{\omega}\right)^2}{\eta\sqrt{\eta}(1-\frac{5}{2}p_{xy}\sin 2\theta - \frac{1}{4}p_{xx}(8-15\sin^2\theta)) - Q(\frac{\eta\pi}{2}\frac{1-3p_{xy}\sin 2\theta - \frac{1}{4}p_{xx}(2-3\sin^2\theta)}{1-p_{xy}\sin 2\theta - \frac{1}{2}p_{xx}(2-3\sin^2\theta)} - 4)},$$

$$Q = \eta\frac{p_{xy}^2\cos^2 2\theta + \frac{9}{16}p_{xx}^2\sin^2 2\theta + \frac{3}{2}p_{xy}\cos 2\theta p_{xx}\sin 2\theta}{1-p_{xy}\sin 2\theta - \frac{1}{2}p_{xx}(2-3\sin^2\theta)}. \qquad (8)$$

The electromagnetic instability occurs provided that $\delta>0$. Without stress, the growth rate of the transverse-longitudinal coupled mode is equal to the electromagnetic instability growth rate for the purely transverse mode.

Results and discussion

The dependence of the stress threshold value for the growth of the purely transverse mode and the transverse-longitudinal coupled-mode on the angle of propagation is shown in figure 1. a and figure 1. b, respectively. The region of the electromagnetic instability in the P-θ plane is shown with the shaded region. When the stress rate is greater than P_{min}, the electron emission is unstable. As shown in Fig. 1.a, for the purely transverse the body stress rate threshold becomes minimum; $P_{xx,cut} = -2[(kc/\omega_p)^2+1-\eta]/3\eta)$, when $\theta_{cut}=n\pi(n=0, 1, 2, 3)$. If $|P_{xx}|>P_{xx,cut}$, the state is unstable. The threshold has the minimum values, $P_{xy,cut}=(1/2\eta)[(kc/\omega_p)^2+(1-\eta)]$, when the propagation angle satisfies the condition $\theta_{cut}=(2n+1)\pi/4$, (n=0, 1, 2, 3). If $|P_{xy}|>P_{xy,cut}$, the state is unstable. At θ_{cut} angles, the transverse-longitudinal coupled mode is decoupled, and it reduces to the ordinary transversal mode. As the stress flow increases beyond the threshold, the range of the propagation angles of growing modes of instability in plasma becomes wider. As can be seen from figure 1.b, the threshold has the minimum values, $P_{cut} =[3\eta+(kc/\omega_p)2+(1-\eta)]/3\eta$, when the propagation angle satisfies the condition $\theta_{cut}=(2n+1)\pi/2$, (n=0, 1, 2, 3). The contour of the distribution function is nearly an ellipse in the k-E plane. Therefore, the threshold value reaches the minimum one when the propagation direction coincides with the short axis of the ellipse-like contour. The growth rate of the electromagnetic modes as a function of angle, θ, for different values of the density gradient, is shown in Fig. 2. Noticeable quick changes in the electromagnetic instability occur around η=0.1. By heating the plasma by laser radiation in the small region of the fuel, the instability growth rate maximum for the transverse-longitudinal coupled mode is about 100 times higher than that of the purely transverse mode.

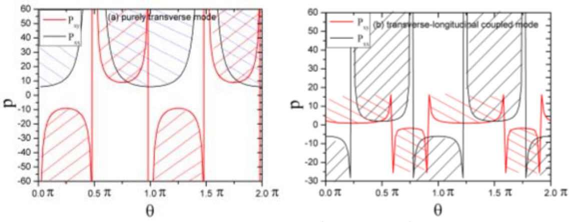

Figure 1. The stress, $P=P_{xx}$, P_{xy}, as a function of the angle between the velocity and the wave vector, θ for (a) the purely transverse mode,(b) the transverse-longitudinal coupled mode.

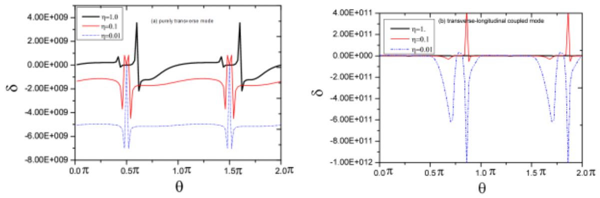

Figure 2. The growth rate of (a) the purely transverse mode and (b) the transverse-longitudinal coupled mode , as a function of the rotation angle, θ, for the different value of η.

Conclusions

In the present work, the influence of plasma turbulence due to the shear stress and body stress flow on the growth of the electromagnetic modes in the fusion fuel has been discussed. The effect of fuel plasma turbulence on electromagnetic instability due to anisotropic temperatures and perturbation of the energy deposition symmetry is considered. The electromagnetic instability plays a vital role in stopping the hot electrons and the energy deposition mechanism. The range of angles of propagation of unstable modes in the fusion fuel for body stress will be wider than that of shear flow. The minimum value of the shear stress threshold for the instability of the transverse-longitudinal coupled mode is 1.2 times the minimum value of the body stress. Whereas the minimum value of the body stress threshold for the instability of the purely transverse mode is 1.5 times the minimum value of the shear stress. The electromagnetic instability growth rate for the transverse-longitudinal coupled mode is 100 times the purely transverse mode. By 0.001 times of the density gradient leads to about 35 times the unstable wave-number threshold. By decreasing the density gradient of the plasma toward the fuel core, the stress threshold is increasing, and the range of the propagation angles of growing modes is limited. Therefore, by increasing the steps of the density gradient plasma in the near electron beam-emitting region, electromagnetic instability occurs at a higher stress flow.

References

[1] S. Atzeni and J. Meyer-tar-Vehn, Inertial Fusion-beam Plasma Interaction, Hydrodynamic, Dense Plasma Physics, Clarendon, Oxford(2003).

[2] Liu, Xu, and Lunjin Chen, *Instability in a relativistic magnetized plasma*, Physics of Plasmas 26, 042902 (2019).

[3] Gremillet, L., D. Bénisti, E. Lefebvre, and A. Bret. *Linear and nonlinear development of oblique beam-plasma instabilities in the relativistic kinetic regime,* Physics of plasmas 14, 040704(2007).

[4] Bret, A., M-C. Faro and C. Deutsch, *Characterization of the initial filamentation of a relativistic electron beam passing through a plasma*, Physical review letters, 94, 115002(2005).

[5] M. Mahdavi, and F. Khodadadi Azadboni, *The effect of density gradient on the growth rate of relativistic Weibel instability*, Phys. Plasmas 21, 055501(2014).

[6] T. Abe and K. Ni, *Anomalous Viscosity due to Weak Turbulence in Imploding Target Plasma,* Tokyo Institute of Technology Yokohama, 1980.F

[7] Khodadadi Azadboni, *Quantum effects role on the electromagnetic instability growth rate in turbulent state of the fuel fusion*, Chinese Journal of Physics 71, 375-384 (2021).